Influence of Water Contents on the Electrical behavior of polymeric insulators

S.S.Dessouky and K.A. Helal.
Department of Electrical Engineering, Faculty of Engineering, Port-Said University, Port-Said, Egypt

Abstract- Outdoor insulators are subjected to electric stress and weather conditions like rain, fog and dew. These conditions give rise to the danger of leakage currents forming on contaminated or wetted surfaces and finally leading to insulation degradation and failure. Thus, outdoor insulation materials not only have to withstand the electric stress during service, but also they must be resistant against ageing phenomena by dust or humidity. The polymeric insulators were widely used in the last decades because of high contamination resistance, lightweight, mechanical strength and hydrophobicity of their surfaces. The electric stress in the presence of water droplets provokes partial discharges giving way to local reduction of hydrophobicity of insulator surfaces.

In the present study the degradation arising from applying uniform AC electric field on wetted polymeric surfaces has been studied. The electric field distribution around droplets located over polymeric insulator has been calculated by Boundary Element Method. Different factors that affect the behavior of insulation materials under wet conditions have been investigated.

Keywords- Water droplets, polymeric insulators, hydrophobicity, uniform electric field.

I. INTRODUCTION

The insulating materials of high voltage equipments are stressed in service over years by several environmental factors. One ageing factor is the humidity which in combination with the electrical stress causes changes of the conditions on the insulating surface. In the recent years, the application of polymer insulators has been increasing widely because of their advantages of high contamination resistance performance, lightweight, mechanical strength, etc. Especially surface hydrophobicity is one of the important factors that contribute to the superior performance of the silicon rubber to resist wetting due to its low free surface energy. Around the water drops the electrical field intensifies, especially at the triple point between the water drop, air and insulating material. The sessile drops will be deformed, always elongated along the direction of the lines of force of the electric field. These distortions shorten the insulating distance and cause partial discharges on the silicon rubber surface and finally can lead to deterioration [1].

For polymeric or non-ceramic insulators, hydrophobicity loss or reduction causes serious effects. Hydrophobicity affects the polymeric silicon rubber materials / insulators in two ways. Firstly, the loss of hydrophobicity causes reduction in electrical insulation and pollution withstand performance. Secondly, it is also prominently influences the ageing process of silicon rubber (SIR) insulators [2].

In the Present work, factors that affect the hydrophobicity level and the electric field distribution over the insulators under wet conditions have been illustrated.

II. EXPERIMENTAL SETUP

Regarding the field distribution over the insulators in over head transmission lines, there are areas where the line of electric flux either is perpendicular or parallel to the surface.

The stress provoked on the material may differ according to the geometry of the electric field near the surface [3].

Therefore it is of a great interest to carry out an investigation on electric field distribution over the surface of the insulator at wet conditions. Inception voltage, breakdown voltage, and leakage current have been also reported for silicon rubber samples subjected to uniform alternated electric field at wet conditions.

In order to simulate both kinds of stresses, two different setups have been used. The first setup with a tangential field direction to the assayed sample surface is presented in figure 1.a. It consists of two metal parallel plates having 6 cm diameter. This diameter is constant at the both setups. One electrode is contacted to high voltage and the other is grounded. The air gap distance between the plates varies from 2 to 5 cm and the insulator samples used are inserted between the plates. The second arrangement with normal field direction to the assayed sample is represented in figure 1.b. The insulator samples are placed on the lower (grounded) electrode. These electrodes were rubbed down with ethyl alcohol to restore uniform starting conditions after each breakdown test. The AC voltage that has been applied between the electrodes has r.m.s values varying between 0 - 80 kV. The droplets have been presented over the insulators with the using of micro - pipette. The impact of changing droplets number, volume, shape, and position with the respect to the electrodes has been studied because of their correlation to the insulators degradation.

III. BOUNDARY ELEMENT METHOD

In order to calculate the electric field distribution, one has to solve Laplace's partial differential equation with boundary conditions. When complicated geometries are encountered, as in the case of HV engineering applications, numerical
techniques are generally the only viable approach. [4]. One of the numerical techniques has been used in this study namely boundary element method.

![Figure (1): Schematic diagrams of the experimental setups, (1.a) with tangential field direction to the assayed sample, (1.b) with normal field direction to the assayed sample.](image)

The boundary element method does not rely upon fictitious charges; instead it seeks to calculate the charges distributed over boundaries. Then, approximating the real charge distribution rather than assigning values to non physical ones. The electric potential due to surface charge density is written as in [4].

\[
\Phi(r) = \left(\frac{1}{2\pi\varepsilon_0}\right) \int \rho_s(r')\Phi^*(r, r')dl(r')
\]

(1)

Where \(\Phi(r)\) represent the potential at location \(r\)

\(\omega\): is a constant equal to 1 or 2 for two or three dimensional respectively.

\(\rho_s(r')\): is the surface charge density at position \(r'\).

\(l\): represent the boundary between different regions.

\(r\): denotes a field point and \(r'\) denotes a source point.

\(\Phi^*(r, r')\): is the fundamental solution of the potential problem.

Equation (1) is the basic equation of the source formulation of boundary element method. A system of boundary conditions is required for determining the unknown charge density. After successive simplification, a set of linear equations that required to satisfy the Dirichelt boundary conditions on energized conductors and flux continuity through dielectric boundaries are obtained and expressed by:

\[ [A] [\rho] = [\Phi] \] (2)

Where \([A]\) is a known potential-coefficient vector matrix. \([\rho]\) is the unknown surface charge density vector matrix. \([\Phi]\) is the potential vector matrix.

By solving this system of equations, the unknown values of charge density can be found. Consequently, using this charge distribution, potential and electric field values can be calculated. In the following part, the electrical field distribution at wet conditions, which has been calculated by boundary element method, will be illustrated.

IV. ELECTRICAL FIELD DISTRIBUTION RESULTS

The water drops intensify the local electric field stress. This intensification is strongly dependant on the geometrical configuration of the droplet, which, is deformed by the alternating electric field. Sharp point can rise from the drop in the case of perpendicular setup and the junction between water, air and sample can be shifted to the electrodes in the tangential setup. [1]

The applied voltage by the electrodes assumed to be (1.0 and 0.0) p.u. The air gap distance between the parallel plates assumed to be constant at electrical field calculations and equal 50 cm at tangential setup, and 35 cm at the perpendicular one. The field strength values are calculated for the both test arrangements in the absence of the water drops as a reference values, and to notice how the electric field distribution will be changed in the presence of water droplets.

In Fig (2), a comparison between the electric field distribution over silicon rubber sample wetted by different shapes of the droplets and subjected to tangential electric field is illustrated. It is crystal clear that the electric field is uniformly distributed on the surface of the dielectric at dry conditions. In the presence of droplets, the highest electrical field stress is located at the lower part of the sessile drop and toward the electrodes. The electric field at the boundary of hemispherical droplet is much higher than the case of the spherical one. Thus, the probability of partial discharge (PD) occurrence due to electric field intensification increases with the deformed droplet. The distance where the electric field reported is given as a percentage from position (a).

![Figure (2): the electric field distribution with different droplets shape at tangential arrangement.](image)
The effect of droplet deformation on the electric field distribution over silicon rubber sample is also studied when the electric field is normal to the sample surface. The sessile drops are deforming and elongating in the direction of electrical field. In the perpendicular arrangement, the critical points are at the top of the droplet where the highest electrical field stress is reached. [1].

Figure (3) shows a comparison between the electric field distributions at the case of sphere droplet, conical deformed droplet and dry conditions. The results indicate that the electric field is uniformly distributed in the case of dry condition. But in the presence of droplet the electric field isn’t uniform anymore. Another worthwhile result illustrate that, the highest field strength is located on the top of the droplet. The field strength on the top of conical deformed droplet is higher than the field strength at spherical one.

![Figure (3): the electric field distribution with different droplets shape at normal arrangement.](image)

In this arrangement, the droplets number is another vital parameter that affects the electric field distribution. During the study of this factor the droplets were arranged in the center of the silicon rubber sample in order to minimize the effect of being close to the electrodes. In this test silicon rubber sample assumed to have an excellent hydrophobic property as the droplets must not overlap with each other; however they are arranged in too closed volume. The electric field distribution results are represented in figure (6) in the case of one, two, and three drops located on silicon rubber sample which is subjected to tangential electric stress. These results show that the highest electric stress is reported at the case of three drops. The localization of the electric stress at the boundary of the droplets increases with the increasing of the number of the droplets.

![Figure (5): the electric field distribution with different droplet volumes at normal arrangement.](image)
The position of the droplet on the insulator surface is another parameter that influences the field distribution. Figure (7) shows the impact of positioning the droplet, near Low voltage (L.V) electrode, near high voltage (H.V) electrode, and at the center of silicon rubber sample, on the electric field distribution. The electric stress was assumed to be tangential to the silicon rubber assayed sample. It is fitting to say that the electric field is uniformly distributed till the boundary of the droplet. It is previously indicated that, the electrodes play a determining role for the flashover voltage since; as the droplets are near the electrodes, the electron emission and/or the electric field applied provoke much intense phenomena. The higher electric field is related to so called "triple point" i.e. to those common points where the electrodes, the polymeric surface and the water droplet meet each other [5].

In the previous part the impact of different factors on changing the electric field distribution over silicon rubber sample have been studied. In the following part, experimental study has been introduced as an attempt to verify the influence of these parameters on the degradation that happened to wetted insulator subjected to electric stress.

V. EXPERIMENTAL RESULTS

In the present study, breakdown voltage, inception voltage and leakage current characteristics have been studied for silicon rubber samples which are subjected to normal and tangential electric stress. Inception and breakdown voltages values that plotted in the following curves are the mean values of at least ten measured values. Leakage current measurements have been carried out by connecting high resistance in KΩ in series with the ground electrode. The potential across the resistance was directly fed to the oscilloscope to obtain the current value. [6]

In order to represent the most existing environmental contaminants, two test solutions have been used, ammonium chloride (NH₄CL) and sodium chloride (NACL) with different by mass of salts that dissolved in distilled water. These solutions were recommended by IEC publication standards and in many experimental studies as good simulation for the realistic contaminated conditions. [5, 6, 7].

Impact of changing the number of the droplets was the first parameter that has been studied. The droplets number changes from one to three droplets having the same size of 0.3 ml and located over silicon rubber sample that is subjected to both tangential and normal electric stress. Figures (8) and (9) illustrate the influence of changing the number of droplets on inception voltage of silicon rubber samples subjected to tangential and normal electric stress respectively. When normal electric stress is applied, the distance between the electrodes remains constant as 10 mm and thickness of samples changes from 2mm to 6mm. It is crystal clear that the presence of droplets over the insulator sample leads to a great reduction in inception voltage. These results also show that the more water drops (three) the lower inception and breakdown voltages, however the highest values of inception and breakdown voltages are reported in the case of dry condition (without droplets).
Hudrophobicity of the insulator material plays an important role with the increasing of droplets number. When a single droplet is placed over a sample inserted between the electrode, at first it oscillates and then elongates under the effect of electric field. The droplet oscillation depends on the roughness of the surface that is more pronounced in silicon rubber because of its hudrophobicity. As the number of droplets increase the droplets oscillate more and wet paths between the droplets are created which may endure even after the removal of electric field. Droplet oscillation is more intense on low rough surfaces. Thus, it is remarkable that, the higher surface roughness and hudrophobicity the lower droplets oscillation i.e. the probability of forming paths between the droplet, which increase the wetted area and reduce the inception voltage, decreases.

Position of the droplets is the second parameter that has been studied. Figures (10) and (11) illustrate the impact of positioning the droplets with respect to the electrodes, as at the center of the sample, near high voltage electrode (H.V), near low voltage (L.V) electrode, on the breakdown voltage of silicon rubber sample subjected to tangential electric stress. The droplets number changes from one to four droplets arranged vertically at the previously indicated positions with the same volume of 0.3ml. The droplets solutions changes between NACL and NH4CL having the same by mass of the salt. The results show that the lower inception and breakdown voltages were reported when the droplets located near (H.V) electrode. It is also remarkable that there is a slight difference between breakdown voltages while being at the center of the sample and near the grounded electrode.

One can draw parallels between this droplet behavior and the behavior of enclosed cavities in a solid insulation in which one of the boundaries is the metallic electrode. In both cases the emission of electrons and / or the uneven field distribution are more pronounced. The uneven field distribution is the result of maximum field which occur at the points better known (triple point) i.e. at the common points where air, polymeric insulation and metallic electrode meet each other [7].

Volume of water droplets also strongly affects the electrical characteristics of silicon rubber at wetted conditions. Figures (12.a), (12.b), and (12.c) show leakage current waveforms in case of 0.2ml, 0.3ml, and 0.4ml NACL droplet respectively with 0.2 by mass presented over silicon rubber sample. The applied electric stress is tangential to the assayed sample and the applied voltage doesn’t exceed 22 kV. These figures show that the highest leakage current magnitude and oscillation have been reported at 0.4 ml droplet; have been remarked at the case of 0.2ml. This is due to the fact that an increase in the droplets volume not only decreases the distance between the electrodes which may lead to a discharge or an arc formation, but also increases the probability of reaching the nearest electrode by one of the droplets[8].

Figure (9): relation between inception voltage and thickness of the sample at normal arrangement.

Figure (11): relation between breakdown voltage and different number of droplets at tangential arrangement.
Figure (12): leakage current waveforms initiated over SIR sample surface subjected to tangential stress with different droplet volume over that surface.

The behavior of different insulating materials has been studied experimentally, to enhance the study depending on comparison view. Figures (13) and (14) illustrate the inception and breakdown voltages characteristics respectively for silicon rubber (SIR), epoxy resin (EP), Polyvinyl - Chloride (PVC), and bakelite (BA) samples when they are subjected to normal electric stress and two droplets of 0.1 by mass NaCl located over them. The droplets have the same volume of 0.4ml. It is so remarkable that SIR material has the best behavior under the wet conditions; however the worst behavior has been recorded in the case of BA sample. The behavior of (EP) is a bit worse than the behavior of (SIR) but still better than (PVC) and (BA). Silicon rubber has demonstrated better hydrophobicity and lower surface energy than most organic polymers. Surface of silicon can recover its hydrophobicity between contaminations and/ or PD episodes, while other materials progressively deteriorate. PD exposure temporarily increases the "wetability" of silicon rubber, a phenomenon associated with the increase of the surface oxygen contents. After rest period, the water repellency of the material returns. This hydrophobic recovery is though to be a result of diffusion of low molecular weight (LMW) of (PDMS) (polydimethylsiloxane) fluid to the insulation surface. The speed of hydrophobic recovery is directly proportional to the amount of LMW components left inside the bulk of silicon rubber insulator. There should be enough amounts of LMW in total SIR bulks to continue process of their diffusion for many years to maintain LMW concentration at the surface. According to many laboratory tests, most of the commercial silicone rubbers available today for making composite insulators have enough LMW to sustain excellent property of hydrophobicity recovery. The artificial increase of LMW through adding low molecule silicone oil into the raw silicone rubber cannot remarkably improve the hydrophobicity property. However, effect of adding fillers like alumina trihydrate has been observed positive.[2].

![Figure (13): relation between breakdown voltage and thickness of the sample at normal arrangement.](image1)

![Figure (14): relation between inception voltage and thickness of the sample at normal arrangement.](image2)

VI. CONCLUSION

In this study, some basic parameters that affect the behavior of the water droplets on polymeric surfaces have been studied. The electric field distribution over the insulator sample has been calculated at wet conditions when it is normal or tangential to the assayed insulator sample. Two arrangements have been used in order to explain the parameters that affect the degradation of polymeric insulators. The obtained results in the present study can be briefly summarized in the following points:

- In the tangential arrangement, the highest electrical field stress is located in the lower part of the droplet and towards the electrodes; however in perpendicular arrangement, the critical point is reported at the top of the droplet where the highest electrical field stress is reached.

- At dry conditions the electric field is uniformally distributed over the surface of the insulator; but at wet conditions the water droplets intensify the electric field stress. This intensification strongly depends on the geometrical configuration of the droplet, which is deformed by alternating electric field.

- Regardless the electric field direction, increasing the droplets volume leads to increase the field intensification at
the boundary of these droplets and also leads to increase the leakage current forming over the surface of the insulators at wet conditions.

- Droplet positioning near the electrodes leads to inception and breakdown voltages reduction. The lower breakdown voltage has been reported when the droplet locates near (H.V) electrode. Slight difference can be detected between breakdown voltages when the droplet locates near L.V electrode and at the center of the sample.

- Increasing the droplets number greatly reduces the inception voltage of polymeric insulators. Surface roughness and hydrophobicity of the insulating material are important factors which eliminate the impact of increasing the droplet number on polymeric materials degradation.

- SIR insulating material has the best performance under wet conditions and BA insulating material has the worst one. SIR water repellency decreases the wetted area by the water droplets. SIR can recover its hydrophobicity by diffusion of low molecular weight (LMW) of (PDMS) (polydimethylsiloxane) fluid to the insulation surface.

REFERENCES


