

# Using Design of experiments to Evaluate the Partial Discharges Evolution in Mixed Dielectric Structures

Lazhar HEROUS\*, Smilli KARIMA\*\*, Mokdad REMADNIA\*, Abdelwaheb BENRETEM\*\*,  
Miloud KACHI\*, Dalila KHALFA\*\*, Mohamed NEMAMCHA\*

\*Laboratoire de Génie Electrique de Guelma (LGEG). Université de 8 mai 1945, B.P 401 – 24000, Guelma, Algérie.

\*\*University of Annaba, B.P 12 – 23000, El Hadjar, Annaba, Algeria.

lherous@yahoo.fr, lallakari@yahoo.fr remadnia.m@gmail, Benretem\_a@yahoo.fr, m.kachi@yahoo.fr,  
Maint\_dal@yahoo.fr, nemamcha@gmail.com

**Abstract:** *This paper addresses the more delicate issues of electrostatic industry and the phenomena that lead to the equipments breakdown. The partial discharge evolution in mixed dielectric is multifactorial process. The initial potential as well as the temperature are known to influence the partial discharge evolution. The aim of the present work is to demonstrate the effectiveness of the experimental design methodology for evaluating the effects of these factors. Thus, a full factorial experimental design was carried out on mixed dielectric structures. It consists of a plastic material (Teflon) in which two aluminium ribbons disposed at 90 degree and separated by polypropylene film of 13.6  $\mu\text{m}$  thickness. The study cell is filled with a dielectric liquid: The Jarylec C100. The variation domains for the two factors are respectively: 5000 V to 7000 V; + 28 to - 28°C. The partial discharge evolution was characterized by two output variables: The number of negative partial discharge and the number of positive partial discharge. It was found that the effect of temperature is more important than initial potential. This effect is observed in the two mathematical models but also the influence of negative temperature is more important than positive.*

**Key words:** *Partial discharge, mixed dielectric, design of experiments, capacitor model, low temperature..*

## 1. Introduction

During the last decades, the development of electrostatic industry has been accompanied by a growing interest in understanding the phenomena that leads to breakdown of equipment. Since, numerous studies have shown that the insulation can be submissive to transitional phenomena causing its progressive deterioration. One of the most important phenomenon is partial discharge [1,2,3]. Moreover, it is acknowledged that defects accidentally introduced during manufacturing of electrical equipments (failing of impregnation, hole in a film ...) can generate partial

discharge. The conduction and breakdown mechanism of concerning gas or solid insulation have been largely studied and the evaluation of characteristics of the partial discharge in the space and in the time is relatively well understood. The study of partial discharge in mixed dielectric structures makes always the object of intense investigations. Indeed, mixed dielectric structures (solid-liquid) offer the advantage to have a best dielectric rigidity [4,5].

In a previous work [6], experimental measurement on the partial discharge evolution in the models of capacity made in impregnated polypropylene film pointed out the effect of the low temperature and the initial potential on the regime of discharge in function of time. The aim of the present work is to demonstrate the effectiveness of Experimental Design Methodology [7,8] in quantifying the effects of these factors, as well as the interactions between them, by evaluating the number of negative partial discharge and the number of positive partial discharge.

## 2. Experimental Design Methodology

It allows predicting the number of experiments to be performed in accordance to a clear objective, to reduce the dispersion related to the measure, to evaluate the coupling effects between factors, to assess the influence of factors and their interaction. This method is based on statistical rules and analytical model for studying the process to reduce and control the maximum time for testing and to detect the doubtful experimental measurement. Regardless the domain of application Experimental Design is useful for three objectives: screening, optimization, and robustness testing [8,9,10]. The screening experiments described hereafter were designed to explore tow of the factors

that might affect the partial discharge evolution at the models of capacity made of impregnated polypropylene films:

- initial potential  $V_0$  [V];
- Low temperature  $T$  [°C];

The full-factorial experimental design [9] supports linear polynomial models. With such models, the response  $y$  of the process is expressed as a function of  $e$  factors  $u_i$  ( $i = 1, \dots, e$ ):

$$y = f(u_i) = c_0 + \sum c_i u_i + \sum c_{i,j} u_i u_j \quad (1)$$

A normalized centered value can be defined for each factor as follows:

$$x_i = (u_i - u_{ic}) / \Delta u_i = u_i^*, \quad (2)$$

where

$$u_{ic} = (u_{imax} + u_{imin})/2; \Delta u_i = (u_{imax} - u_{imin})/2. \quad (3)$$

So defined,  $x_i$  obviously takes the value  $-1$  for the minimum input value  $u_{imin}$  and the value  $+1$ , for the maximum input value  $u_{imax}$ . With the above notations, the response function becomes:

$$y = f(x_i) = a_0 + \sum a_i x_i + \sum a_{i,j} x_i x_j \quad (4)$$

For the two factors considered in the present study:

$x_1 = V_0$ ,  $x_2 = T$ , the linear model is:

$$y = a_0 + a_1 V_0 + a_2 T + a_{12} V_0 T + a_{11} V_0^2 + a_{22} T^2 \quad (5)$$

In the above equation,  $a_0$  is the predicted value of the response  $y$  in the centre of the experimental domain (i.e.,  $u_i = u_{ic}$  ( $i = 1, \dots, e$ ), or  $x_i = u_i^* = 0$ ),  $a_i$  estimates the effect of the factor  $x_i$ , and  $a_{i,j}$  quantifies the interaction between the factors  $x_i$  and  $x_j$ . These coefficients can be computed from the measured values of the process response in the conditions prescribed by the composite experimental design (Fig. 1), using a commercial software (MODDE 8.0, developed by Umetrics, Umea, Sweden).

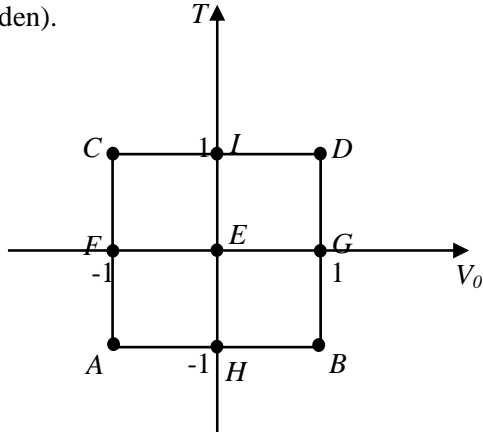


Fig.1. Central composite experimental design for the study of partial discharge evolution

The statistical significance of the coefficients  $a_i$  and  $a_{i,j}$  can be evaluated by calculating the residues  $e_i$ , i.e., the difference between the experimental value and the one predicted by the model, and then estimating the variance

$$s^2 = \frac{1}{n-p} \sum e_i^2 \quad (6)$$

Where  $n$  is the number of experiments and  $p$  the number of the model coefficients. A coefficient  $a_i$  of the model is statistically significant if it satisfies the Student's  $t$  test

$$t_i = \frac{|a_i|}{s_i} > t_{crit} \quad (7)$$

With  $t_{crit}$  a function of the degrees of freedom ( $n - p$ ), and

$$s_i^2 = \frac{s^2}{n} \quad (8)$$

In the present study, the software was employed for validating the models using the Fischer's test [11] for evaluating their predictive ability.

### 3. Experimental procedure

The detection and measurements of partial discharge was carried out with a device manufactured at LEMD Grenoble [4]. This device uses the electrical and optical expressions of partial discharge. An apparent current flows through the external circuit due to the appearance of partial discharge in the study cell. It allows making measures of discharge in the order 0.05 pC and the minimum duration between two successive discharges is 330 ns. The diagram represented on the Figure 2 shows the basic circuit for the principle of electric partial discharge detection. The current circulates in the RLC impedance that allows to suppress the low component frequency of the current  $i$ . Impetuses are put in form and amortized with a time constant  $RC = 40$  ns. When a discharge is detected, its amplitude, its polarity as well as the instant of its appearance are measured. The phase of the discharge appearance is deduced from this instant. The device includes a thermostatic drying-room that reaches temperatures until  $-40$  °C.

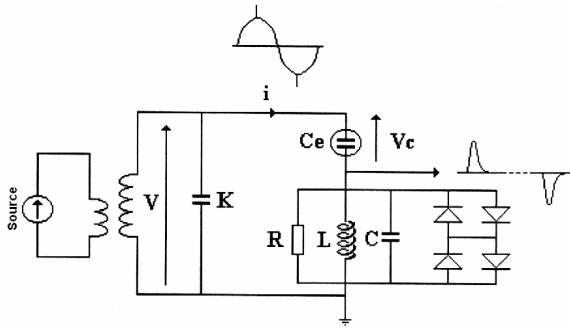


Fig.2. Principle of partial discharge measure

The study cell figure 3 is a model for any film impregnated capacitor.

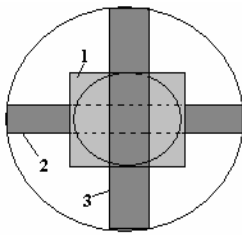


Fig.3. Study cell, top view

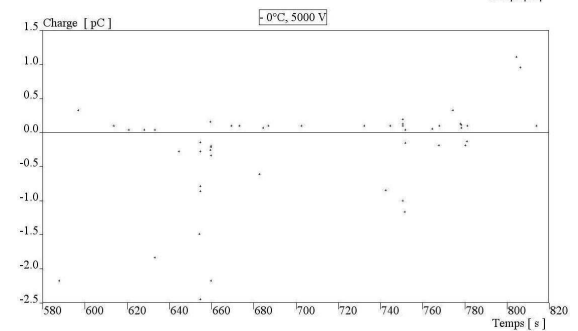
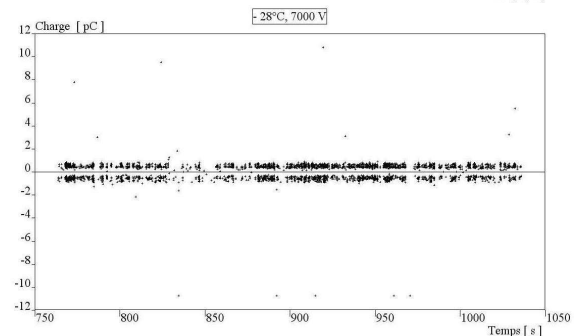
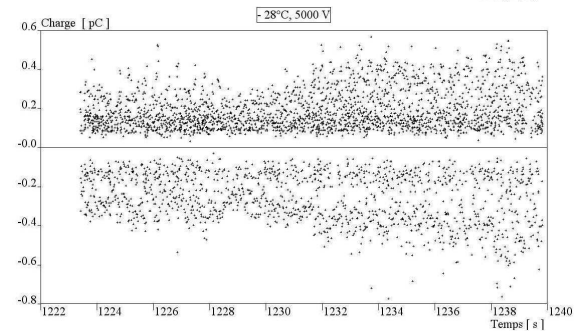
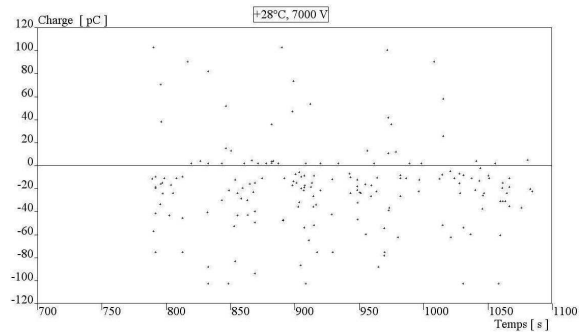
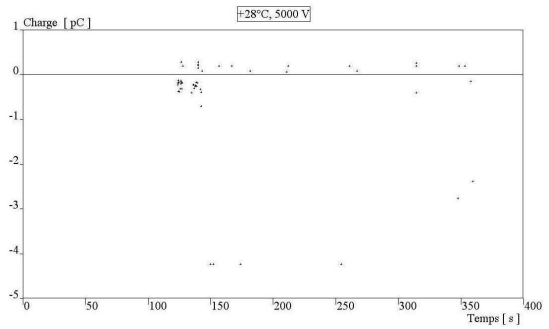
It consists of a plastic material (Teflon) in which two aluminium ribbons disposed at 90 degrees and separated by polypropylene films of 13.6  $\mu\text{m}$  thickness. The study cell is filled with a dielectric liquid: the jarylec C100, used in powers capacitors.

The Jarylec is a mixture of monobenzyltoluene and dibenzyltoluene, also with traces of tribenzyltoluene. The impregnation's role is to fill any air pockets in the dielectric in order to avoid the initiation of a partial discharge at relatively low voltage. This type of insulation is used in condensers for the compensation of reactive energy here the evaluation of discharge often constitutes a precursory factor of their dielectric rupture.

Based on the previous study result [6], the limits of the experiments domain were established:

Potential:  $V_{0min} = 5000 \text{ V}$ ,  $V_{0max} = 7000 \text{ V}$

Temperature:  $T_{min} = -28^\circ\text{C}$ ,  $T_{max} = +28^\circ\text{C}$



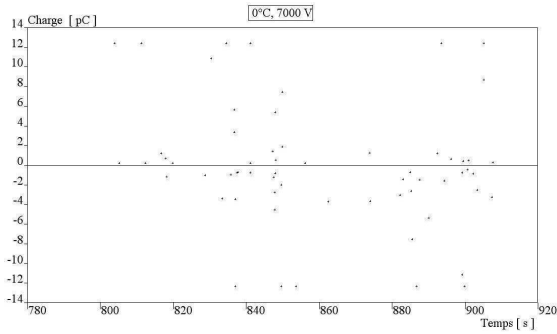


Fig. 4 The evolution of the apparent charge  $Q$  in pC during the acquisition duration at different temperature. 5000 V correspond to the first regime of discharge and 7000 V to the second regime.

#### 4. Results and discussion

The experimental study has allowed in identifying two regimes of partial discharge which exist at different temperature values, this confirms the results of our previous work [6].

The transition from the first to the second regime is carried out by a roughly rise in the frequency and intensity of discharge. Figure 4, shows the apparent charge  $Q$  in pC during the acquisition.

The left picture of this figure corresponds to the first regime and the right one to the second regime.

Based on the experimental data shown in table 1, the following linear models of the partial discharge evolution are proposed by the software Modde 8.0.

**Table 1:** Results of experiments centered composite design

N°	Factors		Responses		
	$V_0$ (V)	$T$ (°C)	$N_-$	$N_+$	Sum $N$
1	5000	-28	1410	2320	3730
2	7000	-28	1650	2336	3986
3	5000	+28	30	19	49
4	7000	+28	138	44	182
5	5000	0	20	25	45
6	7000	0	40	54	94
7	6000	-28	1560	2308	3868
8	6000	+28	49	33	82
9	6000	0	30	38	68
10	6000	0	32	39	71
11	6000	0	31	40	71

$$N_- = 3078 + 60.50V_0 - 73383T + 2.02V_0^2 + 774026T^2 - 33V_0T \quad (9)$$

$$N_+ = 3663 + 1250V_0 - 114467T + 3.92V_0^2 + 113742T^2 + 2.25V_0T \quad (10)$$

The statistical analysis of the data, using Student's test indicates that the initial potential effects ( $V_0$ ) and the interaction between the initial potential and temperature in negative discharge ( $N_-$ ) and positive discharge ( $N_+$ ) are not significant. The descriptive and predictive capabilities of the two models are evaluated by the statistical coefficients  $R^2$  and  $Q^2$ . The goodness of fit coefficient  $R^2$  which is a measure of how well the regression model can fit the raw data is close or equal to 1 for models, 0.998 and 1.00 respectively. The goodness of prediction coefficients  $Q^2$  of two models is also rather elevated: 0.970 and 1.00 respectively. The aspect of the predicted response curves, computed with (9) and (10) are respectively represented in fig 5.

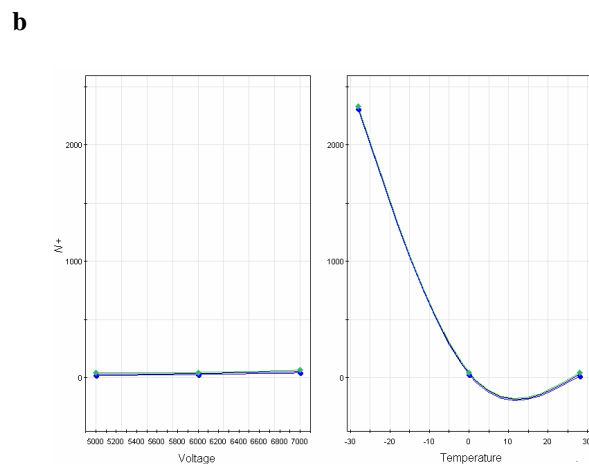
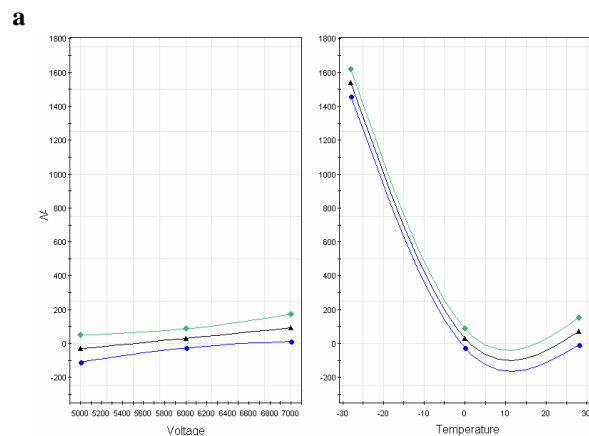


Fig 5. Predicted response of the partial discharge

evolution, negative partial discharge (a) and positive partial discharge (b)

The interesting point revealed by the examination of the coefficients of the two polynomial models is that the effect of the initial potential  $V_0$ , and to a much lesser extent that of the temperature  $T$ , is stronger on the number of positive partial discharges, than on the number of negative partial discharges (fig. 5 and 6). This might reflect the fact that the physical mechanisms affecting the positive partial discharges evolution is more influenced by this factor than those that are responsible for the negative partial discharges evolution in mixed dielectric structures.

Figures 5 and 6 shows that in the range  $[0^\circ\text{C} - 28^\circ\text{C}]$ , the temperature does not affect significantly the number of partial discharges, on the other side, in the range  $[-28^\circ\text{C} - 0^\circ\text{C}]$  it has an important influence, the decreasing of temperature increases the number of partial discharges. It can also be noted that the increasing of the potential accelerates the initial number of partial discharges (fig. 5).

Another interesting result is the influence of the voltage which is greater on the number of negative discharges ( $N_-$ ) (fig. 5).

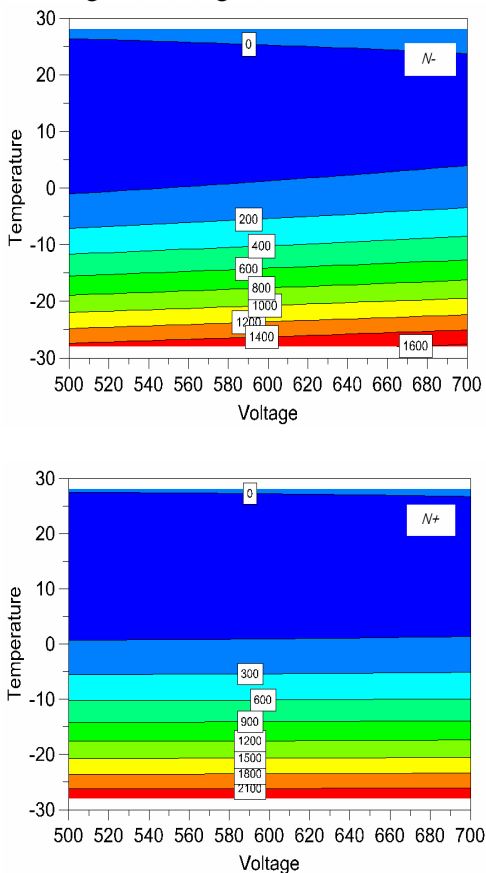


Fig 6. Iso-response curves predicted by MODDE 8.0 for the partial discharge evolution

## 5. Conclusions

Experimental Design Methodology proves to be an effective tool in the analysis of the partial discharges evolution in mixed dielectric structures composed of impregnated polypropylene of Jarylec. Mathematical models have allowed the quantification of the effect of each considered factors ( $T$ ,  $V_0$ ). The results show that the low temperature has a more influence on the number of discharge than the initial voltage which was explained by the viscosity of the impregnated liquid. Moreover it is found that the voltage has an important effect on the appearance of negative discharge ( $N_-$ ) and less important influence on positive discharge ( $N_+$ ). As consequence partial discharges are more pronounced in cold climate like in the winter morning.

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