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, plywood 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.

However, since polymer insulators are made of organic materials, deterioration through ageing is unavoidable. Hence,
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: Al₂O₃·3H₂O) 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 field distribution along the specimen having straight shed higher than the specimen having alternated sheds.

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]:

\[ \mathbf{E} = -\nabla \mathbf{V} \]  

From Maxwell’s equation

\[ \nabla \cdot \mathbf{E} = \nabla \left( -\nabla \mathbf{V} \right) = \frac{\rho}{\varepsilon} \]  

where \( \rho \) is resistivity \( \Omega/m \), 
\( \varepsilon \) is material dielectric constant \( (\varepsilon = \varepsilon_0 \varepsilon_r) \) 
\( \varepsilon_0 \) is free space dielectric constant \( (8.854 \times 10^{-12} \text{ F/m}) \) 
\( \varepsilon_r \) is relative dielectric constant of dielectric material

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

\[ \varepsilon \cdot \nabla \left( -\nabla \mathbf{V} \right) = -\rho \]  

Without space charge \( \rho = 0 \), Poisson’s equation becomes Laplace’s equation.
\[ \mathbf{S} \mathbf{u} = \mathbf{T} \]

\[ \mathbf{S}_{ij} \{u_i\} = \{T_j\} \quad i, j = 1, 2, \ldots, np \quad (10) \]

where \( \mathbf{S}_{ij} \) 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). Plywood 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 \textit{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 \textit{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 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 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 plywood 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.

![Fig. 5 Two Dimension of the Straight Sheds Polymer Insulators for FEM Analysis](image)
Fig. 6 Finite Element Discretization Results

(a) Without Water Droplets
4672 nodes and 9114 elements

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

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

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

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

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

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

World Academy of Science, Engineering and Technology

International Scholarly and Scientific Research & Innovation 3(5) 2009 scholar.waset.org/1999.5/5689
Fig. 7  FEM Analysis Results under Clean Condition
(i) Potential Distribution  
(ii) Electric Field Distribution  
(a) Uniform Contamination and Without Water Droplets

(b) Non-uniform Contamination and Without Water Droplets

(c) Uniform Contamination and With Uniform Water Droplets

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

Fig. 8  FEM Analysis Results under Plywood Dust Contaminated Condition
Potential Distribution

(a) Uniform Contamination and Without Water Droplets

(b) Non-uniform Contamination and Without Water Droplets

(c) Uniform Contamination and With Uniform Water Droplets

(i) Potential Distribution

(ii) Electric Field Distribution

Fig. 9 FEM Analysis Results under Cement Dust Contaminated Condition
Fig. 10  Under Clean Condition with and without Water Droplets

Fig. 11  Under Uniform Contamination Conditions without Water Droplets

Fig. 12  Under Non-uniform Conditions without 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 plywood 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. 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.

REFERENCES


Boonruang Marungsri, was born in Nakhon Ratchasima Province, Thailand, in 1973. He received his B. Eng. and M. Eng. from Chulalongkorn University, Thailand in 1996 and 1999 and D. Eng. from Chubu University, Kasugai, Aichi, Japan in 2006, all in electrical engineering, respectively. Dr. Marungsri is currently a lecturer in School of Electrical Engineering, Suranaree University of Technology, Thailand. His areas of interest are electrical power system and high voltage insulation technologies.

Winai Ouchantuek was born in Nakhon Ratchasima Province, Thailand in 1983. He received in B. Eng. in Electrical Engineering from Suranaree University of Technology, Nakhon Ratchasima, Thailand in 2005. He has been teaching assistant in School of Electrical Engineering, Suranaree University of Technology for one year. Recently, he is graduate student in School of Electrical Engineering in the same university. His research interesting area are Finite Element Method and high voltage insulation technology.

Anant Oonsivilai, was born in Khon Kaen Province, Thailand, in 1963. He received his B. Eng. from Khon Kaen University, and M. Eng. from King Mongkut Institute of Technology North Bangkok, Thailand and PhD. from Dalhousie University, Canada, all in electrical Engineering, in 1986 , 1992 and 2000, respectively. Dr. Oonsivilai is currently an Assistant Professor in School of Electrical Engineering, Suranaree University of Technology, Thailand. His areas of interest are electrical power system, stability, control technology, advance alternative, and sustainable energy.

Thanatchai Kulworaowanichpong was born in Nakhon Ratchasima Province, Thailand, in 1975. He received his B.Eng. with first-class honour in Electrical Engineering from Suranaree University of Technology, Thailand (1997), M.Eng. in Electrical Engineering from Chulalongkorn University, Thailand (1999), and Ph.D. in Electronic and Electrical Engineering from the University of Birmingham, United Kingdom (2003). He has joined the School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand, since June 1998. He is currently an assistant professor in the same school. His fields of research interest include a broad range of power systems, power electronics and electrical drives, high-performance computing, optimization and artificial intelligent techniques.