Investigation on leakage current, erosion, and hydrophobic performance of high-voltage insulator coatings of different thicknesses

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Abstract: Room-temperature vulcanizing (RTV) silicone rubber is used as a high-voltage insulator coating to enhance the pollution performance of conventional insulators, and the electrical performance of RTV coating depends on the several parameters. The present study shows the effects of the thickness on the leakage current, erosion, and hydrophobic performance of high-voltage insulator coating. Several different thicknesses of RTV silicone rubber were taken into consideration on porcelain substrates. Erosion and leakage current performances of the samples were evaluated by using inclined-plane tests (IPTs) based on the IEC 60587 standard. Eroded masses and fundamental and harmonic components of the leakage currents were investigated with respect to coating thicknesses. On the other hand, hydrophobic features of the samples were evaluated by using dynamic drop tests (DDTs) with regard to CIGRE TB442 documentation. Time to loss of hydrophobicity and the level of the leakage currents were investigated in DDTs considering the thicknesses.

Key words: RTV coating, hydrophobicity, eroded masses, inclined-plane tests, dynamic drop test

1. Introduction
Pollution is one of the main issues affecting the electrical performance of high-voltage outdoor insulation systems that operate close to industrial areas as well as coastal regions. Insulation problems due to pollution are frequently encountered for conventional porcelain and glass insulators since they have hydrophilic surface features [1–3]. Over a few decades, several solutions have been developed in order to minimize the pollution-related problems for outdoor insulation systems. Replacing the conventional insulators by silicone rubber (polymeric) insulators and applying high-voltage insulator coating to the conventional insulators, such as porcelain and glass ones, are the main solutions to overcome the pollution-related problems [2, 4, 5].

Room-temperature vulcanizing (RTV) silicone rubber material is used as a high-voltage insulator coating for conventional porcelain and glass insulators. There has been considerable interest in RTV-coated insulators for new and available power transmission lines, mainly in industrial and coastal regions. There are several good experiences of using RTV-coated insulators all over the world. Some good applications of RTV coatings in Qatar, China, the USA, Italy, and Saudi Arabia were reported in [6]. In Turkey, RTV silicone rubber coatings have only been applied to high-voltage substations, and there are almost no applications for overhead line insulators.

The state-of-art of RTV-coated insulators and guidelines of the coatings were provided in [6]. Good adhesion to the surface of the glass and porcelain insulators, surface hydrophobicity (water repellency), and

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therefore the suppression capability of the leakage current and the flashover performance are the expected features from RTV silicone rubber coatings [7, 8]. Several parameters affect the performance of the coatings, such as electrical field strengths, degree of contamination, moisture, and hydrophobic recovery ability of the coating [9]. The thickness of the coating plays a role in the coating life in wet and polluted conditions when the magnitude of the leakage current reaches a damaging level [8–10].

Several tests can be applied to high-voltage insulator coatings to evaluate their electrical performances. Salt-fog tests are used to evaluate and rank coatings in terms of their ability to suppress the development of the leakage current as well as the erosion after the tests. Inclined-plane tracking and erosion tests (IPTs) with respect to [11, 12] are beneficial to evaluate insulating materials in terms of their tracking-erosion performances. On the other hand, the dynamic drop test (DDT) has been shown to be an appropriate test method to evaluate the dynamic hydrophobic properties of high-voltage insulating materials when subjected to pollution-initiated microdischarges [13]. Relevant test procedures of the DDT are provided in CIGRE TB442 documentation [14]. An innovative testing procedure for service-aged RTV and silicone rubber insulators and surface pollution flashover characteristics considering RTV coating damages were presented in [15] and [16], respectively.

Electrical performances of RTV coating with respect to the coating thicknesses were evaluated by using salt-fog tests [9, 10]. The rate of the current pulses and their cumulative number were investigated with respect to coating thicknesses. Moreover, the roughness of the surface and content of low-molecular-weight (LMW) silicone fluid were studied before and after the salt-fog tests [9]. Another study related to the effects of coating thickness, solvent type, etc. on the leakage current and lifetime of the RTV silicone rubber coating was presented in [10]. Dry-band discharges started sooner in the thicker coatings, and current pulse rate and intensity of the discharges were affected by the thickness. More intensive discharges occurred on the thicker coating than the thinner one [9, 10]. However, erosion and dynamic hydrophobicity performances of the coatings with respect to coating thicknesses were not evaluated in IPTs and DDTs, respectively.

In this paper, a comparative analysis of coatings of different thicknesses were conducted by using IPTs and DDTs. Porcelain plates with 120 mm length and 50 mm width were used as substrates, and different coating thicknesses starting from 0.176 mm were applied to the substrates with the help of a spraying method. Leakage current and erosion performance of the samples were compared and evaluated by using IPTs with the aim of exposing the dry-band discharges to the samples for equal times for a better comparison of the samples. On the other hand, time-to-hydrophobicity loss of the samples was evaluated with a DDT, which was not used before to evaluate RTV-coated samples.

2. Experimental study

2.1. Test specimens

A commercial RTV silicone rubber coating was applied to porcelain substrates of 12 cm in length and 5 cm in width. The coating was applied by spraying method with adequate number of consecutive applications, depending on the desired thickness. Figure 1 shows the rectangular porcelain samples coated by RTV silicone rubber. Thicknesses of the samples were measured by using a digital micrometer, and at least ten separate measurements at different locations were conducted. Five test samples were used for each thickness condition. The averaged measured dry thicknesses with their standard deviations are illustrated in Table 1.

Thermogravimetric analysis (TGA) of RTV-coated samples were conducted up to 900 $^\circ$C maximum temperature with 20 $^\circ$C per minute temperature increase rate. Figure 2 displays the TGA profile of the sample

Figure 1. Rectangular porcelain samples coated by RTV silicone rubber.

Table 1. Coating thickness of the samples.

	Dry thickness (mm)	Standard dev. (mm)
Sample-1 (S-1)	0.176	0.019
Sample-2 (S-2)	0.339	0.011
Sample-3 (S-3)	0.533	0.031
Sample-4 (S-4)	0.646	0.048

together with derivative loss of the weight. It is clear from the figure that the loss of the weight starts at around 200 °C, corresponding to the release of the water, which verifies that the coating has alumina trihydrate (ATH, $Al_2O_3.3H_2O$) filler as an extending filler.
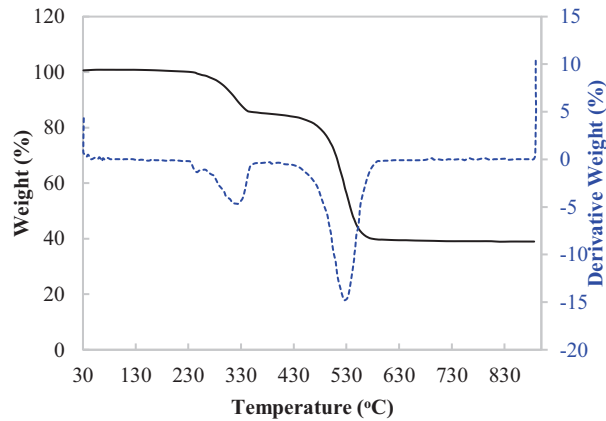

Figure 2. TGA analysis of the RTV coating.

2.2. Inclined-plane tests (IPTs)

The tracking-erosion performances of the RTV-coated samples were investigated in accordance with IEC 60587 standard [12]. Five identical test samples were used for each thickness condition. A constant test voltage condition was considered, and the test voltage was selected as 4.5 kV since the coating should be able to satisfy the 1A4.5 criterion in terms of tracking-erosion resistance for applications in extreme coastal conditions [8].

Moreover, for track-resistant materials like RTV coating, erosion is more usual than tracking in service [8]. Therefore, erosion performance of the coating was evaluated in IPT. Flow rate of the contaminant was adjusted to 0.6 mL/min, and $33k\Omega$ ballast resistors were selected. The test voltage was supplied through a 50 Hz, 220/22 kV, 30 kVA medium voltage power transformer. Assembly of the IPT is given in Figure 3, and test parameters are summarized in Table 2.
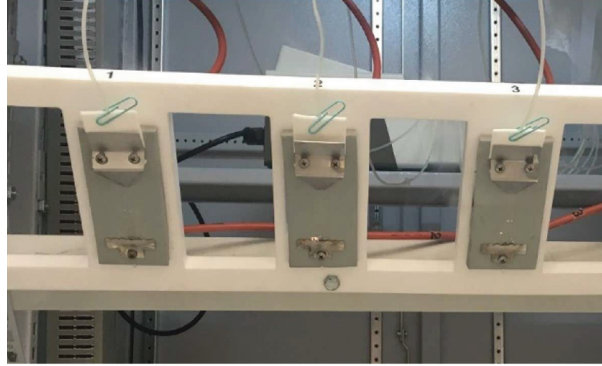
Figure 3. Assembly of the IPT setup.

Table 2. Test parameters for IPT tests.

Test voltage	4.5 kV, 50 Hz
Flow rate	0.6 mL/min
Test duration	6 h
Temperature	23 $\pm$2 °C
Humidity	45 $\pm$5%

In IPT tests, maximum, r.m.s., and fundamental and harmonic contents of the leakage currents were recorded for the 6-h test period. A moving averaged technique was applied to smooth the leakage currents. The LabVIEW data acquisition platform was used in order to record the current by considering 10 kHz sampling frequency. 50Ω shunt resistors were used to measure the leakage current data. Figure 4 shows the LabVIEW data acquisition for the leakage current monitoring and recording task.

In addition to the leakage current data, eroded masses were investigated for samples of different thicknesses. Figures 5a–d illustrate photos of the samples subjected to the IPT.

Figure 6 shows the leakage current variations for the average of the five samples smoothed by the moving average technique both for the r.m.s. and maximum values as in Figure 6a and Figure 6b, respectively. Magnitude of the leakage currents increased steadily for the first hour of the tests.

It is clear from Figure 6 that for the magnitude of the leakage current, either r.m.s. or max values are high for the thin coating (0.176 mm), especially at the beginning of the tests. Although dry-band arcing starts simultaneously for all coatings, the leakage current for the thinnest coating is higher than those of other coatings. Erosion develops sooner in the thinnest coating due to less material and exposes the substrate, which in turn increases the leakage current [9, 10]. As shown in Figure 5a, large erosive areas occurred for the thinnest coating. Leakage current for the 0.533 mm coating thickness (S-3) is the lowest, which in turn caused less
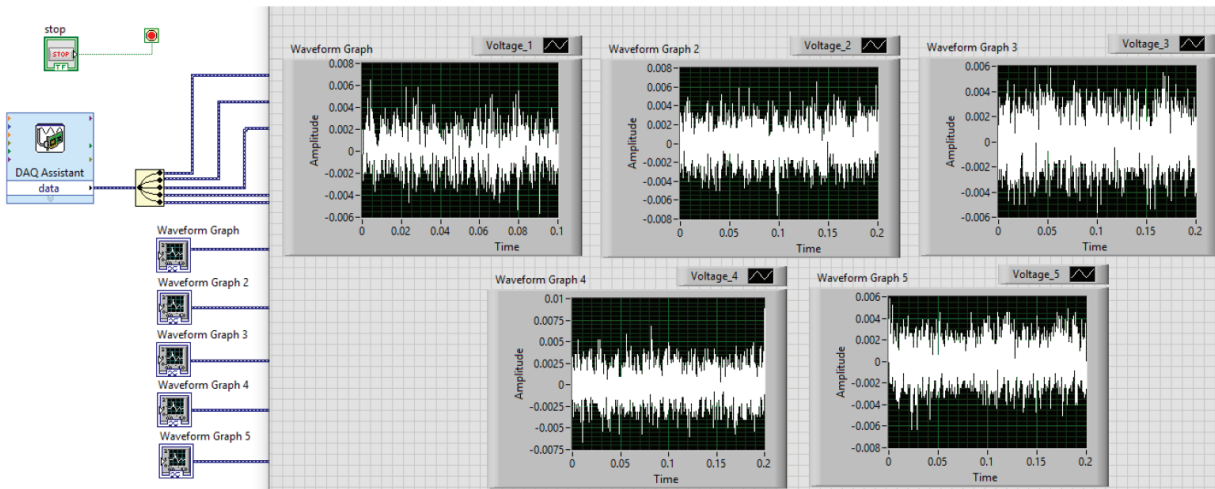
**Figure 4**. LabVIEW data acquisition for the leakage current monitoring and recording.
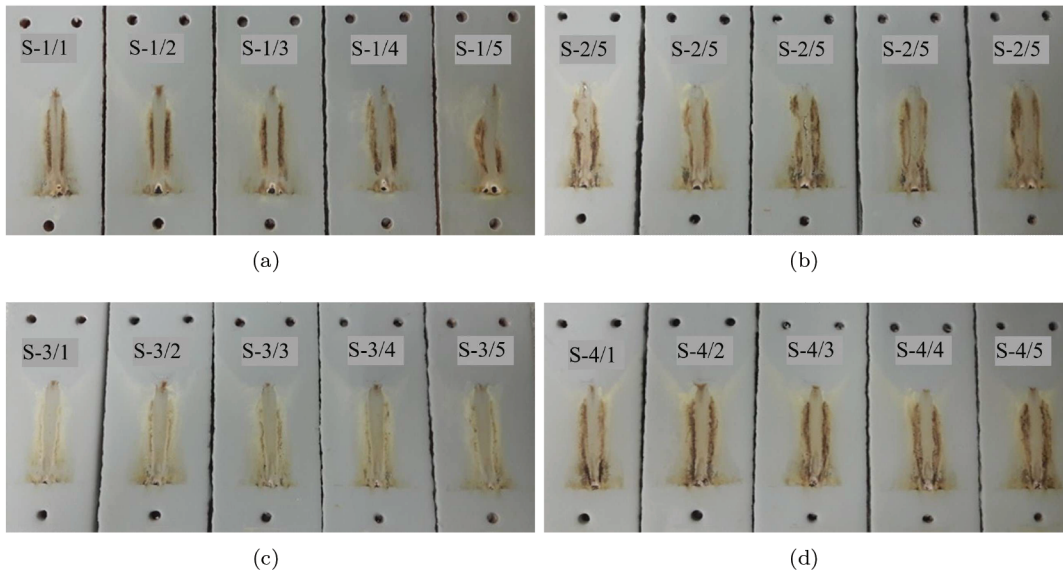
Figure 5. Photos of the test samples after the IPT tests: (a) Sample-1 (S-1), (b) Sample-2 (S-2), (c) Sample-3 (S-3), (d) Sample-4 (S-4).

eroded masses as shown in Figure 5c. This would be due to a thermal balance between the generated heat due to the dry-band discharges and the dissipated heat to the substrate [9, 10].

During the dry-band discharges on the surface of the silicone rubber samples, magnitude of the third harmonic component of the leakage current becomes bigger compared to other harmonic components [17], and the third harmonic component gives information about the intensity of the discharges. Figure 7a and Figure 7b show the third and fifth harmonic components of the leakage current for all samples, respectively. It is clear from Figure 7 that the magnitude of the third harmonic component is greater than that of fifth harmonic one.

Figure 7 shows that more intensive dry-band arcing occurred for the thinnest coating at the initial phase of the testing. For the 0.533 mm coating thickness (S-3), the third harmonic component of the current is less

as compared to other thicknesses, which in turn caused less erosive damage to the coating, as shown in Figure 5. For the thicker coatings, the intensity of the arcing was low at the beginning of the test, and its magnitude increased as the test progressed. The eroded masses of the coatings of different thicknesses are provided in Figure 8, together with maximum, minimum, and averaged values of the samples.
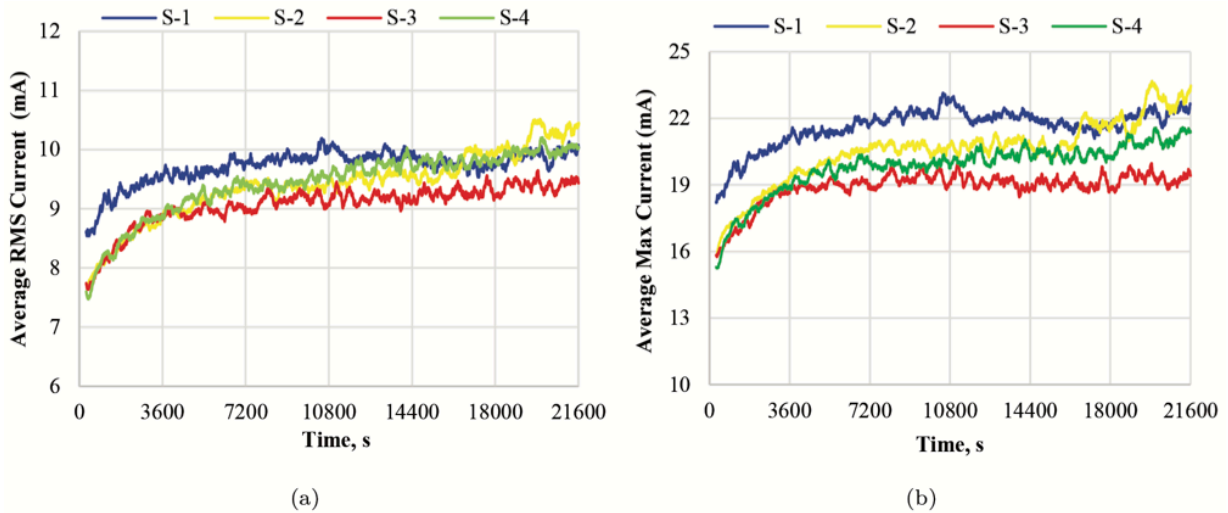

Figure 6. (a) R.m.s. leakage current (average of the five samples), (b) maximum leakage current (average of the five samples) smoothed by moving average technique.
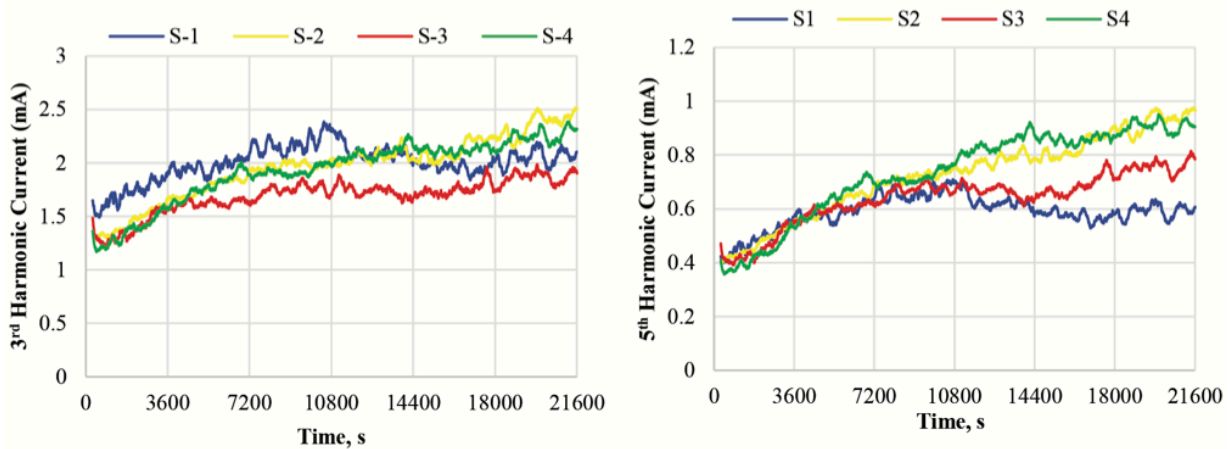
Figure 7. (a) Third harmonic leakage current (average of the five samples) (b) fifth harmonic leakage current (average of the five samples), smoothed by moving average technique.

As shown in Figure 8, there is not a big difference among the eroded masses for different thicknesses; however, S-3 (0.533 mm) has the lowest eroded masses due to the less intensive dry-band discharges, which is also verified by the third harmonic leakage current variations. For each thickness condition, the length of the erosion extending from the bottom electrode is less than 1 inch, which satisfies the requirements in [8, 11, 12].
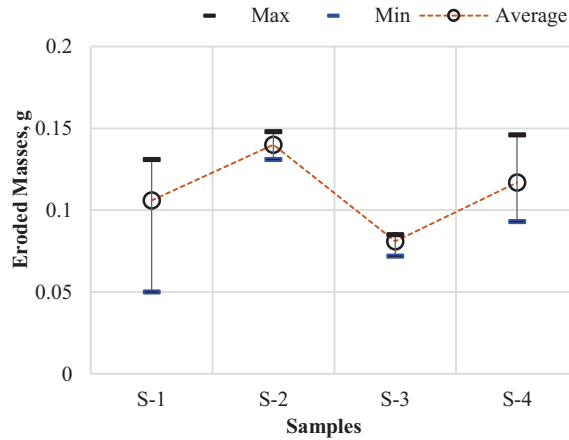
Figure 8. Eroded masses of the samples (error bars show the maximum and minimum values, and the circles show the average values).

2.3. Dynamic drop tests (DDTs)

In addition to leakage current and erosion, the hydrophobicity performance of the coatings of different thicknesses was evaluated by using DDTs in accordance with CIGRE TB442 documentation [14]. Time to loss of hydrophobicity and the leakage currents were investigated. The details of the tests and test conditions were provided in [14]. The DDT setup is given in Figure 9.
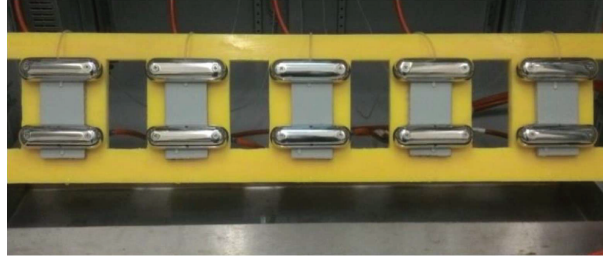
Figure 9. Dynamic drop test setup.

DDTs were conducted under 4.5 kV 50 Hz AC voltage using a 220/22 kV, 30 kVA medium voltage power transformer. The same data acquisition system as explained for IPT studies was used for the leakage current monitoring tasks. DDT parameters are provided in Table 3.

Table 3. Test parameters for DDT tests.

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Test voltage	4.5 kV, 50 Hz
Contamination flow rate	1.0 mL/min
Conductivity of electrolyte	1.5 mS/cm
Ambient temperature	23 $\pm$2 °C
Humudity	45 $\pm$5%
Drop frequency	12 $\pm$1 min
Failure criterion	I = 2 $\pm0.5mA$

Silicone rubber test samples were cleaned with isopropyl alcohol and washed with deionized water at least 24 h before starting the tests. Test voltage of 4.5 kV was applied to five test specimens simultaneously until the specimens lost their hydrophobic properties. As indicated in IPTs, five identical test specimens were used during the DDTs.

Figure 10 shows some pictures from DDTs corresponding to several stages. Figure 10a shows the initial stage of the tests, where the droplet rolls off easily through the silicone surface due to the good hydrophobicity. After microdischarges occur on the surface of the coating due to the charged water droplets, a thin continuous water path starting from the upper electrode develops (Figure 10b), which enhances the electric field strength. Finally, the surface loses its hydrophobic feature, a continuous water path occurs, and a discharge bridging the whole surface develops as shown in Figure 10c. Time to development of whole discharge is considered as the time to hydrophobicity loss, as shown in Figure 10. After the loss of hydrophobicity, the magnitude of the leakage current increases, and it reaches up to 8–10 mA ranges.

Figure 11 shows the time to hydrophobicity lost for the samples. It is clear from the figure that time to the loss of hydrophobicity changes as the thickness of the coating changes. Among the tested conditions, 0.339 mm thickness (S-2) showed the best performance in terms of time to hydrophobicity lost. Thin coating such as 0.177 mm (S-1) and thick coating such as 0.646 mm (S-4) showed poor performance, and it took less time to lose their hydrophobic features. Therefore, an optimum thickness is available that provides the longest time to the loss of hydrophobicity in a DDT. Note that there is no available literature related to effects of RTV coating thickness on the temporary loss of hydrophobicity by using DDTs, but there are some studies on a similar topic conducted by salt fog tests [9, 10]. An optimum thickness was obtained in a salt fog test in terms of time to failure of the samples rather than time to the loss of hydrophobicity [10].
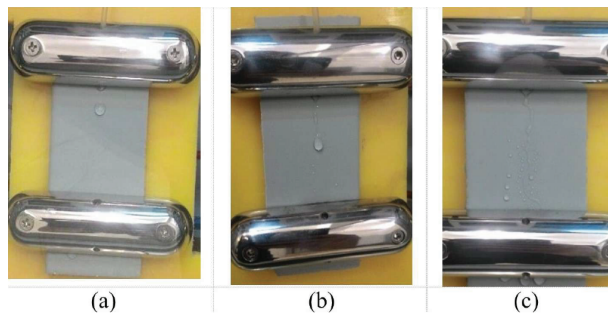
Figure 10. Stages of the hydrophobicity loss for RTV silicone rubber coating: (a) initial setup of the test, (b) formation of continuous water path from the upper electrode, (c) loss of the hydrophobicity.
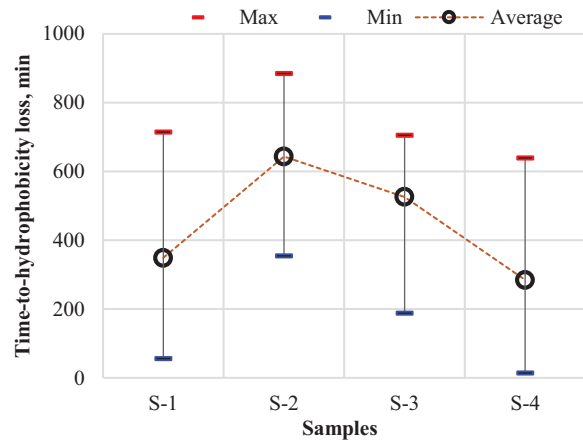
Figure 11. Time to hydrophobicity loss of the samples (error bars show the maximum and minimum values, and the circles show the average values).

Considering the results of the DDTs as shown in Figure 11, there would be some reasons why the time to hydrophobicity loss showed this behavior with respect to coating thickness. The available studies have shown that surface roughness of the specimens may affect time to hydrophobicity loss in a DDT [18, 19]. If R_a increases, advancing and receding dynamic contact angles decrease and droplet length increases, which in turn

enhances the electric field strength and reduces time to the loss of hydrophobicity [18]. Moreover, the roughness would also affect the flashover voltage of the silicone rubber dielectric [20].

Surface roughness of the RTV-coated samples of different thicknesses were measured, and R_a, R_{rms}, and R_{max} roughness parameters were determined. The roughness measurements were conducted at ten different locations with the aim of increasing the reliability of the results, and maximum, rms, and average values are given in Figure 12a, Figure 12b, and Figure 12c, respectively. The uncoated porcelain substrate has 0.56 μm, 0.80 μm, and 0.36 μm rms, maximum, and average roughness parameters, respectively. Application of the coating to the porcelain surface increases all roughness parameters, as illustrated in Figure 12.

Among the tested conditions, the thinnest coating (0.176 mm, S-1) showed the highest $R_{\max}$ parameter, and 0.339 mm (S-2) showed the lowest $R_{\max}$ parameters. Beyond 0.339 mm thickness (S-2), $R_{\max}$ parameter tends to increase, as shown in Figure 12a. As explained in the DDTs, 0.339 mm coating thickness (S-2) showed the best performance in terms of time to hydrophobicity lost, and the same thickness showed the lowest $R_{\max}$ parameter. R_{rms} and R_a roughness parameters showed similar results with respect to coating thicknesses, although a slight reduction was observed for the 0.339 mm thickness (S-2).
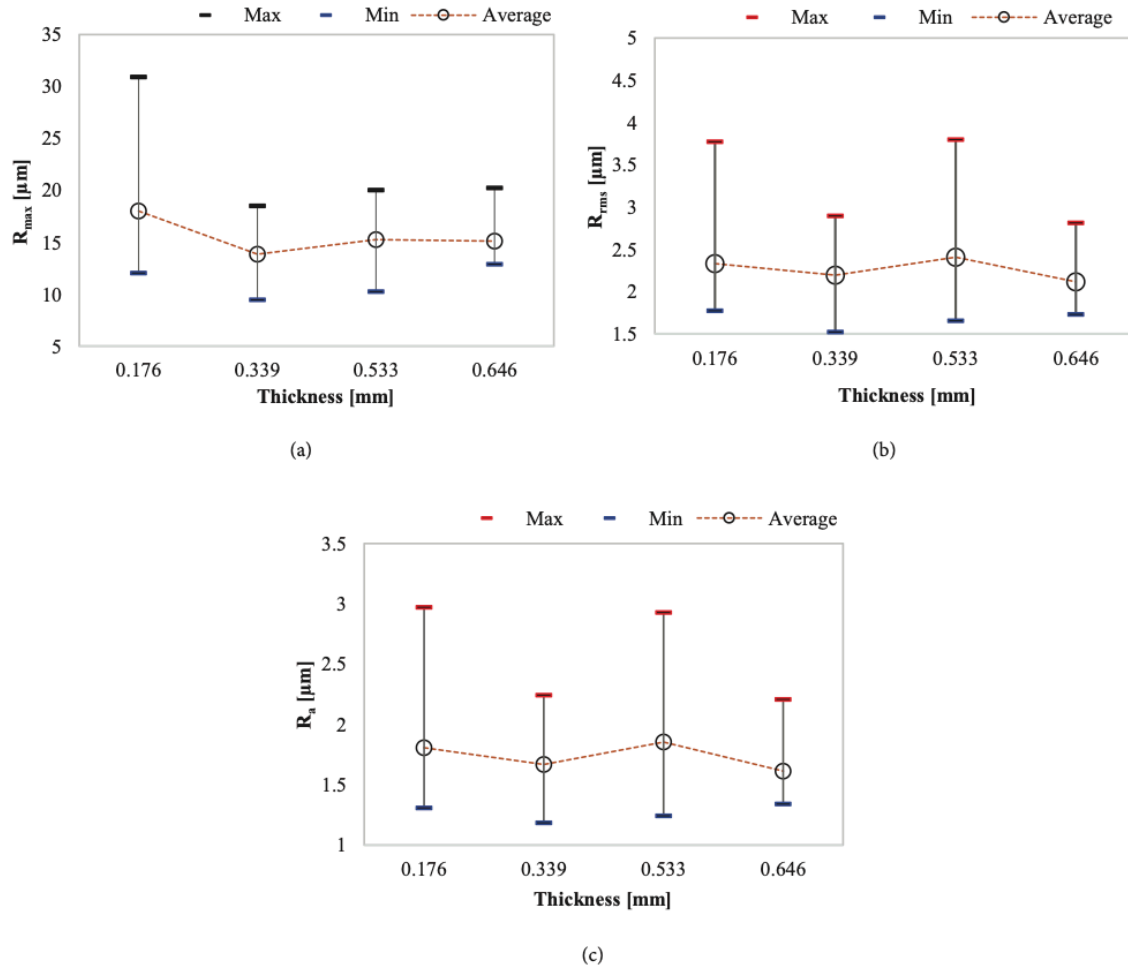
Figure 12. Surface roughness measurements: (a) peak roughness values, (b) rms roughness values, (c) average roughness values.

3. Conclusions

In this study, effects of the thickness of high-voltage insulator coating on the hydrophobicity, leakage current, and erosion performance were investigated. The investigated RTV silicone rubber had ATH as an extending filler. Leakage current as well as erosion performance of the samples were studied by using inclined-plane tests in order to expose the dry-band discharges to the samples with equal times for a better comparison. The rms, maximum, and third harmonic contents of the leakage currents were analyzed, and the moving average technique was applied to smooth the leakage current data. Hydrophobic performances of RTV coatings of different thickness were compared in the DDT method, which was not used before to evaluate RTV-coated samples in terms of hydrophobicity. The following points summarize the research work:

- The samples with 0.176, 0.339, 0.533, and 0.646 mm coating thickness passed IPT 4.5 kV tests since the length of the erosion was less than 2.5 cm. The eroded area of the coatings was the biggest for the thinnest coating.

- The minimum erosion occurred for the coating thickness of 0.533 mm. This result was also verified by the leakage current data. The rms, maximum, and third harmonic component of the leakage current of 0.533 mm coating thickness were less than those of the other thicknesses.

- The magnitude of the maximum and rms leakage current values, which were smoothed by the moving average technique, may reach up to 22 mA and 10 mA, respectively.

- In the dynamic drop tests conducted under 4.5 kV AC voltage and 1.0 mL/min contamination flow rate, the coating thickness of 0.339 mm was found to be the optimum thickness among the tested conditions since it performed better than either the thinner or the thicker coatings in terms of time to loss of hydrophobicity.

- Application of the coating to the porcelain substrates increases the surface roughness parameters. The surface roughness parameter may be one of the variables affecting the time to hydrophobicity loss. The samples with 0.339 mm thickness showed lower maximum roughness parameters than those of other thicknesses; however, other roughness parameters showed similar behavior with respect to thickness.

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