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Experimental Study of the Leakage Current in Coated Insulators Under Salt-Fog Conditions

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Abstract. The accumulation of contaminants in electrical insulators reduce their performance and may lead to failures. Estimating the degree of pollution of in-service equipment is not a trivial task as the process of contamination depends on several factors. It is necessary to monitor the insulators so that preventive measures can be taken in a timely manner. In this context, this paper aims to study how the amplitude, angular phase and total harmonic distortion (THD) of the leakage current can be used to monitor insulators and how these parameters are affected by the application of hydrophobic coatings. For this purpose, standard uncoated and coated glass insulator samples were subjected to electrical tests in a salt-fog chamber while the leakage current was monitored. The results show that the analyzed parameters provide relevant information about the insulation condition and how the application of hydrophobic coatings results in improvements in the insulator performance.

Keywords: diagnostic. leakage current. phase angle. total harmonic distortion.

1 INTRODUCTION

Although outdoor insulators represent a relatively small portion of the costs of a transmission line (FRONTIN et al., 2010), they play a key role in the efficient and continuous operation of electric power transmission systems. Therefore, studies aimed at increasing the reliability of the insulators may represent significant reduction in the operation and maintenance costs of the lines.

In highly contaminated areas solid particles accumulate on the surface of the insulators. When moisture is present and the surface becomes wet, a conductive aqueous film is formed allowing leakage current to flow. This can increase line losses, accelerate the insulation degradation processes, trigger dry band discharges and even shutdowns if the discharges increase in size and reach the full extent of the insulating surface (KUFFEL; ZAENGL; KUFFEL, 2000).

The accumulation of contaminants and the resulting layer conductivity depend on different factors such as the speed of the winds, the temperature, the humidity, the type of insulator and the type of contaminants in the region (VINOTHKUMAR; KANNAYERAM; SHUNMUGALAKSHMI, 2015; SYAKUR; BERAHIM; ROCHMADI, 2012). Therefore, estimating the degree of contamination of an insulator based only on the climatic condition and on the time of exposure is not a trivial task. It is necessary to carry out tests and routine inspections to verify the real state of the insulating surface.

In this paper, an investigation on the leakage current as a parameter for monitoring an insulator was performed. Samples of glass insulators with different surface characteristics were subjected to electrical tests in a salt-fog chamber. The measured current waveforms were then processed and the relationship between different current parameters and the phenomena that occur in contaminated insulators was investigated.

The following parameters were analyzed: (I) the current magnitude, aiming to provide an overview; (II) the angular phase difference between the applied voltage and the resulting current, allowing to model the equivalent electrical circuit of the insulator; and (III) the

Total Harmonic Distortion (THD), the ratio between the sum of all harmonic components and the fundamental one, which is related to the occurrence of dry band discharges along the insulator surface (SUWARNO, 2005; BASHIR; AHMAD, 2010).

2 EXPERIMENTAL

2.1 Samples

Three standard type glass suspension insulators, in accordance with IEC 60305, were used. They have the following dimensions: diameter of 255mm, arc distance of 156mm and leakage distance of 320mm.

One of the insulators was kept uncoated, while the other two were coated with hydrophobic materials, a property that hinders the formation of a continuous aqueous path on the glass surface (VINOTHKUMAR; KANNAYERAM; SHUNMUGALAKSHMI, 2015), which results in significant reductions in the magnitude and harmonic content of the leakage current, as well as considerable increments in the flashover voltage (AL-FIADI et al., 2017) (INMR, 2018).

One sample was coated with solid Vaseline. Prior to application, the insulator was sanitized with a soft cloth and running water. After completely dry, a layer of the product was manually applied throughout its surface to keep the coating as uniform as possible.

In the other sample, Acquella silicone (Vedacit) was applied. This product is advertised as a water repellent for houses. Due to its liquid nature, the application on a curved surface was not a simple task and, therefore, a different application procedure was adopted. The product was applied with a soft brush on the top of the insulator, and after two hours, it was applied on the bottom of the insulator. Four coating layers were applied with a 24-hour interval between applications, ensuring that the entire insulator was coated and that the product was completely dry before the next application.

As the coatings used were not made for coating glass surfaces, it was not certain whether they would adequately stick to the insulator surface or whether the hydrophobic properties would be maintained during the tests in the salt-fog chamber. Because of that, shortly after the electrical tests, a preliminary hydrophobicity test was carried out. In this test the samples were humidified with a spray, inspected and photographed.

Additionally, other tests were carried out to measure the contact angles of the surfaces. With a Digipet WCS-200 micropipette, three water droplets of 50μL were deposited in each insulator. They were photographed and later, using an image editing software, the angle between the line tangent to the tip of the droplets and the surface of the insulator (Fig. 1) was measured. The contact angle of each surface was then obtained from the average value taken from the three droplets.

2.2 Assembly and Test Procedures

The artificial contamination of the insulators was performed in a salt-fog chamber measuring approximately 2.80m x 5.30m x 3.00m (width x length x height). Inside the chamber, at two opposite corners, eight standardized atomizers, according to IEC 60507, were installed. Each atomizer consists of two nozzles perpendicularly disposed. When water is injected into the lower nozzle and compressed air into the upper nozzle, fog is produced. The flow of water in each nozzle was controlled by individual taps, allowing to individually adjust the flow rate in each nozzle and ensuring an uniform fog distribution.

An epoxy resin stand was installed in the center of the chamber. The insulators were hanged at the stand by the top socket, which was powered by a 55kV and 5kVA transformer. A 4-digit Agilent U1242A True RMS digital multimeter was installed in the low end terminal, making it easier to control the voltage and soften the inaccuracies of the analog meter.

Leakage current was measured using a $1\mathrm{k}\Omega$ resistive shunt connected to the lower pin of the insulator. To record the waveforms, a Tektronix TBS-2000 digital oscilloscope with a sampling rate of 62.5kS/s and DC coupling was used. The voltage applied to the insulator was measured directly on the transformer bushing with a 10kV AC probe with an attenuation ratio of 1:1000. The gain of each oscilloscope channel was accordingly adjusted to compensate the attenuation factors. The schematic diagram of the assembly and the external view of the salt-fog chamber are shown in Figures 2 and 3.

Preliminary tests indicated that a 30-second interval would be more than sufficient to observe the desired phenomena. So, in order to monitor the behavior of the insulator in an increasing electrical stress situation, each sample was exposed to 10 voltage steps, from 1 to 10kV, lasting 30 seconds, totaling 300 seconds of experiment.

The samples were initially tested with clean fog to establish a benchmark and then with salt-fog with a sodium chloride concentration of $40\mathrm{kg/m^3}$, simulating an average contamination level (KUFFEL; ZAENGL;

KUFFEL, 2000). The salt level control was made by measuring the water conductivity, which was maintained at approximately 62mS/cm. Measurements were performed with an Instrutherm CD-850 digital conductivity meter, with a scale of 0-200mS/cm and an error of 2% of full scale. The complete step-by-step test procedure is described bellow:

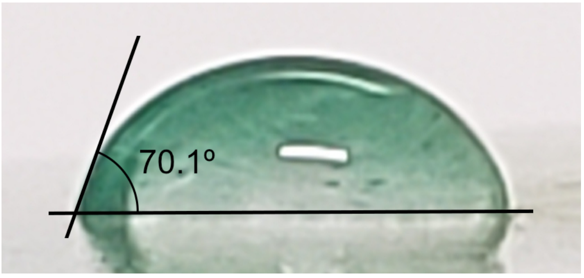

Figure 1: Procedure for measuring the contact angles.

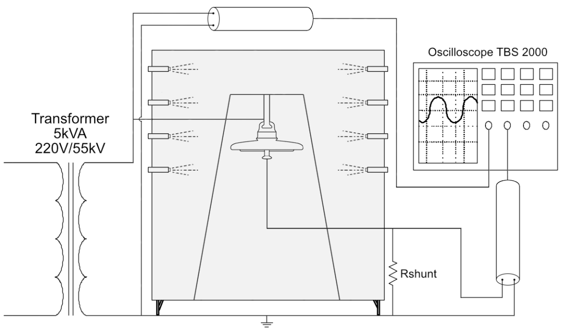

Figure 2: Schematic diagram of the assembly.

Figure 3: External view of the salt-fog chamber.

1. Adjust the saline concentration;
2. Turn on the water pump;
3. Check and, if necessary, adjust the water flow at each nozzle;
4. Seal the chamber;
5. Turn on the air compressor;
6. Wait 30 seconds for the fog to spread;
7. Apply 1kV voltage to the sample;
8. Increase the voltage in 1kV steps every 30 seconds until 10kV is reached.

3 RESULTS AND DISCUSSION

3.1 Hydrophobicity Tests

Figure 4 presents the results of the preliminary hydrophobicity and contact angle measurement tests. Comparing the insulators surfaces with the typical surface examples given in STRI Guide (GUIDE, 1992), it was noticed that the surface coated with Vaseline resembles the HC1 classification, the one with Acquella resembles the HC2 classification, and the uncoated one the HC6 classification. Regarding the contact angles, for the Vaseline coated insulator an average angle of 110.6º was measured, for the one with Acquella 92.5º, and for the uncoated sample 80.8º.

As the methodology used was designed for measure contact angles on flat surfaces, its use on a curved surface has limitations. However, it was ensured that all drops were deposited in the flatter region of the insulator, trying to minimize this problem.

The results of both tests indicate that the coatings retained their hydrophobic properties after the salt-fog tests and that the Vaseline is the most hydrophobic of the two coatings used.

3.2 Electrical Tests in the Salt-fog Chamber

3.2.1 Leakage Current

The leakage current development during the tests in all three samples are shown in Figure 5. The average current peak values during the final 30 seconds of each experiments, period when the arrangements were exposed to the highest electrical and contamination stress, are shown in Figure 6.

In general, the application of coatings resulted in the reduction of the leakage current magnitude. Based on the last 30 seconds of the clean fog tests, the measured mean peak values were 0.79mA for the uncoated insulator, 0.43mA for the Acquella coated sample, and 0.39mA for the Vaseline coated sample, differences of approximately 50%. When comparing these values with those observed in the salt-fog tests, there were increments of approximately 384% in the uncoated insulator, 97% in the Acquella coated, and 15% in the Vaseline coated, indicating that the coatings promoted a significant performance improvement for the levels of contamination considered.

Regarding dry band discharges, none were observed on the uncoated insulator in the clean fog tests. In the coated ones, few low intensity arcs were observed. These arcs are not harmful for the insulator, and were even expected, as the hydrophobicity of the coatings makes the aqueous film on the surface of the insulator more uneven, as water does not accumulate along the entire surface. This creates small high and low impedance areas, favoring the occurrence of low intensity electrical arcs.

In the salt-fog tests, dry band arcs were also observed on the uncoated insulator. The discharges started with low intensity and were difficult to identify. As the applied voltage and, hence, the leakage current increased, sufficient power started to dissipate to dry a larger area of the insulator. This greater unevenness of the conductive layer allowed the occurrence of higher intensity electric arcs, which were observed after 210s of experiment. The coated insulators presented more intense and frequent discharges when compared with the clean fog tests, but they were still lower than the ones observed in the uncoated insulator at the end of the salt-fog test.

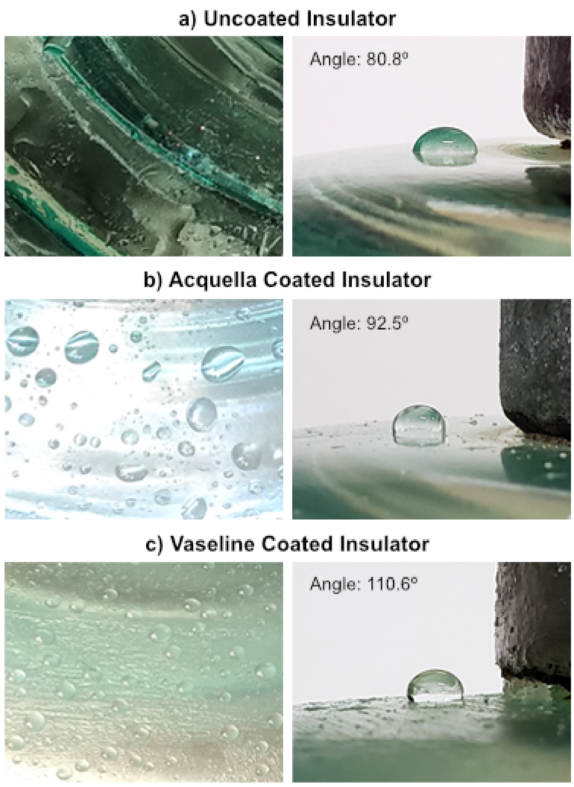

Figure 4: Results of the preliminary hydrophobicity tests, on the left, and of the tests for measuring contact angles, on the right.

3.2.2 Phase Angle

The phase angle allows the modeling of an equivalent circuit of the insulating arrangement. The measured values in all three samples are shown in Figure 7. In the clean fog tests, the Acquella and Vaseline coated insulators showed nearly constant angles during all the test, with values of 83.81° and 88.31°, respectively. Thus,

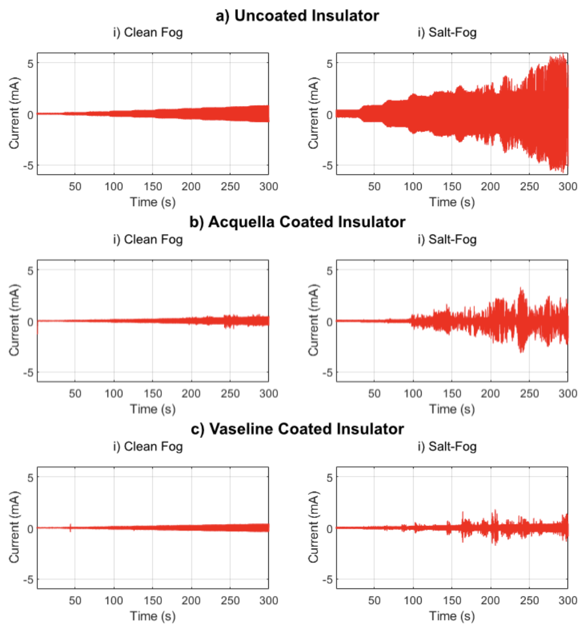

Figure 5: Current throughout the (i) clean and (ii) salt fog tests (a) on the uncoated insulator, (b) on the Acquella coated insulator and (c) on the Vaseline coated insulator.

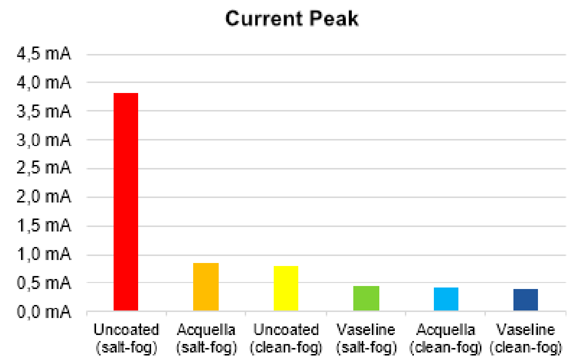

Figure 6: Mean value of current peak during the last 30 seconds of the experiment.

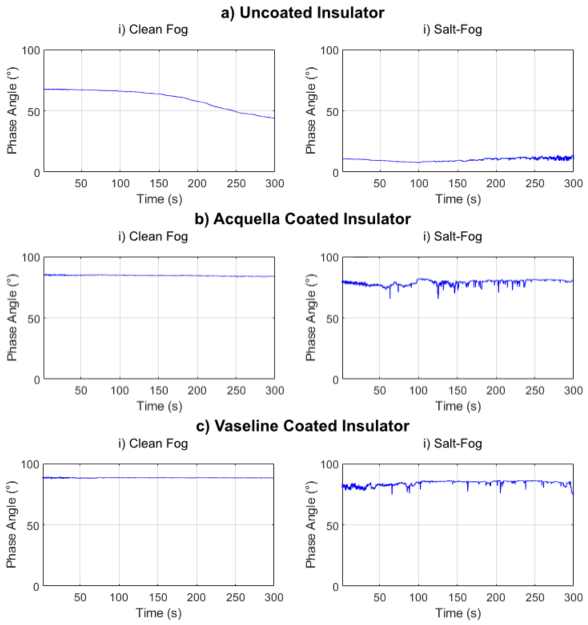

Figure 7: Phase angle throughout the (i) clean and (ii) salt fog tests (a) on the uncoated insulator, (b) on the Acquella coated insulator and (c) on the Vaseline coated insulator.

they can be modeled as RC circuits with impedance of (3,89-j32,65)MΩ and (1,07-j36,24)MΩ. So, in this case, the leakage current was almost entirely capacitive, having only a small resistive component.

The phase angle measured on the uncoated sample varied during the experiment. At the beginning of the clean fog test, the angle was 68º, lower than the coated samples, indicating a RC circuit with a lower resistance. Over the course of the test, the value was further reduced, reaching approximately 45º at the end. These results indicate that the resistivity of the arrangement decreased due to the progressive accumulation of contaminants and moisture on the insulator surface. In the final condition, the insulator can also be modeled as a RC circuit, but with an impedance of (12,57-j12,75)MΩ, which indicates a more equal distribution between the capacitive and the resistive component of the leakage current.

In the salt-fog tests, the phase angle measured on the coated insulators showed small reductions. However, the angle still remained relatively constant throughout the experiment. Some rapid oscillations were observed due to dry band discharges. The mean values for the arrangement coated with Acquella and Vaseline were 80.4º and 83.2º, respectively. Therefore, they continue to be modeled as high impedance RC circuits. The calculated impedances were (2,76-j16,40)MΩ and (3,72-j31,21)MΩ, respectively.

The uncoated insulator also had a relatively constant angular phase throughout the test, but with a much smaller value of approximately 9.0º, indicating that the best model in this case is a resistive network with impedance of (3,52-j0,79)MΩ. Therefore, the leakage current is almost entirely resistive.

Just to make the comparison easier, Figure 8 presents the average values of the phase angle in the final 30 seconds of each experiment. It is easy to see that the application of coatings has resulted in significant improvements in the insulator performance. It is interesting to point out that the coated insulators exposed to salt-fog presented average values that indicate superior performance than the uncoated insulators exposed to clean fog.

3.2.3 Total Harmonic Distortion

The analysis of the mean values over a given time frame of the Total Harmonic Distortion does not become so interesting for the evaluation of the occurrence of dry band discharges. As these are very fast transient, when considering a large time interval, discharges tend to be hiden in the signal, since the elevation of the THD in a given cycle tends to be "dissolved"by others. Therefore, in this case, the evaluation of one cycle or of a reduced number of cycles provides better indications about the occurrence of surface arcs.

Figure 9 shows six cycles of the leakage current in the uncoated insulator for the two contamination levels

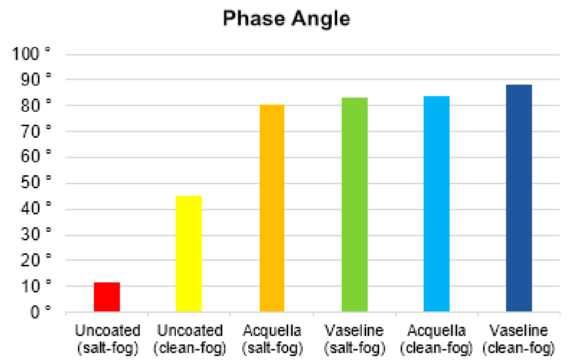

Figure 8: Mean value of phase angle during the last 30 seconds of the experiment.

used. When exposed to clean fog, the leakage current waveform was very close to a pure sine wave, with a THD of 7.58%. Although, when the insulator was exposed to the salt-fog, it is noticed that the current ceases to present a linear behavior. The various transient peaks indicate the occurrence of successive dry band discharges and the THD measured in this case was 20.76%.

In Figure 10 the THD throughout the tests on all the samples are shown. In all tests, a greater Total Harmonic Distortion is noticed in the first minute. This is because the acquisition was made in a fixed measurement scale. As the current amplitude was very low in the initial seconds, the measurement in this period was not ideal. A similar problem was observed in the acquisition of the leakage current in the coated insulators. As the same measurement scale was used to acquire the waveforms in all the test, due to the smaller amplitude of the leakage current in this insulators, the waveforms recorded for these samples presented greater distortions. Consequently, the coated insulators have higher THD throughout the entire time of the experiments, of approximately 10%.

Comparing Figures 5 and 10, it is clear that the elevations in the Total Harmonic Distortion happen at the same time of the dry band discharges. On the coated insulators, as the current measurements showed higher THD than desired, the identification of some low intensity discharges was compromised, but it was still possible to detect arcs with medium and high amplitude. In the uncoated sample, it is possible to identify even low intensity discharges that were difficult to detect through the current magnitude analysis.

Overall, the performance of the samples was proportional to the hydrophobicity level of their surfaces, with the Vaseline-coated insulator being the most hydrophobic and best performing, followed by the Acquella-coated insulator and, finally, the uncoated insulator.

4 CONCLUSIONS

4.1 Conclusions

The main objective of this paper was to investigate the leakage current behavior during phenomena that occur in artificial contamination tests, to determine useful parameters for monitoring insulating arrangements and how they are affected by the application of hydrophobic coatings. The main conclusions are summarized below:

- The isolated analysis of the leakage current magnitude satisfactorily portrays the condition of the insulator surface. This can, however, be associated with other parameters to facilitate the inspection, especially under dry band discharge conditions;
- The phase angle allows to model an equivalent circuit of the insulator, making it possible to establish the distribution of the capacitive and resistive components of the leakage current;
- The Total Harmonic Distortion is effective for the identification of dry band discharges. It is capable of detecting even low intensity arcs that are difficult to identify by the amplitude alone. For this, it

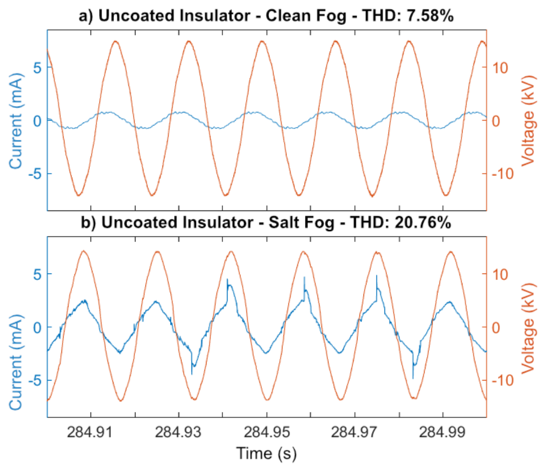

Figure 9: Six cycles of the leakage current in the uncoated insulator under (a) clean fog and (b) salt fog for the same level of electrical stress.

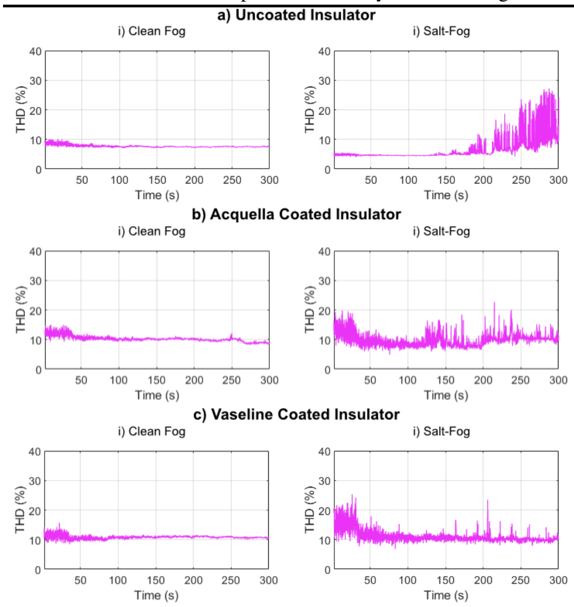

Figure 10: THD throughout the (i) clean and (ii) salt fog tests (a) on the uncoated insulator, (b) on the Acquella coated insulator and (c) on the Vaseline coated insulator.

is required to have a satisfactory measurement and monitor a reduced number of cycles.

- Although the application of Vaseline and Acquella on the insulators causes low intensity dry band discharges to occur with lower stress and contamination levels, the coatings can considerably inhibit the increase of the surface conductivity and the occurrence of intense discharges.

- The performance improvement provided by the coatings is directly associated with the degree of hydrophobicity, with the Vaseline being the most hydrophobic material which resulted in the best performance considering the samples under investigation.

4.2 Further work

A few work proposals are presented below to deepen the investigation and improve the understanding of the obtained results:

- Reassessment of the leakage current, the phase angle and the Total Harmonic Distortion as monitoring tools in tests with operating voltage under different levels of contamination;

- Performance evaluation of conventional hydrophobic coatings, such as RTV silicone, in partially and fully coated insulators with the leakage current;

- Extension of the experiments for polymeric insulators and other insulating arrangements exposed to contamination.

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