Surface Tracking on Pressboard in Natural and Synthetic Transformer Liquids under AC Stress

X. Yi and **Z. D. Wang**
School of Electrical and Electronic Engineering
The University of Manchester
Manchester, M13 9PL, UK

ABSTRACT

Experimental investigations were carried out to study the tracking process on pressboard in esters under ac voltages. The evolutions of creepage discharges were analyzed by correlating the visual records of surface tracking, the phase resolved PD patterns, the discharge current signals and the high speed shadowgraph images. It is found that the impregnated pressboard is susceptive to discharge erosion occurring on and inside the pressboard, which is characterized by "tree-shaped white and carbonized marks". The gaseous "white mark" channels would attract the subsequent discharges to follow the same routes, and the accumulative energy dissipation in these channels would then result in the carbonization of the channels and the emergence of a "carbonized mark". Once formed, the tree-shaped mark can continue to grow even under a reduced voltage or after a re-impregnation, until it bridges the gap and causes a final flashover. For a mineral-oil-impregnated pressboard, high moisture content (>3.5% by weight) is a necessity to initiate a "white mark"; whereas the "white mark" appears at a lower voltage and develops more easily on a dry ester-impregnated pressboard.

Index Terms — **Creepage discharge, mineral oil, natural ester, partial discharge, synthetic ester, surface tracking.**

1 INTRODUCTION

CREEPAGE discharges along the solid-liquid interface tend to cause damage to the solid insulation [1-3]. The damage to the solid surface is called tracking which includes two types: one is driven by sustained ac stress and can cause long-term damage to the pressboard surface through accumulative erosion; the other is driven by instant flashover, in which the pressboard surface fibres are burnt by the high current arcing [4]. The instant flashovers are usually observed during transformer factory impulse tests. For operating transformers, with the protection of arresters or co-coordinating rod gaps [5], the instant flashover rarely occurs unless in extreme situations, whereas the long-term erosion type of tracking is the dominant one, and, over a period of time, it can cause irrecoverable carbonized paths to spread on pressboards and lead to a final flashover. This type of surface tracking can be found in scrapped old transformers with tree-shaped mark left on the pressboard barriers [1, 3, 6]. Figure 1 shows an example of such cases.

During long-term tracking, the tree-shaped white mark tends to appear on the pressboard surface before the formation of carbonized mark. The white mark was considered to be created by the evaporation and decomposition of mineral oil and moisture, due to the discharges on the surface layers [1, 3].

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The recent work published in [7] and [8], indicated that white mark on the dry mineral-oil-impregnated pressboard (moisture content less than 0.5% by weight) is extremely difficult, if not possible, to initiate. On the other hand, white mark can be initiated by discharges on wet pressboards in mineral oil. It is clear that moisture should be one of the key factors responsible for the white mark on the mineral-oil-impregnated pressboard in aged transformers.

Figure 1. Tree-shaped mark on the pressboard barrier in a scrapped transformer [1].

Due to good biodegradability and high resistance to fire risk, synthetic and natural esters have been widely used for distribution and traction transformers. However, before applying esters in high voltage and large power transformers, it is important to understand the dielectric performance of cellulose-ester composite insulation, especially its capability to withstand the long-term surface tracking.

This paper addresses the surface tracking phenomenon along the pressboard-ester interface under sustained ac stress. The various stages of surface tracking and the evolution of the accompanying creepage discharge patterns were investigated. The surface tracking process on the pressboard in esters was also compared with that in mineral oil.

2 TECHNICAL BACKGROUNDS

In operating transformers, especially the aged ones, local electric field concentrations might exist, such as sharp edges caused by winding deformation, moisture and particles in oil [1]. These internal defects could initiate discharges. After the discharges are initiated, their propagation from winding to winding is prevented by pressboard cylinders. Instead, the discharges would propagate on the surface of a pressboard along which the electric field is divergent. Therefore, in many laboratory research, needle-plane electrodes were usually chosen to initiate creepage discharges and to study the discharge propagation and surface tracking [7-14].

Regarding the flashover under impulse stress, it is reported in [9, 11, 14] that, for point-plane gaps up to 150 mm, the presence of a pressboard barrier does not reduce the 50% breakdown voltage, when compared to an open gap test. The pressboard surface only tends to speed up the creepage streamer. At 50% impulse breakdown voltage, the powerful arc can burn and carbonize the surface fibres, leaving tree-shaped mark on the pressboard. This instant surface tracking is more significant under negative polarity and on pressboards impregnated by mineral oil than by esters [4].

Regarding the creepage discharges under sustained ac stress, our previous work [15] found that pressboard surface tends to promote the development of discharges, especially those occurring in the negative half cycles, and make more discharges shift towards the zero-crossing phase angles. These may be caused by the memory effect of pressboard surface for residual charges and low-density channels. Due to higher discharge intensity and higher viscosity, esters tend to exhibit the discharge promotion effect more evidently than mineral oil, especially when the samples are stressed at a higher voltage.

When the pressboard is overstressed by further increasing the applied voltage, tree-shape white mark would appear on the pressboard surface, as we reported in [16]. In this preliminary study, how the white mark was initiated and developed into flashover was reported, but the carbonized mark as seen in scrapped transformers was not observed, as the white mark grew fast and soon induced a complete flashover. It was then assumed that the white mark should be a channel of trapped gaseous bubbles within the surface layers of pressboard. Based on our preliminary work, extensive verification experiments were conducted in order to deepen the understanding of the long-term surface tracking mechanisms. In particular, the carbonization process of white mark was restored and the carbonized mark as seen in scrapped transformers was reproduced. Meanwhile, the gaseous nature of white mark was proved by verification experiments. The details are presented in this paper.

3 EXPERIMENTAL DESCRIPTIONS

3.1 LIQUIDS UNDER INVESTIGATION

A synthetic ester MIDEL 7131 and a natural ester FR3 were studied; a mineral oil Nytro Gemini X was used as the benchmark for cross comparisons.

The insulating liquid samples used in the tests were directly obtained from barrels without further filtering. During the whole period of the experiment, the moisture contents of the samples were measured according to Karl Fisher titration method, using Metrohm 684 coulometer and 832 Termoprep oven. The moisture contents of the three liquids were below 100 ppm (less than 10% of the moisture saturation level) for esters and below 10 ppm (less than 20% of the moisture saturation level) for mineral oil.

3.2 PRESSBOARD PROCESSING

The pressboard samples were dried in an air circulating oven for 48 hours at 105 °C. Then the dried samples were transferred into a vacuum oven for further drying at 85 °C for 24 hours. Afterwards, the dried pressboard samples were impregnated with insulating liquids in the same vacuum oven at 85 °C for another 48 hours. The pressure in the vacuum oven was kept below 5 mbar. After these procedures, the moisture contents of pressboards impregnated in the three liquids were all below 0.5% by weight and the pressboard samples can thus be defined as dry according to [17]. For mineral-oil-impregnated pressboards, some dry samples were humidified with a uniform moisture content of about 3.5 or 4.3%. This was achieved by placing the dry mineral-oil-impregnated pressboard into a desiccator with the relative humidity controlled by a glycerol-water solution for several months [18].

3.3 TEST CONFIGURATION

Needle to plate electrodes were adopted to initiate discharges. Medical needles were used as the point electrode. The needles were selected under an optical microscope. The tip radius was steadily controlled between 6-7 μm from the front view and 2-3 μm from the lateral view. The half taper shaped needle tip can help ensure its close contact with the pressboard surface. The plate electrode is 60 mm in diameter and 5 mm in edge radius. The gap distance is 50 mm.

In the current configuration, the pressboard was in parallel with the needle-plane axial line, so the electric field is the highest along the tangential direction of the pressboard. Therefore, creepage discharges would be aided. If the needle exhibits a slope angle to the pressboard, the tracking would require a higher voltage. In the experiment, multiple samples were tested for each type of liquid. This is to offset the influence of the needle position on the tracking process, because the pressboard surface is with meshed extrusions, and the distribution of fibres and pores in the pressboard exhibits a certain degree of randomness.

The test circuit is shown in Figure 2. An 1 MΩ water resistor was connected between the test cell and the supply transformer. This can limit the energy during breakdown/flashover and reduce the damage to the samples. An over-current relay at the 240 V side was set to trip off the power supply when the current exceeded 3 A. An LDS-6 PD detector was used to measure the apparent charges. A 50 Ω resistor and a wideband oscilloscope were used to obtain discharge current signals. A digital camcorder was utilized to record the tracking process on the pressboard surface from the front view. In addition, the samples were lit up by an intense light source and a high-speed CCD camera was used to observe the discharges and the generated bubbles from the lateral side.

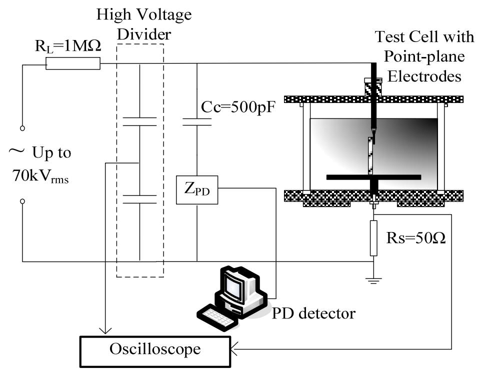


Figure 2. Test circuit diagram.

4 TEST RESULTS

4.1 INITIAL CONDITIONS FOR SURFACE TRACKING

An ac voltage was applied continuously. If there was no visible trace on the pressboard surface within 30 minutes, the voltage was further increased by a step of 4-5 kV, until visible changes on the pressboard surface could be observed by the naked eye.

As shown in Figure 3, at lower voltages, a dark shadow was observed on the pressboard. This indicates the carbonization of insulating liquid and surface cellulose fibres by local discharges. When the voltage was further increased, a white dot gradually appeared on the pressboard surface around the needle tip. The white dot would expand into a tree-shaped white mark over time.

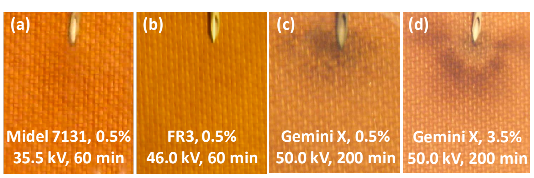


Figure 3. Shadow areas on pressboards around needle tip (the percentages indicate the moisture content by weight).

The white mark was sometimes observed on the pressboards at 36.5 kV in MIDEL 7131 and at 47.0 kV in FR3, after applying the voltage for more than 10 minutes. On the dry pressboard in Gemini X, no white mark was observed until 52.0 kV at which flashover would occasionally occur. On the wet pressboard with a moisture content of 3.5% in Gemini X, at up to 52.0 kV, only a dark shadow area was observed, with its centre dried by the intense discharge around the needle tip. For wetter pressboards with a moisture content of 4.3%, a white dot would emerge on three out of four samples tested at 50.0 kV.

The test results above indicate that, only with sufficiently intensive discharges, could the white mark be initiated on the pressboard surface. Particularly, for the pressboard impregnated in mineral oil, excessive moisture is necessary to stimulate intense discharges and thus the surface tracking process on the pressboard. This is because of the lower ionization potential of water molecules than that of mineral oil (1 eV compared to above 7 eV [19]). Water molecules in wet pressboards can be easily ionized and generate intense discharges.

After the emergence of a white mark, the surface tracking was observed and correlated with the discharge signals. The tracking process and evolutions of the accompanying discharge patterns were found to be similar in the three liquids investigated; therefore, in the following section, only the surface tracking on the pressboard in MIDEL 7131 is given in detail.

4.2 SURFACE TRACKING PROCESS ON PRESSBOARD IN MIDEL 7131

The surface tracking process on a pressboard sample in MIDEL 7131 is shown in Figure 4. The voltage was sustained at 43.0 kV. The surface tracking process was classified into five stages before the final flashover. This is based on correlating the phase-resolved PD patterns (Figure 5), the discharge current signals (Figure 6) and the shadowgraph images (Figure 7). The details are given below.

4.2.1 STAGE ONE

4.2.1.1 VISUAL RECORD

After the pressboard was added, spark discharges were frequently observed and they are shown in Figures 4b and 4c.

4.2.1.2 PD PATTERN

The PD pattern in stage one is shown in Figure 5a. The introduction of the pressboard increased the discharge amplitude when compared to the test in open gap (2300 pC maximum); but the overall PD pattern did not differ from the open gap test.

4.2.1.3 DISCHARGE CURRENT SIGNALS

The discharge current signals in stage one are shown in Figures 6a, 6b and 6c. The current signals of discharges occurring in the positive half cycles comprised a train of high frequency pulses superimposing a continuous dc component, whereas the discharge current signals in the negative half cycles were composed of a train of high frequency pulses which were larger and more coarsely spaced at the tail part. The patterns of the discharge currents in this stage were similar to those in open gap and those creeping along the pressboard surface at lower voltages [15].

4.2.1.4 SHADOWGRAPH IMAGES

As shown in Figure 7a, at this stage, the discharges had long channels extending along the pressboard surface or in the liquid near the surface, which confirms that discharges in this stage are the liquid type of discharges.

4.2.2 STAGE TWO

4.2.2.1 VISUAL RECORD

The energy dissipated by the local spark discharges initiated a small white dot on the surface of the pressboard (shown in Figure 4d). After the white dot appeared, the spark discharges concentrated on the white dot area (shown in Figure 4e) and drove the extension of the white dot with time.

4.2.2.2 PD PATTERN

As shown in Figure 5b, the PDs during this stage started to differ from those in stage one, in terms of both the amplitude and the pattern. The accompanying PDs could be as large as 6000 pC. The phase shift over the zero-crossing instants of the ac voltage can be clearly seen and the discharges occurring around or even

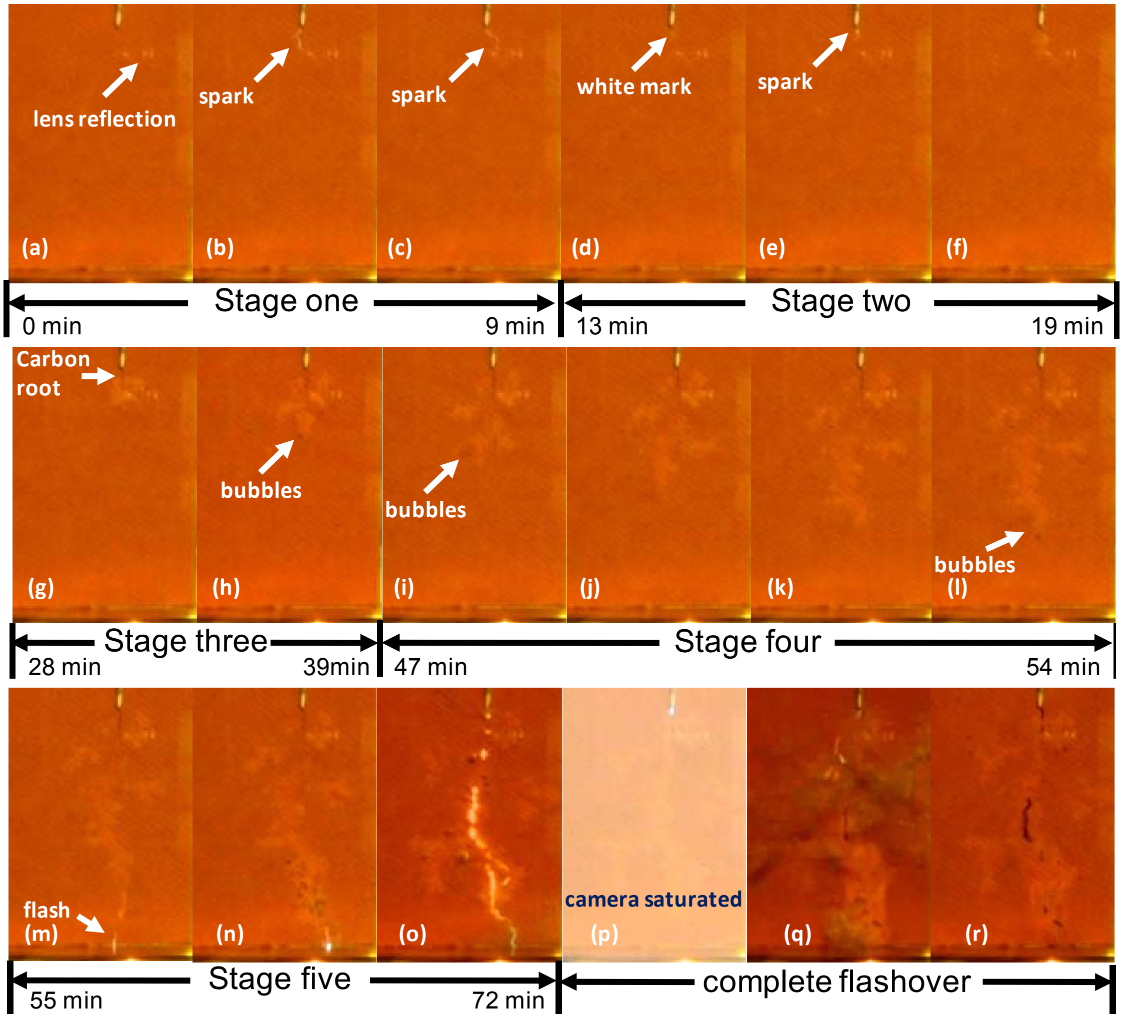


Figure 4. Surface tracking process on a pressboard in MIDEL 7131 at 43.0 kV.

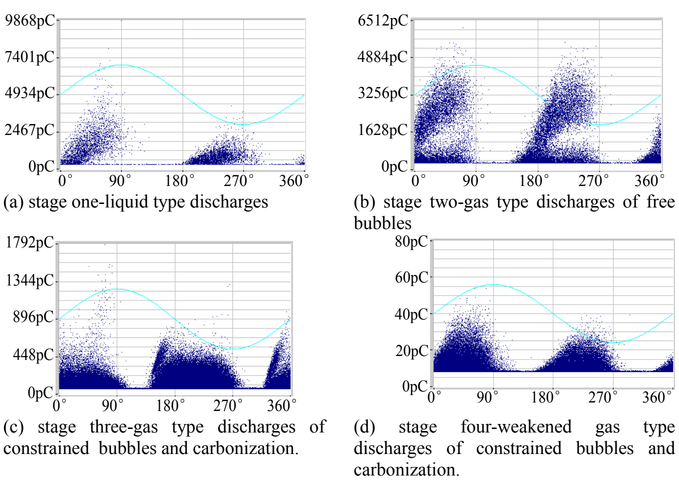


Figure 5. Evolution of phase resolved PD pattern at different stages of surface tracking process on a pressboard in MIDEL 7131 at 43.0 kV.

before the zero-crossing instants could still maintain apparent charge values as large as 2000 pC.

4.2.2.3 DISCHARGE CURRENT SIGNALS

The discharge current signals at this stage are shown in Figures 6d and 6e. The current signals were significantly different from those in stage one; they resembled gaseous discharges in terms of a very fast rising edge and short sustaining time [20]. The pulse peak values were up to 60 mA.

4.2.2.4 SHADOWGRAPH IMAGES

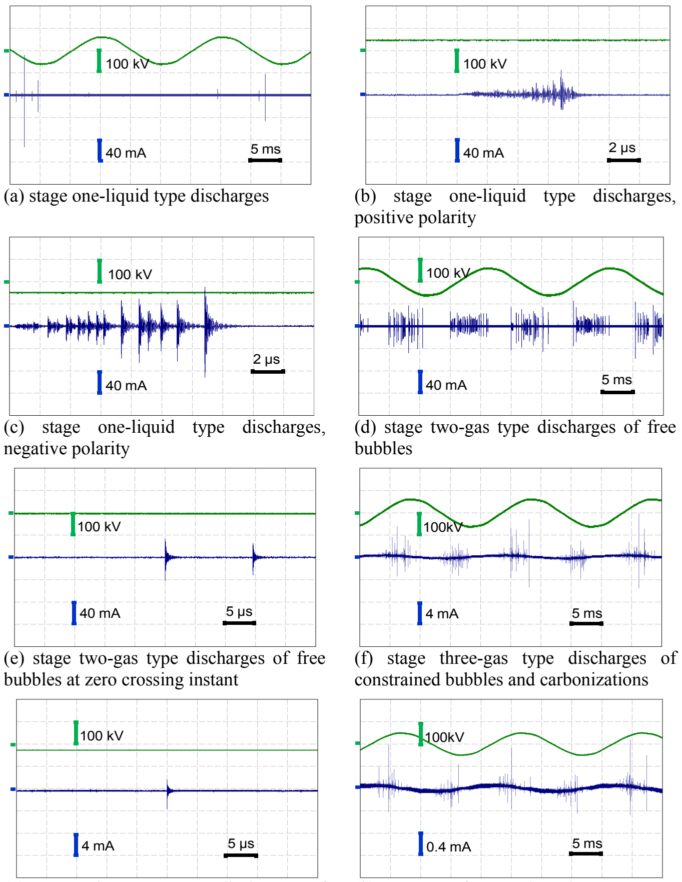
The shadowgraph images in Figure 7b show that, at this stage, a cloud of small gas bubbles rose from the pressboard surface around the needle tip where the electric field was the highest. Inevitably there would be some bubbles trapped in the surface layers as well.

The gas bubbles near the needle tip area, including both those dispersing freely into the liquid and those trapped between the cellulose fibres in the pressboard, could easily discharge in the high electric field; meanwhile the space charges left by discharges in the previous half cycles further facilitated the gaseous discharges. These reasons can explain why in this stage, the discharges, and even those around the zero-crossing instants, have large apparent charges and large discharge current peaks.

4.2.3 STAGE THREE

4.2.3.1 VISUAL RECORD

The growth of a white mark in this stage is shown in Figures 4g and 4h. The spark discharges disappeared; creepage discharges might be developing underneath the pressboard surface and driving the white mark to expand in both size and length. Bubbles rose from the tip and the body of the white mark: some attached to the surface of the pressboard and became larger with time; whereas some small bubbles dissipated freely into the liquid. Due to the accumulative discharges along the white mark, the root of the white mark was carbonized and turned to black.



(a) stage one-liquid type discharges

(b) stage one-liquid type discharges, positive polarity

(c) stage one-liquid type discharges, negative polarity

(d) stage two-gas type discharges of free bubbles

(e) stage two-gas type discharges of free bubbles at zero crossing instant

(f) stage three-gas type discharges of constrained bubbles and carbonizations

(g) stage three-gas type discharges of constrained bubbles and carbonizations

(h) stage four-weakened gas type discharges of constrained bubbles and carbonizations

Figure 6. Evolution of discharge current signal at different stages during surface tracking process on a pressboard in MIDEL 7131 at 43.0 kV.

4.2.3.2 PD PATTERN

At this stage, most PDs decreased dramatically from above 6000 pC in stage two to below 1000 pC, as shown in Figure 5c.

4.2.3.3 DISCHARGE CURRENT SIGNALS

The discharge current signals shown in Figures 6f and 6g indicate that the discharge current signals were still composed of fast pulses, like in stage two, but the pulse peak values were merely 8 mA, much smaller than those in stage two.

4.2.3.4 SHADOWGRAPH IMAGES

The shadowgraph images for discharges in Figure 7c show that, at this stage, fewer small bubbles dissipated from the pressboard surface and they distributed coarsely in the surrounding liquid. Some bubbles attached to the pressboard surface and expanded with time.

For the discharges of bubbles trapped in cellulose fibres along the white mark, their spatial propagations were constrained; consequently the discharges of these bubbles were weakened. For the bubbles freely dispersing from the body and the tip of the white mark into the liquid, they were far from the needle tip, so their discharges were only of small apparent charges. Apart from this, during the carbonization process, the semi-conductive carbonized channels could easily dissipate the charge carriers and hamper the discharges [21], so the discharges along the carbonized traces were also small.

4.2.4 STAGE FOUR

4.2.4.1 VISUAL RECORD

In this stage, the white mark kept on growing steadily towards the earthed plane electrode, as shown in Figures 4i and 4l. The roots of the white mark channels were further carbonized, with a tree-shaped carbonized mark forming on the pressboard surface.

4.2.4.2 PD PATTERN

The PDs in this stage further decreased to less than 100 pC, as shown in Figure 5d.

4.2.4.3 DISCHARGE CURRENT SIGNALS

The discharge currents were still with fast rising edge and short sustaining time, like those in stages two and three; however, the pulse peaks became less than 0.4 mA, as shown in Figure 6h, which were much smaller than those in stages two and three. The currents were too small and too fast, so the apparent charges obtained by the PD detector were less than 100 pC at this stage.

4.2.4.4 SHADOWGRAPH IMAGES

In this stage, small bubbles emerged from the pressboard surface and distributed in the surrounding liquid, some bubbles attached to the pressboard surface and grew larger with time, as shown in Figure 7d.

The bubbles caged in or arising from the new channels of the white mark were farther away from the needle tip and their discharges became much weaker; furthermore, much energy was consumed by carbonizing those channels and the semi-conductive carbonized channels also hampered the discharges. For these reasons, the discharges in this stage are extremely small.

4.2.5 STAGE FIVE

When the head of the white mark nearly reached the opposite plate, a luminous flash bridged the white mark and the plane electrode, with part of the flash path beneath the surface layers of the pressboard. The energy associated with the flash was not large enough to trip off the power supply, so that more flashes followed the white mark paths. Every time a flash occurred, the pressboard was damaged, with cracks in surface layers and carbonization traces along the white mark paths. This stage with consecutive flashes damaging the pressboard is termed as stage five (as shown in Figures 4m to 4o).

Since the two electrodes were bridged by the luminous flash, the discharge was not partial discharge anymore, so the apparent charges were not recorded. In case of damage to the resistor and oscilloscope, the resistor was removed from the circuit.

4.2.6 COMPLETE FLASHOVER

With the flashes repetitively damaging the pressboard surface, a final flashover occurred; the powerful arc tripped off the power supply, cracked the surface layers of the pressboard and left obvious carbonized mark, as shown in Figures 4p to 4r.

The discharge patterns shown above indicate that the appearance of white mark makes the discharge patterns more diverse and complicated. Once the white mark appears, the

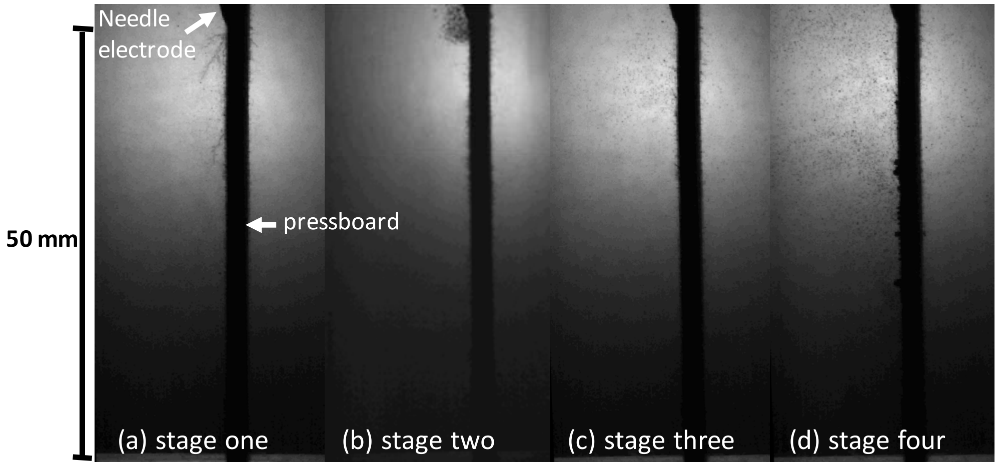


Figure 7. Evolution of discharge phenomena shown by shadowgraph images during surface tracking process on a pressboard in MIDEL7131 at 43.0 kV.

discharges are not only governed by the insulating liquid and the pressboard, but also by gas pockets; discharges in solid, liquid and gaseous states are all involved in the surface tracking process. Especially, the gaseous discharges in trapped bubbles dominate the development of tracking. This is uniquely associated with the pressboard-liquid composite structure, as impregnated pressboard is a porous and fibrous material.

After tracking is initiated by high energy dissipation, the liquid pockets between cellulose fibres can discharge easily around the needle tip, and evaporate and decompose into bubbles. These bubbles can be trapped and further enhance discharges. In this context, discharges develop both *'on'* and *'into'* the surface layers. Whereas for the dense and smooth solid materials, such as Perspex and glass, the creepage discharges are mainly influenced by surface charging and bubble residence [10, 12]. Under those conditions, the creepage discharges develop *'on'* the surface.

On different pressboard samples, the tree-shaped mark differs in the shape and the growing time. For the three samples investigated at 43.0 kV, the growing time of the white mark from the inception to the stage of bridging the whole gap were 40, 55 and 62 minutes, respectively. These differences are reasonable, since the alignment of cellulose fibres in each pressboard would have a degree of randomness and hence the liquid pores where the white mark grows would randomly differ in the same manner [8].

The current configuration with 50 mm gap is a miniature model for the pressboard barriers in transformers. If the gap distance is larger, it is expected that it takes longer time for the tree-shaped mark to span the gap and induce a final flashover.

4.3 SURFACE TRACKING PROCESS ON PRESSBOARD IN FR3

The surface tracking process on a pressboard sample in FR3 is shown in Figure 8. The voltage applied was 50.0 kV.

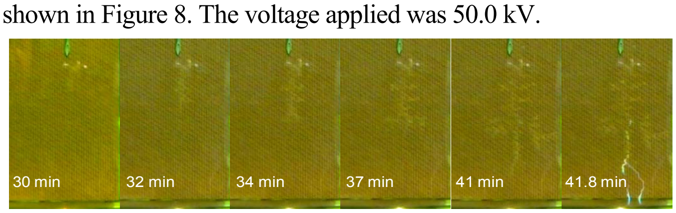


Figure 8. Surface tracking process on a pressboard surface in FR3 at 50.0 kV.

It can be seen that the surface tracking process on the FR3-impregnated pressboard included similar stages to those impregnated by MIDEL 7131. The discharge pattern also exhibited similar changes from liquid type discharge, to gas discharge of free bubbles, till discharge of constrained bubbles and carbonizations, as shown in Figure 9. The white mark also grew fast; it soon bridged the whole gap and caused a flashover. At 50.0 kV, the growing time of the white mark from the inception till bridging the whole gap for the three samples were 43, 41 and 71 minutes, respectively.

4.4 SURFACE TRACKING PROCESS ON WET PRESSBOARDS IN GEMINI X

Figure 10 shows an example of the growth of white mark on the surface of a wet pressboard in Gemini X.

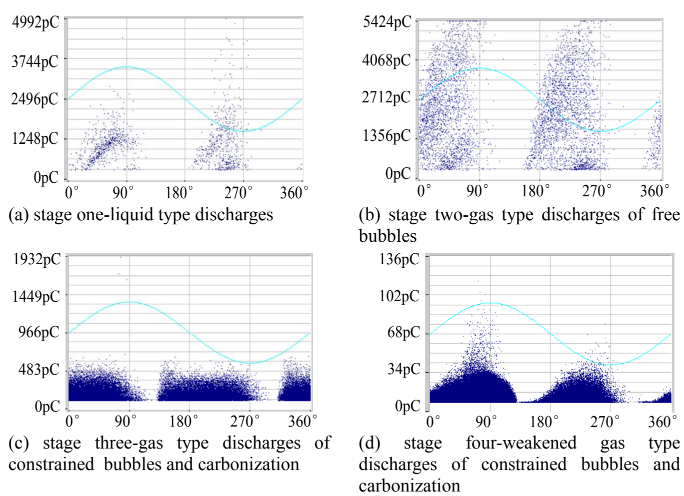


Figure 9. Evolution of phase resolved PD pattern at different stages of surface tracking process on a pressboard in FR3 at 50.0 kV. (in subfigure (b), the maximum discharges were out of scale because the PD amplitudes in stage two changed too rapidly with the dispersion of free bubbles, the amplitude scale was not easily adjusted on time)

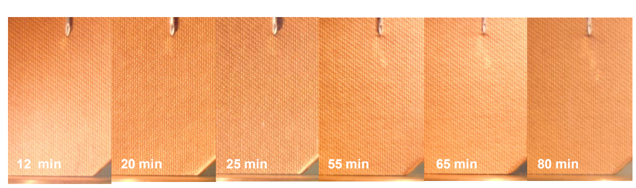
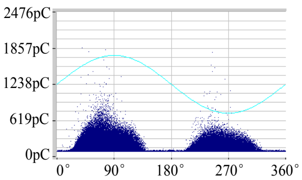
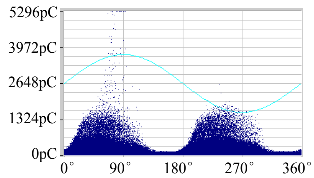


Figure 10. Surface tracking process on a wet pressboard surface (moisture content: 4.3%) in Gemini X at 50.0 kV.

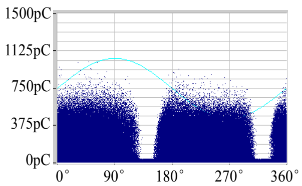
The growing speed of the white mark on the pressboard in mineral oil was much lower than that in esters. After 60 minutes, the white mark only grew to 15 mm, whereas in esters white mark has usually bridged the 50 mm gap. The white mark on the pressboard in mineral oil had fewer branches than those in esters. However, the discharge pattern evolution was similar to that in esters, and could be classified into similar stages to those in esters, as shown in Figure 11.



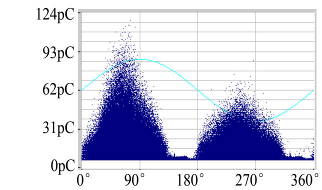
(a) stage one-liquid type discharges



(b) stage two-gas type discharges of free bubbles



(c) stage three-gas type discharges of constrained bubbles and carbonization



(d) stage four-weakened gas type discharges of constrained bubbles and carbonization

Figure 11. Evolution of phase resolved PD pattern at different stages of surface tracking process on a wet pressboard in Gemini X at 50.0 kV.
(In subfigure (b), the maximum discharges were out of scale because the PD amplitudes in stage two changed too rapidly with the dispersion of free bubbles, the amplitude scale was not easily adjusted on time).

4.5 LONG-TERM SURFACE TRACKING ON A COMPOSITE PRESSBOARD STRUCTURE

In transformers, to prevent the pressboard cylinders deviating from the designed positions, spacers are used to firmly fix them. The spacer and cylinder form a T-junction composite pressboard structure. In this test, two pressboards impregnated in MIDEL 7131 were used to study the surface tracking on the composite pressboard structure. A pressboard was attached to the needle tip and was in a vertical direction (marked as vertical pressboard); the other covered the earthed plane electrode and was in a horizontal direction (marked as pressboard cover).

In preliminary tests, it was found that when the white mark on the vertical pressboard was about to reach the pressboard cover, sparks appeared at the bottom edge of the vertical pressboard with the PDs up to several thousand pC and severely damaged the pressboard cover. By further adding Perspex sheets (total thickness of 6 mm) between the pressboard cover and the plane electrode, the spark discharges were avoided.

A pressboard sample was tested at 60.0 kV for as long as 124 hours. During the surface tracking process, only small bubbles were observed coming out from the tree-shaped mark on the two pressboards and at the overlapping region between them.

It can be seen from Figure 12 that the white mark could transit to light-shadowed mark and finally to the obvious tree-shaped carbonized mark. Meanwhile, the tree-shaped carbonized mark was also seen on the reverse of the vertical pressboard and it also extended to the pressboard cover, as shown in Figure 13.

This test verifies that a white mark will develop into carbonized mark when a pressboard is stressed by discharges for a sufficiently long time and the tree-shaped mark can extend from one pressboard to another. The carbonized mark is similar to that seen on pressboard cylinders in scrapped transformers as shown in Figure 1.

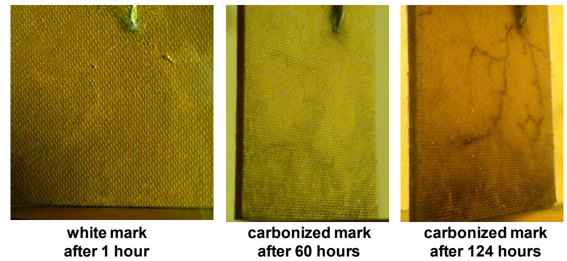


Figure 12. Transition from white mark to carbonized mark on a pressboard in MIDEL 7131 under 60.0 kV.

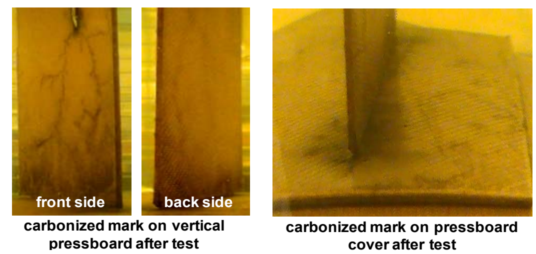


Figure 13. Carbonized mark on the reverse of the vertical pressboard and on the pressboard cover.

5 MECHANISMS OF SURFACE TRACKING ON PRESSBOARD

5.1 THE GASEOUS NATURE OF WHITE MARK

A lot of tiny gas bubbles rose from the white mark during its growth. After the test, the pressboard sample with white mark immersed in the liquid was degassed in a vacuum oven. A large amount of gas bubbles were extracted from the white mark area and the white mark disappeared afterwards. These phenomena indicate that the white mark is gaseous channels on and inside the pressboard.

The discharge current signals during the white mark growth are composed of single pulses with a fast rising edge and short sustaining time, like the discharges in gases, which also evidences the discharges in white mark are mainly of a gaseous type.

Since the white mark is of gaseous nature, the gas contents in the white mark channels were further identified by DGA analysis.

After the white mark grew to 15 mm on a pressboard in MIDEL 7131, the pressboard was taken out of the test vessel and immersed in a large beaker filled with fresh MIDEL 7131. The pressboard was cut to obtain the small piece with the white mark. This piece was then put into a syringe filled with fresh MIDEL 7131. This is to prevent the pressboard piece with white mark from contacting with air, so no air bubbles can be trapped in the cutting edges. This syringe was then placed into a vacuum oven. During the vacuum process, small gas bubbles were extracted from the white mark areas and formed a headspace over the liquid when the syringe volume expanded. The vacuum was released when no more gas bubbles came out. After being taken out of the vacuum oven, about 3 ml headspace was collected and the headspace gases were analysed by Gas Chromatography. Meanwhile, the MIDEL 7131 liquid around the needle tip was also sampled for comparison. The DGA results are shown in Figure 14.

As can be seen, the components of fault gases in the white mark were similar to those generated by PDs in the open gap test in [22]; the key gases were H_2, CO and C_2H_2, which indicates the partial discharge fault in MIDEL 7131 [22]. It is therefore proved that the trapped bubbles in the white mark are related to the decomposition of liquid in the pores between cellulose fibres, due to creepage discharges. Meanwhile, the liquid around the needle tip above the pressboard also has similar gas components. They should be both from the streamers creeping along the pressboard and the free bubbles dispersed from the white mark.

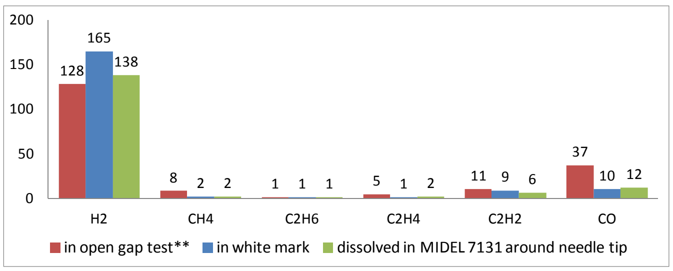


Figure 14. Gas concentrations (in ppm) in the white mark, in the liquid around needle tip and comparison with open gap test in MIDEL 7131.
(** note: the results for open gap were generated under PDs up to 1000 pC, from [22]).

5.2 THE EXTENSION OF WHITE MARK AT A REDUCED VOLTAGE

The white mark could continue growing at a reduced voltage. Taking a test in MIDEL 7131 as an example, 37.0 kV was applied to trigger a white mark on the pressboard. Then the voltage was reduced to 30.0 kV at which level the white mark could not be initiated on an intact pressboard; however the white mark could keep on growing slowly but steadily at 30.0 kV.

Understanding this phenomenon is crucial: transformers may sometimes suffer from a temporary overvoltage, which might be able to induce intense creepage discharges and trigger the incipient tree-shaped mark. After the overvoltage, the tree-shaped mark might continue to spread on the pressboard under the normal operating voltage. Although this process might be slow, the cumulative growth of the surface tree-shaped mark would also be able to cause catastrophic failure of a transformer.

5.3 THE RE-GROWTH OF WHITE MARK AFTER RE-IMPREGNATION

After the cellulose fibres are damaged and carbonized along the white mark traces, the carbonized mark will direct the subsequent discharges and further steer the extension of white mark. This was evidenced by a white mark re-growing test. As shown in Figure 15a, a white mark had grown to 13 mm long on a pressboard in FR3; then this pressboard was re-impregnated in a vacuum. After the re-impregnation, the white mark disappeared and the carbonized mark became more obvious as shown in Figure 15b. Afterwards, a 50.0 kV voltage was re-applied to this sample, and it was found that the white mark could re-grow on the pressboard surface, with the branches extending based on the previous channels, as shown in Figure 15c.

White mark is gaseous pockets caged among cellulose fibres. After re-impregnation, the trapped gas pockets were degassed and re-filled by the insulating liquid; therefore, the white mark would disappear under vacuum. However, along the white mark, the carbonized fibres remained, even after the gaseous pockets in the form of white mark were degassed by the vacuum. These carbonized channels would steer the subsequent discharges and the upcoming white mark would follow the existing traces and extend further.

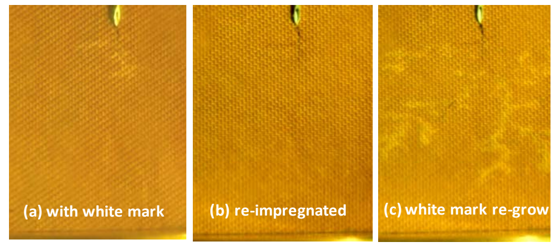


Figure 15. The re-growth of the white mark after re-impregnation.

5.4 THE PENETRATION OF TREE-SHAPED MARK INTO THE PRESSBOARD

The white mark newly initiated is very shallow and only exist on the surface when they have not been carbonized yet. In this case, when the voltage is stopped, the white mark would be re-impregnated by the insulating liquid and disappear.

However, the white mark will gradually penetrate into the inner layers. For the tests on the wet pressboards in Gemini X at 50.0 kV, the white mark penetrated so deep into the pressboard that they could be seen on the reverse of the pressboard and some small bubbles were observed from the reverse, as shown in Figure 16. This proves that white mark is an object of three dimensions with length and width as well as depth, rather than two dimensions only spreading on the surface.

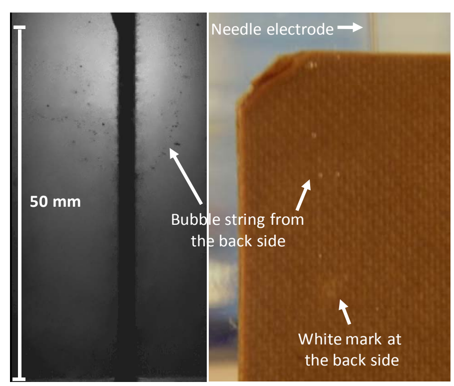


Figure 16. White mark and bubbles appearing on the reverse of a wet pressboard in Gemini X.

Carbonized mark can also develop deep inside the pressboard. As an example, a test on a composite pressboard structure in MIDEL 7131 lasted for 3 hours at 43.0 kV and 6 hours at 55.0 kV.

During the test, a hole developed around the needle tip and a 10 mm tree-shaped carbonized mark could be seen on the pressboard surface, as shown in Figure 17. Afterwards, this pressboard was cut into 10 strips and peeled into different layers for further observations.

Figure 18 shows the carbonized mark inside the pressboard. The carbonized mark had spanned the whole pressboard, although the traces on the surface were merely 10 mm. The carbonized mark could go deeper and deeper during the growth. Those channels underneath the surface layer are more susceptive to the carbonization under the cumulative discharge erosion. The gas bubbles formed in the surface layer can easily escape from the cellulose fibres into the liquid. However, the gas pockets in the inner layers would be trapped by the cellulose fibres, so the gaseous channels are conserved and more discharges would follow these channels. Given sufficient stressing time, the inner carbonized traces can grow thicker and darker so that the tree-shaped carbonized mark can be observed on the pressboard surface and even on the reverse surface, as shown in Figures 12 and 13.

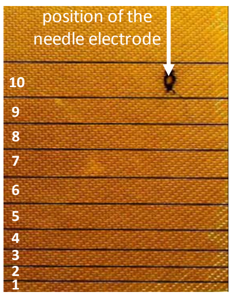


Figure 17. The pressboard with carbonized mark was cut into 10 strips.

Figure 18. Tree-shaped carbonized mark inside the layers of the vertical pressboard stressed for 3 hours at 43.0 kV and 6 hours at 55.0 kV in MIDEL 7131.

6 DISCUSSIONS

6.1 TRACKING ON PRESSBOARD IN TRANSFORMERS

In scrapped transformers, although only the black carbonized mark was observed, it is reasonable to believe that there were preceding white mark occurrence. Before scrapped, the transformers had usually been stopped operating for some time and the insulating liquid had been drained. During this period, pressboard barriers were exposed to the ambient environment, and the white mark could have vanished.

As shown in the tests, stressed by the creepage discharge energy, the insulating liquid and the moisture in the pressboard surface layers would evaporate and decompose into gases. Some of the generated gases are trapped between cellulose fibres due to the viscosity of surrounding insulating liquid and this changes the local light reflection index on the pressboard; therefore, these areas turn into a white mark.

Due to the gaseous nature, the white mark is the easy site for discharges, so the subsequent discharges are attracted to this area. The cumulative discharges along the same paths carbonize these channels. The carbonized mark can steer the subsequent discharges and expand with more branches until it bridges the gap and causes a final flashover. High energy is required for cellulose carbonization and the local temperature should be above 280 °C [23]. However, the high energy is not registered as large PD amplitudes. The apparent charges accompanied by the tracking process are usually small, even lower than the background noise levels in the substations. This makes it difficult to pinpoint the internal tracking fault by conventional PD monitoring.

6.2 COMPARISONS BETWEEN ESTERS AND MINERAL OIL

As summarized in Table 1, white mark could be easily initiated on dry pressboards in esters at a relatively low voltage; whereas in mineral oil, white mark can only be induced on sufficiently wet pressboards. The white mark extends much faster with more and longer branches on pressboards in esters than in mineral oil. Also, the white mark is easier to be carbonized and transit to carbonized mark on the pressboards in esters.

Table 1. Comparisons of surface tracking in the three liquids.

		MIDEL 7131	FR3	mineral oil	
moisture content		*<0.5%*	*<0.5%*	*4.3%*	*<3.5%*
tracking inception		appear from 37 kV	appear from 47 kV	exist at 50 kV	none up to 52 kV
tracking growth	length	bridging the 50 mm gap in 60 min		less than 15 mm in 60 min	N/A
	size	many branches forming a tree shape spreading on the pressboard		a short main trunk with subtle side branches	
	depth	only seen on the front surface		also observed on the reverse	

Under the same voltage, the discharges in esters are more intense than in mineral oil, with greater PD amplitude and higher PD repetition rate; besides this, the high viscosity of esters [18] would more readily trap the gas bubbles than mineral oil within the cellulose texture. This explains why pressboards impregnated by esters are more susceptive to surface tracking erosion.

For the mineral-oil-impregnated pressboard, high moisture is a necessity to initiate the surface tracking; therefore, much energy is consumed by the evaporation of moisture all around the needle tip, including the bulk of the pressboard. In addition, due to the lower viscosity of mineral oil, the generated vapour can migrate more easily between the fibres, and from the pressboard to surrounding liquid. Therefore, the white mark can penetrate all through the depth of pressboard and have fewer branches and slower growing speed for pressboards in mineral oil than in esters.

7 CONCLUSIONS

Based on the experimental investigations on the tracking on pressboard and the accompanying discharge patterns, it can be concluded that a liquid-impregnated pressboard is susceptive to discharge erosion characterized by white mark and carbonized mark, due to the intense discharges on and inside the pressboard.

The trapped gaseous channels from the liquid decomposition take the form of white mark on the surface layers of the pressboard. As the easiest channel for discharges, the gaseous white mark will attract the subsequent discharges; the accumulative energy dissipation will carbonize the channels. Once formed, the tree-shaped mark can continue to grow even under reduced voltage levels until it bridges the gap and finally causes a flashover.

The comparative study between esters and mineral oil suggests that, for ester-impregnated pressboards, the white mark would appear at a lower voltage, expand and transit to carbonized mark more easily. This is due to more intense discharges and more gas generation as well as the higher viscosity of esters than mineral oil. Consequently, attention should be paid to the weaker resistance of ester-impregnated pressboards to surface tracking when applying esters in large power transformers.

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Xiao Yi received the Ph.D. degree in electrical engineering from the University of Manchester, UK in 2012. She is currently a research associate at the School of Electrical and Electronic Engineering, the University of Manchester, UK. Her present research interest is on the dielectric performance of insulating liquid-pressboard composite insulations, DGA diagnosis of liquid-filled transformers and ageing assessment of transformer liquids.

Zhongdong Wang (M’00) received the B.Eng. and M.Eng. degrees in High Voltage Engineering from Tsinghua University in 1991 and 1993, and the Ph.D. degree in electrical engineering from UMIST in 1999. Currently she is Professor of High Voltage Engineering at the School of Electrical and Electronic Engineering, the University of Manchester, UK. Her current research interests include condition monitoring, transformer modelling and FRA & transients’ simulation, insulation ageing and alternative insulation materials for transformers