Electric Power Systems Research 143 (2017) 66–72

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Flashover voltage of silicone insulating surface covered by water droplets under AC voltage

F. Aouabed[a], A. Bayadi[a,*], R. Boudissa[b]

[a] Département Electrotechnique, Université Ferhat Abbas de Sétif 1, Sétif, Algeria
[b] Labo Génie Electrique, Université A. Mira, Béjaia, Algeria

ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form
13 September 2016
Accepted 10 October 2016

Keywords:
Contamination
Flashover
Testing
Silicone rubber insulators
Surface wettability
Water droplets

ABSTRACT

Discharges caused by water droplets on the surface of polymeric insulators can affect the long-term reliability of the component by lowering the surface hydrophobicity boosting surface discharges. The main objective of this work is to quantify the effect of different types of water drops arrangements, their position and dry bands width on the flashover voltage of the silicone insulating surface with non-uniform electric field systems. The tests were done on a rectangular sample under AC voltage. Water droplets with different conductivities and volumes were placed on the silicone rubber surface with a micropipette. A rod-rod electrode system is used.

The findings of this work indicate that the performance of the samples decreases with the presence of water drops on their surfaces. Further, these experimental findings show that there is a limiting number of rows from which the flashover voltage of the insulation is minimal and constant. This minimum is a function of the distance between two successive rows.

Finally, it is concluded that the system withstand voltage increases when the row of droplets on the electrode axis is removed.

1. Introduction

Nowadays, silicone rubber insulation materials are widely used in high voltage outdoor insulation systems as they can combat pollution flashover problems.

The difference in pollution flashover performance of silicone rubber and other insulating materials is due to the way that water wets their surfaces. It resides as discrete drops on silicone rubber, and the mechanism of flashover is due to the breakdown of the air between the water drops and the deformation of these drops in the direction of the electric field which brings the insulation to degradation and failure.

During the past 25 years polymeric materials have emerged as a viable option to porcelain and/or glass for outdoor insulation [1,2]. Polymeric insulators are increasingly being used in both the distribution and transmission systems because of their very strong resistance to the contamination, their lightness, their mechanical resistance and their very good wettability. The deterioration of insulator surface is one of main problems to the safety and reliability of electric systems. This is due to environmental conditions (light rain, morning dew), which significantly affect its performance. It is known that water droplets may cause, under applied electric field, deterioration of the surface of a non-ceramic insulator even in conditions of low pollution. This is due to the fact that water droplets on a polymer surface locally increase the applied electric field. Local field intensifications will lead to partial discharges and/or localized arcs. These partial discharges destroy the hydrophobicity and cause the degradation of the insulators which can play an important role in long-term performance [9–13]. The influence of various parameters on the behavior of water droplets on polymeric surfaces under high electric fields has been the subject of several investigations [3–13]. The main objective was to increase the alternating electric field. Karady [5], for example, presented the results of an experimental investigation which provides a better understanding of the phenomena leading to flashover. It was shown that the hydrophobic nature of silicone rubber surface results in a flashover mechanism different from that of porcelain insulators. Changes in surface resistance induced by discharge activity on wet and contaminated surface have been identified as one of the sources of flashover of silicone insulators. Phillips et al. [10] published the results of a research that correlates the insulators aging with corona activities from water droplets. Using small-scale experiment, it was shown that Water drops on the sheath surfaces of SiR insulator can

* Corresponding author at: Département d'Electrotechnique, Faculté de Technologie, Université Ferhat Abbas Sétif 1, Algeria. Tel.: +213 665 303 202; fax: +213 36 611 211.
E-mail addresses: fatiha_ess@yahoo.fr (F. Aouabed), a_bayadi@yahoo.fr, a_bayadi@univ-setif.dz (A. Bayadi), raboudissa@yahoo.fr (R. Boudissa).

http://dx.doi.org/10.1016/j.epsr.2016.10.025
0378-7796/

produce corona, and the field necessary to produce corona depends on the droplets size and the surface hydrophobicity.

Swift [14] studied theoretical and experimental investigation of droplets on the surface insulator from the viewpoint of water triggered electrical breakdown of an air-dielectric interface. It was shown that greatly reducing the hydrophobicity of the surface by sparking the flashover voltage, but recovery to the fully-hydrophobic value takes only a few minutes. and that for the fully hydrophobic case, flashover is triggered by gross distortion of the water droplet.

In Ref. [15], the authors have presented an experimental study on the problems arising from the application of uniform ac electric fields on water droplets deposited on polymer surfaces.

Different polymeric materials were used. It was shown that various parameters such as water conductivity, droplet volume, droplet positioning and polymer surface roughness affect the flashover voltage. It was also reported that the positioning of the droplets plays a greater role in determining the flashover voltage than the droplet volume.

In Ref. [16], tests have been done on water droplets of different conductivities and volumes deposited on the surface of silicone rubber. Factors affecting the corona discharge of water droplets were analyzed by calculating the electric field. The authors reported that water droplets increase the electric field and can cause corona discharge. They also observed that the droplet vibrates and lie down to the positive electrode in a wave synchronism with the applied voltage frequency.

Fernando et al. [17] studied the behavior of leakage current on composite insulators of different materials. They concluded that the leakage current is capacitive in nature and often has a sinusoidal shape. When the hydrophobicity is lost, the leakage current becomes more resistive, with peaks due to discharges in dry bands.

Lopes et al. [20] measured partial discharge (PD) from water droplets on a silicone rubber insulating surface in an ac field. They have shown that the presence of water droplets on a silicone rubber surface produces an electric field enhancement. The field enhancement factor depends on the size and number of droplets. They also observed that the electrostatic forces change the droplet shapes and spread them in the field direction.

Souza et al. [21] investigated the corona inception and its relation with polymer surface conditions. They concluded that the association water droplets and pollution, enhance the electric field and can lead to corona discharges and eventually to failures, under heavy contaminated regions.

Phillips et al. [22], for example, presented summarized the findings of the extensive research carried out by these two organizations (EPRI and STRI) to determine a practical limit for the permissible e-field on insulator surfaces for design purposes.

However, to the authors' best knowledge, A few theoretical and experimental works studying the influence of the combination the droplets arrangements with dry bands on polymeric surface have been done [18].

To form a better view of the behavior of water droplets under a non-uniform electric field, we carried out several experimental tests in the high voltage laboratory. We investigated the influence of the number of water droplets rows and the distance between them. This paper summarizes findings of experiments which allow quantifying these effects on the flashover voltage.

2. Experimental setup and test procedure

The withstand voltage measurement and visualization of the air gap disruption phenomenon were conducted using equipments depicted in Fig. 1. The test circuit consists of a HV transformer (Tr) having a maximum secondary voltage of 140 kV. A control unit (CU) for automatic or manual speed ramp control. A digital peak voltmeter (V) at the low-voltage arm of a capacitive divider (C_1, C_2) was used for voltage measurements. A current-limiting resistance (R_a) was connected in series with test object (To). The development of the electrical discharge along the sample surface was visualized and recorded from inception to full flashover using a video camera system

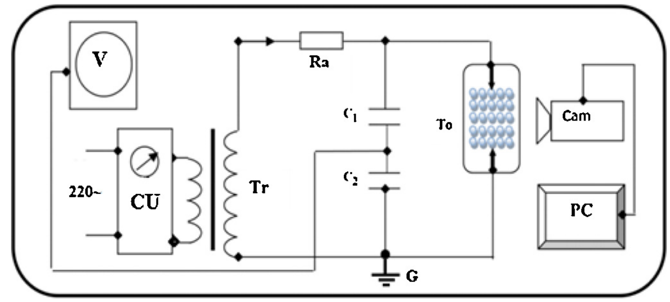

Fig. 1. Laboratory test setup.
(CU: transformer control unit; Tr: HV transformer; Cam: came scope; PC: personal computer; To: test object; C1, C2: capacitive divider; Ra: resistance; V: digital peak voltmeter).

The air gap system has two point electrodes. The high-voltage and earth electrodes consist of a cylindrical stainless steel rod 5 mm in diameter. They are terminated by a conical tip having an angle of 60° and radius of curvature of 0.5 mm.

The rods are fixed on the holes of two PVC tubes.

The test specimen is a plate-shaped silicone rubber having 120 mm in length, 80 mm in width and 5 mm in thikness. The pollution solution comprises salt and distilled water. The water droplets have been deposited on the hydrophobic surface using a micropipette. The volume of these droplets can be obtained by tuning the micropipette at the desired size. In this case, the volume of water droplets deposited is 40 µl. The volume conductivity σ_v of the polluting solution was directly measured by a mobile probe volume conductimeter and was found to be about 180 µS/cm.

The air gap distance was taken equal to 6 cm. Twenty five tests were carried out and voltage steps ΔV of approximately 5% of U_c were used. These test parameters are well within the recommended values for such statistical measurements where the number of tests **n** should be between 20 and 60 tests and the voltage step ΔV between 1% and 10% of the flashover voltage. Before each new test, the sample is cleaned and rinsed with water then dried using paper tissue. Then cleaned with the isopropanol alcohol. For each calculated mean value, by applying correction factors, a disruptive discharge voltage measured in given test conditions (temperature *T*, pressure *P*, humidity *H*) is converted to the equivalent value under the standard reference atmospheric conditions ($T_0 = 20\,°C$, $P_0 = 101.3\,kPa$, $H_0 = 11\,g/m^3$) [19]. The group of water droplets is characterized by a couple of variable (ar, dg). The distance ar is the width between two successive rows and dg is the distance between two successive columns of water droplets as shown in Fig. 2.

3. Results and discussion

To investigate the influence of water droplet on the flashover voltage of a silicone rubber insulating surface a series of experiments have been conducted as follows:

3.1. Effect of water conductivity

Fig. 3 shows the influence of the water droplets conductivity on the mean value of the insulator flashover voltage for two different numbers of rows.

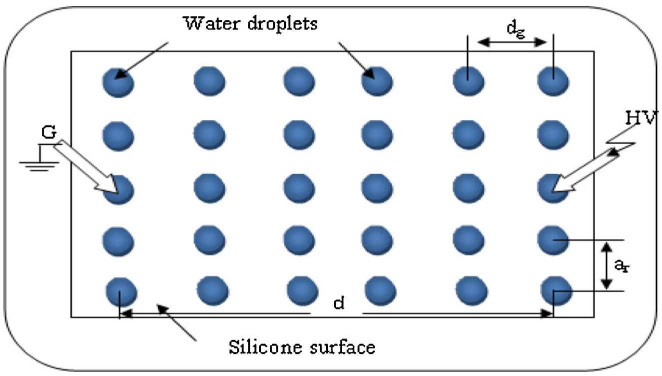

Fig. 2. Distribution of water droplets on the sample.

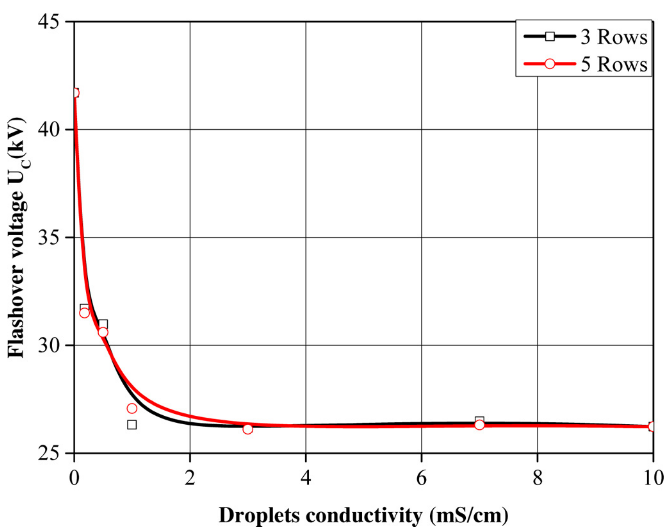

Fig. 3. Influence of the water droplets conductivity on the insulator flashover voltage.

The obtained results show that the chosen values of rows does not significantly affect the characteristic $Uc = f(\sigma_v)$.

Furthermore, as can be seen, the average flashover voltage decreases by approximately 38% with the pollution conductivity until a limit value of about 2.5 mS/cm beyond which the dielectric strength of the system remains constant. This is mainly due to the fact that from this limit, the water becomes conductive.

3.2. Number of rows of water droplets

In this part of our investigations, experiments were performed without any droplets between the electrodes. This was done in order to have reference values of the flashover voltage. In order to understand the influence of droplets number of rows between the electrodes, the latter is varied from 1 to 11. The volume conductivity is maintained constant at about 180 µS/cm. The obtained results are shown in Fig. 4. The observations with the video camera system have shown that the flashover process from the inception to full flashover is described essentially as follows:

a) First, the group of water droplets deposited on the sample surface, before its energization, is shown in Fig. 4a. The middle row coincides with the electrodes axis and its extreme droplets got in contact with their points.
b) In the second phase, When an electric field is applied, It is observed that the water droplets shape change along the electrode axis leading to the decrease of the ignition distance (Fig. 4b) and the sharp edge of the water droplets at the triple line together with the opposite electrode form a non-homogeneous field configuration which is the basic cause to have the streamer inception on the sample surface.
c) Next, for the reason that the electric-field strength near the HV electrode is strong enough, electrical discharge is established along the electrode axis as shown in Fig. 4c,
d) Finally, the tested sample after the full flashover is shown in Fig. 4d.

The variation of flashover voltage as a function of water droplets number is illustrated in Fig. 5. It can be seen that the presence of water droplets covering the hydrophobic insulating surface energized with alternating voltage causes the reduction of its performance. Indeed, the flashover voltage decreases as the number of rows increases. This can be explained by the decrease of the ignition distance due, in one hand, to the space occupied by volume of water droplets before deformation and in the other hand, to the their stretching along the path followed by the electric discharge.

Taking into account these results it can be seen that the flashover voltage decreases rapidly to a limit value of the number of rows

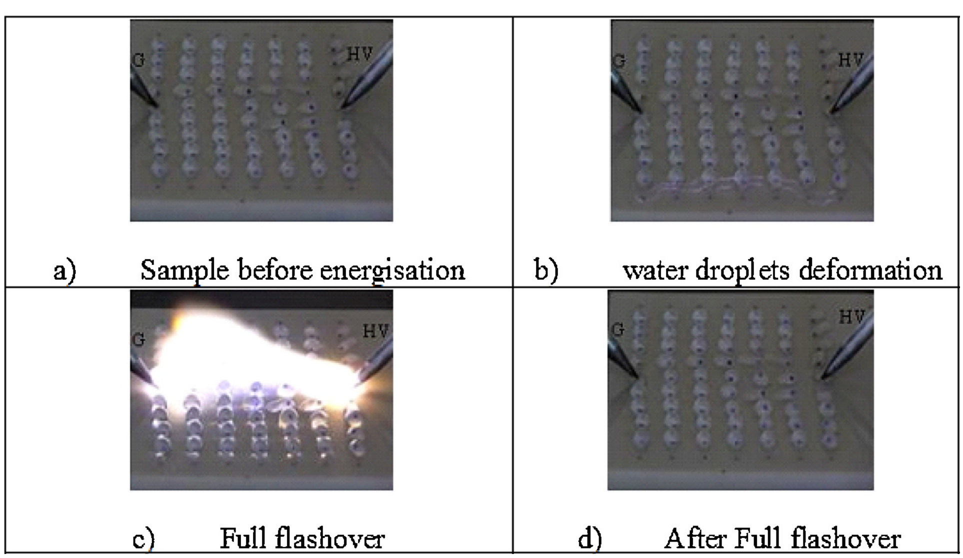

Fig. 4. Discharge development stages on the sample fully covered by water droplets.

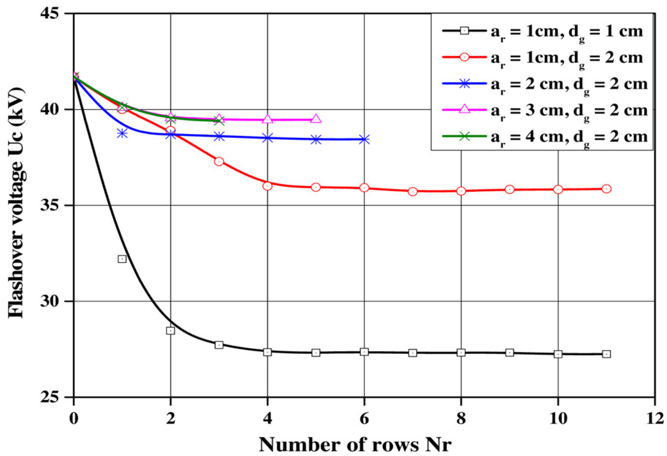

Fig. 5. Flashover voltage vs the number of rows droplets for different distances between them.

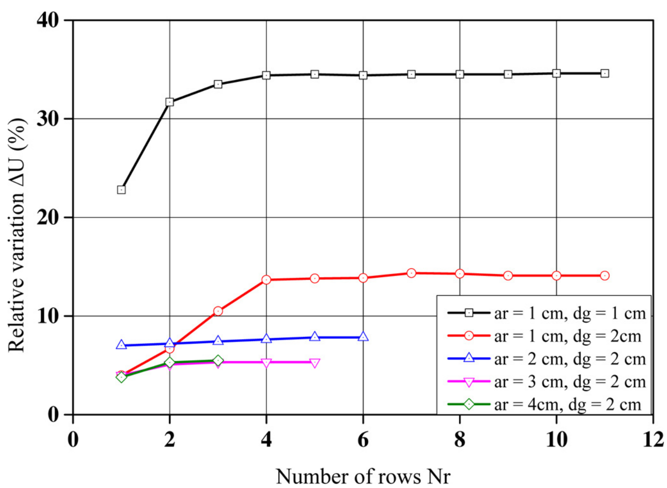

Fig. 6. Relative reduction of flashover voltage as a function of rows number.

from which, it becomes constant, the maximum variation of electric performance is estimated to 35%. The value of this limit is a function of the distance between two successive rows. Furthermore, when the distance ar is decreased along the creepage distance of the sample, a significant decrease in its performance is observed as well.

Fig. 6 shows the relative reduction of flashover voltage as a function of rows number. We can see that the relative reduction increases rapidly to a limit value (5 rows) of the number of rows from which, it becomes relatively constant, which is in accordance with the results previously obtained.

The relative reduction between flashover voltage and water droplets rows can be obtained as follows:

$$\Delta U = 100\% \times (U_0 - U_i)/U_0 \quad (1)$$

where U_0, U_i are the flashover voltage corresponding to the case without and with water droplets rows respectively. i is varied from 1 to 11.

Quantitatively, Table 1 summarizes the results obtained for the maximum relative variation of U_C when i is taken equal to 0 and 5 respectively. The maximum flashover voltage of the air gap with five rows is about 35% lower than that obtained in the case of a dry clean atmosphere. It should be noted that for the last value in the table, only 3 rows were used due to the dimensions of our samples.

Table 1
Relative reduction of flashover voltage with number of rows.

	Number of rows	Uc (kV)	ΔU (%)
ar = 1 cm, dg = 1 cm	0	41.7	35%
	5	27.31	
ar = 1 cm, dg = 2 cm	0	41.7	14%
	5	35.94	
ar = 2 cm, dg = 2 cm	0	41.7	8%
	5	38.43	
ar = 3 cm, dg = 2 cm	0	41.7	5.35%
	5	39.47	
ar = 4 cm, dg = 2 cm	0	41.7	5.5%
	3	39.4	

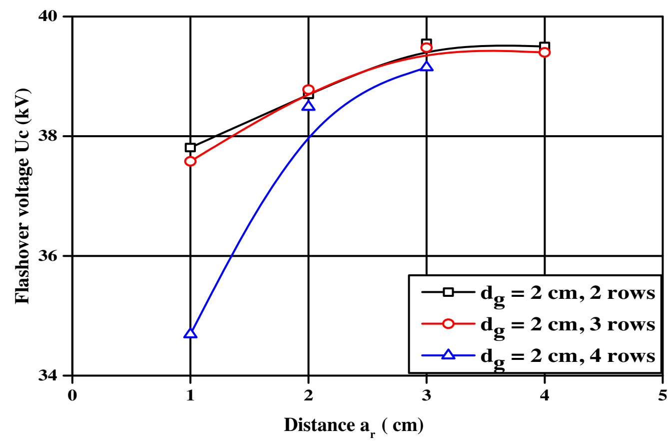

Fig. 7. Effect of the distance ar on the insulator flashover voltages.

3.3. Distance between two successive rows

In this section the effect of the distance ar is investigated. The arrangement of water droplets on the surface of the sample is designed such that there is no row along the electrode axis. The obtained results are illustrated in Fig. 7 for three different values of ar. As can be seen the flashover voltage increases with the distance between two rows. Besides this we can see that the voltage increases rapidly up to a limit from which no improvement is detected.

3.4. Position and width of a dry zone perpendicular to the electrodes axis

Fig. 8 shows the shape of the insulation performance vs the number of rows of water droplets deposited on the surface perpendicular to the electrodes axis. The total number of perpendicular rows is 7. The number of parallel rows in this case is equal to 5. The distance between two successive rows is equal to 1 cm and the water droplets conductivity is about 180 μS/cm.

Results of Fig. 8 show that when creating a dry band in the vicinity of the grounded electrode, the flashover voltage passes through a maximum for an air gap distance equal to approximately 6 cm which corresponds to a single row of water droplets in contact with the high voltage electrode. This optimum can be explained by the fact that after deformation of water droplets (Fig. 9a, b, d), the discharge arc over water droplets arises far away from the end of the high voltage electrode along a path characterized by a peak in its middle (Fig. 9c).

This path is longer than that between the two points without water droplets. The system in this case is more rigid than when the dry band is at the high voltage side. However, when the width of the dry band is equal to half the distance between the electrodes, the withstand voltage of the system with a dry band in the vicinity

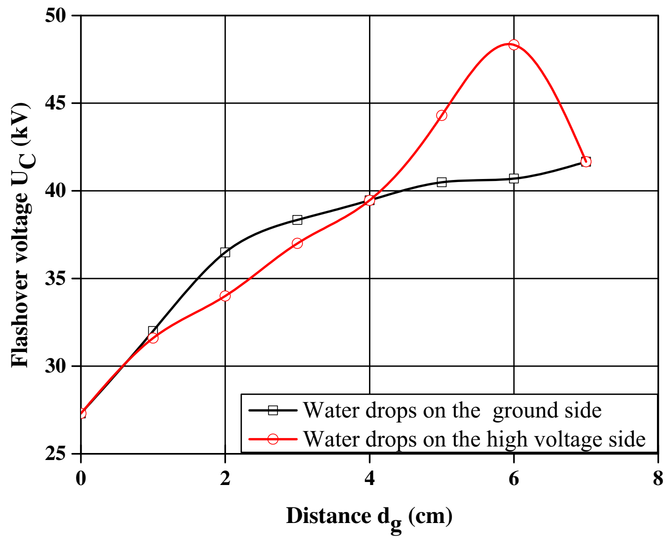

Fig. 8. Relation between the flashover voltage and the distance dg.

of the high voltage electrode is higher than the same system with the dry band in the ground electrode side. This discrepancy is due to the fact that deposited water droplets in the vicinity of the HV electrode shorten the inter-electrode path

3.5. Position and width of a dry band parallel to the electrodes axis

In this section, the effect of the dry band distance l_{db} parallel to the electrode axis on the flashover voltage is investigated. This investigation was achieved by removing droplets rows from selected areas of the insulator surface. The water droplets are characterized by an electric conductivity equal to 180 μS/cm having ar = 1 cm and dg = 2 cm. the initial total number of rows is equal to 11.

As shown in Fig. 10, two scenarios were studied:

a) After covering the entire surface of the sample by water droplets, row n°6, by which we mean the row along the electrode axis, was removed first, then row n°5 on its right next comes row n°7 on its left.

This practice continues until only one row remains on the sample surface,

b) In the second scenario, the droplets rows were removed one by one starting from row n°1 until only one row remains on the sample surface as well.

The obtained results are shown in Fig. 11, where the variation of the flashover voltage is plotted as a function of the dry band distance l_{db} position and width.

As can be seen, in the case where water droplets row on the electrode axis was removed, the dry band created causes an increase in the dielectric strength of the system at its maximum value. From this limit removal of any other row does not produce any improvement. This means that the existence of the row along the electrodes axis contributes significantly to the shortening of the arcing path between the two electrodes. This was verified during the tests by obtaining photographic evidence for the discharges following the insulator surface (Fig. 12). Its removal does not automatically change the path of the electric discharge, despite the increase of the ignition distance and partial deformation of water droplets of the adjacent rows.

In addition to this, Fig. 11 indicates that a dry band having a width less than or equal to 5 cm obtained by deleting five rows to the left of the electrode axis (scenario b) does not affect the system performance and the flashover voltage is always at its minimum. However, Not only the removal of the droplets row n°6, which is on the electrode axis, increases the dielectric strength of the system but it produces the highest flashover voltage as well. From this limit no improvement was seen when deleting the rest of the droplets rows.

4. Conclusions

The analysis of the effect of different types of arrangements of water droplets on the flashover voltage of a silicone surface with a non-uniform field electrode system led mainly to the following conclusions:

- The performance of a insulating surface is reduced when it is uniformly covered by water droplets;
- Under the influence of water droplets, there is a limited number of rows for which the insulation performance is minimal (about 35% lower than that obtained in the case of a dry clean atmo-

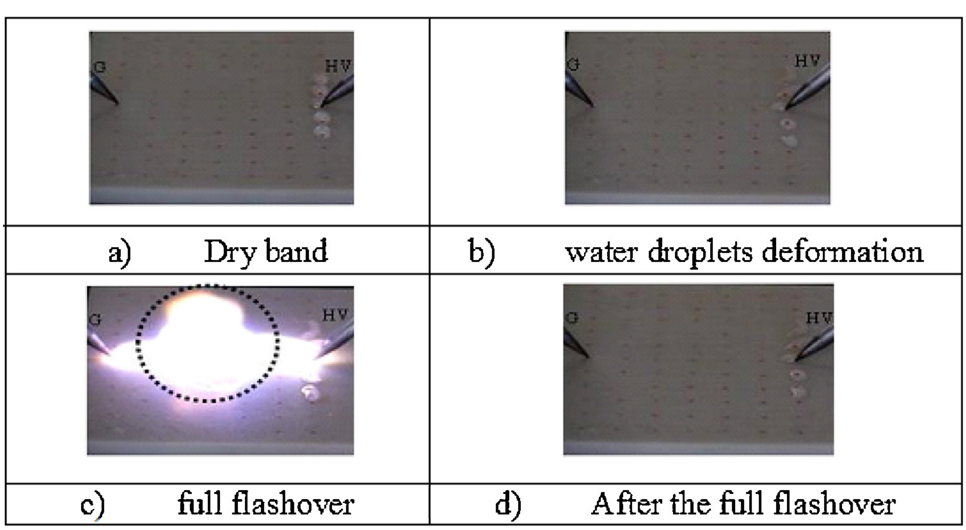

Fig. 9. Flashover process across the insulating surface: case of a single row at the HV electrode.

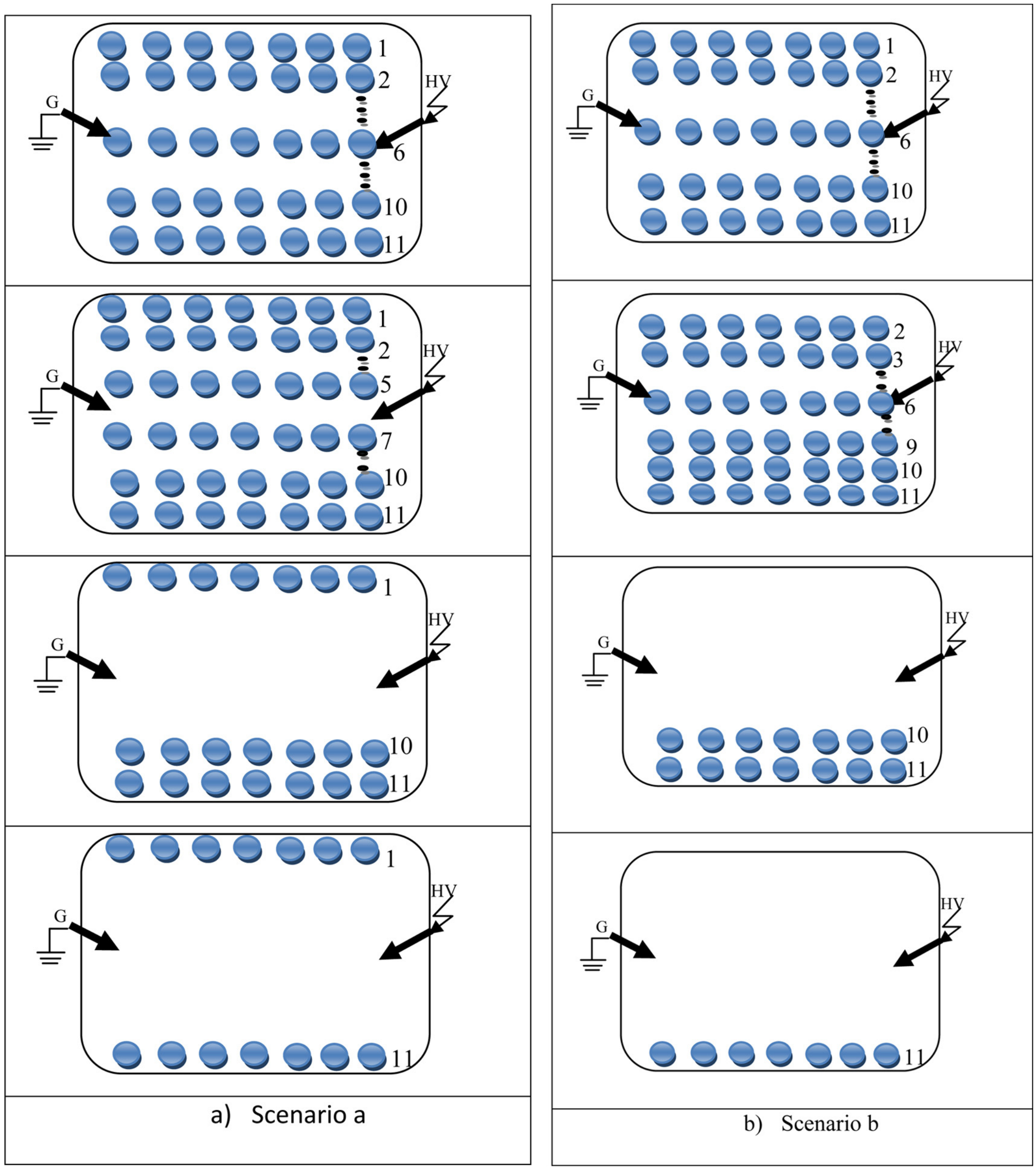

Fig. 10. Considered scenarios of the dry band.

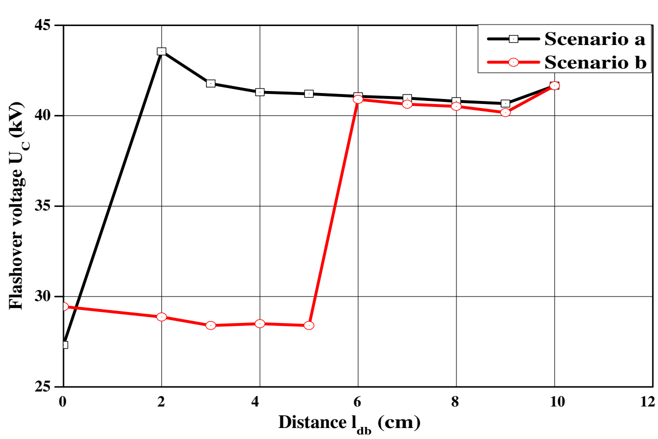

Fig. 11. Variation of the flashover voltage vs the dry band distance l_{db}.

sphere) and is quite constant beyond it. This minimum value depends on the distance between two successive rows of water droplets;

- In the case where water droplets row on the electrode axis does not exist, the created dry band increases the dielectric strength of the system;
- For the case where a dry band is created in the vicinity of the ground electrode such that a single row exist along the line passing through the high voltage electrode, the withstand voltage of the system is higher than that in the case of absence of water droplets on the surface.
- The flashover voltage decreases in a non-linear manner and is slightly affected by the increase of the water conductivity, in high conductivities region. Finally, the effect of the electrical conductivity of water droplets on its performance, erected falling to 38%.

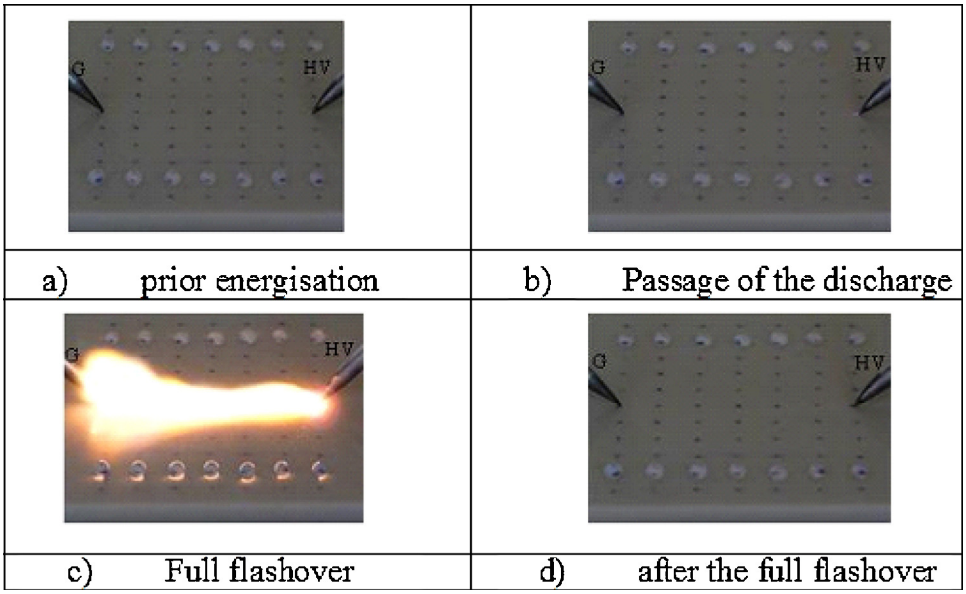

Fig. 12. Discharge stages: case of a dry band parallel to the electrode axis.

Acknowledgements

This work is a part of a research project approved under the number: J0201220120004. The authors would like to thank the Ministry of higher Education and Science Research of Algeria for the financial support of this project.

References

[1] R. Hackam, Outdoor HV composite polymeric insulators, IEEE Trans. Dielectr. Electr. Insul. 6 (5) (1999) 557–585.
[2] E.A. Cherney, R.S. Gorur, RTV silicone rubber coatings for outdoor insulators, IEEE Trans. Dielectr. Electr. Insul. 6 (5) (1999) 605–611.
[3] J. Ndoumbe, A. Beroual, A.M. Imano, Behaviour of water droplets on insulator surfaces submitted to DC voltage – coalescence, Proceedings of the Annual Report Conference Electrical Insulation and Dielectric Phenomena (CEIDP) (2012) 725–728.
[4] L. Yong, X.D. Boxue, Recurrent plot analysis of leakage current in dynamic drop test for hydrophobicity evaluation of silicone rubber insulator, IEEE Trans. Power Deliv. 28 (4) (2013) 1996–2003.
[5] G.G. Karady, Flashover mechanism of non-ceramic insulators, IEEE Trans. Dielectr. Electr. Insul. 6 (5) (1999) 718–723.
[6] M.G. Danikas, R. Sarathi, P. Ramnalis, S.L. Nalmpantis, Analysis of polymer surface modifications due to discharges initiated by water droplets under high electric fields, Int. J. Electr. Electron. Eng. 4 (5) (2010) 329–334.
[7] M.H. Nazemi, V. Hinrichsen, Partial discharge inception electric field strength of water droplets on polymeric insulating surfaces, IEEE Trans. Dielectr. Electr. Insul. 22 (2) (2015) 1088–1096.
[8] H.P. Nagaraj, N. Vasudev, K.N. Ravi, S. Aradhya, Behaviour of water droplets on polymer surface, Proceedings of the IEEE 10th Intern. Conf. on the Properties and Applications of Dielectric Materials (2012) 1–4.
[9] Y. Zhu, K. Haji, M. Otsubo, C. Honda, N. Hayashi, Electrohydrodynamic behaviour of water droplet on an electrically stressed hydrophobic surface, J. Appl. Phys. 39 (2006) 1970–1975.
[10] A.J. Phillips, D.J. Childs, H.M. Schneider, Aging of non-ceramic insulator due to corona from water drops, IEEE Trans. Power Deliv. 14 (3) (1999) 258–263.
[11] S.M. Rowland, F.C. Lin, Stability of alternating current discharges between water drops on insulation surfaces, J. Appl. Phys. 39 (2006) 3067–3076.
[12] D.A. Swift, C. Spellman, A. Haddad, Hydrophobicity transfer from silicone rubber to adhering pollutants and its effect on insulator performance, IEEE Trans. Dielectr. Electr. Insul. 13 (4) (2006) 820–829.
[13] H. Wang, Z. Peng, S. Zhang, P. Liu, Simulation study on E-field distribution and corona characteristics of composite insulator with water droplets, Proceedings of the Annual Report Conference Electrical Insulation and Dielectric Phenomena (CEIDP) (2013) 422–425.
[14] D.A. Swift, Flashover of an insulator surface in air due to polluted water droplets, Proceedings of the 4th Int Conf. on Properties and Applications on Dielectric Materials 2 (1994) 550–553.
[15] M.G. Danikas, P. Rakitzis, K. Karakoulidis, Study of parameters related to deterioration phenomena due to water droplets on polymeric surfaces, J. Electr. Eng. 57 (3) (2006) 130–137.
[16] S. Zhu, N. Yamashita, M. Anami, C. Otsulbo, Y. Honda, Corona discharge phenomenon and behaviour of water droplets on the surface of polymer in the AC electric field, Proceedings of the 7th Int. Conf. on Properties and Applications of Dielectric Materials vol. 2 (2003) 637–641.
[17] M.A.R.M. Fernando, S.M. Gubanski, Leakage current patterns on contaminated polymeric surfaces, IEEE Trans. Dielectr. Electr. Insul. 6 (5) (1999) 660–667.
[18] M.G. Danikas, P. Ramnalis, R. Sarathi, Experimental results on the behaviour of water droplets on polymeric surfaces under the influence of electric fields: the case of an inclined test arrangement for PVC, rubber and silicone rubber, Funktechnikplus J. 1 (2) (2013) 19–39.
[19] BS EN 60060-1 High-voltage test techniques. Part 1: general definitions and test requirements, (2010).
[20] Ivan J.S. Lopes, Shesha H. Jayaram, Edward A. Cherney, A study of partial discharges from water droplets on a silicone rubber insulating surface, IEEE Trans. Dielectr. Electr. Insul. 8 (April (2)) (2001) 262–268.
[21] B.-A.L. Souza, I.J.S. Lopes, Experimental investigation of corona onset in contaminated polymer surfaces, IEEE Trans. Dielectr. Electr. Insul. 22 (2) (2015) 1321–1331.
[22] C.-A.J. Phillips, A.J. Maxwell, I. Engelbrecht, Electric-field limits for the design of grading rings for composite line insulators, IEEE Trans. Power Deliv. 30 (3) (2015) 1110–1118.