3D Model of partial discharge in defects with different sizes and positions in power cable for distribution and transmission networks

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Abstract: The knowledge of partial discharge (PD) phenomena inside electrical insulation of power cables is an important issue for assessing the insulation condition and its degradation state, obtaining information about the likelihood of failure. PDs cause signals to propagate along the cable, as noise phenomena, and contribute to the insulation degradation, culminating in a disruptive fault with the interruption of power supply. Therefore, PDs are considered the best ‘early warning’ indicators of insulation degradation and their modelling, with the development of on-line PDs location methods, are important topics to increase the networks’ electricity security. In this study, a three-dimensional (3D) model of PD events using the CST STUDIO® Dassault software is proposed. PDs inside air inclusions in epoxy-resin are analysed with different shapes, positions and sizes of the defect. The electric field distribution is evaluated with the conduction current inside the void and the apparent charges induced on the electrode. The effectiveness of the model is validated by comparing the simulation results with other published experimental results. Finally, a description of a 3D–1D hybrid model useful to describe the propagation of PD signals in power networks is given.

1 Introduction

Partial discharge (PD) phenomena, inside electrical insulation of high voltage plants, cover a great number of physical events that lead to the degradation of the material performance, including the eventual breakdown and failure of the plant [1]. Moreover, PD events cause electromagnetic signals that, propagating along the cable, act as noise in the receiving and source ends. For these reasons, PDs are considered one of the best ‘early warning’ indicators of insulation degradation [2].

The modelling and studying of such phenomena, together with the measurement [3] and the development of on-line PDs location methods [4, 5] are, therefore, important topics for the assessment of network integrity. They are useful means to define solutions to methods [4, 5] are, therefore, important topics for the assessment of network integrity. They are useful means to define solutions to improve the power networks’ electricity security, which can be defined as the power system’s capability to withstand disturbances (events or incidents producing abnormal system conditions), or contingencies (failures or outages of system components) with a minimum acceptable service disruption [6].

The PD events occur inside the defects of the insulation material, where the defect characterised by a lower breakdown strength than the surrounding dielectric material. The most common defect is the presence of air inclusions, due to voids or cavities of various shapes, formed during the manufacturing process, the installation or the operation of the high voltage system [1].

The development of PD models is an important topic to better understand the PD phenomena, to investigate the physics behind PD events and to identify the critical parameters that characterise PD behaviour in the various condition of defects, i.e. size and location of the defects, and in various electrical stress conditions, i.e. frequency and magnitude of the applied voltage [7–9]. PD modelling is still an active research area and PD models can be classified into three main categories [10]:

- the three-capacitance model or ‘a, b, c’ model [11, 12];
- the analytical based model that uses the induced charge concept, proposed by Gutfleisch and Niemeyer [1] and Niemeyer [9];
- the finite elements analysis (FEA) that uses electric current models or electrostatic models [13–17].

Each modelling type has its own strengths and weaknesses [10]. The three-capacitance model can reproduce the transient related to a discharge event, describing the apparent charge magnitude and the PD current, but a possible limitation of treating the void surface as an equipotential surface is inherent [11, 12]. The analytical models are based on the induced charge concept, i.e. the charge distribution on the void surface due to discharges. They can be used to simulate PD inside ellipsoidal, cylindrical or spherical voids in a dielectric material. These models tend to assume that PD affects the whole void uniformly and therefore it can be used only for uniform field distributions. This assumption may not be true for large-sized voids, or voids of highly irregular structure, where the surface charge distribution cannot be represented using an analytical based model [1, 9]. Finally, in FEA models of PD phenomena, the distribution of the electric field (E-field) is determined numerically after defining the subdomain and boundary conditions [13–17].

The advantage of FEA models is that field distribution figures can be obtained, which gives an insight into the PD event. Using a numerical method, non-uniform field distribution inside the defect can be modelled and the influence of the electrode and of the surface charge distribution along the void wall is taken into account. Moreover, multiphysics, i.e. electrical and thermal behaviour, can also be added to the model and can be calculated at the same instant. However, FEA models have the disadvantages of long simulation time and the need to refine the meshing in parts of interest of the model, to obtain a better result, further increasing the simulation time. Even with these disadvantages, FEA models are an improvement over earlier models, although their description of the discharge event still contains significant simplifications of the complex processes of the physical discharge phenomena.

In this paper, a three-dimensional (3D) model of PD in a disc-cavity within an epoxy-resin dielectric material for application in high voltage power networks was developed using CST Studio by Dassault Systems simulation software. This model is an improvement of previous works [16, 18] developed by the authors where the first results of a 3D model of PD in a 15 kV, 50 Hz power network are reported. In [16, 18] the PD model was developed adopting the CST electro-quasistatic solver, which is useful to describe the E-field distribution inside the system and to...
understand the dynamics of the currents when PD occurs. In this work, the high frequency (HF) solver of CST is adopted to connect the new 3D model of PD to a 1D TLM model of a power line, improving the hybrid model with the multi-solver approach presented by the authors in [18]. The hybrid model, here described, is useful to analyse the propagation of the discharge signal on the power line. A detailed analysis of the modelling procedure of PD event using this new solver, with the description of the non-linear behaviour of the system during the discharge event, is presented and the effectiveness of the proposed model is evaluated by comparing the simulation results with other published experimental works [8, 19]. The E-field distribution inside the system is simulated, the dynamics of the currents during the discharge event are described and the real and apparent charge are evaluated in relation with different sizes and positions of the defect inside the insulation material.

The importance of the approach investigated in this paper is that it is working towards a full model where the effects of the cables, in terms of dispersion, reflections etc. can be included in the simulation of PD. This will help a more detailed study of the distribution system in which PD occurs. The paper is more concerned with the approach to this analysis than addressing the materials and geometries of the model. In a more directed analysis, the materials and geometries can be changed.

2 Geometry of the 3D model of PD

An improvement of a 3D model of PD developed by the authors in previous papers [16, 18, 20] is described in this work. The proposed 3D model is shown in Fig. 1. It represents a generic but representative first-order approximation of a real section of cable.

The model consists of three main domains: the insulation material, the air-cavity, with a non-linear behaviour, and the conductive electrodes. The air of the inclusion has a relative permittivity of $\varepsilon_r = 1.0009$. The epoxy-resin is a homogenous material with $\varepsilon_r = 4$.

An air disc cavity with a height $h = 1\, \text{mm}$, $r = 2\, \text{mm}$ is positioned between two parallel electrodes. The two electrodes are positioned at a distance $D = 3\, \text{mm}$.

Moreover, PD event inside a sphere shape has been also investigated in this work. To reduce the number of mesh cells and therefore the simulation time, the sphere has been approximated using a dodecahedron, as shown in Fig. 2. The dodecahedron model has been obtained from a freeware animation program and imported in CST software. Different sizes of the disc and sphere, with a different diameter value, and different positions of the cavities inside the dielectric have been investigated. To verify the effectiveness of the developed model, the same geometry and electrical stress of the systems experimentally analysed in [8, 19, 21] were adopted to compare the obtained simulation results with the measurements.

3 Field equations

The basic governing equations of the field model for the system under study are as follows (Maxwell Equations) [17, 22]:

\begin{align}
\nabla \cdot D &= \rho \tag{1} \\
\nabla \cdot J + \partial \rho / \partial t &= 0 \tag{2}
\end{align}

where $D$ is the electric displacement field, $\rho$ is the free charge density, $J$ is the free current density. For linear, isotropic and non-dispersive dielectric material, the following relation can be written:

\begin{equation}
D = \varepsilon E = -\varepsilon \nabla V \tag{3}
\end{equation}

\begin{equation}
J = \sigma E = -\sigma \nabla V \tag{4}
\end{equation}

where $\sigma$ is the conductivity and $\varepsilon = \varepsilon_0 \varepsilon_r$, with $\varepsilon_0$ is the vacuum permittivity and $\varepsilon_r$ the relative permittivity of the material. Thus, the electrical potential distribution in the model is governed by the equation [17]:

\begin{equation}
\nabla \cdot \left( -\sigma \nabla V - \frac{\partial}{\partial t} \varepsilon \nabla V \right) = 0 \tag{5}
\end{equation}

where $V$ is electric potential.

4 PD event

A streamer discharge [9] has been used as the basis for the PD event. Detailed modelling of the complex physical mechanism of the streamer phenomena, which takes into account the motion of free electrons and ions during the discharge, depending on the parameters, temperature and pressure parameters inside the insulation defect, has not been addressed because it is not the scope of this work. Here a simplified model of one PD event has been realised because only the amplitude of the discharge is of interest to evaluate the value of E-field inside the system and the displacement current and apparent charge induced on the electrode during the discharge to analyse the propagation of these charges on power networks is the final aim of this work.

The PD may occur in the cavity when the voltage across the cavity $U_{cav}$ exceeds the inception voltage, $U_{in}$ and there are free electrons to start the avalanche [8]. The inception voltage depends on the inception E-field, $E_{in}$ formulated in [23] through the streamer breakdown criterion that depends on the cavity geometry, the pressure of the gas inside the inclusion and the characteristics of the ionisation process:

\begin{equation}
E_{in} = (E/p)_{in}\left(1 + \frac{B}{(2pr)^n}\right) \tag{6}
\end{equation}

where $p$ is the pressure in the cavity, $r$ is the cavity radius and the parameters, $(E/p)_{in}$, $B$ and $n$ depend on the ionisation processes in the gas of the inclusion. The values for these parameters for the air are $(E/p)_{in} = 25.2\, \text{VPa}^{-1}$, $n = 1/2$ and $B = 8.6\, \text{m}^{1/2}\text{Pa}^{1/2}$ [12].

The discharge in the air inclusion has been modelled dynamically by changing the state of the cavity from a non-conducting condition to a conducting one, realising a simple behaviour like a diode. This has been realised by considering an increase of the conductivity of the air, $\sigma_{air}$, from an initial value, $\sigma_{air,0}$, that is around zero, when there is no PD, to a maximum value $\sigma_{air,max}$ during PD event. The conductivity, $\sigma_{air,max}$, causes the reduction of the $U_{cav}$ across the cavity during a PD until it becomes lower than the excitation voltage. During the discharge event, the conductivity of the streamer channel has been simulated.
considering the electron conductivity in the plasma of the void and in this condition \( \sigma_{\text{air max}} \) is given by [8]:

\[
\sigma_{\text{air max}} = \left( \alpha_{\text{e}} N_0 \lambda_e / (m_e c_e) \right)
\]

(7)

where the value of the coefficient \( \alpha_{\text{e}} \) depends on the electron energy distribution and mean free path, \( e \) is the electric charge of the electron, \( m_e \) is the electron mass, \( \lambda_e \approx 4 \mu \text{m} \) is the mean free path, \( c_e \approx 3 \times 10^8 \text{ms}^{-1} \) is the electron thermal velocity and \( N_0 \) is the electron density given by [8]:

\[
N_0 = n_e / V_{\text{cav}}
\]

(8)

where \( n_e = q_{\text{air}} / e \) is the number of electrons in the streamer channel, \( V_{\text{cav}} \) is the volume of the cavity and \( q_{\text{max}} \) is the maximum measured PD charge magnitude, taken from [8, 19] for each analysed cavity type.

Since the discharge event is modelled dynamically, the discharge process makes this model charge consistent [21], therefore, it can be used to evaluate numerically the discharge magnitude. Real charge in the cavity surface and the apparent charge on the electrode due to PD have been calculated by time integration of current flowing through the surface of the cavity and of the electrode during the PD time interval. In models [9, 24], the real charge in the cavity was evaluated by using \( q = C \Delta U_{PD} \), where \( \Delta U_{PD} \) is the voltage drop across the cavity caused by PD and \( C \) the cavity capacitance. To this end, a dipolar surface charge distribution is associated that is the ‘true’ physical charge that has flowed during PD [9]. This charge is responsible for insulation ageing because it controls the damage produced by PD events [9]. The charge distribution on cavity surface induces a charge on the electrodes which is defined as an induced charge. The induced charge produces signals that travel from the defect location to the part of the system where a PD measurement device is coupled. The response produced on these devices is the measured PD charge quantity defined as the apparent charge [9, 25]. The apparent charge depends on the defect location in the material, the geometry and dimension of the defect, the gas pressure and the compositions in the defect [17, 19]. Considering a measurement device coupled with the electrode of the model, the apparent charge has been evaluated by time integration of current flowing through the surface of the electrode. The current on the electrode, \( I_{PD} \), was calculated by integration of the displacement current density, \( J_D \), over the surface area, \( S \), of the ground electrode that depends on the E-field distribution [22]:

\[
I_{PD} = \int \int J_D \cdot dS = \int \int \frac{\partial D}{\partial t} \cdot dS = \frac{\partial}{\partial t} \int \int D \cdot dS
\]

(9)

where \( \Phi_D \) is the flux on \( S \) of the field displacement, \( D \), and \( e = 35,416 \times 10^{-12} \text{F/m} \) for epoxy resin.

5 Simulations results

The phenomena under study was simulated using CST Studio Suite-Dassault simulation software [26]. The FIT method was adopted to solve Maxwell’s equations and hexahedral meshing was used [26]. PD events produced in different shapes, sizes and positions of the cavity inside the dielectric were investigated. In particular, a disc and a sphere cavity were investigated with different values of the diameter and in different positions inside the insulation. The dynamic variation of the conductivity inside the cavity is realised using a feature of the CST-Dassault solver that allows one to define a non-linear behaviour of the material conductivity in time domain [26]. Here, only one PD event has been simulated because the aim is to evaluate the PD signal induced on the electrode to study the propagation of it on power networks. An impulsive shape of \( \sigma_{\text{air}} \) was realised that increases from the initial value \( \sigma_{\text{air}} = 1 \times 10^{-18} \text{Sm}^{-1} \) to a \( \sigma_{\text{air max}} \) with a duration of about 1 \( \mu \text{s} \) to reproduce a PD event of a few \( \mu \text{s} \) [5]. The value of \( \sigma_{\text{air max}} \) was evaluated using (7) for each size and shape of the considered cavity.

5.1 Proof of the model effectiveness with disc and sphere cavity

To verify the validity of the developed model to reproduce the induced charge on the electrode, the results obtained with the model were compared with the apparent charge measured in [8, 19]. The model was verified using both a disc and a sphere as a cavity inside the dielectric material. To this end, the same geometry and electrical stress of the systems experimentally analysed in [19], for the disc, and in [8], for the sphere, were used.

The parameters values used for the simulations are reported in Table 1. As stated in Section 4, \( q_{\text{air max}} \) is the maximum apparent charge measured from the experiment in [8, 21] used to assess the effectiveness of the model. The cavity is in the middle between the two electrodes that are at a distance of 3 mm apart for the disc and of 2 mm for the sphere. A diameter of 1 mm was used for the disc cavity. The supply voltage was applied to the top electrode while the bottom was grounded.

Figs. 3 and 4 show the variation in the time domain of the conduction current in the cavity, the displacement current on the electrode and of the E-field on the top of the insulator, close to the electrode, and in the cavity centre when a PD occurs. Before the PD, the E-field is higher in the cavity than on the surrounding dielectric material because the permittivity of the cavity is lower than the permittivity of the dielectric surrounding dielectric material because the permittivity of the cavity is lower than the permittivity of the dielectric. This is also shown in Fig. 5 that shows, the E-field along the z-axis, at \( z = 0 \) in Fig. 1, before (solid line) and during (dashed line) PD event in the disc, for example. Moreover, without PD, the E-field in the areas of the dielectric close to the cavity surface, nearer to the electrodes, is lower, as Fig. 5 shows, because the E-field is perpendicular to the surface and the charges are concentrated there. This can be observed also in the 3D distribution of E-field inside the cable section before and during PD shown in Figs. 6 and 7, respectively.

When a PD occurs, a conduction current starts in the cavity as shown in Figs. 3 and 4, and the E-field changes significantly. Due to the movement of the charge inside the cavity, the E-field in the cavity is reduced and in the E-field in the dielectric close to the cavity surfaces increases. The displacement currents induced on the electrode by the PD event are also reported in Figs. 3 and 4. They show impulsive behaviour, characterised by a rise time and a fall time \( t_r = 0.154 \mu \text{s} \) and \( t_f = 0.357 \mu \text{s} \), with a disc inclusion, and \( t_r = 0.094 \mu \text{s} \) and \( t_f = 0.197 \mu \text{s} \), with a sphere inclusion. Their time integral gives the apparent charge induced on the electrode. In Table 2 the simulated real and apparent charge obtained for the two analysed cases are reported and the apparent charge obtained in simulation is compared with the measured one in [8, 21]. As the table shows, the proposed 3D model of PD reproduces the PD

Table 1 Simulation parameters

| Parameter       | Disc | Sphere |
|-----------------|------|--------|
| electrical stress | 8 kV–50 Hz | 20 kV–50 Hz |
| diameter, mm     | 4    | 1.4    |
| \( q_{\text{max}} \), measured, pC | 1000 [19] | 2250 [8] |
| \( \sigma_{\text{air max}} \), Sm\(^{-1}\) | \( 1.6 \times 10^{-4} \) | \( 3.8 \times 10^{-3} \) |
magnitudes with a good approximation in both the two considered cases; the obtained simulation results are in fact of the same order of magnitude as the measured ones. The analysis of the propagation of these charges on a power network will be developed in future works.

5.2 PD analysis varying cavity size and position

An analysis of the effect of the size and position of the defect inside the dielectric on the PD magnitude was also undertaken. The distribution of the E-field inside the system and the induced charge on the electrode were evaluated. In Fig. 8 the E-field along the z-axis when the position of the cavity changes is shown, together with the conduction current inside the cavity and the displacement current on the electrode. In particular, the position of the disc with \( d = 4 \text{ mm} \) was changed, moving the disc so that its top surface was 0.5 mm from the top electrode.

As the figure shows, the proximity of the inclusion to the electrode produces a higher increase of the E-field in the dielectric between the inclusion and the electrode. In the analysed case, the displacement current is a little higher when the cavity is closer to the electrode and it is characterised by rise and fall times of \( t_r = 0.154 \mu s \) and \( t_f = 0.371 \mu s \).

Finally, the values of the apparent charge induced on the electrode were evaluated varying the disc dimensions and, in particular, increasing the radius. Fig. 9 shows the simulated real charge and the induced apparent charges on the electrode versus the disc radius and Fig. 10 shows the E-field in the time domain for each disc dimension. In Table 3 the simulated values are reported together with the measured one from [19]. Both real and apparent charge increase with the diameter of the disc, as expected. This is because a larger cavity produces a larger size of the electron avalanche that produce a larger PD magnitude as it is demonstrated by the measurements too.
6 3D–1D hybrid model for the propagation of PD signal on power networks

PD events generate electromagnetic signals that propagate along the cables of the power networks, acting as disturbances. The online measurements of these signals are useful to determine the PDs activity on the cables and to assess the cable deterioration and ageing. For this reason, sophisticated PD measurements techniques are under development to detect and locate PD sources on power networks [27–29]. PD signals are high frequency signals and their propagation in power cables is subject to the phenomena of the attenuation, that reduces the signal amplitude during propagation, and dispersion which dispersion changes the shape signal along the cable. The main consequence of these phenomena is the reduction in the accuracy of the PD location methods for long cables and complex networks topologies [5].

To model the propagation of PD in power networks, a first simplified hybrid model was designed where a previous developed 3D model of PD was connected to a 1D TLM model of a power line. This was realised adopting a multi-solver solution in CST Dassault software. Using the schematic co-simulation feature of CST Dassault software, the simplified hybrid 3D–1D model, shown in Fig. 11, was developed by the authors in [20]. This hybrid 3D–1D model serves as a first model to study the propagation of PD signals in a power line and to demonstrate dispersion and attenuation of PD impulse only, provided its limitations are considered.

The resulting PD pulses at the output of the 3D model (P3 in Fig. 11), at the output of the third node (P4 in Fig. 11) and at the matched load (P5 in Fig. 11), when the system is supplied with a voltage of 30 kV at 50 Hz, are shown in Fig. 12 and matches the results of [30] reasonably well. As Fig. 12 shows, the attenuation of the PD signals and phase shift are apparent demonstrating the effects expected for high frequencies on power lines, i.e. that the signals will degrade. Therefore, when a PD signal is measured in a point of a power network some work is necessary to determine its original form and its source. An improvement of the propagation model is the objective of future works, to achieve accuracy in determining the shape and origin of the PD pulse from a signal detected at a distance.

7 Conclusion

In this work, a 3D model of PD event inside an air inclusion in epoxy-resin insulation material, for a high voltage power network cables, is presented. The CST Dassault software® was used to simulate the PD phenomena. The proposed 3D model provides a dynamic simulation of the discharge events and evaluates
numerically the field inside the cavity, the current inside the inclusion and the charges induced on the electrodes. The model was used to investigate PD events in different conditions of sizes, shapes and positions of the defect inside the dielectrics. The effectiveness of the proposed 3D model of PD was verified comparing the simulation results with the experimental results of other published works. The proposed model is useful to reproduce the charge on the electrode induced by the PD event. The propagation of these charges in the power network was finally described. To this aim, a hybrid 3D–1D model where the 3D PD model is connected to a 1D TLM model of a power line is described. A multi-solver solution in CST Dassault software was adopted to simulate the 3D–1D hybrid model and preliminary results of the propagation of a PD signal generated by a 3D PD model were obtained. The improvement of the propagation model is under development with the aim of designing a method to locate PD sources on-line in power distribution networks.

Fig. 8  E-field along z-axis, conduction current and displacement current inside the system when PD occurs in a disc cavity with diameter 4 mm at 1 mm from the electrode and with a supply voltage of 8 kV, 50 Hz.

Fig. 9  Real charge and displacement charge with different values of the disc diameter.
8 Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 838681.

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