Modeling of the AC Breakdown Voltage in Point/Plane Air Gaps with Insulating Plexiglas Barrier by using the Design of Experiments Method

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***Abstract*-The breakdown paths and conditions of air-insulated rod-plane gaps under alternating voltages were investigated for plexiglass barrier inserted at different gap positions.In the present paper methods of the Modeling of the AC breakdown voltage in Point/Plane Air Gaps with insulating Plexiglas barrier are investigated by using the design of experiments method, An analysis based on experiments design method has been developed with indicates that,measures to contain tests of relevant information in the early stages of the short-time investigation were carried out on a one-time basis with a barrier varying in position and size. The results of our work are carried out at the High Voltage Laboratory of BISKRA University in the field of dielectric strength of air in system peak-barrier.**

Keywords— breakdown voltage, point-plane gap, insulating barrier ,experiments design method, factors.

I. INTRODUCTION

The study of dielectric breakdown phenomena in large air gaps is of interest in several sectors of industry such as the protection of power transmission networks[1].
Solid insulating materials are frequently used in air gaps due to dielectric strength. In this case, one of the means used to reduce the insulation distances and increase the voltage is the insertion of dielectric barriers in the inter-electrode space. These can be live metal parts of various equipment, conductors of overhead lines or high voltage terminals in test laboratories. When the electric field applied to an insulating system exceeds the dielectric strength of the medium considered, a rupture occurs in the sample, in other words an electric arc is established between the two electrodes, which is formed when an electric current passes between two electrodes separated by a short distance from each other[2][3].
The introduction of an insulating barrier drastically changes the breakdown voltage, and improves the stiffness of a system without increasing the inter-electrode distance[4]-[6]. The effect of barriers in the point-plane air gaps has been the subject of several Investigations, these have shown that the influence of the barrier is mainly related to the accumulation of charges on its surface on the side of the active electrode. The barrier constitutes a mechanical and electrostatic obstacle to the development of the electric discharge[7]-[11].
The small air gaps between the active and metallic parts of this equipment are electrically equivalent to configurations with a non-uniform electric field, under the protection of point-plane insulating barriers.
In this paper, in order to model the AC breakdown voltage in point-plane 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[12]-[18].
Most of the realizations of the plans of experiments call upon a prior specialized knowledge of the field of application. To be accessible.
The objective initially set in our work is to apply a new approach based on the application of the design of experiments methodology in the determination and prediction of the voltage of the point-barrier-plane air gap breakdown.

Geometric configuration studied: The following figure represents the geometric configuration point (positive)-plane:

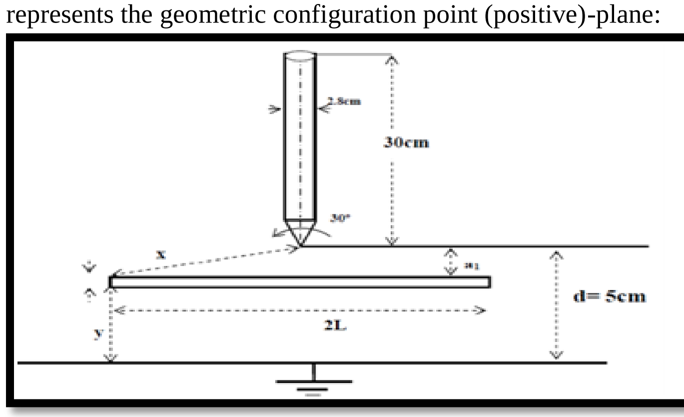

Fig .1.Point-barrier system

II. MODELING AND PREDICTION OF DISRUPTIVE TENSION BASED ON THE DESIGN OF EXPERIMENT METHODOLOGY

The plane used in this work is the centered composite plane; the purpose of this modeling is to model the variation of the point-plane air gap voltage as a function of the inter electrode distance and the width of the barrier and also we used perforated barriers, under alternating voltage (50 Hz) and continues with positive polarity[19][20].
The experimental results are used as the basis of the data in the development phase of the models based on the experimental designs.
During this stage of work we relied on the use of MATLAB

III. POINT-BARRIER-PLAN SYSTEM UNDER ALTERNATING VOLTAGE (50HZ)

A. Plexiglas barrier

Plexiglas barriers (εr=**3.3**) are squares of different widths (5cm, 10cm, 15cm) and different holes (4mm, 8mm and 12mm) and its thickness is 1mm, 3mm.
In this section we will present the various tables which represent the results of point-plane air breakdown modeling.
In the table.1, we give details of the values of the experimental tests for concreteness of the centered composite plan[21]–[23].

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
- T (mm) is the hole in the back
- L(cm) is the width of the barrier

Table1. Factor levels studied

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

Proposal of a model

Our choice fell on composite planes with centered faces, for the study of response surfaces[24].
A face-centered composite plane is defined by:

- A full 2k factorial design,
- n_0 repetitions in the center of the experimental domain, dedicated to statistical analysis.
- Two star points per parameter and positioned on the axes of each of them.

These points contribute to the evaluation of the quadratic terms of the polynomial model, i.e. they give information about the curvature of the response surface[25]-[30].

$$N = 2^k + 2.K + n_0$$
$$n_0 = 3, \quad K = 3 \qquad (1)$$
$$N = 2^3 + 2.3 + 3 = 17$$

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

$N^0$of experience	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

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 of the matrix experiments.
So that it meets the uniform precision requirement, ensuring an almost constant deviation in the experimental field[31]-[35].
If the vector of coefficients of the analytical model sought: It is defined by the vector of coefficients of the analytical model is defined as follows:

$$b = \left(X^t.X\right)^{-1} X^t.Y \qquad (2)$$

When X is the matrix experience, X^t is the transposed matrix experience, y the breakdown voltage (of the reaction)[36][37]. The number of unknown parameters (b_i) of the polynomial is determined by the following formula:

$$b = \frac{(K+2)!}{k!2!} \Rightarrow b = \frac{(3+2)!}{3!2!} = 10 \quad (3)$$

Mathematical models

Estimation of the coefficients of the model, we used the program Matlab, which gives an analytical form of the surface of response studied they are calculated using equation (2).

Finally, the model is given by the equation:

$$y = b_0 + \sum_{i=1}^{3} b_i.X_i + \sum_{i=1}^{3} b_{ii}.X_i{}^2 \sum_{i=1}^{2}\left[\sum_{j=i+1}^{3} b_{ij}.X_I.X_J\right] (4)$$

from where:

$$y = b_0 + b_{1.}x_1 + b.x_2 + b_3.x_3 + b_{11}.x_1{}^2 + b_{22}.x_2{}^2 + b_{33}.x_3{}^2 + b_{12}.x_{12} + b_{13}.x_{13} + b_{23}.x_{23} \quad (5)$$

So we can write the mathematical model (experimental domain) as follows[38]-[40]:

$$U_C = 33{,}97567568 + 6{,}384.P - 1{,}12.T - 1{,}0075.L - 0{,}9625.P.T - 0{,}6125.P.L - 0{,}77.T.L + 1{,}8975.P^2 - 0{,}412432.T^2 + 0{,}9483.L^2 (6)$$

The obtained results can be plotted to compare the measured responses with the estimated one. For this it is necessary to plot the relevance of the model. The measured responses are placed on the x-axis and the estimated responses are on the ordinate in Figure.2. The trouble points are aligned with the y=x line, which means that the accuracy of the model is quite good

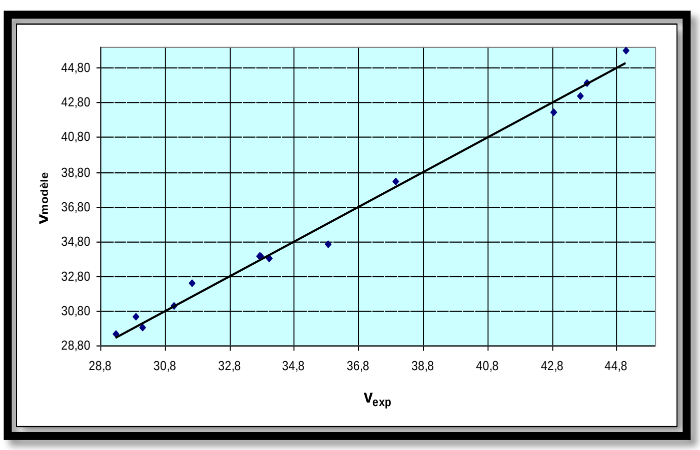

Fig. 2.Model Fit Chart

IV. RESULTS AND DISCUTIONS

The empirical model equation is only an approximation of reality. Estimation coefficients of the second degree polynomial model are based on the test results which are, for each treatment plan experiment, the particular values of a random variable.

The implementation of statistical tests must make it possible to make a judgment on the results obtained by knowing a model describing the variation of the response in the experimental field.

This stage of the statistical analysis of the results involves the construction of the regression analysis table and the determination of the descriptive quality of the model. The regression analysis is to explain the total change in the response of the sum of the squares of the defined deviations between the test results and their mean.

The statistical analysis of the model as a whole is followed by the construction of a statistical test which consists in asserting that the model does not make it possible to describe the α equal to 5%.

The regression analysis table is used to immediately calculate the determination of the coefficient R^2 , R^2_{ajus} et Q^2 : the descriptive quality of the models will be evaluated, these take the following values:

Table. 3.Descriptive model quality determination coefficients

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

A good descriptive quality is ensured because the coefficients R^2 , R^2_{ajus} et $Q^2 > 0.9$ (close to unity), which reflects the good quality of the model.

For a risk of de$\alpha = 5\%$, $N - P = 17 - 10 = 7$ From the Student table:

t_{crit}=(0,05,7)=2.37 (7)

The effect will be significant at the 5% risk if ($t_i > 2.37$).

$$t_i = \frac{|b_i|}{s_i} (8)$$

Table.4. Significance test of the coefficients

Factors	Effect	$t_i = 2.37$	Results
Constant	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

According to Table.4, only the coefficients providing t descriptive quality of the model will be preserved.
This is to reject the coefficients (T^2).The reduced mo equation becomes:

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

In this case, the interval of a confidence effect is given by:

$[A_i - 1,96\ .\ 0,189]$ lower bound;

$[a_i + 1,96\ .\ 0,189]$ upper bound.

Table.5.Confidence interval 5% of Risk zone factors

Factors	Effect	Interval	
		Lower bound	Upper bound
Constant	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
L^2	0,94837838	0,58	1,32

Table.6. Analysis of variance before significance test

Variation	sum of squares	D D L	Mean Square	F
Connection	470,52	9	52,279	85,510
Residues	4,28	7	0,611	
Total	474,80	16		

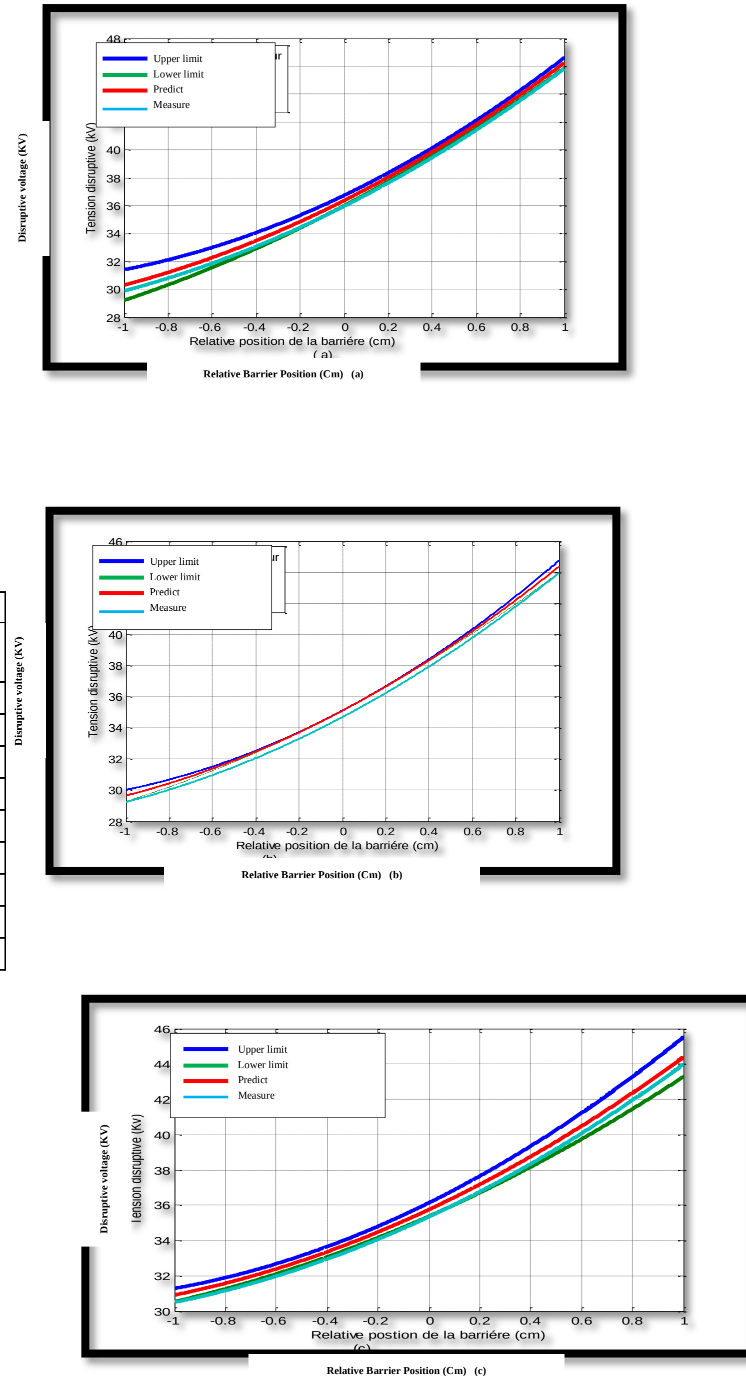

Fig.3. Influence of the relative position of the barrier on the breakdown voltage different width (a) of 5 cm, (b) 10 cm and (c) of 15 cm, in alternating voltage (50 Hz)

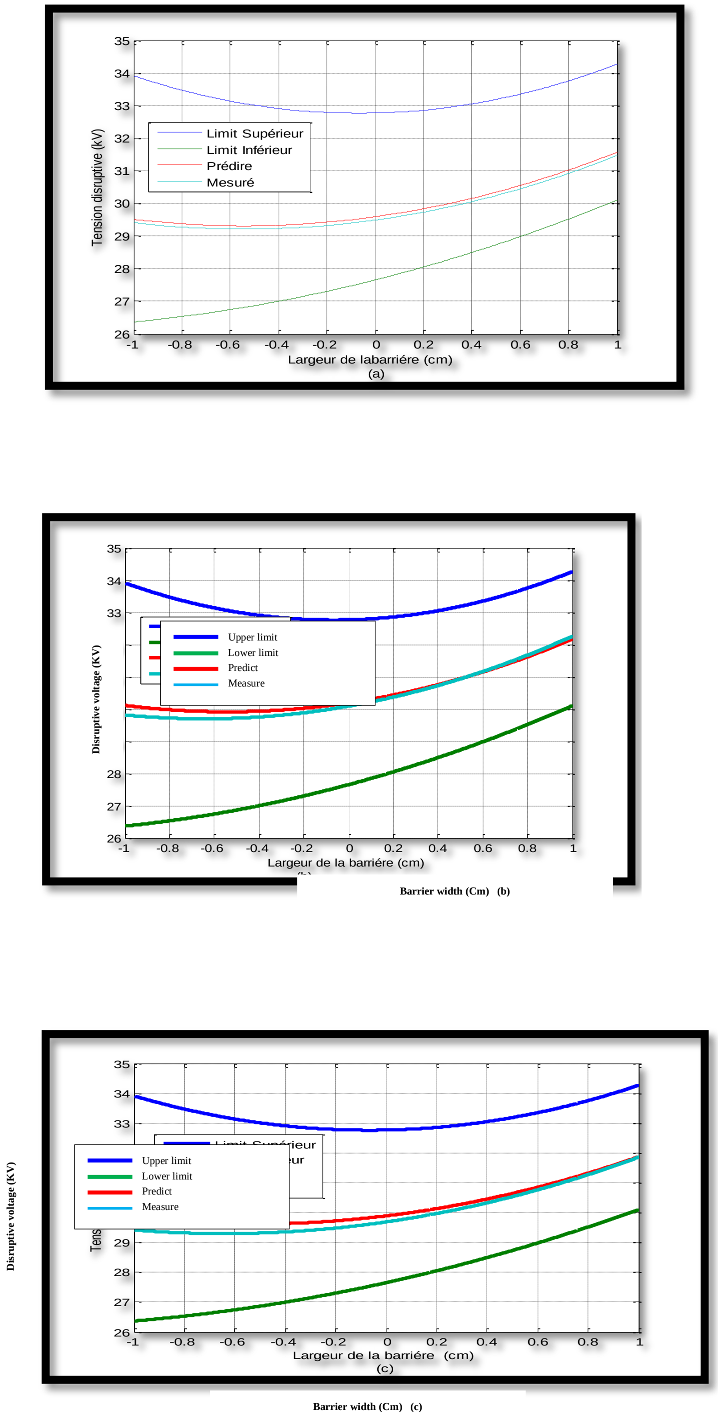

Fig. 4. Influence of barrier width on breakdown voltage: Different position in alternating voltage (50 Hz)

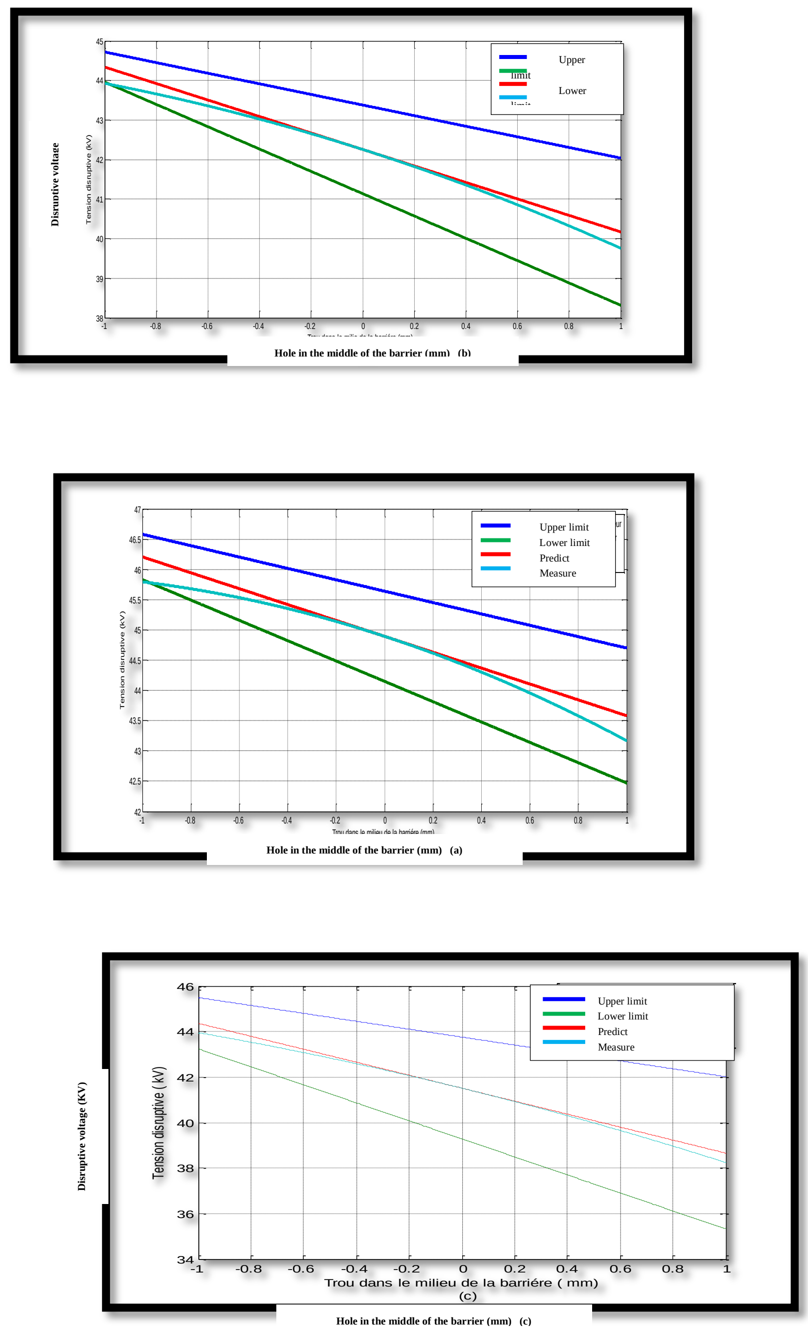

Fig .5. Influence of the hole in the middle of the barrier on the breakdown voltage: different position, in alternating voltage (50 Hz)

V. Conclusion

Concerning the method of the plans of experiments the validation of the results given by the model is to check if the hypotheses formulated in the departure of experiments are well verified, can be carried out additional testing outside the experiments of test plan to validate the behavior of the model obtained by the design. In our case study, we took the test performed to investigate the influence of parameters apart from testing the experimental design. The results of these tests are compared with the results of the mathematical model
Experimental results showed that the design of experiments method is a useful tool to find the parameters influencing the fixed objective and the optimization. Methodology of the experiments was giving indications on the effects of different factors. It consists in a first step to research parameters influencing the set objective. For this, the use of the method of the surface turns response to be very effective, because it allows to classify the effect of the parameters in the order of importance. The study on the effects of factors has on the one hand and the restriction of choosing the parameters of the desired model on the other hand to define the limits of the discourse of the universe for each. A model with a good description of the system studied has therefore been defined and leads to an improvement in the performance of the system. The modeling of the dielectric breakdown in the point-plane arrangement with barrier in the air gap has been studied. We proposed a mathematical modeling using the design of experiments method. It leads to analyze the interactions between different parameters: distance between the electrodes, the diameter of the barrier and the relative position. This method has given good results and makes it possible to minimize the cost of the study, expressed in number of tests. The use of this methodology has been shown to be very useful for tracking operating parameters affecting insulation reliability and modeling service life. In this study, we can say that the methodology of the design express show a good performance to the investigations in the analysis of the different stages of discharge of the air gap.

Future work

It is proposed in the future to use barriers with other minerals such as glass or bakelite and others and other sizes to make a comparison with previous research.

Reference

[1] Ayman El-Hag High Voltage Engineering and Applications published in Energies, 2020.
[2] A. Küchler, High Voltage Engineering: Fundamentals-Technology Applications. Springer, 2017.
[3] Wolfgang Hauschild, Eberhard LemkeHigh-Voltage Test and Measuring Techniques PublisherSpringer Cham ,2014.
[4] Peter Mackintosh High Voltage Engineering Larsen and Keller Education , 2018.
[5] S. Ghoneim, S. Dessouky, Ahmed B. Abou Sharaf Modelling and experimental verification of barrier effect on breakdown voltage of transformer oil using Box-Behnken Design,PhysicsMeasurement ,2019.
[6] S. Ghoneim, S. Dessouky, M. DarwishAccurate Insulating Oil Breakdown Voltage Model Associated with Different Barrier Effects , Physics Processes,2021.
[7] S. Ghoneim, S. Dessouky, A. SharafPrediction of insulating transformer oils breakdown voltage considering barrier effect based on artificial neural networks , Physics ElectricalEngineering,2018.
[8] Elham Foruzan, A. Akmal, D. SharmaComparative study on various dielectric barriers and their effect on breakdown voltage , Physics ,2017.
[9] B. SeokElectrical breakdown characteristics in non-uniform electrode system with bakelite barrierunder the lightning impulse Voltage, Published, Physics Electrical Engineering,2020.
[10] E. P. Waldi, Y. Murakami, M. NagaoBreakdown on LDPE film due to partial discharge in air gap and its correlation with electrical properties and surface degradation, Physics TELKOMNIKA ,2019.
[11] PitchasakChankuson, M. Nisoa Simulations of High Non-Uniform Electric Field in DielectricBarrier Electrode System Physics Walailak Journal of Science and Technology (WJST), 2021.
[12] Yuesheng Zheng, Peibin Zhang, Tongtong HeBreakdown path control by barrier effect forimproving withstand characteristics of air-insulated gaps under alternating voltages , Physics High Voltage ,2022.
[13] M. Talaat, A. El-Zein, A. SamirNumerical and simulation model of the streamer inception atatmospheric pressure under the effect of a non-uniform electric field, PhysicsVacuum,2019.
[14] H. K. Meyer, F. Mauseth, A. Pedersen, J. Ekeberg, Breakdown mechanisms of Rod-Plane Air aps with a Dielectric Barrier Subject to Lightning Impulse Stress, IEEE Trans. on Dielectr. Electr. Insul, Vol. 25, No. 3, pp. 1121-127,2018.
[15] S. Merabet, R. Boudissa, S. Slimani, A. Bayadi, Optimisation of the Dielectric Strengthof a Non-uniform Electric Field Electrode System under Positive DC Voltage by Insertion of Multiple Barriers, IEEE Trans. on Dielectr. Electr. Insul,

Vol. 21, No. 1, pp. 74-79,2014.

[16] E. Foruzan, A. A. S. Akmal, K. Niayesh, J. Lin, D. D. Sharma, Comparative Study on VariousDielectric Barriers and Their Effect on Breakdown Voltage, High Voltage, Vol. 3, No. 1, pp. 51-59,2018.

[17] G. Li, J. Wang, Y. Wei, S. Li, J. Wang, H. Zan, Effect of insulation barrier on AC breakdown voltage of rod- plane gaps and analysis of surface residual charge property, J. of Materials Science: Materials in Electronics, Vol. 30, No. 10, pp. 9513-9519,2019.

[18] A.Rouini, D. Mahi, T.Seghier :Prédiction the AC Breakdown Voltage in Point/Plane Air Gaps with Barrier Using Design of Experiments, Journal : TELKOMNIKA Indonesian Journal of Electrical Engineering , Volume 12 N°12 ,2014.

[19] A. Kara, O. Kalenderli, K. Mardikyan, Modeling and Analyzing Barrier Effect on AC Breakdown Strength of Non-uniform Air Gaps, IEEE Trans. Dielectr. Electr. Insul. Vol.24, pp. 3416-3424,2017.

[20] Y. Zheng, Q. Li, Y. Chen, S. Shu, C. Zhuang, Breakdown Path and Condition of Air-insulatedRod-plane Gap with Polymeric Barrier Inserted under Alternating Voltages, J. of AIP Advances,,Vol. 9, No. 105207,2019.

[21] S. Singh, Y. V. Serdyuk, R. Summer, Streamer propagation in hybrid gas-solid insulation, inAnnual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 387-390,2015.

[22] Seok Bok-Yeol , W. Choi, , Lightning Impulse Breakdown Path and Characteristicswith Dielectric BMC Barrier inserted Sphere-plane Electrode, IET Sci. Meas. Technol, Vol. 14, No. 8, pp. 872-876,2020 .

[23] Bok-Yeol Seok, Electrical Breakdown Characteristics in Non-uniform Electrode Systemwith Bakelite Barrier under the Lightning Impulse Voltage, J. of Electrical Engineering, Vol. 102, No. 4, pp. 2363-2368,2020.

[24] Dessouky, S.; Ghoneim, S.; Elfaraskoury, A.; Abosharaf, A.B. Barrier Effect on the Dielectric Strength of the Transformer Insulating Oils. In Proceedings of the 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, 27 August–1 September 2017.

[25] Mohd, A.; Khan, W. Breakdown Characteristics of Ambient Medium in Presence of Barrier underVarying Field Conditions. Int. J. Adv. Res. Electr. Electron. Instrum. Eng. 2016,

[26] A.Rouini, D. Mahi :Modelling of the AC Breakdown Voltage of Point-Plane Air Gaps with Insulating Barrier, Journal : International Journal of Electrical and Computer Engineering (IJECE) Volume 05 N°03 ,2015.

[27] Schueller, M.; Blaszczyk, A.; Krivda, A.; Smajic, J. Influence of the surface conductivity of a single glass barrier on the breakdown voltage in an air insulated rod plane arrangement. In Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Toronto, ON, Canada, 16– 19 October 2016.

[28] Meyer, H.K.H; Mauseth, F.; Pedersen, A.; Ekeberg, J Breakdown Mechanisms of Rod-Plane Air Gaps with a Dielectric Barrier Subject to Lightning Impulse Stress .IEEE Transactions on Dielectrics andElectrical Insulation, 25(3), 1121-1127. Doi:10.1109/TDEI..007023,2018.

[29] A. Pedersen and A. Blaszczyk. “An Engineering Approach to Computational Prediction of Breakdown in Air with Surface Charging Effects,” IEEE Trans. Dielectr. Electr. Insul., vol. 24, pp 2775-2783, 2017

[30] Z. Qiu, J. Ruan, C. Huang, W. Xu, L. Tang, D. Huang, and Y. Liao, “A method for breakdown voltage prediction of short air gaps with atypical electrodes,” IEEE Trans. Dielectr. Electr. Insul., vol. 23,pp.2685–2694, 2016.

[31] F. Mauseth, J. S. Jørstad, and A. Pedersen, “Streamer inception and propagation for air insulated rod- plane gaps S. Singh, Y. V. Serdyuk, and R. Summer, “Streamer propagation in hybrid gas-solid insulation,” in Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena(CEIDP), pp. 387–390,2015.

[32] J. Qin and V. P. Pasko, “On the propagation of streamers in electrical discharges,” J. Phys. D: Appl.Phys.,vol. 47, p. 435202, 2014.

[33] H. Kojima et al., “Classification of impulse breakdown mechanisms under non-uniform electric field in air,” IEEE Trans. Dielectr. Electr. Insul., vol. 23, no. 1, pp. 194–201, 2016.

[34] H. K. H. Meyer, F. Mauseth, A. Pedersen, M. Husøy, and J. Ekeberg, “Breakdown in short rod-plane air gaps under positive lightning impulse stress,” in Proceedings of the Nordic InsulationSymposium, 2017.

[35] H. K. Meyer, F. Mauseth, A. Pedersen, and J.

Ekeberg, “Streamer propagation in rod-plane air gaps with a dielectric barrier,” in Annual Report on IEEE Conference on Electrical Insulation and DielectricPhenomena, pp. 1037–1040,2016.

[36] T. Kitamura, H. Kojima, N. Hayakawa, K. Kobayashi, T. Kato, and T. Rokunohe, “Influence of space charge by primary and secondary streamers on breakdown mechanism under non-uniform electric field in air,” in Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp. 22–125,2014.

[37] H. K. Meyer, F. Mauseth, A. Pedersen, and M. Husøy, “Surface charging of dielectric barriers bypositive streamers,” in Annual Report IEEE Conference on Electrical Insulation and DielectricPhenomena, pp. 802–806,2017.

[38] Angela Dean, Daniel Voss, DanelDraguljić Design and Analysis of Experiments 9th Edition Publisher:John Wiley & Sons, Inc , 2022.

[39] John LawsonDesign and Analysis of Experiments with R (Chapman & Hall/CRC Texts in Statistical Science) 1st Edition Publisherby Taylor Et Francis ,2015.

[40] Sammy Shina Industrial Design of Experiments: A Case Study Approach for Design and Process Optimisation 1 sted edition Springer ,2022.