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

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Abstract

The flashover of high-voltage polluted insulators is considered as one of the most severe problems that occur in the transport of electrical energy. There are many mathematical models of the flashover voltage that have been proposed to analyze the flashover phenomenon. However, no model based on the geometric factors of the electrolyte channel and their interactions was found in the literature. The aim of the present work is the modeling of the flashover voltage in the presence of a metal plate, dipped in the electrolyte at different positions along the elongation path of the discharge. A mathematical model was obtained using response surface modeling technique, which was used for analysing the effect of the geometric factors on the flashover voltage V_c according to the metal plate length, the distance between the metal plate and the high-voltage electrode and the resistivity of the electrolyte. It was found that the voltage V_c in the presence of the plate was significantly increased, because the distribution of the field lines around the discharge is changed due to the fact that the potential of the metal plate surface remains invariable.

Keywords: Electrical discharge, response surface modeling, high voltage, polluted insulator, flashover.

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1. Introduction

The flashover that occurs in the high-voltage polluted insulator of overhead lines causes short-circuit to ground, due to the propagation of an electrical discharge on its surface. First, an electrolyte appears on the insulator surface due to the combination of the dry pollution deposited on the surface of the insulator with the ambient humidity. Therefore, a non-uniform distribution of a leakage current, flowing at the polluted surface of the insulator, results in a non-uniform heating of the electrolyte layer causing the formation of dry bands [1−4]. Then, partial discharges are initiated over the dry bands which lead to complete flashover of the insulator [5−7].

Nowadays, the insulators placed in different industrial zones are polluted with various industrial contaminants and their flashover is considered as one of the most serious problems for the safe operation of the overhead transmission lines and the design of the external insulation.

Mathematical models to predict the critical flashover voltage exist and are primarily directed towards the comprehension of 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 [8−12].

Note that there are only a few research works about the flashover in the presence of a conductive object between the electrodes, dipped in the electrolyte or placed on its surface. The main obtained results of these studies have shown that the presence of the object affects significantly the conditions of the discharge propagation [13−15]. However, the 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.

Moreover, several factors such as the current, the discharge length, the electrolyte length and the resistivity have been analyzed using mathematical models of the flashover voltage. However, no model based on the geometric factors of the electrolyte channel, such as the width and the depth, was developed.

The objective of this paper is to carry out an experimental modeling of the flashover voltage with a laboratory experimental cell, using the experimental designs methodology, by performing a centered-face composite design. A mathematical model was deduced to analyze the influence of the presence of a metallic plate on the flashover voltage, taking into consideration the geometric factors of the experimental cell. The practical interest of the study is to show the improvement of the dielectric strength of the polluted insulators by using a metal plate placed on the discharge propagation path that causes the increase of the flashover voltage.

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 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/30 kV transformer, through a diode rectifier bridge. The transformer is supplied by using a 0−220 V variac in order 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.

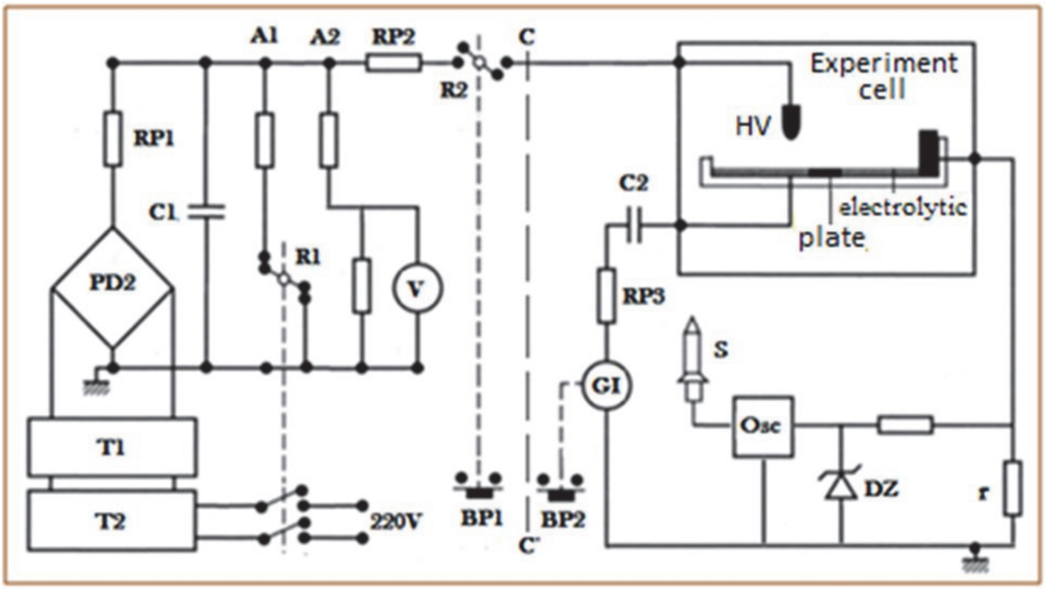


Fig. 1. Descriptive schematic of the experimental setup. T1 – HV transformer (220 V/ 30 kV), T2 – Variac (autotransformer) 0/220 V, PD2 – Single-phase HV bridge rectifier, C1–Battery of 10 capacitors 5 C = 1.67 μF – 30 kV, A1– Automatic discharge circuit of the capacitor C1, A2–Scaling resistor, R1, 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–Oscilloscope memory, S – Measuring HV probe; Tektronix P6015, RP1, RP2 and RP3 – Resistors of protection, R – Resistor (0.7 Ω) 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 made on a plexiglas plate of thickness 2 cm was used for the flashover experiments (Fig.2); It has constant values of width a and depth p but variable values of the plate length l (cm) and the distance d (cm) between the metal plate and the high-voltage (HV) electrode. Note that the effective length $L_0 = L - l$ of the electrolyte was kept constant (Fig. 2), so that for each metal length sample corresponds a different total length L of the experimental cell. The channel is filled with an electrolyte, which is a mixture of distilled water and sodium chloride salts ($NaCl + H_2O$), who's dosage enables to vary the resistivity of the electrolyte. The HV electrode is placed above the electrolytic surface at a fixed height $h = 0.3$ cm, and is distant at L (cm) from the ground electrode. In addition, a metal plate of same width and thickness e but variable length l is placed on the discharge path between the two electrodes.

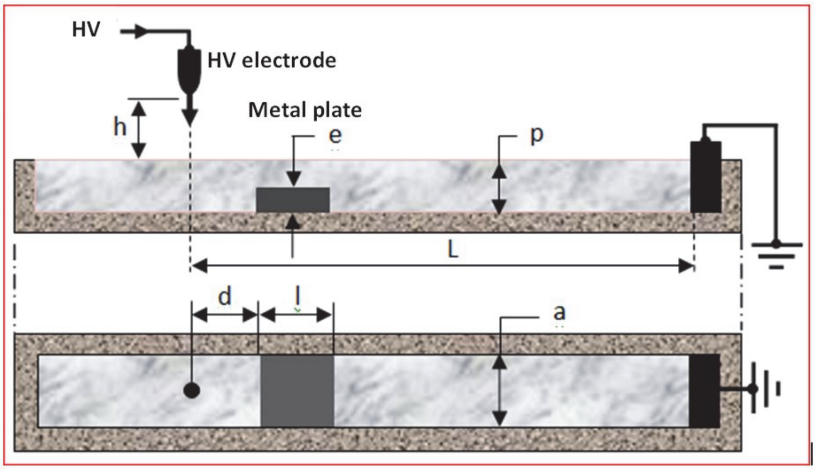


Fig. 2. Descriptive representation of the experimental cell and its dimensions (Top) Front view; (Bottom) Top view.

The experiments were performed by varying the values of length l and distance d. After each performed test, a new electrolytic solution was replaced and the capacitors are charged again to a voltage $V = V_d$. The critical flashover voltage V_c 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 which are the length l (cm), the distance d (cm) and the per unit length resistance r (kΩ cm^{-1}). 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 a composite design, were performed according to the following experimental procedure:

- Identification of the variation domain of the factors by performing the three “one-factor-at-a-time” experiments;
- Experimental modeling by performing the composite design;
- Analysis of the flashover voltage V_c using the obtained mathematical model.

2.2 Experimental designs methodology

The methodology of the experimental designs is particularly used 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 [16–20]. 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):.

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

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:

$$x_i = (u_i - u_{i0})/\Delta u_i \tag{2}$$

With these new variables, the output function becomes:

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

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 the evaluation of experimental designs [21]. The program calculates the coefficients of the mathematical model and identifies also the best adjustments of the factors for optimizing 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.

Except the results obtained in the CCF experimental design, all the experiments in the study were repeated twice and the mean value was used for plotting.

3 Results and discussion

3.1 Preliminary experiments

In Fig. 3 it is plotted the variation of the flashover voltage as a function of the resistivity for three different values of the electrolyte length, without using the metal plate. As expected, the flashover voltage V_c increases almost linearly with the resistivity of the electrolyte. Indeed, the voltage V_c has a linear dependence with both the resistivity r and the length L of the electrolyte, because both are related to the total resistance R of the electrolyte ($R = r*L$).

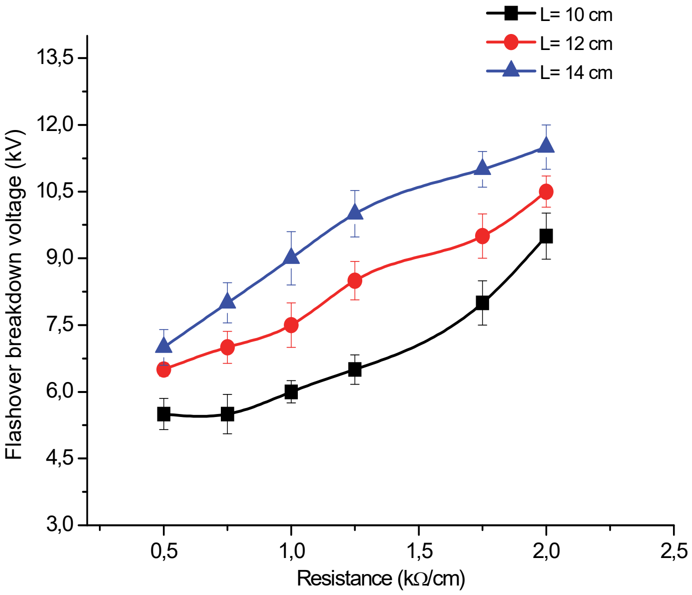


Fig. 3. Variation of the flashover voltage as a function of the resistivity for three different values of the electrolyte length.

The methodology of experimental designs is a powerful tool for screening and modeling. 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 variation limits of the three factors are defined by following "one-factor-at-a-time-experiments" obtained by varying one factor and keeping the two other constant at fixed values. The obtained results are plotted in Figs. 4−6, representing the variation of the flashover voltage V_c as a function of the plate length l, the distance d and the resistance r, respectively.

At a first glance, the obtained results plotted in Fig. 3 and in Figs. 4−6 show clearly that in the presence of a metal plate on the discharge path, the flashover voltage is significantly increased. This difference is discussed at the end of the paper. Results obtained in the previous section served to the definition of the following variation domains of the three factors for modeling step:

Length l: $l_{min} = 2$ cm; $l_{max} = 6$ cm
Distance d: $d_{min} = 1$ cm; $d_{max} = 7$ cm
Resistance r: $r_{min} = 0.5$ kΩ cm^{-1}; $r_{max} = 2$ kΩ cm^{-1}

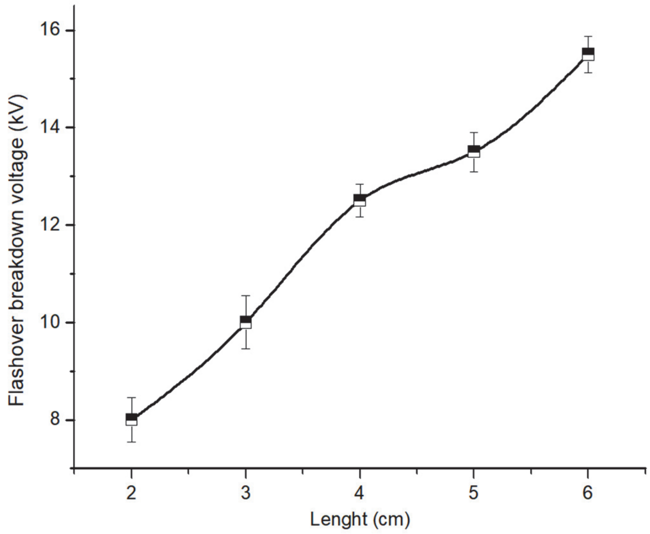


Fig. 4. Variation of the flashover breakdown voltage as a function of the length *l* (cm).

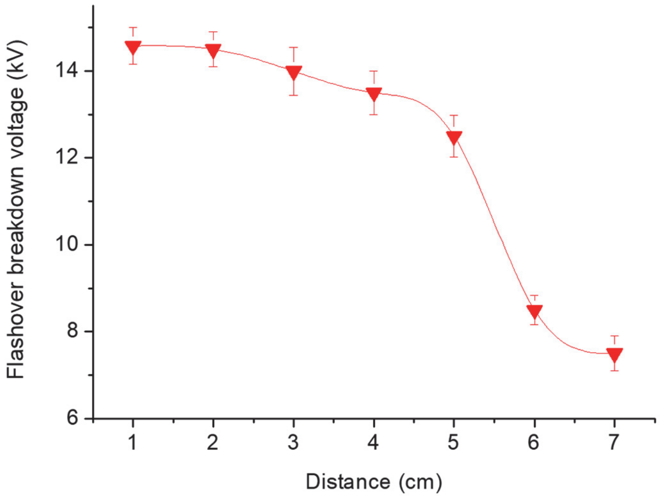


Fig. 5. Variation of the flashover breakdown voltage as a function of the distance *d* (cm).

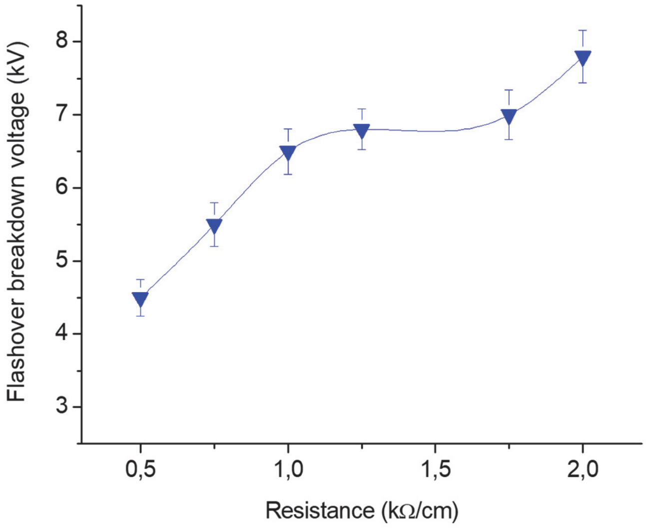


Fig. 6. Variation of the flashover breakdown voltage as a function of the resistance *r* (kΩ cm^{-1}).

3.2 Modeling of the flashover voltage

The modeling step was performed by using a CCF design; the two levels "max" and "min" are the limits established in previous section for each of the three variables(l_{min}, l_{max}), (d_{min}, d_{max}) and (r_{min}, r_{max}), the central point (l_c, d_c and r_c) being calculated as follows:.

$$l_c = \frac{l_{min}+l_{max}}{2} = (2+6)/2 \quad = 4\text{ cm} \tag{4}$$

$$d_c = \frac{d_{min}+d_{max}}{2} = (1+7)/2 \quad = 4\text{ cm} \tag{5}$$

$$r_c = \frac{r_{min}+r_{max}}{2} = (0.5+2.0)/2 \quad = 1.25\text{ k}\Omega\text{ cm}^{-1} \tag{6}$$

After the identification of variation domains of the factors, an experimental design was performed. Figure 7 shows experiments of a CCF design with 3 factors. It consists of 8 experiments located at the tops of the cube (square points A,B…H), 6 experiments located in the centres of the cube faces (round points a,b…f) and 3 identical experiments done in the central point M (star point). Thus, a CCF composite design with 3 factors includes 17 experiments.

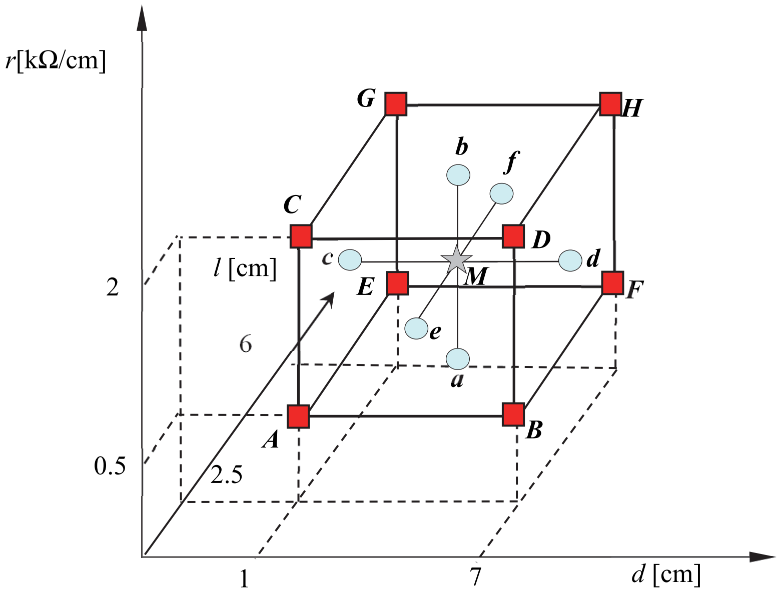


Fig. 7. Diagram of experiments of a CCF design with 3 factors.

The obtained results of the CCF design with the metal plate are given in Table1. The statistical tests lead to a valid mathematical model since R^2 and Q^2 reach higher values: $Q^2 = 0.897$ and $R^2 = 0.989$. The mathematical model suggested by MODDE.05, without the non-significant coefficients, is:

$$V_c = 14.58 + 1.5\, l^* - 4.75\, d^* + 2\, r^* - 2.65\, l^{*2} - 0.875\, l^* r^* \tag{7}$$

Moreover, the coefficients of the obtained mathematical model are represented by the plotted diagrams in Fig.8. As expected, and according to the obtained results plotted in Fig. 8, it appears that the flashover voltage increases with the resistance *r* and the length *l*. Indeed, the voltage becomes greater as the length of the metal plate increases; this corresponds in fact to the increase of the total resistance *R* of the electrolyte. On the other hand, since the coefficient associated with the distance *d* is negative, corresponding thus to the decrease of the flashover voltage, the metal plate should be placed as close as possible to the high voltage electrode to make the flashover more difficult to happen. Furthermore, the coefficients associated with the different interactions between the three factors show that the interaction between the metal length and the resistance of the electrolyte is the most significant. On the other hand, the effect of other interactions remains negligible.

Table 1. Obtained results of the CCF design.

Exp. N°	l (cm)	d (cm)	r (kΩ cm^{-1})	V_c (kV)
1	2	1	0,5	13.0
2	6	1	0,5	18.0
3	2	1	2	19.5
4	6	1	2	20.0
5	2	7	0,5	4.5
6	6	7	0,5	9.0
7	2	7	2	8.5
8	6	7	2	10.5
9	2	4	1,25	10.5
10	6	4	1,25	13.5
11	4	4	0,5	12.5
12	4	4	2	18.5
13	4	1	1,25	19.5
14	4	7	1,25	10.0
15	4	4	1,25	14.5
16	4	4	1,25	14,0
17	4	4	1,25	15

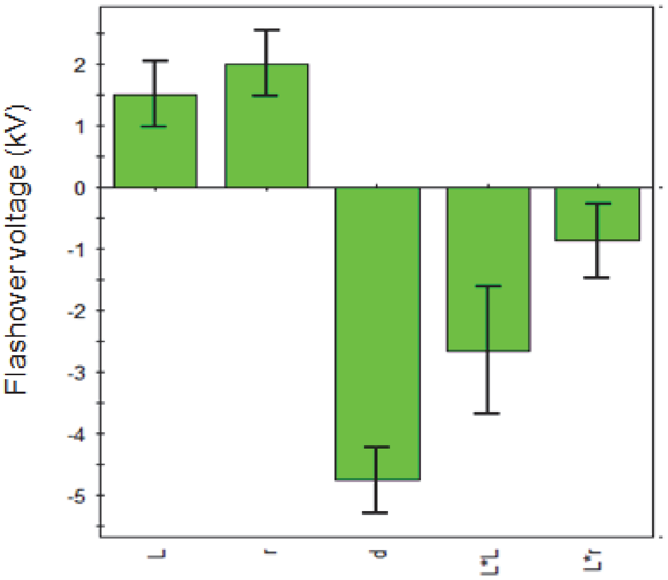
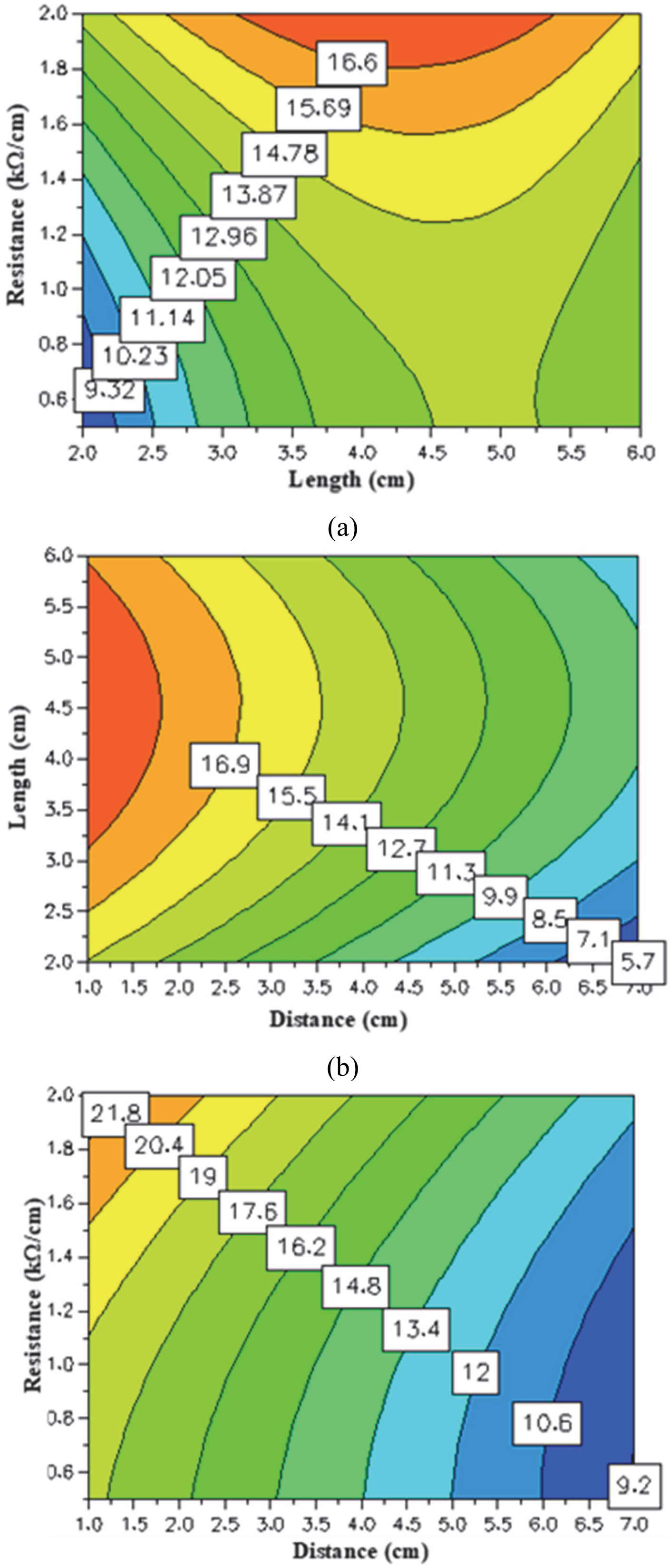


Fig. 8. Diagram of the plotted coefficients of the mathematical model.

Iso-response contours plotted with MODDE.05 make it possible to analyze and deduce the value ranges of the factors for which the maximum flashover voltage is obtained (Fig. 9). According to the contour plots, we notice that the effect of the distance remains preponderant compared to the two other factors (Figs. 9 b and 9 c), i.e. the length *l* and the resistance *r*. Indeed, the flashover voltage varies continuously according to the distance d but remains in almost the same surface contour with a slight change according to the length and the resistance of the electrolyte. The distance *d* has a much larger effect and the position of the metal blade has thus a significant influence on the flashover voltage. Moreover, the RSM figures show that an optimum distance of the blade from the electrode lies between 1 and 1.5 cm for an optimum configuration of the cell. It was also deduced, as expected, that the resistance at its maximum value corresponds to a high flashover voltage.



(a)

(b)

(c)

Fig. 9. Iso-response contours of the flashover voltage V_c (kV) plotted with MODDE.05.
(a) Resistance/Length (*r*/*l*) iso-response (*d* = 4 cm)
(b) Length/Distance (*l*/*d*) iso-response ($r = 1.25$ kΩ cm^{-1})
(c) Resistance/Distance (*r*/*d*) iso-response (*l* = 4 cm)

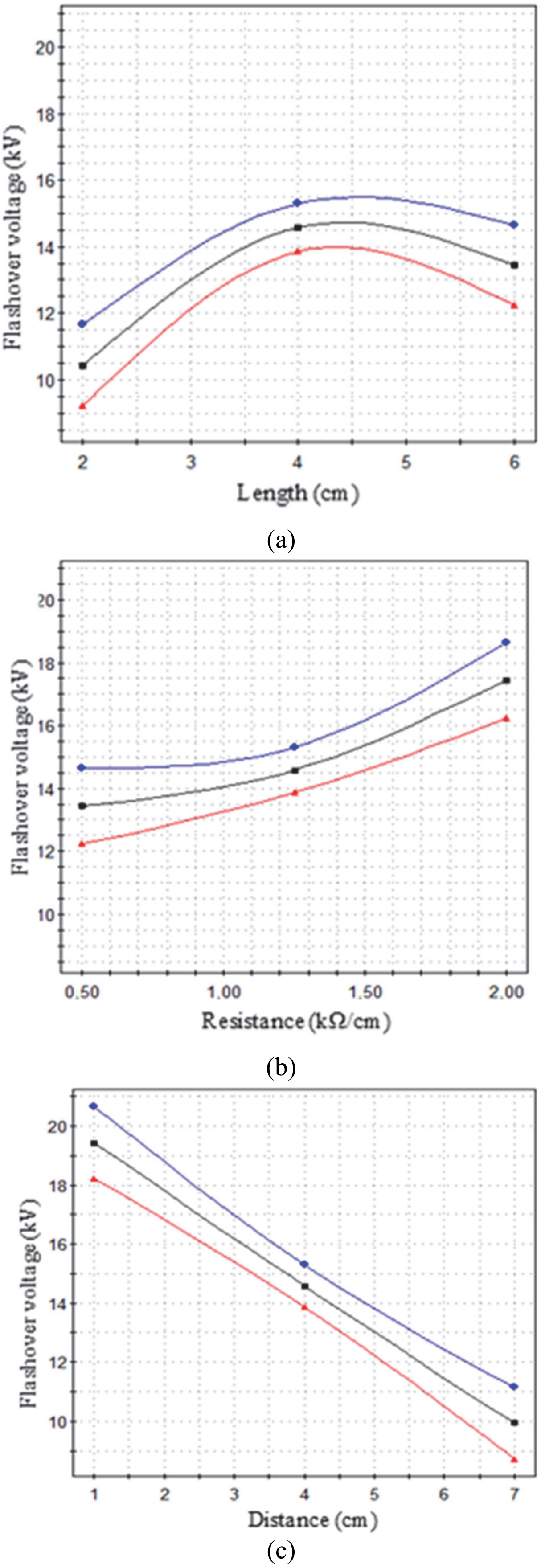


Fig. 10. Predictive plots of the voltage V (kV) according to a) Length *l*; b) Linear resistance *r*; c) Distance *d*.

Moreover, the prediction curves plotted with MODDE.05 confirm definitely that the distance d has a much more significant effect than the other two factors (Fig. 10), because the variation according to the factor *d* is much greater than to the other two factors.

According to Flazi's hypothesis, after initiation of the vertical cylindrical discharge, the propagation is caused in this case by the ionisation of air which happens not only near the foot region of the discharge but around all the body of the discharge (Fig.11). This is caused by the electric field lines which become current lines after ionisation [8−9].

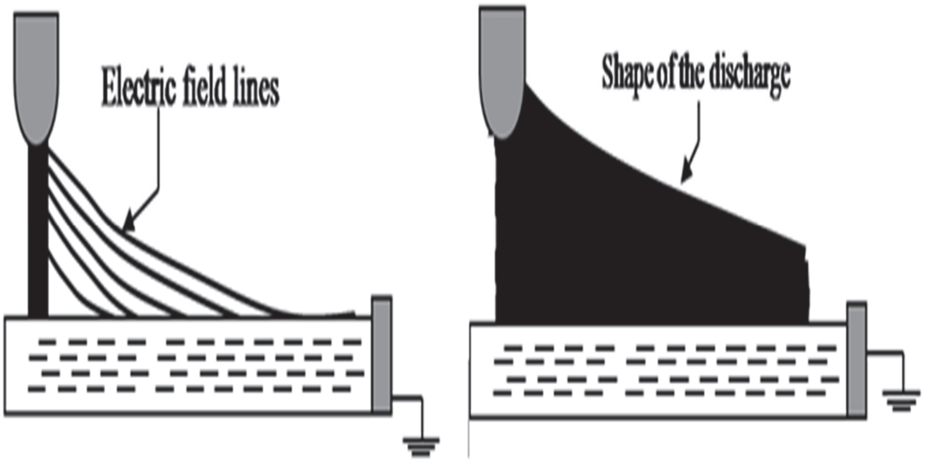


Fig. 11. The distribution of the electric field lines around the vertical starting discharge according to Flazi's hypothesis.

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 become in "short circuit" state remaining constant along the metal plate [22−24]. In the presence of the metal plate, which represents an equipotential surface, the potential on the plate remains constant, which results in the increasing of the flashover voltage.

4. Conclusion

An experimental study was carried out to analyze the flashover voltage of the propagating discharge on the surface of an electrolyte 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 the geometric factors was obtained and used for analysis. On the other hand, the flashover voltage in the presence of the plate is significantly inceased, because the distribution of the field lines around the discharge is changed due to the fact that the potential of the metal plate surface remains invariable.

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