The Effects of Applied Voltage, Contamination Level and the Length of Dry-Bands on the Electric Field and Leakage Current of Polymeric Insulator

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***Abstract*— The hydrophobicity and dry-bands formation have a considerable effect on the electric field and potential distributions of polymeric insulators. In this paper, the influences of hydrophobicity and the length of dry-bands on electric field distributions are investigated. Also, this paper studies the effects of contamination level and surface conductivity on the leakage current of polymeric insulator.**

The calculations are performed by finite element method based computational software (Maxwell-Comsol) along a 10-unit silicon rubber insulator string. This insulator is simulated in polluted and clean areas. In hydrophilic insulators the applied voltage will mostly drop along the dry-band. The partial arcing are observed when the voltage is high. If the applied voltage is high enough, these partial arcing will extend and causes a total flashover. Moreover, it can be seen that the humidity and dry-bands formation cannot cause a serious problem in the operation of insulator when the surface is hydrophobic. The electric field has a direct relation to the applied voltage and is inversely proportional to the length of dry-band. Besides, the leakage current rises with the increase of surface conductivity and contamination layer accumulated on the insulator surface.

***Index Terms*— polymeric insulator, hydrophobicity, dry-band, Leakage current**

I. Introduction

THE insulators are one of the most important devices in the power system having a significant effect on the power system reliability. Environmental conditions such as contamination and humidity of the environment and ultraviolet radiation can lead to weakening the insulation system, and eventually cause the dielectric breakdown [1-2].
Due to various advantages of polymeric insulators to non-polymeric ones they attracted much more attention. Hydrophobic surface, light weight, resistivity to human destruction are the examples of the advantages of polymeric Insulators [3-4].
Resistance of any material to flow of water on its surface is called hydrophobicity. The hydrophobic property is reduced as the insulator's surface ages due to environmental effects and the electric activity caused by wetting and pollution. The hydrophobicity is divided into six degree levels from HC1 to HC6 [5].

The combination of humidity and surface contamination, and weakening the surface hydrophobicity can reduce the dielectric strength and cause insulator breakdown. The presence of contamination and humidity due to high conductivity and permittivity increases the electric field and the leakage current of the insulator [6-7]. Since the leakage current density and other environmental factors, causing the heat, are asymmetric, the dry-bands are formed. It occurs in the surface areas with higher leakage current density due to heat generated [7]. In hydrophilic areas, because of the high conductivity of water, a major proportion of the voltage is applied across the dry-bands. It results in an extreme electric field across the dry-bands and arcing in these areas. As a result, erosion and aging in the insulator surface will happen. In some conditions, it causes an overall insulator breakdown. Therefore, investigating the leakage current can indicate the conditions of the insulator surface and the probability of arcing in dry-bands.
The electric field strength on polymeric insulators needs to be calculated to satisfy four objectives [8]:

- Preventing the significant discharge on the surface material.
- Avoiding the internal discharge activity inside the fiberglass rod and the sheath rubber material.
- Preventing corona phenomenon.
- Optimization of insulator design.

Hence, study the effect of dry-bands and surface hydrophobicity degree on electric and potential field distribution of polymeric insulators, simulations were carried out using Maxwell and Comsol software at 5 states:

- Dry and without pollution contamination insulator
- Hydrophobic surface insulator.
- Hydrophilic surface insulator.
- Without dry-band insulator.
- With dry-bands insulator.

A lot of research on the electric field and potential distributions of polymeric insulators has been carried out due to their importance and special features. However, it can be claimed that there is much less attention paid to the electric field of these insulators in condition of dry-bands

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formation and surface hydrophobicity [7]. Also, the effect of the length of dry-bands on the electric field, and the influence of intensity and thickness of contamination layer as well as applied voltage on the leakage current are other important factors discussing in this paper.

II. Method Analysis

A. Electric Field and Potential Distributions

For evaluating the electric field distribution, a prevalent method is to calculate the potential distributions and then calculate the electrical field distribution by subtracting gradient of electric potential distribution from it. This can be written as follows:

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

It can be derived from Maxwell's equation:

$$\nabla E = \nabla . \varepsilon \nabla V = -\rho \tag{2}$$

Where ε and ρ are material dielectric constant and volume charge density (Ω/m) respectively. In the absence of space charge ρ is equal to zero, and Poisson's equation changes to Laplace's equation.

$$\nabla . \varepsilon \left(\nabla V \right) = 0 \tag{3}$$

B. Equations for FEM Analysis of Electric Field

The Equation (4) represents two dimensional function F(v) in the Cartesian system of coordinates:

$$F(u) = \frac{1}{2} \int_D \left[\varepsilon_x \left(\frac{du}{dx}\right)^2 + \varepsilon_y \left(\frac{du}{dy}\right)^2 \right] .dxdy \tag{4}$$

Where ε_x and ε_y are x- and y- components of dielectric constant in the Cartesian system of coordinates. The Equation (4) can be re-written as Equation (4) when isotropic permittivity distribution $\varepsilon_x = \varepsilon_y = \varepsilon$:

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

When take the effect of dielectric loss on the electric field distribution into account, the complex functional *F*(*u*) should be written as following:

$$F(u)^* = \frac{1}{2} \int_D w\, \varepsilon_0 (\varepsilon - j\, \varepsilon tg\, \delta) \left[\left(\frac{du}{dx}\right)^{*2} + \left(\frac{du}{dy}\right)^{*2} \right] .dxdy \tag{6}$$

Where ω is angular frequency, ε_0 is the permittivity of free space ($8.85 \times 10^{-12} \frac{F}{m}$), $tg\,\delta$ is tangent of the dielectric loss angle, and $u*$ is the complex potential [9].

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 [10]:

$$\frac{\partial F_{uj}}{\partial V_i} = \frac{\varepsilon_0 \varepsilon_r}{2} \int_i \frac{\partial}{\partial V_i} \left(\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} \right) drdz \tag{7}$$

III. Insulator Modeling

Generally a composite insulator is comprised of a core material, end fitting, and a rubber insulating housing. The core is made of fiber reinforced plastics (FRP) [11].

The structure of a composite insulator and dry-bands location are demonstrated in figure 1. For modeling, a String insulator employed on the 33 kV network is used. Table I demonstrates relative permittivity and conductivity and in Table II insulator condition have been shown.

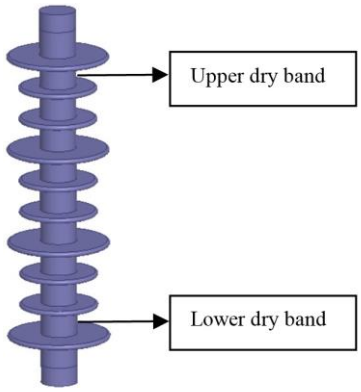


Fig. 1. Structure of composite insulator with dry-bands location.

TABLE I
Relative Permittivity and Conductivity Considered

Material	Water droplets	Pollution layer	Film water mixed to pollution	FRP	SiR*
Permittivity	83	15	20	7	3.45
Conductivity (S/m)	0.01	0	0.01	0	0

*Silicon Rubber

TABLE II
Insulator Assume Condition

Creepage distance (mm)	Sheds Diameters (mm)	Dry-band Length (mm)	Pollution layer thickness (mm)
680	65-84	20	1

IV. Flashover of Wet Polluted Insulator

A layer of pollutants is generally accumulated on the insulator surface since of the installation or the last cleaning operation. The insulator strength can significantly decrease in some zones due to the pollution layer deposited. As a result, flashover faults may happen under certain environmental conditions. For example, industrial areas or the suburbs of large cities, installations near the sea and exposed to strong winds coming from the sea, or near deserts where the strong winds lead to sand and salt. The dry pollution layer normally does not endanger the power system operation. Nevertheless, this can result in flashover faults when the contamination layer is wetted. In general, the flashover process on polluted insulators have some essential steps as following [12]:

1. With drenching the contamination layer accumulated on the insulator surface, the leakage current flows in the mixture of water and contamination. This current is proportional to the conductivity.
2. Generally, the leakage current density is asymmetric

based on insulator shape and profile. In some regions in which the leakage current density is higher, there is more producing heat that can lead to dry-bands formation.

3. Since electrical resistance of dry-bands is much more than that of wet layer, the most of applied voltage drop along dry-bands. If this voltage is big enough, the air around the dry band will be broken down and a partial arc will appear.
4. The partial arc may develop in two different ways based on the conditions. In one way, it may die out. In another way, it can move to find a more stable position corresponding to a shorter arcing distance. If the apply voltage is high enough, flashover will occur.

The major point in flashover insulator is that partial arc occurs when dry-band electric field of insulator exceed its wet surface. It happens when injected power to the arc from the source be more than its loss power. If the power of the source decreases, the resistance of the arc rises, and as a result, the arc extinguishes.

V. Simulation Results

In this section, the simulation results for clean and polluted condition are presented. The results illustrate the effect of applied voltage, contamination, hydrophobicity degree, the location and the length of dry-bands on the electric field and potential distributions of silicon rubber insulator. They also show the impact of conductivity, contamination layer thickness and hydrophobicity degree on the leakage current of silicon rubber insulator. These results are achieved with applying v_{1x} ,v_{2x} to lower electrode ($v_{1x} = \left(\frac{33}{\sqrt{3}} \times \sqrt{2}\right) = 26.94kv$,$v_{2x} = \left(\frac{20}{\sqrt{3}} \times \sqrt{2}\right) = 16.93kv$), using Maxwell and Comsol software. The States of A, B, C and D are simulated with Maxwell software and states of E and F are simulated with Comsol software.

In the following figures the results have been displayed in two graphs the red graph shows potential distribution and the violet graph shows electric field distribution.

In sub-section F, the effects of conductivity and hydrophobicity degree on the leakage current (LC) are investigated.

A. Clean and Dry Insulator

In this part the simulation is carried out in clean and dry insulator surfaces. Figure 2 illustrates the electrical field intensity distribution and electrical potential of insulator on clean and dry condition.

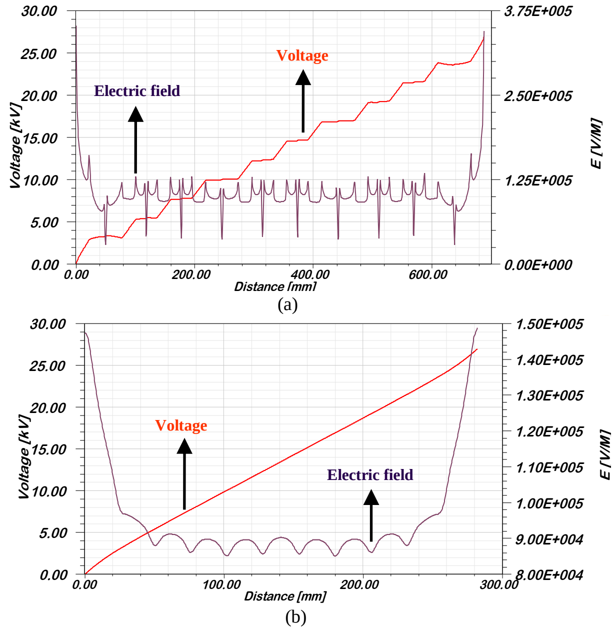


Fig. 2. Electric field and potential distributions on clean and dry insulator by applying v_{1x} ; (a) along the creepage path , (b) inside the insulator core

B. Hydrophobic and Polluted Surface Insulator

In this step, hydrophobic surface insulator is covered with 1mm thickness of contamination layer. This step is similar to HC1 state of hydrophobicity classification [5].

The figures 3 to 4 and Tables III to IV show electric and potential distributions in two below states:

- Without dry-band wet polluted insulator
- With lower-upper dry-bands wet polluted insulator

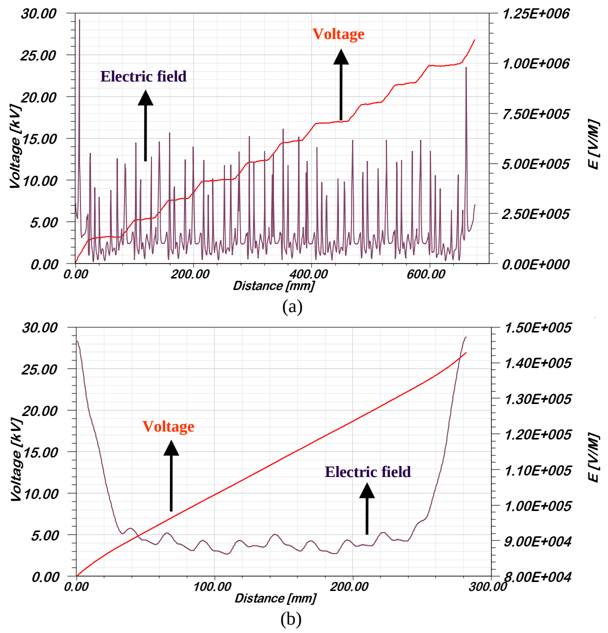
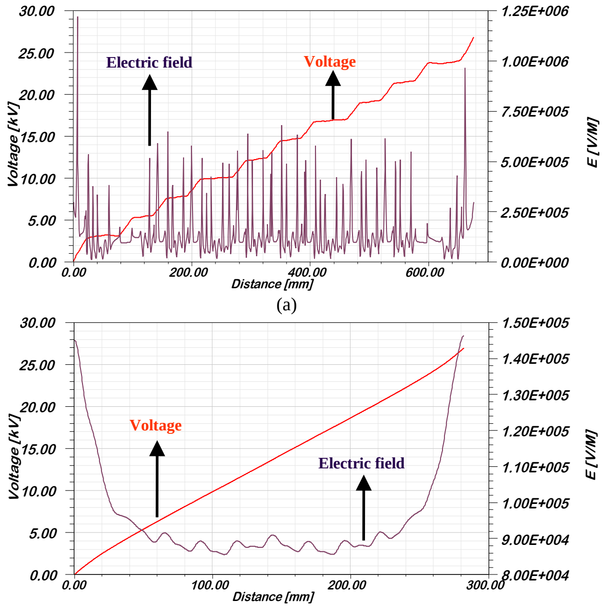


Fig. 3. Electric field and potential distributions on hydrophobic and polluted surface insulator condition, and without dry-band, by applying v_{1x} ; (a) along creepage path , (b) inside the insulator core

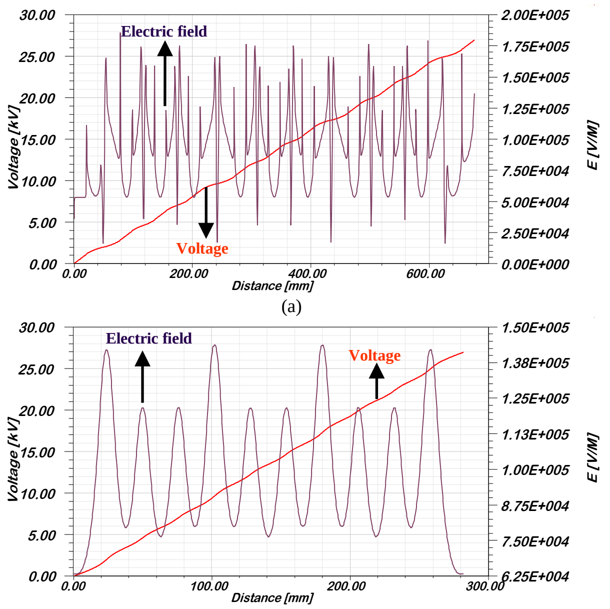


(a)
(b)
Fig. 4. Electric field and potential distributions on hydrophobic and polluted surface insulator condition, and with lower-upper dry-bands, by applying v_{1x} ; (a) along creepage path , (b) inside the insulator core

C. Hydrophilic and Polluted Surface Insulator

In this part the hydrophobic property is reduced as the insulator's surface ages due to environmental effects and the electric activity caused by wetting and contamination accumulated. This step is similar to HC6 state of hydrophobicity classification. Due to high conductivity of water, a leakage current flows through the wetted insulator surface. The value of leakage current depends on conductivity. The thickness of pollution film mixed with water is assumed 1 mm. The figures 5 to 7 will show electric and potential distributions in three below states:

- Without dry-band wet polluted insulator
- With lower dry-band wet polluted insulator
- With lower-upper dry-bands wet polluted insulator



(a)
(b)
Fig. 5. Electric field and potential distributions on hydrophilic and polluted surface insulator condition without dry-band and by applying v_{1x} ; (a) along creepage path , (b) inside the insulator core

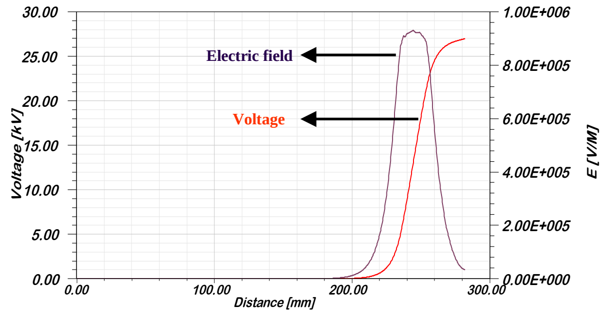


Fig. 6 Electric field and potential distributions on hydrophilic and polluted surface insulator condition with lower dry-band, with applying v_{1x} ; inside the insulator core

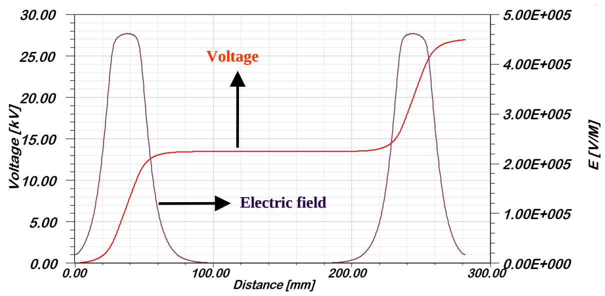


Fig. 7. Electric field and potential distributions on hydrophilic and polluted surface insulator condition with lower-upper dry-bands, by applying v_{1x} ; inside the insulator core

D. Investigation the Effect of the Length of Dry-Bands on the Electric Field and Potential Distribution

In this section, the length of dry-band has been reduced from 20 mm to 10 mm in order to survey the effect of the length of dry-bands.

The maximum intensity of the electric field in the hydrophilic state with the length of dry-band equal to 10 mm in two voltage levels v_{1x} and v_{2x} is presented in figures 8 and 9 as well as Table V.

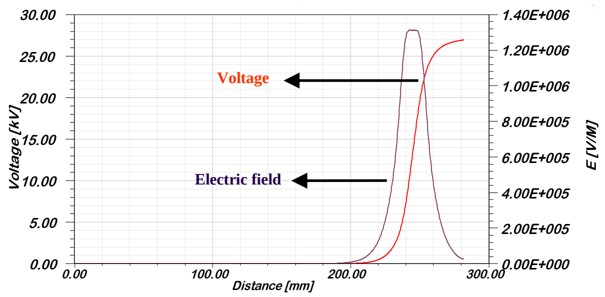


Fig. 8. Electric field and potential distributions in the hydrophilic state with lower dry-band and with the length of 10 mm in voltage level v_{1x} , inside the insulator core

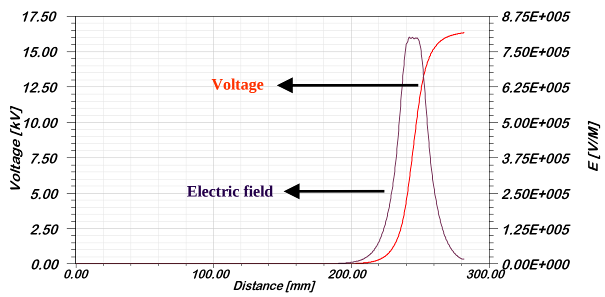


Fig. 9. Electric field and potential distributions in the hydrophilic state with lower dry-band and with the length of 10 mm in voltage level v_{2x} , inside the insulator core

E. Hydrophilic and Polluted Surface Insulator Simulated by Comsol Software

In order to validate the results obtained from Maxwell software, the simulation of insulator is also performed by the Comsol software in this part.

The results based on figures10 and 11 show the similar trend in the electrical and potential field in any dry-bands positions. They illustrate that the electric field and potential distributions have similar values at any location of dry-bands in hydrophilic surface.

The small mismatch between the output results achieved from Maxwell and Comsol is mainly due to little difference in their simulated insulator profiles.

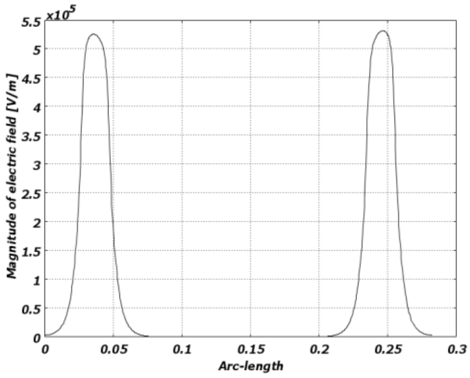


Fig. 10. Electric field and potential distributions on hydrophilic and polluted insulator surface with lower-upper dry-bands by applying v_{1x} ; inside the insulator core path

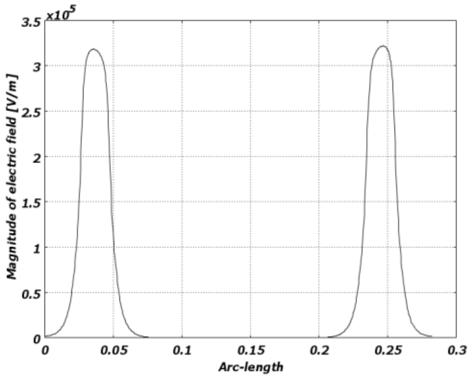


Fig. 11. Electric field and potential distributions on hydrophilic and polluted insulator surface with lower-upper dry-bands by applying v_{2x} ; inside the insulator core path

TABLE III
The maximum intensity of the electric field along the creepage distance path and inside the core of insulator with applying v_{1x}

State	Dry clean	Hydrophobic surface	Hydrophilic surface	Lower dry-band*	Lower/ upper dry-bands*
E(kv/m)[1]	354	1220	185	3300	2250
E(kv/m)[2]	149	147.5	145	930	460

* In hydrophilic surface after forming dry badns
[1] Along creepage path
[2] Into core

TABLE IV
The maximum intensity of the electric field along the creepage distance path and inside the core of insulator with applying v_{2x}

State	Dry clean	Hydrophobic surface	Hydrophilic surface	Lower dry-band*	Lower/ upper dry-bands*
E(kv/m)[1]	210	730	105	1400	960
E(kv/m)[2]	90	89.5	87.5	590	280

* In hydrophilic surface after forming dry bands
[1] Along creepage path
[2] Into core

TABLE V
The maximum intensity of the electric field in hydrophilic state with lower dry-band and with the length of 10 mm

State	applying v_{1x}	applying v_{2x}
E(kv/m) at creepage Path	5300	3350
E(kv/m) inside core	1300	800

F. The Investigation of the Leakage Current of the Insulator

In this section, the effects of hydrophobicity degree, the applied voltage magnitude, intensity and thickness of contamination on the LC of the insulator are examined.

According to IEC60815 standard, the intensity of contamination on the insulator surface depends on equivalent salt deposit density (ESDD). Based on IEC60507, in order to measure the value of ESDD, the insulator surface is firstly washed with a specific volume of water, and then the conductivity of the solution as well as its temperature are measured. The conductivity of the mentioned solution is calculated in $20^{o}C$.

$$\sigma_{20}=\sigma_{\theta}(1\text{-b}(\theta\text{-}20)) \quad (8)$$

Where σ_{θ} is the volume conductivity at a temperature of $\theta(^{o}C)$, *b* is a temperature dependent factor.

The salinity of the solution (S_a) and the value of ESDD can be calculated by (9) and (10) respectively.

$$S_a = (0.57\sigma_{20})^{1.03} \quad (9)$$

$$ESDD = \frac{S_a \times V}{A} \quad (10)$$

Where V is the solution volume (cm^3) and A is the cleaned surface area (cm^2) . Finally, by calculating the value of ESDD through IEC 60507 standard, the intensity of contamination can be obtained based on IEC 60815 standard. As a result, the values of ESDD and contamination degree are dependent on surface conductivity of insulator. Therefore, the change in surface conductivity can be considered as the intensity of the contamination of insulator.

In the following section, the influence of the hydrophobicity degree, the applied voltage magnitude and the intensity and thickness of the surface contamination on the leakage current of the insulator are investigated in two voltage levels of v_{1x} and v_{2x} .

The intensity of the leakage current of the insulator in the clean and dry modes by applying v_{1x} is shown in figure 11.

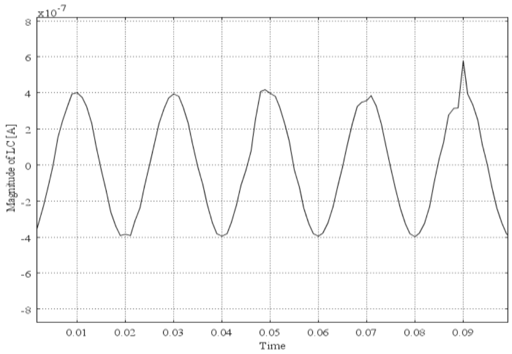


Fig. 11 .The leakage current of clean and dry insulator by applying v_{1x}

The leakage current magnitude for clean and dry, hydrophobic and polluted hydrophilic surfaces with different conductivities under two voltage levels of v_{1x} and v_{2x} are presented in Tables VI-VII respectively.

Since the hydrophobicity level of the hydrophilic surface has been considered HC6, and water layer has been assumed continues and uniform, any change in its conductivity will affect the leakage current directly based on Equation 11 and Table VI and Table VII.

$$J = \sigma E \quad (11)$$

Considering the results of Tables VI-VII, the applied voltage magnitude and the contamination layer thickness have a direct relationship with the leakage current.

In level of v_{1x} , from the conductivity(s/m) of 10^{-1} to 10^{-5}, the relationship between the conductivity and the leakage current is direct and linear. Between the conductivity of 10^{-5} to 10^{-7} , the leakage current varies with a lower slope. However, from the conductivity of 10^{-7} , the leakage current becomes saturated. In this condition, despite the decrease in the conductivity, the leakage current does not see a significant change. Similarly, the conductivity is directly proportional to the leakage current from the conductivity(s/m) of 10^{-1} to 10^{-5} in level of v_{2x} . Here, the leakage current goes to saturation point from the conductivity of 10^{-8}. Therefore, the leakage current does not vary considerably with the change in the conductivity.

In this paper, the effects of applied voltage magnitude, intensity of contamination and surface hydrophobicity on the electrical field and potential of polymeric insulators before and after the formation of dry-bands with different lengths were studied. Also, this paper studies the influence of the contamination thickness, conductivity and surface hydrophobicity on the leakage current magnitude of polymeric insulators before the formation of dry-bands.

TABLE VI
LC measurement in various pollution conductivity

State conductivity (s/m)	Clean	HC_1	10^{-8}	10^{-7}	10^{-6}	10^{-5}
LC(μA) at v_{1x}	0.4	1	1.1	1.5	7	17
LC(μA) at v_{2x}	0.25	0.63	0.638	1.05	4.2	11

* Hydrophobic surface (HC_1 degree)

TABLE VII
LC measurement in various pollution conductivity

Conductivity (s/m)	10^{-4}	10^{-3}	10^{-2}	10^{-2} Thickness (2 mm)	10^{-1}
LC(μA) at v_{1x}	120	1200	12000	20000	120000
LC(μA) at v_{2x}	70	700	7000	12000	70000

VI. Conclusion

In the presented work, the effects of contamination, hydrophobicity and dry-bands as well as the applied voltage magnitude on electric field distribution were simulated and analyzed. In the clean and dry surface insulator state, electric and potential intensity had less fluctuation and value. In the wet hydrophobic surface insulator state, electric and potential distributions had higher value and more non-uniform distributions compared to the dry and clean state. However, the insulator operated normally. In the wet hydrophilic surface insulator state, electric and potential intensity did not change considerably, but after dry-band formation, its value saw a sharp increase and therefore, partial discharge may happen. It can be seen that in the hydrophilic state resulted from lower and upper dry-bands, the electric field and potential distributions have similar values regardless of dry-bands location.

Also, the electrical fields of the dry-band areas have a direct relation to the applied voltage, and are inversely proportional to the length of dry-bands. It also was observed that there was a direct relation between the intensity of the leakage current and applied voltage magnitude, the contamination layer thickness and conductivity.

References

[1] I.Ahmadi-Joneidi, Alireza Majzoobi, Amir AbbasShayegani-Akmal, Hossein Mohseni, "Aging Evaluation of Silicone Rubber Insulators Using Leakage Current and Flashover Voltage Analysis," *IEEE Trans. Dielectr Elec Insul*, vol. 20, pp. 212-220, Feb. 2013.

[2] I. Ahmadi-Joneidi, M. Kamarposhti, A. Shaygani-Akmal, H. Mohseni, " Leakage current analysis, FFT calculation and electric field distribution under water droplet on polluted silicon rubber insulator," *Electr Eng,* vol.0, pp.315-323, Jan. 2013. 2013; 95: 315-323.

[3] S. M. Gubanski, "Modern outdoor insulation-concerns and challenges,"*IEEE Electr. Insul. Mag*, vol. 21, no. 6, pp. 5-11, 2005.

[4] R. Btehamdan, "Electric field study of Silicon Rubber insulator using finite element method (slim)," M.S. thesis, Dept. Electron. Eng., Teknologi Univ., Malaysia, 2006.

[5] Hydrophobicity Classification Guide. Swedish Transmission Research Institute (STRI), 1992; 1: 1-16.

[6] Suwarno. A. Pradana, "Properties of Leakage Current on 20kv Ceramic Insulators and Computer Simulation Based on Electrical Equivalent Circuit," in *Lecture Notes in Engineering and Computer Science: World Congress on Engineering 2010,* pp. 895–899.

[7] S. M. H. Hosseini and M . M. M. Tavakoli, "Investigation of the Influence of Hydrophobicity and Dry Band on the Electric Field and Potential Distributions in Silicon Rubber Insulator," *Lecture Notes in Engineering and Computer Science: Proceedings of The International Multiconference of Engineers and Computer Scientist 2017,15-17 March, 2017, Hong Kong,* pp. 1074–1080.

[8] W. Que, "Electrical field and voltage distribution along non- cream insulators," Ph.D. dissertation, Dept. Elect. Eng., The Ohio State Univ, 2002.

[9] B. Marungsri, W. Onchantuek, and A. Oonsivilai, "Electric Field and Potential Distributions along Surface of Silicone Rubber Polymer Insulators Using Finite Element Method," *World Academy of Science, Engineering and Technology*, vol. 2, no. 6, 2008.

[10] S.Z mousavi, B. Sheikhdoragh, A.A. Shayegani-Akmal "Investigation on pollution factors on electric field and potential distribution of polymeric insulator," *J. Basic. Apple. Sci. Res,* vol. 2, no. 12, pp. 12482–12491, 2012.

[11] M. T. Gençoğlu, "The comparison of ceramic and non-ceramic insulators", *New World Sciences Academy,* vol. 2, no. 12, 2007.

[12] J.Farzaneh-Dehkordi, "Experimental study and mathematical modeling of flashover of EHV insulators covered with ice," M.S.Thesis, UQAC Univ, Quebec, Canada, July, 2004.

[13] IEC Standard 60815, "Selection and Dimensioning of High Voltage Insulators Intended for use in Polluted Conditions," IEC Standard, Edition 1.0, 2008.

[14] IEC Standard 60507, "Artificial pollution tests on high-voltage insulators to be used on ac systems," Int'l. Electrotech. Comm., Geneva, Switzerland, 1991.