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Optimization of $nSiO_2$-Filled RTV Silicone Rubber Coatings for Enhanced High Voltage Outdoor Insulator Performance

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Abstract

This paper presents the experimental results of leakage current testing on nanosilica ($nSiO_2$)-filled room-temperature vulcanized (RTV) silicone rubber (SiR) coatings for outdoor insulators. Nanosilica composition is prepared based on the optimization results of surface hydrophobicity, surface resistivity, and relative permittivity of the RTV SiR matrix with varying $nSiO_2$ contents. The study found that the insulator with a 4 wt.% $nSiO_2$-filled RTV SiR coating had the highest surface resistivity, better hydrophobicity, and higher permittivity compared to the unfilled RTV SiR coating. Leakage current tests are performed under several conditions (dry, clean fog, and salt fog) to evaluate the insulation characteristics of the modified RTV SiR coating applied on an actual high-voltage insulator. The results indicate that the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator significantly reduces the leakage current magnitude and Total Harmonic Distortion (THD) when compared to that of the uncoated as well as to that of unfilled RTV SiR-coated insulators. Under all fog conditions, the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator with a polluted surface showed the smallest leakage current THD percentage of all insulator samples. Additionally, the cross product of the leakage current magnitude and THD is also calculated to determine the condition of the insulator. The cross-product results show that the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator is more effective at reducing it under dry conditions, with a reduction range of 68%–81% compared to the uncoated isolator and 70%–77% compared to the unfilled RTV SiR-coated isolator. This study shows the effectiveness of RTV silicone rubber coating material with $nSiO_2$ filler particles in reducing the magnitude of leakage current and harmonics in polluted environments.

Keywords:

Nanosilica Filler;

RTV Silicone Rubber;

Leakage Current;

Outdoor Insulator.

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1- Introduction

Insulators provide an important function in high-voltage transmission and distribution systems. The primary role of overhead line insulators is to mechanically support the conductor and electrically isolate it from towers and adjacent conductors. Environmental conditions and atmospheric contaminants negatively impact the effectiveness of outdoor insulator units, potentially reducing transmission line reliability [1]. Pollutants, such as salt, cement dust, water vapor,

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and moisture from coastal areas, industrial regions, power plants, and rainfall accumulate on insulator surfaces, carried by wind or fog [2, 3]. This pollutant layer leads to the formation of dry bands on the localized insulator surfaces, eventually resulting in surface arcs [4].

Porcelain insulators generally have low hydrophobicity, making them less effective in suppressing leakage current in environments with high humidity and extreme pollution levels. Mitigation strategies are necessary to address this issue and enhance insulator performance in extreme environmental conditions. Coating porcelain insulators or replacing them with polymers are the two main methods available for mitigation. Polymer insulators have superior hydrophobicity, resulting in efficiency in minimizing leakage current compared to porcelain insulators. Nonetheless, polymer insulators have several drawbacks, including reduced mechanical resistance. Moreover, replacing porcelain insulators with polymer insulators incurs additional expenses for procurement and reinstallation, potentially making them less cost-effective overall. Therefore, choosing a coating method for porcelain insulators is a more efficient alternative, as it can increase the hydrophobicity, permittivity, and surface resistivity without the need to replace the existing infrastructure, making it more suitable for use in environments with high humidity and extreme pollution levels.

Room-temperature vulcanized (RTV) silicone rubber (SiR) is a widely used elastomer that vulcanizes at room temperature, allowing it to cure without heating. This material consists of silicon, oxygen, carbon, and hydrogen atoms. Its Si-O bonds stabilize RTV SiR at high temperatures and are weather- and chemical-resistant. Its curing at room temperature makes it appropriate for flexible insulation applications. RTV SiR performs effectively at continuous operating temperatures of up to 150°C, with brief exposure tolerance up to 250°C. Additionally, it retains flexibility down to -60°C, surpassing organic rubber. An important feature of RTV SiR is its hydrophobic nature, which serves as an essential function in preventing water absorption and surface contamination. This characteristic holds major importance for applications in environments with high pollution levels, such as in coastal areas, where the buildup of contaminants may significantly affect performance [5]. RTV SiR also exhibits outstanding electrical insulation properties, making it a reliable material for outdoor insulators due to high resistivity and resistance to corona and arcing [6]. Therefore, these attributes make RTV SiR a promising insulator coating material, effectively preserving hydrophobicity and electrical properties while reducing surface contamination and preventing corona discharge and arcing.

However, pure silicone rubber exhibits low tracking and erosion resistance performance. Improved properties of silicone rubber are necessary to extend its service life. Filler particles are added to the polymer to improve certain properties and reduce costs. A higher filler content for certain materials increases the tracking performance but may also inhibit the hydrophobic properties [7, 8]. Filler materials with particle sizes between 1 and 100 nanometers (nm) are classified as nanofillers. Nanofillers provide excellent mechanical properties, scratch resistance, barrier properties, and fire resistance at low concentrations [9]. Silicon dioxide (SiO_2), commonly known as silica, performs as a semi-reinforcing filler that enhances the physical properties of silicone compositions by forming molecular bonds with silicone polymers. Silica exhibits superior thermal stability below 800°C [10]. Additionally, silicone rubber filled with nanosilica ($nSiO_2$) particles creates a UV shielding/blocking that is more efficient at reflecting UV light, thereby reducing its susceptibility to UV radiation damage [11].

Ilhan et al. have previously studied porcelain insulators coated with RTV SiR and fillers. This study investigates the leakage current testing of RTV SiR-coated porcelain insulators that were coated with either alumina trihydrate (ATH) or ground quartz (silica) in salt fog conditions. This study demonstrated that the RTV SiR coating effectively maintains its hydrophobicity, preventing leakage currents from occurring in the creepage path, which could potentially cause dry band, coating erosion, and flashover problems. The results show that the performance of the insulator with silica filler is superior to that of the coating filled with ATH. The maximum leakage current of a silica-filled RTV SiR-coated insulator is lower than that of an ATH-filled RTV SiR-coated insulator [12]. Tariq Nazir et al. have attempted to explain how silica filler loading can affect hydrophobic properties and degradation of RTV silicone rubber under AC corona discharge. It has been observed that with a silica loading of 5 weight percentage (wt.%), the reduction in hydrophobicity is 24º less in comparison to unfilled samples after 72 hours of corona exposure. Additionally, the surface energy increase for the aged silica-filled sample was 21.38 mJ/m² lower than for unfilled samples. Nanosilica also prevented crack formation and polymer penetration, thus reducing degradation [13]. However, this research did not thoroughly explore the optimization of silica concentration for electrical properties, thus necessitating further discussion.

Zolriasatein et al. earlier investigated the application of silicone rubber as a porcelain insulator coating reinforced with nanosilica. This study examines the impact of varying nano silica concentrations in RTV silicone rubber on its surface microstructure, hydrophobicity, and electrical characteristics. It compares RTV silicon rubber with nano silica and pure RTV silicon rubber before and after UV irradiation. The study's findings show that RTV silicone rubber coatings with the right amount of filler can make the surface rougher and more hydrophobic. Furthermore, using micro silica fillers allows the surface contact angle to reach the initial level faster once contaminants are present. This means that the coating can increase the insulator's resistance to external factors such as humidity and UV radiation. Adding nanoparticles like nano silica can also make RTV silicone rubber last longer. Based on the tests, the composite samples worked better than the pure RTV silicone rubber, and the samples with 3% nano silica had the best properties [14]. However, the study did not discuss further the leakage current tests in various environmental conditions.

Past studies by Rachmawati et al. examined the coating material on semiconducting glazed insulators (SGI). Nevertheless, SGI reveals greater conductivity than conventional porcelain insulators, leading to increased leakage current [15]. The rise in leakage current causes an increase in the surface temperature of SGI, hence advancing material aging and causing the deterioration of the semiconducting glazing layer over time. In addition, Bagaskara et al. conducted previous research on how environmental conditions influence leakage current parameters, using various types of insulators and under different environmental conditions [16]. This research only focuses on leakage current measurement and the factors that influence it; it does not discuss mitigation strategies to reduce the impact of leakage current on insulators. There are still some limitations that could potentially lead to development opportunities, such as the use of nano-fillers or the optimization of electrical characteristics to reduce the impact of pollutants. Diantari et al. have also conducted previous research on the addition of gum rosin to RTV SiR [17]. However, the addition of gum rosin to RTV-SiR does not have much effect on surface resistivity and reduces the relative permittivity value. The coating of RTV SiR with gum rosin is less effective at reducing the cross-product of I_{rms} and THD under polluted conditions compared to RTV SiR alone. Therefore, we need to conduct further research on fillers capable of reducing leakage currents in both polluted and non-polluted conditions.

Previous studies identified that RTV SiR filled with 3 wt.% of $nSiO_2$ significantly enhances hydrophobicity, permittivity, and reduces tan delta. Under salt fog conditions, the leakage current was reduced by 31% to 41% (for clean surfaces) and 41% to 55% (for polluted surfaces) compared to uncoated insulators. Under dry conditions, reductions were less significant, at 3% to 6.2% (for clean surfaces) and 0.8% to 2.9% (for polluted surfaces) [18]. However, surface resistivity was not analyzed in these studies. Therefore, the current study aims to evaluate and optimize $nSiO_2$ content (0 to 5 wt.%) based on hydrophobicity, surface resistivity, and permittivity (ε), applying the optimal formulation on high-voltage outdoor insulators and validating the findings through comprehensive leakage current tests and result comparison to uncoated and RTV SiR-coated insulators. The leakage current magnitude, total harmonic distortion (THD), and their cross-product (I_{rms} × THD) are systematically assessed on both clean and polluted surfaces, as well as under dry and humid artificial environmental conditions.

The structure of this journal begins with an introduction that explains the background that underlies this research, as well as some of the previously described literature, suggesting that the development of coating materials that are more effective in reducing leakage currents in extreme environmental conditions is required. The Materials and Methods section discusses the materials used in this research, including RTV SiR as the base material and $nSiO_2$ as the filler material. The methodologies include the evaluation steps of hydrophobicity tests, permittivity, surface resistivity, and leakage current measurements under various environmental conditions. Furthermore, the Results and Analysis section presents the experiment results of electrical characteristics with variations in $nSiO_2$ composition and assesses the insulator's leakage current performance under several environmental conditions. Finally, the conclusion section summarizes the main findings of this study and makes recommendations regarding the use of optimized materials to enhance the performance of high-voltage outdoor insulators.

2- Materials and Methods

In general, the flowchart of the research carried out to develop and evaluate the effectiveness of $nSiO_2$-filled RTV SiR coatings for enhanced insulator performance is as shown in Figure 1.

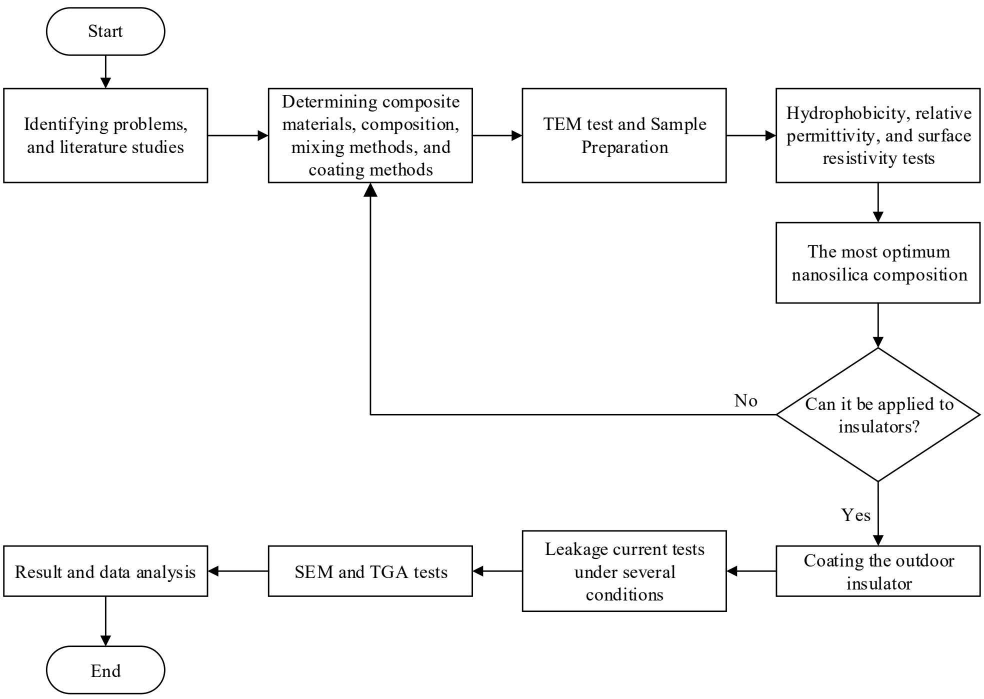
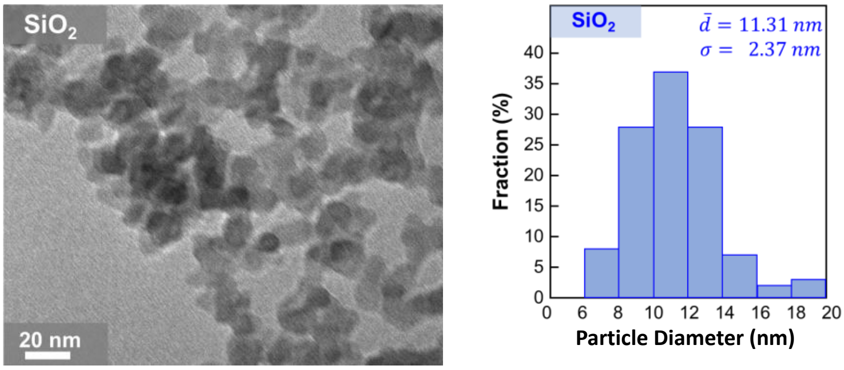


Figure 1. Flow chart of the research method

2-1- Materials

The composite materials are composed of RTV SiR as the base material, nanosilica ($nSiO_2$) as the filler, hardeners, thin silicone, and thinner. The $nSiO_2$ content ranges from 0 to 5 wt.%, with increments of 0.5 wt.%. The hardener and thin silicone accounted for 4 wt.% of the RTV SiR. The hardener initiates the vulcanization or curing process in silicone, while the thin silicone decreases the viscosity of RTV SiR, facilitating mixing and promoting a more uniform particle distribution. In this study, the mass of the thinner accounts for 23% of the total mass. Thinner serves to dilute the mixture, making it easier to apply. The mass of RTV SiR is calculated by subtracting the total mass of the other components ($nSiO_2$, hardener, thin silicone, and thinner) from the total mass remaining.

The $nSiO_2$ filler particles are characterized using a transmission electron microscope (TEM) to confirm their nanoscale size. Based on the TEM test results, images of the test samples were obtained, and the diameters of 112 samples were then measured. The results showed an average particle size of 11.31 nm, with a standard deviation (σ) of 2.37 nm. Figure 2 shows a TEM image and diameter distribution of $nSiO_2$ particles.



(a) (b)

Figure 2. (a) TEM image, and (b) diameter distribution of $nSiO_2$ particles

2-2- Sample Preparation

The samples that need to be prepared are bulk samples, coated ceramic specimens, and actual coated porcelain insulators compared to uncoated porcelain insulators. Bulk samples are used for testing relative permittivity and surface resistivity. Meanwhile, ceramic specimen samples are used for hydrophobicity testing.

Bulk samples and coated ceramic specimens are prepared as follows: First, the $nSiO_2$ fillers are dispersed with thinner and isopropyl alcohol until the dispersion is uniform. In parallel, RTV SiR and thins silicone are mixed together. Then, $nSiO_2$ fillers that have been dispersed with thinner and isopropyl alcohol are mixed with RTV SiR. After mixing, the sample is vacuumed to remove voids. The final step is to mix the hardener into the sample. The sample is ready to be molded as a bulk sample and applied to ceramic specimens. This process takes 2-3 hours in room temperature conditions until the sample is hardened and can be used for testing. Figure 3 shows a sample of uncoated, unfilled RTV SiR-coated and $nSiO_2$-filled RTV SiR-coated insulators.

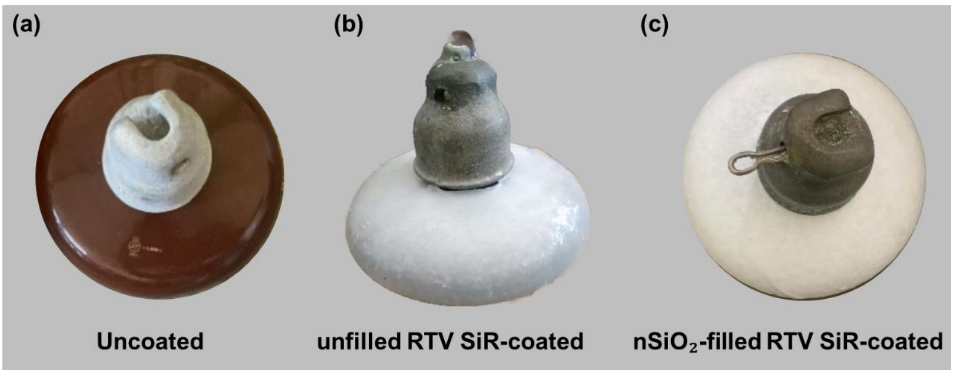


Figure 3. Insulator samples: (a) Uncoated, (b) unfilled RTV SiR-coated, and (c) $nSiO_2$-filled RTV SiR-coated

The procedures for preparing porcelain insulator coating materials are similar to those for bulk samples. The primary difference is the extended mixing duration resulting from the larger mass of the mixture. Before application, the insulator is cleaned with isopropyl alcohol and sprayed with adhesive to enhance the adhesion between the coating material and the insulator surface. The coating material is applied to the insulator with an average thickness of 4 mm, as illustrated in Figures 3-b and 3-c.

2-3- Hydrophobicity Test

This test utilizes static contact angle measurement in accordance with the IEC TS 62073-2018 standard. The contact angle method measures the angle formed between a water droplet and the surface of the material. The measurement carried out is a static contact angle by dripping water onto the horizontal surface of a specimen. The volume of water dripped ranges from 5 to 50 µL, with a recommended volume of 50 µL. For rough surfaces, the amount of water dripped can be larger. Measure the contact angle as soon as possible, ideally within minutes, after dripping water onto the surface [19]. The images of droplets are then captured and processed using image processing software to measure the contact angle.

2-4- Permittivity and Surface Resistivity Test

The characteristics of electrical properties are measured using an LCR meter to determine the relative permittivity value and tan delta. This measurement utilizes bulk samples with silver conductive paste to ensure contact between the sample and electrode surfaces. The LCR meter outputs the measurement value as capacitance (*C*) at frequencies ranging from 0.1 kHz to 2 kHz, and then relative permittivity (ε_r) is calculated using Equation 1.

$$\varepsilon_r = \frac{Cd}{\varepsilon_0 A} \tag{1}$$

where *d* is the sample thickness in [m], A is the sample's surface area in [m], and ε_0 is the permittivity in vacuum (8.85×10^{-12} F/m).

Surface resistivity measures a material's ability to resist the flow of electric current at its surface. The value is derived by dividing the DC voltage between a pair of electrodes located on the same surface of a test object by the current flowing through the surface layer. The surface resistance of the sample is measured by applying a voltage ranging from 10 V to 1000 V and measuring the current using electrodes arranged in a specific manner. The surface resistivity is then calculated from the measured resistance. The electrode configuration consists of a main electrode, a ring electrode, and a counter electrode, as specified in JIS K6271-1:2015. The equation for surface resistivity is expressed by Equation 2,

$$\rho_S = \frac{\pi(D+d)}{(D-d)} \times R_S \tag{2}$$

where ρ_s is surface resistivity (Ω), *d* is the outer diameter of the main electrode (cm), *D* is the inner diameter of the ring electrode (cm), and R_s is surface resistance (Ω).

2-5- Leakage Current Test

Figure 4 illustrates the experimental setup for the leakage current test used in this research. The aim of this leakage current test is to compare the leakage current performance of several insulator samples. The insulator samples tested in this study are uncoated, unfilled RTV SiR-coated, and $nSiO_2$-filled RTV SiR-coated insulators. The measurement is subjected to an input voltage ranging from 5 kV to 25 kV in 5 kV increments. To ensure repeatability and accuracy, each measurement is performed three times, and the results are obtained by averaging the values from these three trials. This leakage current test utilizes two different insulator surface conditions: clean surfaces and polluted surfaces. We conducted tests on polluted surfaces using NaCl and kaolin as pollutants. 512.65 mg of NaCl represents equivalent salt deposit density (ESDD), while 2563.24 mg of kaolin represents non-soluble deposit density (NSDD). IEC 60815 (2008) categorizes these concentrations as highly polluting. Additionally, the environmental conditions varied with three different types of fog: dry conditions (no fog) with a relative humidity (RH) of 70%, clean fog with an RH of 90%, and salt fog with a conductivity of 0.6 S/m and an RH of 90%, as shown in Table 1. Fog conditions in the chamber refer to the IEC 60507 standard.

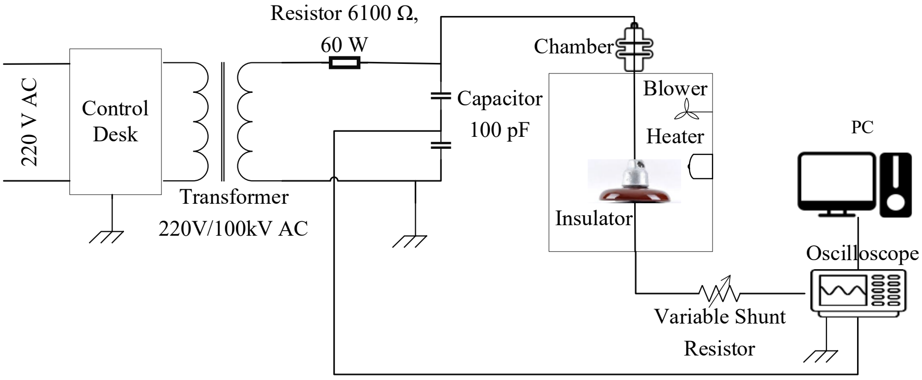


Figure 4. Leakage current test experimental setup

Table 1. Leakage current test experimental conditions

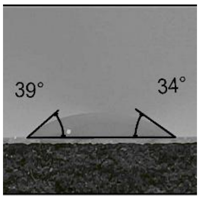
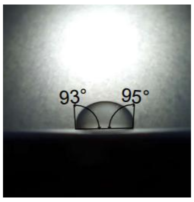
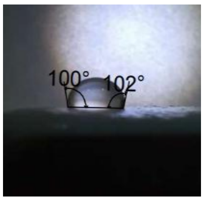
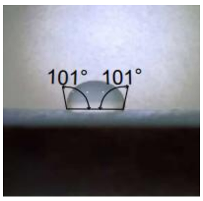
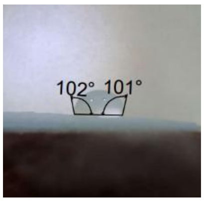
Sample	Surface Condition	Fog Condition		
Uncoated insulator	Clean	Dry (No Fog), RH:70%	Clean Fog (CF), RH: 90%	Salt Fog (SF), RH: 90%
	Polluted			
Unfilled RTV SiR coated insulator	Clean			
	Polluted			
$nSiO_2$-filled RTV SiR coated insulator	Clean			
	Polluted			

3- Experimental Results and Analysis

3-1- Contact Angle Measurement

Contact angle measurements are taken on uncoated and coated ceramic specimens with RTV SiR coating, containing variations in the $nSiO_2$ composition of 0-5 wt.%. Measurements are taken at 10 different points on the surface of the ceramic specimen and then averaged between the left and right angles of the water droplets. Table 2 presents the contact angle measurement results for several samples with various $nSiO_2$ compositions. The contact angle is measured using the AutoCAD application. The overall results from 10 experiments for each sample are presented in Figure 5.

Table 2. Contact angle measurement of ceramic specimens

Uncoated	0 wt.% nSiO2	0.7 wt.% nSiO2	1 wt.% $nSiO_2$	1.5 wt.% $nSiO_2$	2 wt.% $nSiO_2$
					
2.5 wt.% $nSiO_2$	**3 wt.% $nSiO_2$**	**3.5 wt.% $nSiO_2$**	**4 wt.% $nSiO_2$**	**4.5 wt.% $nSiO_2$**	**5 wt.% $nSiO_2$**
					

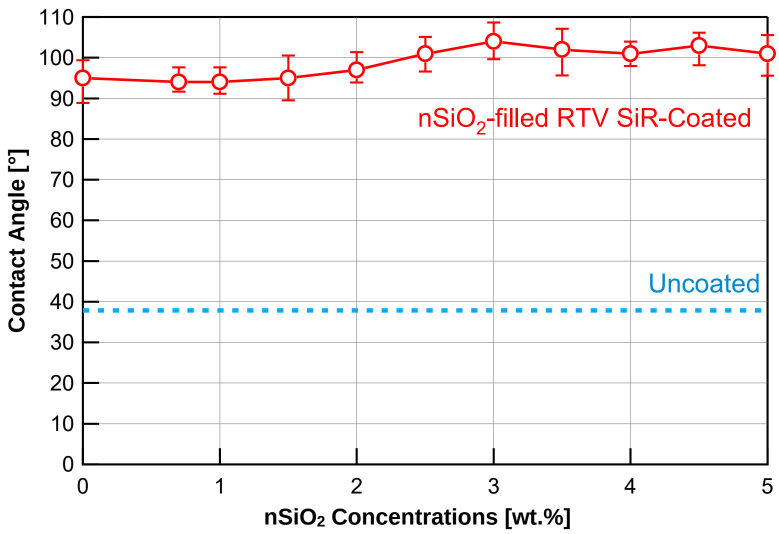


Figure 5. Static contact angle measurement results of coated ceramic specimen

The uncoated sample has a lower contact angle than those coated using RTV SiR or $nSiO_2$-filled RTV SiR samples. The uncoated sample also exhibits hydrophilic properties, with a contact angle of less than 90°. Therefore, applying RTV SiR coating will increase the contact angle on the ceramic specimen. Figure 5 presents a stable contact angle of 0 to 2 wt.% of $nSiO_2$-filler RTV SiR samples. The graph also shows that small additions of $nSiO_2$ do not significantly affect the surface properties. The increase in angle starts from 2 wt.% $nSiO_2$, reaches 97°, and peaks at 3 wt.% with a contact angle of 103.85°. However, when the $nSiO_2$ concentration increased from 3.5 wt.% to 5 wt.%, the contact angle decreased slightly, indicating saturation or uneven particle distribution.

3-2- Relative Permittivity Measurement

Relative permittivity measurements are made at varied frequencies. As shown in Figure 6, with every increase in frequency, the capacitance (C) value decreases, resulting in a corresponding decrease in the relative permittivity value.

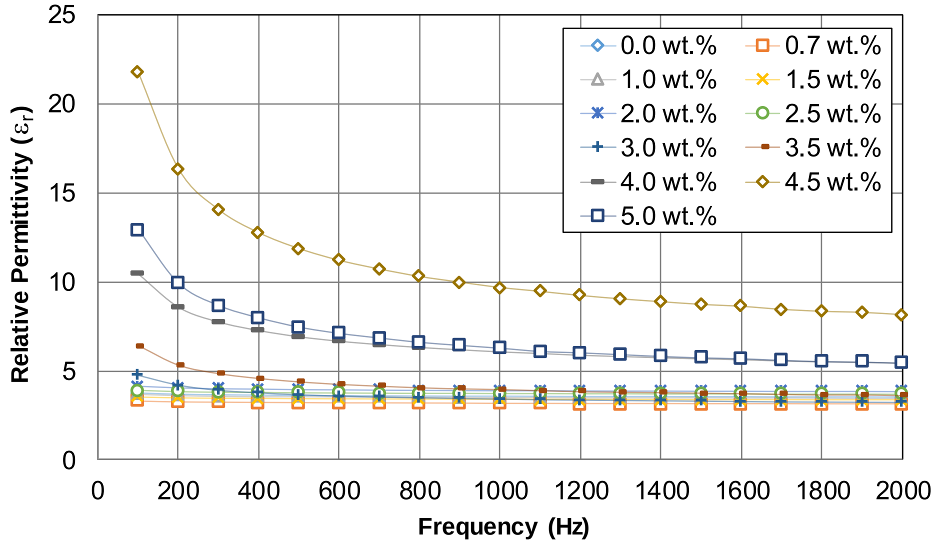


Figure 6. Relative permittivity with frequency variation

The trend shows that the highest permittivity occurs at low frequencies, while the higher the frequency, the closer the permittivity approaches a constant value. The decrease in relative permittivity as frequency increases is generally due to the dielectric material not being able to keep up with changes in the electric field as quickly at low frequencies. Dipole polarization takes time to respond to the electric field. So, when the frequency of the electric field increases, especially when the frequency is high, the polarity of the molecules in the material cannot change synchronously with the change in the electric field. As a result, the relative permittivity decreases with increasing frequency [20-23].

Figure 7 shows the relative permittivity value at a frequency of 100 Hz as a function of $nSiO_2$ composition variations. The graph reveals that the relative permittivity value of the composite fluctuates slightly from 0 to 3.5 wt.%, indicating that lower concentrations have a minimal impact. A significant increase in permittivity occurs when the $nSiO_2$ concentration reaches 4 and 4.5 wt.%, resulting in the relative permittivity value reaching 21.76 at 4.5 wt.%. This indicates better insulation properties due to increased resistance to external electric fields; however, at 5 wt.% of $nSiO_2$, the relative permittivity decreased to approximately 12.92, which is attributed to uneven particle distribution [12].

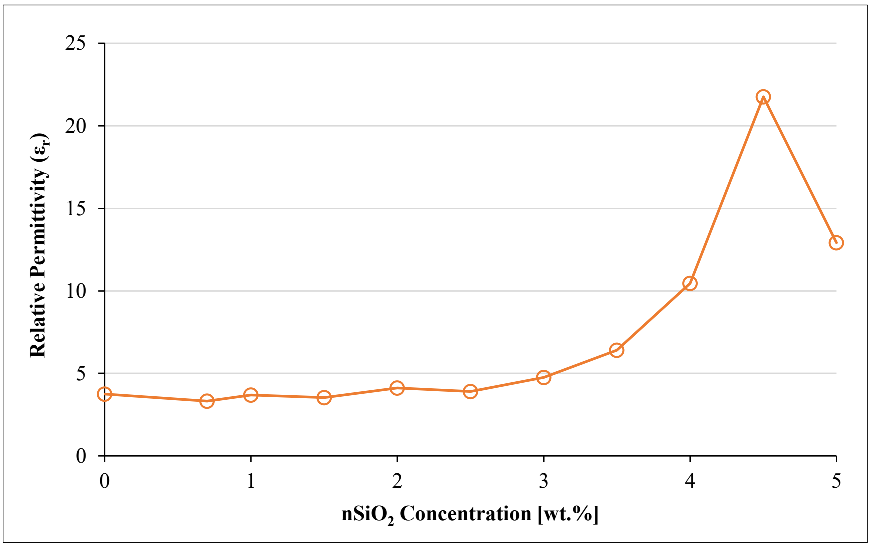


Figure 7. Relative permittivity measurement results

Figure 8 shows tan δ of filled-RTV SiR with various concentrations of $nSiO_2$ at 100 Hz. At low $nSiO_2$ concentrations (0 to 2.5 wt.%), the tan δ values remain generally low with minimal fluctuation. This suggests that small additions of $nSiO_2$ have a minimal effect on dielectric loss, indicating excellent insulating properties within this range. The value of tan increases significantly to 0.273 at a concentration of 3 wt.%, indicating the start of increased dielectric losses. The value rises abruptly to 0.662 at 4.5 wt.%, reaches its peak, then decreases to 0.59 at 5 wt.%. At higher concentrations, there is a significant increase in tan δ, indicating enhanced dielectric loss and decreased insulation performance. The slight decrease at 5 wt.% indicates that the material may have reached a saturation point or experienced particle agglomeration.

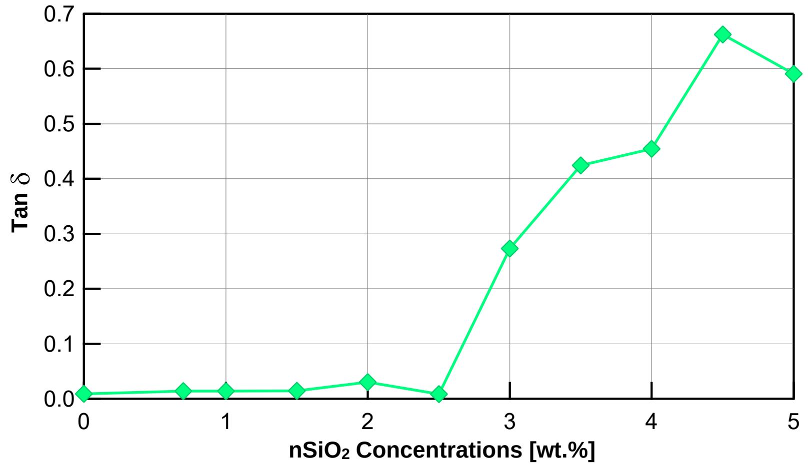


Figure 8. Tan δ measurement results

3-3-Surface Resistivity Measurement

Surface resistivity is measured using bulk samples coated with a silver conductive paste with a variation in composition from 0 to 4.5 wt.% $nSiO_2$. The graph shown in Figure 9 reveals the surface resistivity value at a voltage of 1000 V against variations in the $nSiO_2$ composition. The graph reveals that the surface resistivity increases slightly between 32 and 36 GΩ for $nSiO_2$ concentrations ranging from 0 to 3.5 wt.%. This indicates that the addition of $nSiO_2$ does not significantly impact the surface resistivity until it peaks at 4 wt.%, after which it slightly decreases at 4.5 wt.%. At a concentration of 4.5 wt.%, the $nSiO_2$ particles start to agglomerate. This makes it harder for the particles to spread out evenly, which creates a conductive path for electricity to flow through the composite material and lowers the surface resistivity.

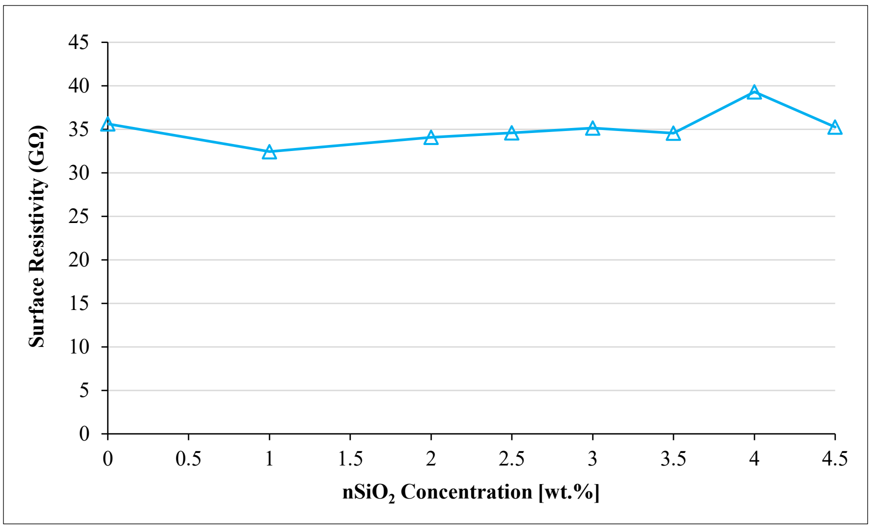


Figure 9. Surface resistivity measurement results

This measurement result led to the selection of the most optimal composition for application as a coating material. Figure 5 displays the highest contact angle, 103.85°, at 3 wt.%. However, this 3 wt.% composition is not considered optimal, as there is no significant increase in relative permittivity. While the 2 wt.% composition is not chosen as the optimum composition because it has a contact angle, relative permittivity, and surface resistivity that are not much different from 0 wt.%. Similarly, 5 wt.% is also not chosen because, during the mixing process, particle agglomeration begins to occur, making it difficult to apply as an insulator coating material. From Figures 7 and 8, the increase in relative permittivity reaches a peak at 4.5 wt.%, accompanied by a high tan delta. Therefore, the selection of the most optimal composition is based on the surface resistivity value. Based on the surface resistivity test results, 4 wt.% $nSiO_2$ is chosen as the coating material for the porcelain insulator because it has the highest surface resistivity with a value of 39.3 GΩ compared to other $nSiO_2$ contents. In addition, 4 wt.% $nSiO_2$ exhibits a high relative permittivity, with a tan δ value that is not too high, being below its peak, and it also possesses good hydrophobic properties. Furthermore, leakage current testing is conducted on RTV SiR-coated, $nSiO_2$-filled RTV SiR-coated, and uncoated insulators. Three insulator samples are tested for leakage current to compare the magnitude of leakage current, total harmonic distortion (THD), and the cross-product of these two parameters.

3-4- Leakage Current Waveform

Leakage current measurement tests are conducted with supply voltages ranging from 5 kV to 25 kV. The following leakage current waveforms in Tables 3 to 5 are the results of leakage current waveforms on uncoated, RTV SiR-coated, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators under various environmental conditions: dry, clean fog, and salt fog conditions, respectively.

Table 3 shows that under dry conditions, the uncoated and unfilled RTV SiR-coated insulators have distorted waves, and at a voltage of 25 kV, a spike indicates a discharge. The half-wave form displays two identical peaks and one valley in both the positive and negative phases, resulting in a symmetrical shape. On the polluted surface, we observe a more significant increase in leakage current and greater fluctuations in the leakage current wave compared to the unpolluted surface. This indicates that pollutants such as kaolin and salt lead to higher leakage currents. The unfilled RTV SiR-coated insulator still exhibits fewer spikes than the uncoated insulator that is not contaminated. This suggests that an unfilled RTV SiR coating can minimize noise or high-amplitude increases in a short time. Unfilled RTV SiR-coated insulators have better insulation performance when compared to the condition of uncoated polluted insulators, as proven by the appearance of fewer spikes at higher voltages. The 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has a sinusoidal waveform that is less distorted when compared to uncoated and unfilled RTV SiR-coated insulators. In the half-waveform of the 4 wt.% $nSiO_2$-filled RTV SiR coated insulator, there is only one peak, unlike the uncoated waveform, which has two peaks and one valley in its half-wave. This indicates that adding 4 wt.% $nSiO_2$ to RTV SiR can reduce distortion in sinusoidal waves. While the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator on a polluted surface, it can be seen that the shape of the waveform does not show any spike. This indicates that a 4 wt.% $nSiO_2$-filled RTV SiR-coated material can reduce the appearance of spikes, thereby enhancing the insulation performance.

Table 3. Leakage current waveforms of uncoated, RTV SiR-coated, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator with clean and polluted surface under *dry (no fog)* conditions

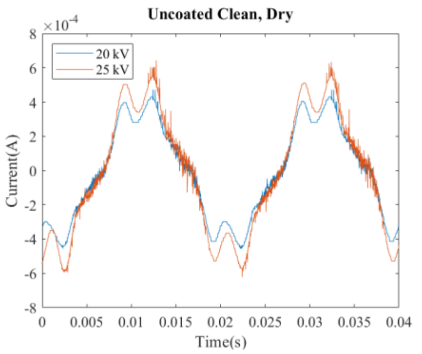
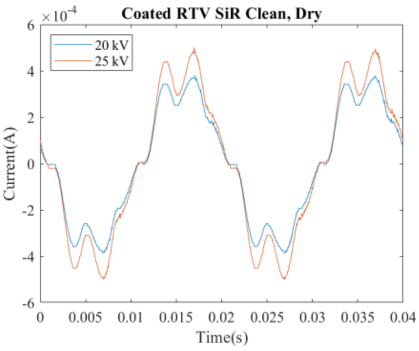
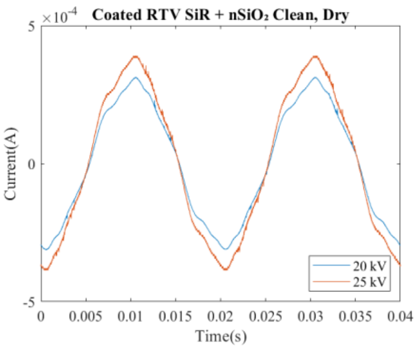
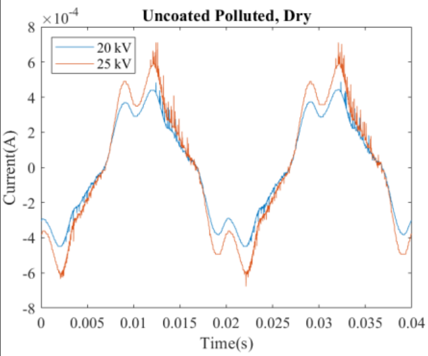
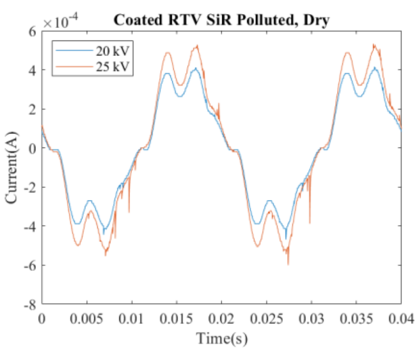
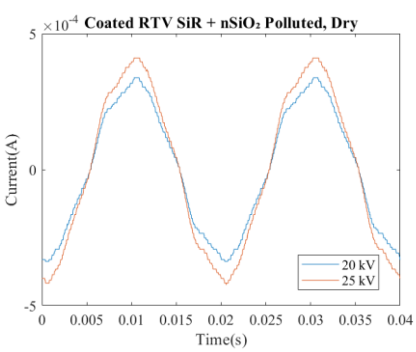
Uncoated sample	RTV SiR-coated sample	RTV SiR + $nSiO_2$-coated sample
		
		

Table 4. Leakage current waveforms of uncoated, RTV SiR-coated, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator with clean and polluted surface under *clean fog* conditions

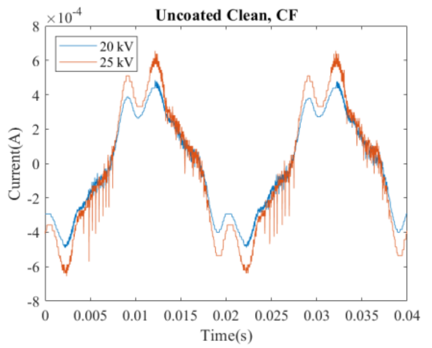
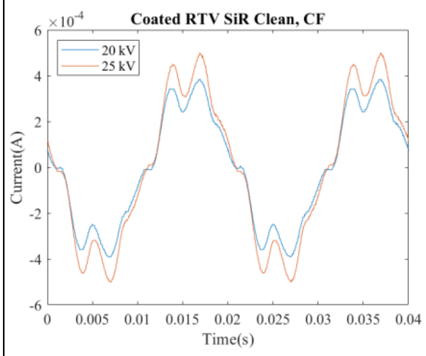
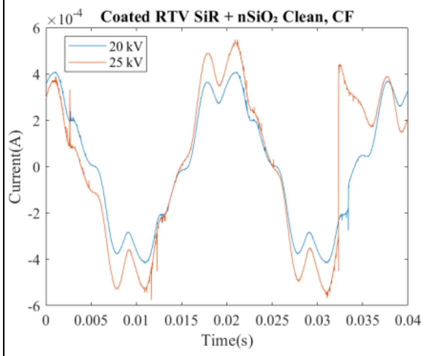
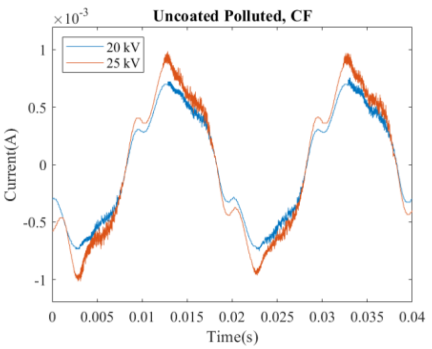
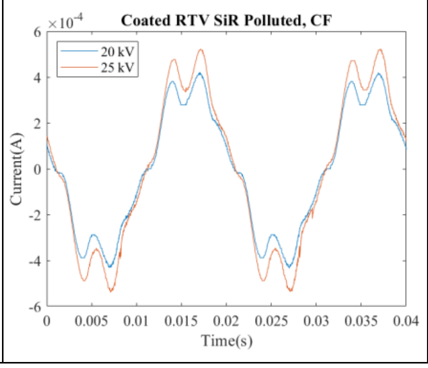
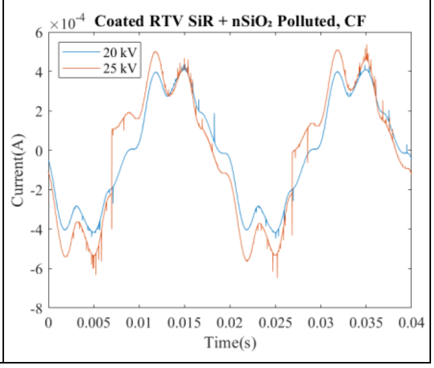
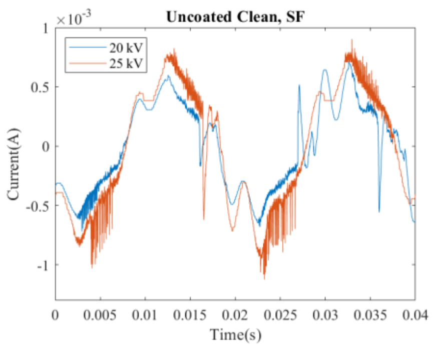
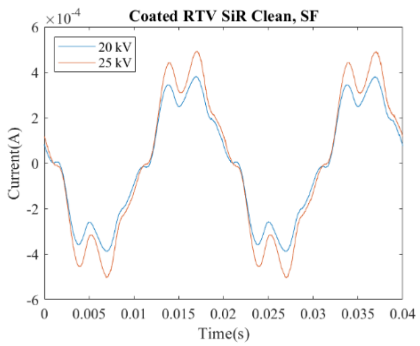
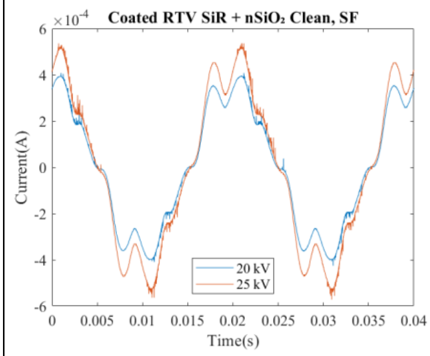
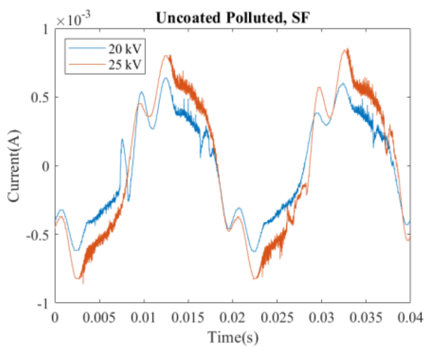
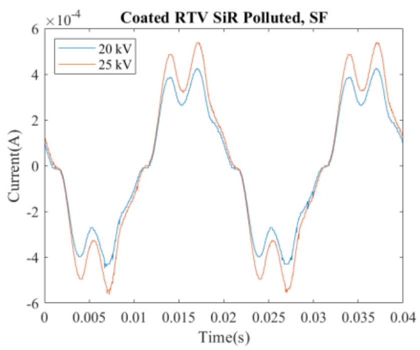
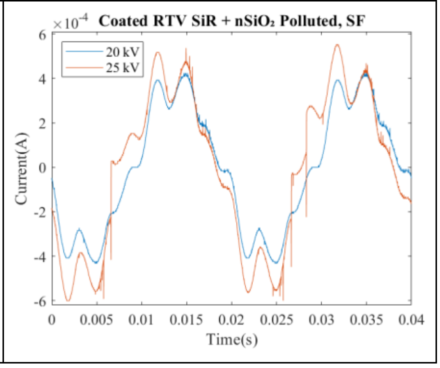
<table>
<tr><th>Uncoated sample</th><th>RTV SiR-coated sample</th><th>RTV SiR + $nSiO_2$-coated sample</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

Table 5. Leakage current waveform of uncoated, RTV SiR coated, and 4 wt% $nSiO_2$-filled RTV SiR coated insulator with clean and polluted surface under *salt fog* conditions

<table>
<tr><th>Uncoated sample</th><th>RTV SiR-coated sample</th><th>RTV SiR + $nSiO_2$-coated sample</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

Leakage current waveforms under clean fog conditions, as depicted in Table 4, show that the waveform characteristics on the polluted, uncoated insulator have a higher peak than those on the surface without pollutants. In contrast, the clean surface conditions exhibit a spike with a larger amplitude than the polluted conditions. This is because the presence of pollutants leads to a more stable flow of leakage current, which not only creates conductive paths but also has a significant magnitude. The unfilled RTV SiR-coated insulator shows a distorted sinusoidal pattern with two peaks and one common valley. The wave is also symmetrical at each voltage level. The presence of the RTV SiR layer makes the waveform less spiky than the uncoated insulator. This demonstrates that the RTV SiR layer can also suppress the occurrence of discharge on the insulator surface. The 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has a distorted sinusoidal pattern with 2 peaks and one common valley. When comparing the surface condition without pollutants to the polluted condition, we observe some spikes with a slight increase in amplitude. In polluted conditions, there are minimal spikes at voltage levels ranging from 5 kV to 20 kV, but more spikes appear at a voltage level of 25 kV. This suggests that the discharge will also increase as the voltage level increases.

Table 5 reveals the leakage current waveform characteristics under salt fog conditions, where the polluted, uncoated insulator exhibits a higher peak value than the surface without pollutants. In clean surface conditions, the waveform characteristics display a higher amplitude spike than those in polluted conditions. This is because pollutants create a conductive path, allowing the leakage current to flow more steadily and increasing its magnitude. The unfilled RTV SiR-coated insulator exhibits two identical peaks and one symmetrical valley at every voltage level. When the surface is polluted, a very small intensity spike appears at the 15 kV - 25 kV voltage level. When compared to the surface without pollutants, there is no spike in the leakage current waveform. The presence of the RTV SiR layer makes the waveform less spiky than that of the uncoated sample. This demonstrates that the RTV SiR layer can also suppress the occurrence of discharge on the insulator surface. The 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has a distorted sinusoidal pattern with two peaks and one common valley. In the clean surface condition, some spikes exhibit insignificant increases in amplitude compared to the polluted condition. In polluted conditions, there are minimal spikes at voltage levels ranging from 5 kV to 15 kV. However, at a voltage level of 15 kV, more spikes begin to appear up to 25 kV. This suggests that the discharge will also increase as the voltage level increases.

3-5-LC Characteristics Under Dry Conditions

To better understand the leakage current characteristics in quantitative parameters, Figures 10-a to 10-c show the leakage current magnitude (I_{rms}), total harmonic distortion (THD), and the cross product of I_{rms} and THD for each insulator samples, respectively, in dry (no fog) condition with clean and polluted surfaces.

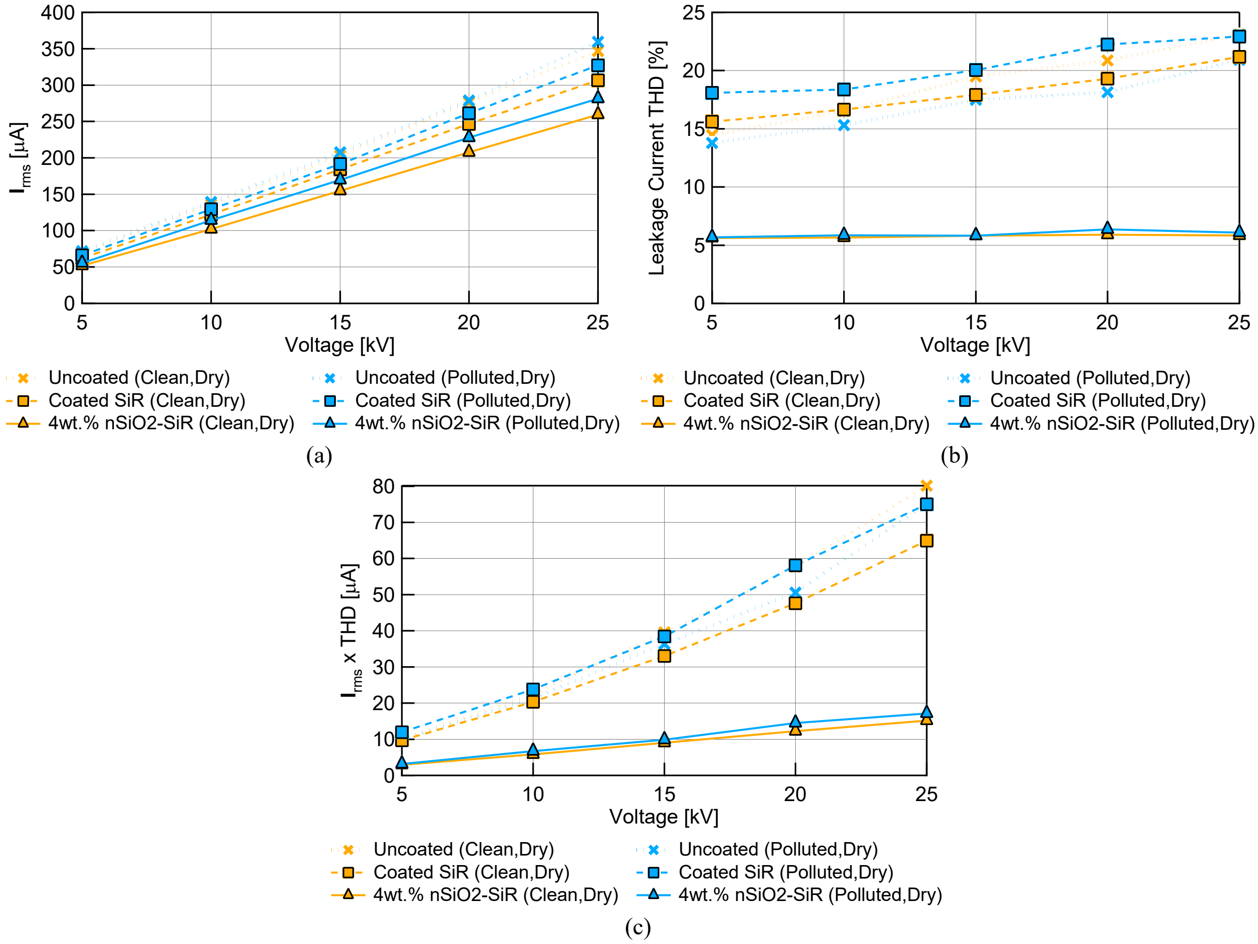


Figure 10. (a) Leakage current magnitude (I_{rms}), (b) leakage current THD, and (c) cross product of I_{rms} and THD of uncoated, unfilled RTV SiR-coated and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators with clean and polluted surface under dry conditions.

As the voltage increases from 5 kV to 25 kV, the magnitude of the leakage current (I_{rms}) also increases. This occurs because the surface resistance of the insulator remains constant while the applied voltage increases. Similarly, the THD value also increases as the voltage level rises. Figure 10-a shows that the uncoated insulator has a higher leakage current magnitude than the unfilled RTV SiR-coated insulator, followed by the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator, which has the lowest leakage current magnitude. Additionally, all insulator samples with polluted surface conditions have a higher leakage current magnitude trend than those without pollutants. This confirms that the presence of pollutant contamination causes a decrease in the surface condition of the insulator. Overall, under dry conditions, the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator performed better than the other insulators.

The leakage current THD under dry conditions is shown in Figure 10-b. Uncoated insulators and unfilled RTV SiR-coated insulators experience fluctuations in THD as the voltage increases, unlike the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator, which tends to remain more stable. The unfilled RTV SiR-coated insulators have a higher THD than 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators. The addition of $nSiO_2$ to RTV SiR can reduce the occurrence of discharge on the surface of the insulator, as demonstrated by the leakage current waveform in the previous discussion. By reducing the incidence of discharge, the leakage current waveform becomes more sinusoidal, which means that the THD will decrease. On top of that, the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has a relatively small and stable rise in leakage current THD compared to the other two insulator samples. This indicates that $nSiO_2$ in the silicone layer contributes to minimizing harmonic distortion, even at high voltages.

The distribution of pollutants among samples is often uneven, and when combined with humidity factors, the THD values can fluctuate. Therefore, it would be more reliable to examine the LC characteristics from the result of the multiplication between the LC and THD values [15]. The cross product of I_{rms} and THD represents the condition of the isolator compared to using only magnitude and THD parameters. The higher the cross-product value, the worse the condition of the insulator, and the easier it is for a flashover to occur [24]. Figure 10-c illustrates that an increase in the cross-product coincides with an increase in the voltage level. This is because the value of leakage current and THD positively correlates with the increase in voltage level, so that the cross-product also increases. Uncoated and unfilled RTV SiR-coated insulators have a significant increase in cross-product as the voltage rises. The figure also shows that the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has the lowest cross-product. This demonstrates that under dry conditions, we can reduce the cross-product by adding 4 wt.% $nSiO_2$, as it results in a smaller leakage current and THD. The greater the cross-product value, the worse the insulator surface condition and the closer it approaches flashover voltage.

3-6- LC Characteristics Under Clean Fog Conditions

Similarly, Figures 11-a to 11-c depict the leakage current magnitude, THD, and cross-product of I_{rms} and THD, respectively, of insulator samples under clean fog conditions for clean and polluted surfaces. Figure 11-a presents the comparison of leakage current magnitude results of uncoated insulators, unfilled RTV SiR-coated insulators, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators under clean fog conditions. From the figure, it can be seen that as the test voltage applied to the insulator increases, the magnitude of the leakage current flowing also increases. The uncoated polluted insulator exhibits the largest leakage current magnitude, whereas the uncoated insulator sample without pollutants follows closely behind. Pollutants cause a decrease in the sample's surface resistance, which increases the magnitude of the leakage current. Coating an insulator with RTV SiR can significantly reduce leakage current compared to uncoated insulators, both for polluted and clean surfaces. The leakage currents in unfilled RTV SiR-coated and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators are very low. It is due to the hydrophobicity of the surface; pollutants do not significantly affect the leakage current. Compared to dry conditions, clean fog exhibits a higher leakage current magnitude due to its high humidity levels. This high humidity leads to a more even water distribution, facilitating the formation of a water film and a more conductive path for the leakage current to flow.

Figure 11-b compares the THD of leakage current across three insulator samples under clean fog conditions. The Total Harmonic Distortion (THD) of leakage current in uncoated insulators with pollutants exhibits a low value due to the large fundamental current in the measurement results. This fundamental current acts as a divider for the sum of all odd and even harmonic components. The percentage of THD increases as the applied test voltage rises. The difference in leakage current THD between the unfilled RTV SiR-coated and the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators is not significant under clean fog conditions. This is because the environmental conditions affect the surface conditions. While both samples exhibit hydrophobic properties, their hydrophobicity is not absolute; a high humidity level in the chamber (RH 80%) could potentially cause a thin water film layer or condensation on the insulator surface. A thin water film layer creates a micro-conductive path, ensuring more uniform leakage current characteristics. With the dominant water film on the surface, the effect of adding $nSiO_2$ to RTV SiR becomes less influential on its THD value.

Figure 11-c compares cross-products on the three insulator samples in clean fog conditions. The cross-product result can be used as a method to diagnose the insulator surface. If the cross-product results are increasing, it means that the worse the condition of the insulator surface and the more flashover voltage is detected. The increase in cross product is influenced by several factors, one of which is the increase in voltage level. The higher the voltage level, the higher the magnitude of the leakage current. In addition, at low voltage (5-15 kV), the difference between samples is relatively small; however, at higher voltage (20-25 kV), there is a more pronounced divergence, where the uncoated polluted sample increases more sharply than the other samples. Under clean fog conditions, the uncoated insulators yield the highest cross-product results and slight fluctuations. The cross-product results show that the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator exhibits significant pollution rise when the voltage increases from 20 kV to 25 kV. The increase is due to high leakage current THD, as evidenced by the leakage current waveform, which has numerous spikes and discharges at a voltage of 25 kV. In general, the unfilled RTV SiR-coated and the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator do not differ significantly in cross-product results. This is because the leakage current magnitude and THD results also show minimal differences. When compared to the unfilled RTV SiR-coated insulator, adding 4 wt.% $nSiO_2$ does not significantly impact the results. The insulator's constant exposure to high humidity in the clean fog chamber accelerates the formation of a thin water film on its surface. As a result of the dominant water film on the surface, the addition of $nSiO_2$ to RTV SiR has a lesser impact on the leakage current magnitude and THD values.

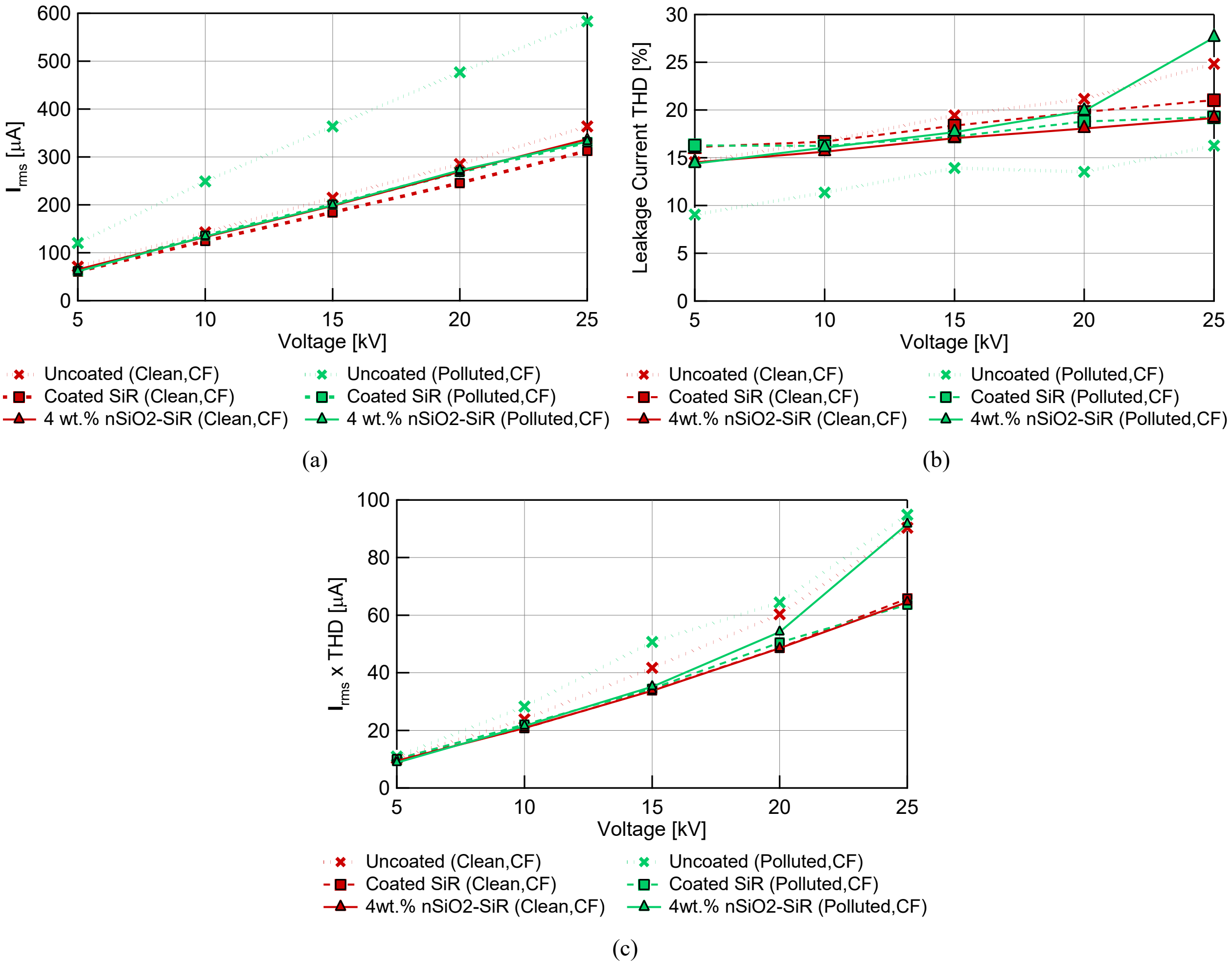


Figure 11. (a) Leakage current magnitude (I_{rms}), (b) leakage current THD and (c) cross product of I_{rms} and THD of uncoated, unfilled RTV SiR-coated and 4 wt% $nSiO_2$-filled RTV SiR-coated insulators with clean and polluted surface under clean fog conditions.

3-7-LC Characteristics Under Salt Fog Conditions

At last, Figures 12-a to 12-c show the leakage current magnitude, THD, and cross-product of I_{rms} and THD, respectively, of insulator samples under the most severe environmental condition, which is salt fog conditions for clean and polluted surfaces.

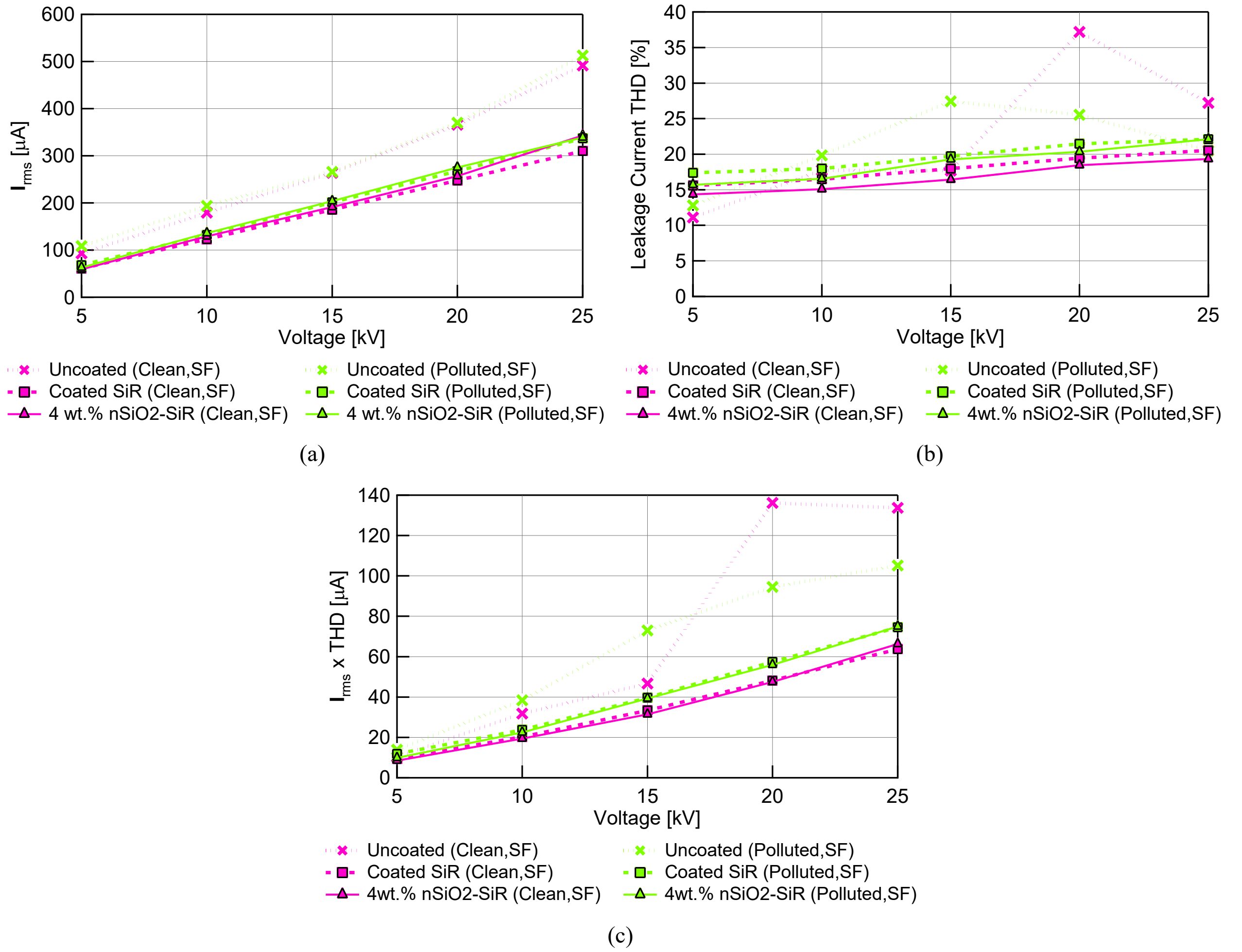


Figure 12. (a) Leakage current magnitude (I_{rms}), (b) leakage current THD and (c) cross product of I_{rms} and THD of uncoated, unfilled RTV SiR-coated and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators with clean and polluted surface under salt fog conditions.

The comparison of the leakage current magnitude results of uncoated insulators, unfilled RTV SiR-coated insulators, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators under salt fog conditions is shown in Figure 12-a. At low voltages (5-15 kV), the differences between the samples are not very noticeable, but at higher voltages (20-25 kV), the variations between samples become more apparent, especially for uncoated insulators, which experience a sharper increase. In uncoated insulators without pollutants, the leakage current increases with increasing voltage. However, in polluted uncoated insulators, the leakage current is higher than that without pollutants. This shows that contamination from pollutants will increase the leakage current and accelerate discharge. Under salt fog conditions, the trend is similar to that of clean fog conditions. The magnitude of the leakage current in the unfilled RTV SiR-coated and the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator is also not much different. High humidity and salt ions influence the leakage current, accelerating the formation of a water film on the insulator surface. Despite the surface's hydrophobic properties, a leakage current still flows and tends to flow on a more conductive surface, specifically along the path contaminated by salt.

Figure 12-b shows the THD of leakage current in the three insulator samples with salt fog conditions. In general, there is a trend of increasing THD with the increase in voltage from 5 kV to 25 kV for most samples. At lower voltages (5–10 kV), the differences between samples remain relatively small; however, at higher voltages (15–25 kV), the variations between conditions become more pronounced, especially for uncoated insulators, which experience sharp fluctuations with increasing voltage levels. Salt fog significantly contaminates and affects the insulator's surface, causing a discharge that impacts the THD of the leakage current. The 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator also appears to have a lower leakage current THD than the unfilled RTV SiR-coated insulator, but the difference is not too significant. This is due to the inherent hydrophobic properties of RTV SiR, which allow for minimal discharge compared to uncoated insulators. However, due to the formation of a water film on the surface, leakage currents still tend to flow on the surface. Adding 4 wt.% $nSiO_2$ might make the dielectric stronger, but if the RTV SiR is good enough to keep its hydrophobic properties, adding $nSiO_2$ will not make a big difference in lowering the harmonic leakage current compared to insulators that are coated with RTV SiR.

Figure 12-c shows the cross product of uncoated, unfilled RTV SiR-coated, and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators in salt fog. In the graph, it can be seen that the higher the voltage level, the higher the cross-product result, which is related to the increase in the RMS current value and the growth of harmonic components as the voltage level increases. Uncoated samples, with both clean and polluted surfaces, show a significant increase, particularly under polluted conditions (polluted, salt fog (SF)), where a drastic spike occurs at voltages of 20 kV and 25 kV, resulting in the highest values among all samples. The cross-product results of 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators are lower than those of uncoated insulators in salt fog, but they are not very different from those of unfilled RTV SiR-coated insulators. It doesn't make a big difference between unfilled RTV SiR-coated and 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators in terms of leakage current or THD. This indicates that the addition of 4 wt.% $nSiO_2$ does not significantly influence the cross-product. Despite the excellent hydrophobic properties of both samples, the salt fog constantly encounters conductive water droplets. The insulator's surface becomes more conductive due to increased exposure to salt pollutants, leading to a tendency for leakage currents to flow on it.

3-8- SEM (Scanning Electron Microscopy) and TGA (Thermogravimetric Analysis) Test Results

After evaluating the electrical characteristics and performance through the leakage current test, 4 wt.% $nSiO_2$-filled RTV SiR coating was further analyzed using SEM and TGA tests, as depicted in Figures 13 and 14, respectively. Figure 13 depicts the SEM cross-section of the 4 wt.% $nSiO_2$-filled RTV SiR sample, revealing a heterogeneous and rough surface morphology. This roughness is attributed to the presence of well-dispersed $nSiO_2$ filler particles within the RTV SiR matrix. The $nSiO_2$ particles form a strong interaction with the polymer network, enhancing the composite's structural integrity and ensuring uniform filler distribution. The rough surface observed in the SEM image significantly contributes to the improved hydrophobicity, as evidenced by the increased contact angle (Figure 5), which reduces the adherence of contaminants and water on the insulator surface. Additionally, the uniform dispersion of the $nSiO_2$ particles is critical in enhancing the dielectric properties of the material, including higher surface resistivity (Figure 9) and lower leakage current (Figures 10 to 12).

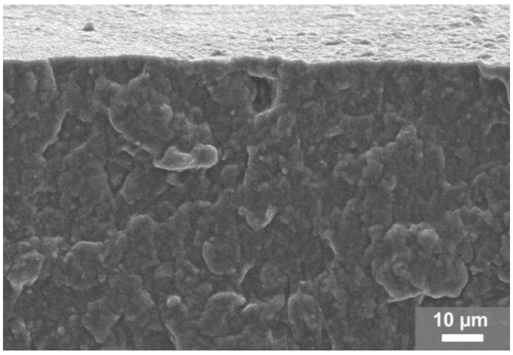


Figure 13. **SEM results of cross section of $nSiO_2$-filled RTV SiR sample**

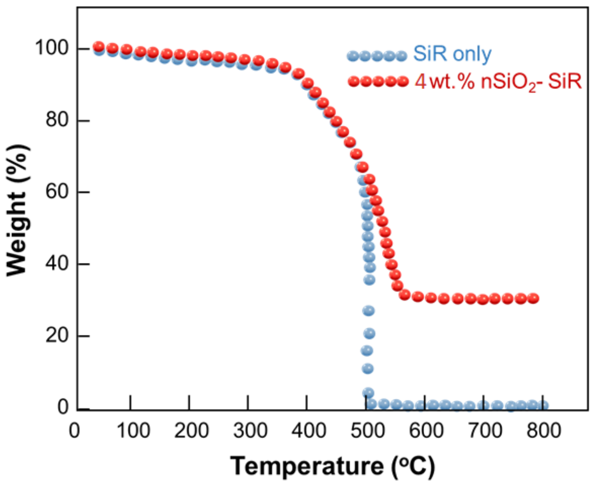


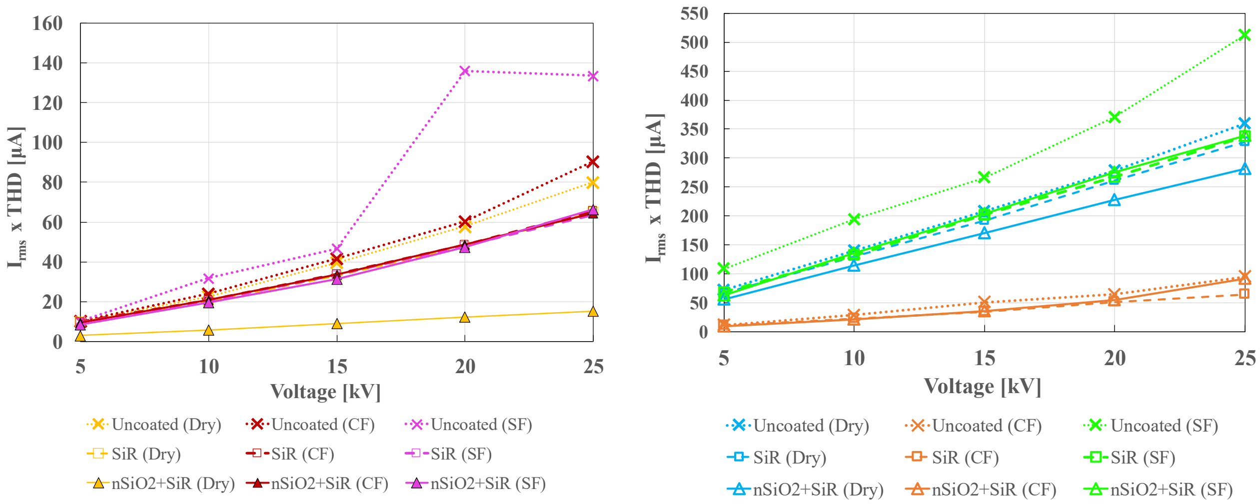
Figure 14. **TGA test results of $nSiO_2$-filled and unfilled RTV SiR samples**

Figure 14 presents the TGA test results for $nSiO_2$-filled and unfilled RTV SiR samples, illustrating the thermal degradation behavior of both samples and providing insight into their thermal stability. The unfilled RTV SiR sample exhibits a sharp weight loss, beginning at approximately 500°C, which leads to complete degradation near 550°C. In contrast, the 4 wt.% $nSiO_2$-filled RTV SiR sample degrades more gradually, retaining about 35% of its mass even at

800°C. This enhanced thermal stability is attributed to the strong interactions between the $nSiO_2$ particles and the RTV SiR matrix, which reinforce the polymer structure and delay thermal decomposition [25, 26]. Additionally, it has been reported that nanosilica fillers enhance thermal stability by creating a barrier effect and improving the materials' resistance to thermal breakdown [27, 28]. This improvement directly supports the superior electrical insulation performance observed in leakage current tests, where the 4 wt% $nSiO_2$-filled RTV SiR demonstrates lower leakage current (Figure 10-a), higher surface resistivity (Figure 9), and improved hydrophobicity (Figure 5). The ability of the $nSiO_2$-filled material to maintain its structural integrity under high temperatures ensures the stability of its dielectric properties, even in extreme environmental conditions. Therefore, the TGA results serve as a critical supporting dataset, validating the role of $nSiO_2$ in enhancing the thermal and electrical performance of RTV SiR coatings. These findings not only validate the effectiveness of $nSiO_2$ as a critical additive in improving insulator performance but also highlight its potential for further development in next-generation insulation materials designed to withstand harsher operational environments and higher voltage stresses.

3-9- Analysis and Discussion

The experimental results previously discussed, which focus on the leakage current characteristics, are summarized in Figure 15 below, which shows the cross-product of I_{rms} x THD characteristics with Figure 15-a for a clean surface, and Figure 15-b for a polluted surface.



(a) Clean surface (b) Polluted surface

Figure 15. Summary of I_{rms} X THD cross-product for insulators' leakage current with (a) clean surface and (b) polluted surface

First, it is obvious that the polluted surface condition (in Figure 15-b) shows an increase in leakage current compared to the surface without pollutants (in Figure 15-a). Pollutants on the insulator surface cause the formation of a conductive layer. This conductive layer easily allows the leakage current to flow through the insulator surface. As contamination increases, this leakage current increases, reducing the resistivity of the insulator surface and potentially causing flashover [29, 30]. Conversely, on a clean surface (Figure 15-a), the results of the leakage current measurement are lower than that of a polluted surface. This is because no pollutants induce a conductive layer on the surface.

Both with or without pollutants on the surface, under dry conditions or no fog, 4 wt.% $nSiO_2$-filled RTV SiR-coated insulators effectively reduce the magnitude of leakage current, even compared to unfilled RTV SiR. This is because 4 wt.% is the optimum composition with the highest surface resistivity. A higher resistivity value indicates a better insulating material with less leakage current [31, 32]. Moreover, permittivity (ε) is another parameter used to characterize the electric properties of an insulator. A higher permittivity value represents a higher ability to store charge, which creates a good capacitance and can reduce the electric field inside the material. This helps to protect the material from high voltage stress.

Under clean fog and salt fog conditions, it shows that unfilled SiR and filled SiR+$nSiO_2$ insulators have a lower leakage current magnitude than uncoated insulators. It is very important for RTV SiR-coated insulators filled with $nSiO_2$ at 4 wt.% to have a high surface resistivity. This lets SiR stand up to environmental and electrical stresses. Furthermore, high surface resistivity not only provides a barrier against leakage current but also signifies that the SiR has a greater contact angle, thereby exhibiting better hydrophobic properties [33]. The unfilled RTV SiR-coated and $nSiO_2$-filled RTV SiR-coated insulators have good hydrophobicity properties, which means they have high surface resistivity and lower LC results when water flows on their surface. In clean fog and salt fog conditions, pollutants can affect hydrophobicity, but SiR has the ability to transfer hydrophobicity to contaminated surfaces, restoring its water-repellent properties even after pollutant accumulation [34]. In addition, hydrophobicity protects SiR from humidity and pollution while also preventing the formation of conducting paths that could limit the leakage current on SiR [35]. Generally, it is preferable to use an insulator with high surface resistance and low leakage current, as research has proven that high leakage current improves tracking and erosions [36].

The uncoated insulator shows a lower THD value on the polluted surface compared to the clean surface. This is caused by an increase in the fundamental current and the presence of insulator surface pollutants. The high fundamental current on the polluted surface will lower the THD value, as the THD formula uses the fundamental current as a dividing factor. Therefore, a higher fundamental current results in a smaller total harmonic distortion. On the other hand, the unfilled RTV SiR-coated and $nSiO_2$-filled RTV SiR-coated insulators tend to have low THD values on clean surfaces. This means that the leakage current wave distortion is not as harmful as it is on polluted surfaces. Generally, a higher THD value suggests the possibility of initiating the surface degradation process if the discharge duration exceeds one second [37]. Under different conditions, THD shows a varying trend due to the presence of insulator surface pollutants and humidity variations. Pollutants and humidity affect the magnitude of the fundamental current, which influences the percentage of each harmonic spectrum. The larger the fundamental current, the smaller the THD, which will affect the waveform. There is a relationship between the waveform and total harmonic distortion (THD); an increase in THD leads to a more non-sinusoidal waveform. Moreover, components like surface non-linear resistance influence the waveform characteristics of the leakage current from the insulator.

It was found that the 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator has a significant reduction under dry conditions compared to the uncoated insulator, with a reduction of 68.11% to 81.11%. Under clean fog conditions, it decreased by 8.24% - 30.58%, while in salt fog conditions, it decreased by 17.58% - 65.15%. On the other hand, the use of different fillers in the study conducted by Diantari et al. [17] indicated that the addition of 5 wt.% gum rosin to RTV-SiR also improves the performance of the insulator by increasing hydrophobicity and surface resistivity. The following are the percentages of cross-product (I_{rms} x THD) reduction after being applied with different fillers, namely gum rosin and nanosilica, under both polluted and non-polluted conditions.

Table 6 compares the cross-product of I_{rms} x THD reduction under non-pollutant conditions. It shows that using RTV SiR modified with $nSiO_2$ and gum rosin reduces the cross-product value (I_{rms} THD) compared to insulators that are not coated. At a voltage of 20 kV (RH 70%), RTV SiR + $nSiO_2$ showed a reduction of 78.8%, while RTV SiR + gum rosin had a reduction of 24% compared to the uncoated insulator. At high humidity (RH 90%), both samples exhibited results that tended to fluctuate and did not differ significantly in reduction, as they both possessed good hydrophobicity. Meanwhile, Table 7 shows a comparison of cross-product reduction under polluted conditions. Both tables suggest the same trend in polluted and non-polluted conditions. This evidence indicates that both materials are capable of enhancing insulation performance, albeit with varying effectiveness. The more significant reduction in RTV SiR + $nSiO_2$ is attributed to the change in relative permittivity resulting from the addition of $nSiO_2$, which helps inhibit leakage currents on the insulator surface. Meanwhile, although RTV SiR + gum rosin also showed a decrease in cross product (I_{rms} × THD), its effectiveness is slightly lower compared to RTV SiR + $nSiO_2$. This difference may be due to the higher relative permittivity of $nSiO_2$ compared to gum rosin. The relative permittivity results for gum rosin-filled RTV SiR were 3.5-3.6, while for 4 wt.% $nSiO_2$-filled RTV SiR it was 10.4. This evidence suggests that the 4 wt.% $nSiO_2$-filled RTV SiR exhibits improved insulation properties, attributed to its increased resistance to external electric fields. Based on these results, it can be concluded that at 70% relative humidity, $nSiO_2$-filled RTV SiR is more effective in reducing the cross-product (I_{rms} x THD) compared to modification using gum rosin. However, both materials still show improved performance compared to uncoated insulators, making them a solution for enhancing electrical insulation performance in both clean and polluted environments.

Table 6. Comparison of cross-product (I_{rms} x THD) reduction of $nSiO_2$-filled RTV SiR-coated and gumrosin-filled RTV SiR-coated under non-pollutant conditions

Voltage (kV)	Humidity			
	70%		90%	
	RTV SiR + Gum Rosin Coated	RTV SiR + $nSiO_2$ Coated	RTV SiR + Gum Rosin Coated	RTV SiR + $nSiO_2$ Coated
5	23%	71.1%	19%	8.2%
10	27%	74.3%	9%	12.8%
15	17%	77.2%	29%	19.1%
20	24%	78.8%	29%	19.5%
25	18%	81.1%	20%	28.6%

Table 7. Comparison of cross-product (I_{rms} x THD) reduction of $nSiO_2$-filled RTV SiR-coated and gum rosin-filled RTV SiR-coated under pollutant conditions

Voltage (kV)	Humidity			
	70%		90%	
	RTV SiR + Gum Rosin Coated	RTV SiR + $nSiO_2$ Coated	RTV SiR + Gum Rosin Coated	RTV SiR + $nSiO_2$ Coated
5	-	68.1%	19%	19.2%
10	-	68.7%	39%	23.9%
15	15%	72.8%	39%	30.6%
20	12%	71.3%	17%	16.0%
25	14%	77.2%	21%	3.4%

Testing insulators within a chamber using dry, clean fog and salt fog conditions is an artificial scenario that does not fully represent actual conditions. Among various environmental factors, rainfall significantly impacts ceramic insulator performance by increasing leakage current and reducing insulation resistance. Experimental results indicate that higher rainfall intensity leads to a decrease in insulation resistance and an increase in leakage current [38]. In addition to rainfall, several other factors, such as temperature fluctuations, ultraviolet (UV) radiation, and chemical exposure, influence the long-term performance of insulating coatings. Over time, prolonged exposure to these elements accelerates oxidation and decomposition reactions, leading to a reduction in static contact angle and weakening of hydrophobic properties [39]. This degradation negatively affects the coating's ability to maintain insulation performance in harsh outdoor conditions. Despite these challenges, silicone rubber is known for its superior UV resistance, as it remains relatively stable under prolonged exposure to wind, rain, and UV radiation [40]. Nanosilica-filled SiR establishes a more effective UV-blocking barrier that reflects ultraviolet rays, thereby reducing susceptibility to UV radiation damage [11]. Consequently, 4 wt.% $nSiO_2$-filled RTV SiR is anticipated to diminish the surface deterioration of the coating. Long-term testing in real-world conditions is required to validate this improvement and confirm that the coating's insulation properties effectively enhance the insulator's performance.

4- Conclusions

This research evaluated the insulating properties of RTV SiR coatings reinforced with nanosilica ($nSiO_2$) for high-voltage outdoor applications. The subsequent conclusions were derived:

- The application of RTV SiR on uncoated ceramic insulators modified their surface characteristics from hydrophilic to hydrophobic. The ideal $nSiO_2$ concentration for maximizing the contact angle was determined to be 3 wt.%, resulting in a maximum value of 103.85°.
- The relative permittivity exhibited a frequency-dependent decline, stabilizing at higher frequencies. Permittivity reached its maximum at 4 wt.% to 4.5 wt.% $nSiO_2$, indicating improved dielectric characteristics. Surface resistivity reached a maximum of 39.31 GΩ at 4 wt.%, signifying enhanced surface insulation.
- Leakage current increased with voltage and contamination on the surface, although THD exhibited varying trends under different conditions. The 4 wt.% $nSiO_2$-filled RTV SiR-coated insulator exhibited the lowest THD under all conditions.
- Overall, in dry conditions, the 4 wt.% $nSiO_2$-filled RTV SiR coating markedly diminished the cross product of leakage current magnitude and THD in comparison to uncoated and unfilled RTV SiR-coated insulators, achieving reductions of up to 81.11% on clean surfaces and 77.22% on contaminated surfaces.

These findings validate that the 4 wt.% $nSiO_2$-filled RTV SiR coating delivers exceptional insulation performance, especially in dry and contaminated environments, making it an effective option for high-voltage outdoor insulators.

5- Declarations

5-1- Author Contributions

Conceptualization, R.R. and A.D.N.; methodology, A.D.N., R.R., and A.R.A.; software, A.D.N. and A.R.A.; validation, R., F.A.P., and S.S.; formal analysis, A.D.N. and F.A.P.; investigation, A.D.N. and A.R.A.; resources, R.R. and S.S.; data curation, A.D.N. and R.R.; writing—original draft preparation, A.D.N.; writing—review and editing, R.R., F.A.P., and S.S.; visualization, A.D.N., R.R., and F.A.P.; supervision, S.S.; project administration, A.R.A.; funding acquisition, R.R. and S.S. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5-3- Funding and Acknowledgements

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5-4- Institutional Review Board Statement

Not applicable.

5-5- Informed Consent Statement

Not applicable.

5-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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