Analysis of Electric Field and Potential Distributions along Surface of Silicone Rubber Insulators under Various Contamination Conditions Using Finite Element Method

B. Marungsri, W. Onchantuek, A. Oonsivilai and T. Kulworawanichpong

Abstract**—**This paper presents the simulation results of electric field and potential distributions along surface of silicone rubber polymer insulators under clean and various contamination conditions with/without water droplets. Straight sheds insulator having leakage distance 290 mm was used in this study. Two type of contaminants, playwood dust and cement dust, have been studied the effect of contamination on the insulator surface. The objective of this work is to comparison the effect of contamination on potential and electric field distributions along the insulator surface when water droplets exist on the insulator surface. Finite element method (FEM) is adopted for this work. The simulation results show that contaminations have no effect on potential distribution along the insulator surface while electric field distributions are obviously depended on contamination conditions.

Keywords**—**electric field distribution, potential distribution, silicone rubber polymer insulator, finite element method

I. Introduction

POLYMER insulators, which have been used increasingly for outdoor applications, give better characteristics over porcelain and glass types: they have better contamination performance due to their surface hydrophobicity, lighter weight, possess higher impact strength, and so on. Polymer insulators are quite different from the conventional porcelain and glass insulators. The advantages of silicone rubber polymer insulators are as follows[1]:

1. Silicone rubbers have low surface tension energy and thereby maintain a hydrophobic surface property, resulting in better insulation performance under contaminated and wet conditions.
2. Polymer insulators have higher mechanical strength to weight ratios compared with those of porcelain or glass insulators which enables the reduction of costs for construction and maintenance of transmission or distribution lines.
3. Polymer insulators are less prone to serious damage from vandalism such as gunshots.

The disadvantages of polymer insulators are as follows[9]:

1. Polymer insulators are made of organic materials and so subjected to chemical changes on the surface due to weathering and dry band arcing.
2. Polymer insulators may suffer from erosion and tracking which may lead ultimately to failure of the insulators.
3. Long term reliability is unknown and life expectancy of polymer insulators is difficult to estimate.
4. Faulty insulators are difficult to detect.

Structure of a polymer insulator is shown in Fig. 1. The basic design of a polymer insulator is as follows; A fiber reinforced plastic (FRP) core, attached with two metal fittings, is used as the load bearing structure. The presence of dirt and moisture in combination with electrical stress results in the occurrence of local discharges causing the material deterioration such as tracking and erosion. In order to protect the FRP core from various environmental stresses, such as ultraviolet, acid, ozone etc., and to provide a leakage distance within a limited insulator length under contaminated and wet conditions, weather sheds are installed outside the FRP core. Silicone rubber is mainly used for polymer insulators or composite insulators as housing material.

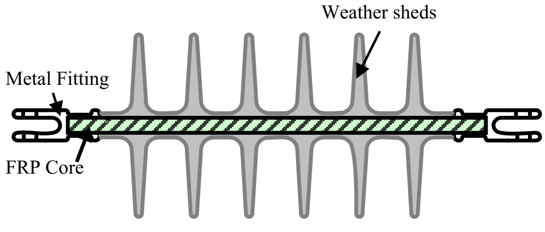

Fig. 1 Structure of a Polymer Insulator

However, since polymer insulators are made of organic materials, deterioration through ageing is unavoidable. Hence,

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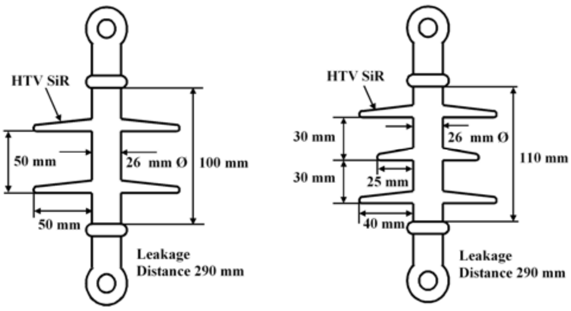
ageing deterioration is a primary concern in the performance of polymer insulators. Artificial salt fog ageing tests have been most widely conducted on simple plates, rods, and small actual insulators for evaluating the anti-tracking and/or anti-erosion performance of housing materials for polymer insulators [2–8].

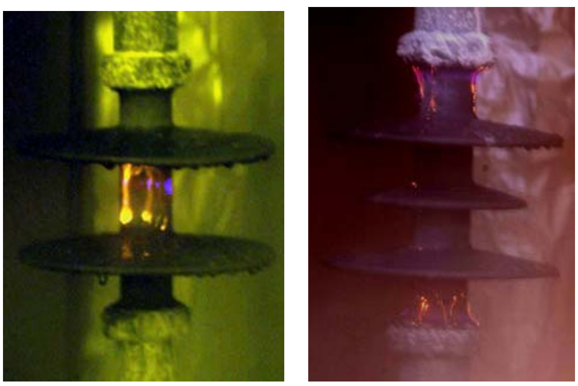
In previous work, salt fog ageing test have been conducted on specimens having different configurations [9]. Two insulator-type specimens, having straight and alternate sheds, illustrate in Fig. 1. All the specimens were made of high-temperature vulcanized silicone rubber (HTV SiR) with alumina trihydrate (ATH: $Al_2O_3{\cdot}3H_2O$) filler contents of 50 parts per 100 by weight (pph). The insulator-type specimens were prepared by molding HTV SiR onto the FRP rods.

During 50 test cycle of salt fog ageing test, stronger surface discharges were observed on the specimen having straight sheds comparing with the specimen having alternate sheds although all specimens having the same leakage distance and made of the same materials. The observation result is illustrated in Fig. 2. After 50 test cycles, severe surface ageing was observed on the trunk between sheds of specimens having straight shed comparing with the specimen having alternate sheds, as shown in Fig. 3. Considering the results, the assumption is electric filed distribution along the specimen having straight shed higher than the specimen having alternated sheds.



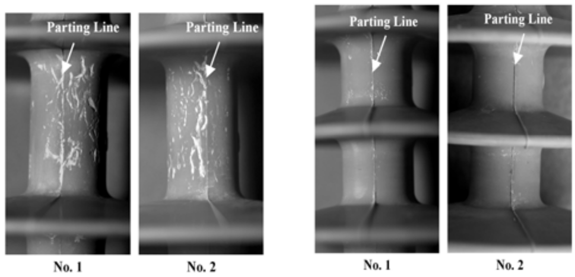
(a) Straight Shed (b) Alternate Shed

Fig. 2 Test Specimens.



(a) Straight Shed (b) Alternate Shed

Fig. 3 Discharge on specimen surface during Salt Fog Ageing



(a) Straight Shed (b) Alternate Shed

Fig. 4 Ageing of specimen surface after salt fog ageing test.

Even tested specimens having the same leakage distance and made of the same material, obviously degree of surface ageing on tested specimens was obtained. Also, obviously degree of contaminants on tested specimens was obtained. Fully results and discussions are found in [9]. From the test results, electrical performances of polymer insulator surface under contamination conditions should be studied.

In order to study the effect of contamination conditions in the view point of electric field and potential distributions along the specimen surface, Finite Element Method (FEM) was adopted as mathematical tool for simulation electric field and potential distributions. Effect of contamination condition was simulated and analyzed.

II. PROBLEM SOLUTION EQUATION

A. Electric field and potential distributions calculation

One simple way for electric field calculation is to calculate electric potential distribution. Then, electric field distribution is directly obtained by minus gradient of electric potential distribution. In electrostatic field problem, electric field distribution can be written as follows [10]:

$$E = -\nabla V \tag{1}$$

From Maxwell's equation

$$\nabla E = \nabla\left(-\nabla V\right) = \frac{\rho}{\varepsilon} \tag{2}$$

where ρ is resistivity Ω/m,

ε is material dielectric constant ($\varepsilon = \varepsilon_0 \varepsilon_r$)

ε_0 is free space dielectric constant (8.854×10^{-12} F/m)

ε_r is relative dielectric constant of dielectric material

Placing equation (1) into equation (2) Poisson's equation is obtained.

$$\varepsilon \cdot \nabla\left(\nabla V\right) = -\rho \tag{3}$$

Without space charge $\rho = 0$, Poisson's equation becomes Laplace's equation.

$$\varepsilon \cdot \nabla\left(\nabla V\right) = 0 \tag{4}$$

B. FEM analysis of the electric field distribution

The finite element method is one of numerical analysis methods based on the variation approach and has been widely used in electric and magnetic field analyses since the late 1970s. Supposing that the domain under consideration does not contain any space and surface charges, two-dimensional functional $F(u)$ in the Cartesian system of coordinates can be formed as follows[11]:

$$F(u) = \frac{1}{2}\int_D \left[\varepsilon_x\left(\frac{du}{dx}\right)^2 + \varepsilon_y\left(\frac{du}{dy}\right)^2\right] \cdot dxdy \tag{5}$$

where ε_x and ε_y are *x*- and *y*-components of dielectric constant in the Cartesian system of coordinates and u is the electric potential. In case of isotropic permittivity distribution ($\varepsilon = \varepsilon_x = \varepsilon_y$), equation (5) can be reformed as

$$F(u) = \frac{1}{2}\int_D \varepsilon\left[\left(\frac{du}{dx}\right)^2 + \left(\frac{du}{dy}\right)^2\right] \cdot dxdy \tag{6}$$

If the effect of dielectric loss on the electric field distribution is considered, the complex functional $F(u)$ should be taken into account as

$$\overset{*}{F}(u) = \frac{1}{2}\int_D \omega\varepsilon_0(\varepsilon - j\varepsilon \cdot tg\delta)\left[\left(\frac{d\overset{*}{u}}{dx}\right)^2 + \left(\frac{d\overset{*}{u}}{dy}\right)^2\right] \cdot dxdy \tag{7}$$

where ω is angular frequency, ε_0 is the permittivity of free space (8.85 $\times 10^{-12}$ F/m), $tg\ \delta$ is tangent of the dielectric loss angle, and u^* is the complex potential.

Inside each sub-domain D_e, a linear variation of the electric potential is assumed as described in (8)

$$u_e(x,y) = \alpha_{e1} + \alpha_{e2}x + \alpha_{e3}y \quad ;(e = 1,2,3,..n_e) \tag{8}$$

where $u_e(x, y)$ is the electric potential of any arbitrary point inside each sub-domain D_e, α_{e1}, α_{e2} and α_{e3} represent the computational coefficients for a triangle element *e*, n_e is the total number of triangle elements.

The calculation of the electric potential at every knot in the total network composed of many triangle elements was carried out by minimizing the functional $F(u)$, that is,

$$\frac{\partial F(u_i)}{\partial u_i} = 0 \quad ;i = 1,2,..np \tag{9}$$

where *np* stands for the total number of knots in the network.

Then a compact matrix expression

$$\left[S_{ji}\right]\left\{u_i\right\} = \left\{T_j\right\} \quad i,j = 1,2,..np \tag{10}$$

where $[S_{ji}]$ is the matrix of coefficients, $\{u_i\}$ is the vector of unknown potentials at the knots and $\{T_j\}$ is the vector of free terms. After (10) is successfully formed, the unknown potentials can be accordingly solved.

C. Implementation for FEM analysis

Straight sheds polymer insulator was selected to simulate electric field and potential distributions in this study. The basic design of a polymer insulator is as follows; A fiber reinforced plastic (FRP) core having relative dielectric constant of 7.1, attached with two metal fittings, is used as the load bearing structure. Weather sheds made of HTV silicone rubber having relative dielectric constant of 4.3 are installed outside the FRP core. Surrounding of the insulator is air having relative dielectric constant 1.0. A 15 kV voltage source directly applies to the lower electrode while the upper electrode connected to ground. Two dimensions of the alternate sheds polymer insulators for FEM analysis are shown in Fig. 5 (a).

In order to study the effect of water droplets on the insulator surface under clean condition, two cases of water droplets, as shown in Fig. 5 (b) to Fig. 5 (c), were simulated using FEM analysis. It notes that relative dielectric constant of water droplet is 81.

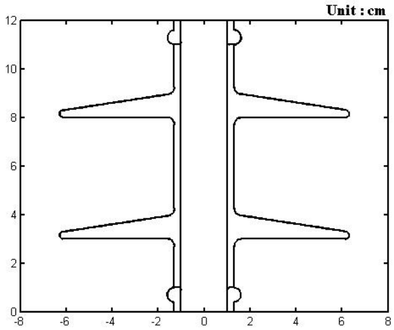
In the similar manner, the effect of water droplets on the insulator surface under contamination conditions are investigated by simulating four cases of contamination, as shown in Fig. 5 (a) to Fig. 5 (f). Playwood and cement dusts used in this simulation were characterized by 1.5 and 8.0 of relative dielectric constants, respectively.

The whole problem domains in Fig. 5 are fictitiously divided into small triangular areas called *domain*. The potentials, which were unknown throughout the problem domain, were approximated in each of these elements in terms of the potential in their vertices called *nodes*. Details of Finite Element discretization are found in [12]. The most common form of approximation solution for the voltage within an element is a polynomial approximation. PDE Tool in MATLAB is used for finite element discretization. The results of FEM discretization for clean and contamination conditions illustrate in Fig. 6.

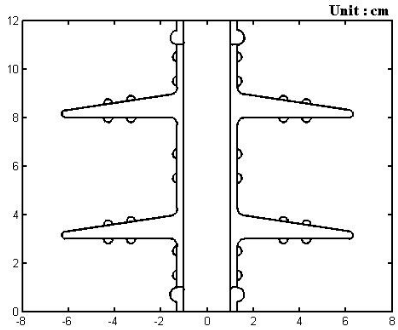
III. SIMULATION RESULTS AND DISSCUSSIONS

In this study, clean and contamination conditions, were simulated using FEM via PDE Tool in MATLAB. As illustrated in Fig. 7, water droplets have no effect on potential distribution along the insulator surface. No obvious difference in potential distribution can be seen. In contrast, in case of electric field distribution, significant difference in electric field distribution can be seen even clean surface. In addition, electric field intensity on the trunk portion increased with a number of water droplets.

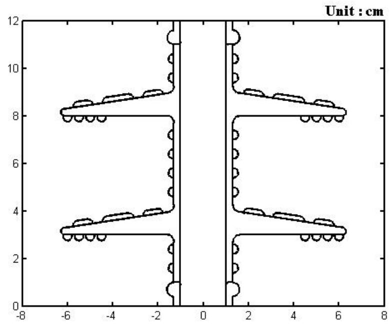
In case of palywood dust contaminated condition, water droplets have no effect on potential distribution along the insulator surface, as illustrated in Fig. 8. No obvious difference in potential distribution can be seen. In contrast, in case of electric field distribution, significant difference in electric field distribution can be seen. Electric field intensity increased with a number of water droplets especially on the trunk portion between sheds.



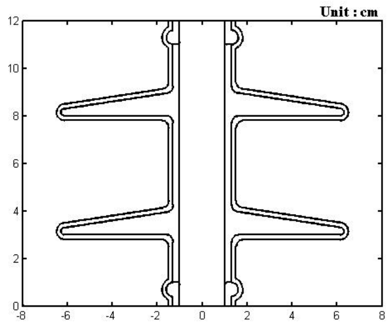
(a) Without Water Droplets



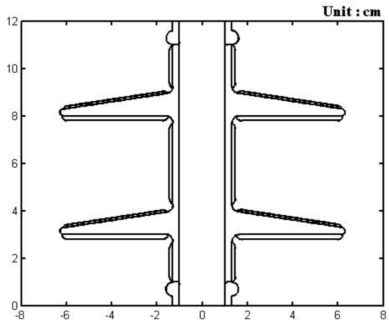
(b) With Uniform Water Droplets



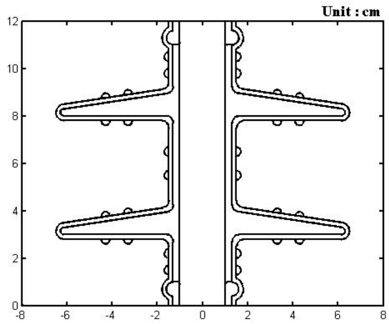
(c) With Non - uniform Water Droplets



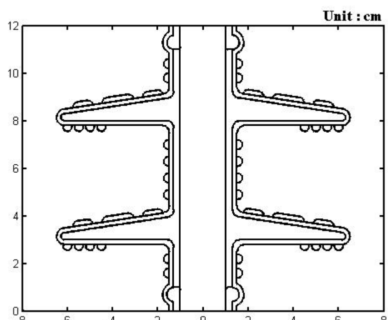
(d) Uniform Contaminants Without Water Droplets



(e) Non - uniform Contaminants Without Water Droplets

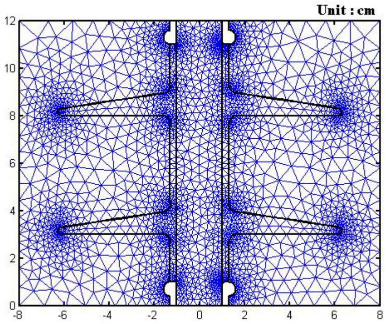


(f) Uniform Contaminants with Uniform Water Droplets

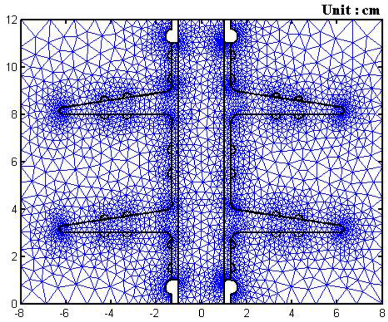


(g) Uniform Contaminants with Non - uniform Water Droplets

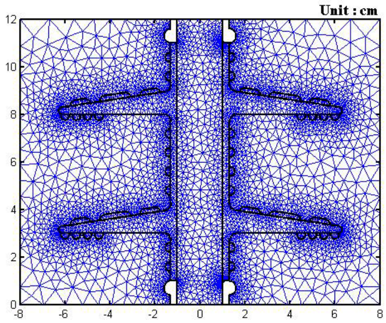
Fig. 5 Two Dimension of the Straight Sheds Polymer Insulators for FEM Analysis



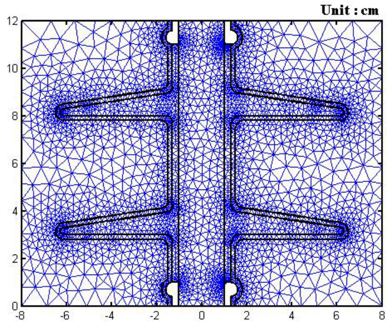
4672 nodes and 9114 elements
(a) Without Water Droplets



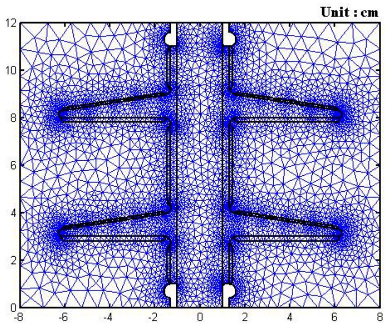
6183 nodes and 12128 elements
(b) With Uniform Water Droplets



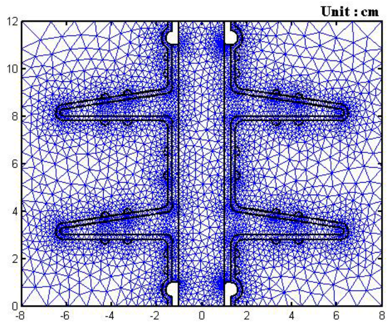
4830 nodes and 9424 elements
c) With Non - uniform Water Droplets



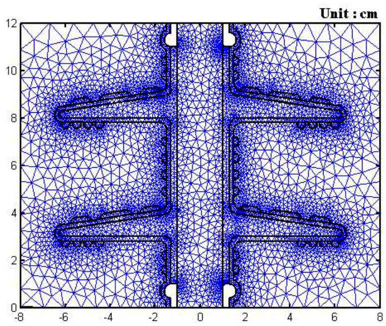
4588 nodes and 8937 elements
(d) Uniform Contaminants Without Water Droplets



4992 nodes and 9796 elements
e) Non - uniform Contaminants Without Water Droplets

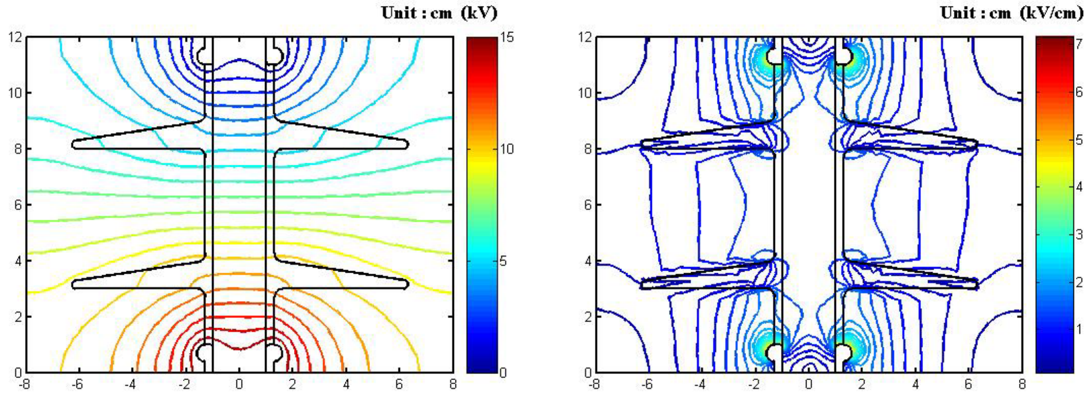


5664 nodes and 11088 elements
(f) Uniform Contaminants with Uniform Water Droplets



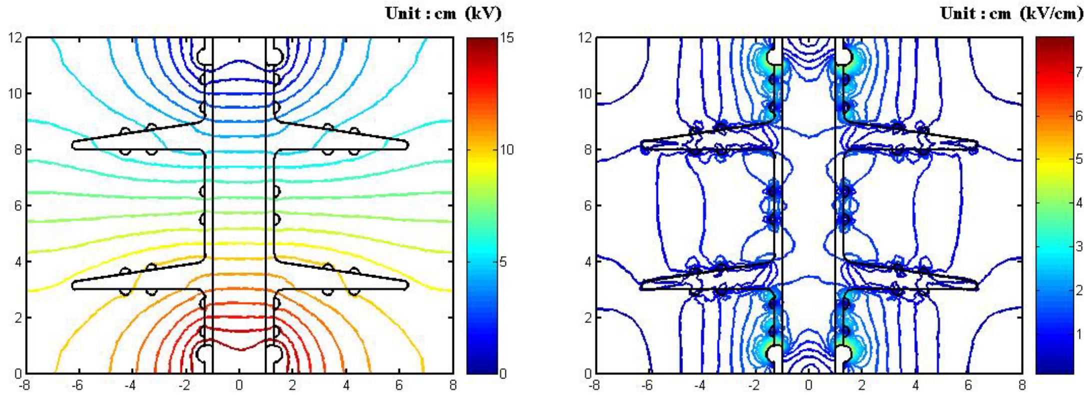
7156 nodes and 14070 elements
(g) Uniform Contaminants with Non - uniform Water Droplets

Fig. 6 Finite Element Discretization Results



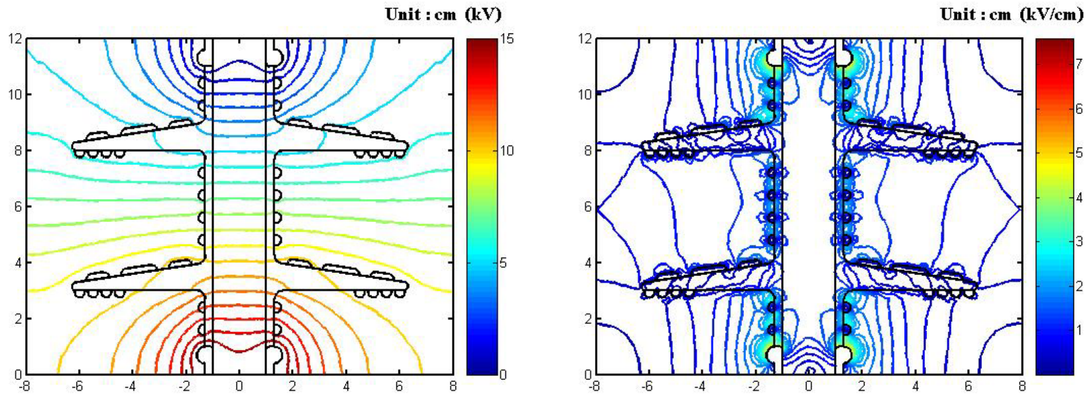
(i) Potential Distribution (ii) Electric Field Distribution

(a) Without Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

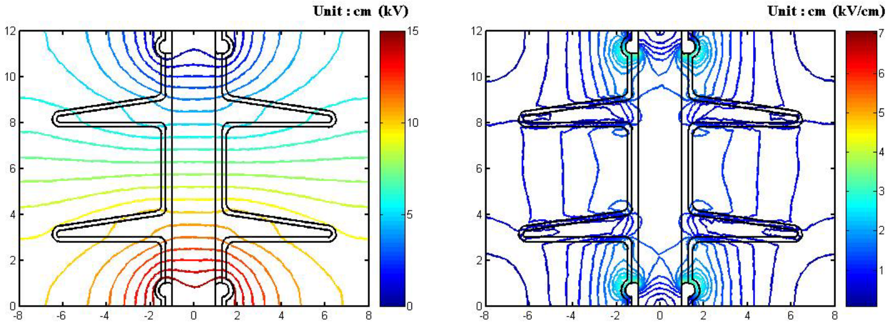
(b) With Uniform Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

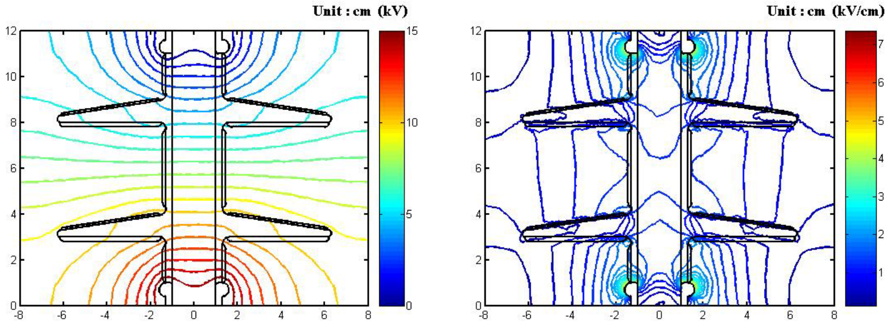
(c) With Non - uniform Water Droplets

Fig. 7 FEM Analysis Results under Clean Condition



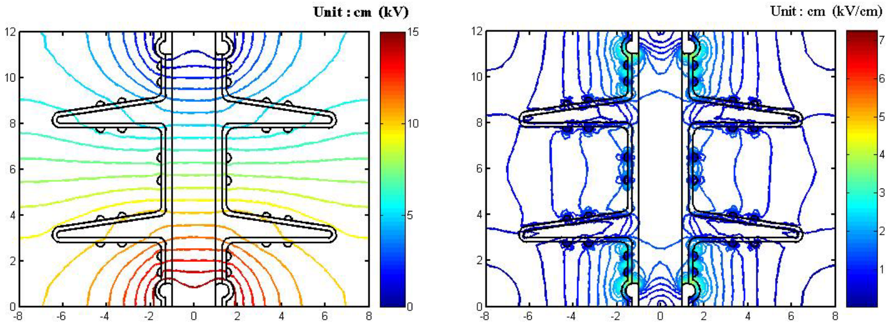
(i) Potential Distribution (ii) Electric Field Distribution

(a) Uniform Contamination and Without Water Droplets



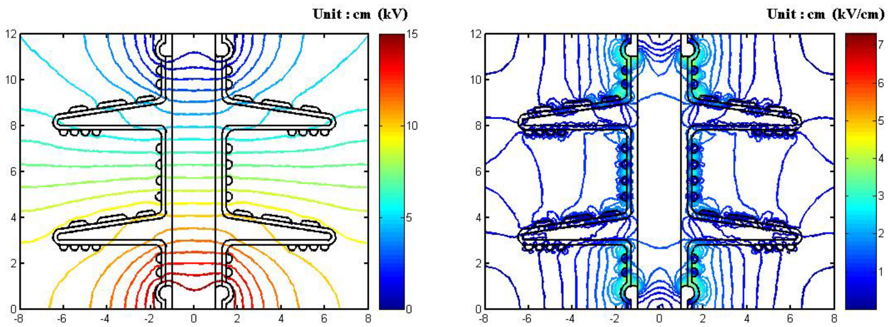
(i) Potential Distribution (ii) Electric Field Distribution

(b) Non - uniform Contamination and Without Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

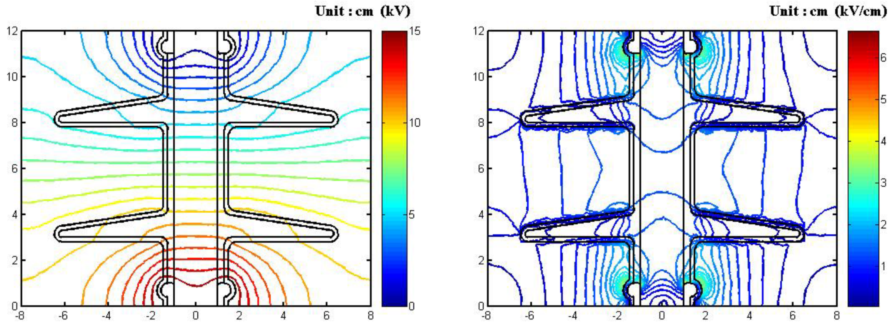
(c) Uniform Contamination and With Uniform Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

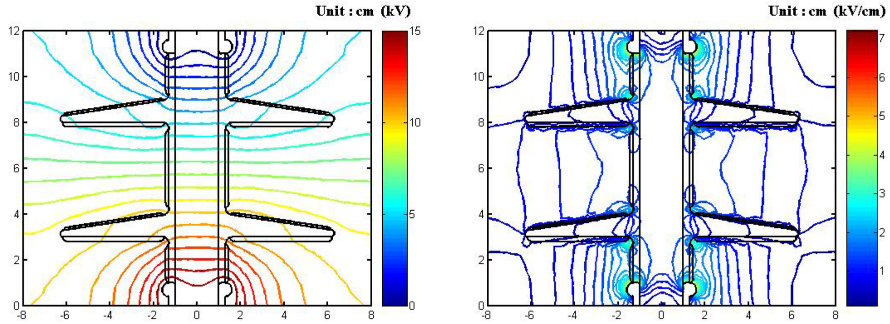
(d) Uniform Contamination and With Non - uniform Water Droplets

Fig. 8 FEM Analysis Results under Plywood Dust Contaminated Condition



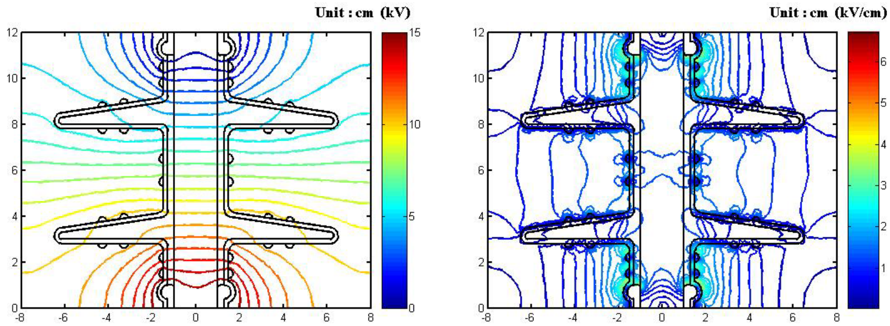
(i) Potential Distribution (ii) Electric Field Distribution

(a) Uniform Contamination and Without Water Droplets



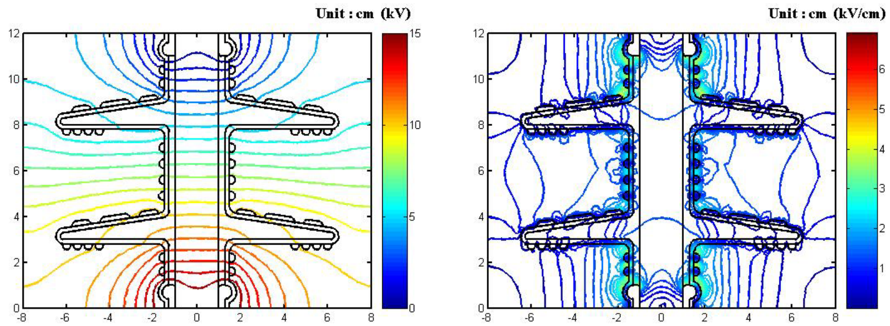
(i) Potential Distribution (ii) Electric Field Distribution

(b) Non - uniform Contamination and Without Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

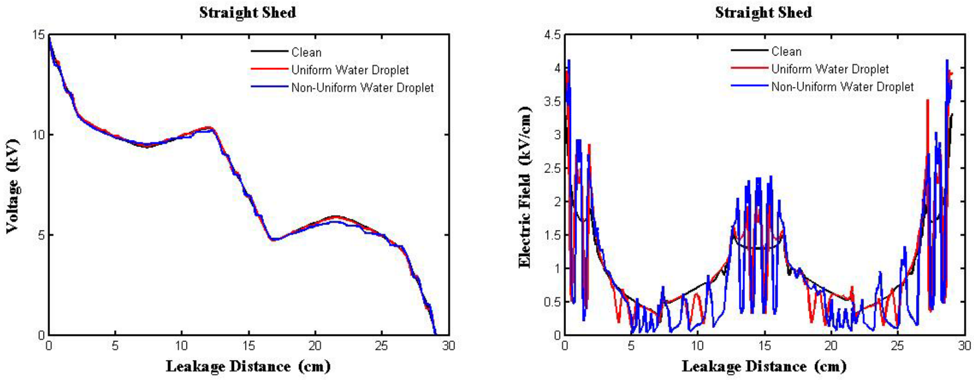
(c) Uniform Contamination and With Uniform Water Droplets



(i) Potential Distribution (ii) Electric Field Distribution

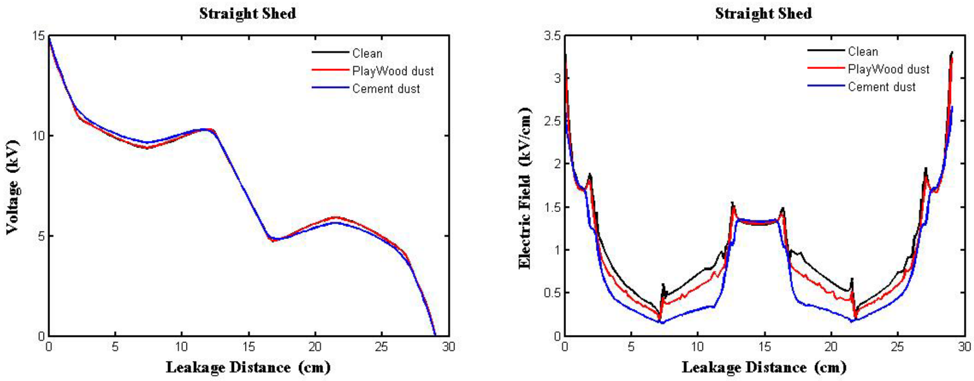
(c) Uniform Contamination and With Uniform Water Droplets

Fig. 9 FEM Analysis Results under Cement Dust Contaminated Condition



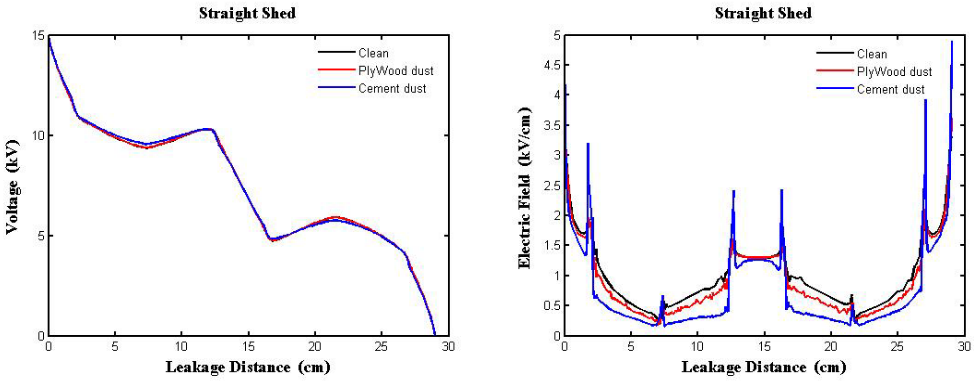
(a) Comparison of Potential Distributions (b) Comparison of Electric Field Distributions

Fig. 10 Under Clean Condition with and without Water Droplets



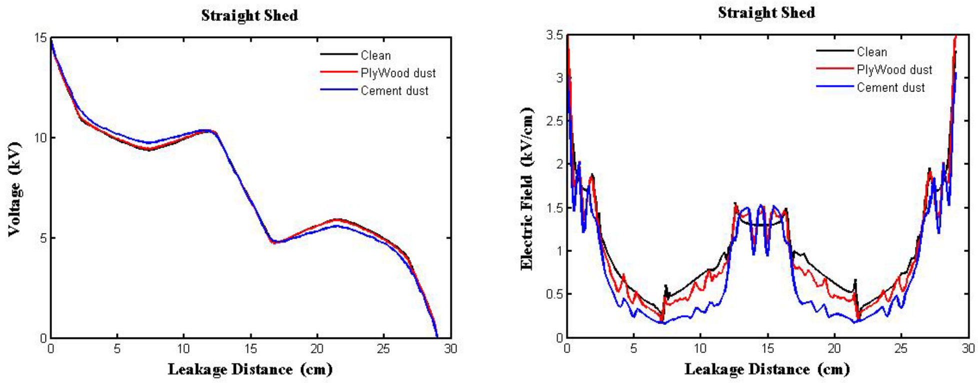
(a) Comparison of Potential Distributions (b) Comparison of Electric Field Distributions

Fig. 11 Under Uniform Contamination Conditions without Water Droplets



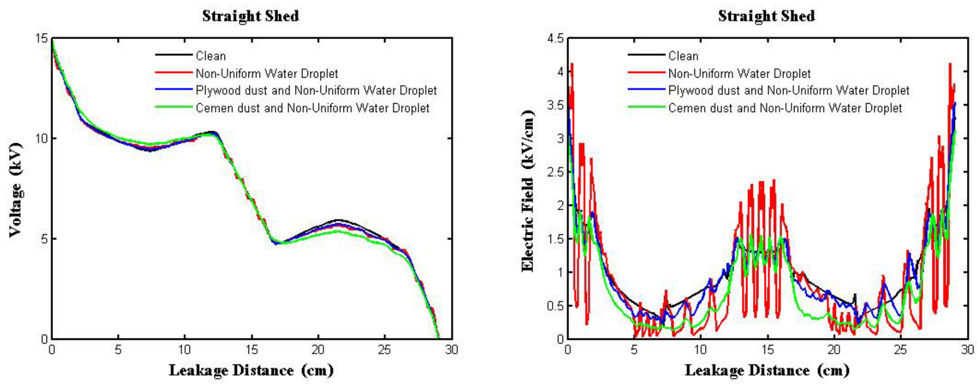
(a) Comparison of Potential Distributions (b) Comparison of Electric Field Distributions

Fig. 12 Under Non - uniform Conditions without Water Droplets



(a) Comparison of Potential Distributions (b) Comparison of Electric Field Distributions

Fig. 13 Under Uniform Contamination Conditions with Uniform Water Droplets



(a) Comparison of Potential Distributions (b) Comparison of Electric Field Distributions

Fig. 14 Under Uniform Contamination Conditions with Non - uniform Water Droplets

In case of cement dust contaminated condition, water droplets have no effect on potential distribution along the insulator surface, as illustrated in Fig. 9. No obvious difference in potential distribution can be seen. In contrast, in case of electric field distribution, significant difference in electric field distribution can be seen. Electric field intensity increased with a number of water droplet especially on the trunk portion between sheds as that of playwood dust contaminated condition.

As illustrated in Fig. 10, comparison of potential distributions in Fig. 10 (a) show that water droplets, uniform and non – uniform, have no effect on potential distribution along the insulator surface. No difference in potential distribution can be seen. While, comparison of electric field distributions in Fig. 10 (b) show that water droplets, uniform and non – uniform, have obviously effect on electric field distribution along the polymer insulator surface. As illustrated in Fig. 10 (b), water droplets cause higher magnitude of electric field on trunk surface comparing with that of shed surface of the polymer insulator. In case of uniform and uniform water droplets, no significant in magnitude of electric field on shed surface can be seen when comparing with that of clean surface. Obvious difference in magnitude of electric field can be seen on trunk surface between sheds of the polymer insulator. High magnitude of electric field on such portion may caused by a number of water droplets.

In case of uniform contaminant without water droplets, comparison results illustrated in Fig. 11 show that dry contaminants have no effect on potential and electric field distributions along the insulator surface when comparing with that of clean condition. No obvious difference in potential and electric field distributions among two cases of contaminants can be seen.

In case of non-uniform contaminant without water droplets, comparison results illustrated in Fig. 12 show that dry contaminants have no effect on potential distribution along the insulator surface. Difference in electric field magnitude among two cases of contamination can be seen. Higher magnitude of electric field can be seen in case of non – uniform cement dust contaminated condition.

Comparison results illustrated in Fig. 13 show that uniform contaminants with uniform water droplets have no effect on potential distribution along the insulator surface when comparing with that of clean condition. No obvious difference in electric field distribution among two cases of contaminants can be seen. The simulation results confirmed the electrical performance of polymer insulator under contamination conditions.

Comparison results illustrated in Fig. 14 show that uniform contaminants with non-uniform water droplets have no effect on potential distribution along the insulator surface when comparing with that of clean condition. However, obvious difference in electric field distributions among two cases of contaminants and clean surface with non-uniform water droplet can be seen. Highest magnitude of electric field distribution occurred in case of clean surface with non-uniform water droplets on the trunk portion surface. In practice, however, clean surface with water droplets on the polymer insulator surface may not be found in outdoor applications due to its hydrophobic property.

V. Conclusion

In this paper, electric field and potential distributions on straight sheds silicone rubber polymer insulators under clean and various contamination conditions were investigated by using FEM. As results, contaminants and water droplets have no effect on potential distribution along the polymer insulator surface. However, for electric field distribution they caused highly non–uniform electric field distributions especially on the trunk portion. Also, dry contaminants have no effect on electric field distribution when comparing with that of clean conditions. Water droplets caused higher magnitude of electric field on the trunk portion surface than the shed surface. The simulation results confirmed good electrical performance under contamination conditions.

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