

PARTIAL DISCHARGES IN POWER CABLE JOINT INSULATION MODELS

Cristina Stancu¹, Petru V. Notingher¹, Lucian Taranu¹, Laurentiu Badicu²

¹University Politehnica of Bucharest, Bucharest, Romania

²OMICRON Energy Solutions GmbH, Berlin, Germany

Abstract

High-voltage power cables, terminations and joints are factory-tested before installation to ensure quality and reliability according to customer requirements and standards. However, cables can be damaged during transportation, laying and during the installation of terminations and joints. These defects may not cause initial failure under voltage but can create partial discharge (PD) in the insulation system. If allowed to continue, partial discharge will erode the insulation, usually forming a tree-shaped pattern of deterioration (electrical tree) and eventually result in complete breakdown and failure of the cable or accessory. Such failures cause unplanned power outages, loss of plant production, equipment damage, and/or personnel injury. Partial discharges may intensify during the operation of electrical equipment due to electrical, thermal or environmental stresses.

In this paper, partial discharge parameters defined in the IEC 60270 (apparent charge, inception field and pulse repetition rate), on unaged and thermally aged joint plane models, made of XLPE/EPR, are measured. The results show that the inception field decreases on thermally aged samples. If the ageing time increases the inception field decreases further. On the other hand, the apparent charge and pulse repetition rate increase with the ageing time as well.

Keywords: Cable joints, XLPE/EPR models, thermal ageing, partial discharges, specific apparent charge

1. INTRODUCTION

Insulation is the most important, but in the same time the weakest component of an electrical equipment. During manufacturing processes and operation of electrical equipment, due to thermal, electrical and mechanical stresses some defects (cavities) may occur in insulations (probably because of non-uniform cooling of cables during extrusion process, detachments of insulations from conductors (due to mechanical stresses)) (Stancu 2017, Rycroft 2017) (Fig. 1). These may lead to discharges inception and even to insulations failure.

These cavities may contain gas or water. In the case of gas-containing cavities, if the electric field strength in the cavity exceeds a limit value of the electric field known as the inception field, electric discharges occur in the cavity (Notingher 2002). The strength of the inception field (E_i) can be determined from the Paschen curves according to the gas pressure in the cavity and the distance between the walls of the cavity (Stancu 2017). Because these discharges do not cross the entire insulation, they are known as partial discharges (PD). In case of cavities containing water, if the strength of the electric field exceeds a limit value, specific to each type of material, they generate electric and water trees (Notingher 2002) which in turn is a source of PD. Critical values of the electric field are: 3 kV / mm - for the initiation of partial discharges, 300 kV / mm - for the initiation of electrical trees and 1.9 kV / mm - for the initiation of water trees (Dissado 1992).

Partial discharges (PD) may occur in the insulation of all electrical equipment. In the insulation of cables and their joints PD can occur in defects inside the bulk insulation, interfaces between insulating layers, insulation-conductor interfaces, etc. (Stancu 2016, Lanz 2015).

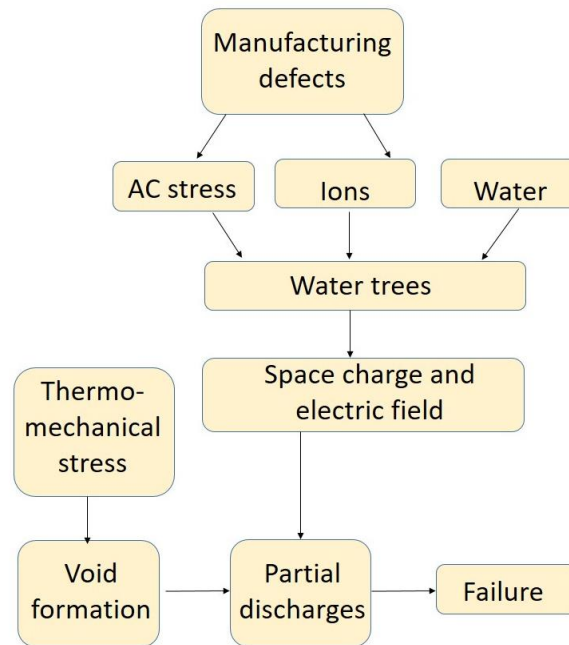


Fig. 1. Degradation mechanisms of cable insulations (Rycroft 2017)

Partial discharges are local electrical discharges that occur in the gas cavities of solid insulation, in the contact area of the conductive parts of the insulation and in the gas bubbles in the electrical insulating liquids (Notingher 2002) of all electrical equipment (cables, electric machines, transformers, etc.). Inception and development of PD depend on the shape and dimensions of the cavities, the nature of the gas in the cavities, pressure, temperature, and frequency and the electric field (Illias 2011). These discharges occur at the test object terminals as current pulses with rise times in the range of few ns, and are accompanied by light and sound emissions.

If the voltage at the terminals of a capacitor containing a dielectric with cavities (a "test object") is $u_c(t) = \hat{U}_c \sin \omega t$, producing partial discharges (PD) in the dielectric cavities causes a voltage drop at the test object terminals from the inception U_i to the extinguishing value U_e (Fig. 2) (Notingher 2002).

The number of discharges in a half-period ($T/2$) (Fig. 2) is calculated with the expression (Notingher 2002):

$$N = \frac{2(\hat{U}_c - U_e)}{U_i - U_e} \quad (1)$$

in which $\hat{U}_c$ is the maximum value of the voltage drop in the cavity, U_i the effective value of the inception voltage of the PD, and U_e - the effective value of the PD extinction voltage.

According to the IEC 60270, the inception voltage is defined as the lowest voltage value at which a PD parameter, usually the apparent charge, reaches a detectable minimum value. In our case, the inception voltage of PD's is defined as the voltage value for which the apparent charge has the value of 1 pC.

The active power corresponding to PD is defined by the expression (Notingher 2002):

$$P = 2\varepsilon_0 f V_r h_0 A_0 (\hat{E}_c - E_e)(E_i + E_e) \quad (2)$$

where ε_0 represents the permittivity of the vacuum, f - the frequency of the applied voltage to the capacitor, V_r - the relative volume of the cavity, h_0 - the thickness of the insulating plate, A_0 - the area of the insulating plate, E_i - the intensity of the electric field in the cavity, E_e - the intensity of the PD's extinguishing field.

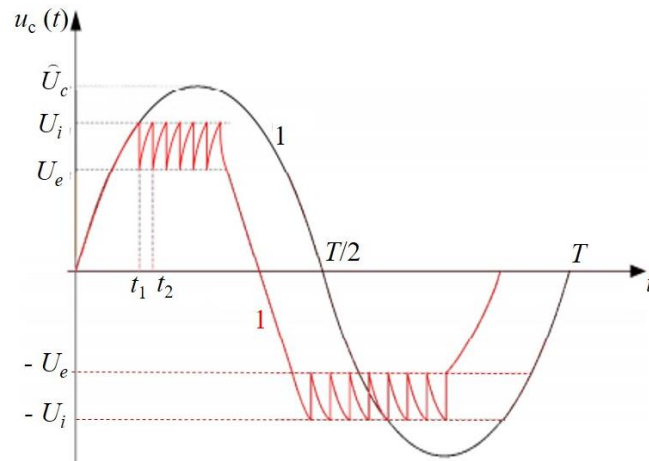


Fig. 2. Time variation of the voltage at the test object terminals: u_c – voltage at the test object terminals, U_i – inception voltage of PD's, U_e – extinguish value of PD's, 1 – variation of voltage in the absence of PD's, 2 – variation in the presence of PD's, T – period, t_1 – the instant at which the first PD occurs, t_2 – the instant at which the second PD occurs (Notingher 2002)

The intensity of the PD's inception field is the value of the electric field at which the first discharges are detected and is calculated as the ratio between the PD's inception voltage and the sample thickness.

The loss factor corresponding to PD is determined by the expression:

$$\text{tg}\delta = \frac{2\varepsilon_r V_r}{\pi} \frac{(\hat{E}_c - E_e)(E_i + E_e)}{\hat{E}_c^2} \quad (3)$$

The energy transported by the cavity's discharges is (Notingher 2002):

$$W = C_c (\hat{U}_c - U_e)(U_i + U_e) \quad (4)$$

where C_c represents the electrical capacitance of the cavity.

Partial discharges are measured during the type and routine testing in accordance with IEC 60270, which defines the following PD parameters: the apparent charge (Q), the pulse repetition rate (N), the pulse repetition frequency, the phase angle and the time of occurrence of a PD pulse, the average discharge current, discharge power, square rate, PD's inception voltage (U_i), PD's extinguishing voltage, etc. In the present paper, for the PD characterization, the apparent charge, the PD's inception voltage, the PD's extinguishing voltage and the pulse repetition rate are used (Stancu 2017).

IEC 60270 defines the apparent charge, Q , as that charge which, if injected in a very short time at the terminals of the test object, would give the same indication of the meter as the DC current pulse itself. The inception voltage of the PD's (U_i) is the applied voltage observed for the first time for repeated partial discharges in the object to be tested when the voltage applied to this object is gradually increased starting from a low value at which no partial discharges are observed. The pulse repetition rate (N) is the ratio of the total number of PD's pulses recorded over a given time interval and the duration of this interval.

For most electrical equipment, limit values for partial discharge parameters (especially PD's inception voltage, apparent charge, etc.) (depending on rated voltage U_n) are set. Limit values of apparent charge are presented in Table 1.

The PD level is influenced by a number of factors: the chemical nature and physical structure of the insulation, the intensity of the field, the nature and pressure of the cavity gases, mechanical stress and temperature, etc.

This paper presents the results of an experimental study on the influence of thermal stress on partial discharges (inception voltage, apparent charge and pulse repetition rate) on power cable joints plane models.

Table 1. Normalized values of apparent charge for cables and joints (Lanz 2015, Wood 1993)

Equipment	Standard	Voltage	Apparent charge [pC]
MT cable	IEC 60502_2	$1.7 U_n$	$< 10 \text{ pC}$
HV cable	IEC 62067	$1.5 U_n$	$< 10 \text{ pC}$
Joints	IEC 60502_4	$1.7 U_n$	$< 10 \text{ pC}$
Transformers	IEC 60270	$1.6 U_n$	$< 500 \text{ pC}$
Generators	IEC 60034_18_41	-	$> 1000 \text{ pC}^1$

2. MEASUREMENT OF PARTIAL DISCHARGES

There are two circuits for direct detection and measurement of PD, namely the "parallel" and the "series" circuit shown in Figures 3 and 4. In these figures C_x represents the object to be tested, C_k - coupling capacitor, Z_m - impedance, M - measuring device, E - protection switch, Z_s - internal impedance of the source, C_s - filter inductance (at high frequencies). The measuring device M records the voltage drop on impedance Z_m , which, together with C_x and C_k , determines the shape and duration of the measured pulses.

For each discharge in a cavity of the test object (i.e., in dielectric of the capacitor C_x), the voltage at its terminals drops suddenly and then returns to normal (after the apparent charge loss q is compensated by the source). Inductance L (connected in series with the source) has, at high frequencies (corresponding to partial discharges) a very high reactance. For that, the inductance L does not allow for charge compensation (by itself) from the source. This is done from the capacitor C_k .

The voltage pulse occurring at the test object terminals generates a current pulse in the $C_x - C_k - Z_m$ circuit, whose characteristics depend on the resulting impedance of the circuit. The voltage drop on Z_m is detected and integrated by M , indicating a size proportional to q , respectively:

$$\int u dt = Z_m \int i dt = Z_m q. \quad (5)$$

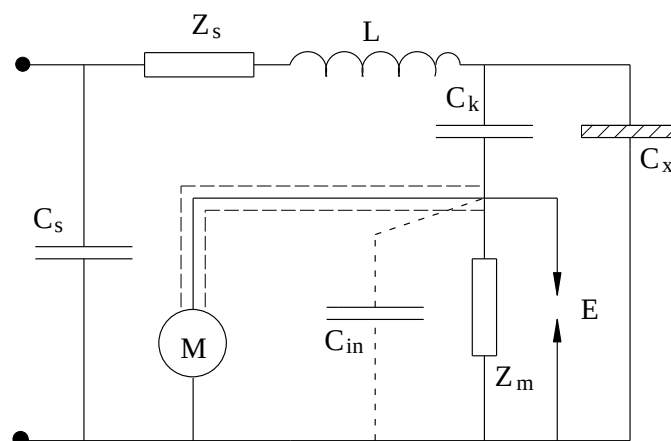


Fig. 3. Parallel circuit for PD measurement (Notinghamer 2002)

¹For more than 25 years of service

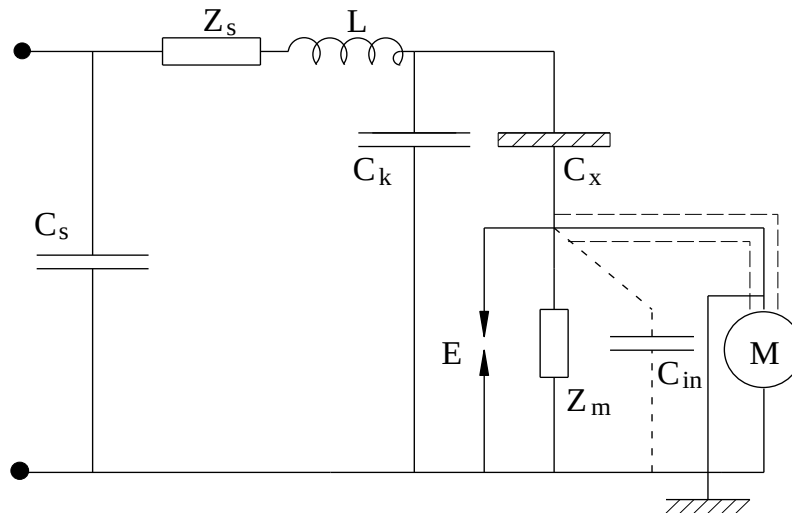


Fig. 4. Series circuit for PD measurement (Notingher 2002)

The voltage variation at the terminals of C_x (caused by loss of q load) is independent of the circuit impedance. Consequently, the test object can be replaced by a voltage generator which will produce a current pulse in the outer circuit. From this pulse, one side closes through the source circuit (if it cannot be neglected) and the other through the circuit of the coupling capacitor. In this way, a calibration of the measuring system can be performed: the pulse given by the source is known and the apparent charge is measured (with M).

In principle, the two circuits do not differ from each other, but only in terms of work safety and disturbance, the parallel circuit being the preferred version (Notingher 2002).

3. EXPERIMENTS

3.1. Samples

Two groups of 3-5 samples of cross-linked polyethylene (XLPE) with width $l = 90$ mm and thickness $g_1 = 0.3$ mm and ethylene propylene rubber (EPR) with a width of $l = 90$ mm and thickness $g_2 = 0.5$ mm were used for the experiments. The third group (XLPE / EPR) consisted of 3-5 "sandwich" samples made of one XLPE and one EPR plate and represents the insulation model of a DC joint (Fig. 5) (Stancu 2016). All samples were manufactured at ICME ECAB Bucharest. Some of the samples were thermally-aged in a RAYPA oven for 30 ... 90 days at 125°C .

3.2. Set-up

The measurement of PD parameters was performed with the set-up shown in Figure 6 a, consisting of a high voltage transformer with the U_s / U_p transformation ratio = $60\text{ kV} / 220\text{ V}$, the MCC 124 coupling capacitor ($U = 24\text{ kV}$, $C = 1.2\text{ nF}$) - for the capacitive coupling to the test object, CPL 542 ($I = 0.5\text{ A}$) quadripole, MPD 600 measurement unit, a MCU 502 control and a high frequency current transformer MCT 120 - for inductive coupling to the test object. The PD calibration was performed with a calibrator able to inject charge values from 1 to 100 pC .

The voltage was applied between two flat electrodes of copper band with thickness $g_3 = 0.07\text{ mm}$, diameter $D = 50\text{ mm}$ (Fig. 5) using two cylindrical electrodes (Fig. 6 b) and ranging from 0 to 10 kV . Effective values of PD inception voltage (U_i), apparent charge (Q), and pulse repetition rate (N) were measured.

For sensitive PD detection, the digital band pass filter of the MPD 600 was set to the center frequency of 250 kHz and to the bandwidth of 300 kHz . The acquisition time of the phase resolved PD (PRPD) patterns was set to 30 s and kept constant.

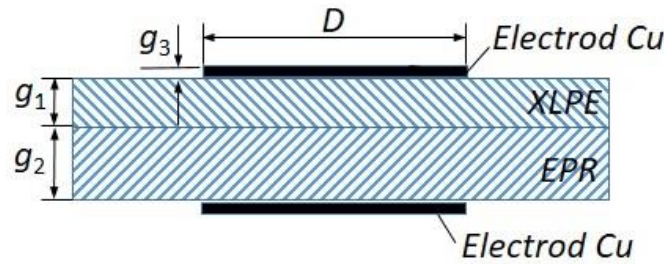


Fig. 5. (XLPE / EPR) "Sandwich" sample

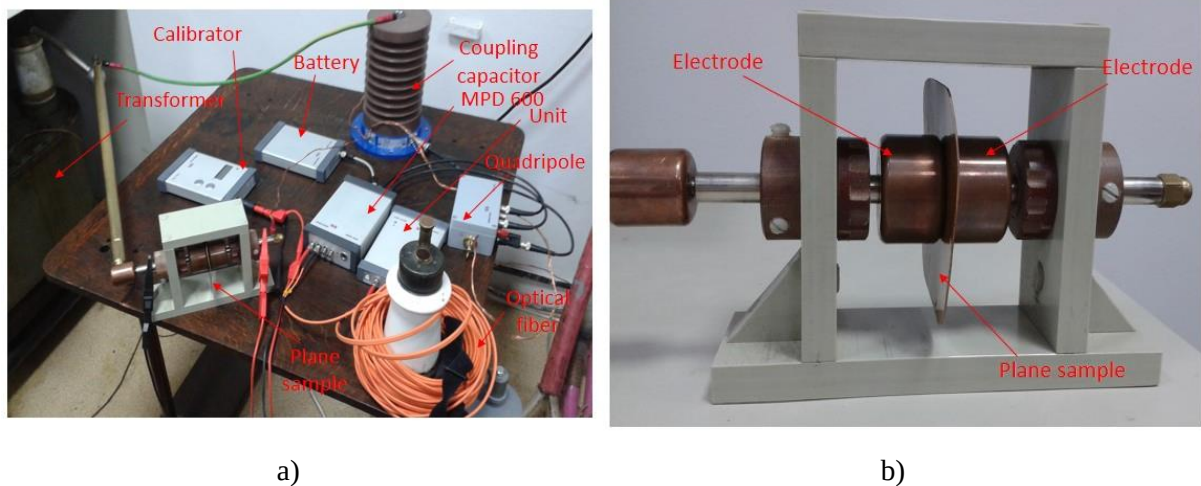


Fig. 6. Set-up PD measurement: a) Set-up structure; b) Sample between electrodes

4. RESULTS

4.1. Unaged samples

Parameters related to partial discharges, i.e. inception voltage (U_i), apparent charge (Q) and pulse repetition rate (N), were measured on plane samples made of XLPE, EPR and XLPE / EPR for values of the applied electric field E between 5 and 35 kV / mm. In order to compare the PD values in the three sample types, their specific values (Q_v) were calculated as the ratio between the measured values to sample volumes (V_e):

$$Q_v = Q / V_e \quad (6)$$

Some of the results obtained are presented in Table 2 and Figures 7 ... 22.

Table 2 shows the inception voltage and field values E_i for unaged samples. It is noted that the PD are initiated at different electric field values, and that it takes the lowest values in the XLPE / EPR samples (4.7 kV / mm) and the highest ones in the XLPE (11.2 kV / mm).

Figures 7-9 show the phase resolved PD (PRPD) patterns in the unaged samples. It is found that the apparent charge has the highest value for EPR samples, and the smallest in XLPE / EPR. On the other hand, it is observed that the shape of the patterns indicate the presence of some cavities at the interface of XLPE / EPR samples.

It is also noted that the increase of the field strength values leads to the intensification of PD in all types of samples and that this intensification is more pronounced in the EPR samples. For example, increasing field values from 5 kV / mm to 35 kV / mm causes an increase in the apparent charge of 20 times - for XLPE, 50 times - for EPR and 35 times for XLPE / EPR (Fig. 10).

Table 2. Values of the inception voltage U_i and field E_i for unaged samples

Sample	U_i (kV)	E_i (kV/mm)
XLPE	3.7	11.2
EPR	3.75	7.5
XLPE/EPR	3.8	4.7

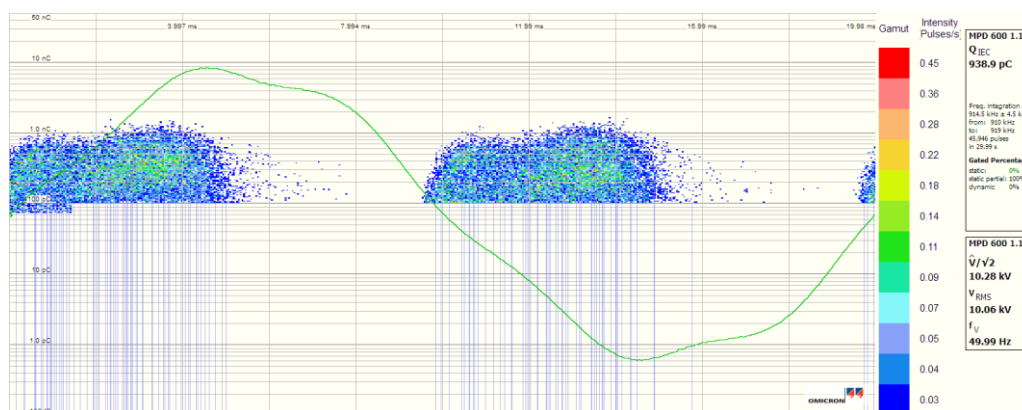


Fig. 7. PRPD pattern of the unaged XLPE sample at 10 kV ($Q = 938$ pC)

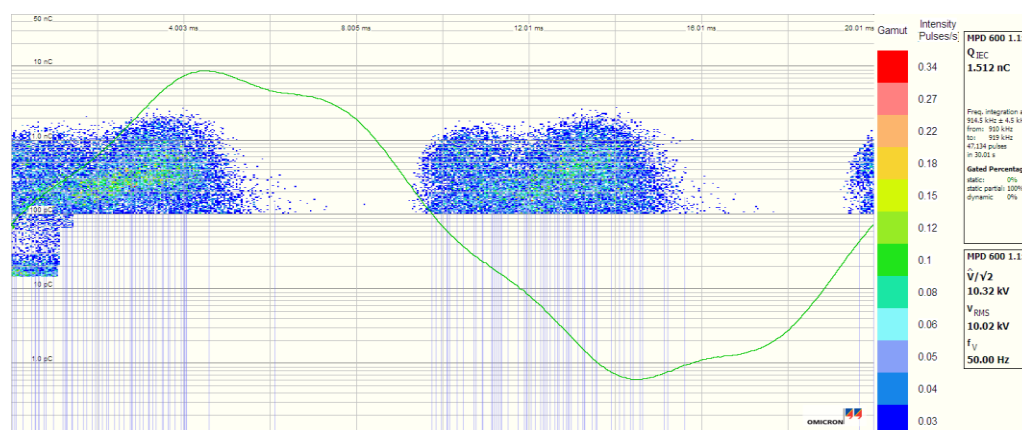


Fig. 8. PRPD pattern of the unaged EPR sample at 10 kV ($Q = 1.5$ nC)

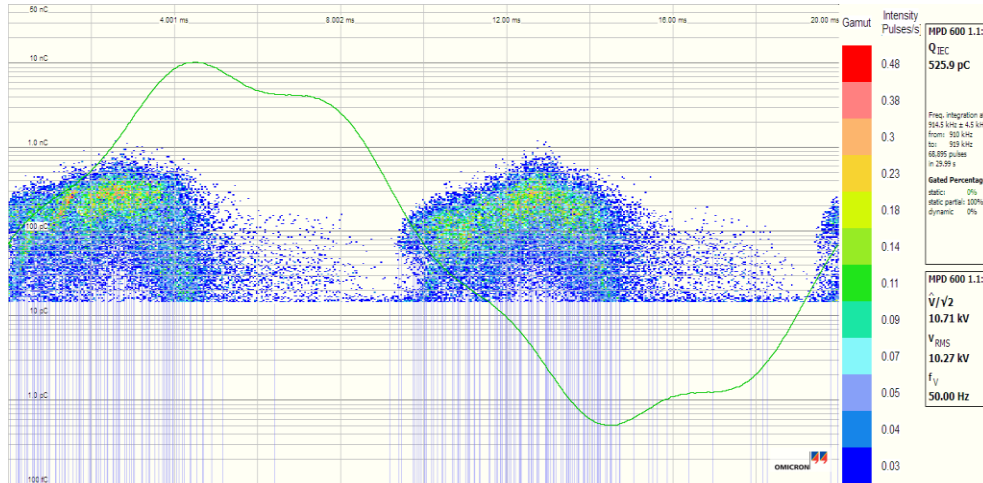


Fig. 9. PRPD pattern of the XLPE / EPR sample at 10 kV ($Q = 525$ pC)

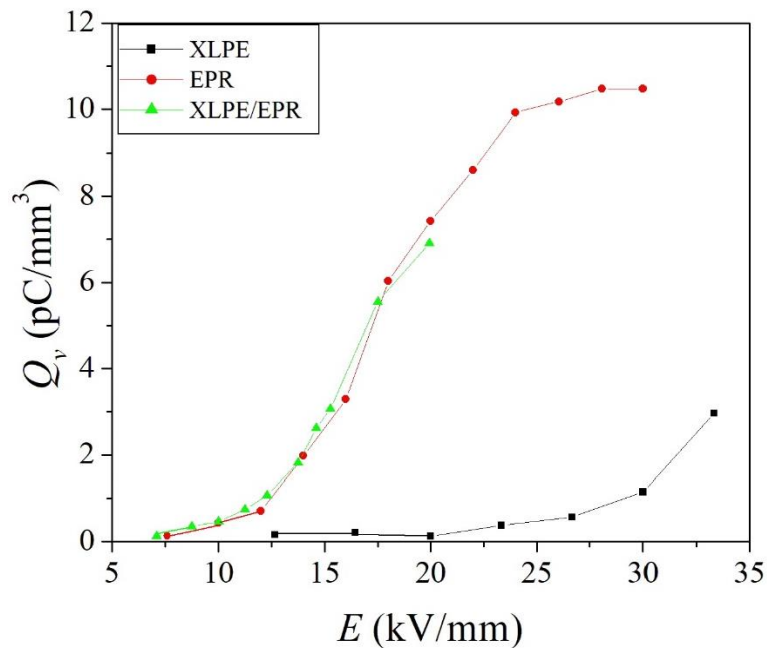


Fig. 10. Variation of specific apparent charge (Q_v) with electric field strength (E)

The specific apparent charge values measured in the EPR samples are higher than those in the XLPE, i.e. the discharge level is more intense in the EPR than in the XLPE. These results may be due to the large number and size of cavities in the EPR than in XLPE (Illias 2016).

Regarding the specific repetition rate (repetition rate) N_v , it increases with the electric field values for all samples (Fig. 11).

From the analysis of the PRPD patterns presented in Figures 7 ... 9 it is found that in the three types of samples internal discharges occurred, which may be due, especially in the case of XLPE / EPR, to the existence of some cavities at the interfaces between the layers of XLPE and EPR (Fig. 12). These cavities probably appeared during the manufacturing process of the samples.

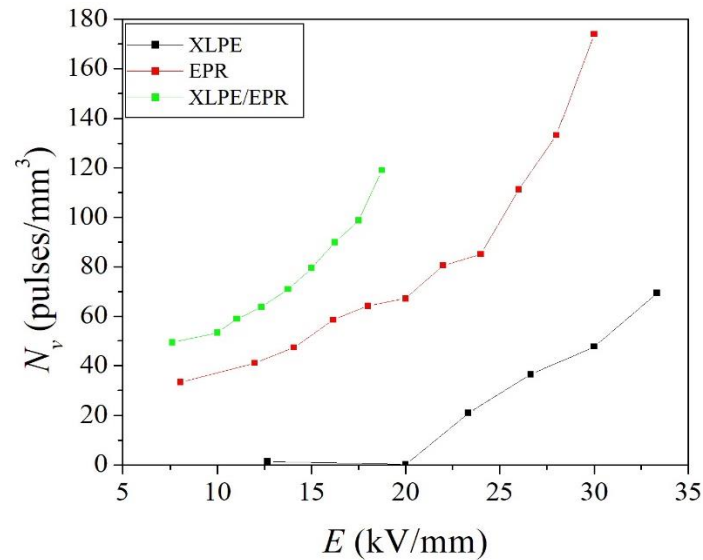


Fig. 11. Variation of specific repetition rate (N_v) with electric field strength (E)

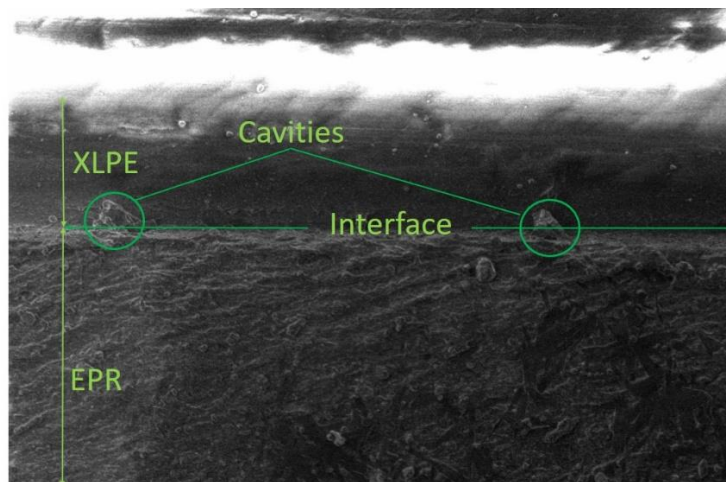


Fig. 12. SEM showing the XLPE/EPR interface (1000 X)

4.2. Aged samples

Some results obtained on thermally aged samples (30 ... 90 days at 125 °C) are shown in Table 3 and Figures 13-20.

Analyzing the results presented in Table 3 it was found that, for all samples, their thermal aging leads to lower values of the inception field of partial discharges E_i . Thus, inception field decreases from 11.2 kV / mm (at $\tau = 0$) to 6.6 kV / mm (at $\tau = 90$ days) - for XLPE and from 7.5 kV / mm (at $\tau = 0$) to 4.1 kV / mm at $t = 90$ days) - for EPR. This decrease is less important for XLPE / EPR samples and more important for XLPE samples. For example, for the same value of aging time, $\tau = 60$ days, the value of E_i decreases by 40 % for XLPE samples, with 27 % for EPR samples and only by 24 % for XLPE / EPR. Less significant of decrease of E_i in XLPE / EPR samples is probably due to the important role that defects have in the interface and does not change much in the aging process. It is also found that for all samples the thermal aging leads to the increase of the apparent charge values (Figs.13-18).

As in the case of unaged samples, in the aged samples the highest values of specific apparent charge Q_v are obtained in EPR samples (Fig. 19). This could be due, on the one hand, to the elimination of some gaseous by-products from the samples (resulting from the sample manufacturing process), respectively

the reduction of cavity gas pressure and, on the other hand, the generation of new cavities (voids) especially at the XLPE / EPR interfaces (Stancu 2017).

The specific repetition rate N_v increases, also, with the aging time for all samples (Fig. 20). This is probably due to the increase in cavity dimensions and concentrations, as in the case of apparent charge.

Table 3. Values of voltage (U_i) and electric field (E_i) inception values for aged samples at different ageing times τ

Sample (τ)	U_i (kV)	E_i (kV/mm)
XLPE (30 days)	2.69	8.96
EPR (30 days)	2.92	5.84
XLPE/EPR (30 days)	3.00	3.75
XLPE (60 days)	2.02	6.73
EPR (60 days)	2.75	5.5
XLPE/EPR (60 days)	2.83	3.53
XLPE (90 days)	1.98	6.6
EPR (90 days)	2.07	4.14



Fig. 13. PRPD pattern of the XLPE thermally aged samples (30 days_125 °C at 10 kV (Q = 1.2nC))



Fig. 14. PRPD pattern of the EPR thermally aged samples (30 days_125 °C at 10 kV (Q = 302 pC))

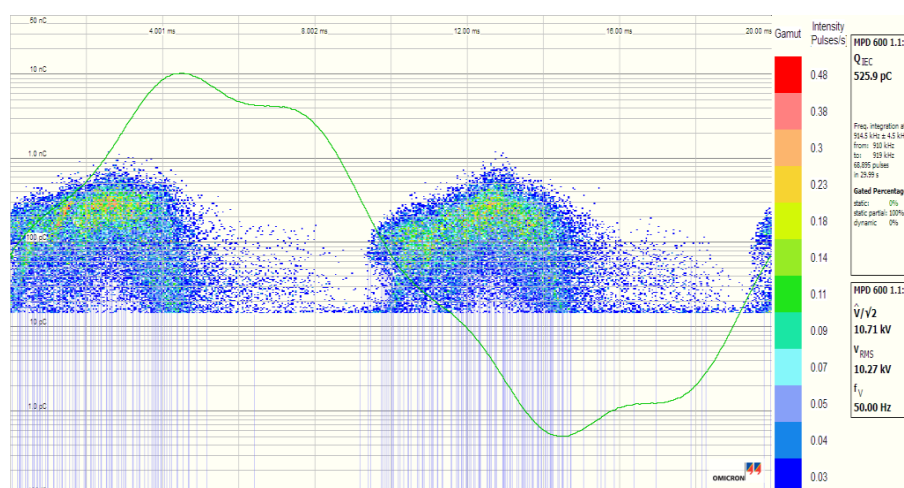


Fig. 15. PRPD pattern of the XLPE/EPR thermally aged samples (30 days_125 °C at 10 kV (Q = 525 pC))

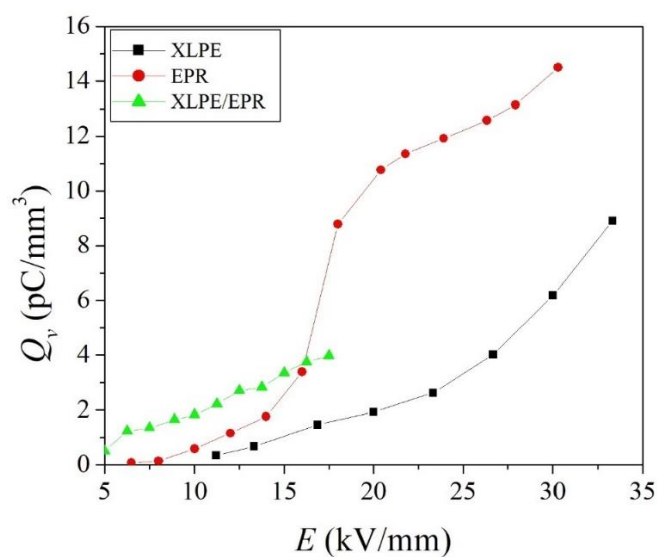


Fig. 16. Variation of specific apparent charge (Q_v) with electric field strength (E) for 30 days aged samples

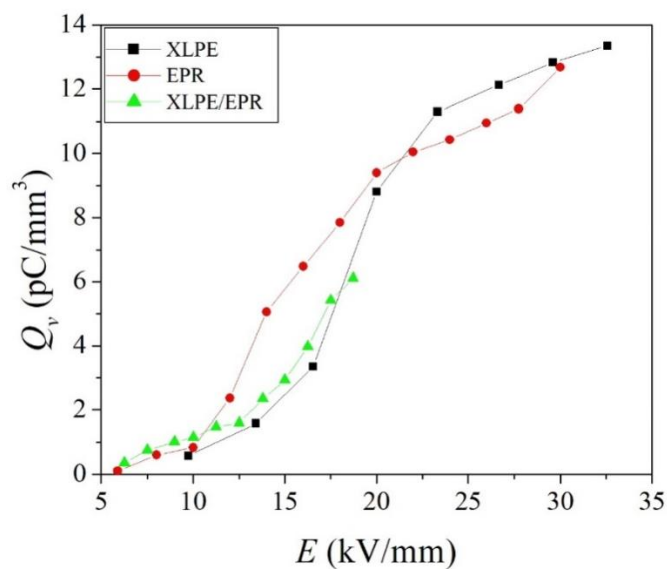


Fig. 17. Variation of specific apparent charge (Q_v) with electric field strength (E) for 60 days aged samples

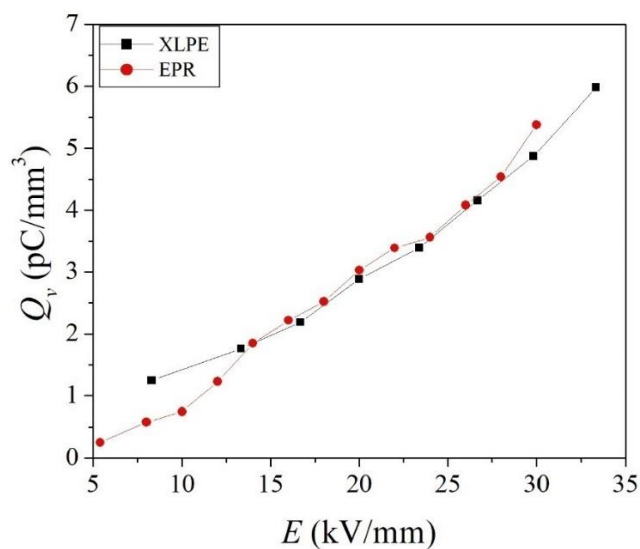


Fig. 18. Variation of specific apparent charge (Q_v) with electric field strength (E) for 90 days aged samples

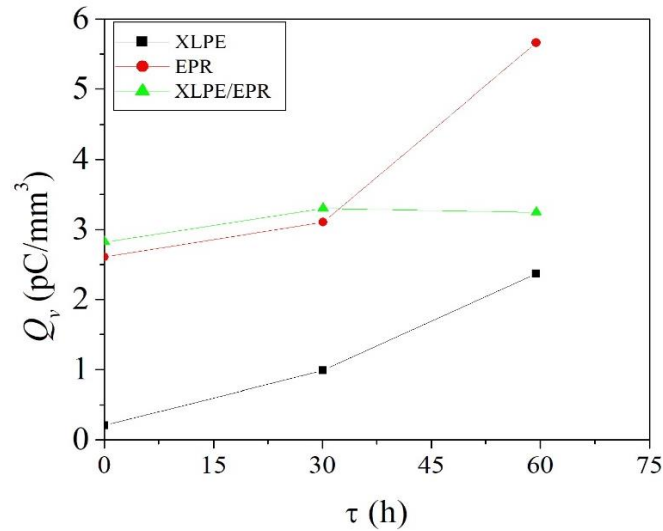


Fig. 19. Variation of specific apparent charge (Q_v) with the ageing time (τ) for $E = 15$ kV/mm

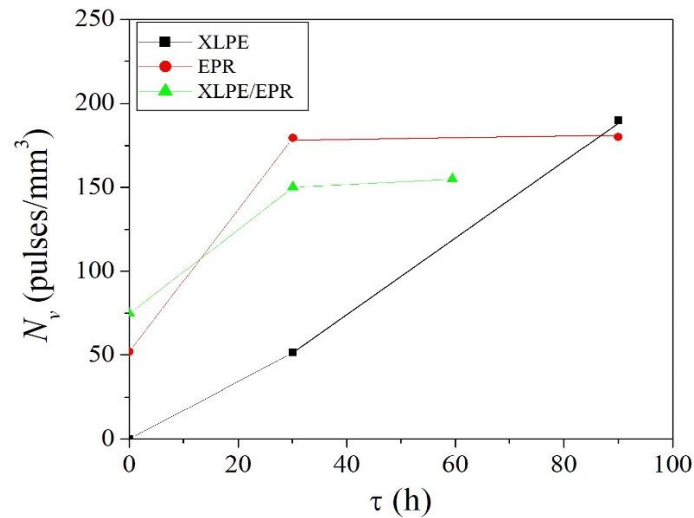


Fig. 20. Variation of specific repetition rate (N_v) with the ageing time (τ) for $E = 15$ kV/mm

5. CONCLUSIONS

This paper presented the results of an experimental study on the influence of thermal aging on XLPE, EPR and XLPE / EPR insulations of some plane joint models of power cables.

The existence of installation defects or cavities on the XLPE / EPR interface makes easier the occurrence of partial discharges.

Thermal aging of the insulation intensifies the level of partial discharges by increasing the specific apparent charge and the pulse repetition rate.

Increasing the aging time leads to the reduction of both the inception voltage and electric field of partial discharges and to an increase in the apparent charge and the repetition rate related to partial discharges.

Determining the PD level is particularly useful in identifying potential manufacturing and installation defects or defects occurring during the operation of electrical cables. Once the PD presence is detected in a joint insulation, this must be immediately replace in order to avoid in service failures.

REFERENCES

- Dissado, L. & Fothergill J 1992, *Electrical Degradation and Breakdown in Polymers*, Peter Peregrinus Press.
- Illias, H., Chen G.& Lewin, P 2011, "Partial discharge within a spherical cavity in a dielectric material as a function of cavity size and material temperature", *IET Science, Measurement and Technology*, vol. 6, no. 2, pp. 52-62.
- Illias, H., Tunio, M., Bakar, A., Mokhlis, H. & Chen G 2016, "Partial Discharge Phenomena within an Artificial Void in Cable Insulation Geometry: Experimental Validation and Simulation", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 1, pp. 451-459.
- Lanz, B 2015, "Assuring the Reliability of Critical Power Cable Systems".
- Notingher, P. 2002, *Insulation Systems*, Printech Publishing, Bucharest.
- Rycroft, M 2017, *Power cable life estimation and extension*, EE Publishers Home.
- Stancu, C., Notingher, P., Dumitran, L., Taranu, L., Constantin, A. & Cernat, A 2016, "Electric Field Distribution in Dual Dielectric DC Cable Joints", *IEEE Int. Conf. on Dielectrics*, pp. 402-405.
- Stancu, C 2016, "Reduction of space charge in composite insulations of DC HV cable joints", Research project PN-II-RU-TE-2014-4-0280, 2016.
- Stancu, C., Notingher, P., Taranu, L. & Dumitrescu, S 2017, "Influence of thermal ageing of electrical equipment insulations on partial discharges level", *Electrical Machines Symposium*, pp. 1-12.
- Wood, J.W., Sedding, H.G., Hogg W.K., Kemp, I.J. & Zhu, H 1993, "Partial discharges in 153 HV machines. Initial considerations for a PD specification", *IEE Proceedings-A*, vol. 140, no. 5, pp. 409-416.