Partial discharge measurements of DC insulation systems: the influence of the energization transient

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***Abstract*- This paper introduces techniques for partial discharge, PD, recognition under DC, both in steady state and in transient condition, during which the field in insulation varies slowly from a permittivity-driven to a conductivity-driven profile. This transient can be significantly long, depending on insulating material characteristics, and condition PD phenomenology and impact of PD on insulation life. Focusing mainly on the behavior of PD repetition rate as a function of time, after insulation energization by a DC voltage step, PD triggered by transient field can be separated from those relevant to steady state, which may indicate a criterion to estimate the partial discharge inception voltage, PDIV, under DC supply.**

I. Introduction

There is a rising awareness that measuring PD under DC voltage for DC insulation systems is an unavoidable requirement for various reasons, the most important being likely the different electrical field distribution in insulation under AC and DC and the large dependence of DC (but not AC) electric field on temperature [1-2]. This would determine operating conditions where defects could incept partial discharges, PD, under AC supply but not DC, and vice versa [4]. Also, PD under DC supply can be activated as a function of load conditions, as shown in [5] and discussed in the next Section.

On the other hand, it is clear, at least for those who try, that measuring PD under DC is a hard challenge, mainly because recognizing PD from noise is still a partly unresolved issue, and the repetition rate of PD may be largely smaller than that of noise impulses [6]. Even if PD could have been successfully measured and amplitude/repetition rate determined, there are still other important issues, that is, how to distinguish PD triggered by the transient and by the steady state conditions of the electric field in a defect upon insulation system energization (and/or voltage polarity inversion), and how to define, then, the partial discharge inception under DC supply, PDIVDC. This is the central topic of this paper, trying to highlight criteria to be able to separate PD occurring during electric field transient variation, thus when the field is distribute following a capacitive (permittivity) law, from those pertinent to steady state electric field, driven by conductivity values.

II. Modelling approach

Based on the drawing of Fig. 1, where a DC voltage step is applied to an insulation system, the behavior of electrical field in insulation can be derived from the following set of equations (under the assumption, as first approximation, of isothermal conditions and uniform geometrical field distribution) [1, 2, 7]:

$$\nabla \cdot \mathrm{E} = \frac{\rho}{\varepsilon} \tag{1}$$

$$\nabla \cdot J + \frac{\partial \rho}{\partial t} = 0 \tag{2}$$

$$J = \gamma E \tag{3}$$

where ρ is the spatial distribution of charge in the insulating material, $\gamma$and ε are conductivity and permittivity.

The same equations hold for the field in a cavity inside insulation. Considering that the cavity is filled by a gas having conductivity γ_c and relative permittivity ε_{rc} , while conductivity and relative permittivity of insulation are γ_b and ε_{rb}, at the beginning of the transient the electric field is given by:

$$\frac{E_c}{E_b} = f\,\frac{\varepsilon_{rb}}{\varepsilon_{rc}} \tag{4}$$

while in DC steady state:

$$\frac{E_c}{E_b} = f\,\frac{\gamma_b}{\gamma_c} \tag{5}$$

where $f = 1$ in the case of a flat cavity.

From (1)-(3), the general equation that describes a transient in an insulation is given by [7-9]:

$$\rho = -\frac{\varepsilon}{\gamma}\frac{\partial \rho}{\partial t} + \sigma E \cdot \nabla\left(\frac{\varepsilon}{\gamma}\right) \tag{6}$$

Charge density will theoretically reach steady state ($\frac{\partial \rho}{\partial t} = 0$) through an exponential relationship having time constant $\tau = \frac{\varepsilon}{\gamma}$.

It is important to stress the fact that this value should be taken to predict only the order of magnitude of transients, since the parameters of Equation (6) are in fact not constants when field distribution and temperature (i.e. applied voltage and loading) are continuously changing, as it occurs in a real transient.

For example, the temperature dependence of conductivity and permittivity follow an Arrhenius-type law, that is [10]:

$$k = k_0 \exp\left(-\frac{\alpha_A}{T}\right) \tag{7}$$

in which k0 is a parameter (e.g. for $k = \gamma$, γ_0 is conductivity at a temperature of 0°K) and α_A is the activation energy (temperature coefficient).

As such dependence it is negligible for permittivity and very large for conductivity, in DC steady state the electric field in insulation (and thus in a cavity embedded or a surface defect) will depend significantly on temperature, thus on electrical apparatus load. This will affect also the time constant τ. As an example, Table 1 shows different time constants values, as function of temperature, for a DC extruded cable with a polypropylene-based insulation.

Given the fact that transmission and distribution systems must withstand a mixture of transients and steady state conditions during their lifetime, proper design should be able to guarantee safe and reliable operation for both of those circumstances.

A potential issue of field transient is that if the partial discharge inception voltage in AC, PDIVAC, is lower than that the steady-state DC voltage, PD can be triggered at each transient and harm insulation life, causing premature breakdown. The impact of such transients on partial discharge inception is dealt with in the next Sections.

Table 1 – Time constant, calculated from eq. (6), as a function of temperature for a polypropylene-based insulating material

Temp. [°C]	Permittivity [F/m]	Cond. [S/m]	Time constant [s]
40	$\varepsilon = 1.94 \cdot 10^{-11}$	$\sigma = 10^{-16}$	$\tau = 194000$
60	$\varepsilon = 1.9 \cdot 10^{-11}$	$\sigma = 6 \cdot 10^{-16}$	$\tau = 32000$
90	$\varepsilon = 1.86 \cdot 10^{-11}$	$\sigma = 2 \cdot 10^{-15}$	$\tau = 9300$

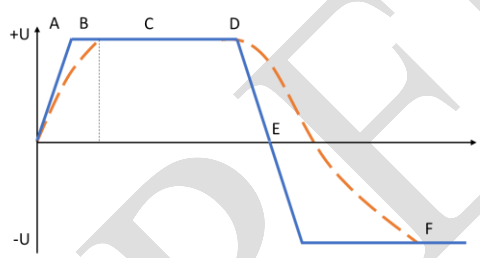

Figure 1 - Different stages when switching on a DC voltage and reversing polarity. Solid (blue) line: applied voltage; dashed (red) line: electric field in insulation.

III. PARTIAL DISCHARGE INCEPTION IN TRANSIENT AND DC STEADY STATE

Partial discharges can incept in a cavity embedded in insulation, regardless the supply voltage be AC or DC, at a filed, E_i, which can be calculated, for a spherical defect of radius r and assuming roughly a deterministic approach, as [11]:

$$E_i = 25.2p\left(1 + \frac{8.6}{\sqrt{2pr}}\right) \quad \left[\frac{V}{m}\right] \tag{8}$$

where p represents the gas pressure inside the cavity and r is the radius of the cylindrical cavity. Let us consider, e.g., a spherical cavity of radius 1 mm, at atmospheric pressure, then $E_i = 4.7\ kV/mm$, which is the value of PD inception field

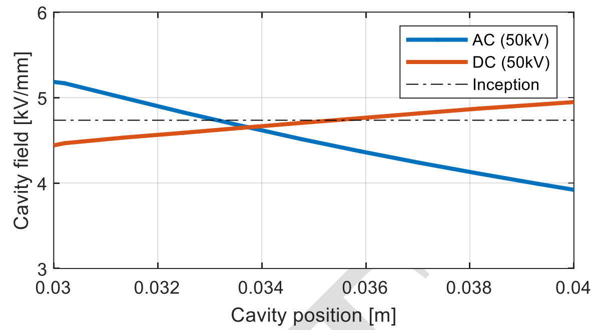

Fig. 2. PD inception field in cavity filled of air, 1 mm thick, compared to the AC and DC field distributions in the cavity as a function of cavity position along the radius of an extruded XLPE 50kV DC cable; temperature gradient 10°C. Note that the maximum field is for a cavity located near to the external semicon (ground side), and that it exceeds the PD inception field.

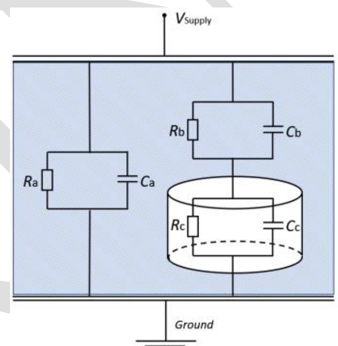

Fig. 3. Equivalent resistive/capacitive circuit to model PD: abc circuit modified to account for AC and DC supply. C_c and R_c are the equivalent capacitance and resistance of the cavity where discharges occur, C_b and R_b are the equivalent capacitance and resistance of the dielectric in series with the cavity, and C_a, R_a are the remaining equivalent capacitance and resistance of the test object.

reported in Fig.2. This figure shows also the field profiles in a cavity, as a function of cavity radial position, comparing AC and DC voltage supply for an extruded, 50 kV(peak) XLPE cable, with temperature gradient of 10°C (inner and outer insulation radius 25 and 45 mm, respectively). Note that the maximum DC field is for a cavity located near to the external semicon (ground side), and that, consequently, it might occur that cavities can activate PD (i.e. their field magnitude is higher than the inception field, eq. (8)) near to the external semicon in DC, they could activate PD near the internal semicon under AC.

According to the modelling approach presented above, PD might occur during transients and also (or not) in DC steady state. Thus, for example, a DC cable can be designed to work below the partial discharge inception voltage in DC ($PDIV_{DC}$), but it may not escape PD inception and accelerated insulation degradation during energization and polarity reversals.

The value of PDIV, based on the approximate, deterministic approach of eq. (3), can be obtained from the classic abc circuit of Fig. 3, valid for both AC and DC power supply, [4, 5]:

$$PDIV_{DC} = V_{ci} \cdot \left[\frac{R_c}{R_b + R_c}\right]^{-1} \tag{9}$$

$$PDIV_{AC} = V_{ci} \cdot \left[\frac{|Z_c(\omega)|}{|Z_b(\omega)| + |Z_c(\omega)|}\right]^{-1} \approx V_{ci} \cdot \left[\frac{C_b}{C_b + C_c}\right]^{-1} \quad (10)$$

where V_{ci} is the PD inception voltage across the cavity, $V_{ci} = h_c E_i$ being h_c the cavity height.

Depending on material conductivity, and thus temperature, the ratio $PDIV_{DC}/PDIV_{AC}$ can be much larger than 1, but also lower, thus it may vary significantly with conductivity and its relationship with temperature (α_A of eq. (7)), see [4].

IV. PARTIAL DISCHARGE MEASUREMENTS UNDER DC SUPPLY

A major issue in PD measurements is how to perform them considering that there is very little experience and knowledge about how to distinguish them from noise. Indeed, the patterns are time, and not phase, resolved, so that the methods developed under AC to recognize PD and reject noise may only in part work [6, 12]. This aspect, however, is not considered in this paper.

We assume that PD can be measured, immediately after a DC voltage is applied by a step of a certain rising time, and the issue is, indeed, how to recognize when PD are triggered by the time-variable field, which is mostly driven by permittivity, or by the steady field, distributed according to conductivity.

An approximate estimation of the time constant, τ, eq. (6), can be obtained, as mentioned, by permittivity and conductivity measurements [10, 11], which is already a considerable help in separating transient from steady state PD. Then, a more direct criterion could consist of the estimation of the PD repetition rate. Because PD are activated mostly during applied voltage gradients, one can expect that the repetition rate will drop drastically when the field in the defect where PD are generated reaches the DC steady conditions (considering that PD repetition rate under DC is much smaller than in AC [4, 5]). Note that PD magnitude might be not a criterion as valid as repetition rate, because it may show smaller time variation than the latter, mostly driven by the random delay time of the incepting electron, which is much more influential for PD amplitude in AC than in DC [4].

As an example, Figs. 4 and 5 show results of PD tests carried out under isothermal conditions at 60°C on objects consisting of three layers of polymeric materials (based on XLPE and PP), with a punched layer in the middle to simulate and internal cavity in insulation. All specimens were produced with the same geometry, featuring a cylindrical cavity of 3 mm of diameter and 0.4 mm height, and mounted on a custom holder in order to ensure repeatability of tests. DC voltage was applied to the test objects, with a rise time of 1 kV/s. As can be seen, large PD activity is seen during the energization transient, while amplitude (Fig. 4) and, in particular, repetition rate (Fig. 5) decrease as function of time under voltage (the former due to the matter of delay time discussed above). The sharp drop of amplitude and repetition rate with time can be associated with the change of permittivity-driven to conductivity-driven electric field distribution, which affects the field in the cavity and, thus, PDIV. It can also be noticed that the time constant calculated from eq. (6) in Table 1 fits well the time required to reach an almost constant value of the repetition rate, corresponding to the achievement of a steady state condition of the electric field distribution.

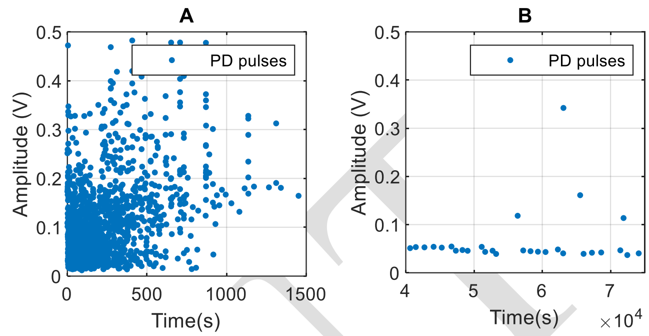

Fig. 4. PD amplitude from tests carried out on objects consisting of three layer of polymeric material (PP), with a punched layer in the middle to simulate an internal cavity in an insulation. DC voltage was applied to the test objects with rise time of 1 kV/s, up to 10 kV. From seconds (A) to hours (B).

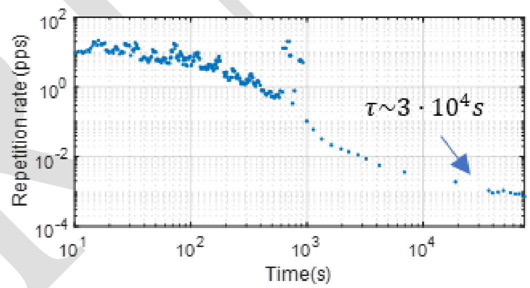

Fig. 5. PD repetition rate from the test of Fig. 4. The time constant τ calculated from eq. (6) is also reported.

It is interesting to note that useful information can be collected from the time evolution of the repetition rate. Figure 6 shows the quality of fitting for an exponential relationship for repetition rate and time. While for PD pulses detected during the initial transient it is possible to recognize a clear exponential correlation and a root mean square error (RMSE) of 3.4, as it is expected since PD activity follows the evolution of field distribution in the specimen, noise acquired during the monitoring displayed a more random, uncorrelated behavior and has a RMSE of about 2700.

Upon separation of PD pulses and noise during the energization transient (an in steady-state), PD-pulse amplitude values fit to a 2-parameter Weibull distribution, as shown already [13]:

$$F(v) = 1 - exp\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right] \quad (11)$$

where v is the measured pulse amplitude (generally given in V), α and β are the scale and shape parameters. Figure 7 reports the Weibull plots for the presumably transient and steady state PD amplitude values. It is noteworthy that, besides the quality of the fitting, the value of the shape parameter, β, are quite different, going from 1.6 during the initial transient to 10.8 in DC steady state. Those values would identify the detected pulses as PD in an internal cavity at steady state conditions, and confirm that, as already speculated in previous papers [14], the shape parameter value for PD amplitude distribution in DC is larger than in AC (due to lower inherent variance).

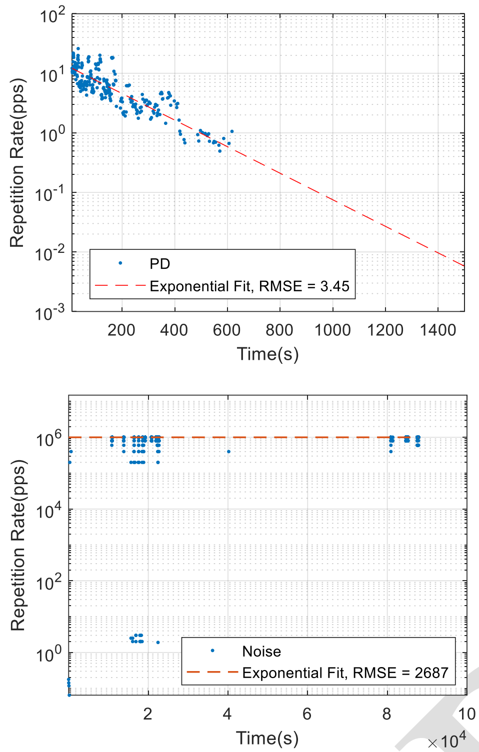

Fig. 6. Repetition rate of PD (A) and noise (B) detected during the initial transient (from the test of Fig. 4).

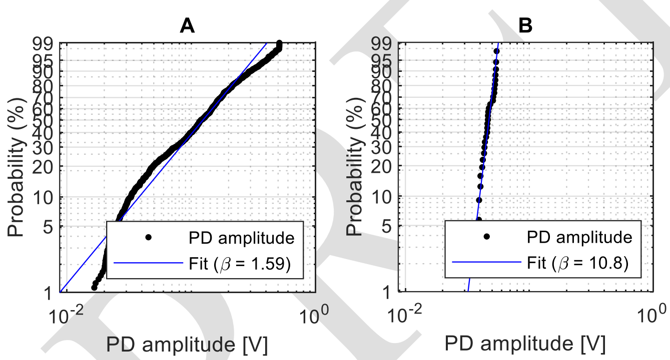

Fig. 7. Weibull plots for the transient (A) and steady state (B) PD amplitude values (from the test of Fig. 4).

V. Conclusions

This paper shows how DC PD measurements have to take care of the energization transient, after DC voltage step application, during which the field will steadily establish following a conductivity-driven distribution. The duration of this transient can last even many hours, and it affects not only PD measurement procedures, but also, and in particular, insulation reliability. In fact, an insulation system working under DC should not be designed only to operate PD free all life in steady state, but also to be PD free (or almost free) during energization and de-energization transients. The methods to evaluate the electric field transient length and the related PD phenomena are discussed and show good fitting to experimental data relevant to PP specimens with artificial defects. A robust methodology, based on the shape parameter of pulse amplitude and the time evolution of the repetition rate, can be successfully applied to separate PD pulses from noise being detected during a long-term monitoring of a defective insulation.

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