Open Access Journal

Journal of Power Technologies 97 (4) (2017) 342–346

journal homepage:papers.itc.pw.edu.pl

Experimental modeling of the flashover of polluted insulator in the presence of a metal plate using RSM technique

Mohamed Bouhmama, Samir Flazi, Said Nemmich, Amar Tilmatine[a]

[a] *School of Mining and Safety Engineering, Anhui University of Science and Technology, Huainan Anhui 232001, China;*

Abstract

Flashover of polluted insulators has been the subject of many experimental and numerical research papers. Several mathematical models of flashover voltage have been proposed in terms of current, discharge length, electrolyte length and resistivity. However, there is no model as yet based on the geometric factors of the electrolyte channel—such as width and depth—and the interaction between them. Furthermore, as very few research papers have been published about discharge elongation in the presence of a metal object between the electrodes, the aim of the present work is to model flashover voltage in the presence of a metal plate, dipped in electrolyte or placed on its surface. Two mathematical models were obtained using response surface modeling and they were used in the analysis of the effect of geometric factors on the flashover discharge.

Keywords: Response surface modeling, high voltage, polluted insulator, flashover,

1. Introduction

The flashover of a high voltage polluted insulator causes lines to short-circuit to ground, due to the propagation of an electrical discharge on its surface. A conducting electrolyte is created on the insulator surface due to the combination of ambient humidity with dry pollution deposited on the surface, causing a leakage current to flow [1, 2]. The non-uniform distribution of the leakage current at the polluted surface of the insulator results in the non-uniform heating of the pollution layer giving rise to the formation of dry bands, accompanied by the ignition of partial discharges which transform to complete the flashover [3, 4].

Due to the development of high energy power grids, flashover of insulators polluted with various industrial contaminants is now considered an important problem for the safe operation of transmission lines and the design of external insulation. Mathematical models have been created to predict the critical flashover voltage and are primarily directed toward understanding the development of electric arcs on the insulator surface. Such modeling can be useful for designing high-performance insulators, thus minimizing time consuming experimental laboratory work. However, the development of a mathematical model still remains quite difficult due to the complex phenomena of the flashover [5, 6, 7, 8].

A few research papers have been published about discharge elongation, in the presence of a conductive object between the electrodes, dipped in electrolyte or placed on its surface. The results of such studies have shown that the introduction of the object affects the conditions of discharge propagation [9, 10, 11]. However, analysis of the influence of each factor is not sufficient for a full understanding of the phenomenon, since it does not take into account the effect generated by the interaction between the various factors. On the other hand, several mathematical models of the flashover voltage have been proposed in terms of current, discharge length, electrolyte length and resistivity. However, there is no model based on the geometric factors of the electrolyte channel, such as width and depth. Furthermore, no model has been proposed in the presence of a metallic plate placed in the path of the flashover discharge.

The objective of this paper is to carry out an experimental modeling of the flashover voltage measured on an Obenaus-model laboratory-cell, using the experimental designs methodology. Furthermore, we analyzed the influence of the presence of a metallic plate by performing two centered-face composite designs of the two configurations, with and without the presence of the plate.

2. Material and methods

2.1. Experimental setup

The experimental setup, shown in Fig. 1, delivers a variable DC high voltage up to 30 kV with a maximum current of

---

*Corresponding author

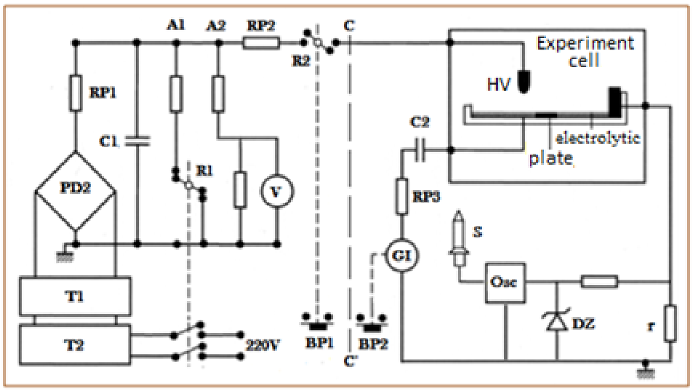

Figure 1: Descriptive schematic of the experimental setup performance

2 A. The voltage supplied by means of a HV capacitor bank of total capacitance C = 16.7 μF, is charged to the desired value by a variable step-up 220V/30kV transformer, through a diode rectifier bridge. The transformer is supplied by using a 0 .. 220 V variac to control the high voltage output.

A measuring set, consisting of a storage oscilloscope (Leader, LBO-5825) and a HV probe (Tektronix, P6015A), serve to measure the applied voltage.

- T1—HV transformer (220 V/ 30 kV)
- T2—Variac (autotransformer) 0/220 V
- PD2—Single-phase HV bridge rectifier
- C1—Battery of 10 capacitors 5 C = 1.67 µF—30 kV
- A1—Automatic discharge circuit of the capacitor C1
- A2—Scaling resistor
- R1, R2—High voltage relay
- GI—Pulse generator.
- BP1—Control push-button of the pulse generator
- BP2—Control push-button of the HV discharge (R2).
- C2—Capacitor of insulation (≈1000 pF).
- Osc—LEADER oscilloscope memory.
- S—Measuring HV probe; Tektronix P6015.
- RP1, RP2 and RP3—Resistors of protection.
- R—Resistor (0.7Ω) for the current measurement.

The experiments were performed using a laboratory “Obenaus-model” cell representing the non-conducting surface of the insulator. A rectangular channel of constant length L = 8 cm, but variable width a and depth p, is made on a Plexiglas plate of thickness 2 cm (Fig. 2). The channel is filled with an electrolyte, which is a mixture of distilled water and sodium chloride salts (NaCl + H2O), with the dosage varying the resistivity of the electrolyte. The HV electrode is placed above the surface of the electrolyte at a fixed height h = 0.3 cm, and 8 cm distant from the ground electrode (Fig. 4). In addition, a metal plate of width a and constant length l = 1 cm, but with variable thickness e, is placed on the discharge path between the two electrodes.

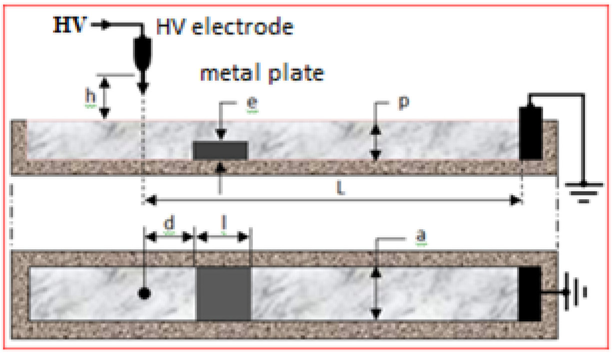

Figure 2: Descriptive representation of the experimental cell and its dimensions (Top) Front view; (Bottom) Top view Variable sizes: width a and depth p of the cell, thickness e of the plate. Constant sizes: height of the HV electrode h = 0.3 cm; Length of the electrolyte L = 8 cm; Length of the metal plate l = 1 cm

The experiments were performed using several experimental cells of different geometric dimensions, having the same constant length L = 8 cm, but different values of width a, depth p and plate thickness e. After each performed test, a new electrolytic solution is replaced and the capacitors are charged again to a voltage V = V_d. The critical flashover voltage Vc measured corresponds to the smallest value of the voltage V_d causing the flashover. The work done in this paper was related to the analysis of three factors: channel width a (cm), channel depth p (cm) and per unit length resistance r (kΩ/cm). Resistance r was considered with the geometric factors, because its value changes with the cell dimensions. Three “one-factor-at-a-time experiments”, followed by two composite designs (without and with plate), were performed following the following experimental procedure: 1) Fixing the variation domain of the factors; 2) modeling step: searching the optimal point corresponding to the lowest value of V_c; and 3) analyzing the influence of the factors.

2.2. Experimental designs methodology

The methodology of the experimental designs is used in particular to determine the number of experiments to be carried out according to a well-defined objective, to study several factors simultaneously and to evaluate the respective influence of the factors and their interactions [12, 13, 14, 15, 16]. The most suitable design which models the process with high precision should be set before starting the experiments. In the present work, the Composite Centred Faces design (CCF), which gives quadratic models, was adopted. A quadratic dependence is determined between the output function to optimize (response) and the input variables u_i (i = 1, .., k) (factors):

$$y = f(u_i) = c_0 + \sum c_i u_i + \sum c_{ij} u_i u_j + \sum c_{ii} u_i^2 \quad (1)$$

Knowing that Δu_i and u_{i0} are respectively the step of variation and the central value of factor i, reduced centred values of input factors may be defined by the following relation:

$$x_i = ((u_i - u_i 0))/(\Delta u_i) \quad (2)$$

With these new variables, the output function becomes:

$$y = f(x_i) = a_0 + \sum a_x x_i + \sum a_{ij} x_i x_j + \sum a_{ii} x_i^2 \quad (3)$$

The coefficients can be calculated or estimated by a data-processing program, in such a way to have a minimum variance between the predictive mathematical model and the experimental results.

MODDE 5.0 software (U metrics AB, Umea, Sweden) was used, which is a Windows program for the creation and evaluation of experimental designs [17]. The program calculates the coefficients of the mathematical model and identifies the best adjustments of the factors to optimize the response. Moreover, the program calculates two significant statistical criteria which make it possible to validate or not the mathematical model, symbolized by R^2 and Q^2. For a model to be validated, both parameters should be high close to the unit, and preferably not separated by more than 0.2 .. 0 .3.

3. Design of flashover experiments

The methodology of experimental designs is a powerful tool for screening and optimization. Screening experiments are designed in this paper to identify the domain of variation of the three factors (classical "one-factor-at-a-time" experiments). The optimization stage of the procedure should determine the factor values for which the flashover voltage is a minimum.

3.1. Variation domain of the factors

The variation limits of the three factors are defined by the following experiments—called "one-factor-at-a-time-experiments"—obtained by varying one factor and keeping the two other constant at fixed values, in both cases without and with the metallic plate. The results obtained are represented in Tab 1.

Obtained results in this section served to define the following variation domain of the three factors for the modeling step:

Width a: a_{min} = 2 cm; a_{max} = 4 cm

Depth p: p_{min} = 0.3 cm; p_{max} = 0.6 cm

Resistance r: r_{min} = 2.5 kΩ/cm; r_{max} = 5 kΩ/cm

Table 1: Obtained values of V_c according to width a, depth p and resistance r

		V_c, kV	
		Without plate	With plate
a (cm) (d = 0.45 cm) (r = 3.75 kΩ/cm)	1	9	15
	2	10	17.5
	3	11	18
	4	11.5	17
p (cm) (r = 3.75 kΩ/cm) (a = 2 cm)	0.3	9.5	17
	0.45	10	17.5
	0.6	11	18
r (kΩ/cm) (p = 0.45 cm) (a = 2 cm)	2.5	9.5	17
	3.75	10	16.5
	5.0	11	16

Table 2: Obtained results of the CCF design without the metal plate

Exp. N°	a, cm	P, cm	r, kΩ/cm	V_{c0}, kV
1	2	0.3	2.5	9.0
2	4	0.3	2.5	10.5
3	2	0.6	2.5	10.0
4	4	0.6	2.5	11.5
5	2	0.3	5.0	10.0
6	4	0.3	5.0	11.5
7	2	0.6	5.0	11.5
8	4	0.6	5.0	12.5
9	2	0.45	3.75	10.0
10	4	0.45	3.75	11.5
11	3	0.3	3.75	10.5
12	3	0.6	3.75	11.5
13	3	0.45	2.5	10.0
14	3	0.45	5.0	11.5
15	3	0.45	3.75	11.0
16	3	0.45	3.75	11.0
17	3	0.45	3.75	10.8

3.2. Modeling of the flashover voltage

The optimal point (a_o,p_o and r_o) was identified using a CCF design; the two levels "max" and "min" are the limits established in the previous section for each of the three variables (a_{min},a_{max}), (p_{min},p_{max})and (r_{min},r_{max}), the central point (a_c,p_c and r_c) being calculated as follows:

$$a_c = ((a_{min} + a_{max}))/2 = (2 + 4)/2 = 3cm \quad (4)$$

$$p_c = ((p_{min} + p_{max}))/2 = (0.3 + 0.6)/2 = 0.45cm \quad (5)$$

$$r_c = ((r_{min} + r_{max}))/2 = (2.5 + 5.0)\ /\ 2 = 3.75k\Omega cm \quad (6)$$

After tthe variation domains of the factors were identified, two experimental designs were performed for both cases, without and with the metallic plate. The obtained results of the voltage V_{c0} (without plate) and V_{c1} (with plate) are given in Tables 2 and 3 respectively. In the configuration without the metal plate (Table 3), a fourth factor was considered, which is the thickness e of the plate (e = 0.15, 0.3 and 0.225 cm). In this case, with four factors, the experimental design comprises 27 experiments.

The coefficients of the obtained mathematical models proposed by software MODDE.05, represented by the plotted diagrams in Fig. 3, show that the coefficients of voltage V_{c1} (with plate) are much greater than voltage V_{c0} (without plate).

Table 3: Obtained results of the CCF design without the metal plate

Exp. N°	a, cm	P, cm	r, kΩ/cm	e, cm	V_{c1}, kV
1	2	0.3	2.5	0.15	16.5
2	4	0.3	2.5	0.15	13.5
3	2	0.6	2.5	0.15	18
4	4	0.6	2.5	0.15	15
5	2	0.3	2.5	0.3	19
6	4	0.3	2.5	0.3	16
7	2	0.6	2.5	0.3	21
8	4	0.6	2.5	0.3	18
9	2	0.3	5	0.15	19
10	4	0.3	5	0.15	17.5
11	2	0.6	5	0.15	20
12	4	0.6	5	0.15	18
13	2	0.3	5	0.3	19
14	4	0.3	5	0.3	18.5
15	2	0.6	5	0.3	23
16	4	0.6	5	0.3	21.5
17	2	0.45	3.75	0.225	18
18	4	0.45	3.75	0.225	17
19	3	0.3	3.75	0.225	14
20	3	0.6	3.75	0.225	19
21	3	0.45	3.75	0.15	17
22	3	0.45	3.75	0.3	21
23	3	0.45	2.5	0.225	17
24	3	0.45	5	0.225	19
25	3	0.45	3.75	0.225	17.8
26	3	0.45	3.75	0.225	18
27	3	0.45	3.75	0.225	18.2

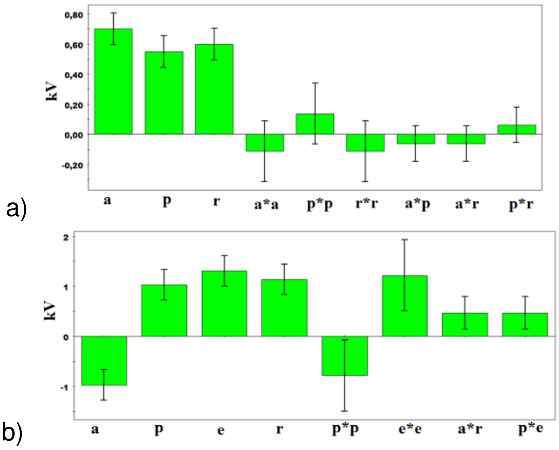

Figure 3: Diagram of the plotted coefficients of the mathematical models

There are currently two different hypotheses about the propagation of the flashover discharge. According to the majority of authors, the vertical starting discharge, which initiates between the high voltage electrode and the electrolytic surface, is cylindrical in shape. According to this hypothesis, the discharge propagates on the polluted surface until flashover while keeping its cylindrical shape. It progresses due to the ionization of the air, which only occurs in the area of the discharge foot [4, 10].

However, according to Flazi's hypothesis, after initiation of the vertical cylindrical discharge, the propagation is caused in this case by the ionization of air, which happens not only near the foot region of the discharge but around the entire body of the discharge (Fig. 4).This is caused by the electric field lines, which become current lines after ionization [6, 7, 8].

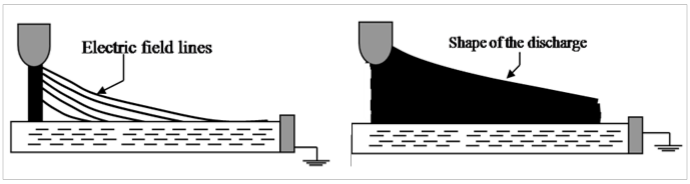

Figure 4: Evolution of the discharge according to Flazi's hypothesis

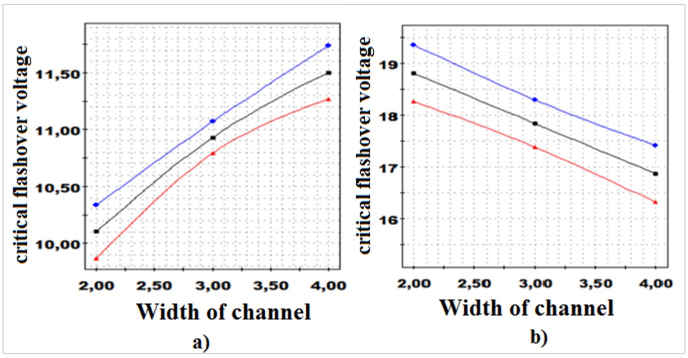

Figure 5: Predictive plots of the voltage in terms of channel width a) without the metal plate b) with the metal plate

We now turn to the distribution of the electric field lines around the vertical starting discharge. According to Flazi's hypothesis, the electric field lines extend to the space between the discharge column and the electrolyte, touch the electrolyte surface and enter into a "short circuit" state, remaining constant along the plate. Indeed, during the flashover, the potential measured at the surface of the electrolyte gradually increases during the propagation of the discharge [18, 19]. In the presence of the metal plate, which represents an equipotential surface, the potential on the plate remains constant, which results in the flashover voltage increasing.

Furthermore, no interaction between the three factors was observed for V_{c0}. In contrast, in the presence of the metal plate, there is a strong interaction between all the factors. This is due to the fact that the presence of the plate provides a physical link between the geometric dimensions of the channel. Prediction diagrams plotted with the software (Fig. 5), show that the variation of the flashover voltage in terms of channel width is clearly different with and without the presence of the metal plate. With the plate, the voltage V_{c1} decreases significantly with the width of the electrolyte due to the constriction effect of the current lines. The tightening of the current lines at the surface of the electrolyte layer, resulting in small values of a, is more important in the presence of the metal plate, causing thus the critical voltage to increase.

Iso-response contours plotted with MODDE.05 can be used to analyze and deduce the value ranges of the factors for which the maximum flashover voltage is obtained. The iso-response contours plotted in Fig. 6, representing the influence of width a and depth p on the flashover voltage, show that in the presence of the plate, the effect of the channel depth is greater than in the case without the plate. Ac-

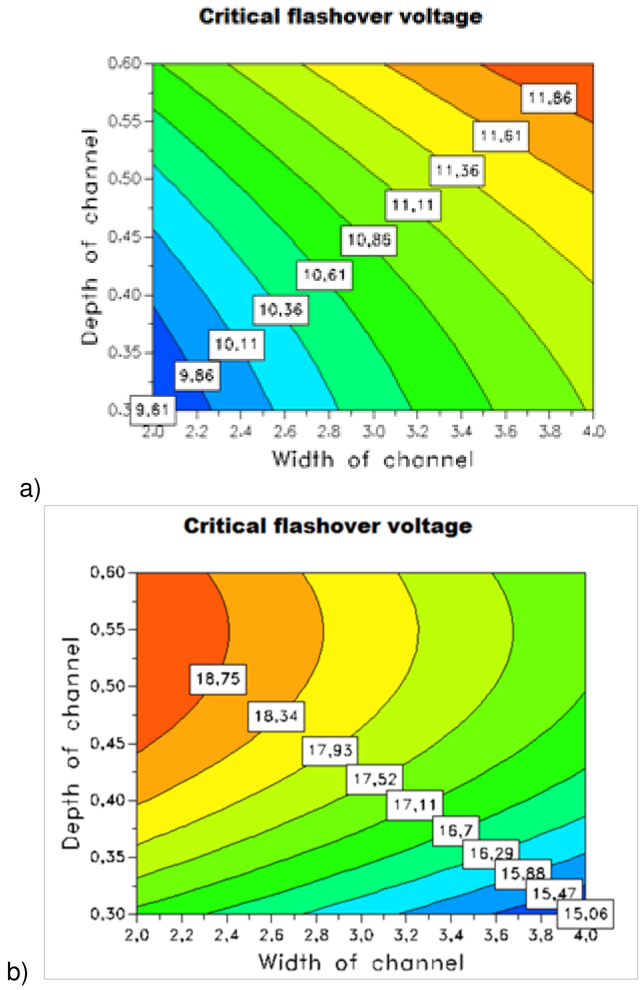

Figure 6: Iso-response contours plotted with MODDE.05 a) Without the metal plate b) with the metal plate

cording to Fig. 5, the flashover without plate occurs at high values of voltage for width a= (3.5. . . 4 cm) and depth p= (0.55. . . 0.6 cm). In contrasts, in the presence of the metal plate the flashover voltage V_{c1} becomes higher for small values of width (2. . . 2.4 cm) and high values of channel depth (0.44. . . 0.6 cm).

4. Conclusions

The flashover discharge propagating to the surface of an electrolyte was analyzed in the presence of a metal strip placed between the high voltage and the ground electrodes. Using the RSM modeling method, a mathematical model based on geometric sizes was obtained and used for analysis and prediction. The flashover voltage in the presence of the plate is much higher, because the distribution of the field lines around the discharge is modified due to the fact that the potential of the metal plate surface remains invariable.

References

[1] X. Jiang, J. Yuan, Z. Zhang, J. Hu, L. Shu, Study on pollution flashover performance of short samples of composite insulators intended for/spl plusmn/800 kv uhv dc, IEEE Transactions on Dielectrics and Electrical Insulation 14 (5).

[2] C.-x. SUN, L.-c. SHU, X.-l. JIANG, W.-x. SIMA, L.-g. GU, Ac/dc flashover performance and its voltage correction of uhv insulators in high altitude and icing and pollution environments [j], Proceedings of the Csee 11 (2002) 024.

[3] Z. Su, Q. LI, Historical review and summary on measures against pollution flashover occurred in power grids in china [j], Power System Technology 12 (2010) 124–130.

[4] R. Wilkins, Flashover voltage of high-voltage insulators with uniform surface-pollution films, in: Proceedings of the Institution of Electrical Engineers, Vol. 116, IET, 1969, pp. 457–465.

[5] R. Sundararajan, R. Gorur, Dynamic arc modeling of pollution flashover of insulators under dc voltage, IEEE Transactions on electrical insulation 28 (2) (1993) 209–218.

[6] P. Ghosh, N. Chatterjee, Polluted insulator flashover model for ac voltage, IEEE Transactions on Dielectrics and Electrical insulation 2 (1) (1995) 128–136.

[7] Z. Aydogmus, M. Cebeci, A new flashover dynamic model of polluted hv insulators, IEEE Transactions on Dielectrics and Electrical Insulation 11 (4) (2004) 577–584.

[8] N. Dhahbi-Megriche, A. Beroual, L. Krähenbühl, A new proposal model for flashover of polluted insulators, Journal of Physics D: Applied Physics 30 (5) (1997) 889.

[9] D. Swift, Flashover across the surface of an electrolyte: arresting arc propagation with narrow metal strips, IEE Proceedings A (Physical Science, Measurement and Instrumentation, Management and Education, Reviews) 127 (8) (1980) 553–564.

[10] R. Wilkins, A. Al-Baghdadi, Arc propagation along an electrolyte surface, in: Proceedings of the Institution of Electrical Engineers, Vol. 118, IET, 1971, pp. 1886–1892.

[11] S. Flazi, N. Boukhennoufa, A. Ouis, Critical condition of dc flashover on a circular sector model, IEEE transactions on dielectrics and electrical insulation 13 (6).

[12] N. L. Frigon, D. Mathews, Practical guide to experimental design, John Wiley & Sons, 1997.

[13] G. Taguchi, G. Taguchi, System of experimental design; engineering methods to optimize quality and minimize costs, Tech. rep. (1987).

[14] L. Eriksson, E. Johansson, N. Kettaneh-Wold, C. Wikström, S. Wold, Design of experiments, Principles and applications (2000) 172–174.

[15] H. Anglart, Modeling of liquid film flow in annuli, Journal of Power Technologies 94 (5) (2015) 8–15.

[16] L. Eriksson, E. Johansson, N. Kettaneh-Wold, C. Wikström, S. Wold, Design of experiments, Principles and applications (2000) 172–174.

[17] A. Umetrics, Modde 5.0. user guide and tutorial, Umetrics, Umea, Sweden.

[18] F. S., Study of flashover polluted insulators ht elongation criteria of the landfill and dynamics of the phenomenon, Master's thesis, Paul Sabatier University, Toulouse (1987).

[19] S. Flazi, N. Boukhennoufa, H. Hadi, F. Taleb, The criterion of dc flashover on a circular sector models, in: Electrical Insulation and Dielectric Phenomena, 2003. Annual Report. Conference on, IEEE, 2003, pp. 277–280.