3D Simulation of Partial Discharge in High Voltage Power Networks

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Abstract

Partial discharge (PD) events arise inside power cables due to defects of cable's insulation material, characterized by a lower electrical breakdown strength than the surrounding dielectric material. These electrical discharges cause signals to propagate along the cable, manifesting as noise phenomena. More significantly, they contribute to insulation degradation and can produce a disruptive effect with a consequent interruption of power network operation. PD events are, therefore, one of the best 'early warning' indicators of insulation degradation and, for this reason, the modeling and studying of such phenomena, together with the development of on-line PDs location methods, are important topics for network integrity assessment, and to define methods to improve the power networks' Electricity Security. This paper presents a 3D model of PD events inside a void in epoxy-resin insulation cables for High Voltage (HV) power networks. The 3D model has been developed using the High Frequency (HF) Solver of CST Studio Suite® software. PD events of a few µs duration have been modelled and analyzed. The PD behavior has been investigated using varying electrical stress. A first study of the PD signal propagation in a power network is described.

Keywords: computational electromagnetics; numerical modelling, partial discharge; power cables; power transmission lines.

1. Introduction

Partial discharge (PD) events arise inside the defects of cables' insulation material, characterized by a lower breakdown strength than the surrounding dielectric material. These defects, such as air inclusions, have various shapes and sizes and are formed during the manufacturing process or the installation of the high voltage system. When the supply voltage is applied, the value of the electric field is greater in the region of lower dielectric constant and electrical breakdown can occur, producing repeated PDs [1-2].

Such phenomena cause electromagnetic signals that, propagating along the cable, act as noise in the receiving and source ends as well as radio frequency emissions. More significantly, PDs contribute to the degradation of cables' insulation and can produce a disruptive effect with a consequent interruption of power network operation. For these reasons, PDs are considered one of the best 'early warning' indicators of insulation degradation. The modeling and studying of such phenomena. Together with measurement [3] and the development of on-line PDs location methods [4-5],the origin and effects of PD are important topics for the assessment of network integrity. They are useful means to define methods to improve 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].

Modeling of PD is an active research area. In the literature, PD models can be classified, into three main categories [7]:

1) the three-capacitance model or "a, b, c" model;
2) the analytical based model, proposed by Niemeyer;
3) models based on Computational Electromagnetics (CEM) techniques.

Each modelling approach has its own strengths and weaknesses [7-8]. Among these, CEM models represent an improvement over the other two modeling approaches, in terms of potential accuracy of representation of the source of the phenomenon itself. However, the description of the discharge event reproducing by these models still contains significant simplifications of the complex physical processes of PD phenomenon and the simulation of a complete cable using a full-wave solver could be costly in terms of time and resources.

In CEM models of PD, the distribution of the electric field is determined numerically after defining the subdomain and boundary conditions. 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. CEM models produce figures of field distribution, giving an insight into the discharge event and multi-physics behavior, i.e. electrical and thermal, can also be added to the model. A significant disadvantage of these models is the potentially long simulation time (potentially days, depending on the solver, the complexity of the simulation and the computational platform). In addition, often, the need to refine the meshing in parts of interest of the model, in order to obtain a better result, further increases the simulation time [8-10]. Most of the CEM based models in the existing literature, are 2D models that use the finite element method (FEM) as numerical method to calculate the potential distribution in the system under study [1, 7, 10].

This paper presents a 3D model of a PD event inside a void in epoxy-resin insulation of a High Voltage power cable. The 3D model has been developed using CST Studio Suite, a Dassault Systems simulation software [11] using the Finite Integration Technique (FIT) numerical method. In previous works [8-9], the authors have developed a 3D model of PD in CST adopting the Electro-quasistatic (EQS) solver, which is useful to help describe the E-field distribution inside the void, the surrounding dielectric material and the cable's electrodes, and to understand the dynamic of the currents inside the systems when PD events occur. Moreover, in [9] an analysis of the effects, produced on the E-field distribution inside the system under study and on the currents' dynamic, caused by the position of the defect inside the cable insulation was investigated. In this paper, an analysis of the PD behavior when the electrical stress changes is reported and a first study of the propagation in a power network of the electromagnetic disturbances generated by PD event is described. To this end, a 3D model of PD has been connected to a 1D model of a transmission line, using the co-simulation feature of CST, and the phenomena of dispersion and attenuation that characterize the propagation of HF PD signals on power networks have been reproduced. The 3D model of PD, developed in the previous works [8-9], has been used and suitably modified in order to use the CST High Frequency (HF) Solver that supports the co-simulation feature of the CST software.

2. 3D Model of PD

The 3D model developed by the authors [8-9] 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 behavior, and the conductive electrodes. An air disk inclusion with $h = 3$ mm, $r = 6$ mm is positioned, at z=22 mm, between two plane parallel electrodes made of perfect electrical conductor (PEC). The two electrodes are positioned at a distance D=30 mm. The air of the inclusion is with a relative permittivity of ε_r=1,0009. The epoxy-resin is a homogenous material with a relative permittivity of ε_r= 4.

A supply voltage was applied to the top electrode while the bottom electrode was grounded.

The electrical potential distribution in the model is governed by the equation [14]:

$$\nabla \cdot \left(-\sigma \nabla V - \frac{\partial}{\partial t}\left(\varepsilon_0 \varepsilon_r \nabla V \right) \right) = 0 \tag{1}$$

where V is electric potential, σ is conductivity, ε_0 is the permittivity of free space and ε_r the relative permittivity of the material.

Moreover, for linear, isotropic and non-dispersive dielectric material:

$$\vec{D} = \varepsilon \vec{E} = -\varepsilon \nabla V \tag{2}$$

$$\vec{J} = \sigma \vec{E} = -\sigma \nabla V \tag{3}$$

where D is the electric displacement field, J is the free current density and $\varepsilon = \varepsilon_0 \varepsilon_r$.

Hexahedral meshing was used with the HF solver of CST to allow the mesh to be conformal with the various geometries, and the FIT method has been adopted to solve Maxwell's equations [11-12].

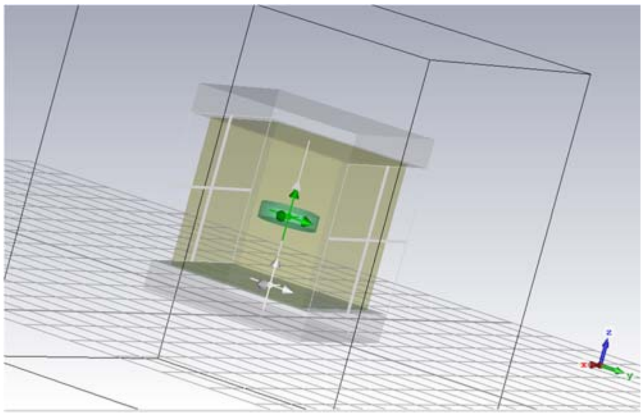

Figure 1. CST Suite 3D model of the disk air void in epoxy-resin insulation between the two plane electrodes.

The discharge in the air inclusion has been modeled dynamically by changing the state of the cavity from a non-conducting condition to a conducting one. This has been obtained by considering an increase of the conductivity, σ_{air} of the air in the cavity. This produces a behavior of the inclusion similar to that of a diode, which starts to conduct when a PD event occurs. This has been realized using a feature of the solver that allows non-linear time-behavior of the material conductivity [11]. In particular, an impulsive behavior of σ_{air} that increases from the initial value σ_{air0} ~ 0 Sm^{-1} to a value of σ_{airmax} of 0.9 Sm^{-1} with a duration of 2 μs was defined in the model.

A streamer discharge [13] was used for the PD event. This discharge may occur when the value of the E field inside the defect overcomes the inception electric field, E_{inc} and there are free electrons to start the avalanche. The E_{inc} depends on the cavity geometry, the pressure of the gas inside the inclusion and the characteristic of ionization process [2-13]. Considering a gas pressure equal to standard atmospheric pressure, with h=3mm, the value of E_{inc} is $2.75 \cdot 10^3$ V/m [13].

The E-field inside the cavity, the surrounding dielectric material and on the electrode has been calculated together with the conduction current inside the cavity. The displacement currents produced by the time variation of the E field flux on the electrode and on the cavity surfaces, due to the PD event, have been evaluated. Moreover, the physical charge in the cavity surface and the apparent charge induced on the electrode surface have been calculated by integrating the electric displacement field, D, on the surfaces [16].

3. 1D Model of Power Network

Partial discharge events generate electromagnetic signals that propagate along the cables of the power networks, acting as disturbances at the receiving and sources ends. The on-line measurements of these signal are useful to determine the PDs activity on the cables and to assess the cable deterioration and ageing. Sophisticated PD measurements techniques [17], using sensors with bandwidth of several megahertz [18], have been developed and are under further development to detect and characterize PD in power cables [19] and to locate PD sources on power networks [20-22].

PD signals are high frequency (HF) signals, typically with a duration of the order of ns. Their propagation in power cables is subject to the phenomena of attenuation and dispersion. Attenuation reduces the signal amplitude during propagation, while dispersion changes the shape signal along the cable. This is because the propagation speed depends on the frequency, therefore low frequency components of the signal will propagate at different speed to the high frequency components. 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, 22].

In order to model the propagation of PD in power networks, in this work the 3D model of PD, described in sections 2, has been connected to a simplified 1D TLM model of a power line obtained from [23], which was previously used in [24]. This has been realized using the Schematic co-simulation feature of CST, as shown in Fig. 2. The simplified model of the power network section is realized using nodes with components values reported in Fig. 2 [23-24]. The power network has been supplied with a 30kV, 50Hz voltage given by Port 1, shown in yellow in Fig. 2.

This network model serves as a first model for a power line, provided its limitations are considered, and because we are interested in demonstrating dispersion and attenuation of the PD impulse only.

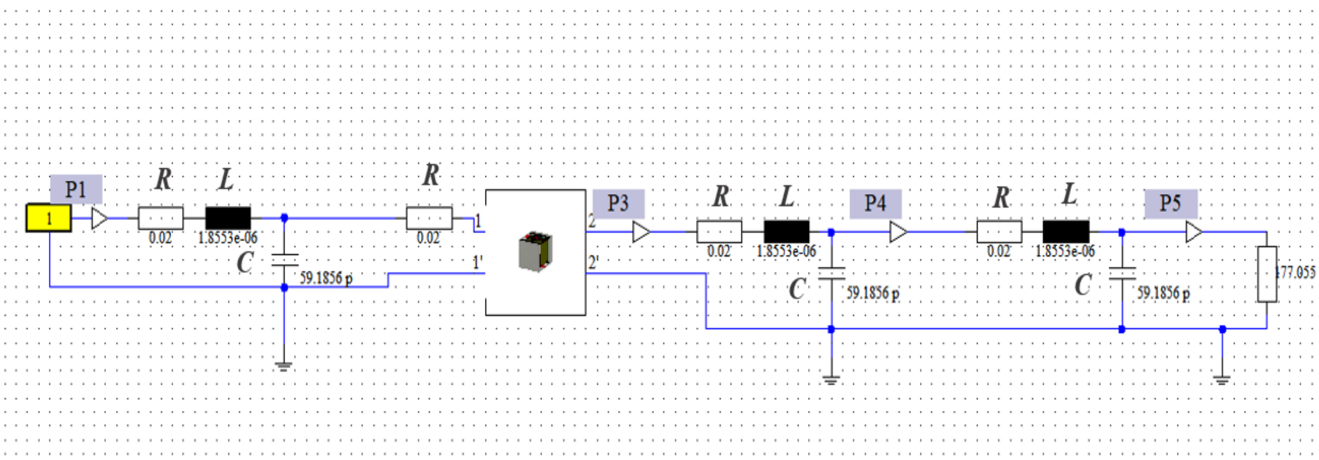

Figure 2. 3D model of PD connected to a 1D transmission line model in a CST schematic co-simulation.

4. Simulation results

The PD phenomenon inside the described 3D system has been analyzed with different electrical stresses, and a first analysis of the propagation of the electromagnetic disturbances generated by PD events has been done. The E field inside the system under study has been evaluated with the conduction current inside the inclusion. Moreover, the displacement current induced on the electrode surface and on the cavity surface during the PD event has been calculated together with the real charge on the cavity surface and the induced apparent charge on the electrode surface.

Figure 3 shows the variation in time domain of the conduction current in the cavity, and of the E field in the epoxy resin close the electrode and in the cavity center when a PD occurs (E field probes in Fig. 1). As the figure shows, 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. This is also shown in Fig. 4 where the E field along the z-axis, at z=0 in Fig. 1, before (dashed line) and during (solid line) PD event is reported. Before the PD, the E-field in the areas of the dielectric close to the cavity surface, nearer to the electrodes, is lower, as Fig. 4 shows, because the E field is perpendicular to the surface and the charges are concentrated there. At t_{PD}=3.1 μs, PD occurs and a conduction current starts in the cavity as shown in the figure 3, and the E field changes significantly. Due to the movement of the charge inside the cavity, the E field in the cavity is significantly reduced and in the same time the E field in the dielectric close to the cavity surfaces increases. The discharge activity produces charges which accumulate on the cavity surface. These produce an opposing E field that reduces the E field inside the cavity and increases the E field in the dielectric.

In fig. 5 the displacement current induced on the electrode and on the cavity by the PD event is reported. Their time integral gives the real charge on the cavity surface and the apparent charge induced on the electrode. As the figure shows, displacement current on the cavity surface is clearly higher the induced displacement current on the electrode.

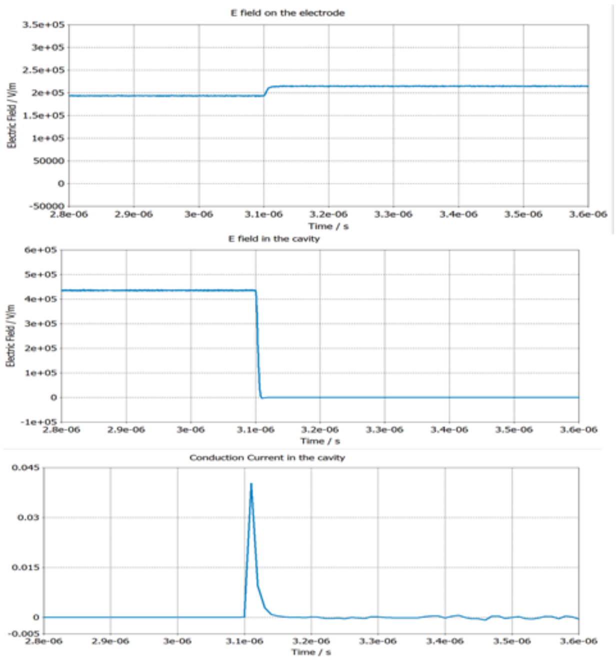

Figure 3. E field inside the inclusion and on the electrode and the conduction current in the cavity during PD with a 15kV, 50Hz supply voltage.

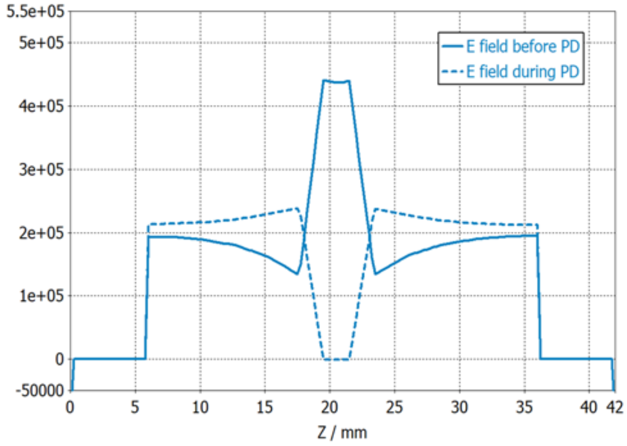

Figure 4. E field along z-axes before a PD event (dashed line) and during PD event (solid line) at 15kV.

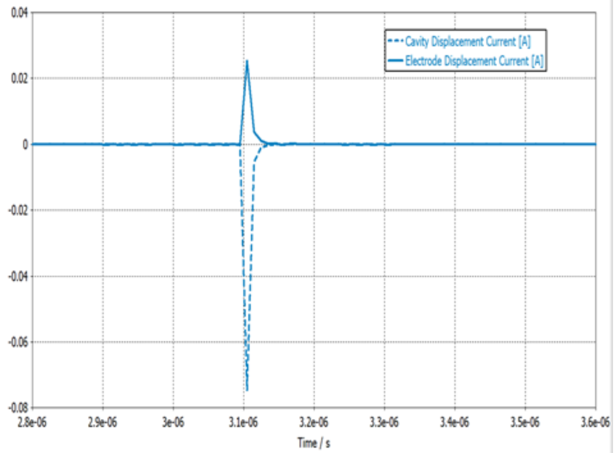

Figure 5. Displacement current on the cavity surface and displacement current induced on the electrode by the PD with a supply voltage of 15kV, 50Hz.

Fig. 6 and 7 show the magnitudes of the displacement currents induced on the electrode, together with the E field on the electrode and in the cavity center, when the electrical stress changes in amplitude and frequency. In particular, supply voltages with magnitudes of 15kV, 30kV, 50kV, 120kV at a frequency of 50Hz and supply voltages at frequencies of 50Hz, 150Hz, 5kHz and 50kHz with an amplitude of 15kV have been simulated.

In tables 1 and 2 the evaluated apparent and real charges are reported for the different working conditions. Figs 8 and 9 show the same results in the form of bar chart. The values obtained are comparable with the results evaluated in other studies [2, 16]

As the figures and table shows, as expected, an increase of the magnitudes in E field, displacement currents and charges is observed when increasing the supply voltage, while a slight increase is observed when the frequency increases.

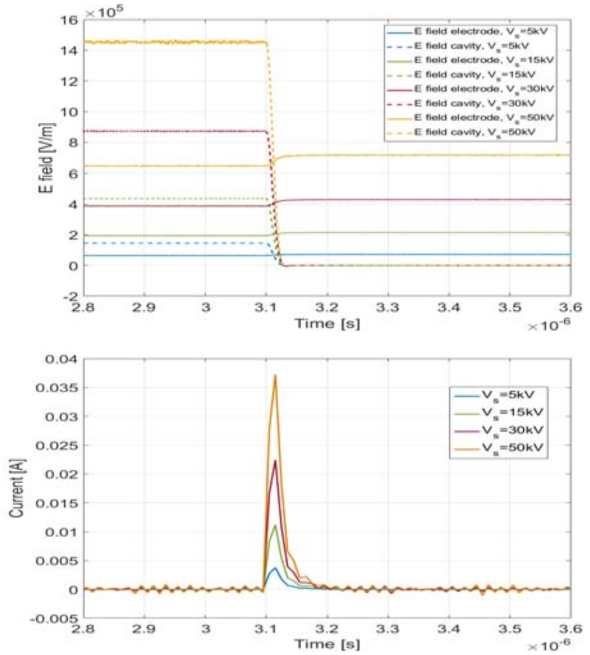

Figure 6. E field on electrode and cavity and Displacement Currents induced on the electrode surface with different amplitude of supply voltage at 50Hz.

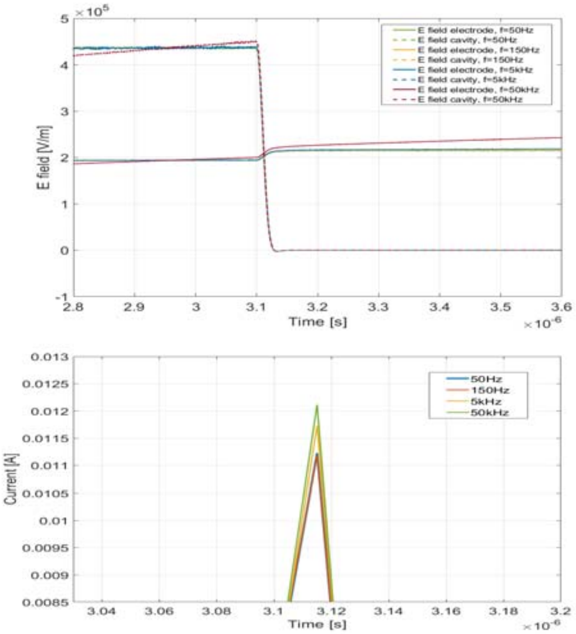

Figure 7. E field on electrode and cavity and Displacement Currents induced on the electrode surface with different frequency of supply voltage at 15kV.

To analyze the propagation of signals generated by PD events on power networks the model shown in Fig. 2 has been used where the 3D model of PD has been connected to a simplified 1D model of a power network. The resulting PD pulses at the output of the 3D model (P3 in Fig.2), at the output of the third node (P4 in Fig. 2) and at the matched load (P5 in Fig. 2) have been evaluated when the system is supplied with a voltage of 30kV at 50Hz.

The results are shown in Figures 10 and 11.

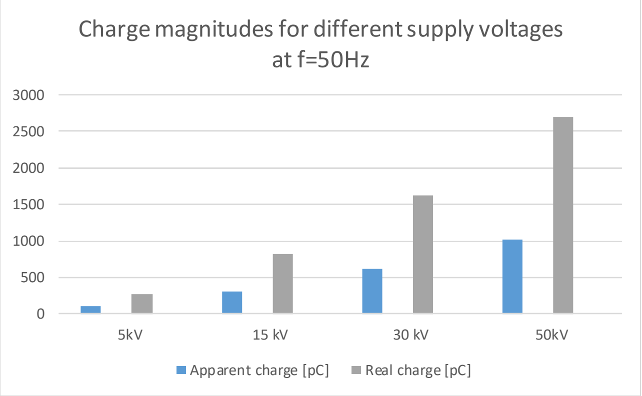

Figure 8. Real and apparent charge evaluated for different supply voltages at 50Hz.

Table 1 - Charge magnitudes for different supply voltages at f=50Hz

Amplitude	5kV	15 kV	30 kV	50kV
Apparent charge [pC]	102	305	611	1019
Real charge [pC]	271	812	1624	2708

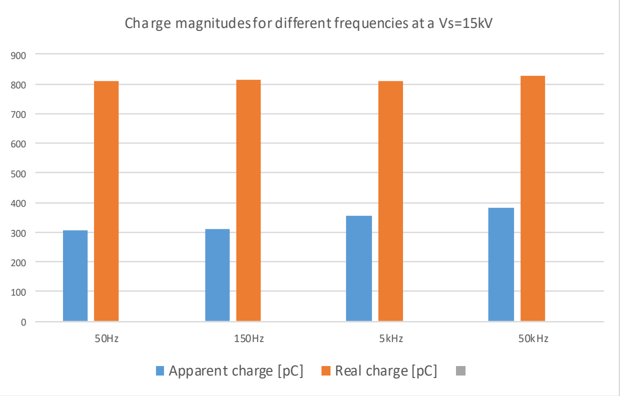

Figure 9. Real and apparent charge evaluated for different supply frequency at 15kV.

Table 2 - Charge magnitudes for different frequencies at a V_s=15kV

Frequency	50Hz	150Hz	5kHz	50kHz
Apparent charge [pC]	305	309	357	381
Real charge [pC]	812	815	811	828

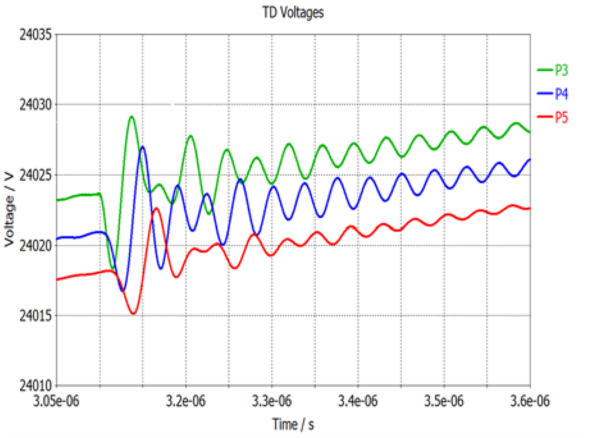

Figure 10. Partial Discharge voltage signal propagation on Power Transmission Line.

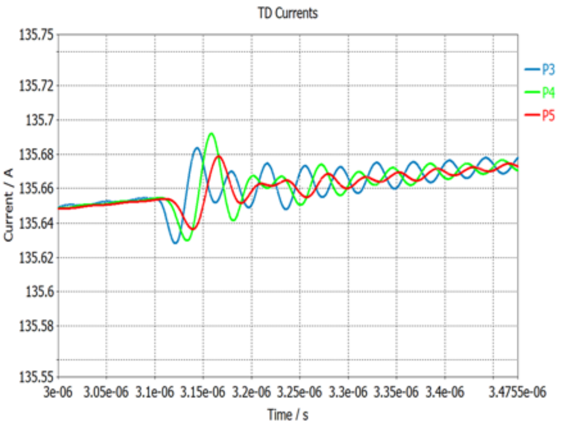

Figure 9. Partial Discharge current disturbance propagation on Power Transmission Line.

The obtained pulse shape matches that of [25] reasonably well, comparing by visual inspection. The attenuation of the PD signals and phase shift are apparent in both the figures. This demonstrates the effects expected for high frequencies on power lines, which are not designed to support them, i.e., that the signals will degrade. Thus when a PD signal reaches a point where it can be detected it some work is necessary to determine its original form and the point of origin. In order to achieve any accuracy in determining the shape and origin of the PD pulse from a signal detected at a distance, it will be necessary to improve the model of the power line and obtain a better model of the cable where the discharge occurs. For example, in the model the epoxy resin has been used, not the usual dielectric material in power cables and also the real geometry is not cuboid but this is only a first approximation of the defect. An improvement of the propagation model is objective of future works.

5. Conclusion

This paper deals with PD (partial discharge) events in the insulation of cables in high voltage power networks. A 3D model of PD inside a void in epoxy-resin insulation of power cables has been developed using CST Studio Suite® software. The PD behavior has been analyzed in relation to different electrical stresses of the cable. The obtained results are comparable with results of other published works developed in the same field. Then, a first analysis of the propagation on power networks of PD signals, generated by discharge events, has been undertaken by connecting the 3D PD model to a simplified 1D model of a power network. The realized simplified model of the electromagnetic disturbance source (PD) with its propagation path (power network), is able to reproduce the phenomena of attenuation and dispersion that characterize the propagation of HF signal on power networks and the obtained results are comparable with other published experimental results. An improvement of the proposed propagation model will be the subject of future works.

6. 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.

Thanks must also go to the ACCREDIT Action of the COST European Cooperation in Science & Technology, by the Horizon2020 Programme for the previous grant ECOST-STSM No. 43865.

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