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Reliability assessment of RTV and nano-RTV-coated insulators concerning contamination severity

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ABSTRACT

Currently, insulator contamination is one of the most critical causes of flashover and security problems in high voltage power systems. To overcome this problem, Room Temperature Vulcanized (RTV) silicone rubber coating and recently nano-RTV composite coating are used in the contamination area as maintenance measures for porcelain insulator in power transmission lines. Nano-RTV coating is an approach to improve the properties of porcelain insulators and reliability of the power grid. This paper proposes a new model for evaluating the relationship between contamination level and critical flashover voltage in the presence of nano-RTV coating based on experimental results. Artificial contamination test was carried out in clean fog test on coated and non-coated insulators. Besides, a comparison was made between the surface hydrophobicity of these insulators through evaluating contact angles. Finally, in order to evaluate the effect of contamination intensity through insulator electrical stability on reliability, the life time expectation model was improved and modified. This modified model was employed to evaluate reliability and performance of RTV-coated, nano-RTV-coated, and non-coated porcelain insulators. Results show that using the nano-RTV- coated insulators can improve life time and failure probability density function of insulators compared to traditional coatings and non-coated ones particularly in contaminated area.

1. Introduction

Contamination is one of the problems which transmission line operators have been facing since the 1900s [1]. Contamination-caused flashovers can trigger transmission line outages and make security problems in high voltage transmission systems [2]. In silicone rubber insulators, surface contamination as a result of dirt and salt fog accumulation leads to the hydrophobicity deterioration, leakage current, and flashover [3]. To overcome this problems, recently nano-RTV composite coating are used in the contamination area as maintenance measures for porcelain insulator in power transmission lines. Nano-RTV coating is an approach to improve the properties of porcelain insulators and reliability of the power grid. Adding nano particles to a polymer matrix may lead to change in parameters such as chain length, molecular weight, size, concentration, reinforcement distribution, and nature of the contact surfaces as well as interactions may affect behavior of the composite material [4]. Besides, the more effective factors which determine the changes in polymer matrix are the kind of nanoparticles, their size and concentration, the process optimization and more particularly the verification of the homogeneous dispersion of nanoparticles in the polymer matrix. The electrical properties of insulator can be improved by uniform mixing and adequate particle dispersion of the nanoparticles [4]. The agglomeration significantly reduces the nanoparticle surface to volume ratio and retards the separation of the particles during mixing. Non-modified nanoparticles tend to agglomerate because of the strong cohesive forces and poor mixing with polymer. Modifying the nanoparticles promotes the favorable interfacial interactions between the nanoparticles and polymer matrix. This may lead to greater dispersion of nanoparticles and improvement of the mechanical and dielectric properties of the composites [5, 6]. Nano SiO_2 is widely used to reinforce RTV, as it can improve the thermal conductivity, stress bearing ability, heat tolerance and optical transmissibility [3, 7, 8]. ZnO additive has outstanding physical and chemical properties, such as chemical stability, high dielectric constant, high luminous transmittance, high catalytic activity, effective bactericidal and antibacterial ability, intense ultraviolet and infrared absorption [3, 4]. There are some studies, e.g. [1], which describe the contamination problem and its different levels in the

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transmission system. As it is reported in [1], the source of pollution can be categorized as saltwater, dust, sand particles, conductive carbon-based particles exhausted from stacks at industrial areas such as refineries, particles from cement factories, rains, and algae.

As electrical components with wide application in transmission power systems, insulators' reliability of performance is mainly affected by environmental contamination. Composite insulators have been installed in transmission lines for many years as they show acceptable performance, especially in contaminated areas [9, 10]. Despite satisfactory performance of these insulators, porcelain insulators have some advantages that justify their application in some cases [11]. Nowadays, using different silicon-rubber-based coatings is a common approach to overcome porcelain insulator problems in the polluted area [12]. Another development is concerned with employing nanotechnology to improve performance in these coatings [13]. The effects of nano-coatings on outdoor insulators are reviewed in [14]. There is a relationship between water repellent quality of insulator surfaces and severity of flashover and many research studies have investigated different types of insulators' surface hydrophobicity. In [1] a comparison was made between electrical stability of porcelain insulators and composite insulators through clean fog test experimental data. Also, [9, 10] introduced a different type of nanoparticle that improves hydrophobicity and other aspects of RTV coatings. On the other hand, there are few studies that investigate insulators' reliability as an electrical component of power systems in different environmental conditions [15].

Water soluble and insoluble surface contaminants are the main causes of flashover on insulator surfaces and they have significant effects on electrical stress withstand of the insulators. Soluble variety consists of diverse types of salinity. According to [1], there are different types of pollutions including sand-based pollution or ground dust, industrial pollution with large amounts of solid deposits, chemical pollution, and smokes.

Flashover process in insulators is accomplished through separate steps. The applied voltage wave, referred to as AC and DC voltages, has a significant effect on the severity of this process. In the case of AC voltages arc-propagation across the insulator surface takes several cycles [1]. Surface characteristics also play an important role in the pollution flashover process of insulators. Insulator surface can be categorized as hydrophilic or hydrophobic [10, 14]. While hydrophilic surfaces are usually associated with glass and ceramic insulators, hydrophobic surfaces are characterized with polymeric insulators or porcelain insulators with polymeric coating, such as RTV or modified RTV with nanoparticles in order to enhance insulator properties [16].

There are several models to estimate the life assessment of electronic equipment, including the proposed methods in [17, 18] which is based on the analysis of "worst-case conditions" and on the use of "safety factors." Many of these methods use past experience and based on the impact of only single facts or numbers, regardless of assigning any degree of likelihood to future expectation. Therefore, in most of these methods, it is not possible to evaluate the impact of environmental conditions and maintenance procedures. In [19] a thorough electro-thermo-mechanical life model of the electrical components, the individual aging phenomena of the representative electrical components and the general aging mechanisms of insulating materials as well as considering environmental events are represented for lifetime estimation and failure rate. The use of this model facilitates the use of experimental results and different environmental conditions. Aforementioned model is electro-thermo-mechanical life model derived from a suitable combination of single-stress which are the Inverse-Power model and the Arrhenius model. This model can help this study with ability of considering experimental results in presence of different level of environmental contamination.

The objective of this study was to compare nano-RTV-coated porcelain insulators with non-coated and RTV-coated insulators in terms of electrical stability under different levels of contamination. The comparison is made through experimental test and employing the life time expectation model. The model employed in this study included thermal, mechanical, and electrical stability of components which were modified to consider the effect of environmental contamination on electrical withstand voltages. First, the relationship between contamination and critical flashover voltage for insulators are dealt with. This helps with easier selection between RTV, nano-RTV-coated, and porcelain insulators concerning the severity of contamination of operation area without needing to expose them in the real situation. Therefore, various coatings in this paper are investigated in terms of hydrophobicity. Finally, based on the proposed life time expectation model as a comparison tool, the expected life time and failure Probability Density Function (PDF) of RTV, nano-RTV-coated, and porcelain insulators are investigated in the presence of different contamination levels.

To sum up, the main contributions of this paper are as follows:

- Implementation of experimental tests in order to compare electrical stability of RTV- and nano-RTV-coated insulators,
- Considering different level of contamination in evaluating critical flashover voltage and withstand voltage,
- Evaluating electrical stability of two different types of nano-RTV-coated porcelain insulators,
- Proposing mathematical relation between levels of contamination and critical flashover voltages as a representative of electrical stability of coated and non-coated insulators,
- Evaluating surface hydrophobicity of nano-RTV-coated, RTV-coated, and non-coated porcelain insulators,
- Improving the reliability model of insulators considering contamination level,
- Comparing life span of the aforementioned insulators under different contamination levels using Equivalent Salt Deposit Density (ESDD) as the criterion, and
- Comparing failure probability of the studied nano-RTV-coated, RTV-coated, and porcelain insulators in the presence of different levels of contamination.

Section 2 will present information about materials and samples used in this study. It also describes expectation life model and related assumption besides brief information about contamination and flashover process on the surface of insulators and related artificial contamination test. Section 3 presents the results of the experimental test in each case and the proposed relation between ESDD as a contamination indicator and critical flashover voltage will be presented. Based on the findings, the expected life time and failure probability of samples under different levels of contamination will be calculated. Furthermore, contact angle test results are presented in Section 3 in order to evaluating surface hydrophobicity of the studied insulators. Finally, Section 4 presents the conclusion of this study.

2. Experimental methods

2.1. Test samples

To investigate the performance of the nano-RTV and RTV coatings on electrical stability of insulators compared to porcelain insulator without coating under different levels of contamination, four samples were prepared as follows:

Sample (a): a porcelain insulator with technical data as presented in Table 1;

Sample (b): the porcelain insulator coated with commercial RTV silicone rubber manufactured by Wacker Co;

Sample (c) and **(d)**: the porcelain insulators coated with two different types of nano-RTV composites as proposed in SubSection 2.2;

Nano-coating of sample (c) (called nano-RTV (I) in this study) contained ZnO particles while sample (d) was composed of hybrid ZnO/

Table 1
Technical data of the porcelain insulator.

Parameter	Value
Porcelain disk diameter [mm]	175
Creepage distance [mm]	190
Unit spacing [mm]	110
Weight [kg]	2.4
Total area [mm^2]	717.82

Table 2
Parameters of (1).

sample	(a)	(b)	(c)	(d)
λ	0.3925	o.6605	0.8486	0.0681
μ	0.3290	0.3603	0.3452	0.3224

SiO_2 nanoparticles (called nano-RTV (II) in this paper). Comprehensive information about preparation procedure of these two nano-RTV composites are presented in SubSection 2.2. Table 2 illustrates the insulators used in this study.

2.2. Samples preparation

Commercial RTV silicone rubber manufactured by Wacker Co was used in the study. Also, nano ZnO with an average particle diameter of 50 nm and nano SiO_2 with average particle size of 30 nm were utilized in this study. Furthermore, (3-Aminopropyl) triethoxysilane (APTES) and Hexamethyldisilazane (HMDS) were purchased from Merck Company as the nanoparticles' surface treatment agents.

Based on the preparation methods typically employed in research on ZnO and SiO_2 nanoparticles to improve RTV properties, e.g. [20], in this paper three different samples were considered as described below. HMDS and APTES were chosen as surface modifiers to investigate their performance as surface modifying agents based on the studies reported in [6, 21].

To prepare sample (c) which is called nano-RTV (I) in this study, nano ZnO particles heated in oven at 150 °C for 2 h were modified by mixing with APTES at a ratio of 100:2 in acetone solution. The mixture was mechanically agitated for two hours and sonicated for 20 min in that order. Then the mixed liquid was filtered and the nanoparticles were dried in an oven at 100 °C for 24 h. The modified ZnO particles were added to the RTV matrix by the proportion of 1.5% and were mechanically mixed and sonicated [6, 7, 21].

To prepare sample (d) which is called nano-RTV (II) in this paper, the nano SiO_2 particles are mixed with ZnO particles. SiO_2 nanoparticles heated in the oven at 150 °C for 2 h were modified by mixing with HMDS at a ratio of 100:1 in acetone solution. The mixture was mechanically agitated for two hours and sonicated for 20 min in that order. Then the mixed liquid was filtered and the nanoparticles were dried in the oven set at 100 °C for 24 h. The prepared ZnO and SiO_2 nanoparticles were added to the RTV matrix with the weight

Fig. 1. Illustration of the samples.

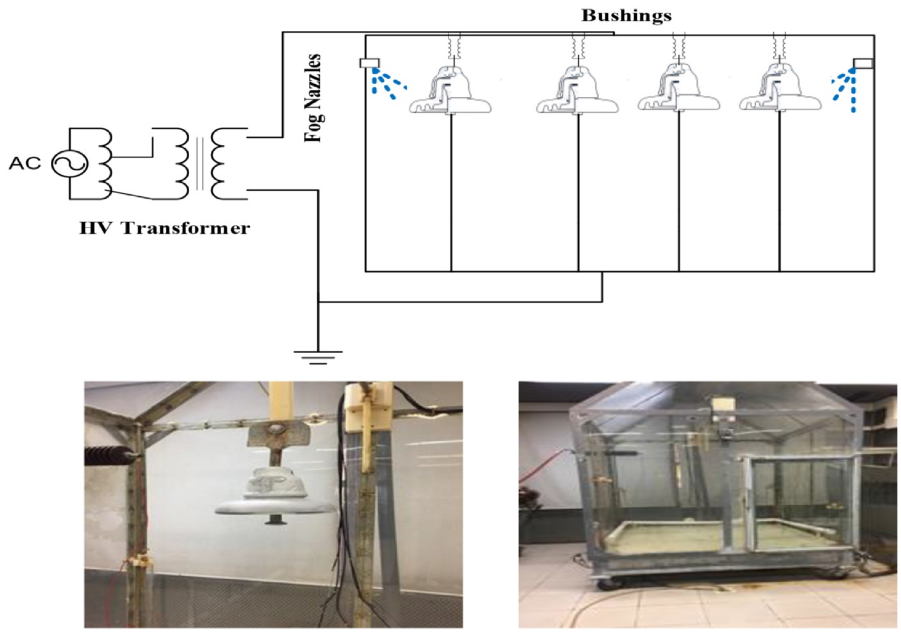

Fig. 2. Clean fog test setup.

proportions of 2% and 1%, respectively before they were mechanically mixed and sonicated [6].

2.3. Test setup and methods

To evaluate electrical stability and hydrophobicity of samples described in the previous section, clean fog test and contact angle measurement test were performed in the study which are described presently.

2.3.1 Critical flash over voltage (clean fog test)

The pollution tests of porcelain insulators were carried out in an artificial fog chamber of $2.0\,m \times 2.0\,m \times 2.0\,\text{m}$, and the power was supplied from a 150 kV/900 kVA high voltage transformer. The test circuit is shown inFig. 2. The solid layer method was used to produce uniform pollution layers on insulators' surfaces. Solid layer method is an artificial pollution test on insulators [22, 23]. The solid layer test procedure simulates type A pollution where a solid layer containing salts and inert materials builds up on the insulator surface, while this wetted layer becomes conductive [23]. The procedure for pollution test by solid layer method has been given in [22, 23]. Composition of the contaminating suspension was based on kaolin containing 40 g Kaolin, 1000 g demineralized water, and some NaCl of commercial purity. The insulators' surfaces were cleaned by demineralized water before spraying the contaminating suspension. The prepared suspension was applied through spraying on the whole sample surfaces and the samples were dried during the rest time which was 24 h for all samples. In addition, variations were considered in the duration of spraying to obtain five contamination levels for each insulator. There are different criteria for determining severity of artificial contamination. The pollution severity can be explained by ESDD and Non-soluble Material Deposit Density (NSDD). The level of contamination ranges between very light, light, moderate, heavy, and very heavy [22]. Fig. 3 depicts the relation between the amount of ESDD and NSDD as a criterion of pollution severity. Clean fog chamber demonstrated in Fig. 2 was equipped with a digital sensor that makes it possible to measure the level of humidity and temperature. After spraying different levels of pollution suspension on insulators by prolonging or shortening the spraying time and the waiting period to dry, insulators were hanged in the fog chamber concurrently so that the test condition was the same for all samples making comparison results reliable for life expectation analysis. After 15 to 20 min waiting time in order to wet the insulator surfaces, the applied voltage was increased by the rate of $2.5\,\text{kV}/sec$ until flashover occurred. Flashover voltage tests in each pollution level were repeated 3 times with 5-minute delay between one flashover and the next test to avoid interaction of effects. For each sample, the flashover voltage of the contaminated insulators at each level of pollution was calculated as the mean flashover voltages, reported in the standard form of kV per leakage distance (cm). In order to convert the average critical flashover voltage into electrical withstand value, coefficient of 0.7 was considered [1, 2]. This assumption is the consequence of allocating 10% for standard deviation. A legitimate criterion for contamination severity of cap and pin insulators is the mean value of ESDD and NSDD. In this paper, equivalent salt deposit density was employed as the touchstone since the amount of NSDD in the calculating results was approximately constant and negligible in comparison with ESDD. The procedure for calculating ESDD values was based on the method suggested in [22].

2.3.2 Contact angle measurement test

The potential of a surface to repel water is called hydrophobicity, as water on the surface forms individual droplets rather than a film. Hydrophobicity is the most important property of insulator surfaces and its measurement has been investigated and widely used as an indicator of the insulators' performance. The insulator whose surface is adequately coated with a wet conducting layer experiences more flashover. Dry salt or other types of contamination deposits does not have enough conductivity to make flashover. In other words, solid salt deposits cannot make the surface of insulators conductive in order to let the leakage current flow. The problem happens when this contaminant layer becomes wet by rainwater or any other means. One of the ways to reduce the probability of this process in porcelain insulators is using RTV coatings which make the surface of insulators repellent. As a result, the conductive film of contamination is less likely to appear on the surface of insulators. Flashover voltage and the severity of this process are affected by the surface material and surface energy. The surface of insulators which has more energy than water makes moisture contribute a low resistance path and let the leakage current flow. RTV coating as a maintenance for porcelain insulators is a low surface energy material (hydrophobic). On the other hand, the surfaces of

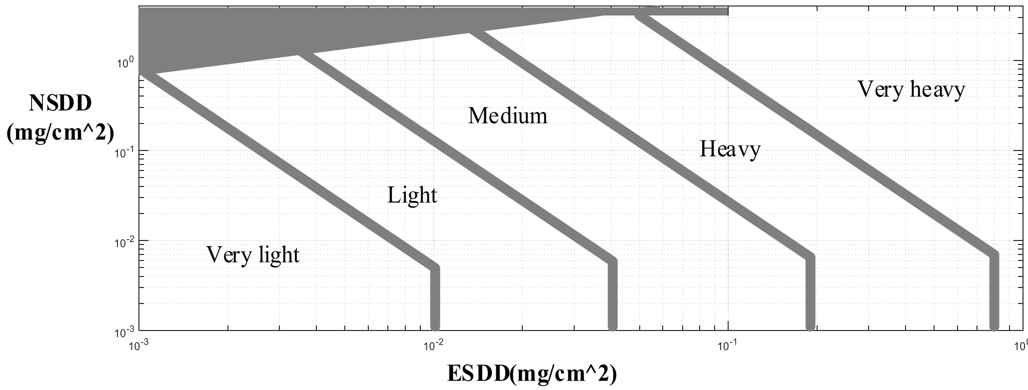

Fig. 3. Relation between ESDD \NSDD and pollution severity.

porcelain and glass insulators are hydrophilic. RTV silicone rubber because of the characteristics of silicone, has favorable performance in reducing flashover probability in contaminated area.

Considering the importance of evaluating hydrophobicity of insulator surfaces, contact angle test is a common method for investigating wettability. The test procedure includes depositing a water drop on each surface and measuring the contact angle of the water drop at the triple point surface of water-air-coating. Classification of the surface hydrophobicity of insulators is presented in [3-5]. Briefly, the test surface is hydrophobic if the measured contact angle is less than 90°. If the measured angle is more than 90°. The surface has the property of repelling of water. In order to investigate the hydrophobicity of the studied RTV, nano-RTV coated, and non-coated insulators, contact angle tests were carried out on four surfaces and the static contact angle values were measured using CAG-20, (Jikan Co) and drops of distilled water (water drop volume ~5).

3. Results and discussion

3.1. Critical flashover voltage

The following relation is proposed between critical flashover voltage representatives of electrical withstand value and ESDD values as a contamination severity criterion for each cases based on the findings of [1, 11, 15]:

$$E_s = \lambda(ESDD)^{-\mu} \quad (1)$$

Where E_s is Electrical withstand voltage (kV/cm), λ and μ are related to the material and shape of the insulators calculated using experimental data of the study and curve fitting. Table 2 presents these parameters for each study sample. To obtain these data for the samples, values of ESDD should be calculated based on the procedure described in [22]. For this purpose, conductivity of the insulators' surface pollution was measured after flashover voltage test for each level of contamination. After collecting all surface pollutions from insulators by a piece of clean cotton fabric and dissolving them in 300 cc water, the conductivity of solution was calculated through (2):

$$ESDD = (5.7 \times \delta 0)^{1.03} \times V_{water}/S \quad (2)$$

where $\delta 0$ is the conductivity of pollution solution recorded at 20 °C (s/m), V_{water} is the volume of distilled water (cm^3), and S is representative of the insulators' surface area (cm^2). Given (2), the amount of ESDD can be reported in (mg/cm^2). As Table 2 suggests, the numeric value of λ in sample (c), i.e. nano-RTV (I) coating, was higher compared to the other samples as a result of the enhanced electrical insulation characteristics. Furthermore, in case of the RTV-coated insulator, this improvement was observed by a higher value of λ compared to non-coated the porcelain insulator. On the other hand, the performance of sample (d) that was coated with nano-RTV (II) was not better than sample (b) due to its nanocomposite characteristic, which is not suitable in electrical stability. The value of μ was between 0.032 and 0.36. Considering the obtained value of λ and μ for all studied insulators, enhancement of the critical flashover voltage performance is concluded in the presence of different contamination severities.

Fig. 4 demonstrates the results for sample (a), which was a non-coated porcelain insulator polluted at five different levels by contaminant suspension. Each point shows an average obtained through experimental data. The flashover voltage results of clean fog test for all samples are reported in the standard form of kV per leakage distance (cm). A noticeable decrease was found in withstand voltages in relation with the intensity increase of contamination.

The obtained flashover voltages under different contamination levels for sample (b), i.e. RTV coated porcelain, are depicted in Fig. 5. There was a noticeable increase in the critical flashover voltage of this nanocomposite in comparison with sample (a). Furthermore, the decrease in voltages was evidently in proportion to the increase in pollution severity. Generally, improved performance compared to porcelain insulator was achieved at all levels of contamination especially light and medium contamination.

The same procedure was applied to sample (c), which was coated with nano-RTV (I). The recorded flashover voltages various contamination levels are depicted in Fig. 6. There was an obvious increase in the critical flashover voltage in comparison with samples (a) and (b). Furthermore, in this sample, the decrease in voltages was also observed in the proportion to the increase in pollution severity. The improvement was particularly remarkable at light, medium, and heavy levels of contamination.

The recorded flashover voltages under different contamination levels for sample (d), nano-RTV (II) coating containing ZnO/SiO_2 hybrid nanoparticles, are depicted in Fig. 7. No significant improvement was observed in electrical performance of the insulators coated with nano-RTV coating in comparison with RTV coating although the decrease in flashover voltages as a result of increase in pollution severity was recognizable too.

Generally, the nanocomposite coatings under study showed different insulation performances depending on the type of nanoparticles and the relevant preparation procedure. For example, nano-RTV(II), which contained ZnO/SiO_2 hybrid nanoparticles, did not perform well in comparison with nano-RTV(I) containing ZnO nanoparticles. In fact, depending on the materials used for surface covering of the insulators, withstand voltages varied. Also, different types of nano-coatings indicated distinct electrical performances.

3.2. Contact angle test

Fig. 8 compares the contact angle values of samples (b), (c), and (d), which are porcelain insulators with RTV, nano-RTV (I), and nano-RTV (II) coatings, respectively. The values are the means of four

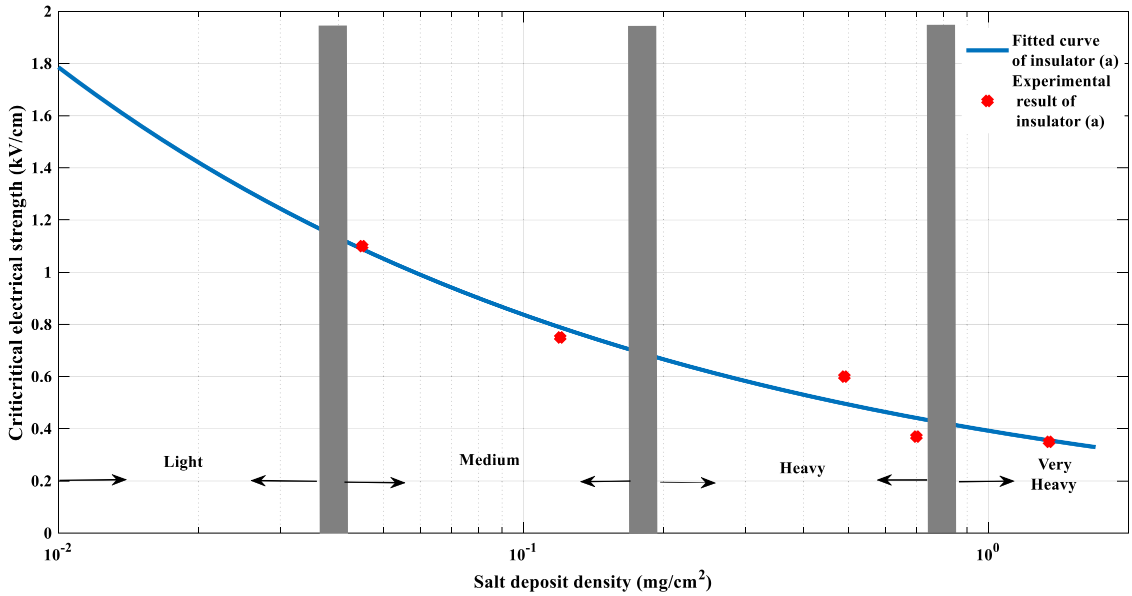

Fig. 4. Withstand electrical stress for sample (a) at different levels of contamination.

measurements made at various points for each sample. The static contact angles of RTV, nano-RTV (I), and nano-RTV (II) samples were 103, 128, and 114°, respectively. The results of the contact angle test for sample (b) shows clearly that the surface had hydrophobic properties. In addition, the result for sample (c) shows a noticeable improvement over RTV-coated sample. Similarly, the contact angle test for the nano-RTV (II) coating (sample d) suggestes an improved water repelling property. In sum, although the findings of this study show that both nano-RTV (I) and (II) coatings enhanced the hydrophobic properties of the insulator surfaces, this did not improve the electrical performance of the insulators proportionately and the properties of nanoparticle composites play an important role in the electrical behavior of surface coating.

3.3. Failure probability expectation

The estimated life time of different electrical components under electrical, mechanical, and thermal stress and also environmental factors is calculated as follows [19]:

$$L = L_0(E/E_s)^{-(n-bv)} \times (M/M_s)^{-m} \times \exp(-\beta v)$$
$$v = 1/\theta - 1/\theta_0 \tag{3}$$

where L_0 represents the corresponding life (year) time and E is the electrical stress (kV/cm) and M is mechanical stress (N/mm^2) on the component; E_s and M_s represent the scale parameter for the minimum limit of electrical and mechanical stress, respectively; n and m are the voltage and mechanical stress endurance coefficient which are equal to 7 and 2.3, respectively; b is a correct coefficient taking into account the reaction of the material due to combined stress application which is 6000 (K), finally, β, θ, and θ_0 represent the constant related to activation energy (K), absolute temperature (K), and base temperature (K), respectively. Based on this life expectation model which contains electrical, mechanical, and thermal stress for each electrical component, it is possible to investigate the effect of various coatings under study on life time and therefore, failure probability of the insulators. The failure probability at year t due to cause j is calculated as follows [19]:

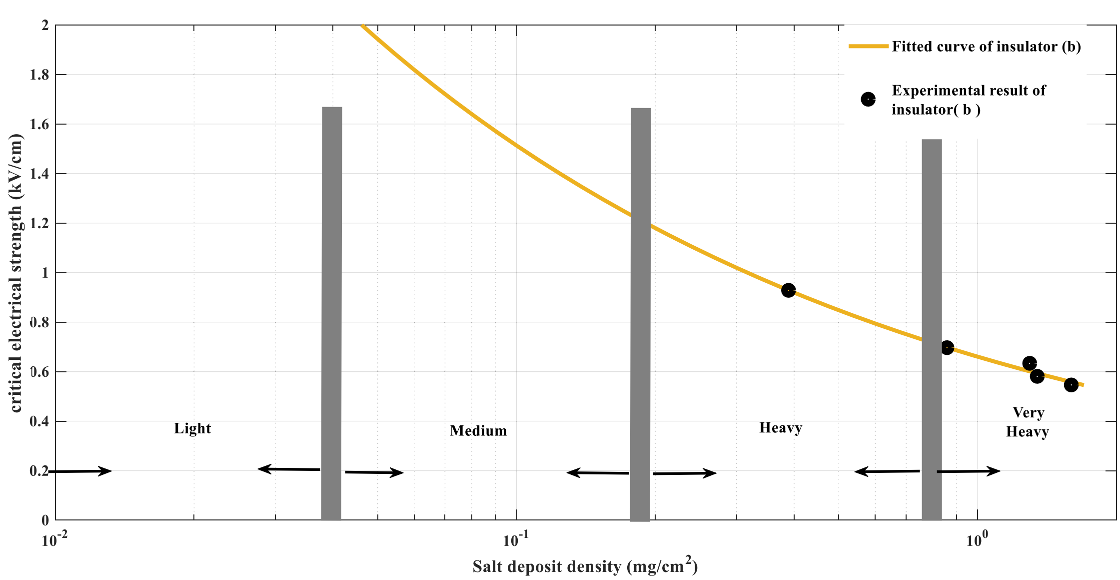

Fig. 5. Withstand electrical stress for sample (b) at different levels of contamination.

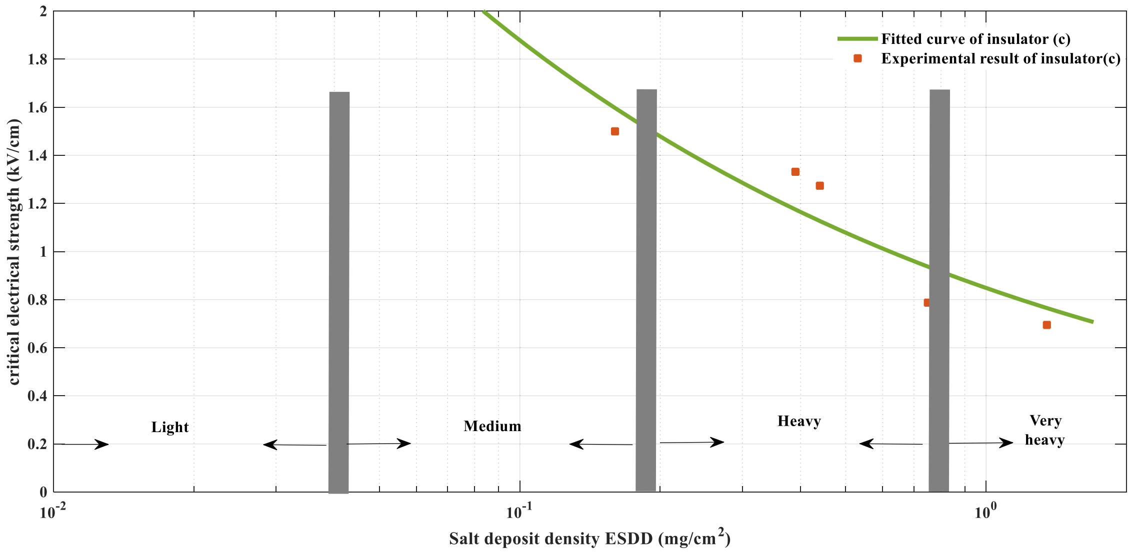

Fig. 6. Withstand electrical stress for sample (c) at different levels of contamination.

$$p_j(t) = \left\{1 - \exp\left[-(E/E_s)^{\alpha(n-bT)} \times (M/M_s)^{-m\alpha}(t/l_0)^{\alpha} \times e^{\alpha\beta v}\right]\right\} \forall j \in J \tag{4}$$

where α is the shape parameter. Failure can be divided into aging and random failure. Random failure is the result of external causes such as storm while aging failure refers to aging process of material under different stress. Both random and aging failure rates can be calculated considering statistical data and replacing parameters for each cause from (4) based on [6, 19]. Based on the statistics of major failures and causes data for porcelain insulator in [24], the total failure probability $p(t)$ and failure PDF $f(t)$ can be obtained as follow:

$$p(t) = \sum_{j\in J} p_j(t) \times w_j, \quad \sum_{j\in J} w_j = 1 \tag{5}$$

$$f(t) = \frac{dp(t)}{dt} \tag{6}$$

Where w_j is the weight factor for cause j. The results obtained in the study were employed to work out the effect of environmental factors and insulators' material properties in the described model. Based on the relations between contamination and electrical withstand stress calculated in previous section for the insulators under study, the effect of contamination level based on ESDD for different types of insulators can be presented in terms of electrical stress in aforementioned equations. In other words, the value of E_s for different cases, including diverse contamination levels and insulator material can vary and affect the electrical stability.

In [6, 20], the values of activation energy for all samples which represent how easily the material decomposes under thermal stress were investigated and the related tests were performed. Considering high thermal stability of porcelain insulators, it was assumed that activation energy related to porcelain insulator was extremely high and therefore, all samples' thermal aging was related to their polymeric coating. Values of parameter of β based on experimental data of [6] were 12,000, 20,000 (K) for RTV and nanoRTV respectively. In case of the porcelain insulator the thermal degradation is not likely to happen because of high thermal stability of porcelain. Life expectation calculation for each case were performed employing these data and the experimental results obtained in this work. It is notable that because of better electrical performance of sample c in comparison with sample (d), it was chosen as the nano-RTV coated insulator in the reliability

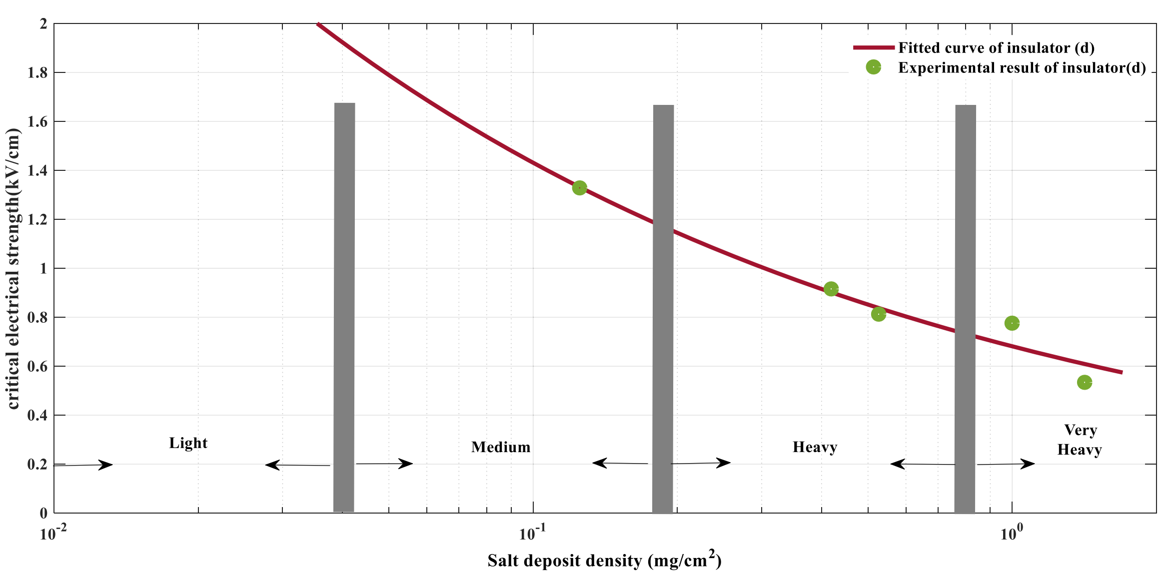

Fig. 7. Withstand electrical stress for sample (d) at different levels of contamination.

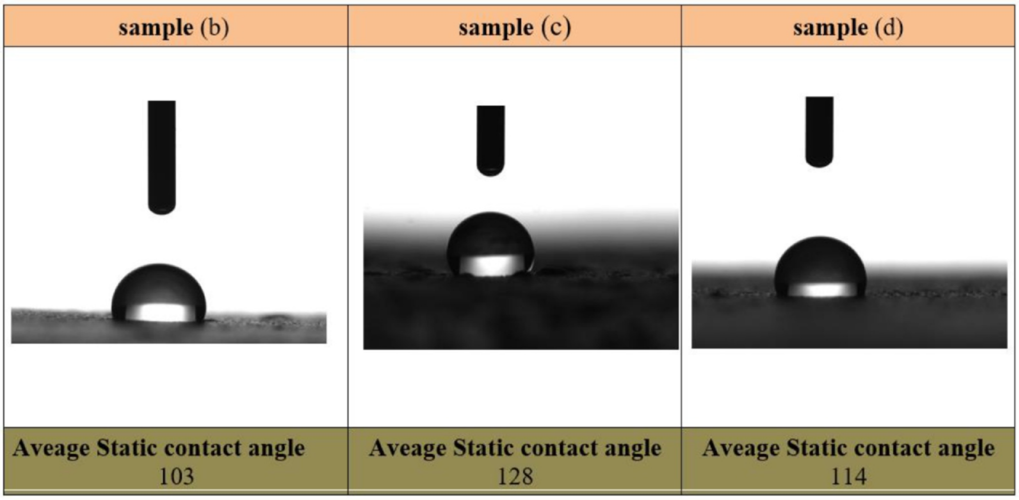

Fig. 8. Contact angle images for samples (b), (c), and (d).

Table 3
Parameters of (3) and (4).

Cause	Parameter α	$E(kV/cm)$	$M(N/mm^2)$	$\theta(K)$
Aging	4.5	13	M_s	308
Random	1	E_s	$19\times M_s$	$\theta_0=298$

comparison in this work. The values of parameters used in (3) and (4) are given in Table 3. It is worth to saying that the mechanical stress and withstand values for all insulators are assumed to be the same according to Table 3.

Fig. 9 shows the result of the expected life time calculated based on the described model for insulators (a), (b), and (c). It can be easily found that the life time of all insulators in the presence of high level of contaminations significantly decreased. However, nano-coated insulators showed enhanced performance in comparison with sample (b) and RTV-coated insulator had better performance compared to the porcelain insulators, i.e. sample (a). Fig. 10 shows failure probability of non-coated insulator in terms of ESDD values. From this result it is clearly observed that by increasing the contamination level of the area, so did the failure probability of insulators increase and this increment happened in high rates especially in moderate, heavy, and very heavy levels of contamination for porcelain insulators. Failure probability values in very light and light contaminated area increased with time by a gentle slope but through increasing contamination level to moderate, heavy, and very heavy levels, remarkable increase and mutation were observed in failure probability curves.

Fig. 11 depicts the failure probability for sample (b) at different levels of contamination. For this type of insulators, the value of failure probability significantly decreased in comparison with sample (a) and failure probability increment happened in the very heavy range of ESDD. As the figure suggests, increasing the failure probability through lengthening application time occurred with a gentle slope in curves which refer to light, moderate, and heavy contamination. By comparing the curves related to contamination level 0.05 in Figs. 11 and 12 at the end of the time horizon, it is noticed that failure probability in RTV-coated insulators reduced to a quarter compared to non-coated insulators. Also, comparing contamination level 0.95 in the relevant curves in these figures reveals that non-coated porcelain failure

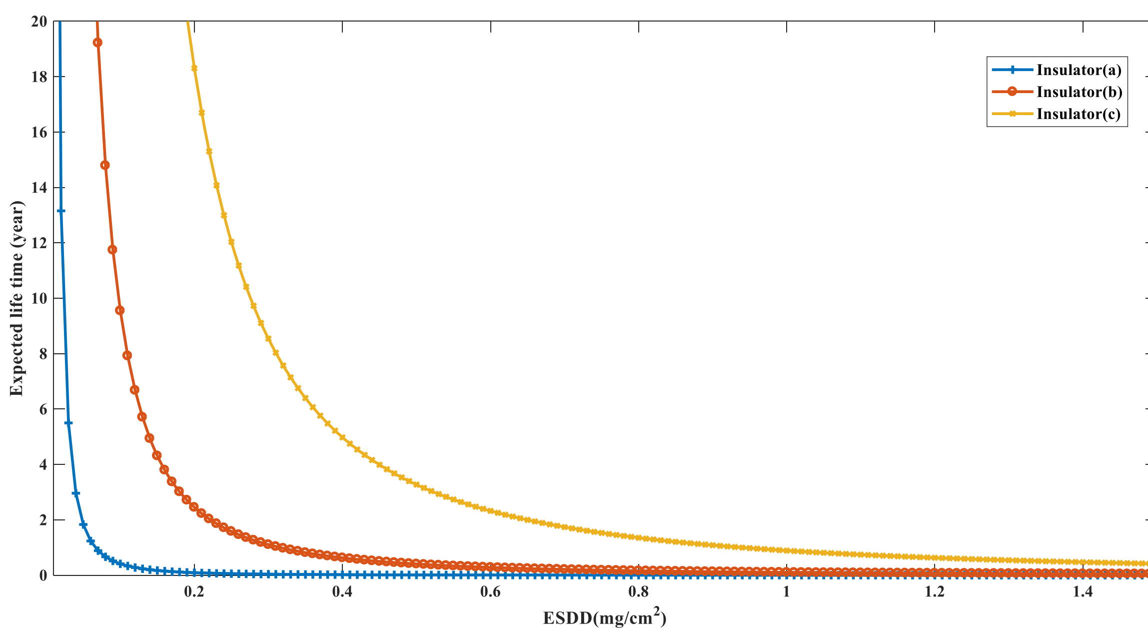

Fig. 9. Expected life time for all insulators considering contamination.

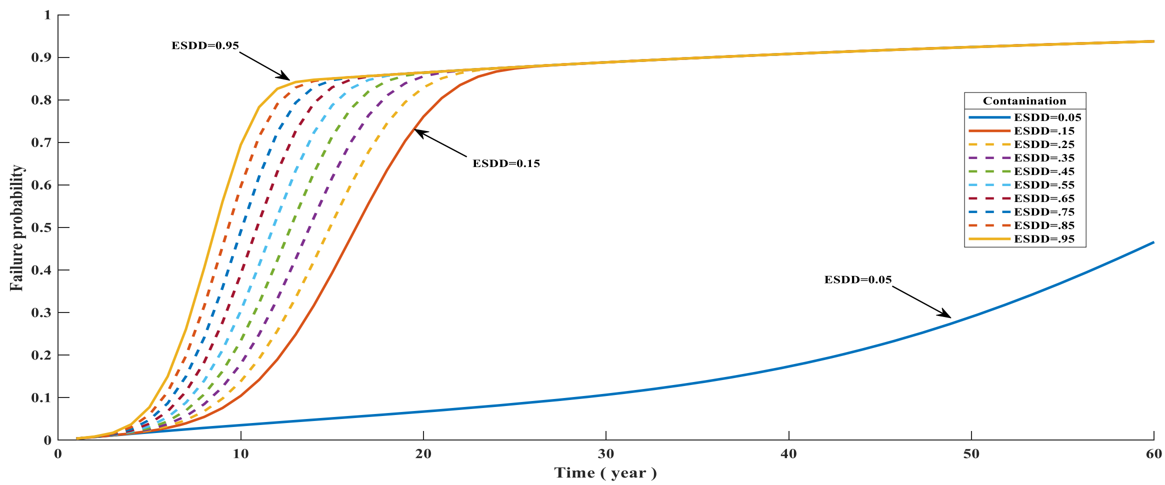

Fig. 10. Failure probability of insulator (a).

probability reached to 0.85 in year 10 of the application period while in case of RTV-coated insulators this probability failure value approximately belonged to the end of the time horizon. Fig. 12 demonstrates failure probability for sample (c) and shows the reliability performance enhancement of nano-coated insulators particularly under approximately very heavy and extremely heavy contamination conditions. As this figure suggests, failure probability values at light, moderate, and heavy contamination levels is negligible. Also, increase in the rate of failure probability for curves related to very heavy contamination was mild through application time.

Based on the model employed in the last section and using (6), failure PDF of the insulators under study are depicted in Figs. 13, 14, and 15 where the PDF values of samples at different ESDD levels are shown for samples (a), (b), and (c). Analysis of these figures reveals that by increasing ESDD values in all studied insulator the mean value of PDF curves decreased. As it is demonstrated in Fig. 13, this reduction occurred with high rates while in Figs. 14 and 15 its rate was softer. Comparing these three figure reveals that probability density of failure curves related to nano-RTV-coated insulators had higher mean values even under very heavy level of contaminations. Also, probability density failure curves related to nano-RTV coatings were wider compared to curves for RTV-coated insulators and RTV-coated insulators were wider compared to porcelain curves. This can imply better electrical stability and increased reliability of these samples because of their improvement in insulation properties which was discussed in pervious section. It is notable that the peak value of probability density curves related to nano-RTV coatings was lower than that of the curves related to RTV coatings while curves for nano-RTV coatings belonged to extremely heavy level and curves for sample (b) coatings belonged to heavy area. Furthermore, peak value of probability density curves related to insulator (b) was lower than curves related to insulator (a) although pollution range of RTV-coated curves belonged to very heavy level of contamination and the pollution range of insulator (a) curves belonged to heavy area. All these data confirm enhancement of reliability and performance of nano-RTV and RTV-coated insulators especially in contaminated area. Given the importance of reliability in transmission power systems and severity of contamination, decision about using appropriate insulators can be made.

In our earlier study [6], two different types of silicon rubber RTV nanocomposites with low content of modified nano ZnO and nano SiO2 particles and pure RTV were compared in terms of thermal decomposition and activation energy, which play an important role in determining the rate of thermal degradation in polymeric materials. Results suggested that activation energy in the nano ZnO and ZnO/SiO2 composites increased in comparison with the pure RTV. This can confirm thermal aging enhancement of the nano RTV in comparison with the pure RTV and estimating the expected lifetime of the coatings, which is valuable in determining the reliability of porcelain insulators. According to the results obtained in current study, the most improvement of electrical insulation performance is related to the sample (c), which is due to the great properties of ZnO nanoparticles [16]. ZnO additive has outstanding physical and chemical properties, such as high dielectric constant [3, 4]. Results show improvement in surface hydrophobicity performance of sample c as compared with the pure RTV. It is indicated that nano-ZnO will increase the hydrophobicity of RTV [10]. The above mentioned factors resulted in increasing the amount of

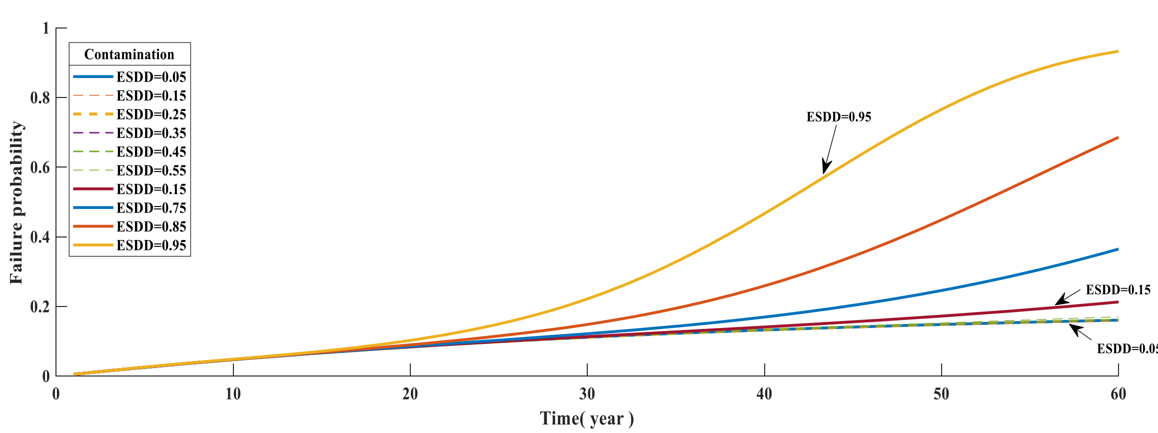

Fig. 11. Failure probability of insulator (b).

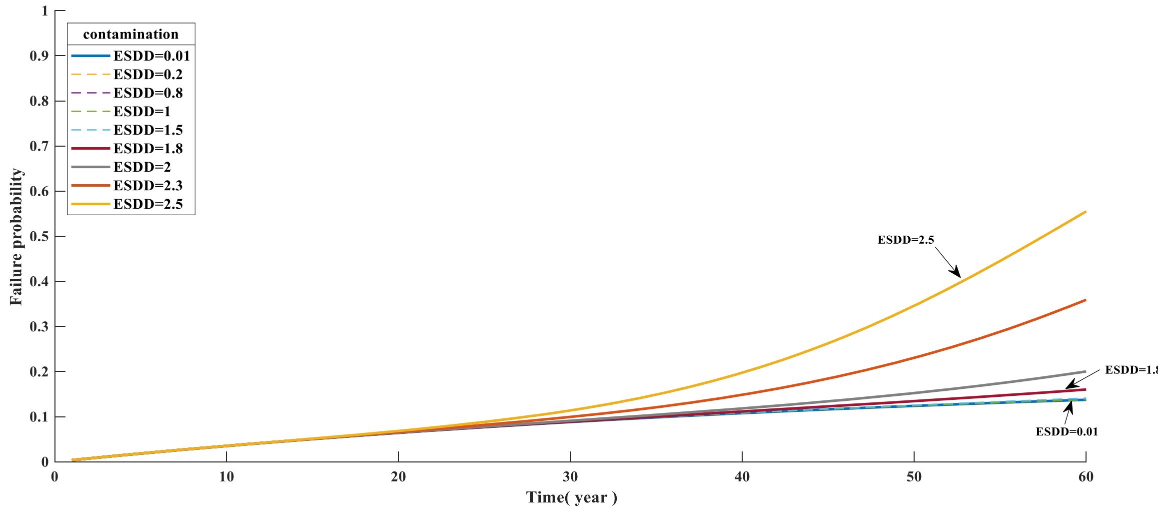

Fig. 12. Failure probability of insulator (c).

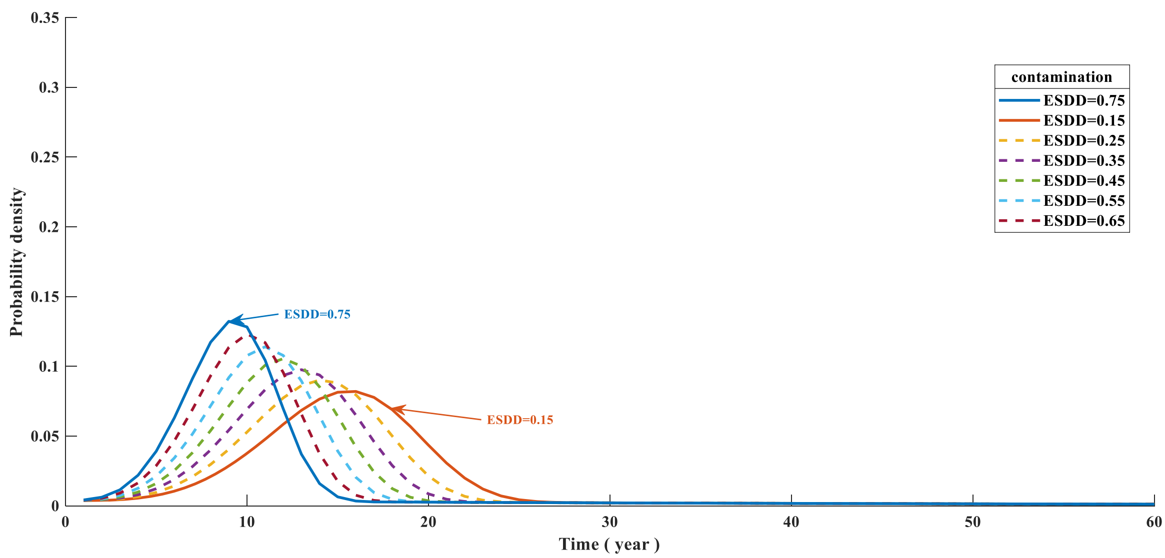

Fig. 13. Failure probability density function of the insulator (a).

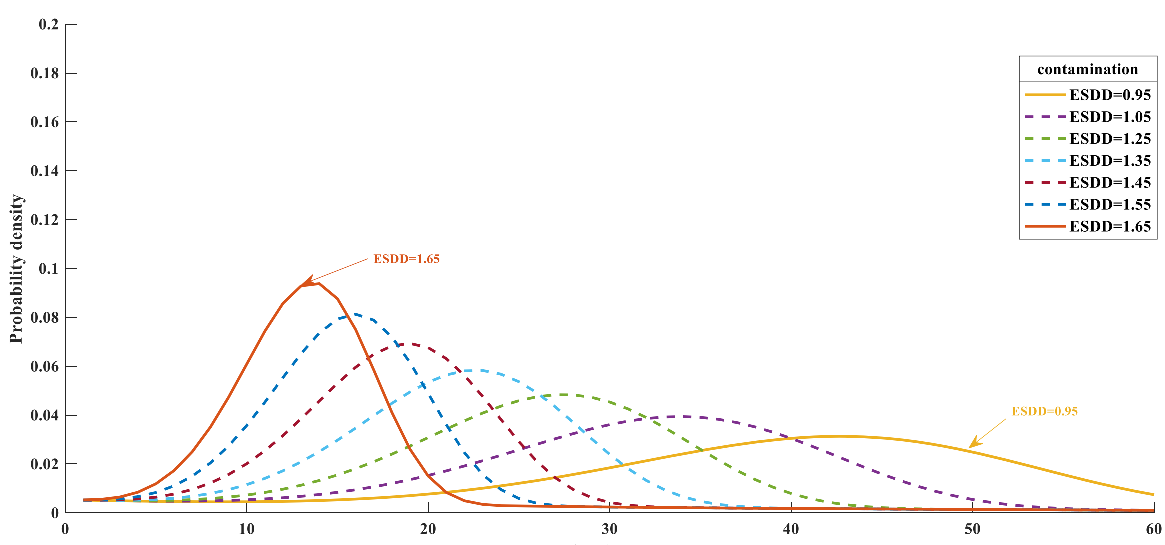

Fig. 14. Failure probability density function of the insulator (b).

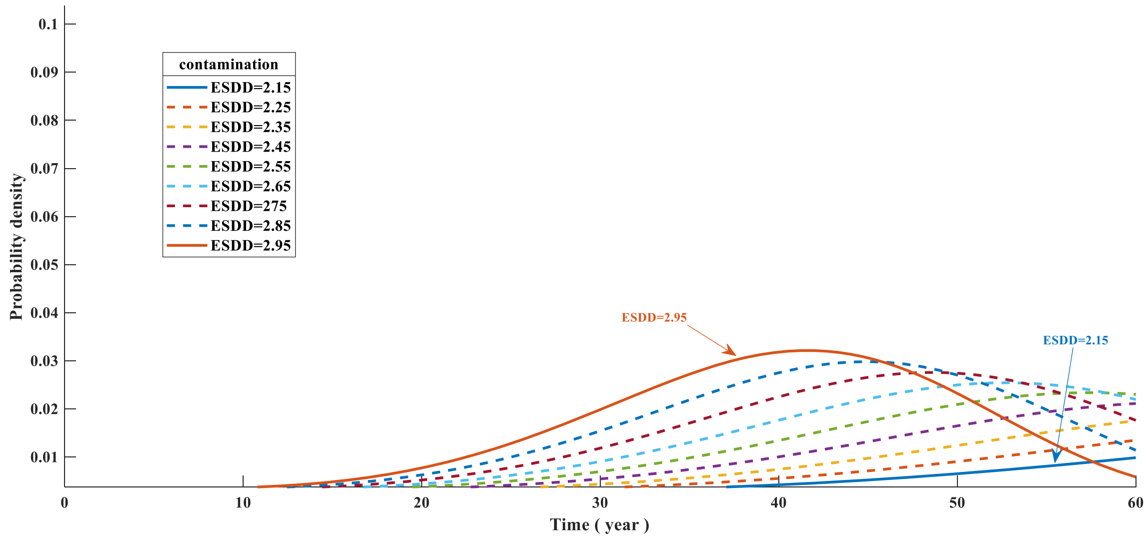

Fig. 15. Failure probability density function of the insulator (c).

tolerable electrical stress in the presence of contamination and moisture for the insulator. It is reported that leakage current for nanocomposite samples in a contaminated environment reduced compared to insulators without any coating, indicating a remarkable improvement after coating [3]. It is shown that in sample (d) (including nano SiO_2 particles), there is a slight improvement in the threshold of electrical stress tolerance in comparison with sample (c). Accordingly, using the nano-RTV-coated insulators can improve life time and failure probability density function of insulators compared to traditional coatings and non-coated ones particularly in contaminated area. Based on the results, it is concluded that the simultaneous improvement of thermal and electrical performance of the desired insulation depends on the type of nanoparticles and their concentration and the surface modification method.

4. Conclusion

In this study, the electrical stability performance of two different types of nano-RTV coatings for porcelain insulators and an RTV coating were compared with non-coated porcelain insulators through measuring critical flashover voltages at different level of contamination. Also, hydrophobic capability of these nano-RTV composites and pure RTV were compared by contact angle test. Based on the obtained experimental data, the relationship between the insulator withstand voltages and contamination severity were proposed. The nano-RTV coatings that showed better performance were chosen and reliability calculations for the nano-RTV-coated, RTV-coated, and non-coated insulators were performed based on life time expectation model and taking into account contamination severity. The findings are summarized as follows:

- Nano-RTV (I) coating which contained ZnO particles showed improvement in withstand voltages in comparison with the pure RTV coating.
- Nano-RTV (II) coating containing hybrid ZnO/SiO_2 did not show sensible improvement in withstand voltages in comparison with the pure RTV.
- Nano-RTV (I) and nano-RTV (II) showed improvement in surface hydrophobicity performance as compared with the pure RTV.
- Using nano-RTV (I) coatings on insulators can improve reliability indices especially in area with a high level of contamination and reduce failure probability.
- Using RTV coating enhanced reliability indices of insulators as compared with non-coated porcelain insulators particularly in area with the moderate and higher levels of contamination.

Declaration of Competing Interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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