Propagation characters of PD UHF signal in a prefabricated joint of XLPE cable

Luliang Wang¹, Xu Yang³,³, Lin Cheng², Fangda Fu¹, Yi Jiang² and Zijun Pan³,⁴

¹ Electric Power Research Institute of Hainan Power Grid Limited Liability Company, Haikou 570311, China
² Wuhan Nari Limited Liability Company of State Grid Electric Power Research Institute, Wuhan 430074, China
³ School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
⁴ E-mail: panzijunw@163.com

Abstract. Investigating the propagation characters of UHF partial discharge (PD) signals in cable joint is helpful to the application of UHF method in XLPE PD monitoring. In this paper, a propagation model about UHF signal in a prefabricated joint is constructed. Based on it, it effects of some factors, i.e. longitudinal distance of detection location, lateral location of detection, detecting angle, pulse width, pulse amplitude, the size of metal shield and the thickness of semiconductive layer, on the PD signal propagation are studied. It is found that the signal amplitude decays faster in the joint than that in the body, and the signal intensity is much stronger inside the metal shield than that outside. The maximum amplitude of electromagnetic wave radiated by the PD source appears in the radial direction along the radius of the cross-section. The short duration of discharge pulse contributes to the appearance of high-order modes, while the response signal is proportional to the PD source. The metal shield and semiconductive layer increase the signal attenuation. These results provide insight into some design parameters of UHF antenna and its installation location.

1. Introduction

Crosslinked polyethylene (XLPE) cables have been widely used because of their excellent electrical properties, good thermal and mechanical properties and convenient installation. However, in the manufacturing, installation and operation processes, it is inevitable that some insulation defects will appear, which can bring about partial discharges (PDs). A survey has proved that the majority of defects are observed in cable joints which play a role to connect two sections of cables [1]. On one hand, PDs induced by insulation defects will deteriorate the insulation performance of cables and even cause the insulation fault. On the other hand, there is a close relationship between PD parameters and insulation character, so the PD measurement is frequently used to detect and identify insulation defects [2].

At present, several methods are proposed to monitor PD signals in XLPE cables, such as high frequency current transducer (HFCT) [3], difference method [4], directional coupling method [5] and so on. But these methods cannot fully meet the requirement of PD monitoring for cable joints due to their complex configuration and electromagnetic interference in the fields. As we all known, ultra-high frequency (UHF) signals could be detected when PDs take place. Since this signal frequency band,
from 300 MHz to 3 GHz, avoids the on-site interference, it is frequently employed to monitor PDs of power equipment [6-9]. However, few researchers try their efforts to apply this method to XLPE cable joint.

In order to ensure some parameters of UHF antenna and its installation location, the propagation characters of UHF PD signals in cable joint should be investigated at first. In this paper, we construct a propagation model about UHF signal in a prefabricated joint which is widely used in the high voltage power cables. With help of the model, effects of installation location, PD source and joint configuration on the propagation characters are studied.

2. Propagation model

Figure 1 shows the configuration of 110 kV cable joint, in which 1 outer semi-conductive layer, 2 cable main insulation, 3 main rubber insulation, 4 PVC, 5 metal shield, 6 stress cone, 7 conductor and 8 inner semi-conductive layer are included. The PD is induced by a metallic needle with length of 2 mm, which is placed at the interface between composite insulation of cable joint and main insulation of cable and indicated by the symbol D in the figure. The detection points of electromagnetic signal are placed at J1-J3 with spacing of 140 mm in cable joint, and at C1-C6 with spacing of 600 mm in cable body. In addition, the distance between J3 and C1 is 455 mm.

Dielectric properties and size of each component are listed as Table 1. In the simulation model, some assumptions are made: the parameters of shielding cover and pressure nozzle are the same as those of wire core, the metal shielding material parameters of lead sheet and cable body are the same, the water-blocking tape is a non-ferromagnetic material and is simplified as an air layer; the material parameters of various self-adhesive insulating tapes and PVC tapes are simplified as the same as that of main rubber insulating parts.

| Components               | Relative permittivity | Conductivity(s/m) | Outer diameter(mm) | Material            |
|--------------------------|-----------------------|-------------------|--------------------|---------------------|
| Wire core                | 1                     | 5.8×10⁷           | 26.7               | Copper              |
| Conductor shielding      | 30                    | 2                 | 29                 | Semiconductive      |
| Main insulation          | 2.3                   | 0                 | 63                 | XLPE                |
| Insulation shielding     | 30                    | 2                 | 65                 | Semiconductive      |
| PVC Conveyor Belts       | 2.3                   | 0                 | 64                 | PVC                 |
| Rubber main insulator    | 3.2                   | 0                 | 89                 | Silicon rubber      |
| Stress cone              | 30                    | 2                 | 87                 | Semiconductive      |
| Metal shield             | 1                     | 5.8×10⁷           | 92                 | Lead, copper        |

Maxwell equations are used to describe the signal propagation, which are solved by the Finite-Difference Time-Domain (FDTD) method. According to the characteristics of transient fast discharge signal in XLPE cable joints, the PD source is simulated by Gauss pulse discrete current source in the form of pulse function, as follows:
\[ I(t) = I_0 \exp\left(-\frac{4\pi(t-t_0)^2}{\tau^2}\right) \]  

(1)

where \( I_0 \) is the peak value, equal to 10 mA, \( t_0=2 \) ns is the time when the peak value appears, and \( \tau \) is the pulse width, with the value of 1 ns.

3. Simulation analysis

When PD signal propagates in cables, its energy intensity and distribution are related to many factors, such as the structure size of cable body and joint, material parameters, relative position between transmitting point and receiving point, angle, amplitude and width of input current pulse, and so on. In the simulation, it is necessary to analyze the influence of various factors on the signal of receiving point, so as to find out the relationship and rules between them to guide the detection, location and recognition of PD.

According to the theory of transient electromagnetic field [10], when a load of 50 voltage probe is set at the detection point, the energy of the received signal can be calculated by the following formula if its length is far less than the minimum wavelength in the whole spectrum.

\[ e(t) = \frac{1}{Z_L} \int v(t)^2 dt \]  

(2)

where \( Z_L=50 \ \Omega \), \( v(t) \) is voltage signals received over a period of time.

\[ v(t) = l \sin \theta \cdot E(t) \]  

(3)

where \( E(t) \) is the electric field, \( \theta \) is the angle between incoming wave and antenna, \( l=1 \) m, and \( \theta=90^\circ \).

3.1. Longitudinal distance of detection location

The detection points are located at J_1\sim J_3 in the joint and C_1\sim C_6 in the body. The transverse angle between each detection point and the PD source is equal to 90°. As shown in Figure 2, the amplitude attenuates with distance as a power function, and the attenuation rate in the body is lower than that in the joint. This is owing to facts that the high frequency energy of PD signal is seriously attenuated when it propagates through the joint to the main body, while the low frequency energy attenuation is small. The average attenuation of signal amplitude in joint and body is about - 8.3 dB/m and - 3.4 dB/m, respectively. When the propagation distance is within 3 m, the signal is less than 500 MHz.

![Figure 2. Change of electric field with distance.](image-url)
3.2. Lateral location of detection
The transverse angle $\phi$ between the detection point J1 and the PD source is set to be 0, and the detection point can be located inside or outside metal shield. Figure 3 shows three components of electric field, from which it is found that the electric field inside the shield is 2-3 orders of magnitude greater than that outside. Therefore, the sensor should be installed within the metal shield of cable joint or body.

![Electric Field Components](image)

(a) inside metal shield  (b) outside metal shield

**Figure 3.** Comparison of electric field inside and outside metal shield.

3.3. Detecting angle
The transverse angle $\phi$ between J1 and PD source is set to be 0°, 45°, 90°, 135° and 180°. In these cases, the electric field is obtained as Table 2. It is found that when the receiving point and the discharge source are at different angles, the average amplitudes of the received signals from all directions are different, but they are basically in the same order of magnitude. For each detection point in the joint, the maximum amplitude of electromagnetic wave radiated by the PD excitation source is in the radial direction along the radius of the cross-section, which is also the direction of the strongest coupling energy of the electric field, i.e. the maximum is in y-direction with 0° and 180°, while the maximum is in z-direction with 45°, 90° and 135°.

**Table 2.** Change of electric field amplitude with angle.

| Angle | $E_x$ (mV/m) | $E_y$ (mV/m) | $E_z$ (mV/m) | Average |
|-------|--------------|--------------|--------------|---------|
| 0°    | 0.045        | 4.1          | 0.08         | 1.41    |
| 45°   | 0.009        | 2.2          | 3.4          | 1.87    |
| 90°   | 0.041        | 0.4          | 4            | 1.48    |
| 135°  | 0.06         | 1.9          | 2.9          | 1.62    |
| 180°  | 0.069        | 4.3          | 0.19         | 1.52    |
| Average | 0.0448      | 2.58         | 2.11         | 1.65    |
3.4. Pulse width
The pulse width is set to be 0.4 ns, 0.8 ns and 1.2 ns, and the amplitude keeps 30 mA. It is found from Figure 4 that when the pulse width is the smallest, the signal amplitude is the largest, which is about one order of magnitude higher than the signal amplitude caused by the other two pulses. Obviously, the pulse width of PD plays an important role in the signal size. The shorter the duration of discharge pulse, the more uneven the spatial field distribution and the more high-order modes appear.

3.5. Pulse amplitude
The pulse amplitude is set to be 30 mA, 50 mA and 100 mA, and the width keeps 0.8 ns. In these cases, the electric field is obtained, as Figure 5. When the original pulse width is fixed, the larger the amplitude of PD pulse is, the stronger the ability of exciting electromagnetic wave is. The coupling energy is approximately proportional to the square of the amplitude of simulation pulse.

3.6. The size of metal shield
The outer diameter of metal shield is set to be 70 mm and 90 mm, respectively. The electric field is obtained at the points J2 and C2, as Figure 6. It is found that the influence of metal sheath on the signal detected at C2 is greater than that at J2. The wave head becomes flat and the oscillation frequency and amplitude decrease. Therefore, XLPE cable with lower voltage level is more suitable for detecting PD signal with high frequency because of its smaller size of metal jacket, but it also increases the difficulty of sensor size design.

3.7. The thickness of semiconductive layer
The thickness of semiconductive layer is set to be 2 mm and 5 mm, respectively. The electric field is obtained at the points J2 and C2, as Figure 7. The increase of the thickness of the semi-conductive layer has a significant impact on the test results, and the distortion of the signal received at C2 is more serious than that at J2 with the increase of the thickness of the semi-conductive layer, and the distortion is more severe. Semi-conductive layer has larger conductivity and dielectric constant than main insulation, and it is a kind of non-linear frequency-varying lossy medium. Different frequency PD
electromagnetic waves produce different catadioptric reflections on the interface, resulting in sharp energy attenuation and waveform distortion. Semi-conductive layer increases the difficulty of high frequency detection of PD signals in XLPE cables. Therefore, sensors should be installed near joints to reduce the influence of semi-conductive layer and improve detection sensitivity.

![Figure 6](image6.png)

**Figure 6.** Change of electric field with pulse amplitude.

![Figure 7](image7.png)

**Figure 7.** Change of electric field with the thickness of semiconductive layer.

4. Conclusions
In this paper, the influences of some factors, i.e. longitudinal distance of detection location, lateral location of detection, detecting angle, pulse width, pulse amplitude, the size of metal shield and the thickness of semiconductive layer, on the PD signal propagation are investigated. There is a higher decay rate of signal amplitude in the joint than that in the body, and the signal intensity is much stronger inside the metal shield than that outside. In addition, the maximum amplitude of electromagnetic wave radiated by the PD excitation source is in the radial direction along the radius of the cross-section. The short duration of discharge pulse is helpful to the appearance of high-order modes, while the response signal is proportional to the PD source. At last, the metal shield and semiconductive layer increase the signal attenuation.

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