Study on the Effect of Void Geometry and Location on Electric Field Distribution and Partial Discharges in HVDC Cables

Sundaramahalingam Subramaniam[1], *Janani Thiruvelmurugan*[2], and *Shanmathi Anbuselvan*[2]

[1]Assistant Professor (Selection Grade), Mepco Schlenk Engineering College, Sivakasi, India.
[2]Undergraduate Student, Mepco Schlenk Engineering College, Sivakasi, India.

Abstract. Nowadays HVDC transmission systems are preferred over HVAC systems because of their less power loss and high reliability. In the HVDC cable transmission system, there is a problem of Partial Discharges (PD) occurring due to cavities of the dielectrics in HVDC cables. The distribution of the electric field may change in the presence of partial discharge, which has an impact on how the electric system normally functions. Under DC conditions, partial discharge characteristics are influenced by the electric field distribution and electrical conductivity. Discharges tend to occur quickly when the cavity field reaches the inception level. Hence it is necessary to monitor the conditions of the HVDC cable for better transmission. A 2-D FEM-based model is developed for the simulation of PD due to various shapes of voids at various locations in the cable insulation using ANSYS. Also, PD modeling is the most important concern in identifying the influencing parameters and physical mechanisms of the PD phenomenon. In this work, the Three capacitances model is used to estimate the model parameters and simulate the partial discharges in MATLAB. The results from the simulation are compared with analytical models. It is observed that pulses of the partial discharges vary with the dimensions of the void, type of void materials, and location of the void.

Keywords: Partial discharge, Void, Electrical field distribution, High voltage, Finite Element Method, Insulation.

1 Introduction

High-voltage direct current (HVDC) cables are widely used in submarine and island power transmission, among other applications HVDC cables frequently use crosslinked polyethylene (XLPE) as an insulator. Space charges build up in the insulating layers of the cables due to high-voltage electric fields, which results in distorted electric fields and insulation breakdown [1]. All insulation inherently deteriorates with time, especially when subjected to high temperatures from heavy loads and even when it is not physically harmed. When energized or tested, there is a distributed flow of leakage current in this situation. Insulation made of crosslinked polyethylene (XLPE) might experience a problem known as "treeing"[2] It has been discovered that the ideal conditions for the emergence and growth of these trees within the polyethylene material are created by the presence of impurities that contain moisture, uneven surfaces, or protrusions in the insulation combined with electrical stress. The size of water trees will not cause discharges in the cable dielectric when exposed to over-voltages for the majority of cables, and as a result, they won't be accumulating damage[3-7]. When it comes to cables, it is known that water and early manufacturing processes might cause some failures. When a breakdown occurs in a cable that has been improperly water-treed, it is typical for subsequent failures to occur, rendering the cable useless. Consequently, it's important to keep an eye on cable insulation and lengthen the cable's lifespan [8-13].

2 Cable Model Geometry

A 500 kV HVDC cable [14] was simulated using a FEM model in ANSYS software as shown in Figure 1. There are three layers present in this cable namely conductor (inner layer), dielectric materials (middle layer), and lead sheath (outer layer). The conductor is made up of copper with a radius of 25mm. Then dielectric materials are made up of cross-linked polyethylene with a radius of 48mm. The lead sheath is made up of lead material and its radius is about 60mm.

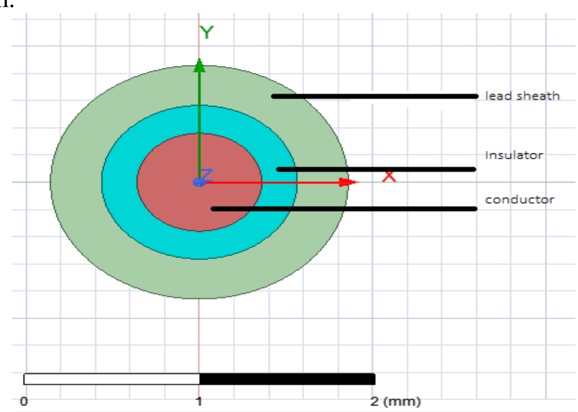

Fig. 1. 2D Cable Model

3 Simulation Results

3.1 Effect of void shapes on Electric field distribution

Below is an analysis of how different types of voids, such as square, elliptical, and circle, affect an HVDC cable[15-18].

Table 1. Electric Field Distribution On Different Shapes

Shape	**Material**	**Size (mm)**	**Distance from the conductor (mm)**	**Electric field (10^9) (V/m)**
Circle	Vacuum	0.02	0.1	2.88
Ellipse	Vacuum	0.02	0.1	2.72
Square	Vacuum	0.02	0.1	2.80
Circle	Vacuum	0.02	0.3	2.03
Ellipse	Vacuum	0.02	0.3	1.91
Square	Vacuum	0.02	0.3	1.96

According to the void forms, the electric field stress varies. In the HVDC cable, voids come in a variety of shapes. The voids might be round or elliptical in shape. In contrast to circular and square-shaped voids, the presence of elliptical voids at the insulation implies a highly concentrated electric field stress.

3.2 Effect of void materials on Electric field distribution

The effects of simulating an HVDC cable with voids filled with various substances, such as vacuum, air, and water, on the cable are analysed below.

Table 2. Electric Field Distribution On Different Materials

Shape	**Void material**	**Size of void (mm)**	**Distance from the conductor (mm)**	**Electric field (V/m) (10^9)**
Circle	Vacuum	0.05	0.2	2.5
Circle	Air	0.05	0.2	2.4
Circle	water	0.05	0.2	3.5

The void material affects the electric field stress. The void could be filled with vacuum, air, or water. Compared to water-filled voids, vacuum, air-filled voids have less of an impact on the insulation's stress response.

3.3 Effect of void size on Electric field distribution

Below is an analysis of how a simulated HVDC cable with voids of various sizes affects the cable.

Table 3. Electric Field Distribution On Different Sizes

Shape	Size (mm)	Material	Distance from the center (mm)	Electric field (10^9) (V/m)	Enhancement factor (10^7)
Square	3	Air	X=-10, Y=0	3.0859	3.69
Square	4	Air	X=10, Y=0	3.1574	3.77
Square	5	Air	X=0, Y=-10	3.2084	3.84

The electric field distribution varies with different void sizes. The electric field stress increases with the increase in size. The void size increases the electric field stress also increases.

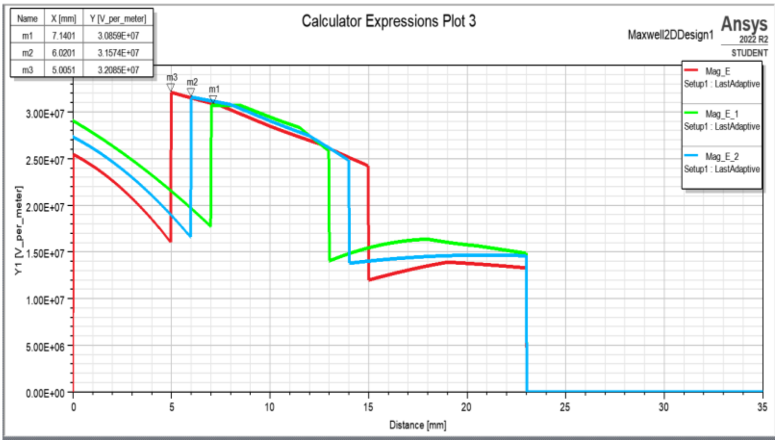

Fig. 2. Electric field distribution on different sizes

3.4 Effect of Protrusion on Electric field distribution

Protrusions, voids, and impurities on the cable's layers are the elements that determine how well Cross-linked polyethylene (XLPE) cables function. The extent of these flaws serves as a gauge for how well XLPE cables insulate. In this case, the protrusion flaw is taken into account. Extrinsic aging behavior can interact with protrusions at interfaces, cavities, and impurities in the materials, which is what mostly causes degradation. The primary indicators of early breakdown are semi-conductive shields that promote electrical treeing and localized increases in electrical stress brought on by conductor protrusions. Power outages will result from cable failures caused by insulation degradation. Finally, utilities must pay for more expensive maintenance and repairs.

The characterization of the electric field enhancement factor depends on parameters such as the outline and dimension of the protrusion yields[19-22]

$$\prod = E_{max}/E_0$$

where E_{max} is the maximum field strength located at the tip of the protrusion and E_0 is the average electric stress without protrusion.

Three primary layers work together to mold a standard Extra High Voltage DC subterranean power line into a specified shape. The layers arrangement in a cable is the Conductor, XLPE insulation layer, and outer lead sheath layer. The protrusion is made in the conductor layer with a radius of 0.02mm. Due to the presence of protrusion in the cable, there will be an uneven distribution of electric field stress.

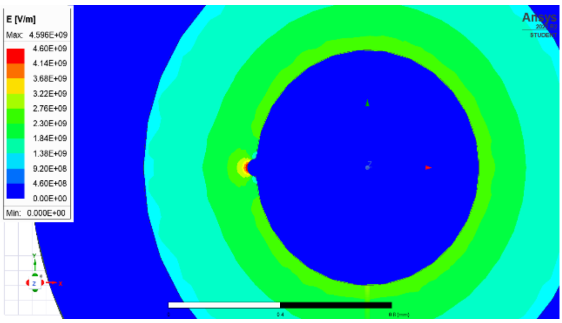

Fig. 3. Cable with Protrusion

The void near the protrusion shows a high electric field stress in the 5.4890*10^7 V/m. Whereas the void present away from the protrusion shows less electric field in the range of 3.2214*10^7 V/m. The enhancement factor value is high for void near protrusion. Figure 3 depicts the HVDC cable with a protrusion in the conductor surface. Table 4 gives the Electric field value for voids with protrusions.

Table 4. Effect of electric field distribution in protrusion

Shape	**Material**	**Size (mm)**	**Distance from the conductor (mm)**		**Electrical field (V/m) (10^7)**	**Enhancement factor**
Circle	Vacuum	2	X=-15	Y=0	5.4890	6.5
Circle	Vacuum	2	X=8	Y=0	3.2214	3.8

4 Numerical model of Partial Discharges using Three Capacitance Method

An underground cable's cable insulation may have flaws and faults that, when put under electrical and physical strains, hasten aging and degradation. These flaws include water bubbles, impurities in the insulating layer, and gaseous cavities that form during manufacture. These flaws prevent the cable from working properly and lead to partial discharge (PD). Cavities in the wire insulation are cause for the distortions of the electric field. We may estimate the geometric circumstances that would lead to the partial discharge using Paschen's law and the field within the cavity that was created by numerically solving the Laplace equation using the finite difference approach. The electric field in a gaseous cavity inside a high-voltage cable is predicted analytically in this paper. The advantage of the suggested technique, which is based on the model of capacity equivalent circuits, is that it takes less time to compute when using numerical methods. Two concentric cylindrical electrodes with inner and outer radii of R1 and R2, respectively, depict the coaxial cable. In Figure 4, the cavity model is displayed [23]. The inner electrode, which is submerged in voltage U, stands in for the conductive core that has been added to the inner semiconductor screen's thickness. The radius R1 plus the insulator's thickness equals the R2-ray electrode when it is grounded (U = 0). The insulating layer is made of polyethylene with an L-shaped permittivity. The insulator has a sphere-shaped air cavity with a permittivity of 0 and a radius Rc. The coaxial-cylinder configuration's center O is placed Xc away from the cavity's center. This cavity's solid angle when viewed from the centre O

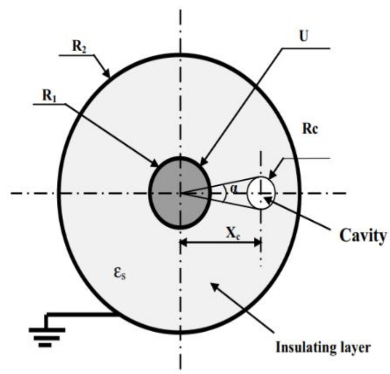

Fig. 4. Cavity Model

The electrical equivalent circuit of the cable with an enclosed cavity is shown in the figure3.2.
Ca is the capacitance of the insulation without the cavity
Cb1 is the capacitance of the insulation between the cavity and the high-voltage conductor
Cb2 is the capacitance of the cavity and outer grounded conductor
The capacitance of the void is Cc.
A single capacitor Cb is made up of two capacitors Cb1, and Cb2.

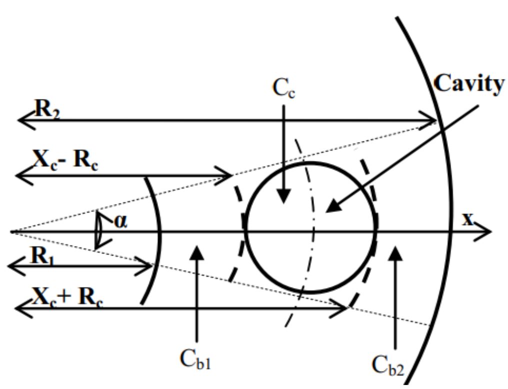

Fig 5. Enlarged Diagram of the Cavity

Equation (1) can be used to express the field inside the cavity

$$E_c = \frac{\varepsilon_s \ln\left(\frac{X_c+R_c}{X_c-R_c}\right)}{2R_c\left[\varepsilon_0\left[\ln\left(\frac{R_2}{R_1}\right)+\ln\left(\frac{X_c-R_c}{X_c+R_c}\right)\right]+\varepsilon_s\ln\left(\frac{X_c+R_c}{X_c-R_c}\right)\right]}U \qquad (1)$$

Equation (2) can be used to calculate the equivalent capacitance of the insulator with a cavity.

$$C_{\mathrm{eq}} = C_{\mathrm{a}} + \frac{C_{\mathrm{c}} \times C_{\mathrm{b}}}{C_{\mathrm{c}} + C_{\mathrm{b}}} \quad (2)$$

$$C_{\mathrm{b1}} = \frac{\varepsilon_{\mathrm{s}} \alpha 2 R_c}{\ln\left(\frac{X_{\mathrm{c}} - R_{\mathrm{c}}}{R_1}\right)}$$
$$C_{\mathrm{b2}} = \frac{\varepsilon_{\mathrm{s}} \alpha 2 R_{\mathrm{c}}}{\ln\left(\frac{R_2}{X_{\mathrm{c}} + R_{\mathrm{c}}}\right)} \quad (3)$$

$$C_{\mathrm{b}} = \frac{C_{\mathrm{b1}} C_{\mathrm{b2}}}{C_{\mathrm{b1}} + C_{\mathrm{b2}}} \quad (4)$$

$$C_{\mathrm{a}} = \frac{\varepsilon_{\mathrm{s}} (2\pi l - \alpha 2 R_c)}{\ln\left(\frac{R_2}{R_1}\right)} \quad (5)$$

The capacityance of void is calculated by equ (6)

$$C_{\mathrm{c}} = \frac{\varepsilon_0 \alpha 2 R_{\mathrm{c}}}{\ln\left(\frac{X_{\mathrm{c}} + R_{\mathrm{c}}}{X_{\mathrm{c}} - R_{\mathrm{c}}}\right)} \quad (6)$$

5 Results and Discussion

5.1 Electric Field Distribution

The variation in the cavity's internal field depends on the Xc position for radii Rc=2 mm, 3 mm, and 4 mm. The electric field is strongest on the conductor's side and is weaker as it gets closer to the ground.

The electric field has an analytical value in the range of $8.33*10^7$ V/m. The electric field stress simulation value is $3.52*10^7$ V/m. The fluctuation of the cavity's internal field concerning its radius at various points, where Xc=7mm, 9mm, and 11mm. Figure 6 illustrates how, for various radii, the field in the cavity varies depending on the point Xc. The fluctuation of the field in the cavity for various positions and radii is shown in Figure 7.

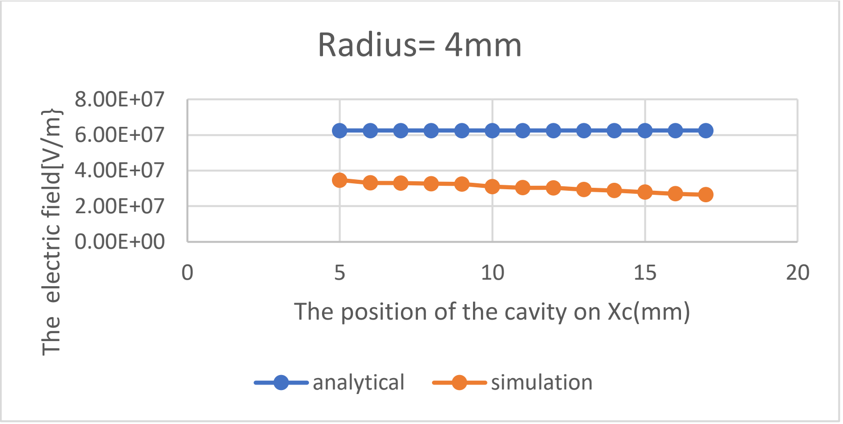

Fig. 6. Field Variation in the Cavity for Different Radii According to the Position Xc

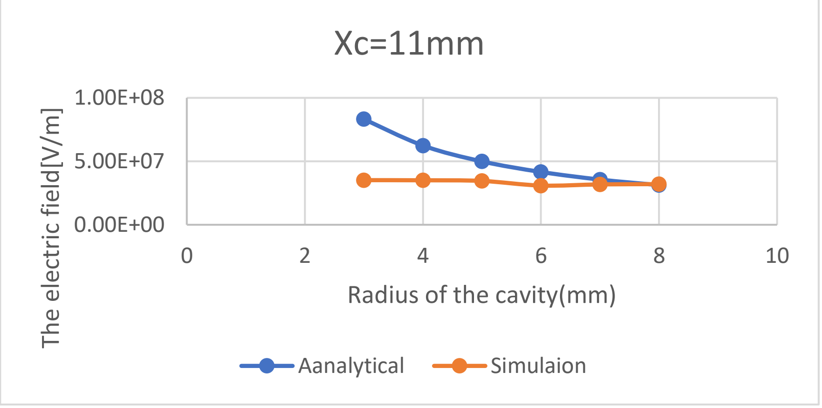

Fig. 7. Field Variation in the Cavity for Different Positions according to the radius

5.2 ELECTRICAL CAPACITANCE

The variation in equivalent capacitance for Rc=0.5, 1mm, 1.5, 2mm, and 2.5mm as a function of cavity position (Xc) [24]. The capacitance is greatest on the conductor's side and is smaller as it gets closer to the ground.

The analytical value of the electric field is in the range of 4.26*10^-10 F. The Simulation value of the electric field stress is 1.90*10^-10 V/m. The variation of the field inside the cavity according to the radius for different positions Xc=5mm, 7 mm, 9 mm. Figure 8 shows the Variation of the capacitance in the cavity according to the position Xc, for different radii, and Fig 9 shows the variation of the field in the cavity according to the radius, for different positions.

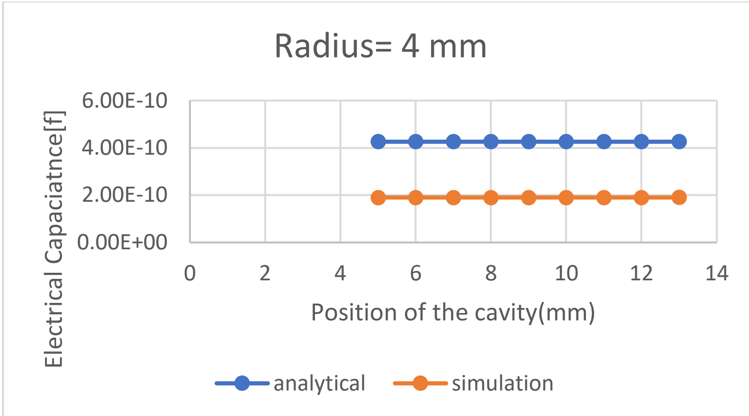

Fig. 8. Variation of the Capacitance in the Cavity According to the Position Xc, for Different Radii

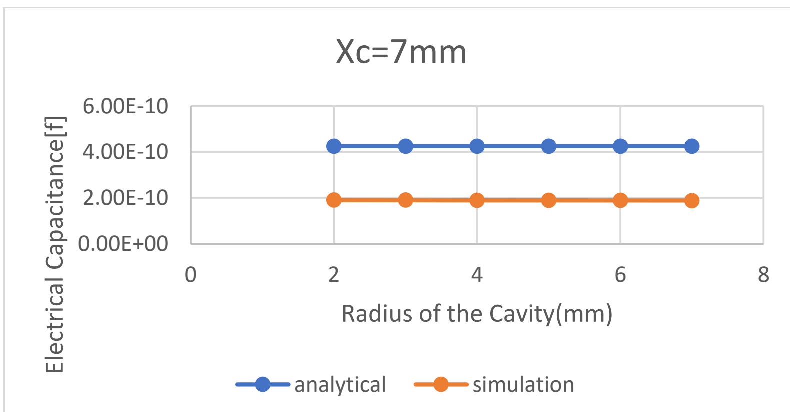

Fig. 9. Variation of the Field in the Cavity according to the Radius, for Different Positions

A high-voltage cable's degeneration is typically primarily caused by the existence of flaws in it. An essential stage of the partial discharges for a high voltage is the appearance of a gas cavity. voltage underground cable due to the dominant electric field. It comes as no surprise that several studies on the behavior of high-voltage cables in the presence of gaseous cavities have been conducted. The importance of this electric field is one of the main concerns of researchers. It enables estimation of the electric partial discharge's initiation voltage that takes place inside the cavity. The physical (Laplace) equation is often solved numerically to determine this electric field. This study provided an analytical model of PD, largely based on the capacitive circuit model and Paschen criterion, to forecast the initiation of the electric field within the void in the insulating cable. The developed model is a very appealing solution because it shortens the computation time while still accounting for the important electro-geometrical factors that affect the threshold electric field in the cavity.

5.3 PARTIAL DISCHARGE MEASUREMENT

Three capacitance-equivalent circuits of partial discharge are developed in MATLAB as shown in Figure 10. It consists of an AC source for energizing the circuit, filter unit (Z), high voltage measuring capacitor (C_m=1000pF), coupling capacitor (C_k = 1000uF), void model of solid insulation which is XLPE cable as a test object, detector circuit for measurement of partial discharge (R=50 ohm, L= 0.6 mH and C = 0.45 uF), MI as measuring instrument, Ca represent as the capacitance of healthy part leaving Cc and Cb, Cb represents as capacitance of the healthy part connected in series with the void and Cc represent as capacitance of the void in the test object [25]. These capacitance values are estimated using an analytical model with different dimensions of the void. Partial discharge measurement is performed by developing the circuit diagram in MATLAB software by supplying the circuit with high high-voltage AC source as shown in Figure 11. The result of partial discharge can be obtained after an AC source of high voltage as shown in Figure 12, Vs is applied across the test object. The voltage across the dielectric, Va is increased thereby and causes the voltage across the cavity, Vc also increases when the void gets charged and breakdown has started.

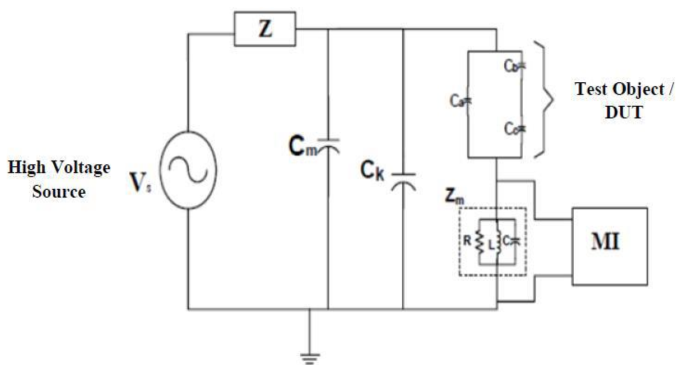

Fig. 10. Schematic Diagram of partial discharge measurement

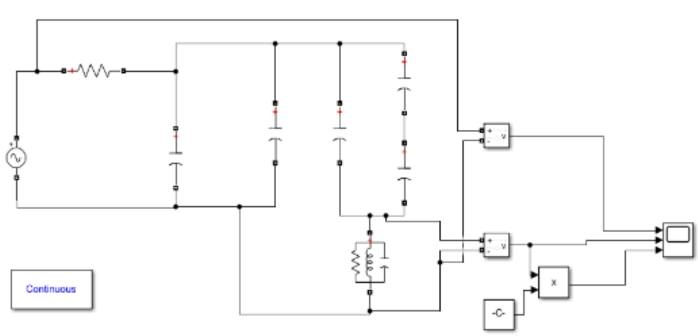

Fig. 11. Simulation of Partial discharges using Three capacitance model

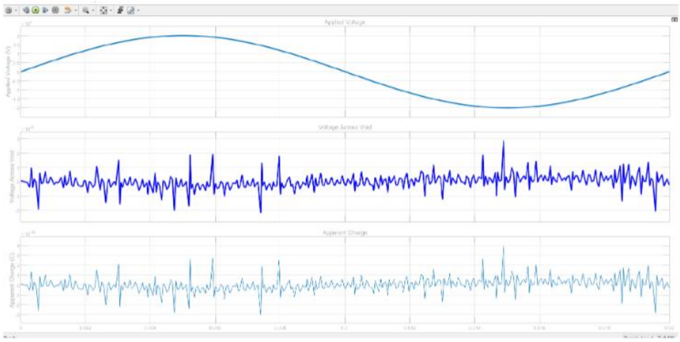

Fig. 12. Partial discharge pulse

6. CONCLUSION

The features of the HVDC transmission cable's electric field are examined, and the interplay between those qualities and the surrounding cables produces effects that are essentially estimated. In the last stage of the simulation, ANSYS is used to model various scenarios that could occur in an HVDC transmission cable's electric field under actual operating conditions. ANSYS ELECTRONICS DESKTOP is responsible for performing the simulation work. A high-voltage cable's degeneration is typically primarily caused by the existence of voids in it. Due to the strong electric field present, the formation of a gas cavity plays a significant role in partial discharges for high-voltage subterranean cables. In comparison to the inner semiconductor compound, protrusions on the conductor's surface have a greater stress impact on the insulation. The electric field is strongest on the conductor's side and is weaker as it gets closer to the ground. The field inside the cavity determined using the finite element technique software has the same order as the one obtained using the analytically proven relation. In contrast to circular and square-shaped voids, the presence of an elliptical void at the insulation denotes a highly concentrated electric field stress. In terms of the materials employed, hoover and air-filled voids have less of an impact on the insulation's stress levels than water-filled voids. As the void size grows, so does the electric field stress. The geometry of the void in the protrusion has a larger enhancement factor and electric field stress, which suggests that the void is detrimental to the performance of the cable. Near the conductor, the electric field stress and capacitance of the vacuum are at their highest levels, and they begin to decline as they go closer to the ground.

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