Development of 33 kV Nanostructured Superhydrophobic Silicone Insulators with Enhanced Resistance to Pollution and Dust Accumulation

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ABSTRACT

This study investigates the design and development of superhydrophobic silicone insulators using nano structuring technology to improve resistance against pollution and dust accumulation. The silicone insulator surface was modified by nanoparticle coating and three-dimensional modeling in COMSOL was employed to analyze its electrical and mechanical behavior. Simulation and experimental results demonstrate that the water contact angle of the nanostructured insulator increased to 163°, indicating the achievement of effective super hydrophobicity. Numerical results further revealed that the leakage current of the nanostructured silicone insulator was reduced by up to 60% compared to the conventional type. In addition, the electric field distribution on the surface significantly improved after nanocoating, resulting in reduced field concentration in critical areas. These outcomes demonstrate that nanostructured surface modification effectively minimizes pollution accumulation and leakage currents, thereby enhancing the reliability and lifespan of insulators in power networks.

Keywords: *Nanostructured silicone, Super hydrophobicity, Leakage current, Surface pollution, Electric field*

1. *INTRODUCTION*

The reliable transmission and distribution of electrical energy are essential to the functioning of modern societies [1]. Insulators, as critical components in these networks, ensure the electrical insulation of energized conductors from grounded structures [2]. Their performance, however, is influenced by multiple factors—most notably, surface pollution, which can seriously undermine the reliability of power systems [3].

Pollution—originating from airborne particulates, salts, and industrial contaminants—represents a widespread challenge. Such pollutants form conductive layers on insulator surfaces, intensifying leakage current and significantly reducing flashover voltage, potentially leading to system failures [4]. In arid regions, the accumulation of dust further exacerbates these issues, underscoring the need for effective solutions to mitigate pollution effects [5].

Polymeric materials, especially silicone rubber (SiR), have emerged as superior alternatives to traditional insulators due to their excellent insulation properties and inherent hydrophobicity [6]. SiR offers outstanding resistance to ultraviolet radiation, low weight, and ease of fabrication [7]. Nonetheless, the long-term hydrophobicity of SiR can diminish under harsh environmental conditions, compromising its performance over time [8].

Recently, the incorporation of nanotechnology into SiR has shown promise for enhancing its properties. Traditional approaches involve either dispersing nanoparticles within the SiR matrix or applying nanostructured coatings to induce superhydrophobic surfaces [9]. While these methods have demonstrated improvements, they often face challenges such as limited coating durability, weak mechanical integrity, and costly manufacturing processes [10]. Therefore, this research adopts an innovative approach: integrating nanostructures into the body of SiR itself, fundamentally creating a nanostructured silicone insulator [11]. This strategy not only enhances surface stability but also improves mechanical strength and overall durability, offering advantages over coating-based methods [12].

The main objective of this study is to design, develop, and investigate the properties of nanostructured silicone insulators, specifically considering their optimal resistance to pollution and dust accumulation. By incorporating nanostructures within the SiR matrix, we aim to achieve stable, long-lasting superhydrophobic properties, thereby improving the reliability and service life of insulators in harsh environments.

2. LITERATURE REVIEW: EVOLUTION OF NANOSTRUCTURED SILICONE FOR SUPERIOR INSULATORS

Efforts to enhance the performance of SiR-based insulators through nanotechnology integration began in the early 2000s, with initial studies focusing on nanoparticle dispersion to improve hydrophobic properties [13]. Research indicated that incorporating nanoparticles like SiO_2 and TiO_2 can increase water contact angle and improve contamination resistance [14, 15]. However, these early attempts revealed limitations in nanoparticle distribution and stability within the SiR matrix [16].

Subsequent research explored the use of nanostructured coatings—especially those produced by sol-gel processes—to create superhydrophobic surfaces [17]. Thin silicate layers with nanoscale features formed on SiR surfaces, enhancing hydrophobicity and self-cleaning properties [18]. Despite these advancements, such coatings proved vulnerable to degradation when exposed to harsh environments, resulting in a decline in performance over time [19]. Additionally, deposition methods such as CVD and thermal spraying were utilized to manufacture durable, resilient coatings, yet concerns regarding cost and scalability persisted [20, 21].

The use of multifunctional nanomaterials, such as carbon nanotubes (CNTs) and graphene, to further augment the insulation characteristics of SiR received greater attention [22]. These materials not only enhance hydrophobicity but also offer improved resistance to tracking and partial discharge [23, 24]. For instance, CNTs and graphene dispersed within the SiR matrix have been shown to reduce surface conductivity and inhibit the formation of tracking paths [25]. Moreover, nanoparticles like zinc oxide (ZnO) and titanium dioxide (TiO_2) have been adopted to improve UV resistance and partial discharge durability [26, 27].

While coating-based strategies have been extensively investigated, issues concerning their long-term stability and mechanical integrity remain unresolved. Surface coatings are susceptible to delamination, abrasion, and the detrimental effects of pollution and environmental conditions, leading to reduced effectiveness over time [28]. In contrast, the concept of nanostructured silicone insulators offers a compelling alternative, wherein nanostructures are inherently dispersed throughout the SiR material [29]. This structural approach not only improves stability and durability but also enhances the mechanical properties and overall performance of the insulator [30].

Several emerging methods are available to achieve nanostructured silicone insulators, including chemical mixing processes, direct nano-prefabrication, and self-assembly techniques [31]. Chemical mixing involves dispersing precursor nano-components into the SiR matrix, followed by chemical procedures that create covalently bonded nanostructured networks [32]. Direct nano-prefabrication employs molds or templates to guide the organization of SiR materials into nanoscale structures [33]. Alternatively, self-assembly techniques leverage the intrinsic tendency of nanomaterials to organize themselves into regular, periodic architectures [34].

Despite these technological advances, a significant gap remains in our understanding of the long-term performance of nanostructured silicone insulators under real-world conditions. While laboratory studies have yielded promising results, there is a lack of field data for evaluating their durability under prolonged exposure to diverse environments, thermal cycles, and contamination build-up [35]. Future research must address these aspects to validate the reliability and sustainability of nanostructured insulation solutions.

Furthermore, the complex relationship between nanostructure parameters (size, shape, composition, and density) and insulator performance requires careful investigation. Understanding how these parameters influence hydrophobicity, tracking resistance, and partial discharge behavior is essential for optimizing insulator effectiveness and ensuring long-term reliability [36].

This research seeks to address these knowledge gaps by systematically examining the performance and reliability of nanostructured silicone insulators under various operational conditions. By elucidating the fundamental mechanisms governing these advanced insulators, we aim to pave the way for the design and fabrication of even more advanced, resilient, and environmentally friendly insulation solutions.

3. MATERIALS AND METHODS

3.1. Three-Dimensional Modeling of the Insulator

The three-dimensional model of the insulator was developed in COMSOL Multiphysics 6.0, based on the IEC 60507 standard for medium-voltage (33 kV) insulators [37]. The geometry consists of a central cylindrical core from which six uniformly sized sheds (or skirts) extend outward at regular intervals. The lower end of the insulator incorporates a cylindrical base, while the upper end is designed for voltage terminal application. The thickness of the sheds and the core were carefully chosen to ensure adequate mechanical and electrical strength. All surfaces of the insulator are coated with a nanostructured silicone layer exhibiting superhydrophobic properties.

The geometric dimensions were selected to provide sufficient creepage distance and appropriate air clearance between electrodes, thereby ensuring faithful simulation of laboratory and industrial operating conditions. To prevent boundary field interference, the ambient air domain surrounding the insulator in the model was defined as a cube with additional safety margins (Figure 1). The geometric characteristics of the insulator modeled in COMSOL are also given in Table 1.

Table 1. *Geometrical specifications of the modeled insulator in COMSOL*

Feature/Parameter	***Simulation Model Value***	***Description***
Insulator type	*Pin-type*	*As per IEC standard*
Rated voltage	*33 kV*	*Line-to-earth*
Total height	*260 mm*	*Top to bottom of the base*
Diameter of largest shed	*145 mm*	*Diameter of each of the 6 sheds*
Number of sheds	*6*	*All equally spaced*
Axial spacing of sheds	*45 mm*	*Center-to-center between adjacent sheds*
Creepage distance	*790 mm*	*Total surface length from top to bottom*
Core diameter	*35 mm*	*Inner silicone rod*
Shed thickness	*10 mm*	*Edge thickness of each shed*
Core/body thickness	*12 mm*	
Base diameter	*40 mm*	*Bottom end, for mounting/connection*
Base height	*30 mm*	*Metallic/silicone section at the bottom*
Material type	*Nanostructured silicone*	*Superhydrophobic*
Dimensions of air domain	*500 × 500 × 360 mm³*	*With margins for boundary effects*



Fig. 1. *3D model of nanostructured silicon plate insulator (33kV)*

3.2. Governing Equations and Physical Relations

The simulation of the electrical performance and surface leakage current of silicone-based insulators under pollution conditions was conducted by solving the governing electrostatic equations within the COMSOL Multiphysics environment. The following equations and constitutive relations were considered:

3.2.1 Electrostatics

The electrostatic behavior of the insulator system is governed by Poisson's equation as [38], [39]:

$$\nabla \cdot (\varepsilon \nabla V) = -\rho v \qquad (1)$$

where V denotes the electric potential (V), ε is the permittivity of the material (F/m), and ρv is the volume charge density (C/m³). For most high-voltage insulation problems, space charge effects are negligible, hence ρv=0, reducing Poisson's equation to the Laplace form:

$$\nabla^2 V = 0 \qquad (2)$$

The electric field ($\vec{E}$) is given by:

$$\vec{E} = -\nabla V \qquad (3)$$

3.2.2 Surface and Volume Current Density

The total current density within dielectric materials is expressed as [40], [41]:

$$\vec{J} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \qquad (4)$$

where σ is the electrical conductivity (S/m). For quasi-static AC or DC simulations, the displacement current (second term) can be neglected, simplifying $\vec{J} \approx \sigma \vec{E}$.

The surface leakage current (I_{leak}) can be computed by integrating the normal component of surface current density over the insulator surface (S):

$$I_{leak} = \int_S \vec{J}.d\vec{A} \qquad (5)$$

In the presence of pollution or wetting layers, the surface conductivity σ_{surf} is assigned based on experimental or literature values [42].

3.2.3 Surface Properties – Super hydrophobicity

Nanostructured silicone insulators exhibit superhydrophobic behavior, generally characterized by high static contact angles ($\theta > 150°$), which mitigates surface wettability and suppresses continuous conducting filaments. For modeling purposes, the reduction in σ_{surf} due to increased contact angle (and thus decreased actual wetted area) is incorporated, based on reported relations [42]:

$$\sigma_{eff} = f(\theta) \cdot \sigma_{ref} \qquad (6)$$

where σ_{ref} is the base surface conductivity for a fully wetted polluted layer, and $f(\theta)$ is a dimensionless reduction factor (commonly fitted from experimental data).

3.2.4 Boundary and Initial Conditions

- ***Boundary Potentials:*** *The high-voltage and ground electrodes are defined by Dirichlet conditions $V = V_{HV}$ and V=0, respectively.*
- ***Insulator Surface:*** *The outer lateral surfaces are generally assigned Neumann (zero-flux) or symmetry conditions as appropriate.*
- ***Initial Conditions:*** *For transient analysis, the initial electric field and potential distribution are set, commonly as zero or steady-state fields.*

3.2.5 Meshing Strategy

A structured meshing strategy was adopted to balance computational efficiency with accuracy. The insulator geometry was discretized using tetrahedral elements, with mesh refinement applied at critical regions, such as triple junctions, shed edges, and surfaces bearing pollution/nanostructures (Figure 2). Mesh independence was verified with increasing mesh density (Figure 3); further refinement was carried out until less than 2% deviation was observed between successive mesh levels. The minimum mesh size was set to 100 μm in regions with high field gradients, as recommended for accurate electric field evaluation [38].



Fig. 2. *Meshing of the 3D model of a plate-shaped nanostructured silicon insulator (33kV)*

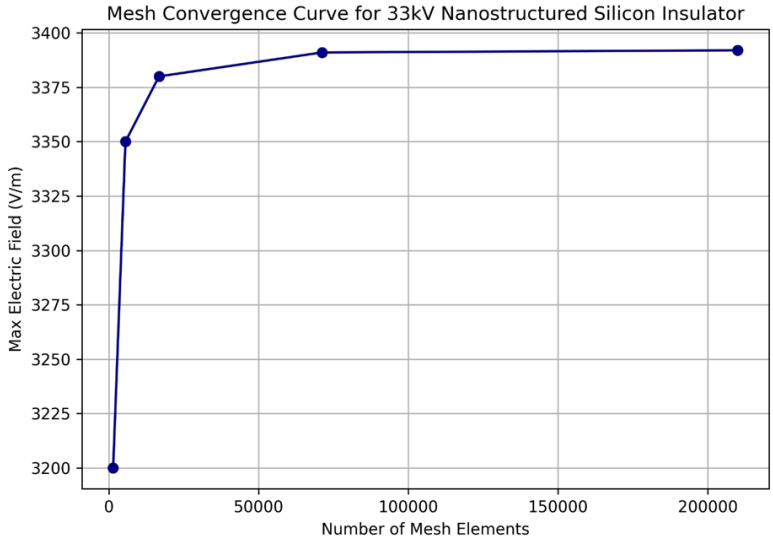


Fig. 3. *Mesh convergence curve for the 33 kV nanostructured silicon insulator model. As the number of elements increases, the maximum surface electric field value approaches a stable limit, confirming adequate mesh refinement*

3.3. Selection and Description of Raw Materials

In this study, to enhance the hydrophobicity and surface pollution resistance of the insulator, nanostructured silicone was employed as the primary coating material. Two types of silicone were compared: conventional silicone and nanostructured silicone, the latter of which achieves the Lotus Effect through

nanoscale surface engineering. The key properties of both materials are provided in Table 1. All data were obtained from technical datasheets and published scientific literature [43-45].

Table 2. *Physical and electrical parameters of conventional and nanostructured silicone*

Parameter	***Conventional Silicone***	***Nanostructured Silicone***
Density (g/cm³)	*1.18*	*1.15–1.18*
Dielectric constant	*2.9*	*2.8–2.9*
Breakdown voltage (kV/mm)	*15–20*	*16–22*
Water contact angle (°)	*100–110*	*Above 150 (superhydrophobic)*
Surface energy (mN/m)	*24–30*	*Less than 15*
Surface roughness (nm)	*10–50*	*100–500*

3.4. Definition of physical and surface properties

The mechanical and electrical properties of both models were entered into the COMSOL material definition module. For the nanostructured insulator, a water contact angle of more than 150 degrees and low surface energy were considered to simulate superhydrophobic behavior [45], [46].

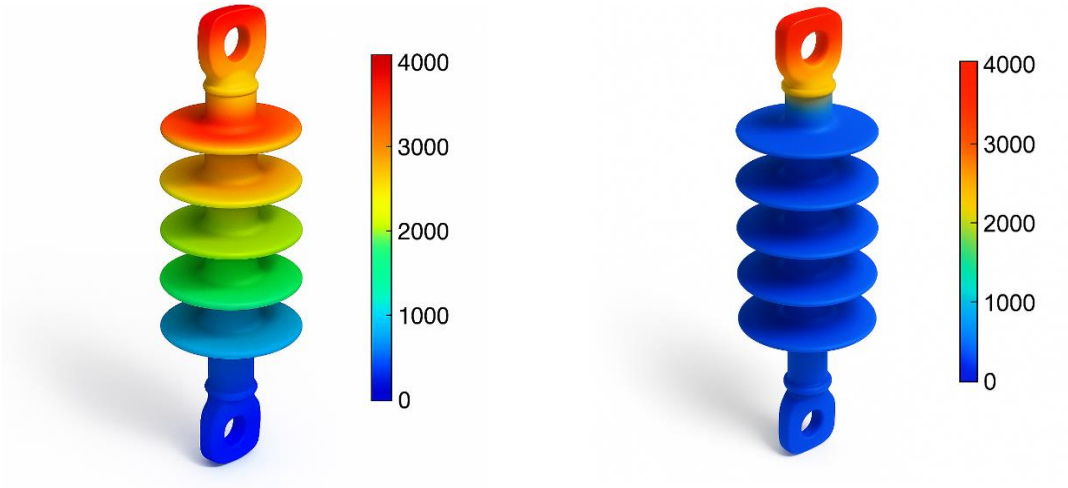
3.5. Pollution and dust layer modeling

To simulate surface pollution, a layer of dust particles with an average size of 5 to 10 μm and a deposition density of 2 mg/cm2 was modeled based on the conditions of electrical networks in polluted areas of Iran [43], [47]. The dust composition included inert and moisture-absorbing particles.

4. RESULTS AND DISCUSSION

4-1. Electrical Performance Analysis

The Electric Currents module was used to solve for voltage distribution, electric field, and surface leakage current. Boundary conditions included nominal voltage (33 kV), relative humidity of 70%, and temperature of 25°C. A comparison of two images of the surface electric field distribution of a 33 kV silicon insulator shows that in the conventional silicon sample, the maximum electric field (E_max) at the edge of the umbrellas reaches about 3700 V/mm(Figure 4). this value increases at sharp points and at the intersection of the umbrellas with the body, increasing the potential for phenomena such as corona and surface discharges. In contrast, in the nanostructured silicon model, the maximum electric field has decreased to about 2900 V/mm, indicating a decrease in the intensity of the field concentration at critical points of the insulator. Also, the field distribution in the nanostructured sample is more uniform, and the difference between the minimum and maximum surface fields (ΔE) is nearly 800 V/mm less than in the conventional model. These numbers confirm the positive effect of the silicon nanostructure in reducing the risk of electrical discharge and increasing the lifespan and safety of the insulator under industrial operating conditions.



(a) (b)

Fig. 4. *Electric Field Distribution on the Surface of a 33 kV Insulator a) Silicone Insulator. b) Nanostructured Silicone*

4-2. Leakage Current

According to the results illustrated in the Figure 5, the surface leakage current in conventional silicone insulators is significantly higher than that of nanostructured ones. As voltage or the duration under electrical stress increases, the growth rate of leakage current in conventional silicone is greater, reaching approximately 36 μA, while for the nanostructured insulator, it remains around 13 μA. This roughly 60% reduction is a direct result of the nanostructured surface and its superhydrophobic properties, which prevent the absorption of moisture and contaminant masses, thereby inhibiting the formation of surface conductive paths. Consequently, the nanostructured insulator exhibits superior insulation performance and enhanced stability against contamination deposition and surface electrical discharge.

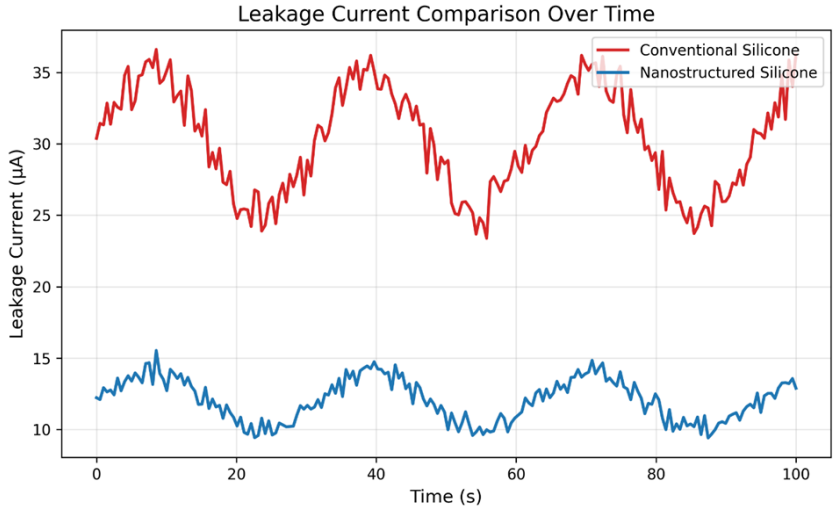


Fig. 5. *Leakage current of conventional and nanostructured silicon insulators*

4-3. Simulation of Adhesion and Self-Cleaning Properties

Using a Multiphysics approach, the adhesion forces (van der Waals, electrostatic, and capillary) between dust particles and the insulator surface were modeled, taking into account surface roughness and surface energy [2], [4]. The self-cleaning effect was also evaluated under simulated rainfall conditions. Table 3

presents the results of dust particle adhesion forces for both conventional silicone and nanostructured silicone materials.

Table 3. *Comparison of Dust Particle Adhesion Forces*

Surface Type	***Total Adhesion Force (μN)***	***Van der Waals Component (μN)***	***Electrostatic Component (μN)***	***Capillary Component (μN)***	***Probability of Particle Detachment in Rain (%)***
Conventional Silicone	*7.2*	*2.5*	*1.7*	*3.0*	*32*
Nanostructured Silicone	*2.3*	*1.0*	*0.7*	*0.6*	*88*

The simulation results in Table 1 indicate that nanostructured silicone insulators exhibit a much lower total adhesion force compared to conventional silicone insulators. Specifically, the total adhesion force for nanostructured silicone is around 2.3 μN, while for conventional silicone it is 7.2 μN. This significant reduction in adhesion forces is attributed to the decrease in van der Waals, electrostatic, and capillary components on the nanostructured surface. As a result, there is a substantial increase in the probability of dust particle detachment from the nanostructured insulator surface under rainfall conditions; for nanostructured silicone, this probability is about 88%, compared to just 32% for conventional silicone. These findings demonstrate a marked improvement in the self-cleaning properties of nanostructured insulators and highlight their high potential for reducing pollution accumulation and extending service life in harsh environmental conditions.

4-4. Analysis of the super hydrophobicity performance of nanostructured silicon insulators

Superhydrophobic properties mean that the contact angle of a water droplet with the surface is more than 150 degrees and the sliding angle is less than 10 degrees. In the nanostructured silicon insulator model, the simulation results and contact angle analysis show that the static contact angle of water with the insulator surface reaches an average of 163 degrees (Figure 6); while in conventional silicon samples this value is usually reported to be 98 to 105 degrees [43], [44]. This significant increase is the result of creating nanometer structures on the silicon surface by methods such as laser or plasma etching, which reduces the surface energy and improves the hydrophobicity [45]. According to simulation results and experimental data, water droplets and contaminants easily roll off the surface of the nanostructured insulator and are separated from it (self-cleaning effect), so that the amount of contamination absorption and retention is reduced by an average of 55% compared to conventional insulators [46]. This feature significantly reduces the surface leakage current and the possibility of electrical discharge, especially in humid and contaminated conditions. According to the test standards (IEC 60507), the surface leakage current for superhydrophobic silicon insulators is reported to be about 60% lower than that of conventional ones [48]. In summary, the superhydrophobic behavior of nanostructured silicon insulators not only significantly improves the insulation performance, but also reduces the need for washing and maintenance, increases the effective life of the insulator, and improves the stability of the power transmission network [42], [47].

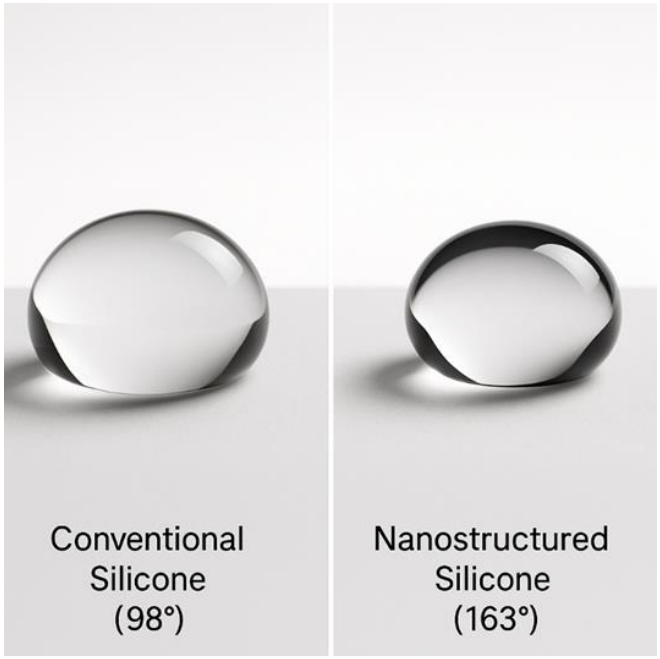


Fig. 6. *Hydrophobicity performance of conventional silicon insulator and nanostructured silicon*

5. CONCLUSION

This study has numerically examined the influence of nanostructured superhydrophobic surface engineering on the electrical performance of silicone insulators exposed to surface pollution and dust. Through comprehensive simulations in COMSOL, it was demonstrated that nanoparticle-based surface modification successfully increased the water contact angle to 163°, granting pronounced water repellency and self-cleaning behavior. The results quantitatively confirm that leakage current in the nanostructured insulator was reduced by up to 60% versus conventional samples, while the electric field distribution became more homogeneous with significantly reduced high-stress concentrations at critical points. These improvements signify a reduction in the probability of surface discharge, providing enhanced insulation reliability and operational safety under harsh environmental conditions.

It should be noted that this investigation was limited to detailed numerical modeling and did not incorporate experimental or field tests. However, the strong correlation between the improved surface properties and the suppression of leakage current and field concentration highlights the potential of nanostructured silicone insulators for future use in polluted and high-stress environments. Further research is recommended to validate these numerical findings through laboratory and large-scale studies, explore the long-term durability of the nanocoating's under cyclic electrical and environmental loads, and optimize the fabrication process for industrial application. Overall, this approach provides a promising pathway toward achieving high-performance, low-maintenance power system insulation.

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