Indonesian Journal of Electrical Engineering and Computer Science
Vol. 6, No. 3, June 2017, pp. 504 ~ 512
DOI: 10.11591/ijeecs.v6.i3.pp504-512

Leakage Current Based Thermal Modeling of Glass Disc Insulator Surface

Mohammed Imran Mousa*[1], Zulkurnain Abdul-Malek[2], Zainab I. M.[3]
[1,2]Institute of High Voltage and High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[3]Babil Division, Ministry of Higher Education and Scientific Research, Babil, Iraq
Corresponding author, e-mail: mohammedimran745@yahoo.com*[1], zulkurnain@utm.my[2]

Abstract

The stability of transmission lines relies on the health of the insulators, such as glass string insulators, which may occasionally flashover during an overvoltage. The likelihood of flashover increases notably when the glass insulator is wrapped by a wet contaminant layer. In this paper a study of the surface thermal profile of glass disc insulators insulation had been carried out for both clean and polluted surfaces. A finite-element simulation with time dependent model was carried out using COMSOL Multiphysics software. The variation of the insulator surface temperature with applied voltage as well as with pollution layer thickness is explained. The results illustrate the significant effect of pollution conductivity on heat propagate along the surface of the glass insulators with the increase higher voltages' magnitudes. Study of the aging level impact on a steady state thermal for glass insulation surface is also carried out.

Keywords: *Glass Insulator, Thermal surface, Pollution, Aging, Finite element analysis*

1. Introduction

Glass disc insulators are widely used in high voltage transmission lines owing to their many advantages such as superior electro-mechanical property, aging versatility, and easier maintenance operation. They are also somewhat better than ordinary porcelain insulators. The strengthened glass is usually combined with the iron hats and steeled pins using cement adhesive. The disc insulators provide both electrical isolation of the conductors as well as mechanical support for transmission lines [1, 2]. The main considerations when designing and selecting glass disc insulators are their flashover voltages and the surrounding environmental conditions [3-5]. The flashover voltage can be greatly influenced by a wet pollution covering the insulator surface [4, 5]. The glass insulator can be severely contaminated because of long service periods, which in turn lead to the presence of leakage current on the insulator surface.

The aggregation of contaminants on high voltage insulators may lead to flash-over across for example the glass insulators. Hence it can be said that the presence of pollution on the glass insulator surfaces means a reduction in the power system efficiency and insulation against lightning overvoltages [3, 6-10]. This is because pollution layers affect voltage distribution along the insulator surface that is an uneven stress could be created. Also, the leakage current that flows on the surface layer of the insulator may cause heat and even leads to surface flashover [11]. The intensity of the contamination layer may increase when exposed to the weather for a long time. The pollution layer is known to have a relatively higher conductivity compared to the insulating material. Subsequently, a higher current will flow through the insulator surface [12-14]. It is when the conductivity of the pollutant is high enough that partial arcs will start to extend along the insulating surface and may finally lead to a flashover. The above describes the familiar breakdown mechanism for a glass insulator [12-20].

Many studies have been done to predict the insulator degradation using different indicators such as using the leakage current pattern, the leakage current waveform, and the leakage current pulse monitoring [3], [11, 12], [21-27]. These are used as offline monitoring of the glass insulator aging. Other research measure the pollution level by several indicators, such as equivalent the salt deposit density (ESDD), the non-soluble deposit density (NSDD), and the pollution index (PI) [28-30]. The main drawback of the above methods is that they are all having

Received January 22, 2017; Revised April 25, 2017; Accepted May 11, 2017

to be implemented offline. The more effective way to detect failure of insulation in a power system is by an online technique. This means the measurements have to be carried out while the insulator is connected and energized.

In this paper, a study of the Joule heating on glass insulator surface because of leakage current with different pollution levels is reported. The main objective of this study is to determine the relationship between the temperature and the pollution levels with various applied voltages. The study aims to achieve the desired online monitoring of the glass insulators by just monitoring the insulator surface temperature.

2. Research Method

The finite-element analysis had been employed to solve the electric potential and electric stress across a glass cap-and-pin insulator. A COMSOL finite-element software with the utilisation of 3D models was used to carry out the simulations study. The simulation took into account the electrical and thermal coupling, surface diffusion, surface to surface radiation, wind effect, and solar effect.

2.1. Simulation Model

The 3D model of the glass insulators was created using AutoCad. The drawn image was then imported into COMSOL. Both the electrical and thermal coupling were selected. Figures 1 shows the cross-section of a standard disc insulator and the corresponding drawing in AutoCAD is shown in Figure 2. Basically, the thermal heating on the insulator is directly due to and converted from the applied voltage. The glass disc insulator consists of three different materials, namely iron to represent cap and pin of insulator, glass for the main insulating medium, and cement which is used to bond both pin and cap to the disc.

The relative permittivity of the glass and cement were set as 4.2 and 15, respectively. The material conductivity (σ) for the glass and the cement were set as $5x10^{-9}$ [S/m] and 10^{-4} [S/m], respectively. The pollution of the glass surface was simulated by a thin layer having a thickness of 1 mm. A voltage of 20 kV was applied across the insulator for one hour. Different aging levels were represented by various conductivities of the pollution layer.

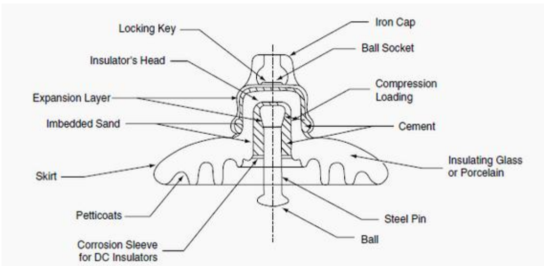


Figure 1. Cross-section of a standard disc insulator

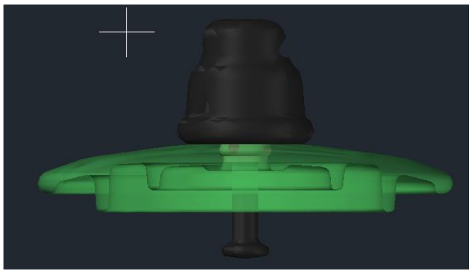


Figure 2. Disc insulator drawn in AutoCAD

2.2. Assumed Equations

Several equations are used in the computations. These equations are described in the following subsections.

2.2.1. Electric Field

The electric potential distribution in the dielectric is described by the field model. The basic governing equations of the field model are as follows:

$$\nabla \cdot J = Q_j \quad (1)$$

$$J = \left(\sigma + \varepsilon_o \varepsilon_r \frac{\partial}{\partial t}\right) E + J_e \quad (2)$$

$$E = -\nabla V \tag{3}$$

where E is the electric field, ε_o is the vacuum absolute permittivity, ε_r is the glass relative permittivity, V is the electric potential, σ is the conductivity of insulation material, and J is the current density.

2.2.2. Heat Transfer in Solids

The heat transfer in solid material follows the following governing equations.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{4}$$

$$q = -k\nabla T \tag{5}$$

For the heat flux, the following equations are relevant.

$$-n \cdot q = q_o \tag{6}$$

$$q_o = h \cdot (T_{ext} - T) \tag{7}$$

$$h = h_{air}(U, p_A, T_{ext}) \tag{8}$$

where Q is heat flux (W/m²), ρ is density (kg/m³), Cp is heat capacity at constant pressure (J/kg·K), ΔT is the change in temperature (K), u is velocity (m/s).

2.2.3. The Joule Heating Multiphysics Interface

To model resistive heating and dielectric heating, the software interface adds an electric current interface and a heat transfer in solids interface. The multiphysics couplings add the electromagnetic power dissipation as a heat source, and the electromagnetic material property is dependent on the temperature. The foolowing equations were used.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k\nabla T) + Q_e \tag{9}$$

$$-n \cdot (-k\nabla T) = Q_b \tag{10}$$

2.3. Geometry and Mesh

Figure 3 shows the standard created model geometry. The model is employed using three-dimensional analysis. The finite element analysis (FEA) solves both electrical field and thermal transfer in solid material. Since the simulation is time dependent, a one-hour simulation time was selected.

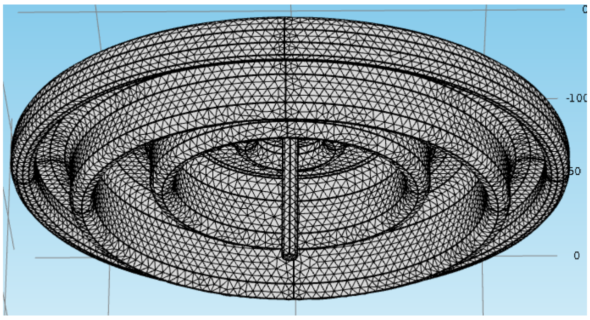


Figure 3. Generated mesh to disc insulator

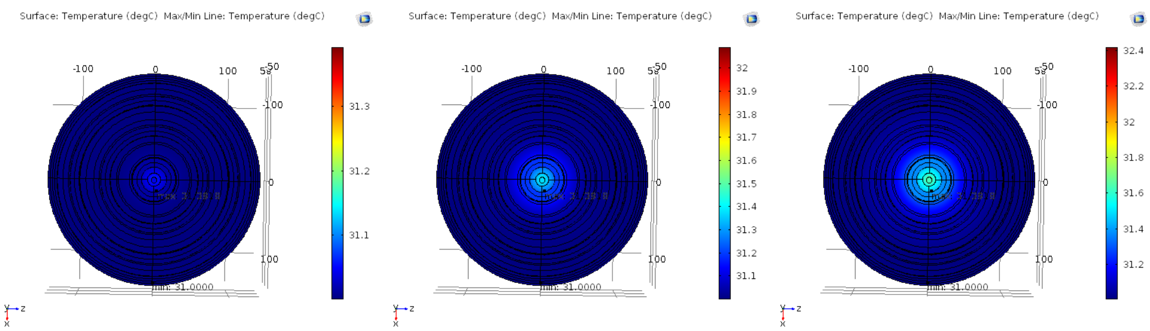
A normal mesh calibrated as general physics with free triangular elements was used. The element size parameters are: the maximum element size =28.1 mm; the minimum element size =5.05 mm; the maximum element growth rate =1.5; resolution of curvature =0.6; and resolution of narrow regions = 0.5. The normal degree of mesh had been chosen instead of finer mesh to make it easier and faster to solve. The generated mesh is as shown in Figure 3. It is noted that the number of elements are dependent on the actual size of the sample.

3. Results and Discussion

Several simulations were carried out. These are three pollution levels of glass insulators (clean, mildly, and heavily). Each glass insulator applied three different applied voltages (10, 15, and 20) kV for 48 hours. For all simulations the wind speed is 0.1 m/s and the initial temperature is 31.0 ^{o}C for the weather and insulators.

3.1. Clean Insulator

Figure 4 shows the thermal profile of a clean insulator surface with 20kV applied voltage for one-hour. The increase in temperature of the glass insulator surface due to the applied voltage during the one-hour duration can be clearly seen. Obviously, the heat on the surface of the insulator increases more or less linearly with time. In other words, the leakage current gradually rises with time. The temperature is higher at the insulator center, and it progressively decreases as the distance from the electrode increases. It is noted that the maximum surface temperature increases slightly for newer insulator. This is because of the higher resistivity associated with the newer insulation.



a. 0.1 h b. 0.5 h c. 1 h

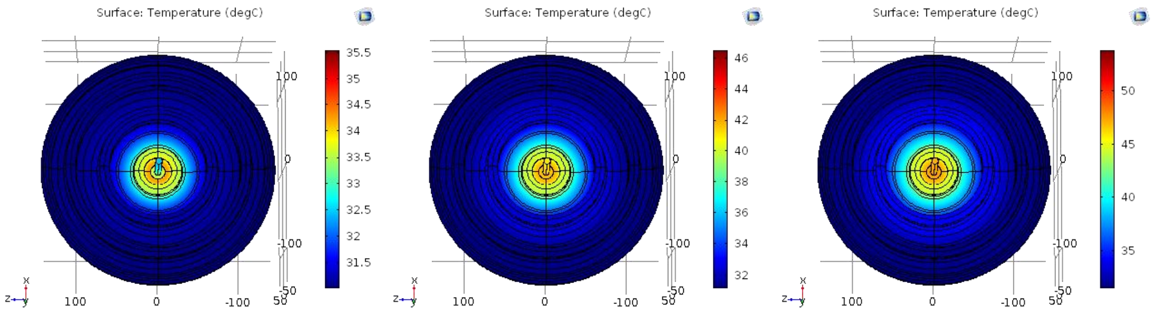
Figure 4. Thermal profiles of a clean insulator surface with 20kV applied voltage for (a) 0.1 of hour, (b) half-hour, and (c) one-hour

Figure 4 shows the thermal profile of a clean insulator surface with 20kV applied voltage for one-hour. The increase in temperature of the glass insulator surface due to the applied voltage during the one-hour duration can be clearly seen. Obviously, the heat on the surface of the insulator increases more or less linearly with time. In other words, the leakage current gradually rises with time. The temperature is higher at the insulator center, and it progressively decreases as the distance from the electrode increases. It is noted that the maximum surface temperature increases slightly for newer insulator. This is because of the higher resistivity associated with the newer insulation.

3.2. Mildly Polluted Insulator

A 1mm-thick pollution layer with a conductivity of 5E-6 S/m was applied on the surface of the glass insulator. This represents the mildly polluted insulator. Figure 5 shows the thermal profile of the mildly polluted insulator surface with 20kV applied voltage for one-hour. The pollution layer somewhat enhances the level of leakage current current flowing through the surface. The temperature of the surface increases with the decrease in the resistivity of the pollution layer. The maximum temperatures after 6 minutes, 30 minutes, and 60 minutes are

35.56 °C, 46.2 °C, and 53.52 °C, respectively. The corresponding minimum temperatures are 31.00, 31.16, and 31.56 °C, respectively.

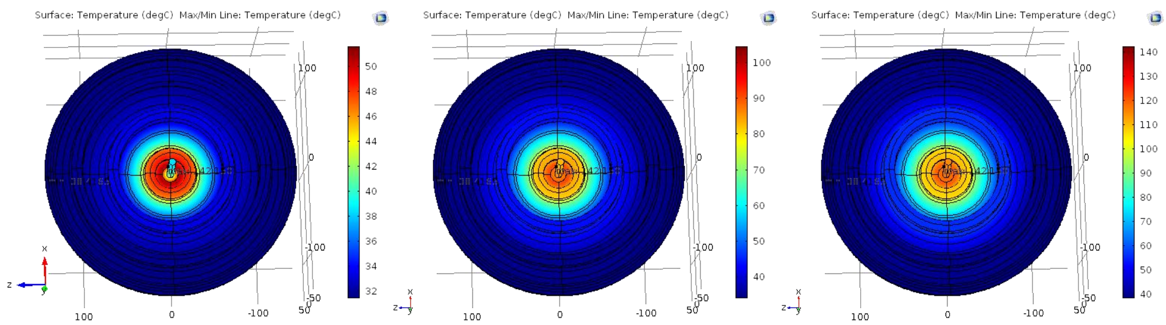


a. 0.1 h b. 0.5 h c. 1 h

Figure 5. Thermal profiles of the mildly polluted insulator surface with 20kV applied voltage for (a) 0.1 of hour, (b) half-hour, and (c) one-hour

3.3. Heavily Polluted Insulator

A 1mm-thick pollution layer with a conductivity of $5E^{-5}$ S/m was applied on the surface of the glass insulator. This represents the heavily polluted insulator. Figure 6 shows the thermal profile of the heavily polluted insulator surface with 20kV applied voltage for one-hour. Obviously, the temperature increases when with the conductivity of the pollution layer. A temperature of 51.54 °C was achieved just after 6 minutes. This temperature was then doubled (104.3 °C) after 30 minutes, and was tripled (142.27 °C) after 1 hour. It is noted that the minimum surface temperature after 1 hour is 38.97 °C.



a. 0.1 h 0.5 h c. 1 h

Figure 6. Thermal profiles of the heavily polluted insulator surface with 20kV applied voltage for (a) 0.1 of hour, (b) half-hour, and (c) one-hour

As can be seen in Figures 4 to 6, the temperature of the glass surface rises with the decrease in the resistivity of the pollution layer. Clearly, the maximum temperature is concentrated in the pin and the cap. Also, as the pollution layer conductivity increases, the generated heat becomes greater. It is also noted that the maximum temperature can be observed near the insulator's central location.

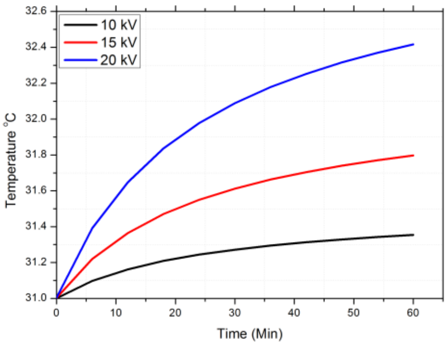


Figure 7. Thermal profile of a clean insulator surface with various applied voltage for one-hour

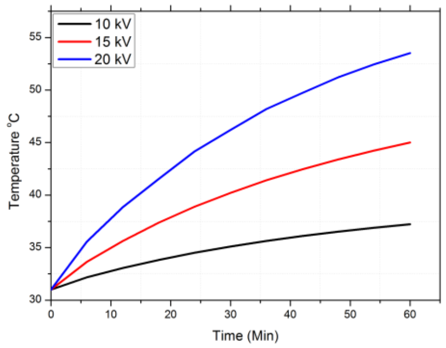


Figure 8. Thermal profile of a mildly polluted insulator surface with various applied voltage for one-hour

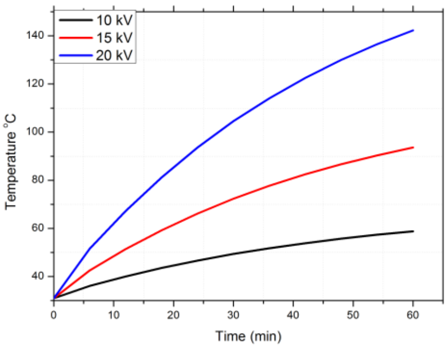


Figure 9. Thermal profile of a heavily polluted insulator surface with various applied voltage for one-hour

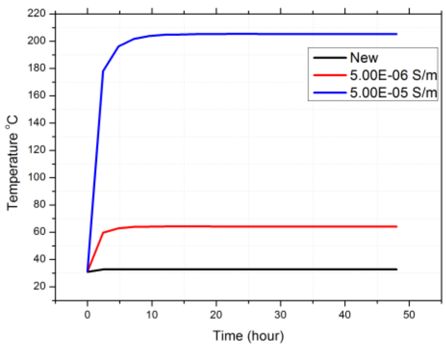


Figure 10. A 48-hour thermal profile of the insulator surface for varying pollution level with 20 kV applied voltage

The effects of the applied voltage on the surface thermal profile of the glass insulator with different pollution levels can be seen in Figures 7 to 9. Significantly, when the voltage increases, the surface temperature becomes higher, and the increase is more noticeable when the resistivity of the pollution layer also decreases. The heat is uniformly distributed on the insulator surface because of the uniform pollution layer. The uniform pollution layer means same thickness and conductivity covering the insulator surface, hence the leakage current is uniform everywhere. Obviously, the magnitude of applied voltage has slight effect on the surface temperature in case the clean insulator, as shown in figure 7. However, that effect been clearer when the conductivity of the pollution layer increased as shown in Figure 8, 9.

Figure 10 shows a 48-hour thermal profile of the insulator surface for varying pollution level with 20 kV applied voltage. The influence of the contaminant layer on the glass insulation as a function of the applied voltage can be clearly seen. The heat generated increases with time to a certain temperature due to the increasing leakage current upto a certain steady state value. The heat generated on the insulator surface reaches a stable temperature after a specific time. The steady-state condition relies on many factors, such as the surface diffusion, current injection, thermal conductivity of material, and other environmental factors including the wind speed, solar radiation, and pollution layer conductivity. The heating time constants had been determined for various pollution layers with all other previously mentioned factors remain constant. It is observed that the heating time constant for a new insulation is less than 2.4 h (with fluctuation 0.05 ^{o}C). The time duration to reach the steady state temperature is almost same for different pollution conductivity.

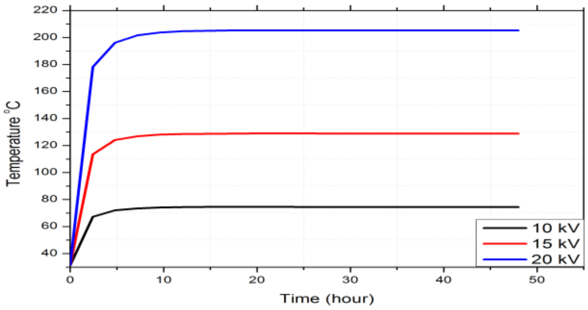


Figure 11. A 48-hour thermal profile of heavily polluted insulator surface for varying applied voltages

The impact of applied voltage on the steady state temperature for the case of heavily polluted layer is shown in Figure 11. The steady-state temperature (maximum) for the case of normal operation is about 75 ^{o}C. The time period taken to reach steady state almost same with increasing the voltage applied. The temperature of insulator surface raises more than 60%, when the voltage increases 50 %, so that when the applied 15 kV, the temperature became close to 130 ^{o}C and so on. The leakage current passing through surface depends on applied voltage at same conductivity, which generates heat at insulator surface.

4. Conclusion

The three-dimensional pattern has been modeled to study the impact of pollution on glass insulators with respect to the surface temperature generated by leakage current. The COMSOL finite element analyses software with employed coupling between electrical and heat in the glass insulators was used. The surface thermal behavior has been simulated as a function of pollution for various applied voltages. Acceptable results have been obtained according to behavior of leakage current and potential distribution along the insulator surface.

1. The heat generated along the insulator surface is strongly dependent on the pollution layer conductivity. The higher the conductivity of the pollution layer, the larger will be the leakage current and hence the heat generated.
2. The duration to steady state surface temperature is slightly increases with the conductivity of the pollution layer. Surface pollution plays a role in the heat capacity of the glass surface by decreasing or increasing its value depending on the pollution level. The duration to steady state surface temperature is not influenced by the applied voltage. However, the applied voltage influences the final steady state surface temperature.
3. The generated heat along the glass insulator surface is because of the leakage current, and these results in the enhancement of the overall pollution layer growth.

Acknowledgements

In preparing this paper, the first author was in contact with many people, academicians, researchers and practitioners who contributed immensely towards his understanding and thoughts. This work was supported by the Malaysian Ministry of Higher Education (FRGS Vot no. 4F828) and Universiti Teknologi Malaysia (RUG Vot. No 10H61).

References

[1] Gorur RS, Cherney EA, Burnham JT. *Outdoor insulators*. Ravi S. Gorur Phoenix, Ariz, USA.1999.
[2] E Kuffel, WS Zaengl. *High Voltage Engineering*. Chichester. UK. Pergamon Press.1984.
[3] Bessedik SA, Hadi H. Prediction of flashover voltage of insulators using least squares support vector machine with particle swarm optimisation. *Electric Power Systems Research*. 2013; 104: 87-92.
[4] Hampton B. *Editor.* Flashover Mechanism of Polluted Insulation. Proceedings of the Institution of Electrical Engineers.1964; 985-990.
[5] Miller HC. Surface Flashover of Insulators. *IEEE Transactions on Electrical Insulation*. 1989; 24(5): 765-86.

[6] Jolly D, Cheng T, Otten D, *Editors*. Dynamic theory of discharge growth over contaminated insulator surfaces. *IEEE PES winter power meeting*. 1974; 068-3.

[7] Arief YZ, Abdul-Malek Z, Muhamad NA, Ahmad MH, Makmud MZ. *Partial discharge monitoring technique for research purpose on solid insulating material.* IEEE Conference on Energy Conversion, CENCON. 2015; 106-111.

[8] Slama ME-A, Beroual A, Hadi H. Influence of the linear non-uniformity of pollution layer on the insulator flashover under impulse voltage-estimation of the effective pollution thickness. *IEEE Transactions on Dielectrics and Electrical insulation*. 2011; 18(2): 384-92.

[9] Tonmitr N, Tonmitr K, Kaneko E. The Effect of Controlling Stray and Disc Capacitance of Ceramic String Insulator in the Case of Clean and Contaminated Conditions. *Procedia Computer Science*. 2016; 86: 333-6.

[10] Zhang B, He J, Zeng R, Liang X. Voltage distribution along a long ceramic insulator string in a high-voltage tower window.*COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*. 2010; 29(3): 811-23.

[11] Salam M, Ang S, Wen F, Fadil M, Hadi H, Rahman Q, et al. *Comparison of pollution level of aged porcelain and silicon rubber insulators*. 2015 IEEE Conference Electrical Insulation and Dielectric Phenomena (CEIDP). 2015: 225-228.

[12] El-Zohri EH, Abdel-Salam M, Shafey HM, Ahmed A. Mathematical modeling of flashover mechanism due to deposition of fire-produced soot particles on suspension insulators of a HVTL. *Electric Power Systems Research*. 2013; 95: 232-46.

[13] Abdul-Malek Z. Correlation between Third Harmonic Leakage Current and Thermography Image of Zinc Oxide Surge Arrester for Fault Monitoring Using Artificial Neural Network. *Applied Mechanics & Materials*. 2014; (554): 598-602.

[14] Hadi NA, Abdul-Malek Z, Mashak SV, Naderipour AR. Three-Dimensional Potential and Electric Field Distributions in HV Cable Insulation Containing Multiple Cavities. *Advanced Materials Research*. 2014; 845:372-377.

[15] Amini MA, Sedighi AR. A new procedure for determination of insulators contamination in electrical distribution networks. *International Journal of Electrical Power & Energy Systems*. 2014; 61: 380-5.

[16] Lv Y, Li J, Zhang X, Pang G, Liu Q. Simulation study on pollution accumulation characteristics of XP13-160 porcelain suspension disc insulators. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2016; 23(4): 2196-2206.

[17] Pretorius P, Britten A, Govender T, Mahatho N, Parus N, Reynders J .*Electric field modelling of HVDC glass insulators preliminary findings from insulation strength studies*. Power Engineering Society Conference and Exposition in Africa (PowerAfrica); IEEE. 2012: 1-5.

[18] Ravelomanantsoa N, Farzaneh M, Chisholm W. *Insulator pollution processes under winter conditions. Electrical Insulation and Dielectric Phenomena*. 2005 CEIDP'05 2005 Annual Report Conference on; IEEE. 2005: 321-324.

[19] Rizk FA, Nguyen D. AC source-insulator interaction in HV pollution tests. *IEEE Transactions on Power Apparatus and Systems*. 1984; 103(4): 723-732.

[20] Rusli H, Gomes C, Kadir Z, Abdul-Malek Z. Surface arcing of insulators due to bentonite contamination. *Journal of Electrostatics*. 2015; 76: 73-77.

[21] Nasir MT, Mysorewala M, Cheded L, Siddiqui B, Sabih M. *Measurement error sensitivity analysis for detecting and locating leak in pipeline using ANN and SVM.* 2014 11th International Multi-Conference on Systems, Signals & Devices (SSD), IEEE. 2014: 1-4.

[22] Ahmad H, Salam M, Ying LY, Bashir N. Harmonic components of leakage current as a diagnostic tool to study the aging of insulators. *Journal of Electrostatics*. 2008; 66(3): 156-64.

[23] Suda T.Study on the frequency characteristics of leakage current waveforms of artificially polluted 12t suspension insulators by the clean fog method. 1999 Eleventh International Symposium on High Voltage Engineering (Conf Publ No 467); IET. 1999; 4: 115-118.

[24] Fernando M, Gubanski S, editors. *Analysis of leakage current wave forms for field-aged and new composite insulators.* 1997 IEEE 1997 Annual Report, Conference on Electrical Insulation and Dielectric Phenomena; IEEE. 1997; 1: 350-353.

[25] Saeed VM, Abdul-Malek Z, Hadi NA, Wooi CL, Khavari AH. Surge Arrester Leakage Current Analysis by Using Particle Swarm Optimization Technique. Applied Mechanics and Materials. 2014; 554: 608-612.

[26] Othman NA, Piah MAM, Adzis Z & Al-Geelani NA. Partial Discharge Characterization based on Leakage Current Pulses Waveform for Contaminated Glass Insulator String. *International Journal of Electrical and Computer Engineering*. 2016; 6(2): 835-843.

[27] Al-Geelani NA, Piah MAM, Saeh I, Othman NA, Muhamedin FL & Kasri NF. Identification of Acoustic Signals of Internal Electric Discharges on Glass Insulator under Variable Applied Voltage. *International Journal of Electrical and Computer Engineering*. 2016; 6(2): 827-834.

[28] Ahmad AS, Ghosh P, Aljunid SAK, Ahmad H. *Estimation of salt contamination level on the high voltage insulators surfaces during rainy season using artificial neural network*. Power System

Management and Control, 2002 Fifth International Conference on (Conf Publ No 488); IET. 2002: 303-308.
[29] Montoya G, Ramirez I, Montoya J. Correlation among ESDD, NSDD and leakage current in distribution insulators. *IEE Proceedings-Generation, Transmission and Distribution*. 2004; 151(3): 334-340.
[30] Abdul-Malek Z, Khavari AH, Wooi CL, Moradi M, Naderipour A. *A review of modeling ageing behavior and condition monitoring of zinc Oxide Surge Arrester*. Research and Development (SCOReD), 2015 IEEE Student Conference. 2015: 733-738.