Comparison of Electric Field and Potential Distributions on Silicone Rubber Polymer Insulators under Clean and Various Contamination Conditions Using Finite Element Method

WINAI ONCHANTUEK, BOONRUANG MARUNGSRI* and ANANT OONSIVILAI
Alternative and Sustainable Energy Research Unit, Power and Control Research Group
School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology
Muang District, Nakhon Ratchasima, 30000, THAILAND

THANATCHAI KULWORAWANICHPONG
Power System Research Unit, Power and Control Research Group
School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology
Muang District, Nakhon Ratchasima, 30000, THAILAND

*Corresponding author: bmshvee@sut.ac.th

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. Alternate sheds silicone rubber polymer insulator having leakage distance 290 mm was used in this study. Two type of contaminants, plywood and cement dusts, have been studied the effect of contamination conditions on the insulator surface. The objective of this work is to comparison the effect of contamination conditions 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 of potential distribution on the insulator surface while electric field distributions are obviously depended on contamination conditions. Water droplets caused higher magnitude of electric field on the trunk portion surface than the shed surface. The simulation results confirmed electrical performance of polymer insulators under contamination conditions.

Key-Words : - Electric field distribution, potential distribution, silicone rubber polymer insulator, alternate shed, clean condition, contamination condition, water droplet, plywood dust, cement dust, finite element method

1 Introduction

Recently, polymer insulators are used increasingly for outdoor applications due to their better characteristics over porcelain and glass types. Polymer insulators give better contamination performance due to surface hydrophobicity, lighter weight, possess higher impact strength, and so on. Electrical properties of polymer insulators under contamination conditions have been widely investigated[1-8].

Polymer insulators are quite different from the conventional porcelain and glass insulators. The advantages of silicone rubber polymer insulators are as follows[9]:

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 [9] .

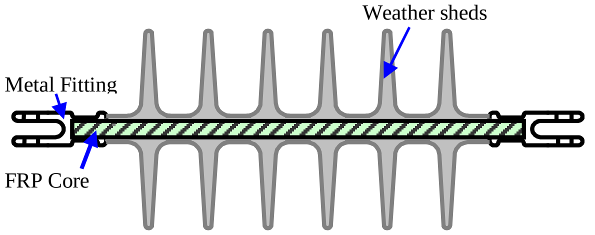


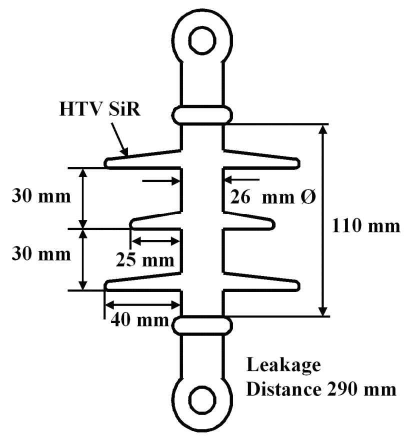
Fig. 1 Structure of a Polymer Insulator

Salt fog ageing test have been conducted on specimens having different configurations but having the same leakage distance and made of the same material by Marungsri et. al [10]. Difference in degree of surface ageing on tested specimens was obviously obtained. Slightly surface ageing was observed on the polymer insulator having alternate shed comparing the polymer insulator having straight shed. Full results and discussion are found in [9,10]. The authors in [10] supposed the effect of electric field distributions. In order to elucidate the effect of electric field distributions on silicone rubber polymer insulators under contamination conditions, electric field and potential distributions have been simulated using Finite Element Method[11]. The simulation results show that higher electric field distribution on the trunk between sheds can be seen significantly when comparing with that of the shed of the two type specimens under contamination condition. High magnitude of electric field can be seen on the trunk between sheds of the straight shed specimen.

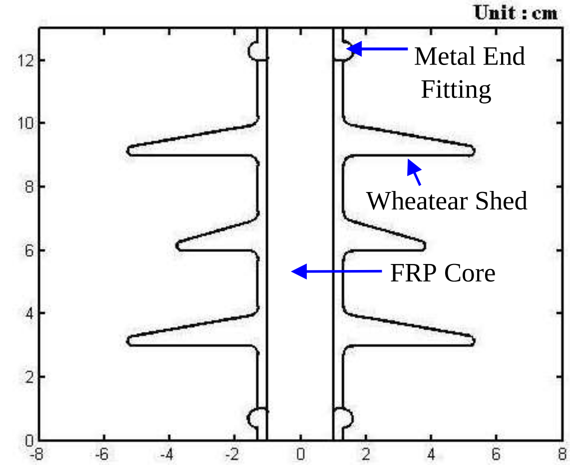
In this paper, electric field and potential distributions along surface of alternate sheds silicone rubber polymer insulators under clean and various contamination conditions with and without water droplets were simulated using Finite Element Method.

2 Problem Formulation

An alternate shed polymer insulator was 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 was prepared by molding HTV SiR onto the FRP rods. Molding lines or parting lines were found on the insulator-surface. Configuration of alternate shed polymer insulator illustrates in Fig. 2 (a). As described in [10], the polymer insulator was subjected to AC voltage 15 kV during 50 cycles of salt fog ageing test. In this study, the lower electrode of a polymer insulator was energized by a 15 kV Ac supply in order to simulate potential and electric field distributions along the polymer insulator surface using Finite Element Method. Two dimensions model for simulation illustrates in Fig. 2 (b). Two cases, Clean and contamination conditions, with and without water droplets were studied. Contaminants are plywood and cement dusts.



(a) Configuration



(b) Two dimension configuration for Simulation

Fig. 2 Alternate Shed Polymer Insulator

3 Problem Solution

3.1 Equations for 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.

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

3.2 Equations for 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 engineering problems, e.g. electric and magnetic field analyses, mechanical and thermal analyses, since the late 1970s [13–16]. Supposing that the domain under consideration does not contain any space and surface charges, two-dimensional functional $F(u)$ in Cartesian system of coordinates can be form as follows[17]:

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

where ε_x and ε_y are *x*- and *y*-components of dielectric constant in 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 rewritten as

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

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

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

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

Inside each sub-domain *De*, 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 function $F(u)$, that is,

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

where n_p stands for the total number of knots in the network.

Then a compact matrix expression is

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

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

3.3 Implementation for FEM analysis

In this study, a polymer insulator model 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 of 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. 3 (a).

In order to study the effect of water droplets on the insulator surface under clean condition, four cases of water droplets, as shown in Fig. 3 (b) to Fig. 3 (e), are 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 six cases of contamination as shown in Fig. 4 (a) to Fig. 4 (f). Plywood and cement dusts used in this simulation were characterized by 1.5 and 8.0 of relative dielectric constants, respectively.

The whole problem domain in Fig. 3 and Fig. 4 are fictitiously divided into small triangular areas called *domain*. The potentials, which were unknown throughout the problem domain, is approximated in each of these elements in terms of the potential in their vertices called *nodes*. Details of Finite Element discretization are found in [18]. 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 were shown in Fig. 5 and Fig. 6, respectively.

4 Simulation Results and Discussions

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 as in Fig. 8, significantly difference in electric field distribution can be seen even clean surface. In addition, electric field intensity increased with a number of water droplets.

In case of plywood dust contaminated condition, water droplets have no effect on potential distribution along the insulator surface, as illustrated in Fig. 9. No significant difference in potential distribution can be seen. In contrast, in case of electric field as in Fig. 10, obvious difference in electric field distribution can be seen especially on the trunk portion. In addition, electric field intensity increased with a number of water droplets.

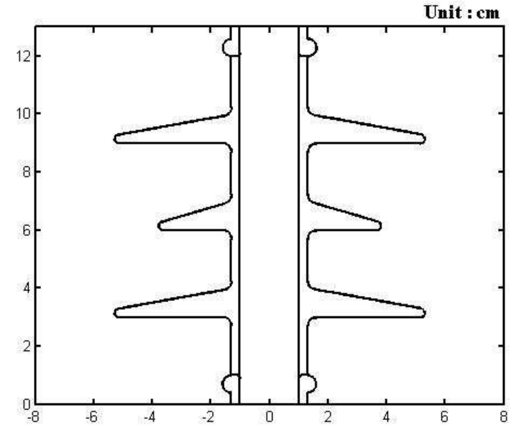
In case of cement dust contaminated condition, water droplets have no effect on potential distribution along the insulator surface, as illustrated in Fig. 11. As the first two conditions, no obvious difference in potential distribution can be seen. Also, in case of electric field as in Fig. 12, significant difference in electric field distribution can be seen especially on the trunk portion between sheds as that of plywood dust contaminated condition. In addition, electric field intensity increased with a number of water droplets.

Comparison results illustrated in Fig. 13 show that water droplets caused higher magnitude of electric field on the trunk portion between sheds when compared with that of the case without water droplets. However, water droplets have no effect on potential distribution along the insulator surface.

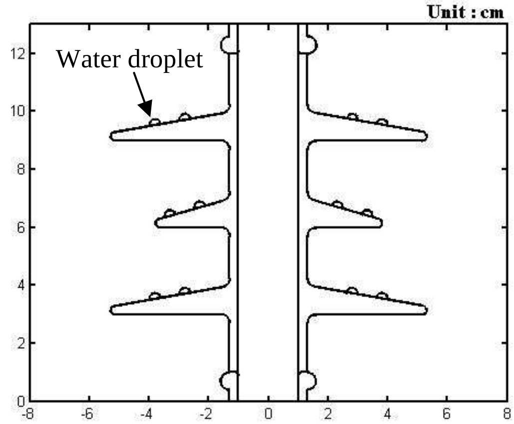
Uniform contaminant without water droplets or dry contaminant, comparison results illustrated in Fig. 14 show that dry contaminants have no effect on potential and electric field distributions along the insulator surface when comparing with that of clean condition. No obvious difference in potential and electric field distributions among two cases of contaminants can be seen.

Non-uniform contaminants without water droplets, comparison results illustrated in Fig. 15 show that dry contaminants have no effect on potential and electric field distributions along the insulator surface as that of uniform contaminant. No significant difference in potential and electric field distributions among three cases can be seen.

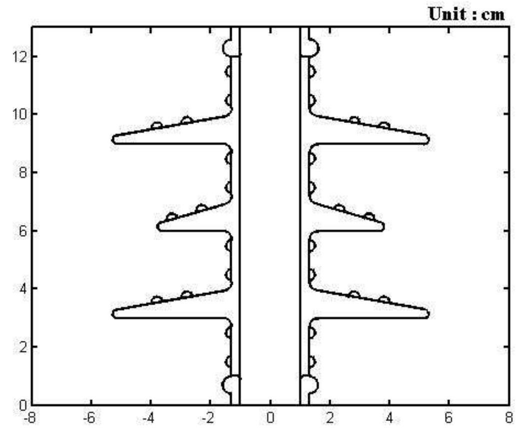
Comparison results illustrated in Fig. 16 show that uniform contaminants with uniform water droplets have no effect on potential distribution along the insulator surface when comparing with that of clean condition. No obvious difference in electric field distribution among two cases of contaminants can be seen. The simulation results confirmed the electrical performance of polymer insulator under contamination conditions.



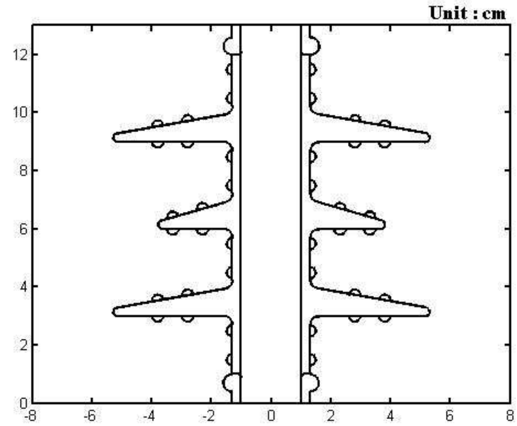
(a) Without Water Droplets



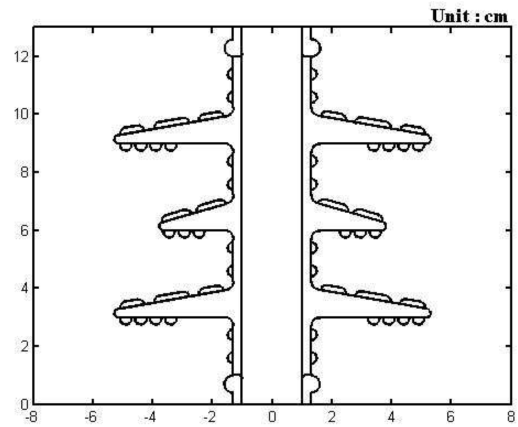
(b) With Uniform Water Droplets on Upper Surface of Shed



(c) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

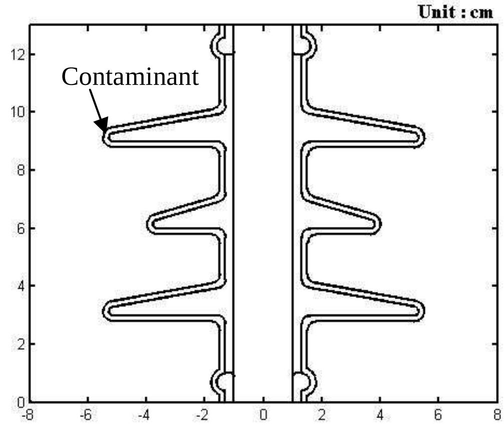


(d) With Uniform Water Droplets on Insulator Surface

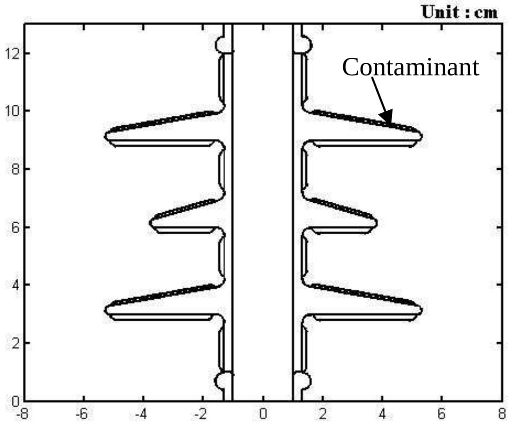


(e) With Non – uniform Water Droplets on Insulator Surface

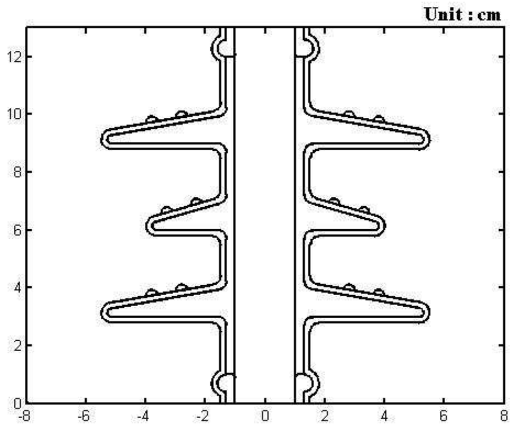
Fig. 3 Two Dimension of the Alternate Sheds Polymer Insulators for FEM Analysis



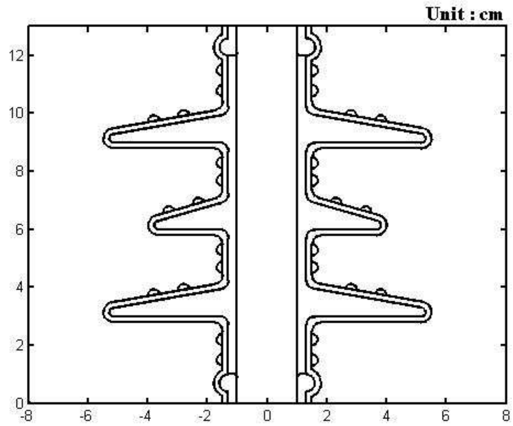
(a) Uniform Contaminant Without Water Droplets



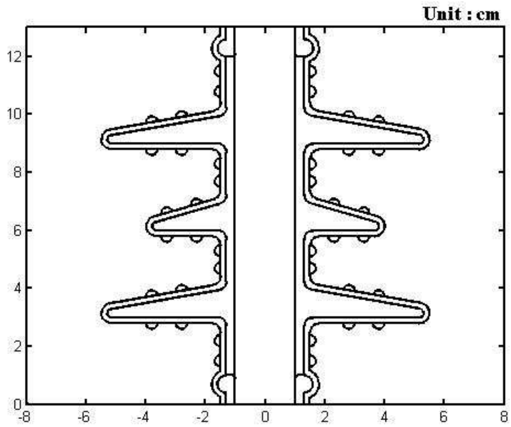
(b) Non - uniform Contaminant Without Water Droplets



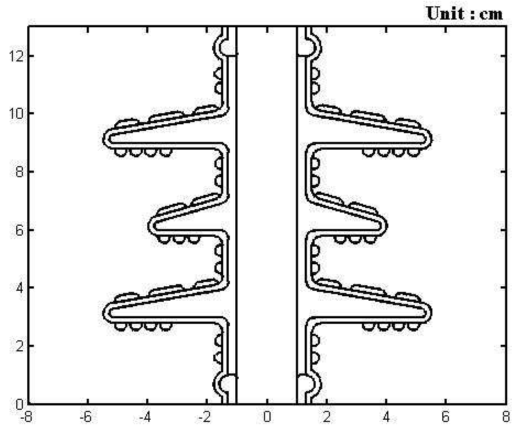
(c) With Uniform Water Droplets on Upper Surface of Shed Surface



(d) With Uniform Water Droplets on Upper of shed and Trunk Surface

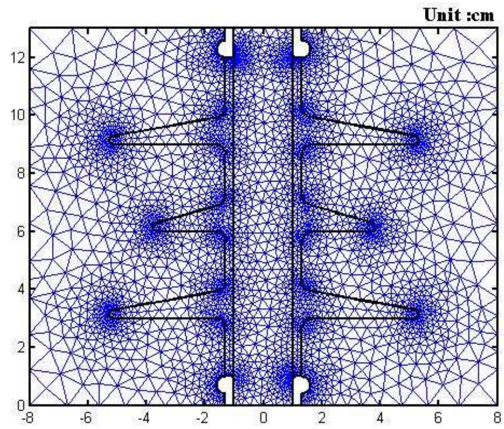


(e) With Uniform Water Droplets on Insulator Surface



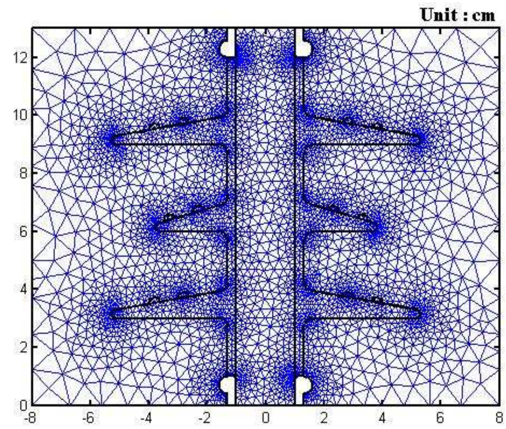
(f) With Non – uniform Water Droplet

Fig. 4 Two Dimension of the Alternate Sheds Polymer Insulator under Contamination Condition on the surface for FEM Analysis



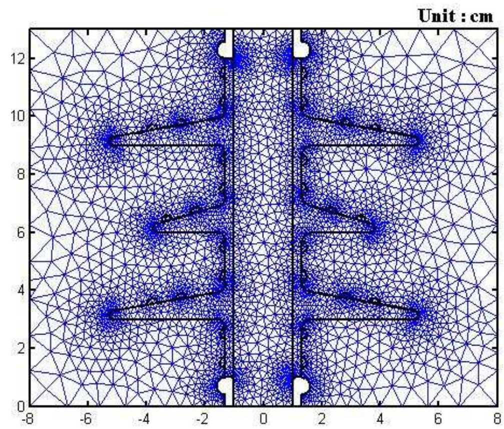
3869 nodes and 7499 elements

(a) Without Water Droplets

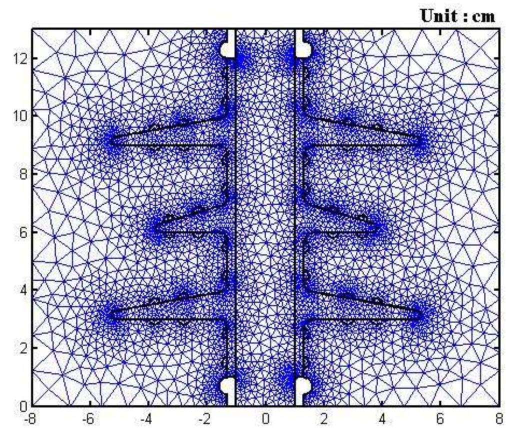


5338 nodes and 10446 elements

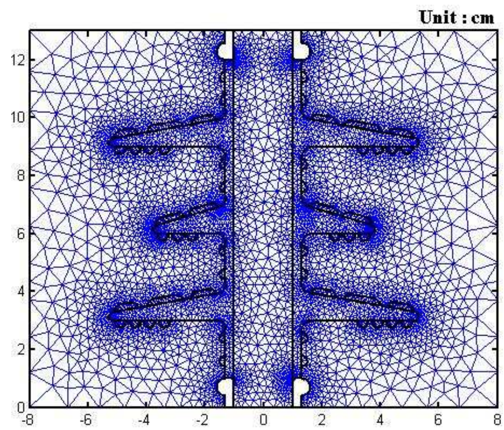
(b) With Uniform Water Droplets on Upper Surface of Shed



5654 nodes and 11078 elements
(c) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

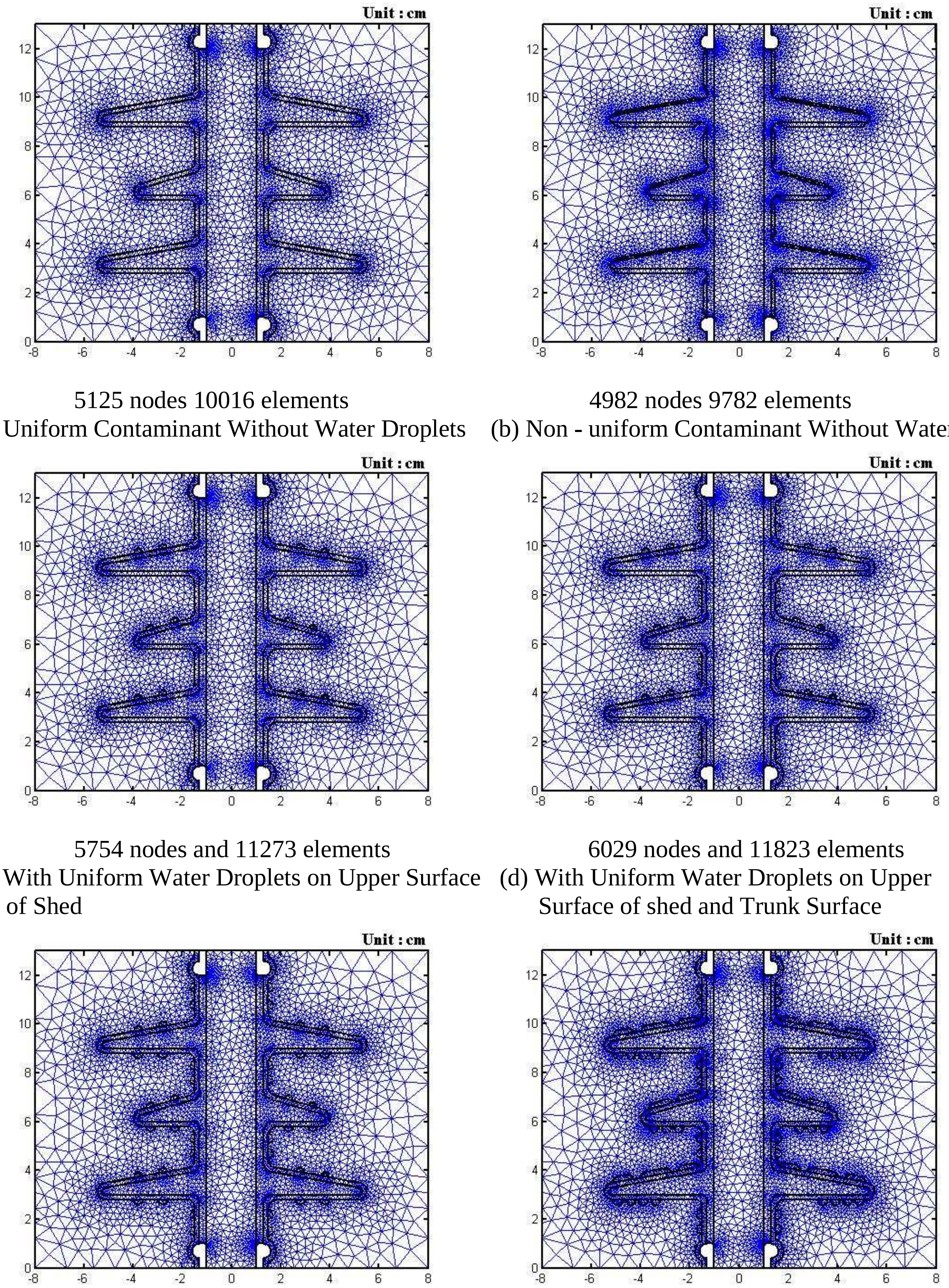


5898 nodes and 11566 elements
(d) With Uniform Water Droplets on Insulator Surface



5245 nodes and 10308 elements
(e) With Non – uniform Water Droplet

Fig. 5 Finite Element Discretization Results for Clean Condition



5125 nodes 10016 elements
(a) Uniform Contaminant Without Water Droplets

4982 nodes 9782 elements
(b) Non - uniform Contaminant Without Water Droplets

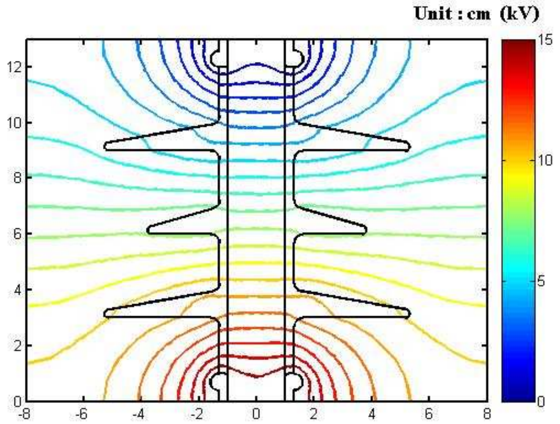
5754 nodes and 11273 elements
(c) With Uniform Water Droplets on Upper Surface of Shed

6029 nodes and 11823 elements
(d) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

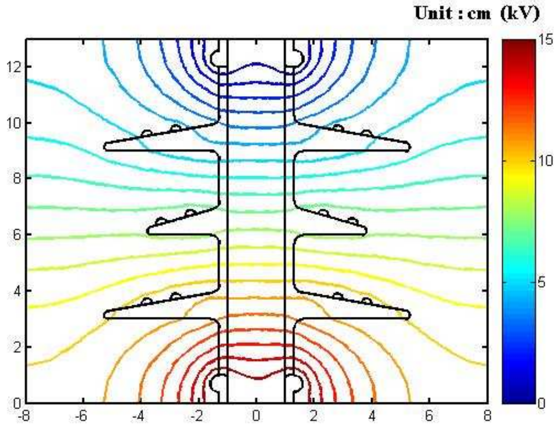
6327 nodes and 12419 elements
(e) With Uniform Water Droplets on Insulator Surface

4756 nodes and 9341 elements
(f) With Non – uniform Water Droplet

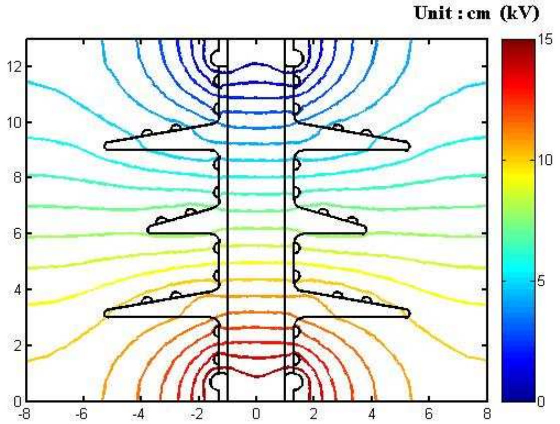
Fig. 6 Finite Element Discretization Results for Contamination Condition



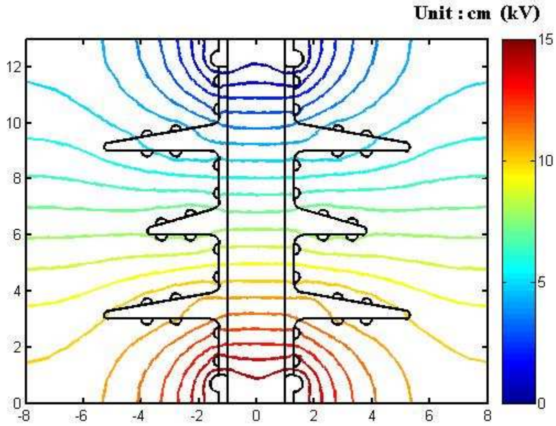
(a) Without Water Droplets



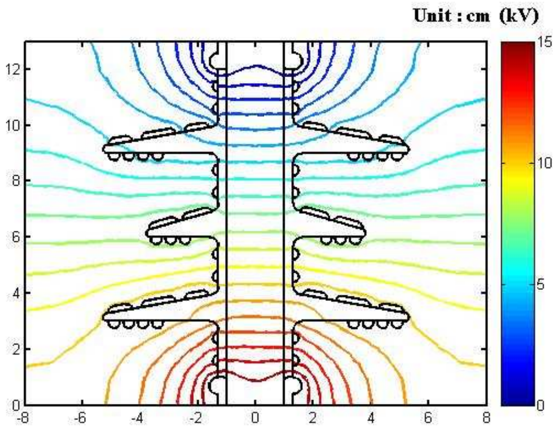
(b) With Uniform Water Droplets on Upper Surface of Shed



(c) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

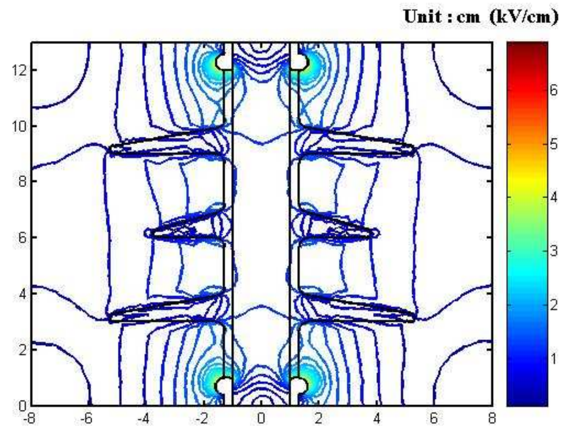


(d) With Uniform Water Droplets on Insulator Surface

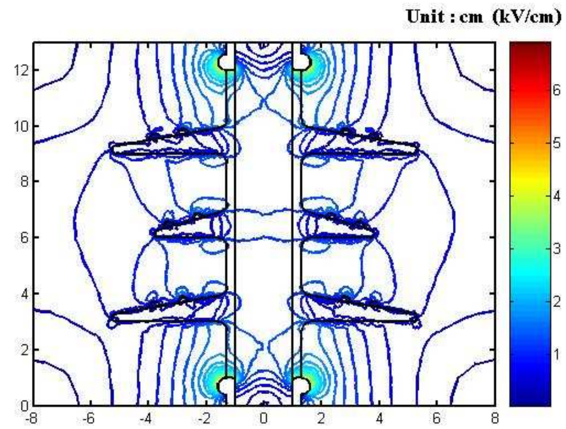


(e) With Non – uniform Water Droplets on Insulator Surface

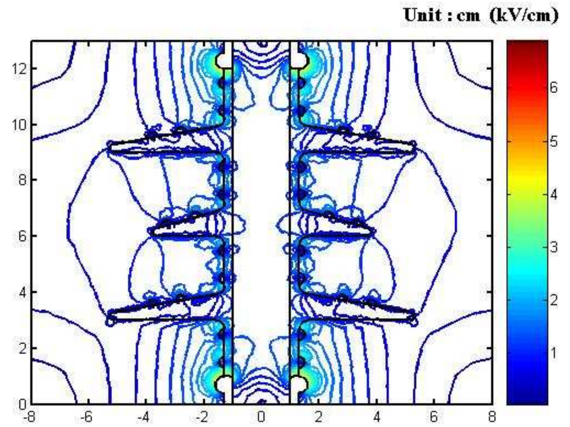
Fig. 7 Potential Distribution under Clean Condition



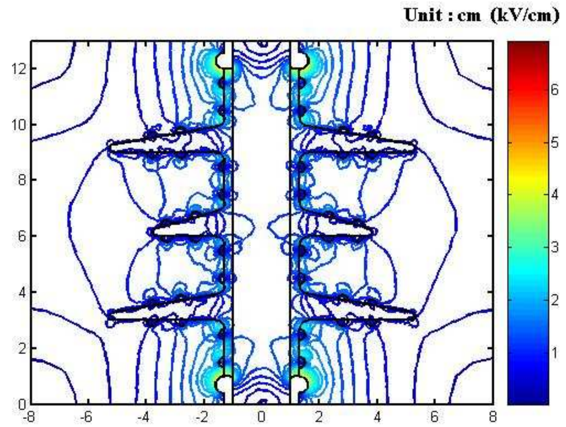
(a) Without Water Droplets



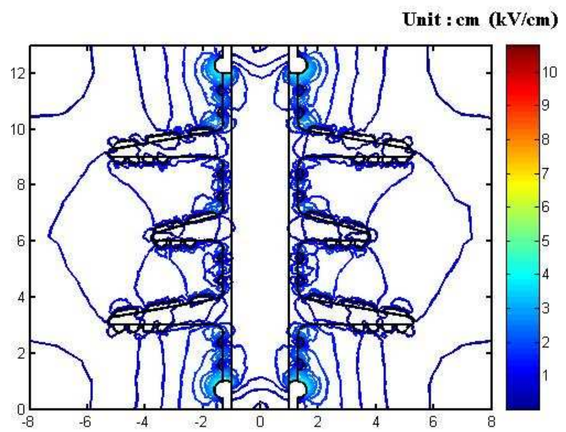
(b) With Uniform Water Droplets on Upper Surface of Shed



(c) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

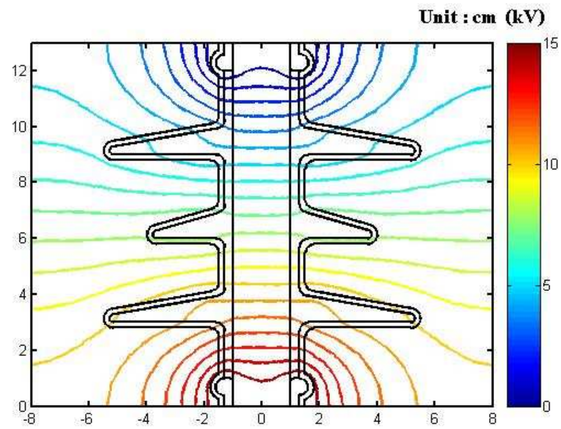


(d) With Uniform Water Droplets on Insulator Surface

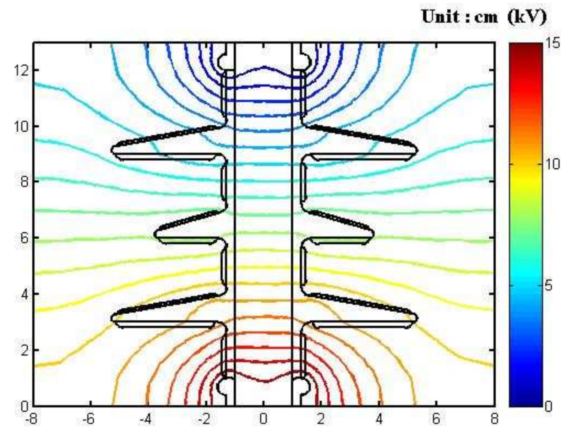


(e) With Non – uniform Water Droplets on Insulator Surface

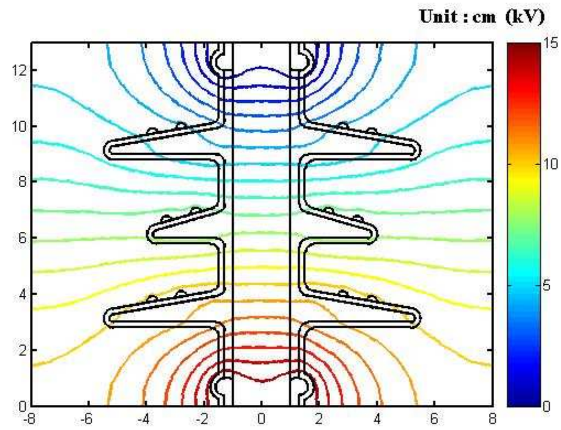
Fig. 8 Electric Field Distribution under Clean Condition



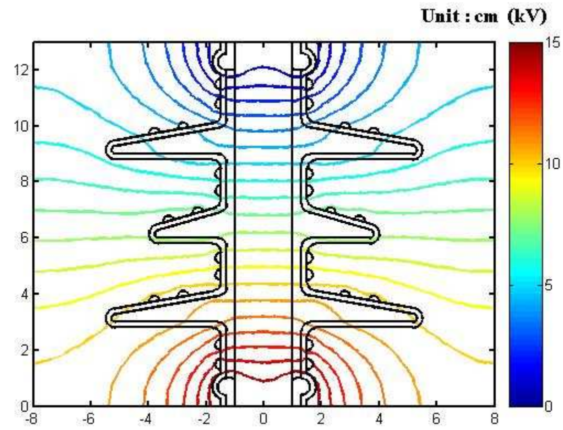
(a) Uniform Contaminant Without Water Droplets



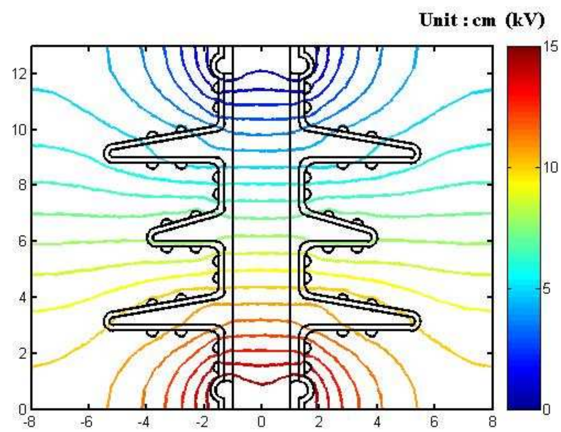
(b) Non - uniform Contaminant Without Water Droplets



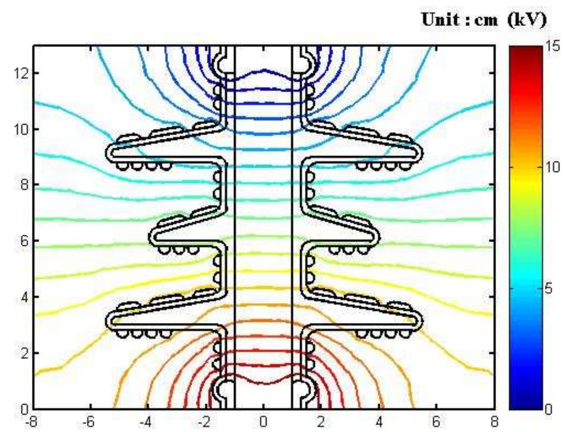
(c) With Uniform Water Droplets on Upper Surface of shed



(d) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

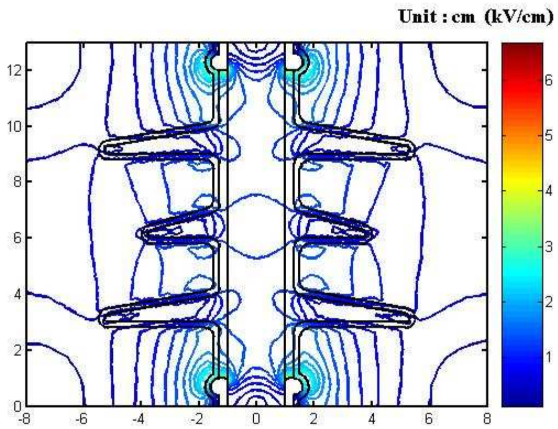


(e) With Uniform Water Droplets

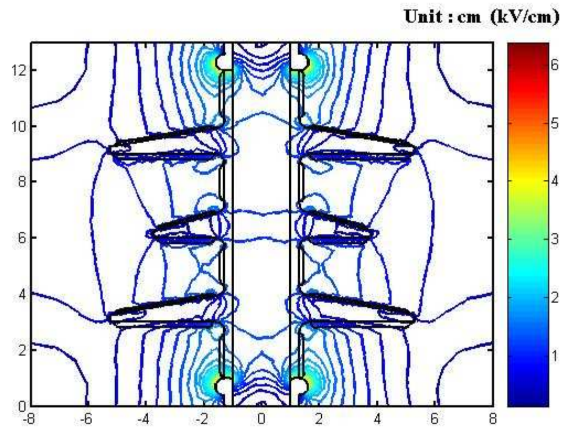


(f) With Non – uniform Water Droplets

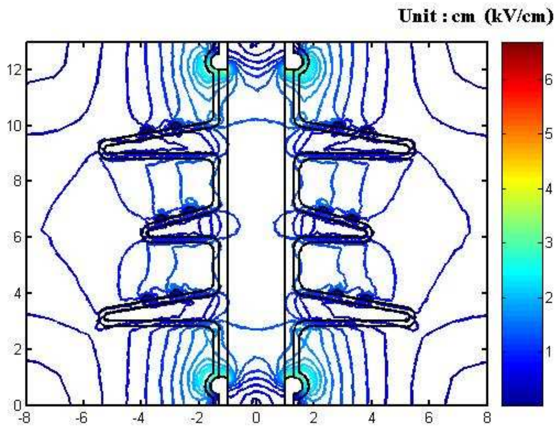
Fig. 9 Potential Distribution under Plywood dust Contaminated Condition



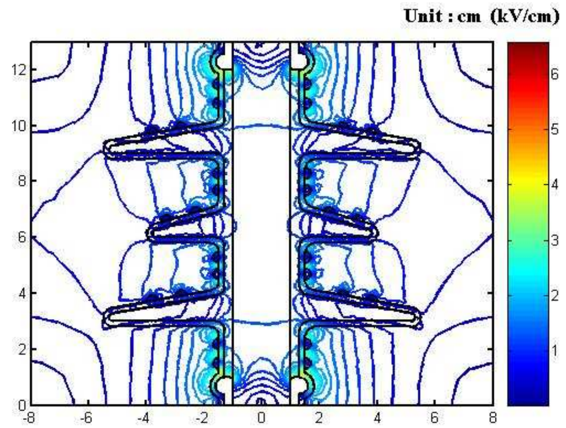
(a) Uniform Contaminant Without Water Droplets



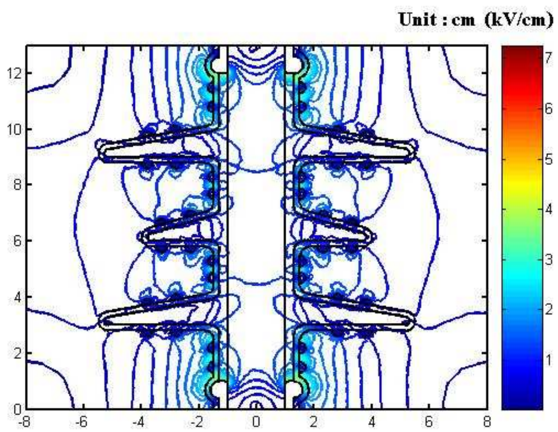
(b) Non - uniform Contaminant Without Water Droplets



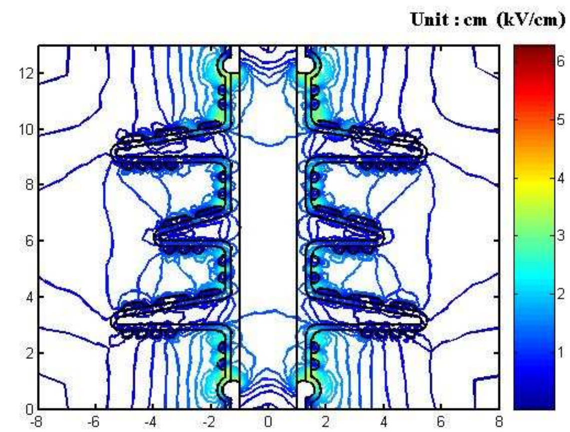
(c) With Uniform Water Droplets on Upper Surface of shed



(d) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

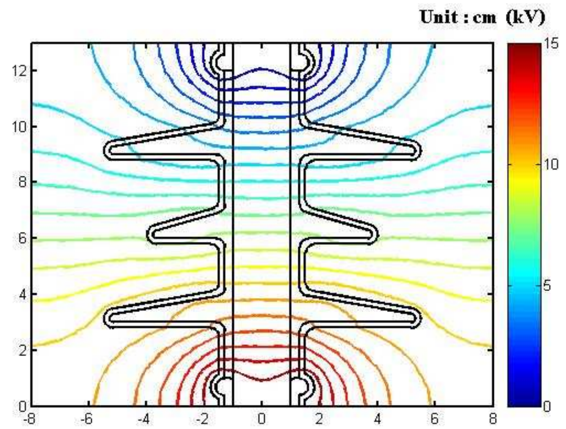


(e) With Uniform Water Droplets

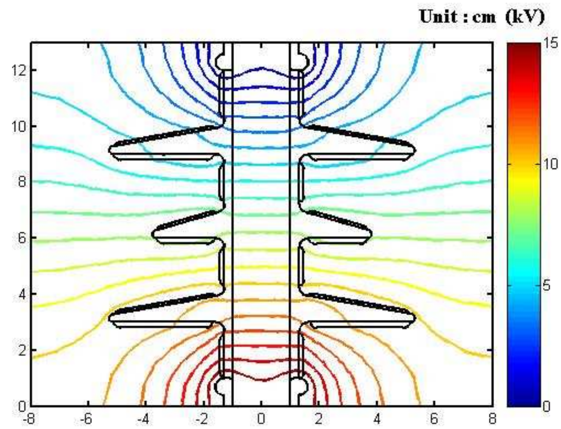


(f) With Non – uniform Water Droplets

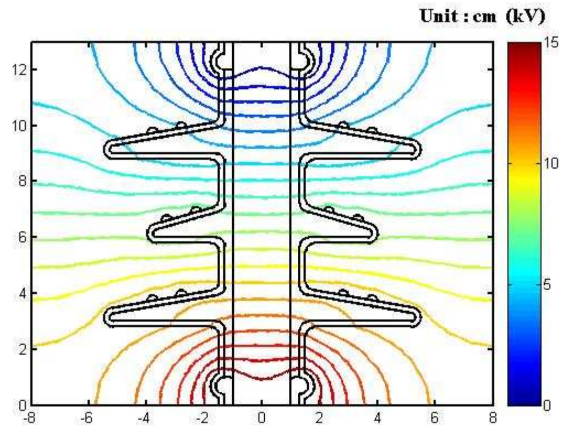
Fig. 10 Electric Field Distribution under Plywood dust Contaminated Condition



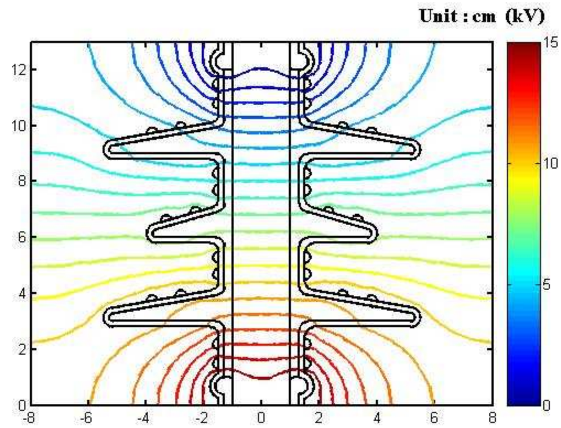
(a) Uniform Contaminant Without Water Droplets



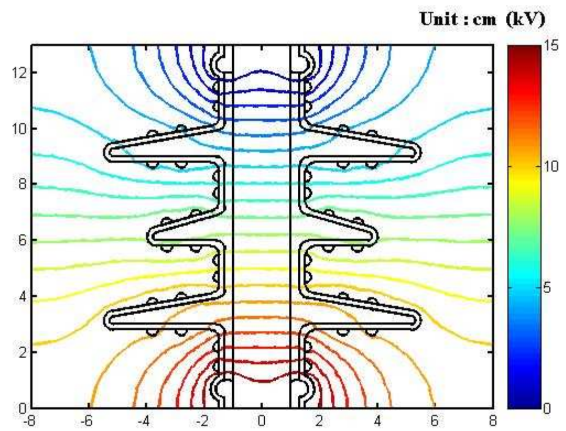
(b) Non - uniform Contaminant Without Water Droplets



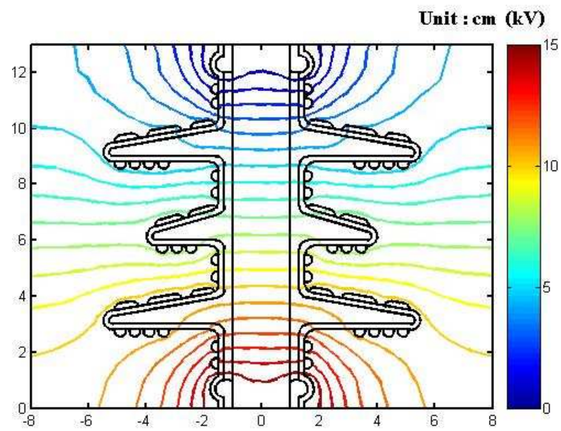
(c) With Uniform Water Droplets on Upper Surface of shed



(d) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

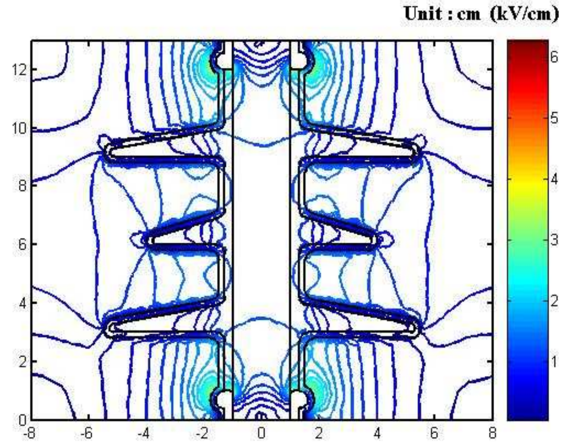


(e) With Uniform Water Droplets

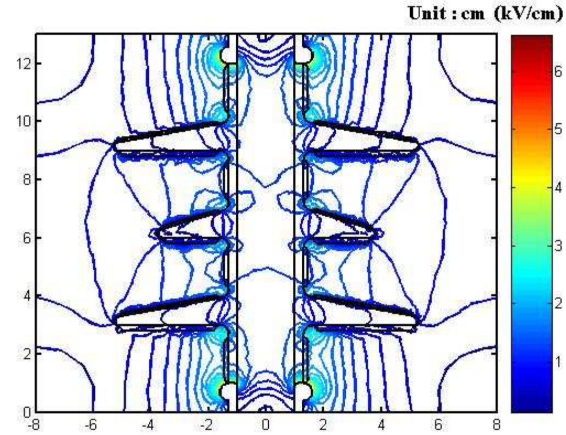


(f) With Non – uniform Water Droplets

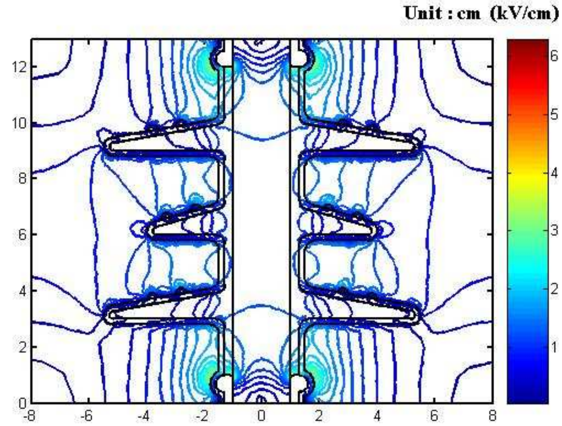
Fig. 11 Potential Distribution under Cement dust Contaminated Condition



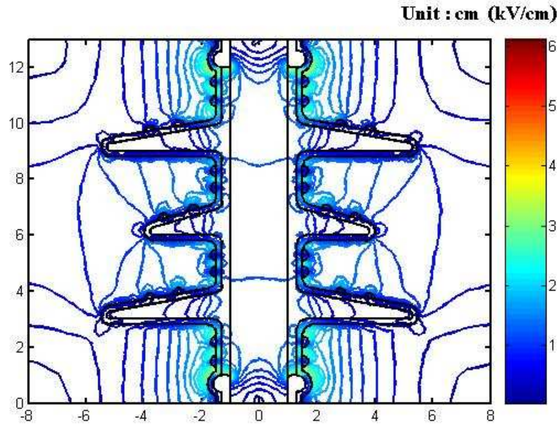
(a) Uniform Contaminant Without Water Droplets



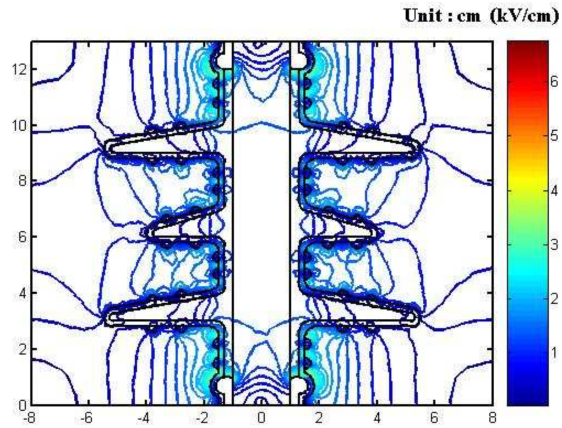
(b) Non - uniform Contaminant Without Water Droplets



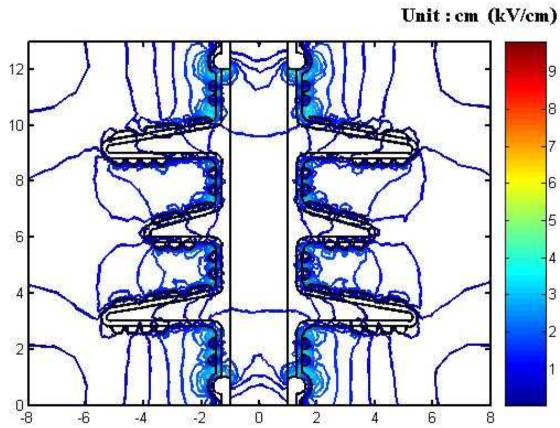
(c) With Uniform Water Droplets on Upper Surface of shed



(d) With Uniform Water Droplets on Upper Surface of shed and Trunk Surface

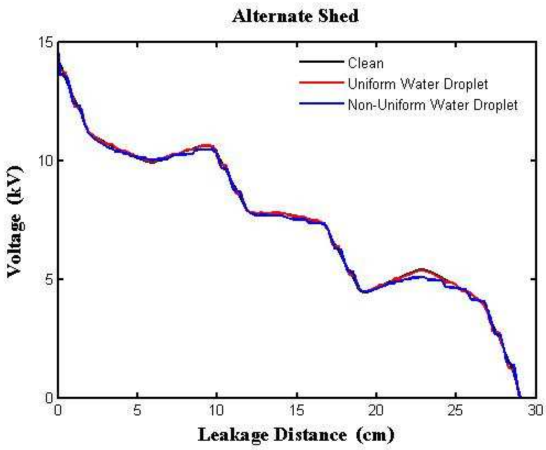


(e) With Uniform Water Droplets

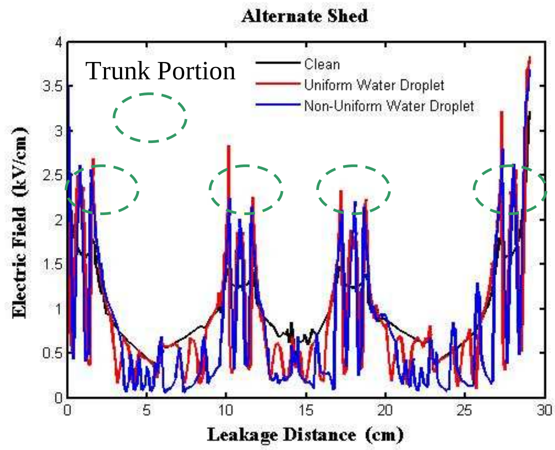


(f) With Non – uniform Water Droplets

Fig. 12 Electric Field Distribution under Cement dust Contaminated Condition

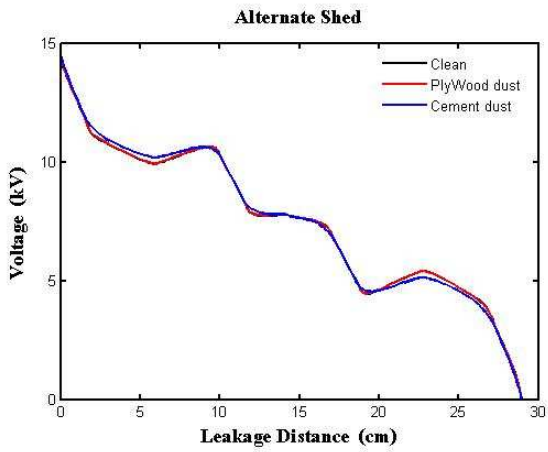


(a) Comparison of Potential Distributions

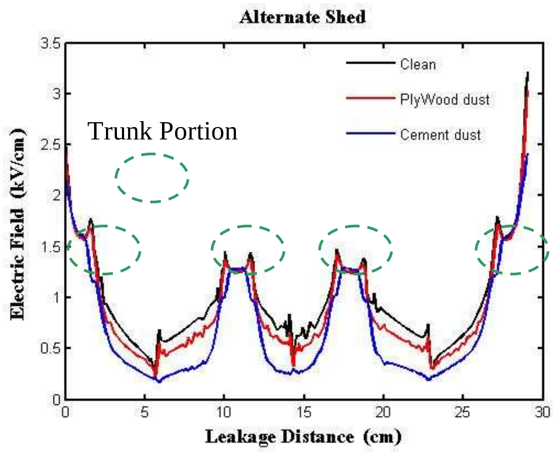


(b) Comparison of Electric Field Distributions

Fig. 13 Clean Condition

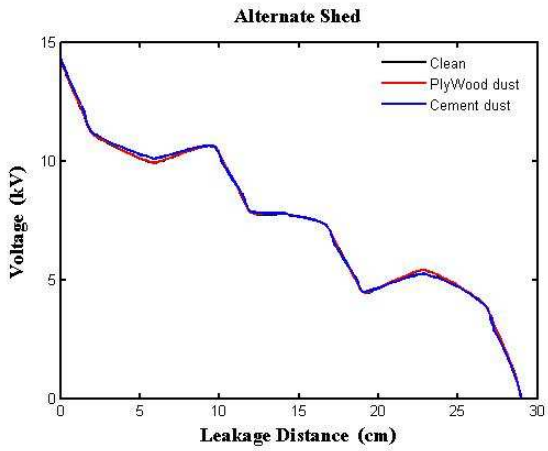


(a) Comparison of Potential Distributions

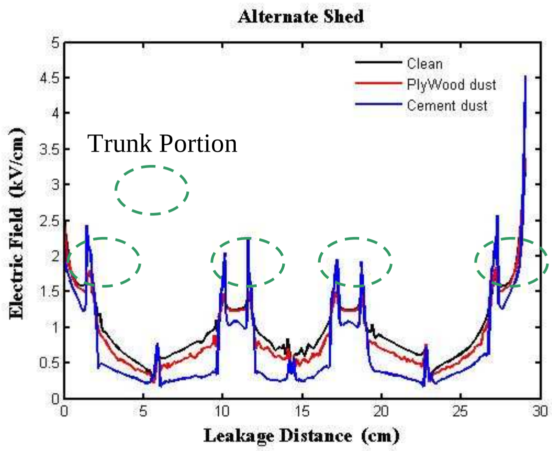


(b) Comparison of Electric Field Distribution

Fig. 14 Uniform Contamination

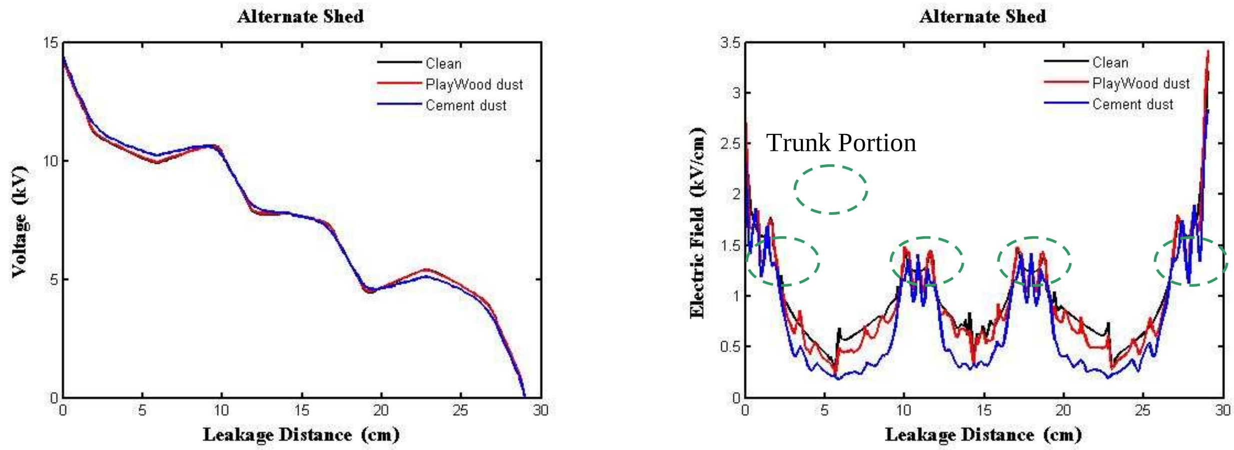


(a) Comparison of Potential Distributions



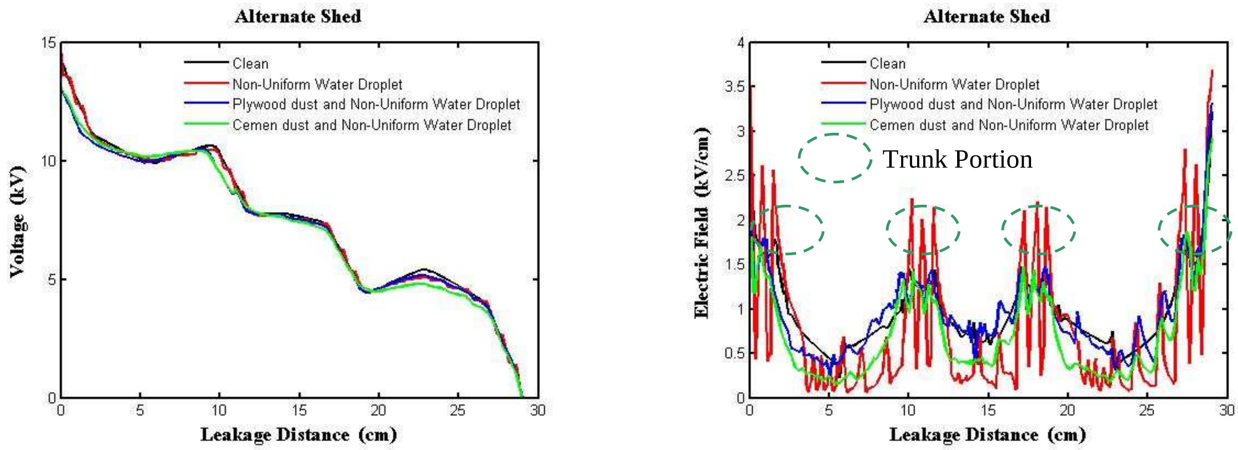
(b) Comparison of Electric Field Distribution

Fig. 15 Non - uniform Contamination



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

Fig. 16 Uniform Contamination and Uniform Water droplets



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

Fig. 17 Uniform Contamination and Non-uniform Water droplets

Comparison results illustrated in Fig. 17 show that uniform contaminants with non-uniform water droplets have no effect on potential distribution along the insulator surface when comparing with clean condition. However, obvious difference in electric field distributions among two cases of contaminants and clean surface with non- uniform water droplets 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 occurred in outdoor applications due to its hydrophobic property.

5 Conclusion

In this paper, electric field and potential distributions on silicone rubber polymer insulators under various contamination conditions were investigated by 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 field distribution. Also, dry contamination conditions have no effect on electric field distribution when comparing with that of clean condition. Water droplets caused higher magnitude of electric field on the trunk portion surface than the shed surface. The simulation results confirmed good electrical performance of polymer insulators under contamination conditions.

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