Modeling of the Dielectric Strength of Transformer Oil in Divergent Field with Bakelite and Pressboard Insulating Barriers by Central Composite Face Method (CCF)

*1M.Zitouni, 1M.Teguar, 1A.Boubakeur
1 Laboratoire de Recherche en Electrotechnique L.R.E, Ecole Nationale Polytechnique (ENP), BP 182, El-Harrach16200, Algiers, Algeria.
*Corresponding Author Email: med.zitouni@gmail.com

***Abstract*— The presence of barriers in point-plane oil gaps has an important role on the insulating oil dielectric strength. This latter closely related to the nature (material), the thickness and the diameter of the barrier, its relative position, the distance between electrodes and theirs interactions. The present work is devoted to estimate the dielectric strength of the transformer oil, the Borak 22 under 50 Hz AC voltage, in presence of Bakelite and Pressboard barriers of 2 and 4 mm thicknesses. To achieve this goal, proposal mathematical models have been built via Central Composite Face method (CCF) which is a robust tool introduced by FISHER. It allowed us to estimate the dielectric strength through a mathematical model. For each barrier, the formulation and the verification of the established models are carried out for several inter-electrodes distance (d=4, 6, 8 10 and 12cm) and relative positions of the barrier (a/d=20, 40, 60, 80 and 100%; a being the point-barrier distance). For each configuration, the corresponding model is verified using graphical and statistical analyses. It is validated as long as the relative mean error between the estimated dielectric strength values and the experimental ones.**

Keywords: dielectric strength; insulating barrier; geometrical parameters; central composite face method; transformer oil (Borak 22).

1. Introduction

In the High Voltage (HV) apparatus, insulating oil is used to ensure the heat transfer and dielectric functions [1]. The heat transfer function concerns the evacuation of energy losses. The evacuated heat is conveyed by natural or forced convection (circulation) of the dielectric liquid to the cooling devices. Through a well distributed circulation, the heat transfer allows avoiding the formation of hot spots [2], [3]. Otherwise, the dielectric function could be improved by inserting insulating barriers in HV equipment. The point-plane arrangement is the most studied because is the less rigid system. The insertion of insulating barriers increases the dielectric strength in such arrangements by improving the electric field distribution. In fact, the point-barrier-plane arrangement is equivalent to two systems namely point-barrier and barrier-plane electrodes. In the second system, the electric field is almost uniform [4].

There are several parameters influencing the dielectric strength in insulating oil. The dielectric strength decreases with increasing inter-electrodes distance [1-5]. Hydrostatic pressure has a considerable effect on the dielectric strength; this latter is higher when the pressure is increased [1], [6].

On the other hand, increasing the temperature leads to a reduction in the dielectric strength of the insulating oil [1], [2], [7]. The presence of moisture in the liquid reduces ist dielectric rigidity [2], [8-12]. Various investigations have been devoted to examine the influence of the insertion of barriers in mineral oil gaps. Moreover, the effects of different parameters have been discussed such as the distance inter-electrodes as well as the relative position, the diameter and the thickness of the insulating barrier [1-9].

GUERBASS [12] pointed out that the influence of the position of the barrier depends on the electro-geometric parameters of the system such as the inter-electrodes distance and the configuration of the electrodes. The dielectric strength is higher when the barrier is near the point.

ZITOUNI et al [5] mentioned that the dielectric strength is maximum at 20% relative position from the point electrode.

ZOUAGHI [8] showed that the point-plan electrode system is less rigid in negative polarity than in positive polarity. For both polarities, the presence of the barrier improves the dielectric strength of the structure. The dielectric strength depends on the position of the barrier inserted in the inter-electrodes gap.

ZITOUNI et al [10] have modeled the AC breakdown voltage in long point-barrier-plane arrangement of transformer. Based on the Design of Experiments method (DOE), this modeling employed three parameters namely the inter-electrodes distance, the relative position of the

barrier and the plane electrode diameter. The concordance of the predicted values with the experimental results has been analyzed in term of mean relative error. This latter has been found equal 10.54%, due to influence of the barrier thickness which has not been taken into account in this modeling.
SHERIF et al [11] presented a comparative study between two tools of DOE namely Central Composite Face method (CCF) and Box Bhenken Design (BBD). They have estimated the AC breakdown voltage in the presence of barrier on hemisphere-hemisphere gap configuration, under AC voltage. They obtained average error results are 7.9% than 10.9% which indicate that the mathematical model based on BBD was better than that developed by CCF.

The main objective of this innovative investigation is to calculate the dielectric strength of the transformer oil in point–insulating barrier–plane arrangement under AC voltage of 50 Hz industrial frequency. The oil consists in the Borak 22.
Bakelite and Pressboard circular barriers of 2 and 4mm thicknesses have been chosen. First, large experimental tests have been carried out using a transparent test cell containing 175 liters of naphthenic oil insulating (Borak 22). The HV point possesses a 6 µm radius and the plane electrode has a circular shape of 35cm diameter. Different insulating barriers diameters varying from 10 to 20 cm have been used. The distance between electrodes has been varied from 4 to 12 cm by step of 2 cm. For a given inter-electrodes distance, several relative positions of each barrier, namely 20, 40, 60, 80 and 100%, have been adopted. In order to estimate the dielectric strength, mathematical models have been developed via Central Composite Face method (CCF) which is a robust tool introduced by FISHER. For each barrier, the calculation is carried out for 4, 8 and 12cm inter-electrodes distances and 20, 60 and 100% relative positions of the barrier, while the validation of each model is done for the other values (40 and 80% relative positions of the barrier and 6 and 10cm inter-electrodes distances). In fact, the prediction results have been verified using a graphical and a statistical analyses (basing on the coefficients of determination R^2, R_{adj}^2 and Q^2).

2. Experimental Setup

The experimental setup consists of a high voltage test transformer 300kV/50kVA/50Hz, a capacitive voltage divider and a transparent test cell of 175 liters of naphthenic oil insulating, characterized by a dielectric constant of ε_r= 2.12 and a dielectric strength of E_c=30kV/mm. Figure (1) shows the real and the scheme test cell containing a point–plane electrode arrangement. The scheme of the test cell with a barrier is presented in figure (2). The test cell dimensions are 71.5 cm ×50 cm ×50 cm. The HV electrode has a radius of 6µm. The plane electrode has a circular shape of 35cm diameter. Also, the insulating barriers have a circular shape. Several diameters, namely *D*=10cm, 14cm and 20cm, have been considered. As barriers natures, we have used Pressboard and Bakelite, with a dielectric constant and dielectric strength (ε_r=3, E_c=25kV/mm) and (ε_r=5, E_c =30kV/mm) respectively, as shown in Figure (2). 2 and 4mm barriers thicknesses have been employed. The electrode gap (*d*) has been varied between 4 and 12 cm by step of 2cm [5].

Figure 1: View of Real Test Cell

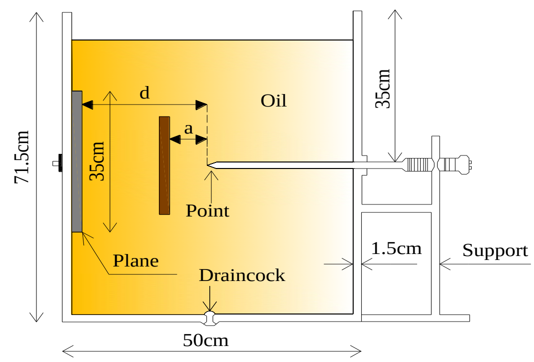

Figure 2: Scheme of the Test Cell Barrier

3. Modeling by Central Composite Face method

The dielectric strength has been estimated for the Bakelite and Pressboard barriers of 2 and 4mm thicknesses. The modeling includes four stages namely: - choice of input parameters; - proposed domain; - graphical analysis of the results and statistical analysis of the model [10].

3.1. Choice of input parameters

The main input parameters consist in *d*, *a/d*, *D* and *e* corresponding to the distance between electrodes, the relative position, the diameter and the thickness of the barrier respectively. These parameters are normalized and limited between three levels: low (-1), medium (0) and high (+1). [10].

Table (1) shows the range of the variation of the considered parameters.

Table1: Parameters Variation Domain of Dielectric Strength (*E*)

Normalised Values	The dielectric strength Parameters (*E*)			
	X_1=d (cm)	X_2=a/d (%)	X_3=D(cm)	X_4= e(mm)
Level -1	4	20	10	2
level 0	8	60	14	3
Level +1	12	100	20	4

3.2. Proposal Model

To analyze the impact of the input parameters, we have used the Central Composite Face (CCF). This latter is defined by:

- The full factorial design which has a dimension of (2^k), where (*k*) is the number of studied parameters. In our case, *k* =4. Therefore, we have sixteen points.
- (n_0): repetition at the center of the experimental domain, dedicated to the statistical analysis (n_0=3).

The total number of tests (*n*) will depend on the number (*k*) of the input parameters and the number of repetition in the center of the domain (n_0) (with n_0= 3), so:

$$n = 2^k + 2k + n_0 \qquad (1)$$

Then (n=27 for k=4 and n_0=3).

The mathematical model type is given as in equation (2).

$$y = b_0 + \sum_{i=1}^{3} b_i \cdot x_i + \sum_{i=1}^{3} b_{ii} \cdot x_i^2 + \sum_{i=1}^{2}\left(\sum_{j=i+1}^{3} b_{ij} \cdot x_i \cdot x_j\right) \qquad (2)$$

Where: (b_0) is a constant, (b_i) the coefficients associated to each parameter, (b_{ii}) the coefficients associated with the quadratic terms and (*bij*) the coefficients associated to the interactions.
(x_i and x_j) are the elements of the experiments matrices.

Table (2) includes the levels of parameters as inputs and the dielectric strength E_{exp} as response output. The response is obtained by varying the distance between electrodes from 4cm to 12cm. For each distance, the dielectric strength value represents an average of six experimental ones, as recommended by IEC 60156 standards [16].
The three last lines of Table (2) correspond to the test of the considered experimental domain center, which should be repeated three times, [10-15], [16- 25].

Table2: Experiment Matrix

N°	d (cm))	a/d (%)	D (cm)	e (mm)	E_{exp}(kV/cm) Pressboard.	E_{exp}(kV/cm) Bakelite
1	-1	-1	-1	-1	21.841	30.379
2	+1	-1	-1	-1	10.463	13.830
3	-1	+1	-1	-1	19.513	21.689
4	+1	+1	-1	-1	9.286	9.784
5	-1	-1	+1	-1	20.525	31.226
6	+1	-1	+1	-1	11.778	15.785
7	-1	+1	+1	-1	17.308	22.434
8	+1	+1	+1	-1	9.711	11.636
9	-1	-1	-1	+1	23.288	32.394
10	+1	-1	-1	+1	11.601	13.823
11	-1	+1	-1	+1	20.071	24.892
12	+1	+1	-1	+1	9.534	10.964
13	-1	-1	+1	+1	20.213	33.304
14	+1	-1	+1	+1	11.156	15.840
15	-1	+1	+1	+1	16.106	25.699
16	+1	+1	+1	+1	8.198	12.879
17	-1	0	0	0	18.841	21.890
18	+1	0	0	0	9.199	7.205
19	0	-1	0	0	14.081	16.405
20	0	+1	0	0	11.439	10.580
21	0	0	-1	0	11.798	15.892
22	0	0	+1	0	10.473	17.273
23	0	0	0	-1	11.861	12.473
24	0	0	0	+1	11.829	14.102
25	0	0	0	0	11.575	12.500
26	0	0	0	0	11.575	12.500
27	0	0	0	0	11.575	12.500

The coefficients vector of the analytical model is determined by the least squares method using equation (3).

$$b = (x^t x)^{-1} x^t y \qquad (3)$$

Where:

(x) is the experiment matrix,(x^t) is the transpose matrix, and (y) is the dielectric strength (the response).

The number of coefficients (b_i) of the polynomial is determined from equation (4).

$$b = \frac{(k+1)(k+2)}{2} \qquad (4)$$

Then, b=15 coefficients, if k=4, so the vector (b_i) is represented as follow:

$$b_i = \left[b_0 b_1 b_2 b_3 b_4 b_{11} b_{22} b_{33} b_{44} b_{12} b_{13} b_{14} b_{23} b_{24} b_{34}\right]^t$$

3.2. Mathematical Model

To estimate the mathematical model coefficients, we have used Matlab program to give an analytical form of the studied response using equation (3). The obtained values of different coefficients are presented in Table (3).

Table3: Mathematical Model Coefficients

	Dielectric strength (*E*)	
Parameters	**Model Coefficien of Pressboard barrier, *e*=2mm**	**Model Coefficients of Bakelite barrier, *e*=4mm**
Constant	b_0=11.575	b_0=12.5
d	b_1= - 4.821	b_1= - 7.34
a/d	b_2= -1.321	b_2= -2.912
D	b_3= - 0.668	b_3= 0.690
e	b_4= - 0.016	b_4= 0.814
d*×*d	b_{11}= 2.445	b_{11}= 2.047
a/d*× *a/d	b_{22}= 1.185	b_{22}= 0.992
D*× *D	b_{33}= -0.439	b_{33}=4.082
e*× *e	b_{44}= 0.270	b_{44}= 0.787
d*× *a/d	b_{12}=0.287	b_{12}=1.160
d*× *D	b_{13}= 0.657	b_{13}= 0.276
d*× *e	b_{14}= -0.077	b_{14}= -0.505
a/d*× *D	b_{23}= -0.222	b_{23}= -0.025
a/d*× *e	b_{24}= -0.222	b_{24}= 0.296
D*× *e	b_{34}= - 0.44	b_{34}= 0.015

From Table 3, the mathematical expression of the dielectric strength when using Pressboard barrier of e = 2mm, is given by equation (5).

$$E = 11{,}5752 - 4{,}8211\,(d) - 1{,}3211\,(\frac{a}{d}) - 0{,}6628\,(D) - 0{,}0161\,(e) + 2{,}4456\,(d)^2 + 1{,}1856\,(\frac{a}{d})^2 - 0{,}4394(D)^2 + 0{,}2706\,(e)^2 + 0{,}2875\left(d \times \frac{a}{d}\right) + 0{,}6575(d \times D) - 0{,}0775(d \times e) - 0{,}2225\left(\frac{a}{d} \times D\right) - 0{,}2225\left(\frac{a}{d} \times e\right) - 0{,}44(D \times e) \qquad (5)$$

The mathematical expression of the dielectric strength when employing Bakelite barrier of e = 4mm, is given by equation (6):

$$E = 12{,}5 - 7{,}3122\,(d) - 2{,}9128\,(\frac{a}{d}) + 0{,}6906\,(D) + 0{,}8144\,(e) + 2{,}0474\,(d)^2 + 0{,}9924\,(\frac{a}{d})^2 + 4{,}0824\,(D)^2 + 0{,}7874\,(e)^2 + 1{,}1606\left(d \times \frac{a}{d}\right) + 0{,}2769(d \times D) - 0{,}5056(d \times e) - 0{,}0256\left(\frac{a}{d} \times D\right) + 0{,}2969\left(\frac{a}{d} \times e\right) + 0{,}0156(D \times e) \qquad 6)$$

The various values of the predicted response are given in Table (4).

Table4: Predicted Matrix

N°	*d* (cm	*a/d* (%	*D* (cm	*e* (mn	E_{exp}(kV/cm) Pressboard.	E_{exp}(kV/cm) Bakelite
1	-1	-1	-1	-1	21.841	30.379
2	+1	-1	-1	-1	10.463	13.830
3	-1	+1	-1	-1	19.513	21.689
4	+1	+1	-1	-1	9.286	9.784
5	-1	-1	+1	-1	20.525	31.226
6	+1	-1	+1	-1	11.778	15.785
7	-1	+1	+1	-1	17.308	22.434
8	+1	+1	+1	-1	9.711	11.636
9	-1	-1	-1	+1	23.288	32.394
10	+1	-1	-1	+1	11.601	13.823
11	-1	+1	-1	+1	20.071	24.892
12	+1	+1	-1	+1	9.534	10.964
13	-1	-1	+1	+1	20.213	33.304
14	+1	-1	+1	+1	11.156	15.840
15	-1	+1	+1	+1	16.106	25.699
16	+1	+1	+1	+1	8.198	12.879

17	-1	0	0	0	18.841	21.890
18	+1	0	0	0	9.199	7.205
19	0	-1	0	0	14.081	16.405
20	0	+1	0	0	11.439	10.580
21	0	0	-1	0	11.798	15.892
22	0	0	+1	0	10.473	17.273
23	0	0	0	-1	11.861	12.473
24	0	0	0	+1	11.829	14.102
25	0	0	0	0	11.575	12.500
26	0	0	0	0	11.575	12.500
27	0	0	0	0	11.575	12.500

The estimated results as well as the experimental ones have been plotted. This allows checking the adequacy of the model. The measured responses are placed on the abscissa axis and the estimated responses on the ordinate axis (Figures3 and 4). The cloud points are aligned with the line *(y= x)* which means that the descriptive quality of the model is good.

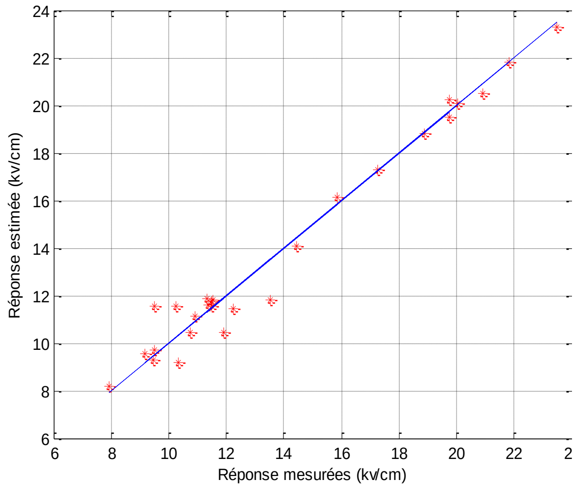

Figure 3: Model adequacy of the dielectric strength for pressboard barrier with 2mm thickness.

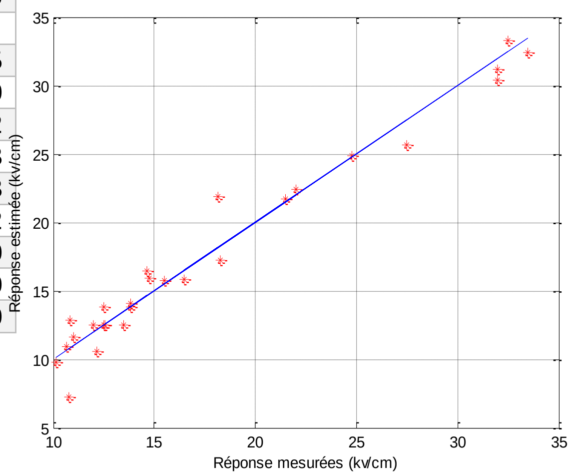

Figure 4: Model adequacy of the dielectric strength for Bakelite barrier with 4mm thickness.

4. Statistical Analysis of Models

The statistical analyses must be done to validate the results obtained by the model. This statistical analysis leads to calculate the coefficients of determination R^2, R_{adj}^2 and Q^2 [10, 12-18].

The various values are given in Table (5) called table of regression analysis.

Where:- R^2 is the descriptive coefficient; it measures the relationship between the model and the response.

- Q^2 is the predictive coefficient; it measures the ability of the model to predict the response at unknown points.

-R_{adj}^2 is the adjusted coefficient; it indicates that the model gives the same result as the experimental measurements if it is close to 1.

Table 5: Table of Regression Analysis

	Pressboard, *e*=2mm			**Bakelite, *e*=4mm**		
Coefficients of *E* (kV/cm)	R^2	R_{adj}^2	Q^2	R^2	R_{adj}^2	Q^2
	0.99	0.99	0.99	0.99	0.988	0.970

From Table (5), it is clear that the estimated values are close to the experimental ones, since R^2 and Q^2 are close to 1. This shows good predictive performance of the model. Otherwise, the application of Student test allows checking the impact of each input parameter. From the Student table, we can read the critical Student value (t_{crit}):

$$t_{crit} = (\alpha, n-p) \qquad (7)$$

Where: *n-p*= 27-15=12; 12 is the degree of freedom number.

Consequently, t_{crit}= (0.05,12)=2.179.

The effect will be significant at the risk of 5% if the Student test model coefficients ti, are higher than the critical Student value, (t_i> t_{crit}). Indeed, (t_i> 2.179) as illustrated in Tables 6 and 7obtanied when using pressboard and Bakelite barriers respectively.

Table 6: Significance of Test Coefficients in the case of Pressboard Barrier with *e*=2mm

Parameters	Effect	t_i>2.179
Constant	b_0=11.5752	t_0=54.858
d	b_1= - 4.8211	t_1= 22.848
a/d	b_2= -1.3211	t_2= 6.2611
D	b_3= - 0.6628	t_3= 3.141
d× d	b_{11}= 2.4456	t_{11}=11.590
a/d× a/d	b_{22}= 1.1856	t_{22}= 5.6189
d× D	b_{33}= 0.6575	t_{33}= 3.1161

Table 7: Significance of Test Coefficients in the case of Bakelite Barrier with *e*=4mm

Parameters	Effect	t_i>2.179
Constant	b_0=12.5006	t_0=31.4085
d	b_1= - 7.3422	t_1= 18.4422
a/d	b_2= -2.0474	t_2= 7.3185
d× d	b_3= 2.0474	t_3= 5.1442
a/d× a/d	b_{11}= 0.9924	t_{11}=2.4934
D × D	b_{22}= 4.0824	t_{22}= 10.257
d× a/d	b_{33}= 1.1606	t_{33}= 2.916

From the obtained results, the mathematical model equation of the dielectric strength can be reduced taking into account only the coefficients providing descriptive quality, as expressed by equations (8) and (9) for pressboard and Bakelite barriers respectively.

$$E = 11{,}5752 - 4{,}8211(d) - 1{,}3211\left(\frac{a}{d}\right) - 0{,}6628(D) + 2{,}4456(d)^2 + 1{,}1856\left(\frac{a}{d}\right)^2 + 0{,}6575(d \times D) \quad (8)$$

$$E = 12{,}5 - 7{,}3122(d) - 2{,}9128\left(\frac{a}{d}\right) + 2{,}0474(d)^2 + 0{,}9924\left(\frac{a}{d}\right)^2 + 4{,}0824(D)^2 + 1{,}1606\left(d \times \frac{a}{d}\right) \quad (9)$$

5. Validation and Discussion

In order to validate the mathematical model, the predicted dielectric strength values have been compared to the experimental ones. For this purpose, a relative error between both estimated and experimental values has been defined and expressed by equation (10). This comparison gives, in fact, a general view on the exactitude of the proposed mathematical models.

$$k_{\%} = \left| \frac{E_{pred} - E_{\exp}}{E_{pred}} \right| \times 100 \quad (10)$$

Where: (E_{pred}) is the predicted dielectric strength value and (E_{exp}) is the measured one.

Influence of the Insertion of the Pressboard Barrier of 2mm Thickness

Figures (5) and (6) present the predicted and the measured values of the dielectric strength as well as the relative errors between them, for relative positions of 40% and 80% respectively. Several barrier diameters has been considered (*D*=10, 14 and 20cm). In the same conditions, figures (7 and 8) illustrate the variation of the both dielectric strength values as a function of the inter-electrodes gap. These figures clearly show that the dielectric strength decreases with the increase of the inter-electrodes distance [12], [14]. Otherwise, a visual inspection of both tables shows that the relative mean error increases with the barrier diameter. According to these tables, the relative mean error between predicted and experimental values of the dielectric strength is less than 5% when the barriers having 10 and 14cm as diameter are inserted at 40% relative position. In these conditions, the dielectric strength estimated values are accepted. For the rest of the results, the relative mean errors are large than 5%; the estimated values of the dielectric strength are then rejected.

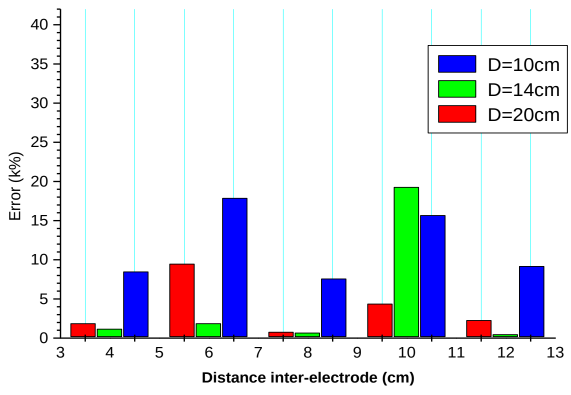

Figure 5: Comparison between experimental and predicted results for Pressboard Barrier with e=2mm, inserted at a/d= 40%

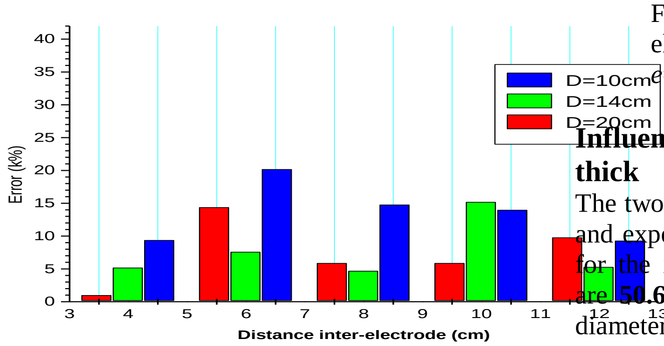

Figure 6: Comparison between experimental and predicted results for Pressboard Barrier with e=2mm, inserted at a/d= 80%.

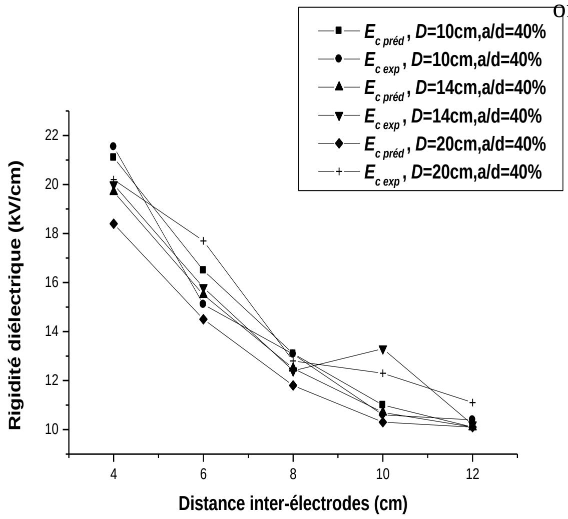

Figure.7: Dielectric Strength Variation vs Inter-electrode distances of the barrier, (Pressboard, e=2mm, a/d = 40%), for different diameters.

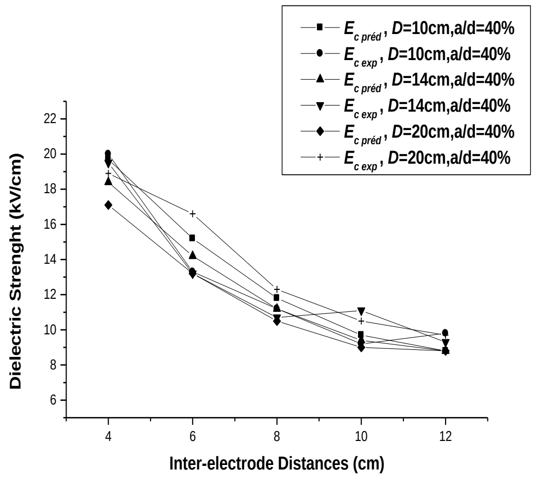

Figure.8: Dielectric Strength Variation vs Inter-electrode distances of the barrier, (Pressboard, e=2mm, a/d = 80%), for different diameters

Influence of Insertion of Bakelite barrier of 4mm thick

The two figures (9 and 10) represent the different predicted and experimental values of the Bakelite barrier. The errors for the inter-electrode distances 6 and 10cm respectively are **50.6** and **39.9%**, for a diameter 10cm. For the 14cm diameter the errors are **17.7** and **19.1%.** For the 20cm diameter the errors are **28.2** and **20.1%.** The errors obtained reach significant value greater than the error of 5% as clearly shown in the figures (11 and12). We also not that the curves resulting from the modeling reproduce the experimental curve despite the large difference observed. The same remarks can be made also for the relative position of the 80% barrier

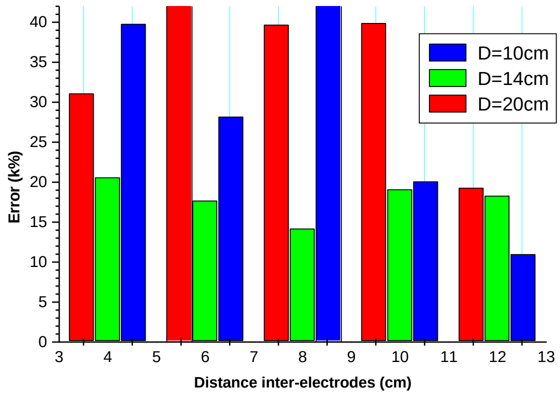

Figure.9: Comparison between experimental and predict for (Bakelite, *e*=4mm, *a/d*=40%).

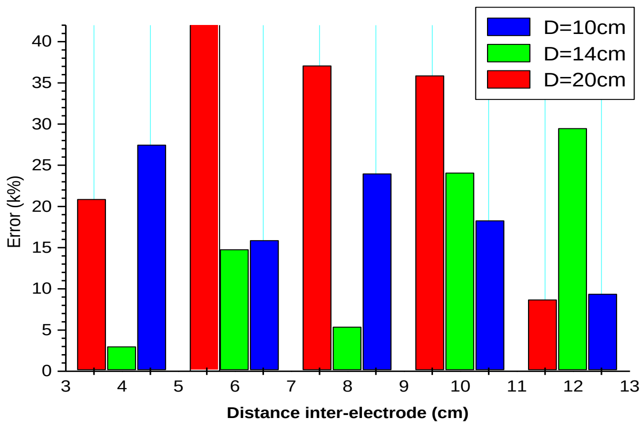

Figure.10**:** Comparison between experimental and predicts for (Bakelite, *e*=4mm, *a/d*=80%).

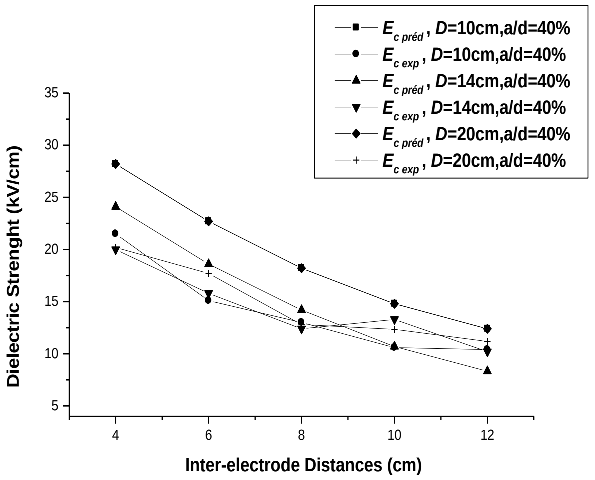

Figure.11**:** Dielectric Strength Variation vs Inter-electrode distances of the barrier (Bakelite, *e*= 4mm, *a/d* = 40%) for different diameters.

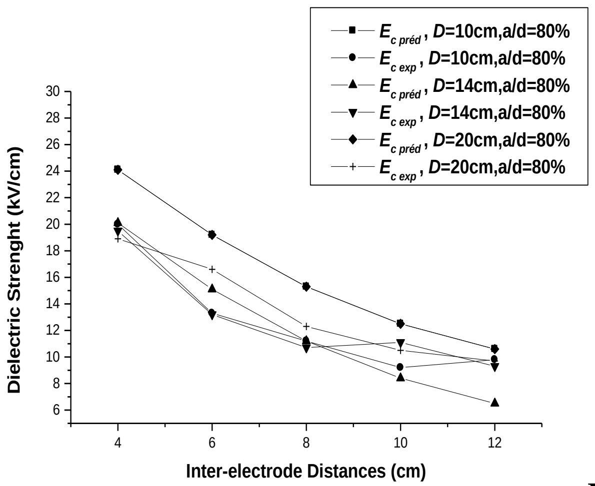

Figure.12**:** Dielectric Strength Variation vs Inter-electrode distances of the Bakelite barrier *(e*= 4mm, *a/d*= 80%) for different diameters.

Influence of position of Pressboard barrier of 2mm thick

For this barrier, the statistical analysis shows the cases characterized by (*d*=6cm. *a/d*=40%, *D*=14cm) and (*d*=10cm. *a/d*=40%,*D*=10cm) and (*d*=10cm. *D*=10cm, *a/d*=80%) give the best results. The relative errors are minimal; they are **1.9%**, **4.4% and 5.9%** respectively (see figures 13 and 14).

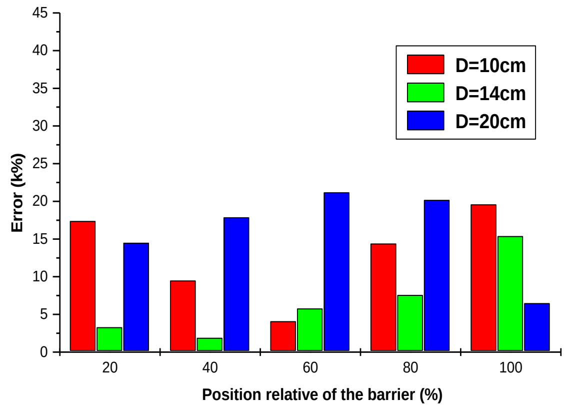

Figure.13**:** Comparison of experimental and predicted results for *(*Pressboard, *e*= 2mm, *d=6cm).*

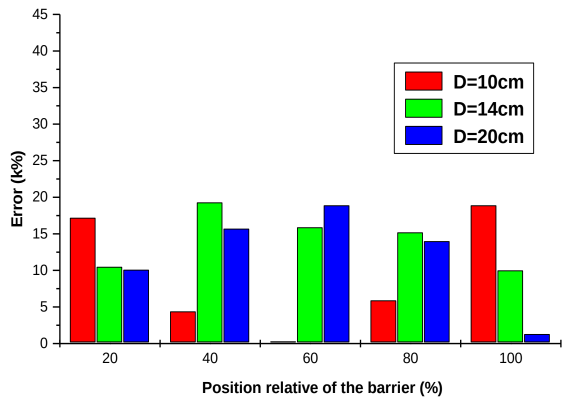

Figure.14: Comparison of experimental and predicted results for (Pressboard, *e*= 2mm, *d*= 10cm*).*

Influence of position of Bakelite barrier of 4mm thick

The statistical analysis presented in tables 14 and 15 stipulates very large deviations for all the diameters of the barrier in the relative positions of 40 and 80%.

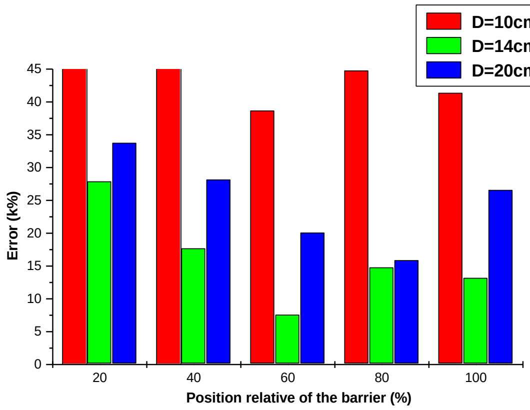

Figure.15: Comparison of experimental and predicted results for (Bakelite, *e*=4mm, *d*=6cm).

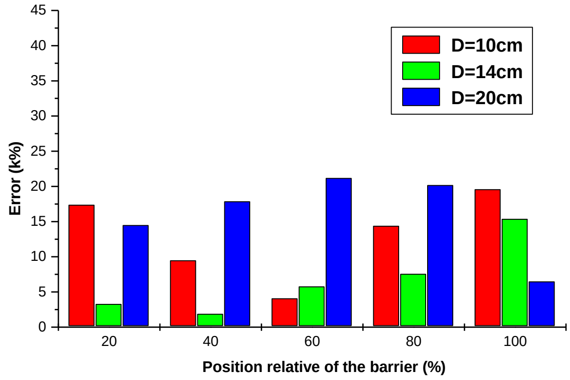

Figure.17: Comparison of experimental and predicted results for *(*Pressboard, *e*=2mm, *d*=6cm*)*.

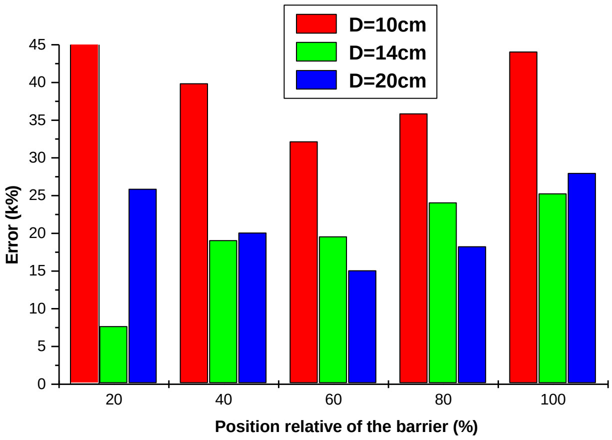

Figure.16: Comparison of experimental and predicted results for *(*Bakelite, *e*=4mm, *d*=10cm*)*.

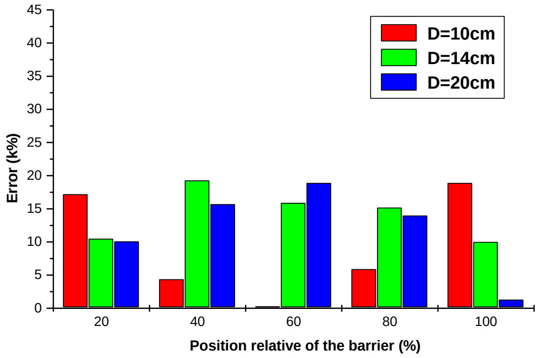

Figure.18: Comparison of experimental and predicted results for *(*Pressboard, *e= 2mm*, *d*=10cm*)*.

Influence of Diameter of Pressboard barrier of 2mm thick

To evaluated the influence of the barrier diameter on the dielectric strength, we consider two barriers of the same nature and thickness for different diameters *D*=10cm, *D*=14cm and *D*=20cm. In these tests, we fix the relative position of the barrier and we vary the inter-electrode distances from 4cm to 12cm. The discharge develops from the tip to the edge of the barrier and from the edge to the plan electrode. The dielectric strength predicted and experimental curves are in decreasing with the increase of the inter-electrode distances. This is due to the lengthening of the disruptive discharge.[5,11,12].

From the results grouped in figures (17 and 18), we note a small deviation in the cases (*d*= 6cm, *D*=14cm) and (*d*= 10cm, *D*=10cm) at the position of *a/d*=40%. As soon as the relative position increases to 80%, only the characteristics (*d*= 10cm, *D*=10cm) give a small value of the error (***K%*= 5.9).**

Influence of Diameter (Bakelite barrier of 4mm thick)

In figures (19 and 20), the relative error converges to very high value exceeding **5%**. When the Bakelite barrier is in the position of 40 and 80% at (*d*=6 and 10cm),

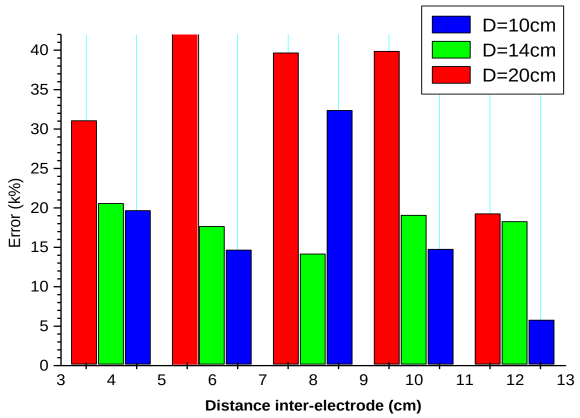

Figure.19: Comparison of experimental and predicted results for (Bakelite, e= 4mm, a/d= 40%).

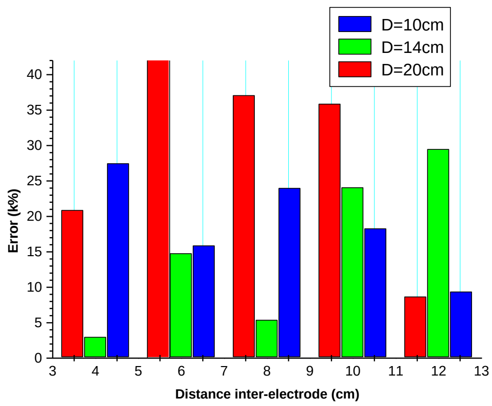

Figure.20: Comparison of experimental and predicted results for (Bakelite, e= 4mm, a/d= 80%).

6. Conclusion

The Central Composite Face method allows having mathematical models from a very large database. It reduces test time and the experiment cost.

From the results obtained, we can affirm the acceptable quality of the approach adopted, although. It presents in some cases an anomaly such as the convergence problem. This prompted us to think to interview on the models developed to adjust the coefficients model in order to reduce the relative errors below the error retained as on optimal choice criterion by our CCF method.

The following remarks highlight the results obtained:

- The predicted results obtained by the models are influenced by the variation of the input variables.
- The validation is made by two configurations (*d*=6 and 10cm, *a/d*=40 and 80%) in the field coded by -1 and +1.
- The results explained that the mean error in 27 tests is 16,95%, it is a large value but this method allowed us to reduce the tests number in a three runs only for each input parameters.
- The results obtained are very satisfactory, and give an idea of the planning of experiments by CCF, in order to do the minimum of tests, limiting the cost and the time.

The future scope

Further work will focus on the reduction of errors in some cases using the optimization of coefficients model such as PSO, ACT and BAT algorithm.

References

[1] Aka N'gnui, "Contribution à l'étude des phénomènes de pré-claquage dans les diélectriques liquides modèles de génération et de propagation des streamers ", thèse de doctorat, Ecole centrale de Lyon, Juin 2000.

[2] R. Fournié, "Les isolants en électrotechnique, concepts et théories". Editions Eyrolles, Paris 1986.

[3] J. Perret, M.Paris, ''Les huiles Silicones pour transformateurs'', E.D.F. Bulletin des études et recherche Série B, Réseaux électriques, Matériels électriques, n°2, 1987, pp.5-13.

[4] F.Guerbas, "Etude de la génération des bulles gazeuses dans les diélectriques liquides et leur transition en streamer," Thèse de Magister, Département de Génie Electrique, Ecole Nationale Polytechnique d'Alger, Mai 1994.

[5] M.Zitouni, "Influence des barrières isolantes sur la rigidité diélectrique de l'huile de transformateur dans l'intervalle pointe-plan sous tension alternative," Thèse de Magister, Ecole Nationale Polytechnique d'Alger, juin 2010.

[6] R. Kattan, A. Denat and N. Bonifaci. “Formation of bubbles in non-polar liquids initiated by current pulses,” IEEE transaction on Electr. Insul., Vol.26,N.4, pp. 656–662, August1991.

[7] S. Abdi, “Influence du vieillissement thermique sur les propriétés de l’huile de transformateur,” Thèse de Magister, Département de Génie Electrique, Ecole Nationale Polytechnique d’Alger, 2002.

[8] A. Zouaghi, “Etude de l’influence des barrières isolantes sur la tenue diélectriques d’intervalle d’huile en chocs de foudre et en continu,” Thèse de doctorat, Ecole centrale de Lyon, décembre 1997.

[9] I. Fofana, H. Borsi. andE.Gockenbach. “Fundamental Investigations on Some Transformer Liquids under Various Outdoor Conditions,” IEEE Transactions on Dielectr.Insul., vol. 8, pp. 1040–1047, Dec 2001.

[10] M. Zitouni,F. Guerbas,L.Boukezzi and A.Boubakeur. ‘Modelling by design of experiments method of the AC breakdown voltage of transformer oilpoint-plan gaps with insulating barrier’ IET Generation, Transmission et Distribution, Vol.10, Iss1,pp 232-239,2016.

[11] S.Sherif, M.Ghoniem, S.Sobhy Desouki, A.Adel Elfaraskoury, A.B.Aboucharef. ‘Modling and Experimental Verification of Barrier Effect on Breakdown Voltage of Transformer Oil Using Box-Benkhen Design’.Mesearment,147, 2019.

[12] F. Guerbas,. : 'Influence des barrières sur la rigidité diélectrique de l’huile minérale'. PhD thesis, Department ofElectrical Engineering, Ecole National Polytechnique, Algiers, June 2011

[13] A. Boubakeur, “Influence des barrières sur la tension de décharge disruptive des moyens intervalles d’air pointe-plan, ”Thèse de Doctorat, E.P. Varsovie, Pologne 1979.

[14] A.Tilmatine, M.Mihailescu,.,A.Luga,, et al: 'A linear interaction optimization model using Taguchi’s experimental design technique'. IEEE Ind. Appl. Mag. Vol 10, N° 10, Nov-Dec 2004, pp 19-25

[15] M..Mihailescu, , A.Samuila, , A.Urs, , et al.: 'Computer-assisted experimental design for the optimization of electrostatic separation processes' , IEEE Trans. Ind. Appl, vol. 38, N° 5, Sep/Oct 2002, pp 1174-1181

[16] CEI, “Méthode de détermination de la tension de claquage à fréquence industrielle - Méthode d’essais, Deuxième édition, Novembre 1995 ”

[17] F.Derler,J.Kirch, C.H. Krause,et al.: 'Development of a design method for insulating structures exposed to electric stress in long oi lgaps and a long oil/transformer board interfaces', 7th Int. Symp. High Volt. Eng, Dresden,1991, pp 73-76, Germany, paper 21.16, B

[18] J.Foucher: 'Les plans d’expériences Pratique de la régression Linéaire pour le réglage de commandes à base de logique floue', PhD thesis, Institut National Polytechnique, Toulouse, France, 2006

[19] P. Saungmin,: 'Statistical Design of Experiments and Analysis on Gate Poly-Silicon Critical Dimension', IEEE Trans Semicond. Manufact. Vol. 17, N° 3, Aug. 2004, pp 362-374

[20] X. Li,. K. Wang ,W. Mu,; 'Research on SID-IIs Rib Characteristic Based on DOE' , Inte. Conf. Electr. &Mechan. Eng. Inform. Tech. (EMEIT), Harbin, China, Vol 7, 12-14. Aug 2011, pp 3482-3484

[21] L. Dascalescu,K. Medles,,S. Das,, et al.: 'Using Desing of Experiments and Vertual Instrumentation to Evaluate the Tribcharging of Pulvelurent Materials in Compressed-Air Devices', IEEE Trans. Ind. Appl, Vol 44, N°1, Jan/Feb. 2008, pp. 3-8

[22] L. Erikson., E. Johansson,,M. Kettaneh , et al.: 'Design of Experiments' , Umetrics Academy, Sweden 2000

[23] K. .Sandrine, 'Application de la méthodologie des plans d’expériences et de l’analyse de données à l’optimisation des processus de dépôt', PhD thesis, Limoges, France, 2004

[24] L. Dascalescu,,A. Tilmatine, F. Aman,, et al.: 'Optimization of electrostatic separation processes using response surface modeling', IEEE Trans. Ind. Appl. Vol. 40, N° 1, Jan/Feb. 2004, pp.53-59

[25] S.Vivier, F. Gillon, P. Brochet,.: 'Optimization Techniques Derived from Experimental Design Method and Their Application to the Design of Brushless Direct Motor', IEEE Trans.on magnitics, Vol.37,N° 5, Sept. 2001,pp.3622- 3626

[26] S. Brisset, F. Gillon,, S. Vivier, et al.: 'Optimization with Experimental Design : An Approech Using Taguchi's Methodology and Finite Element Simulations', IEEE Trans. On magnitics,Vol.37, N° 5, Sept. 2001, pp 3530-3535.

.