

# Behavior of Water Drops in a Uniform Electric Field on Solid Insulating Surfaces under AC Voltage.

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## ABSTRACT

Outdoor insulators are subjected to electric stress and weather conditions like rain, fog and dew. This gives rise to the danger of leakage currents forming on contaminated or wetted surfaces and finally leading to insulation failure. They show a stable hydrophobicity, which forces moisture into the shape of small droplets rather than a wet layer. Yet at the triple junction between the droplet, the air, and the insulating surface, the electric fields are enhanced. If the onset level for water drop corona is reached, the surface locally loses its hydrophobicity. Dew has been found to be a more critical condition than rain or atomized spray.

This paper describes experimental investigations on inception and breakdown voltages at water drops. Experimental investigations are made to describe and understand the phenomena accruing at water drops on insulating surface exposed to the electric field. In that direction, measurements are made using two different test arrangements: First when the applied electric field is tangent to the insulating surface and Second when it is perpendicular. The electrical field distribution around the water drop is calculated by Boundary Element Method. The water drop shape, spherical, hemispherical and a conical, and its dimensions were changed. The study was done on Polyvinyl-Chloride (PVC) and Bakelite (Ba) as insulating surface because of their important industrial application. The number of water drops was changed from one to three at the center of the insulating surface. There are two different solutions of water drops used in this work, namely, NaCl and NH<sub>4</sub>Cl.

## 1-INTRODUCTION

Outdoor insulators are subjected to electric stress as well as to environmental conditions like rain, fog and dew. Being the interface between solid material and ambient air, the surface needs special attention. If conductive layers form on the surface, there may appear a leakage current which leads to a degradation of insulation and eventually to flashover. To avoid this danger, the hydrophobicity of silicon rubber is used. Humid layers will appear as discrete droplets rather than forming continuous wet areas [1-4].

The insulating materials of high voltage equipment 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 quickly because of their advantages of high contamination resistant performance, lightweight, mechanical strength, etc [5-7].

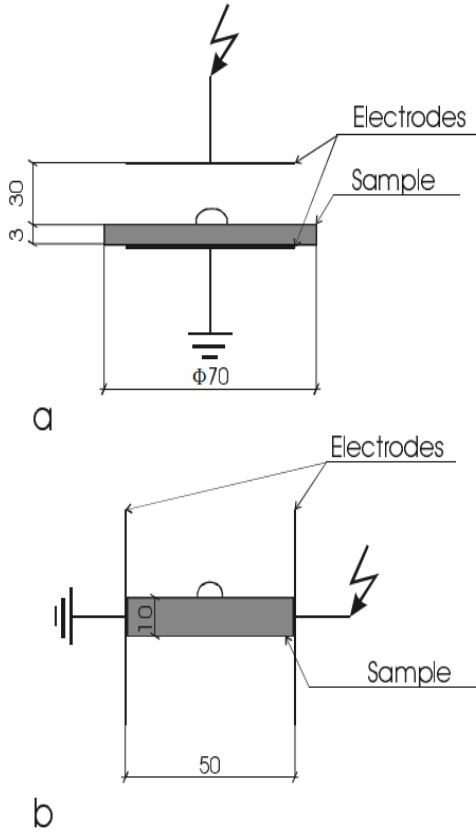
Especially, surface hydrophobicity is one of the important factors that contribute to the superior performance of the silicon rubber to resist wetting due to its low free surface energy. Sessile water droplets will be formed on the surface of polymer exposed to rain and moisture and hence the conductive contamination dissolved with water is discontinuous. Around the water drops the electrical field is intensified, 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 silicone rubber surface and finally can lead to deterioration [1-2].

## 2. Experimental Setup

Regarding the electric field distribution of insulators in overhead transmission lines, one finds areas in which the lines of force run mostly perpendicular to the surface, but also areas in which they are nearly parallel to it. The latter is the case at the rod, the former at the shed.

The electric stress provoked on the material may differ in accordance to the geometry of the electric field near the surface. Therefore it is of great interest to carry out an investigation on inception and breakdown voltages at water drops while reproducing the conditions encountered at different areas of the insulator [1].

In order to simulate both kinds of stresses, we use two different setups. The first arrangement with a normal field direction to the sample surface is presented in Figure 1a. It consists of two parallel metal plates of defined dimensions and shapes (6 cm diameter, 90° Rogowski profile) were arranged with 1 to 5 cm gap distance. The sample of insulating surface is placed on the lower electrode. The second arrangement with tangential field direction to the assayed surface is shown in Figure 1b. A sample block of 10x30x50 mm is put between two plate electrodes with the same diameter as in the first setup. Both arrangements work with water drops which are placed on the sample surface in the central region with the aid of a micro-pipette. The drops vary in volume, number and formation. For the investigations, AC voltage is applied between the electrodes, the rms-value varying from 0 up to 80 kV. After each measurement the lower electrode was rubbed down with ethyl alcohol to restore uniform starting conditions. The water drops were always illuminated indirectly, to avoid rapid evaporation.



**Figure 1: Schematic diagrams of the experimental setups, a) with normal field direction, b) with tangential field direction [1]**

### 3- BOUNDARY ELEMENT METHOD.

The boundary element method does not rely upon fictitious charges; instead it seeks to calculate charges distributed over boundaries. Then, approximating the real charge distribution rather than assigning values to nonphysical ones. The electric potential due to a surface charge density is written as in [8]

$$\phi(r) = \frac{1}{2\pi\alpha\epsilon_0} \int_{\Gamma} \rho_s(r') \phi^*(r, r') d\Gamma(r') \quad (1)$$

Where  $\Phi(r)$ : represents potential at location  $r$   
 $\alpha$ : is a constant and equal to 1 or 2 for two or three dimensional problems respectively.

$\rho_s(r')$ : is the surface charge density at location  $r'$

$\Gamma$ : denotes 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 the boundary element method. A system of boundary conditions is required for determining the unknown charge density. After successive simplification [6], a set of linear equations to satisfy Dirichlet boundary conditions on energized conductors and flux continuity through dielectric boundaries are obtained and expressed by:

$$[A] \cdot [\rho_s] = [\phi] \quad (2)$$

Where:  $[A]$  is a known vector potential-coefficient matrix.

$[\rho]$  is the unknown surface charge density vector matrix.

$[\Phi]$  is the potential vector matrix

By solving this system of equations we can find the

unknown values of charge density. Consequently, using this charge distribution, potential and electric field values can be calculated.

### 4-Electrical Field Distribution

PD inception voltage is a function of the distance of the electrodes and the volume of water drops. Thus the PD inception field strength values are given and compared. The field strength values are calculated for the test arrangement in absence of water drops. But we have to keep in mind that the electric field distribution is significantly changed by the water drop. Permittivity, drop shape and volume are the relevant parameters, which also influence the PD inception condition. The static drop shape depends on the surface energy of the material.

The inception field strength on normal field stress condition is about 1 kV/mm. This measured result is valid for different drop sizes and different material. This result is not unexpected, because the PD inception conditions are given by the field distribution along the path between drop and upper electrode.

Figs. 2 and 3 show examples for field strength diagrams. In the electrostatic field calculations for both arrangements, a single water drop of 1mm radius on the sample surface was considered. Field strength values given in the legend are in kV/mm. They refer to a total voltage of 1 kV applied to the arrangement, which makes them easily scaleable to other voltage values. Where as a normal field provokes the highest field strength on the top of the water drop, as illustrated by Fig. (2) (Corresponding to setup Figure 1a), Fig. (3) indicates that the parallel field generated according to setup Figure 1b causes the highest field strength near the line where the drop contacts the sample surface. These rough simulation results can explain the basically different behavior of the water drops in the two different setups. Due to the surface roughness the electric field strength is enhanced and the PD inception field strength is decreased. A calculation is not available until now but the effect is clearly measurable.

The effect of water droplet shape on the electrical field enhancement along gap distance (as a percentage distance from position A) for two different setups is shown in Figs. (2 & 3). Fig. (2) shows the electrical field distribution in the perpendicular arrangement for bakelite material and NH4CL solution. Different droplet shape are used (namely, spherical, conical deformed and without water drop). The results indicate that, the electrical field is uniformity distributed in the case of without droplet but in the other cases the electrical field is no uniformity distributed. The figure indicates also that, the highest field strength on the top of the water drop in case of conical deformed is higher than in the case of spherical.

Fig. (3) shows the same relation as Fig. (2) for the same conditions but in the case of tangential arrangement. Different droplet shape are used (namely, spherical, hemi-spherical and without water drop). The same results can be obtained for the electrical field distributions. The figure indicates also that, the highest field strength causes near the line where the drop contacts the sample surface in case of hemispherical is higher than in the case of spherical.

Compared to the case without a drop, the water drop is intensifying the local electric field stress. This intensification

is strongly dependent on the geometrical configuration of the droplet, which, again, is deformed by the alternating electric field. Thus, sharp points can rise from the drop in the case of the perpendicular setup and the junction between water, air and sample can be shifted to the electrodes in the tangential setup. These results are a good agreement with the results of reference [1, 2, and 4].

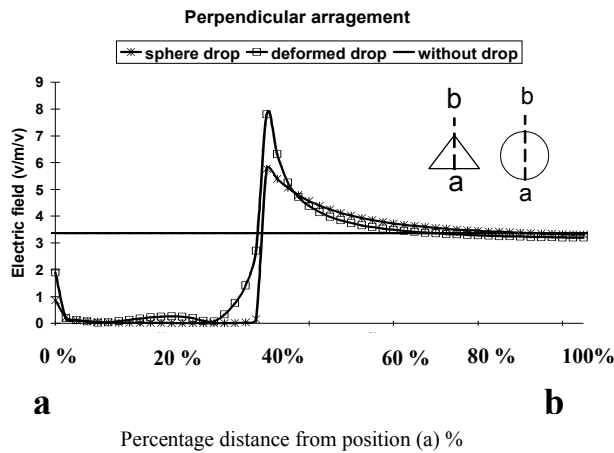


Fig. 2: distribution of the electric field at a spherical and a conical deformed water drop of radius 1 mm in the perpendicular arrangement for Ba material and NH4CL solution

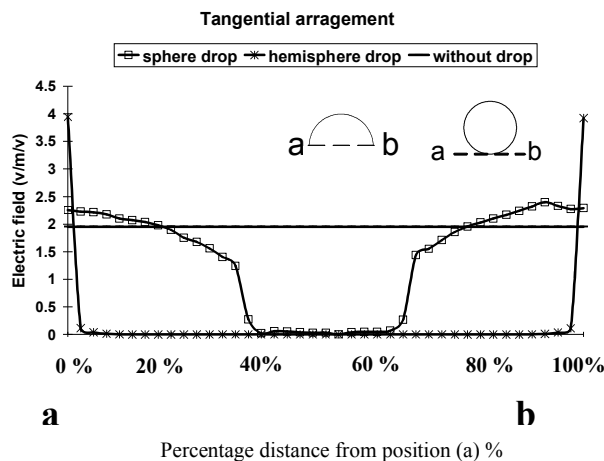


Fig. 3: distribution of the electric field at a spherical and a hemispherical water drop of radius 1 mm in the tangential arrangement for Ba material and NH4CL solution

Fig. (4) shows the electrical field distribution in the bakelite material and NH4CL solution for spherical droplet shape for two different setups (namely, perpendicular and tangential arrangements). The results indicate that, the highest field strength due to present of spherical water droplet in case of perpendicular is higher than in the case of tangential arrangement. In the tangential arrangement, the highest electrical field stress is located in the lower part of the water drop and towards the electrodes. In the perpendicular arrangement, the critical points are at the top of the water drop where the highest electrical field stress is reached. In reality the drop is changing its shape irregularly; therefore the field distribution will be different.

Fig. (5) shows the electrical field distribution in the perpendicular arrangement for bakelite material and NH4CL solution. Different droplet radius is used (namely, 1, 2 and 3 mm). The results indicate that, the highest field strength on the top of the water drop in case of larger droplet radius. The slight decrease of the PD inception field strength with increasing drop size may be attributed to the amount of field intensification in the near of the water drop. The size of the water drops influences the inception voltage slightly as a larger drop volume requires a higher electrical field

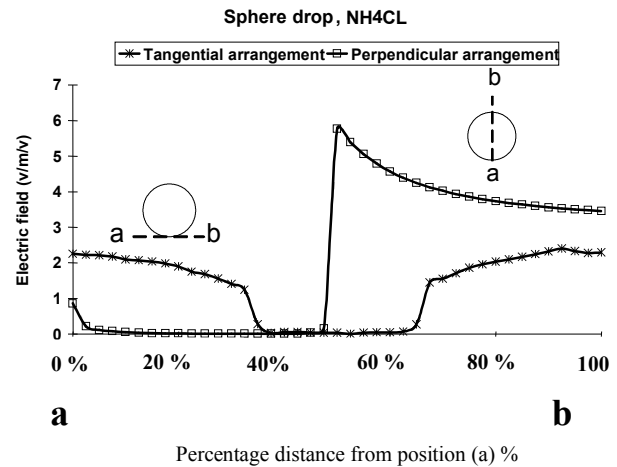


Fig. 4: distribution of the electric field at a spherical water drop of radius 1 mm for both arrangement for Ba material and NH4CL solution

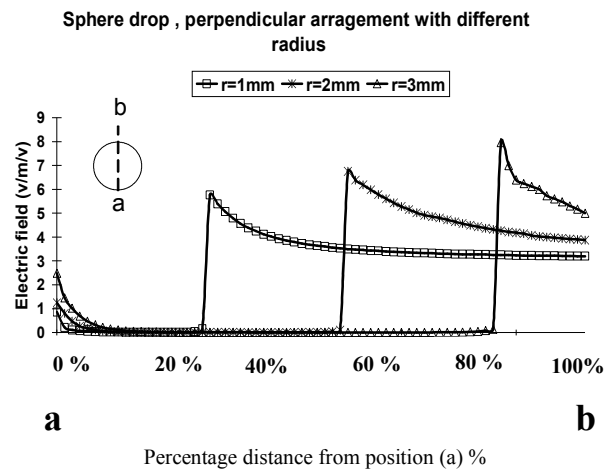


Fig.5: distribution of the electric field at a spherical droplet with different radius in perpendicular arrangement for Ba material and NH4CL solution.

## 5- Experimental Results:

In the present study, the breakdown and inception voltage characteristics, in the perpendicular and tangential arrangement setups, are studied experimentally in the presence of spherical water drops.

The breakdown voltage plotted in the figures is determined as the main value of at least ten measured values of the breakdown voltage. To determine the inception voltage the applied voltage is raised until the first pulse appears on the oscilloscope from which inception voltage can be determined.

The study was done on Polyvinyl-Chloride (PVC) and Bakelite (Ba) as insulating surface. The number of water drop was changed from one to three at the center of the insulating

surface. There are two different solutions of water drops used in this work, namely, NACL and NH4CL.

Fig. (6) shows the relation between the inception voltage and the gap distance, which is varied up to 50 mm in the tangential arrangement for PVC material and NACL solution without and with a spherical water drop with a radius of 0.02 mm at the center of the insulating surface. The curves are obtained at different number of water drop was changed from one to three. From the results it can be deduced that presence of water drop has a great effect in reducing the inception voltage. It can be noticed that, when the water drop is located on the insulating surface the electrical field around the particle is higher with comparable to that at the electrode surface. Thus water drop cause great reduction in inception voltage and this reduction depend on droplet number and size. It is also clear from the figure that, the larger number of water drops (three) the lower is the inception voltage and its value is higher in the case of without water drop due to the uniformity of electrical field between the gap distance. The number of the water drops influences the inception voltage slightly as a larger drop number requires a higher electrical field.

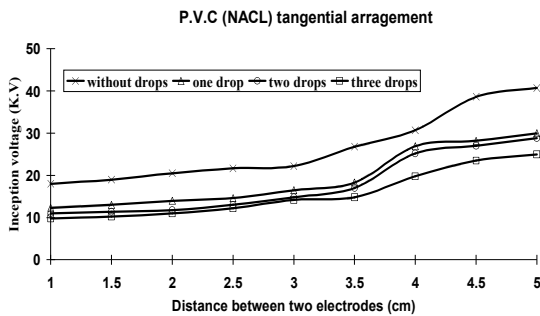


Fig.(6): Relation between inception voltage and gap distance for tangential arrangement at different numbers of droplet

Fig. (7) shows the same relation as Fig. (6) for the same conditions but in the case of perpendicular arrangement.

With perpendicular arrangement no partial discharge could be detected until immediately before breakdown. Then the drops are spraying, and smaller drops forming from the original ones are “jumping” in all directions, some reaching the upper electrode and adhering to it. Breakdown voltage is a function of the distance of the electrodes and the number and volume of water drops. With tangential arrangement the drops are elongating across the surface under voltage stress. This deformation persists when voltage is switched off. If voltage increased, partial discharges can be detected. As a general rule, when voltage attains a certain level, the drops start to vibrate. A further increase in voltage divides the drops into parts, some of which move towards the electrodes.

Fig.(8) shows relation between inception voltage and gap distance at Ba sample of insulating surface, for one spherical water drop and NH4CL solution for two different setups namely, perpendicular and tangential arrangements. It is clear from the figure that the inception voltage in the perpendicular case is higher than in the tangential case. After the onset voltage is reached, the partial discharges are increasing rapidly with growing voltage. The rate of rise is very similar in both arrangements. In the case of

the tangential field, just at a lower value of electrical field the partial discharges are present in comparison with the perpendicular arrangement where they start at a higher value of background field.

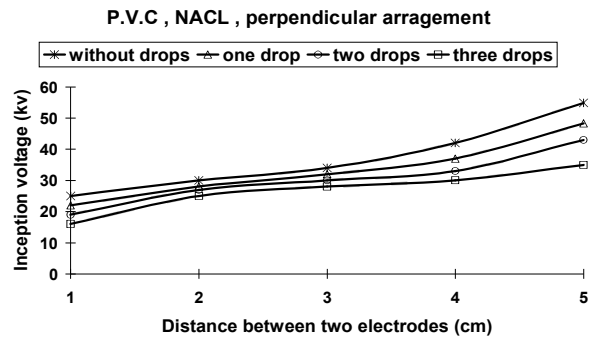


Fig.(7): Relation between inception voltage and gap distance for perpendicular arrangement at different numbers of droplet.

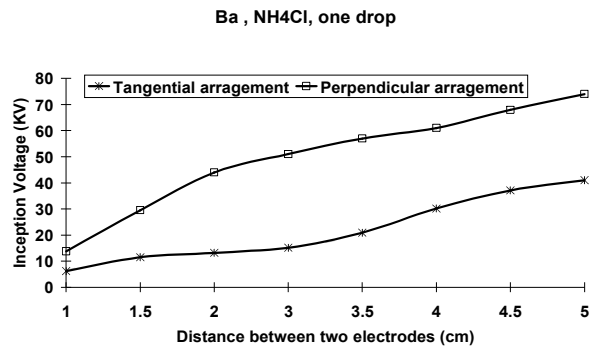


Fig.(8): Relation between inception voltage and gap distance for different arrangement setup at Ba sample of insulating surface, for one spherical water drop.

Fig.(9) shows relation between breakdown voltage and gap distance for perpendicular arrangement at different sample of insulating surface namely, Ba and PVC for two water drops and NH4CL solution.. It's shown from the figure that, the breakdown voltage is higher in the case of PVC sample of insulating surface than the case of Ba sample

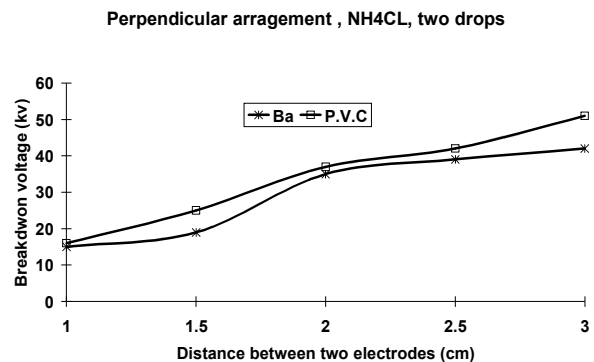


Fig.(9): Relation between breakdown voltage and gap distance for perpendicular arrangement at different sample of insulating surface, for two drops.

Fig.(10) shows relation between inception voltage and number of drops at Ba sample of insulating surface, for 3 cm gap distance and NH4CL solution for two different setups namely, perpendicular and tangential arrangements. The figure indicated that the inception voltage is proportion inversely

with the number of water drops. The inception voltage decreased with increasing the number of water drops and its values for perpendicular arrangement are higher than for tangential arrangement.

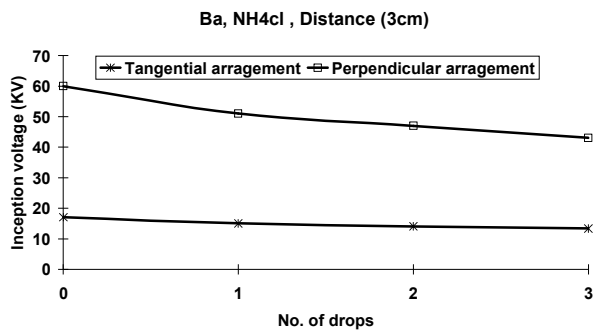


Fig.(10): Relation between inception voltage and number of drops for different arrangement setup at Ba sample of insulating surface, for 3 cm gap distance.

Fig.(11) shows relation between breakdown voltage and gap distance for perpendicular arrangement with three spherical water drops on PVC sample insulating surface. Different solution are used namely, NACL and NH4CL. The figure indicates that, the breakdown voltage values in case of NACL are higher than its values in case of NH4Cl solution.

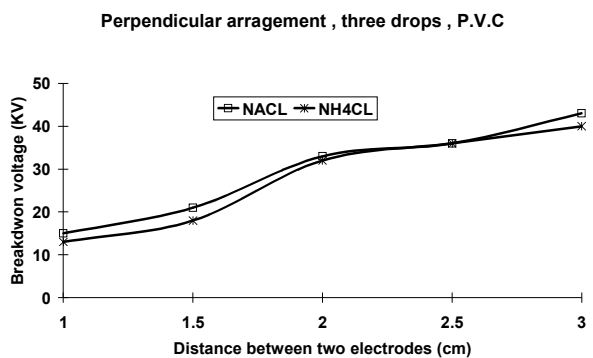


Fig.(11): Relation between breakdown voltage and gap distance for perpendicular arrangement at different solution drop for PVC sample, and three drops.

## 6- Conclusion

In this study, investigations on the water drop deformation, level and location of the partial discharges, as well as electrical field distribution are performed for two different electrodes arrangements. The main results so far are summarized as follows:

1. The size of the water drops influences the inception voltage slightly as a larger drop volume requires a higher electrical field
2. In the tangential arrangement, the highest electrical field stress is located in the lower part of the water drop and towards the electrodes. In the perpendicular arrangement, the critical points are at the top of the drop where the highest electrical field stress is reached. In reality the drop is changing its shape irregularly; therefore the field distribution will be different.
3. Calculated values of the electric field are considered. Compared to the case without a drop, the water drop is intensifying the local electric field

stress. This intensification is strongly dependent on the geometrical configuration of the droplet, which, again, is deformed by the alternating electric field. Thus, sharp points can rise from the drop in the case of the perpendicular setup and the junction between water, air and sample can be shifted to the electrodes in the tangential setup.

4. PD is located between the drop and the electrodes in the tangential arrangement and from the drop tip to the upper electrode in the perpendicular arrangement.
5. Water drop cause great reduction in inception voltage and this reduction depend on droplet number and size.
6. In the case of the tangential field, just at a lower value of electrical field the partial discharges are present in comparison with the perpendicular arrangement where they start at a higher value of background field.

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