Predicting TJ Electric Discharge in Insulators by Developing, Comparing then Validing of Regression Models

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***Abstract*— The discharge and breakdown characteristics caused by triple junctions (TJ) in high-voltage (HV) electrical insulation are becoming increasingly important problems in recent industrial applications. To better organize the tests supporting our study and highlight the parameters and their interactions, we have developed a mathematical regression model of the monovariable polynomial discharge current as a function of the inter-electrode distance (*d*) and the applied voltage (*V*) independently and a two variable quadratique model as a function of *d* and *V*. The latter can simulate the maximum discharge current (I_0) with an adjusted determination coefficient close to 0.99. Therefore, the dual variable quadratic model was tested and validated**.

***Keywords*— Triple Junction, Electric Field, Electrical Discharge Current, Model, Regression.**

I. INTRODUCTION

TJ is considered a weak point in electrical insulation. Indeed, at the level of the TJ the electric field is reinforced. If these areas are not designed as carefully as possible, partial discharges (PD) can occur, which accelerates the aging of the insulation [1- 4].

Then, knowledge of the mechanisms involved in the generation and propagation of electrical discharges at the TJ is an important step for good optimization of these devices [5-7]. Flashover is assumed to be initiated at the surface of the insulator by a mechanism called secondary electron emission avalanche (SEEA) [8-10]. The source of the SEEA is also assumed to be the electron field radiating from the highly charged triple points [11-12]. Béroual et al., M.A. Handala et al. and A. Abahazem et al. treated electrical discharges in their research using different point/plant electrode systems with various insulators. A theoretical model was presented to study the effects of tip curvature radius (*r*) on permeability and thus provide an accurate and reasonable estimation of the optimized design parameters [13-14]. The effect of the voltage waveform and the insulating materials used on the morphology and duration of the discharge was studied in a tip/plane electrode system with liquid surfaces/solid insulators [15-16]. It has been demonstrated that insulating materials significantly influence the properties of discharges and in particular their morphology [17-18]. However, synthetic materials such as silicone have recently been introduced into industrial applications due to their proven rupture properties, but their long-term performance is not yet fully understood and requires further research.

This work consists of a mathematical study of the electrical discharge at the TJ as a function of *d* and *V*. A regression model for electrical discharges at TJ was therefore developed. This model is a characterization of the experiments carried out. Then, we compared the monovariable polynomial models as a function of *d*, *V* and the two variable quadratic model as a function of *d* and *V*. Finally, we tested, validated and implemented the two variable quadratic model.

II. THE CASE STUDY

The tests were carried out in a Faraday cage under atmospheric conditions. The test cell is supplied with alternating voltage from a single-phase 100 kV, 50 Hz and 10 kVA transformer. The voltage is variable thanks to a voltage variator which can be seen on the control console (See Fig. 3).

The HV electrode is a cylindrical rod made of Z200 hard steel, 0.6 cm in diameter, ending in a cone whose tip has r of 0.15 mm and a solid angle of 21.4°. This electrode has a total length of 19 cm with a straight part of 12 cm and another inclined part with a 135° angle of 7 cm. While the plane electrode is rectangular in Z200 hard steel 10.4 cm in length, 0.7 cm in width, 0.16 cm in height whose terminals are rounded in order to eliminate side effects. The HV electrode is placed on the solid insulator and parallel to it, the plane electrode is also placed on the solid insulator, thus allowing only surface discharges oriented in one direction. The samples used are derived from HV insulators made of silicone, porcelain and tempered glass. The method of cutting these samples and their dimensions are shown in Fig. 1. *d* and the position of the sample is adjusted by a mechanical system made of polymethyl methacrylate and bakelite (Fig. 2). The discharge current is obtained from the voltage across a resistance of 48.6 kW. This voltage is obtained by means of a digital storage oscilloscope with an input impedance of 1M and different sample used for each test.

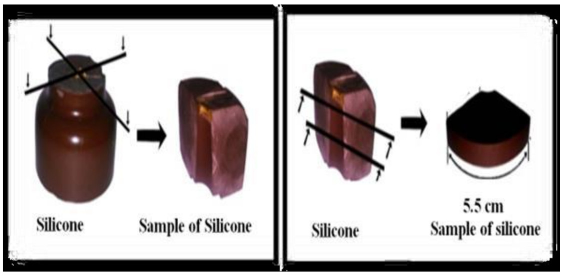


Fig. 1 Dimensions of the samples and their cutting method

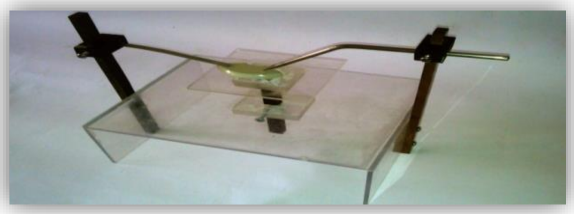


Fig. 2 Tested electrode system

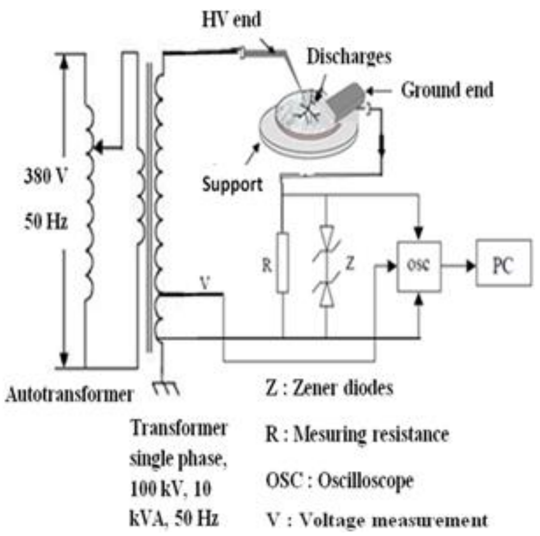


Fig. 3 Schematic diagram of the experimental setup

III. METHODOLOGY

In this part, a simple regression analysis was performed to predict the effect of *d* and *V* on the I_0. It is therefore a mathematical modeling of the phenomena studied experimentally [19].

We give the details of the derivation of our proposed model, the polynomial model [20-22].

III.1. Polynomial model

Let y be the observed (dependent) variable or the variable to be explained. Note that we have n observations, which we denote by y_i , $\forall\, i = 1, \dots,$ n, and we assume that each y_i is corrupted by a normal random noise (Gaussian) ε_i of mean and variance equal to 0 and σ^2, respectively. Our main goal is to find a function f(x), where x is the independent variable (explanatory variable), such that y ≅ f(x). In other words, we are looking for f which minimizes the error between the observations and the proposed model. The choice of f is based on several criteria. It is based in particular on the type of relationship (linear/non-linear) between dependent and independent variables and/or on the type of associated optimization problem. Let the function y ≅ f(x) be a polynomial, our polynomial is of degree (*D*), where $D \geq 2$ is an integer. In this case, the variables to be explained can be written as in equation (1).

$$f(x) = y_i = \sum_{j=0}^{D} a_i x_i^j + \varepsilon_i \tag{1}$$

Where, α are the coefficients of the polynomial to be determined.

For samples y_i (i = 1,…, n: n is an integer) of a function to be modeled, depending on a variable x which itself has samples x_i (i = 1,…,n), we can write:

$$\begin{aligned} y_1 &= \sum_{j=0}^{D} a_i x_1^j \\ y_2 &= \sum_{j=0}^{D} a_i x_2^j \\ &\vdots \\ y_n &= \sum_{j=0}^{D} a_i x_n^j \end{aligned} \tag{2}$$

This system of equations can be put in matrix form, as follows:

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}}_{\boldsymbol{y}} = \underbrace{\begin{bmatrix} 1 & x_1 & \dots & x_1^j \\ 1 & x_2 & \dots & x_2^j \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & \dots & x_n^j \end{bmatrix}}_{\boldsymbol{X}} \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}}_{\boldsymbol{a}} \tag{3}$$

To obtain the coefficients a_i or simply the vector $\boldsymbol{a}$ minimizing the sum of the squares of the errors (between observations and models), one must solve the following optimization problem:

$$minimize \qquad \|y - Xa\|_2^2 \qquad (4)$$

Where: ‖.‖ is the ℓ_2 norm of a vector.
This problem is solvable by taking the pseudo-inverse of the matrix ***X***. Consequently, the optimal solution ***a*** is given by the following equation:

$$a = (X^T X)^{-1} X^T y \qquad (5)$$

III.1.1. Monovariable model of the maximum discharge current

By applying the general equation (1) to our case study, we obtain the model of I_0 for each independent variable *d* and *V* for the three selected materials (Equation (6)).

$$I_0 = \sum_{j=0}^{D} a_i x_i^j \qquad (6)$$

For

- x = *d* : *d* = (3.9, 3.6, 3.4, 2.9, 2.6, 2.4, 2.2, 1.9) cm, *V* = 12 kV, *r* = 0.15 mm and *D* = 4,
- x = *V* : *d* (3.9, 3.4, 2.9, 2.4, 1.9 cm), *V* = (4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 12) kV, *r* = 0.15 mm and *D* = 7.

III.1.2. Quadratic model with two variable d and V of the maximum discharge current

The quadratic model of I_0 corresponds to the variables *d* and *V* obtained for *r* = 0.15 mm, *V* = (4, 6, 8, 10, 12) kV, *d* = (3.9, 3.4, 2.9, 2.4, 1.9) cm, and each selected material, calculated on the basis of the general model (Equation (1)). This model is represented by equation (7).

$$I_0 = a_0 + a_1 (d^2) + a_2 (V \times d) + a_3 (d) + a_4 (V) \qquad (7)$$

IV. RESULTS AND DISCUSSION

IV.1. Analysis of the modeling results

In our study, we are interested in the modeling results. In this part, we will give an analysis of the results found.

Figs. 4, 5 and 6 permit to compare the I_0 obtained from the experiments performed and the monovariable polynomial model for *x* = *d*, *x* = *V* as well that of the two variable quadratic model for *x* = *d* and *x* = *V* in order.

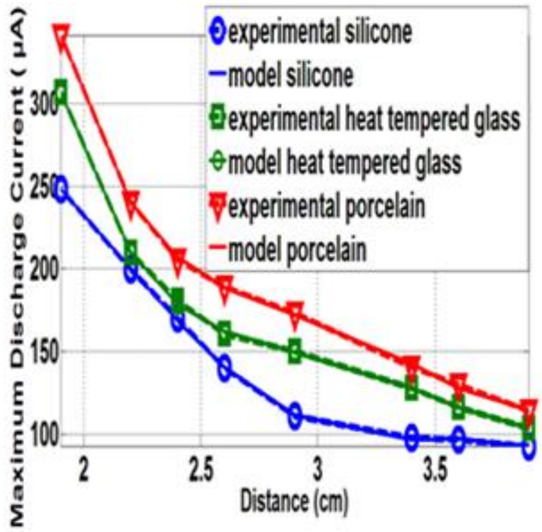
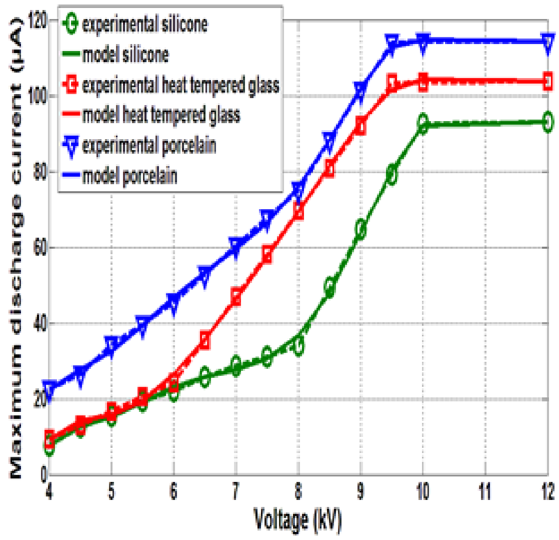
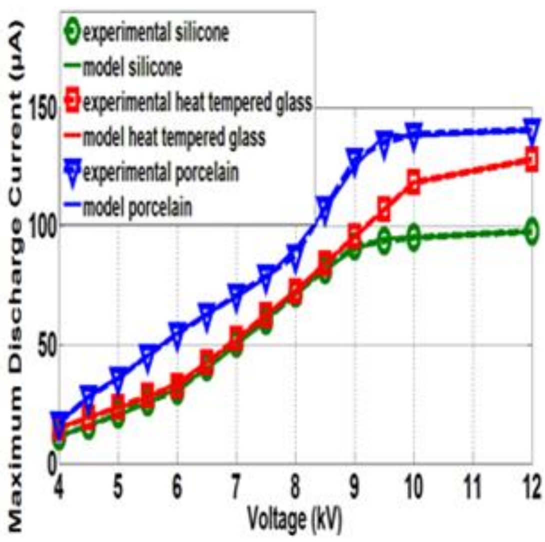


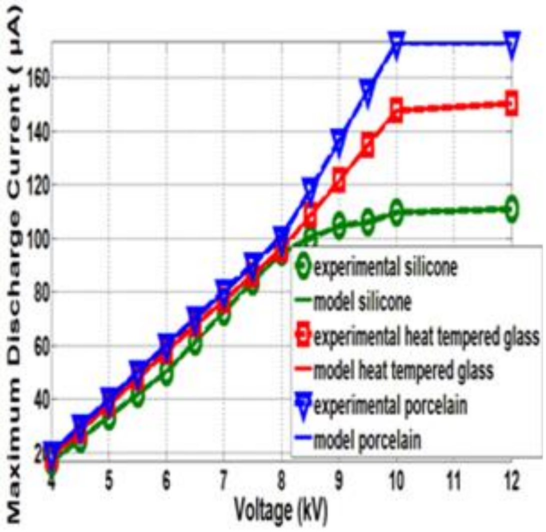
Fig. 4 Variation of maximum discharge current against d obtained experimentally and with the monovariable mathematical model for the three materials where *r* = 0.15mm and *V* = 12 kV



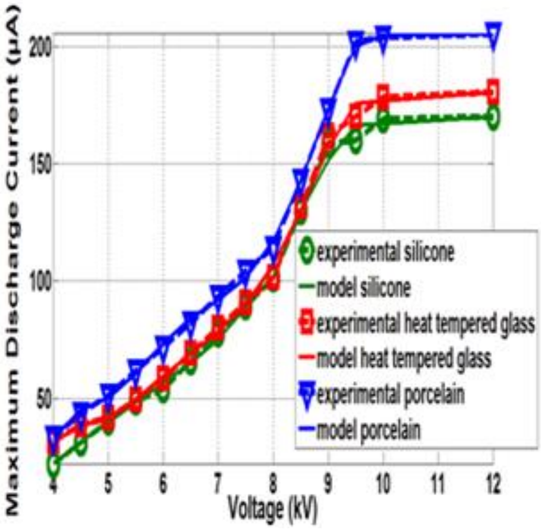
(a) d = 3.9 cm



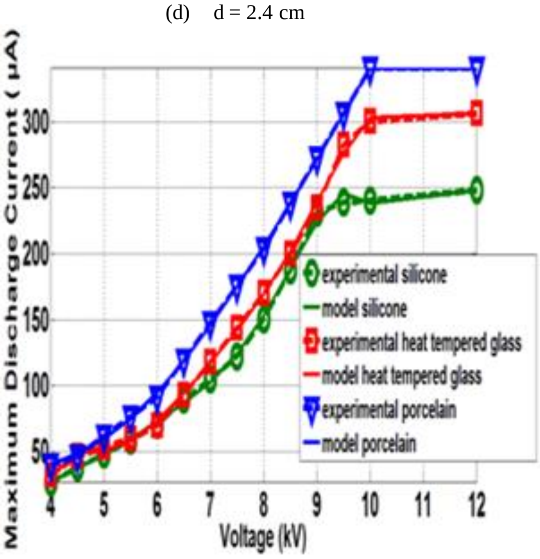
(b) d = 3.4 cm



(c) d = 2.9 cm



(d) d = 2.4 cm



(e) d = 1.9 cm

Fig. 5 Variation of maximum discharge current against *V* obtained experimentally and with the monovariable mathematical model for the three materials where *r* = 0.15 mm

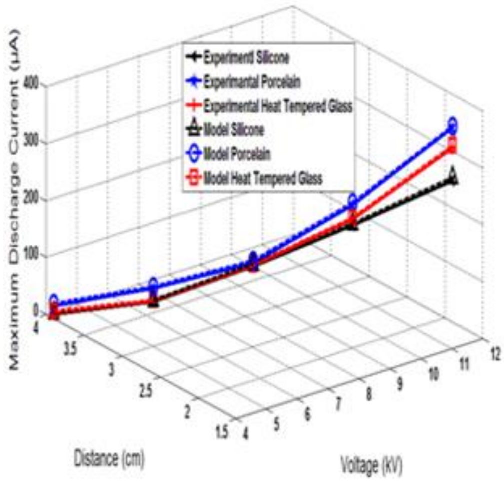


Fig. 6 Variation of maximum discharge current against d and *V* (4 to 12 kV) obtained experimentally and with the two-variable quadratic mathematical model where *r* = 0.15mm for the three materials

In Figs. 4 and 6, we observe that I_0 decreases by increasing *d*.

Indeed, for intense electric field zones (smaller *d*), the discharge regime is important due to high electronic activation, which boosts the streamer propagation, thus involving a larger I_0. Moreover, for a weak electric field zone (increase of *d*), the space between electrode dielectrics undergoes a fall in discharge activity due to a small probability of apparition in the ionization process. In other words electronic attachment is predominant, and therefore the value of I_0 is smaller [23].

In addition, the amplitude of positive porcelain impulses was observed to be higher than that of heat tempered glass and silicone. This can be explained by positive streamers developing over a greater distance [24].

Figs. 5, 6 show that I_0 increases with *V* for the selected materials. This increase can be explained by the phenomenon of accumulated electrical charge at the TJ, due to the strengthening of the electric field at the surface under study, giving rise to discharge in this zone [25].

We observe a perfect agreement between the experimental results and those of the monovariable polynomial and two-variable quadratic mathematical model, with a very small deviation (Figs. 4, 5 and 6).

The results obtained show that the two models studied are precise and efficient. In addition the two-variable quadratic mathematical model makes it possible to simultaneously and successfully evaluate the influence of *d* and *V* on the electric discharge.

IV.2. Validation of the two variable quadratic model

A mathematical model is said to be validated, if only that model is tested outside the range of experimental data from which we developed it.

Fig. 7 gives the results of the test of the two variable quadratic model.

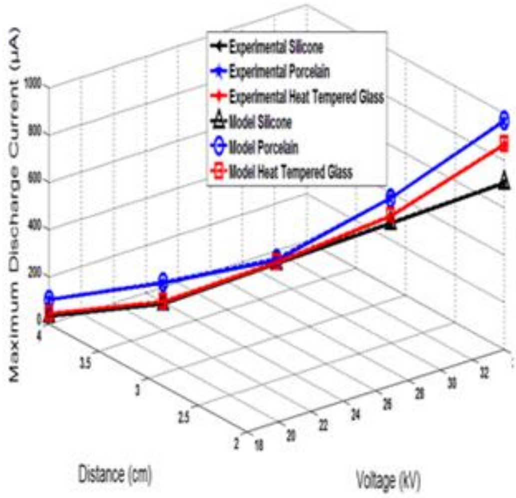


Fig. 7 Variation of maximum discharge current against d and *V* (18 to 34 kV) obtained experimentally and with the two-variable quadratic mathematical model where *r* = 0.15mm for the three materials

The modeling results are in full agreement with the experimental data, with a very small margin of error. The test is good, the validation of the two variable quadratic model was carried out.

V. CONCLUSION

In this work, we have shown from our modeling results of maximum electric discharge currents that the mechanism of surface discharge between two electrodes (tip and plane) on insulator samples (silicone, porcelain and tempered glass) at the triple junction is governed by the inter-electrode distance and the applied voltage.

For this, two explanatory variables (inter-electrode distance, applied voltage) were assimilated as inputs to the monovariate polynomial regression models of the maximum electric discharge current. In addition, quadratic polynomial models with two variables: distance and applied voltage are developed accurately predicting the electric discharge.

The two-variable quadratic mathematical model can simulate the electric discharge simultaneously as a function of two variables: applied voltage V and inter-electrode distance d, this with an adjusted coefficient of determination R^2adj close to 0.99. This last (two-variable quadratic mathematical model) has better predictions. The reason why we tested and validated it.

The proposed models are very reliable, based on a reduced number of experiments whose main objective is the optimization of electrical discharges. These models are a form of energy saving and financing. They provide the industry with information and advice to make the right choice in insulation technology, while paying particular attention to its design presenting the best cost/time/expected performance ratio.

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