

## The process of creeping discharge-caused damage on oil/pressboard insulation

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Received: 21.10.2013

Accepted/Published Online: 31.03.2014

Final Version: 23.03.2016

**Abstract:** This paper presents experimental research on creeping discharge by using cylinder-plate electrode configurations under AC voltages. The process of creeping discharge-caused damage on the oil/pressboard insulation was studied. First, the electric field distribution was achieved by Multiphysics software simulation. Afterwards, the phenomena that occurred in the entire damage process, such as “white smoke”, “white mark”, and “black mark”, were recorded and analyzed. Furthermore, the micromorphology of the oil-impregnated pressboard was observed via scanning electron microscope (SEM). Finally, the inner mechanism of the damage to the oil/pressboard insulation was explored according to the phenomena and the SEM morphologies. Results showed that during damage processes, the high electrical field strength (nearly 25.853 MV/m) at the weak-link point between the cylinder electrode and the pressboard directly caused the incipient discharge. The cavity, moisture, impurity, solid particle, and formation of a gaseous channel all contributed to the development of the damage. The “white smoke” consisted of gases that stemmed from the ionization of oil and evaporation of moisture. The “white mark” was the gas channel and pressboard carbonization was caused by discharge and high temperature, both of which were also the main causes of the emergence of “black mark”. SEM images revealed that the pressboard successively experienced “white solid”, “crack”, and “pitting”, which changed its surface roughness. The distorted electric field caused by gases, solid particles, and pitting further damaged the oil/pressboard. The pitting evolved into the starting point of the electrical trees and gradually led to the final breakdown.

**Key words:** Transformer, oil/pressboard insulation, creeping discharge, damage process, COMSOL simulation, surface morphology

### 1. Introduction

Oil/pressboard insulation systems are widely used in transformers, which play a vital role in the whole electrical power networks. The lifetime of a transformer generally depends on the aging status of the oil/pressboard insulation system including cellulose materials and oil. The insulation aging problem is recognized as one of the major contributors to transformer failures [1,2]. The insulation system gradually degrades as a result of environmental factors such as thermal aging, overvoltage, moisture, mechanical vibration, and oxygen exposure [3]. Among these factors, creeping discharge that propagates over pressboards significantly affects degradation of insulation systems and the damage to the pressboard cannot be recovered or removed. It is therefore of great practical value to understand the damage characteristics of creeping discharge. A thorough investigation of the inner mechanism of the damage process will further provide the theoretical basis for better designs of transformers.

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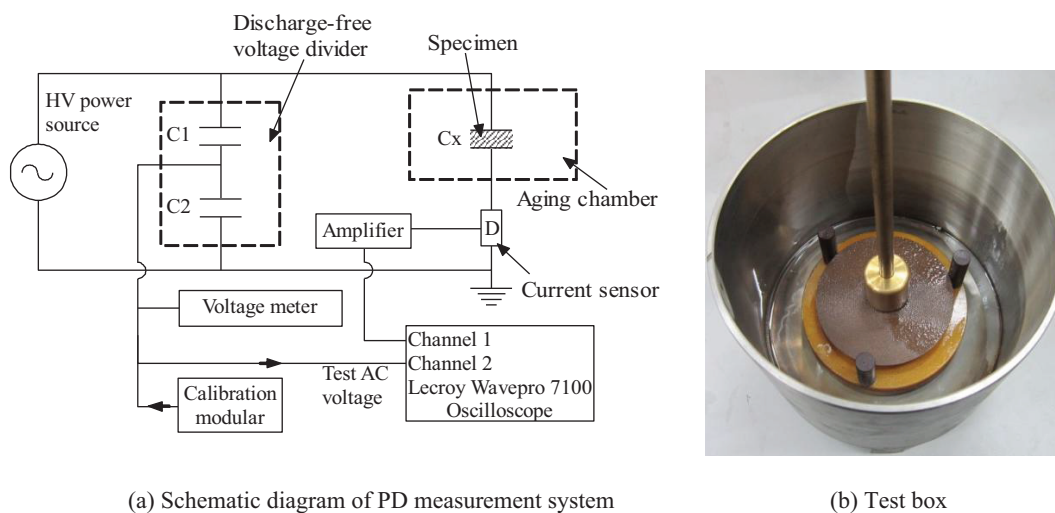
The surface of oil-impregnated pressboards is traditionally the weak link because of the accumulation of oil cavity, moisture, impurities, and other aging products, which increase the complexity degree and decrease the insulation strength. Creeping discharge over the pressboard surface is assisted by the tangential component of the electric field along the surface. The damage to the pressboard causes irremediable failure and leads to incalculable loss [4,5]. Numerous reports have been made about damage research. Liao et al. conducted research on surface topography, surface roughness, surface products, and surface conductivity of an oil-impregnated insulation pressboard during the damage process caused by the discharge using a special model [6–8]. It was confirmed that during the entire damage process, the consumption and generation of gases took place continually. The gas volume and content of electronegative gases declined and increased alternately, while the types of PD within the cavity altered between pulse-type discharge and pseudo-glow-type (or glow-type) discharge. “Ablating”, “peeling”, and “cracking in silk” appeared on insulation surfaces one after another during the damage process, along with sequential generation of droplets and crystalline solids. Surface roughness initially decreased, then increased. The surface conductivity exhibited a general increasing trend, before it eventually stabilized. However, its growth rate varied in different stages of damage. Mitchinson et al. analyzed and explored the characteristics of damage to pressboards under the action of the tangential component of the electric field by adopting a point-plate model [9–11]. It was considered that when placed in close contact with the pressboard surface, the sustained PD activity caused damage to the pressboard surface known as tracking. Once tracking paths were established, significant electrical discharges could occur without breakdown. These produced gassing and particulate degradation by-products, indicating that the discharge started to damage the pressboard. Surface tracking was a local phenomenon that led to surface damage over time. Surface flashover was caused by overvoltage exceeding the voltage withstand capability of the bulk medium. The shape and form of the solid insulation played a role in depressing this withstand capability. On the other hand, Wei et al. studied creeping discharge performance for high-moisture pressboards and discussed the typical creeping discharge trace on pressboard [12,13]. It was confirmed that moisture of pressboard in part could reach 7% in service power transformers when oil moisture was 30 ppm. Creepage discharge inception voltage had a remarkable decrease under high moisture. At the same time, creepage discharge appeared at a small oil gap first and a bright spark could be observed, creepage discharge was intermittent and even stopped at some times, and many bubbles were generated in the creepage growth. Wang et al. [12,13] also considered that the moisture in the pressboard played an important role in the development of creeping discharge, particularly the phenomenon of “white mark”. They explained the formation of white marks on the pressboard surface through a theoretical analysis and experimental verification. It was confirmed that white marks were created by fault gases trapped inside the pressboard and the large hydrogen content in the DGA results indicated low energy discharges. There were also some other studies carried out to explore the creeping discharge [14–16].

In the present paper, a cylinder-plate model of oil/pressboard insulation was adopted to perform creeping discharge damage experiments. The simulation of the electrical field, including tangential and normal directions, based on the cylinder-plate model was carried out using COMSOL Multiphysics software. This simulation was followed by experiments in which damage processes were recorded. Meanwhile, the phenomena of “white smoke”, “white mark”, and “black mark” were analyzed. A scanning electron microscope (SEM) was employed to investigate surface morphology. Accordingly, the inner mechanism of the damage caused by creeping discharge on the oil-pressboard insulation was explored.

## 2. Experiment and establishment of the simulation model

### 2.1. Sample preparation and discharge test

The oil/pressboard insulation consists of insulation oil and insulation pressboard. In this paper, Kraft pressboards (thickness: 2 mm; diameter: 80 mm), which was provided by a local company, was used in the damage experiments. The 25# transformer mineral oil was chosen as the insulation oil. The discharge measurement system and the test box are shown in Figures 1a and 1b. Before discharge experiments, the oil/pressboard insulation must be preprocessed to simulate the real transformer. The pretreatment of the samples was divided into three steps, as discussed in the following paragraphs.



**Figure 1.** The schematic diagram of PD measurement system (a) and experimental test box (b).

Step 1: The pressboards and oil samples were all placed in a vacuum chamber and dried for 48 h at 90 °C and 100 Pa. Nitrogen was then fed into the vacuum chamber and one of the samples was collected to measure the moisture content via Karl Fischer titration. The moisture contents of the pressboard and the oil should be controlled within the ranges of 0% to 0.5% and 0 ppm to 10 ppm, respectively. Otherwise, the samples should be dried longer to ensure that the moisture content is within the ranges.

Step 2: The pressboards were placed in the oil samples immediately to avoid contact between air and the pressboards. The temperature of the vacuum chamber was then adjusted to 60 °C. The samples were kept for another 24 h at 100 Pa to accomplish the oil impregnation.

Step 3: The temperature of the vacuum chamber was cooled down to room temperature, and the oil/pressboard samples were removed. The samples were then in turn placed in the test box, which was contained in the partial discharge measurement system. Experiments were conducted successively.

A cylinder-plate model was used to make the simulation closer to the real situation. The top view of the test box is shown in Figure 1b. The pressboard was surrounded by three epoxy columns, which were used to fix the pressboard. The entire model was placed in a steel container filled with oil. Before the experiment, various explorative damage experiments were conducted. The subsequent test method was as follows: the applied voltage was increased gradually and finally kept at a constant voltage (32 kV) until the failure of oil/pressboard insulation. The entire damage process and the phenomena were recorded by a camera.

## 2.2. Establishment of the simulation model

COMSOL Multiphysics is a mode-based software that can solve stationary and time-dependent partial differential equations with the finite element method. COMSOL simulation software was used in this study to establish the cylinder-plate model and to conduct the further simulation analysis. The distribution of the electrical field, including the tangential and normal directions, was obtained. This distribution directly affects the understanding of creeping discharge and damage characteristics of the oil/pressboard insulation.

The electric field distribution was solved by the static electrical field in the AC/DC module in COMSOL Multiphysics 4.3 software. The spatial distribution of the electric potential was described by Poisson's equation [17–19], which was solved by the relaxation method based on the Gauss–Seidel iteration scheme with successive over relaxation.

$$\nabla \cdot (\varepsilon \nabla \phi) = \rho \quad (1)$$

$$\mathbf{E} = -\nabla \phi \quad (2)$$

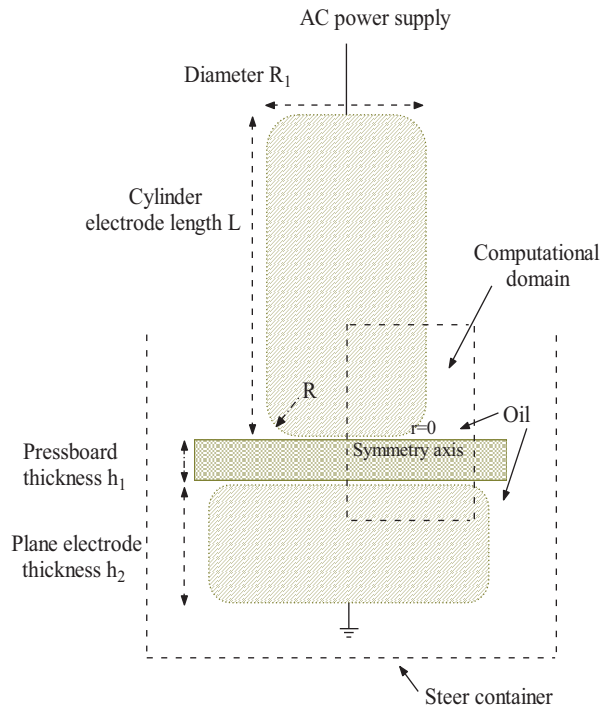
Here,  $\varepsilon$  is the relative permittivity,  $\phi$  is the electrostatic potential, and  $\mathbf{E}$  is the electric field. The temperature is fixed at 298 K and pressure is fixed at 1 atm. Within the numerical model, the key boundary conditions are given below. Positive potential (32 kV) is applied to the cylinder electrode and the plane electrode is grounded as zero potential. The normal gradient of the density of all species is zero ( $\mathbf{n} \cdot (\nabla \rho) = 0$ ) at the open boundaries. The relative dielectric constant and electrical conductivity referred to in the model are given in Table 1.

**Table 1.** The relative dielectric constants of different materials.

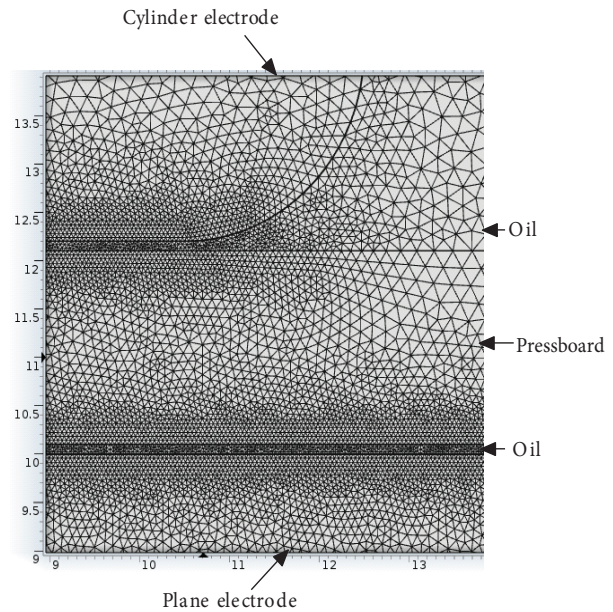
Material \ Property	Cu	Air	Oil	Pressboard	Stainless steel
Relative dielectric constant	10,000	1	2.3	3.5	10,000
Electrical conductivity	$6 \times 10^7$	0	$5 \times 10^{-9}$	$1 \times 10^{-10}$	$1 \times 10^7$

A schematic diagram of the cylinder-plate electrode system model is shown in Figure 2, which is simplified into a two-dimensional representation using a rotational symmetry. The model was solved using COMSOL Multiphysics based on the finite element method. The model consisted of a cylinder electrode with diameter R (25 mm) and height L (50 mm), a plate electrode with diameter of 60 mm and thickness  $h_2$  (10 mm), and a pressboard with diameter of 80 mm and thickness  $h_1$  (2 mm). An oil slick with thickness of 0.1 mm was established at the top and bottom layers of the pressboard because the pressboard was a kind of oil-impregnated pressboard and its surface was filled with oil.

A reasonable mesh serves a key function in the process of finite element solutions, particularly in the area where the physical quantity gradient is evidently large. Creeping discharge develops along the surface of pressboard. Therefore, owing to the high electric field and charge densities, a very fine “unstructured mesh”, which is shown in Figure 3, should be used along the axial symmetry line [20]. The quality of the elements of the mesh is an important consideration that can measure the quality of the mesh [21]. It is reported that when the value of element quality reaches 1, the quality of the mesh is the best. On the contrary, it is very difficult to get the reasonable results when the value is less than 0.1. In this model, the minimum and average element qualities are 0.3903 and 0.9663, respectively, and can ensure solution rationality. The other corresponding mesh parameters are shown in Table 2.



**Figure 2.** Cylinder-plate electrode system model.



**Figure 3.** The unstructured mesh of the model.

**Table 2.** Mesh statistics.

Mesh parameter	
Triangular elements	99,403
Edge elements	2860
Minimum element quality	0.3903
Average element quality	0.9663
Element area ratio	$9.342 \times 10^{-6}$
Elements nodal points	6

### 3. Results and analysis

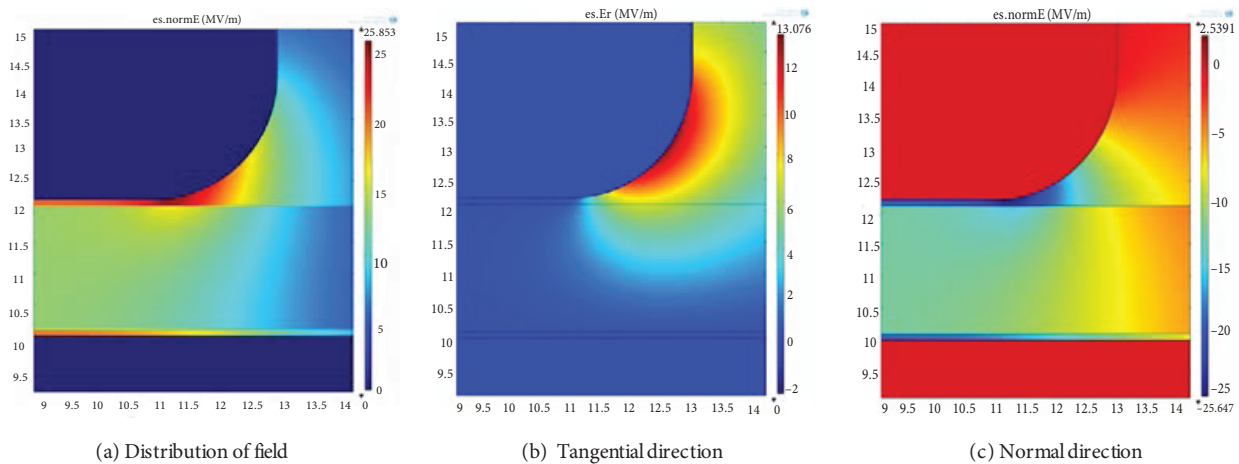
The experimental results are presented in this section, including the simulation of the cylinder-plate model, the phenomenon of the entire damage process, and the SEM surface morphology of the oil-impregnated insulation pressboard.

#### 3.1. Simulation results

Figure 4 demonstrates the simulation results, including the distribution of the entire electric field, the tangential electric field, and the normal electric field. In Figures 4a and 4b, the red color represents a high electric field and the darker color indicates a higher field. The blue color represents a low electric field and the darker color denotes a lower field. The normal direction is defined as the direction perpendicular to the plane and the points from the bottom to the top in general. Hence, the meaning of the colors with regard to the electric field in Figure 4c is opposite to the meaning in the other two figures.

Figure 4a shows the overall distribution of the electric field. It is obvious that the value of the electric field inside the oil is higher than that inside the pressboard, particularly in the areas between the cylinder

electrode and the pressboard. This result is attributed to the electric field strength of each layer dielectric, which is inversely proportional to its permittivity. In addition, the peak value of the electric field reaches nearly 25 MV/m. The distribution of the tangential electric field is shown in Figure 4b. The maximum value reaches 13.08 MV/m. A closer distance to the cylinder indicates a higher value of the tangential electric field. The distribution of the normal electric field is shown in Figure 4c. The absolute value of this distribution reaches 25.65 MV/m.



**Figure 4.** The simulation results of cylinder–plate electrode model: (a) distribution of field, (b) tangential direction, (c) normal direction.

### 3.2. Damage process of the oil/pressboard insulation

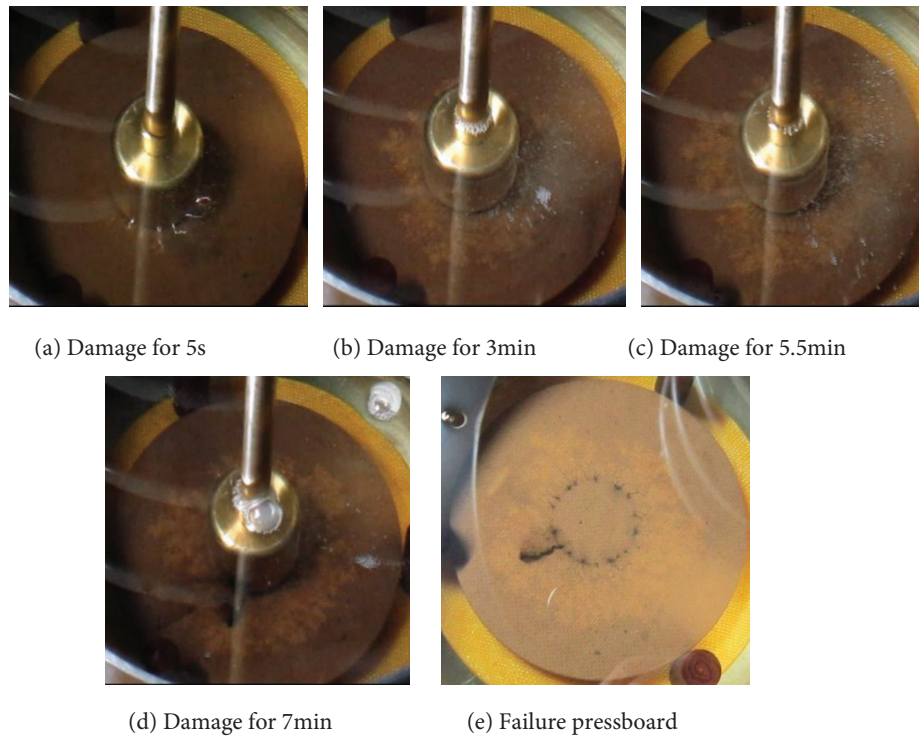
The changes in the macrophenomena were observed via a video camera during the entire damage process. These changes could be classified into four typical damage stages, as shown in Figures 5a–5d. The surface morphology of the pressboard after breakdown is shown in Figure 5e.

During the beginning of the damage process, a discharge spark occurred on the surface of the oil-impregnated insulation pressboard when it was subjected to the sustained damage for 5 s, as shown in Figure 5a. The discharge spark started and developed in clockwise and counterclockwise directions, respectively, around the cylinder electrode. Interestingly, a “white mark” and “white smoke” appeared on the surface of the pressboard and in the bulk oil with air bubbles adsorbed by the cylinder electrode when the damage to the oil–pressboard insulation lasted for 3 min, as shown in Figure 5b. Surprisingly, it is obvious that the “white mark” area expanded compared with the second damage stage, as shown in Figure 5c. However, the expansion speed of the area eventually slowed down or the area did not expand anymore, as shown in Figure 5d. A large quantity of air bubbles and a “black mark” appeared with the failure of the oil/pressboard insulation caused by discharge. Figure 5e clearly shows that the “white mark” and “black mark” remained on the surface of pressboard and could not be recovered. The damage status of the pressboard changed from local damage to complete failure.

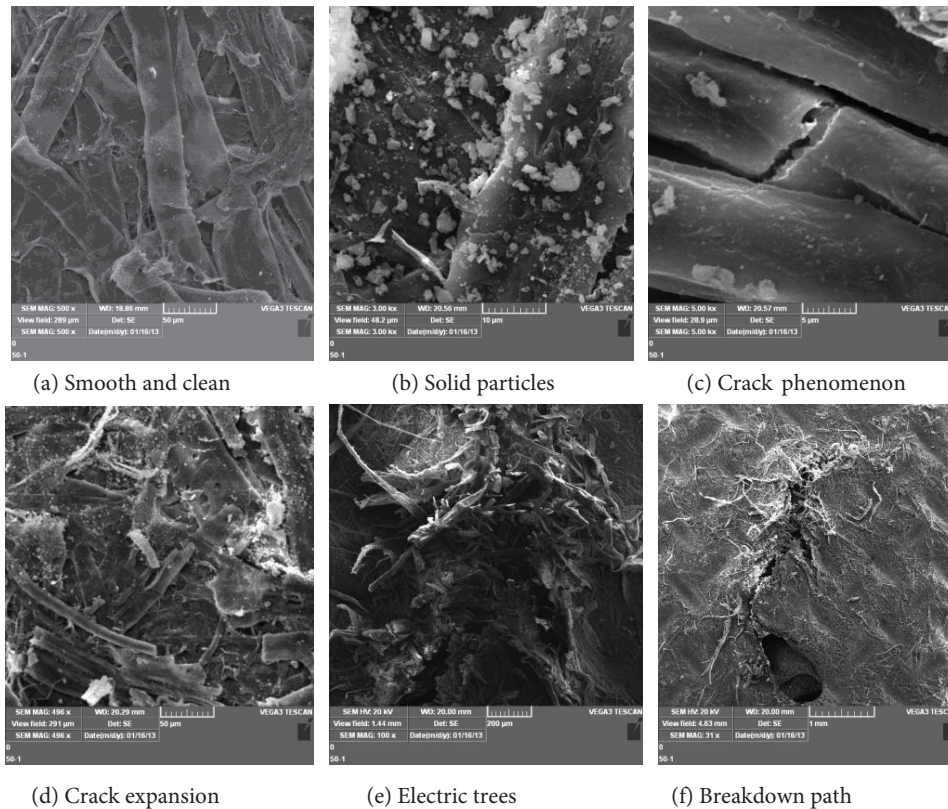
### 3.3. SEM images of the oil/impregnated pressboard surface

The surface morphology of the oil-impregnated insulation pressboard was obtained via SEM during the entire damage process, as shown in Figures 6a–6f. The surface damage can be classified into several stages as well.

The surface of the fiber seemed smooth and clean before the damage, as shown in Figure 6a. However, white particles appeared on the surface of the oil-impregnated pressboard and covered each fiber during the



**Figure 5.** The electrical damage progress of oil-impregnated pressboard: (a) damage for 5 s, (b) damage for 3 min, (c) damage for 5.5 min, (d) damage for 7 min, (e) failure of the pressboard.



**Figure 6.** Surface damage SEM images of oil-impregnated pressboard: (a) smooth and clean, (b) solid particles, (c) crack phenomenon, (d) crack expansion, (e) electric trees, (f) breakdown path.

start of the damage process. The crack phenomenon was then observed on the cellulose fiber, thus indicating that irreparable damage had formed, as shown in Figure 6c. As the damage continued, a large number of cellulose fibers broke down and “pitting” was formed, which became increasingly large, as shown in Figure 6d. Consequently, the “pitting” evolved into the start point or the source of the electric tree and randomly propagated to many directions, as shown in Figure 6e. A final breakdown channel with a “black hole” connecting to the channel end was formed, as shown in Figure 6f.

#### 4. Discussion

In this section, further analysis was carried out on the phenomena of the “white smoke”, “white mark”, and “black mark”. The damage process was also explored from the microperspective level. Based on the phenomena, the essence of electric injury on the oil/pressboard insulation was summarized.

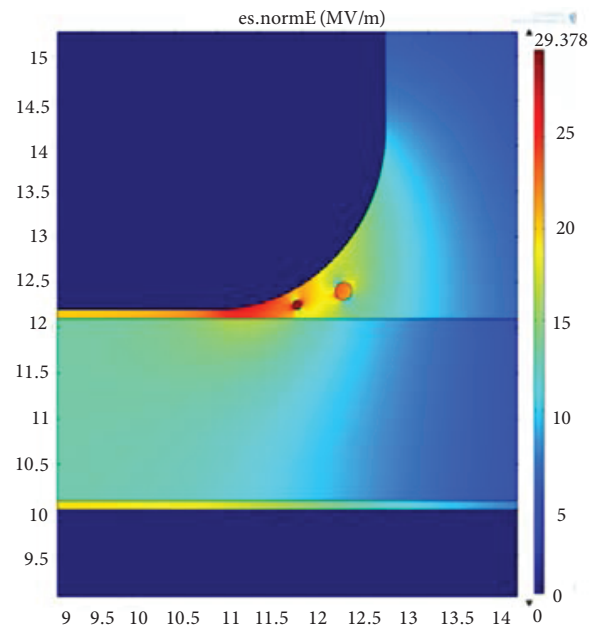
The surface of the oil-impregnated pressboard in the oil/pressboard insulation system is regarded as the weak link; the dielectric strength of the oil gap generally decreases with the introduction of an insulation pressboard [22]. The oil gap between the cylinder electrode and the pressboard typically becomes the overstressed and high-field strength point, wherein the initial discharge spark occurs. As we all know, discharge occurs when the electrical potential gradient reaches 16 MV/m. The simulation results presented in this paper shown in Figure 4a indicate that the electrical field strength in the oil gap reaches 25.853 MV/m, which is greater than 16 MV/m. Accordingly, a discharge spark with a huge amount of energy occurs, as shown in Figure 5a. The simulation analysis directly affects the experiments.

However, the electrical field in the area with a diameter of greater than 13 mm, as shown in Figure 4a, reaches only 8 MV/m or less. This value is significantly small, and thus the discharge does not appear. Interestingly, Figure 5b–5d show that a “white mark” appears on the pressboard surface and vast swarms of bubbles are observed in the bulk oil. It was reported that the emergence of a “white mark” is caused by the bubbles that stem from oil ionization resulting from discharge [23], thus indicating that the discharge still exists. Thus, bubbles have an important role in distorting the electrical field. A continuous discharge is supported by the distorted electrical field caused by the bubbles. Hence, an electric field distribution simulation of the cylinder-plate model with the presence of bubbles was conducted, as shown in Figure 7. The result indicates that the initial distribution of the balanced electric field is disturbed with the introduction of gas because of its lower permittivity compared with that of oil and pressboard. The maximum value of the electric field reached nearly 25 MV/m inside the bubbles, thus facilitating the development of discharge and the damage to the oil/pressboard insulation.

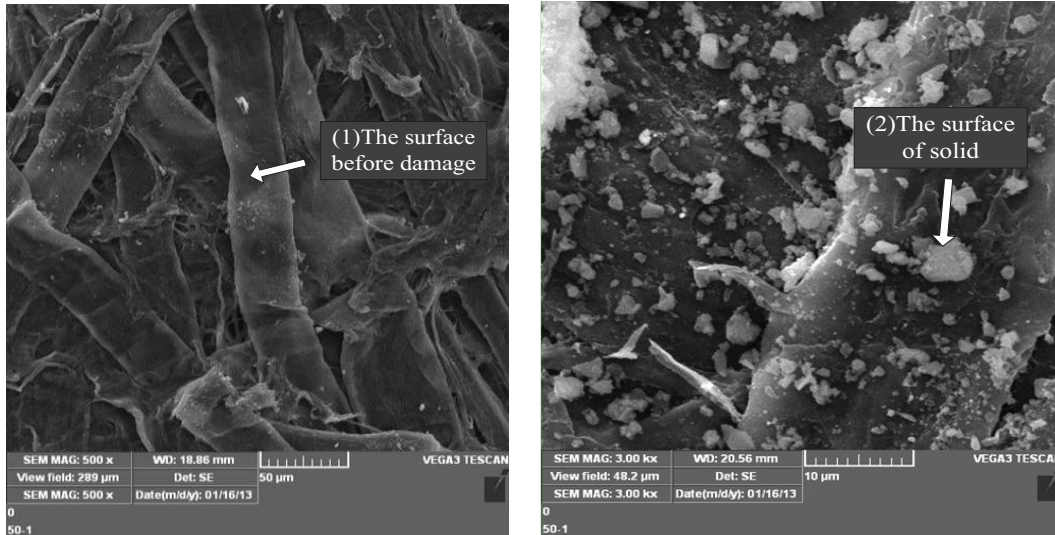
The high electric field strength in the oil gap between the cylinder electrode and the pressboard contributes to producing a discharge spark, which breaks down the oil molecules and generates gases. Simultaneously, the moisture in the pressboard and in bulk oil is vaporized by high temperature because of the discharge spark. The increased amount of gases distorts the electric field, thus leading to more serious discharge and to the gases occupying the pores in the pressboard. The gases expand and push the oil out of the pressboard, and thus bubbles appear in the bulk oil and the surface layer of the pressboard is arched. A “white mark” was created with a gaseous path inside. Wang et al. also analyzed the phenomena. Several “white marks” disappeared, thus indicating some form of recovery [24]. Thus, a “black mark” is inferred as the start of unrecoverable damage to the pressboard from the macroperspective level. Meanwhile, the emergence of solid particles, as shown in Figure 6b, can be denoted as the start of unrecoverable damage to the pressboard from the microperspective level. To obtain more information on damage and to understand these inferences, SEM images were obtained and



elemental analysis for the insulation pressboard was conducted by energy dispersive X-ray (EDX) spectrometry. For comparison, two points were selected for the elemental analysis, as shown in Figure 8.



**Figure 7.** Field distribution with bubbles.



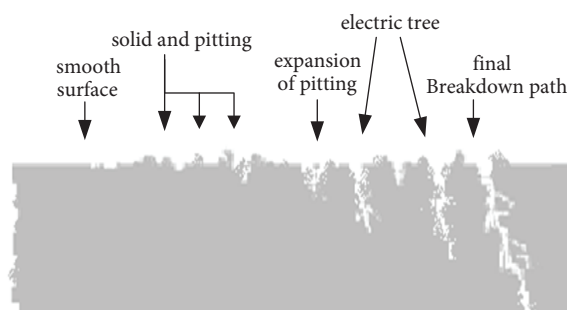
**Figure 8.** Two points were selected for elemental analysis.

The result of the elemental analysis is shown in Table 3, which reveals an increasing tendency of C content, which indicates that the pressboard suffers from carbonization effects and irreversible damage has started. The main component of the solid particle was carboxylic acid, which was generated from the oxidation reactions of decomposition products under the effect of discharge [25]. Thus, it is suggested that the emergence of solid particles or a “black mark” is a sign of the start of the irreversible damage to the pressboard caused by changes in physical and chemical properties of the pressboard.

**Table 3.** Elemental analysis for insulation pressboard.

Element	(1) Surface before damage	(2) The surface of solid particles
	Weight percentage	Weight percentage
C	39.38	40.45
O	42.62	42.53
Si	0.79	3.68
Ca	2.27	0.70
Au	14.94	12.64
Total weight	100.00	100.00

The rough surface of the pressboard increases the probability of discharge because the raised points, such as solid particles, play an important role in distorting the electric field. The distorted electric field destroys the pressboard and breaks down, as shown in Figure 6c. The pitting formed by the crack of cellulose fibers and the accumulation of solid particles increases surface roughness, thus leading to a serious distorted electric field. Accordingly, the pitting evolves into the start point of the electric tree, which damages the pressboard further. The damage procedure according to the microperspective level can be summarized as shown in Figure 9.

**Figure 9.** The damage process of the pressboard in the microperspective.

The preliminary analysis suggests that the damage to the oil/pressboard insulation is a result of the action of a high electric field strength combined with weak insulation strength. The factors that significantly influence electric field distortion, such as gases, solid particles, and other substances, always exist in the entire damage process. Gases seriously distort the electric field because of its low permittivity. The “white solid” and “pitting” increase the surface roughness of the pressboard, thus leading to the emergence of the burr defect, which distorts the electric field and decreases insulation strength undoubtedly. Electric trees develop from the “pitting” and propagate randomly in all directions until the final breakdown. The path of the final breakdown shown in Figure 6f is similar to a tree, which includes a primary channel with numerous secondary channels and a “black hole” connecting to the path’s end. It is considered that the degree of damage to the primary channel is greater than that to any other secondary channels. Maximum electric field strength and minimum insulation strength occur at the primary channel. Therefore, the process of creeping discharge-caused damage to the pressboard is similar to the process of identifying the maximum electric field strength points and the minimum insulation strength points along the surface of the pressboard. The discharge damages these points, during which the chemical characteristic property changes simultaneously. The damage to the pressboard develops toward the longitudinal direction as well and leads to the tree-like trace and breakdown hole left on the pressboard.

The main differences between the results obtained in this experiment and the past studies lie in the degree of damage to the pressboard and the different electrode models used. On the other hand, the variation of micromorphology during the whole damage process was obtained as well.

## 5. Conclusion

The damage to oil/pressboard insulation caused by creeping discharge was investigated by using a cylinder-plate electrode model. The electric field distribution was achieved by Multiphysics software simulation and damage experiments were carried out. Furthermore, the entire damage process was recorded and the phenomena were analyzed. The following conclusions could be drawn from the test:

1) The high electric field in the oil gap between the cylinder electrode and the pressboard directly causes the discharge. The “white smoke” is the bubbles diffused into the bulk oil and the “white mark” is the gas channel. The generation of these gases, which seriously distort the electric field, is attributed to the oil ionization caused by the discharge. A continuous discharge is supported by the distorted electric field caused by gases.

2) The “black mark” indicates that the pressboard is carbonized because of the discharge and high temperature and the emergence of the “black mark” indicates that unrecovered damage starts. The EDX analysis suggests that the presence of “white solid particles” is a sign of the beginning of irreparable damage to the pressboard from the macroperspective level.

3) The SEM images suggest that the pressboard successively experiences “solid particle”, “crack”, “pitting”, and “electric tree”. “Solid particle” and “pitting” increase the degree of surface roughness and have a vital role in distorting the electric field. “Pitting” can be denoted as the start point or the source of electric tree.

4) The process of damage to the pressboard caused by creeping discharge is a result of the action by high electric field strength and low insulation strength. This process pertains to identifying the high electric field strength point and the low insulation strength point. The damage develops toward the tangential and longitudinal directions of the pressboard, thus leading to a tree-like trace and a breakdown hole left on the pressboard.

## Acknowledgments

This project was supported by the Natural Basic Research Program of China (No. 2009CB724505-1) and the National Natural Science Foundation of China (51277187).

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