# Modelling of the AC Breakdown Voltage of Point-Plane Air Gaps with Insulating Barrier

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| Article Info | ABSTRACT |
|---|---|
| | High voltage device dimensioning requires the prediction of the withstand voltage for test conditions like impulses, surges and AC voltage. There is a large need of designer to have reliable design criteria and well-defined simulation procedure for device development. This parametric study is based on the methodology of experimental designs. This method allowed us to propose a mathematical polynomial model. The objective of this paper is to study the discharge phenomena for a point–plane air interval with insulating barrier between them. Firstly on experimental study of a laboratory setup that we designed to carry out the influence of parameters (geometrical) involved in the process of breakdown. The distance between electrodes and different parameters of the barrier such as its position between electrodes dimension and its holes is studied. The barrier acts as a geometrical obstacle against the direct propagation of discharge. Secondly, using results obtained by the experimental setup, we have experiments design methodology of technique to predict the breakdown threshold voltage.<br><br> |

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## 1.  INTRODUCTION

The barriers are widely used in many high voltage devices. It is well known that the dielectric strength of long air gap is significantly increased by the insertion of an insulating barrier. The insulating structure is different stress and particularly to the discharge phenomena [1], [2]. The knowledge of the condition of ionisation and propagation of electrical discharge is of great interest to well understand the mecanism leading to breakdown [3].

Two conditions must be simultaneously fulfielled in order for an impulse discharge to occur in gases: there should be at least one suitably located free electron close to the stressed electrode and the electric field stress should be sufficiently high within the critical volume of the stressed electrode. When these two conditions are satisfied, the electron produces a sequence of avalanches and streamers that lead to a breakdown [4], [5].

In the absence of an initiatory electron in the critical volume, no single avalanche can lead to a breakdown, even if the electric field exceeds the breakdown field strength of the gas medium [6]. When the discharge develops, the accumulation of charges on the surface of the barrier facing the sharp electrode makes the barrier to behave as a floting plan electrode, and the electric field between the barrier and the electrode will be uniform [7].

The insulating barriers influence on the dielectric strength of arrangement point-plan. It is shown that the dielectric strength of such us insulating structures is the improved when the barrier is inserted near the sharp electrode. The effectiveness of the barrier depends on the geometry (the dimension and the position

of the barrier), and the physical nature on the barrier [8]-[10]. The investigation have been done experimentally and simulated in order to study the breakdown phenomena of solid dielectric barrier. The presence of a hole within the barrier significantly reduces the dielectric strength of the system. Tests are conducted to measure the 50Hz AC breakdown voltage of small air gap.

Energized rod and grounded plan gaps are studied with the flat insulating barriers that have three different diameters [11], [12]. The results of the test series show how the breakdown voltage varies with the distance between the electrodes, the size and the material of barrier, the relative position of the electrodes and the barrier between them.

As a result, all three materials show n early same effect when they are used as a barrier, the breakdown voltage varies due to the size of the barriers and the maximum flashover voltages are observed when the barriers are positioned at the nearest point to the electrode and the small sized barriers become effective only in very small air gaps [13]-[19]. An analysis based on experimental design method has been developed which indicates that measurements do contain some relevant information test at early stages in reduced time frame.

The history of design of experiments started in the 1930 in England with M. Fisher [20], which is a useful statistical approach that would lead to a reliable and significant interpretation of the different ordering parameters of the insulation ageing process but it knew an accelerating development since the publication of some predefined tables by Taguchi [21]. The principle of this methodology is to carry out a schedule of experiments designed to obtain the most accurate information for a specific problem with a minimum number of experiments [22], [23]. Its advantages were proved in different areas of application, especially in chemistry and mechanics, where a large number of parameters have to be optimized simultaneously [24]. Different designs exist in order to go with a large number of applications. In order to perform a design method it is necessary to define the problem and choose the variables, which are called factors or parameters by the experimental designer [25].

A design space, orregion of interest, must be defined, that is, a range of variability must be set for each variable. The number of the variables values can assume in design method is restricted and generally is small [26]-[28]. Therefore, we can deal either with qualitative discrete variables, or quantitative discrete variables. Quantitative continuous variables are discretized within their range. At first there is no knowledge on the solution space, and it may happen that the region of interest excludes the optimum design. If this is compatible with design requirements, the region of interest can be adjusted later on, as soon as the wrongness of the choice is perceived. The design method technique and the number of levels are to be selected according to the number of experiments which can be afforded [29]. By the term levels we mean the number of different values a variable can assume according to its discretization. The number of levels usually is the same for all variables, however some techniques allow the differentiation of the number of levels for each variable. In experimental design, the objective function and the set of the performed experiments are called response variable and sample space respectively.

In this paper work, in order to modelling the AC breakdown voltage in point-plan gaps arrangement in presence of barrier, the experiments design method is used. The carried out experimental results are taken to build a model which takes into consideration different parameters such as (the relative position of the barrier, its hole and the width of the barrier) that affect the breakdown phenomena.

## 2. EXPERIMENTAL SETUP

The experimental set-up consists of a high-voltage test transformer 100kV/5kVA/50Hz, a capacitive voltage divider.

Figure 1 and Figure 2 (the experiences have been performed in the laboratory of high voltage University of Biskra) shows the arrangement of electrodes and insulating barrier it contains a point–plan electrode arrangement mounted vertical.

The HV electrodes consist a steel needle point on copper of conical in shape 30°. The grounded plan electrode is a circular steel plate of 30 cm long, 2.8 cm diameter. The plexiglas barriers ($\varepsilon_r = 3.3$) are squares of different widths (5 cm, 10 cm, 15 cm) and different holes (4mm, 8mm and 12mm) and its thicknesses is 1mm, an aluminum plan grounded. To change the positions for several barriers, carriers Bakelite are used
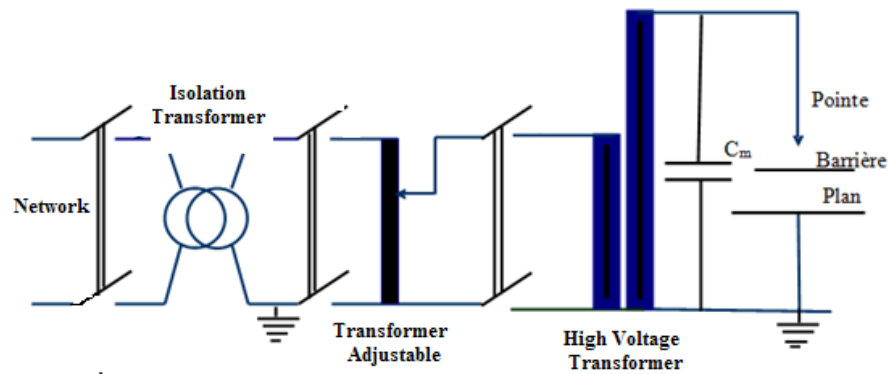
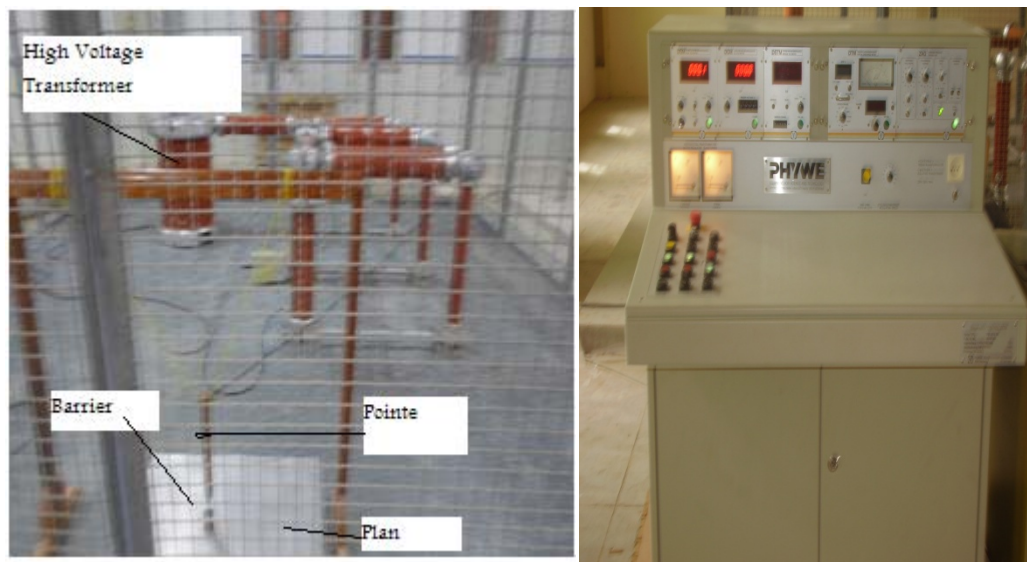Figure 1. Circuit probationary industrial realizes a frequency



Figure 2. View of real test cell and the high voltage laboratory control panel

The barrier is mounted vertically between the electrodes Figure 2. Its surfaces are checked after each breakdown. The position of the barrier is defined by the ratio a /d, where a is the point–barrier distance and d is the point–plan electrode gap.

## 3.    MODELLING AND PREDICTION BY EXPERIMENTS DESIGN METHOD

### 3.1 Principles and Interests

The principle of the technical design of experiments consists in varying levels of one or more factors simultaneous (which are variable, discrete or continuous) in each test.

This will help to reduce significantly the number of experiments to be performed. While increasing the number of studied factors, detecting interactions between the factors and optimal compared to are sponse, that is to say aquantity used as standard and allowing to easily modelling results.

The delicate point in the use of experimental design will be minimized as much as possible the number of experiments to be carried out withouts a crificing accuracy results.

To obtain relevant information, a methodological approach should be as followed [30]:

- Definitions of objectives and criteria,
- Definition of factors studied and experimental field,

- Construction of the experimental design,
- Expérimentation,
- Analysis,
- Conduct any additionnel testing,
- Validation,
- Conclusion of the study.

The traditional methodology for an experimental design consists of four (4) steps: first the preparation study including the definition of responses characterizing the objectives, which is the main scope of this paper and the determination of factor levels, then the choice of factors and experimental domain in the second step, the proposed model it self and finally, the mathematical model.

**a.  Step A: Definition of responses characterizing the objectives**

We want to measure the influence of the following factors Where:

- P (cm) is the relative position of the barrier.
- L (cm) is the width of the barrier.
- T (mm) is the hole in the barrier.

**b.  Step B: Choice of factors and experimental domain**

Determining the field of study is closely related to the initial knowledge held on the physical phenomenon under study, but also to the objectives of the experiment. In addition, care must be taken to minimize the cost of the study, expressed as number of tests.

We define the field of study and validity of the experiment considering the possible limits to the variation factors. For this, we referred to the preliminary study on the influence of various parameters.

We recall now that the results of the study will be valid only on the range of variation of the factors considered. The main factors considered in this plan experiments are:

Table 1. Levels of factors studied

| Factor | P (cm) | L (cm) | T (mm) |
|--------|--------|--------|--------|
| Level – 1 | 0 | 5 | 4 |
| Level  0 | 2 | 10 | 8 |
| Level +1 | 4 | 15 | 12 |

*c.*  **Step C: A Proposed model:**

Our choice felon composite face-centered plans for the study of response surfaces. A face-centered composite design is defined by: two start points by parameters and positioned don each of the axes. These points contribute to the evaluation. The quadratic terms of the polynomial model, i.e., they give information about the curvature of the surface of response:

- a full factorial design 2k
- $n_0$ repetitions at the center of the experimental domain, dedicated to the statistical analysis
- Two start points by parameter and positioned don each of the axes.

These points contribute to the evaluation. The quadratic terms of the polynomial model, i.e., they give information about the curvature of the surface of response.

The total number of tests to be conducted, N, depends on the number of factors k studied and the number of repetitions in the center of the domain, $n_0$

$$N = 2^K + 2.K + n_0 \tag{1}$$

$$n_0 = 3 \text{  With} \qquad N = 2^3 + 2.3 + 3 = 17 \tag{2}$$

The last three rows of Table 2 corresponds to a test center considered experimental field, which should be repeated $n_0$ times to ensure certain properties the matrix experiments.

So that it meets the requirement of uniform precision, ensuring a nearly constant variance within the experimental range.

The used plan is a composite face-centered plan allowing model the evolution of a criterion using form analytical considerations taking into 3 parameters.

Table 2. Composite plan for the study centered on three Factors

| N ° Experiments | Factor | | | $U_C$ (kV) |
|---|---|---|---|---|
| | P (cm) | L(cm) | T (mm) | |
| 1 | -1 | -1 | -1 | 30,1 |
| 2 | -1 | -1 | 1 | 31,08 |
| 3 | -1 | 1 | -1 | 29,89 |
| 4 | -1 | 1 | 1 | 29,26 |
| 5 | 1 | -1 | -1 | 45,08 |
| 6 | 1 | -1 | 1 | 43,68 |
| 7 | 1 | 1 | -1 | 43,89 |
| 8 | 1 | 1 | 1 | 37,94 |
| 9 | 0 | 0 | -1 | 35,84 |
| 10 | 0 | 0 | 1 | 31,64 |
| 11 | 0 | 1 | 0 | 34,025 |
| 12 | 0 | 1 | 0 | 34,025 |
| 13 | -1 | 0 | 0 | 29,26 |
| 14 | 1 | 0 | 0 | 42,84 |
| 15 | 0 | 0 | 0 | 33,76 |
| 16 | 0 | 0 | 0 | 33,74 |
| 17 | 0 | 0 | 0 | 33,72 |

Whether the vector of model coefficients analytical sought: It is defined by The coefficients vector of the analytical model is defined as follow:

$$a = (X^t X)^{-1} X^t y \tag{3}$$

Where $X$ are the matrix experiment, $X^t$ are the transpose matrix experiment, $y$ the breakdown voltage (the response).
The number of unknown parameters $(a_i)$ of the polynomial is determined from the following formula

$$A = \frac{(K+2)!}{k!2!} \Rightarrow a = \frac{(3+2)!}{3!2!} = 10 \tag{4}$$

Finally, the model is given by equation (5)

$$y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ii} X_i^2 \sum_{i=1}^{2} \left[ \sum_{j=i+1}^{3} a_{ij X_I X_J} \right] \tag{5}$$

Or:

$$y = a_0 + a_1.x_1 + a_2.x_2 + a_3.x_3 + a_{11}.x_1^2 + a_{22}.x_2^2 + a_{33}.x_3^2 + a_{12}.x_{12} + a_{13}.x_{13} + a_{23}.x_{23} \tag{6}$$

**d.   Step D: Mathematical model**
        Estimation of model coefficients. To estimate the mathematical models  coefficients, we have used Matlab program, which gives an analytical form of the response studied surface  and they are calculated by using equation (3).
So we can write the mathematical model (experimental domain) as follows:

$$U_C = 33,97567568 + 6,384.P - 1,12.T - 1,0075.L - 0,9625.P.T - 0,6125.P.L - 0,77.T.L + 1,8975.P^2 - 0,4124.T^2 + 0,9483.L^2 \tag{7}$$

        The obtained results can be plotted to compare the measured responses with the estimated one. For this, it is necessary to plot the adequacy of the model. Measured responses are placed on the abscissa and estimated responses are on the ordinate Figure 3. The cloud points is aligned with the line y = x, which means that accuracy of the model is pretty good.
        The descriptive quality of the model is illustrated here but a second analysis of variance will possible to verify this conclusion.
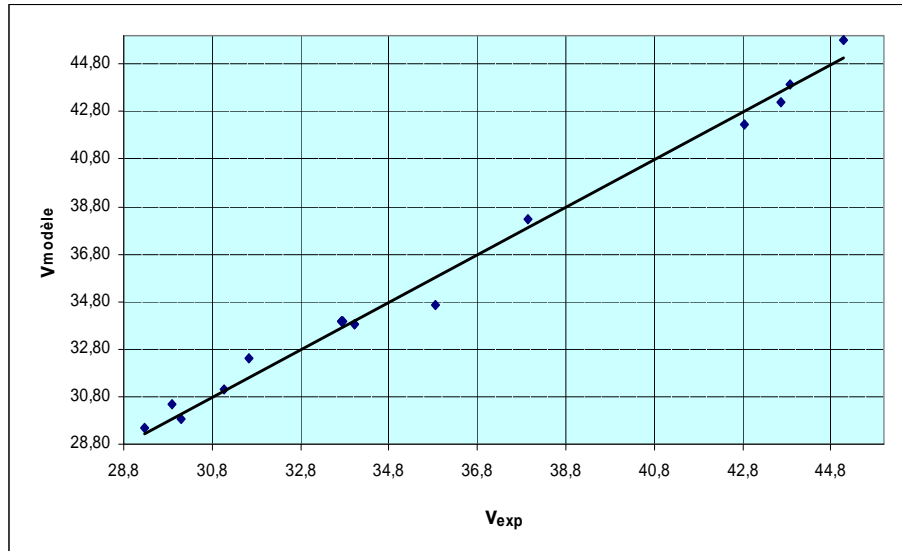
Figure 3. Graph model adequacy

### e.    Statistical analysis of the model

The equation of the empirical model is only approximation of reality. The estimated coefficients of the polynomial model of second degree is based on test results that are, for each of the experimental design treatments, specific values of a random variable.

The implementation of statistical tests must allow a judgment on the results obtained, namely a model describing the variation of the response in the experimental domain. This step of the statistical analysis results in the construction of Table of regression analysis and determining the descriptive quality of the model. Regression analysis is to explain the total change in the response from the defined sum of squared differences between the results testing and their average:

The statistical analysis of the model as a whole is followed by the construction of a statistical test, which is to say that the model does not allow describe the $\alpha$ equal to 5%: Table regression analysis Table 3 includes different steps for lead calculating the probability that.

The regression analysis table is used to achieve immediately calculate the coefficient determination of $R^2$, $R^2$ and $Q^2$ ajustte: the descriptive quality of the model will be evaluated average coefficients of determination, $R^2$ and $R^2_{adj}$.et $Q^2$ These are values following:

Table 3. Determining the coefficients of descriptive quality of the model

| $R^2$ | $R^2_{adj}$ | $Q^2$ |
|-------|-------------|-------|
| 0,991 | 0,979       | 0,986 |

With the coefficients $R^2$ and $R^2_{adj}> 0.9$ close to unity, a good descriptive quality is assured. We can therefore say that the models obtained can used to predict the response values and the determining factor values $R^2$ are close to 1, reflecting the good quality of model. Similarly, values of the coefficient adjusted determination indicate that the model is also applied properly fitted.

Just as one has previously defined the descriptive model quality, it is possible to now define the predictive quality of the model to from the coefficient $Q^2$, the more its value is close to unity, a good descriptive quality is assured.

So we can say that the two models obtained have a good descriptive quality.

Another step in the statistical analysis of the model concerns the statistical analysis of coefficients based statistically test << ti >> Student:

The test used is the "t" test of Student. effect will be said to be significant (that is to say that the variable or interaction associated there with influences response), if, for a given risk significantly different from 0. Therefore will be tested assuming : $H_0 = << ai=0>>$
counter hypothesis:

$$H_0 = << ai \neq 0>> \tag{8}$$

For this, we calculate :

$$t_i = \frac{|a_i|}{s_i}$$
(9)

Student table gives for α = 5% risk, N - p = 17 -10 = 7
From the Student table: $t_{crit}$=(0,005 ,7 ) =2.37
An effect will be significant at the 5% risk if his "$t_i$" and above 2,37.
The following table were obtained:

Table 4. Test of significance of the coefficients

| Factors | Effect | $t_i = 2.37$ | results |
|---|---|---|---|
| Constante | 33,975676 | 179,16 | significant |
| P | 6,384 | 33,66 | significant |
| T | -1,12 | 5,91 | significant |
| L | -1,075811 | 5,67 | significant |
| P.T | -0,9625 | 5,08 | significant |
| P.L | -0,6125 | 3,23 | significant |
| T.L | -0,77 | 4,06 | significant |
| $P^2$ | 1,8975676 | 10,01 | significant |
| $T^2$ | -0,412432 | 2,17 | not significant |
| $L^2$ | 0,9483784 | 5,00 | significant |

From Table 4, only the coefficients providing descriptive quality of model will be preserved. That is to reject the coefficients ($T^2$) the reduced model equation becomes:

$$U_C = 33,97567568 + 6,384.P - 1,12.T - 1,0075.L - 0,9625.P.T - 0,6125.P.L - 0,77.T.L + 1,8975.P^2 + 0,9483.L^2$$
(10)

In this case the confidence interval of an effect is given by:
$[a_i - 1,96 . 0,189]$ lower bound, $[a_i + 1,96 . 0,189]$ Higher bound.

Table 5. Confidence interval of 5% risk zone

| Factors | Effect | interval | |
|---|---|---|---|
| | | lower bound | Higher bound |
| Constante | 33,9756757 | 33,60 | 34,35 |
| P | 6,384 | 6,01 | 6,76 |
| T | -1,12 | -1,49 | -0,75 |
| L | -1,07581081 | -1,45 | -0,70 |
| P.T | -0,9625 | -1,33 | -0,59 |
| P.L | -0,6125 | -0,98 | -0,24 |
| T.L | -0,77 | -1,14 | -0,40 |
| $P^2$ | 1,89756757 | 1,53 | 2,27 |
| $T^2$ | 0,94837838 | 0,58 | 1,32 |

## 4.    RESULTS AND ANALYSIS
The validation of the results given by the model is to check whether the assumptions made in departure of experiments are well verified.
Validation can be carried performing test complementary outside the testing plan experiments to validate the model behavior obtained by the experimental design.
In our case study, we took the made test to study the influence of parameters Apart from testing the experimental design. The results of these tests are compared with results of the mathematical model

### 4.1. Influence of the Width of the Barrier on the Breakdown Voltage
In this test shouts, the different distances between electrodes and barrier (0cm, 2 cm and 4cm), the hole in the middle of the barrier for (4 mm), different width of the barrier (5cm, 10 cm and 15cm) we see clearly, the breakdown voltage is very low with the increasing of large widths of the barrier and very big with the decreasing of them. This can be explained by the fact that the screen plays in a geometric opstacle.

From Figure 6, the breakdown voltage decreases with increasing of the barrier widths. The prediction values  are situated between the two boundaries of the area of risk of 5%. This means that the model founded by the experimental design method is perfect.
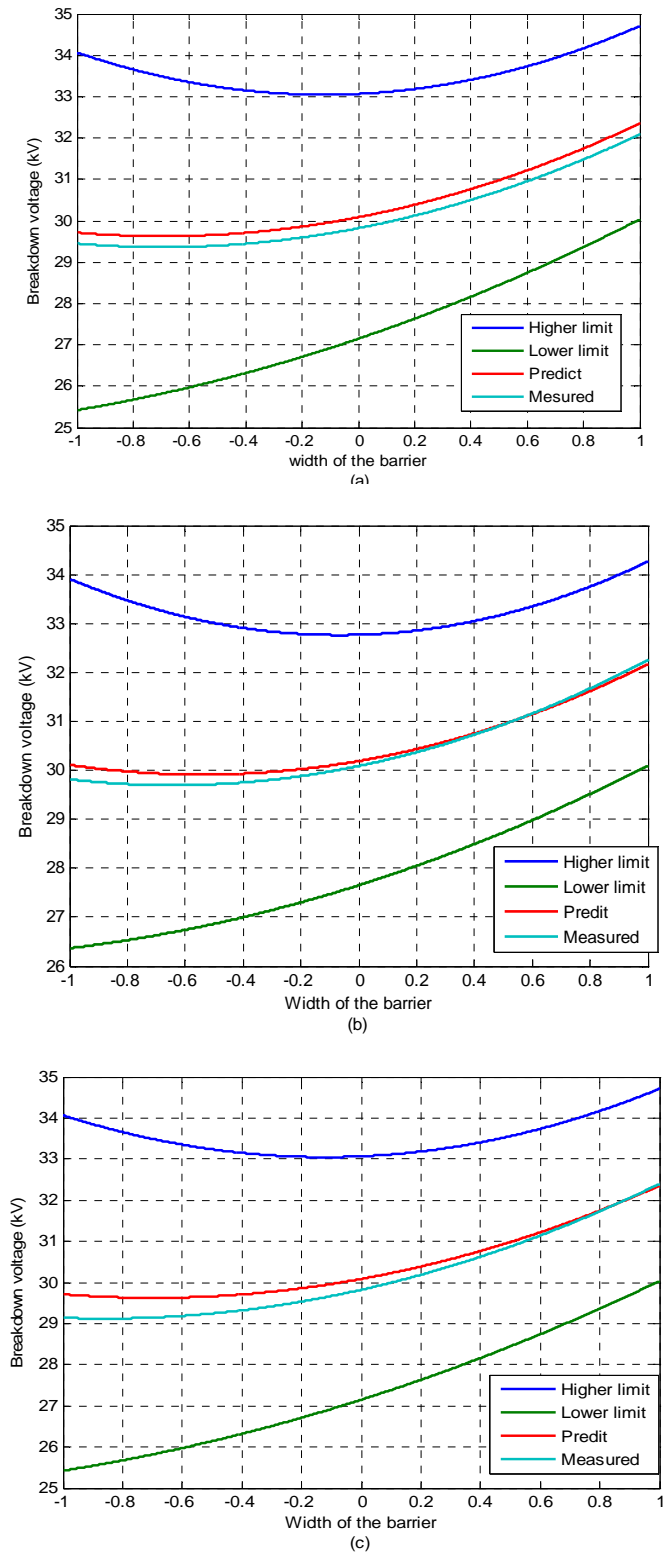


(a)



(b)



(c)

Figure 6. Influence of the width of the barrier on thebreakdown voltage:
different relative position of the barrier

## 4.2. Influence of the Hole in the Barrier on the Breakdown Voltage

In this test, a hole in the middle of the barrier varies (4mm, 8mm and 12mm). The relative position of the barrier values for 4 cm, different width (5cm, 10 cm and 15cm). In reviewing figures, we observe that the decrease of the breakdown voltage with the increase of the holes in middle of the barrier. This result could be interpreted by the fact that the electric charge that passes through the hole is low. When a diameter of hole is greater, a large part of the charging space passes through the hole as well. This can be interpreted by the fact that increasing the diameter of the hole. The prediction values are situated between the two boundaries of the area of risk of 5%.
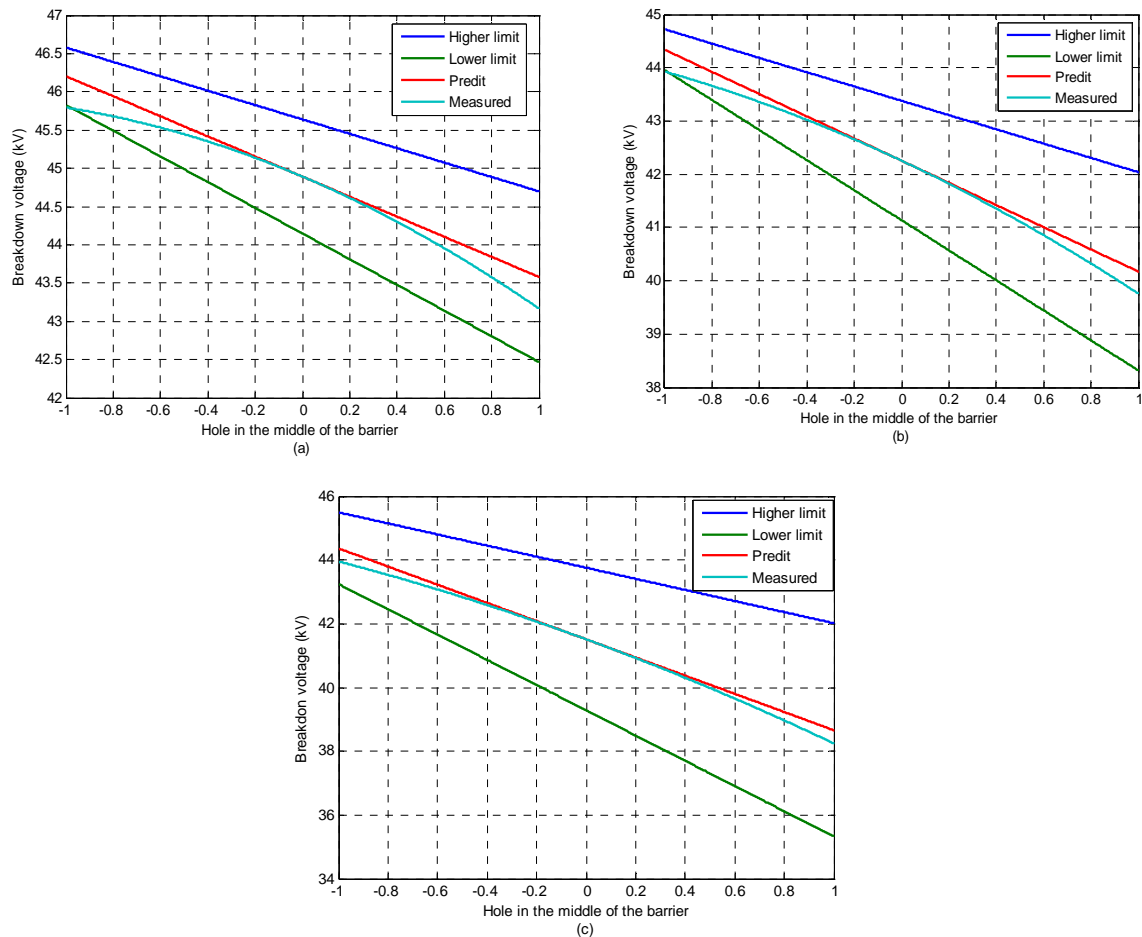


Figure 5. Influence of the hole in the middle of the barrier on the breakdown voltage:
different width (a) 5cm, (b) 10 cm and (c) 15cm).

## 4.3 Influence of the Relative Position Barrier on the Breakdown Voltage

Figure 4 shows the experimental and predicted breakdown voltage as a function of the relative position of the barrier values of the barrier for different width (5cm, 10 cm and 15cm) of the barrier. The hole in the barrier is (4 mm). Different distances between the point and the barrier (0 to 5 cm) were studied.

The insertion of the barrier has a significant influence on the breakdown voltage. The prediction values are situated between the two boundaries of the area of risk of 5%. This means that the founded model by the experimental design method is perfect.
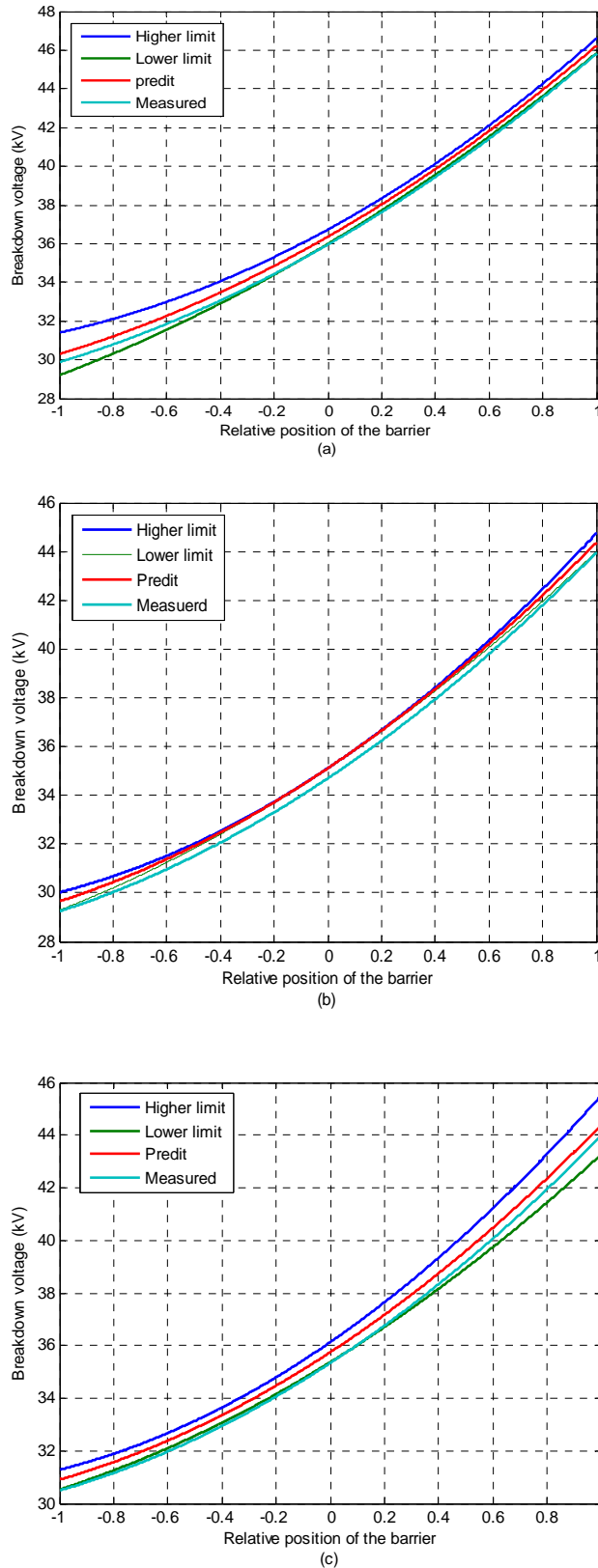
Figure 4. Influence of the relative position of barrier on the breakdown voltage:
different width (a) 5 cm, (b) 10 cm and (c) 15 cm, the hole (4 mm).

The interval between the upper limit and the limit lower is called confidence interval (zone of confidence interval estimation will be small to great coefficient confidence).

Plotted the confidence interval of the theoretical response with a confidence coefficient α=0.05.

Considering experimental conditions in which we have worked and approximations we have made in the numerical model, we can say that results are satisfactory and we note that the experimental results are well within the range of 5% confidence error.

In experiments design method, verification experiments should be done to determine optimum conditions and compared with experimental values. In this study, all values are within confidence levels, as a result of the verification experiments.


## 5. CONCLUSION

Investigational results shown that the experiments design method is a useful tool to search parameters influencing the objective fixed and optimization. Methodology of experiments was giving guidance on the effects of different factors. It consists in a first step to make search parameters influencing the objective fixed. For this, the use of the method response surface turns outto be highly effective, because it allows to classify the effect of parameters in the order of importance.

The study on the effects of factors has on the one hand and restricting choose the parameters of the desired model on the other hand to define the limits of the universe speech for each in.

A model with a good description of the studied system thus have been defined, and led to improvement of system performance.

The modelling of the dielectric breakdown in point-plan arrangement with insulating barrier in air interval has been investigated. We have proposed a mathematical modelling by using experiments design method. It leads to analyze the interactions between different parameters: distance between electrodes, diameter of the barrier and the relative position.

This methodology has provided good results and helps to minimize the cost of study, expressed in number of tests.

It has been shown, that the use of this methodology is very useful for tracking the influent operating parameters on insulation reliability and for the lifetime modelling. In this study we can say that the metodology of experiement design show a good performance to investigations in the analysis of different discharge steps of the air interval.

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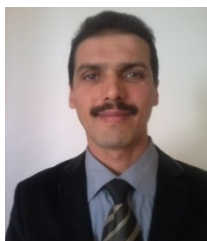
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