A Study on the Propagation Characteristics of Partial Discharge in Cable Joints Based on the FDTD Method

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ABSTRACT Partial discharge (PD) is the main cause of cable insulation deterioration. It is of great theoretical significance and practical value to carry out PD research on high voltage (HV) cable joints for fault detection and operational status evaluation. In this paper, a three-dimensional finite-difference time-domain (FDTD) simulation model of cable joint is built. According to typical fault types of PD in 110kV XLPE cable, four types of insulation defect models, including electrical tree discharge, surface sliding discharge, air gap discharge, and floating discharge, are designed and manufactured. Based on the three-dimensional simulation model of cable joint, the propagation characteristics of PD signals caused by the aforementioned insulation defects are analyzed, the effects of different types of insulation defects and fault locations on the propagation characteristics are investigated. A PD experimental platform based on a cross-bonded three-phase 110 kV cross-linked polyethylene (XLPE) cable system is built for verifying the feasibility of the three-dimensional simulation model. Results show that the model can reasonably explain propagation characteristics of PD signals in cable joints, including polarity, peak values, attenuation characteristics and symmetry, which provided the theoretical basis for judging the fault locations and types of PD caused by insulation defects in cable joints.

INDEX TERMS Cable joint, partial discharge (PD), finite-difference time-domain (FDTD), cross-bonded cable system, insulation defect model, on-line monitoring.

I. INTRODUCTION

With the rapid development of power systems, high-voltage (HV) cable has gradually become an indispensable part of urban power grid construction and long-distance power transmission [1]. Cable joints are an important part of such systems, but partial discharge (PD) faults readily occur for a variety of reasons, such as: interface defects between joint insulation and cable insulation, joint insulation aging, et al [2]. PD, over a long time, will reduce the insulation performance of a cable and eventually lead to insulation failure. Therefore, PD, as an effective index to evaluate the insulation status of power equipment, has been widely used in on-line monitoring field of HV cable [3].

In practice, XLPE cables at a voltage of 110 kV are usually single-core structures, because of the induced electromotive force (EMF) on the metal shield of the cable, reliable grounding of the HV XLPE cables is important. Especially when the cable is longer than 1000 m, a cross-bonded cable system is preferred: a three-phase cable joint structure adopts three-phase cross-bonded lines. Cross-bonded cable systems are used to improve the performance of cable systems by reducing sheath currents, thus improving cable ampacity, and by reducing sheath voltages for preventing breakdown of cable insulation; however, the coupling effect arising when a PD pulse propagates in cross-bonded HV cable system, makes PD signal detection and location more complex [4]. Therefore, it is worth establishing a simulation model of cable joints and studying propagation characteristics of PD signals for accurate PD detection in cross-bonded HV cable systems.

The current research on the propagation characteristics of PD signals in cable joints are mostly based on experimental detection methods [5]–[8]. It is difficult to reflect propagation characteristics of PD signals in cable joints because of...
operational complexity and interference from external signals. Compared with simple experimental detection methods, a combination of simulation and experiment can more accurately reflect the propagation characteristics of PD signals in HV cable joints.

In recent years, some scholars have studied the propagation of PD signals in XLPE cable by simulation and experiment, and built transmission line models for XLPE cable [9]–[11], but little research has been done on propagation characteristics of PD signals in cable joints. Most simulation models constructed for cables have been limited to two-dimensions, which cannot replicate the physical model of a cable joint. Therefore, it is necessary to establish a three-dimensional simulation model of a cable joint to investigate the propagation characteristics of PD signals, which is of great value to the further study of PD characteristics caused by insulation defects inside cable joints and fault diagnosis.

FDTD, as an important numerical method for solving the Maxwell equations, is used to study electromagnetic wave characteristics. Most models constructed by some research institutes based on FDTD method are aimed at cables [12]–[15], but there are few references pertaining to cable joint simulation models. Especially there are few researches into the influence of different types of insulation defects and fault location on the propagation characteristics of PD signals for cable joints, hence our desire to construct a three-dimensional simulation model of a cable joint.

Here, four types of insulation defect models are designed and manufactured: electrical tree discharge, surface sliding discharge, air gap discharge, and floating discharge. A three-dimensional FDTD simulation model of a cable joint is built, and fault locations of PD caused by the aforementioned insulation defects are simulated in the model. The propagation characteristics of PD signals caused by the aforementioned insulation defects are analyzed, the effects of different types of insulation defects and fault locations on the propagation characteristics of PD signals are investigated. A PD experimental platform based on cross-bonded three-phase XLPE cable system is built to verify the feasibility of three-dimensional simulation model, which provides theoretical support for subsequent judgment of fault types caused by PD and fault location.

II. EXPERIMENTAL PLATFORM CONSTRUCTION
A. CROSS-BONDED XLPE CABLE SYSTEM
To cooperate with the simulation of PD signals in cable joints, a complete experimental platform of 110 kV cross-bonded XLPE cable system is built in the laboratory, which is composed of actual engineering cables, terminals, and cable joints. Table 1 lists the model number of the 110 kV cross-bonded XLPE cable system and Fig. 1 shows the experimental platform utilizing the 110 kV cross-bonded XLPE cable system.

The structure of the cross-bonded cable system is shown in Fig. 2: the cable was divided into different sections of equal length and cable joints are installed between every second section (Phase A to Phase C, Phase B to Phase A, and Phase C to Phase B). The cross-bonded method can reduce the induced electromotive voltage and circulating current on the metal sheath and improve the transmission capacity of power cables.

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Based on the aforementioned experimental platform, taking cable joints of the system as research objects, different types of insulation defect models are established inside cable joints, and PD detection is carried out in the fault phase cable joints of the cross-bonded cable system. The experimental results are compared with the simulation results for verifying the effectiveness and correctness of the proposed simulation model.

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**TABLE 1. Model of 110 kV Cross-bonded XLPE cable system.**

| Equipment          | Model            |
|--------------------|------------------|
| XLPE cable         | XLPE-64/110 kV-1*400 |
| Cable joint        | YJJ(T)-64/110 kV  |
| Terminal “1”       | YJZWC3-64/110 kV  |
| Terminal “2”       | YJZWC4-64/110 kV  |
| Terminal “3”       | YJZW14-64/110 kV  |
**B. DESIGN PRINCIPLE OF CABLE INSULATION DEFECT MODELS**

The pre-set design of insulation defect type and fault location inside cable joints are based on the actual situation of cable insulation faults encountered in on-site operation. Common insulation defects and their causes during installation, construction, maintenance and operation of HV cables, are analyzed using four types of insulation defect models.

1. **Electrical tree discharge**: it is common that there are spines in a cable core or inner semiconducting layer or local tip protrusion discharge at the connecting pipe of a cable joint.

2. **Surface sliding discharge**: it is common that the stress cone protrudes from the semiconducting layer of cable, the installation position of the stress cone is wrong and the composite dielectric of cable joint is affected by damp.

3. **Air gap discharge**: it is common that air gap formed by gas by-products inside insulation arise from residual chemicals embedded during extrusion, there are cracks or longitudinal dents on the surface of the insulation, and there is a misplacement because semiconducting layer fractures impair smooth transition between semiconducting layer and insulation layer.

4. **Floating discharge**: it is common that the quality of manufacture of cable joints and the cable-laying process violate installation rules, thus making it easier to leave foreign matter between cable insulation and accessory insulation, such as metal or conducting particles, resulting in the formation of suspended electrodes and insulation deterioration.

**C. CABLE INSULATION DEFECT PHYSICAL MODELS**

Cables used in the insulation defect model of cable joints are designed with a conductor diameter of 35 mm and an insulation thickness of 70 mm in this work. The manufacturing process of each insulation defect model is as follows:

- **Electrical tree discharge model**: the thickness of cable insulation after fine burnishing is $\Phi 69$ mm, and a stress cone with an inner diameter of $\Phi 65$ mm and inner semiconducting length of 70 mm is used. The stress cone is located 40 mm behind the cable semiconducting port. This fits between the thickness of the cable insulation and the inner diameter of the stress cone (a 4 mm difference therein) ensuring sufficient interface grip-force. A pin (4 mm long) is inserted into the cable insulation 20 mm ahead of the semi-conducting port. The electrical tree discharge model is shown in Fig. 3(a).

- **Surface sliding discharge model**: the thickness of cable insulation after fine burnishing is $\Phi 66$ mm, and a stress cone, with its inner diameter of $\Phi 65$ mm and inner semiconducting length of 70 mm is used. In the semi-conductive port of the cable, the 40 mm long tip is coated with a semiconducting paint such that the tip of this coating is visible for some 5 mm in front of the cable semiconducting port. Installation rules governing the stress cone stipulate that the range of size of interference fits between the thickness of cable insulation and the inner diameter of stress cone is 2 mm to 7 mm in order to ensure that the stress cone has sufficient grip-force to prevent PD. Most surface sliding discharge faults occur because stress cones do not generate sufficient grip-force in the process of either their production or installation. Therefore, the size of interference fits between the thickness of cable insulation and the inner diameter of stress cone is 1 mm for simulating surface sliding discharge. The surface sliding discharge model is shown in Fig. 3(b).

- **Air gap discharge model**: the thickness of cable insulation after fine burnishing is $\Phi 69$ mm, and a stress cone with an inner diameter of $\Phi 65$ mm and inner semiconducting length of 70 mm is used. The size of interference fits between the thickness of cable insulation and the inner diameter of stress cone is 4 mm which meets the range standard of 2 mm to 7 mm. A $10 \times 2 \times 2$ (length, width, height, unit mm) pit is formed some 5 mm in front of the cable semiconducting
port. The stress cone is located 40 mm behind the cable semiconducting port. The small pit is buried under the semiconducting layer, which is located in a position subject to a stronger electrical field. The air gap discharge model is shown in Fig. 3(c).

Floating discharge model: the thickness of cable insulation after fine burnishing is Φ 66 mm, and a stress cone with an inner diameter of Φ 65 mm and inner semiconducting length of 70 mm is used. In the semi-conductive port of the cable, an area of 10 × 2 (length, width, unit mm) is coated with semiconducting paint such that this is located 40 mm in front of the cable semiconducting port. The floating discharge model is shown in Fig. 3(d).

The aforementioned four types of insulation defect models can produce PD caused by the experimental platform. With increasing test voltage, the discharge magnitude increases gradually, which can simulate actual PD events in cable joints.

III. GEOMETRIC MODEL OF CABLE JOINT

An HV cable joint has a complex geometric shape. The steps taken when building this geometric model of a cable joint are described below.

A. SUBDIVISION OF CABLE JOINT

Based on the actual 110 kV cable joint structure, YJJJ(T)-64/110 kV, a three-dimensional simulation model of a cable joint is built. According to its geometric characteristics, the cable joint is decomposed into a conductive core, metal connecting pipe, semi-conducting layer, insulting layer, silicon rubber prefabricated joint, metal shielding layer, and outer sheath. The various components are processed separately and finally the components are spliced together. The principle of splitting facilitates data entry for meshing the geometry and structure of the cable joint.

B. DEALING WITH OVERLAPPING AREAS

It is necessary to deal with overlapping areas that appear after the splicing of the various components, and the inner semi-conducting layer wrapped around the metal connecting pipe and the cable insulation layers on both sides are required to realize a smooth transition, and the inner semi-conducting layers wrapped around the metal connecting pipe are connected together, which ensures continuity of the inner semi-conducting layer and uniform distribution of electrical field at the metal connecting pipe, and the smooth transition is also required at the contact between the silicon rubber prefabricated joint on both sides. The various components are connected together and make contact to form a constant dielectric interface and different dielectric interface such that the geometric parameters of various components of cable joint should be coordinated.

C. FDTD SUBDIVISION

FDTD areas of various components are divided and target meshes are marked thereon. It is necessary for mesh generation by the FDTD method to consider the limitations of computing resources and obtain values of factors, such as the minimum mesh element dimensions and the discrete precision.

D. DISPLAY OF GEOMETRIC MODEL OF CABLE JOINT

The geometric model of the cable joint is verified intuitively, the geometric model is visualised using the graphical display function of the corresponding software, including the display of the geometric model before and after FDTD subdivision.

According to the aforementioned steps, a three-dimensional simulation model of a cable joint is built, which consists of a cable joint and a part of the XLPE cable connected thereby.

IV. MATHEMATICAL MODEL BASED ON FDTD METHOD

The FDTD method performs differentiation discrete from Maxwell’s curl equations with time variables to obtain a set of time domain propulsion equations to derive the space electromagnetic field [16].

A. THE BUILDING OF THE MATHEMATICAL MODEL OF CABLE JOINT

Based on the FDTD method, the mathematical model of cable joint is built. The algorithm is implemented as follows:

Assuming that the field and source at the beginning of the time are zero, two curl equations are obtained based on Maxwell’s equations and the relationship between the electrical, and magnetic, fields, as shown in (1):

\[ \nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{B}}{\partial t} - \sigma_m \mathbf{H} \tag{1a} \]

\[ \nabla \times \mathbf{H} = \varepsilon \frac{\partial \mathbf{D}}{\partial t} + \sigma \mathbf{E} \tag{1b} \]

Take \( E_x \) and \( H_x \), equation (1) produces scalar equations in Cartesian coordinates, as shown in (2):

\[ \frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) - \sigma E_x \tag{2} \]

\[ \frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( -\frac{\partial E_z}{\partial z} + \frac{\partial E_z}{\partial y} - \sigma_m H_x \right) \tag{3} \]

According to the basic FDTD notation, positions of the \( E \) and \( H \) fields are calculated at different points on the FDTD structured grid as shown in Fig. 4: the original FDTD paradigm is described by the Yee cell [17].

Mesh generation is performed on the simulation model. The size \( \delta \) can satisfy the conditions of computational accuracy of the simulation model, selection of \( \delta \) for an FDTD discrete mesh is related to the function of space and time it
is denoted thus:

\[ f(x, y, z, t) = f(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = f^n(i, j, k) \]  

(5)

where \((i, j, k)\) denotes a grid point in the space, \(f(x, y, z, t)\) is a central difference approximation with second order precision, as shown in (6):

\[ \frac{\partial f(x, y, z, t)}{\partial x} \bigg|_{x=i\Delta x} = f^n(i + \frac{1}{2}, j, k) - f^n(i - \frac{1}{2}, j, k) \frac{\Delta x}{\Delta x} \]  

(6a)

\[ \frac{\partial f(x, y, z, t)}{\partial t} \bigg|_{t=n\Delta t} = f^{n+1/2}(i, j, k) - f^{n-1/2}(i, j, k) \frac{\Delta t}{\Delta t} \]  

(6b)

The spatial relative position of each component of the \(E\) and \(H\)-fields is applied to the difference calculation of Maxwell’\’s equations and a three-dimensional FDTD simulation in Cartesian coordinates is built. Take \(E_z\) as an example, the space location and time value of the grid point of \(E_z\) is \((i + 1/2, j, k)\) and \((n + 1/2)\Delta t\) respectively. \(E_z\) is taken as the discrete difference based on (2) and (6), as shown in (7):

\[ E^{n+1}_z(i + \frac{1}{2}, j, k) = E^{n}_z(i + \frac{1}{2}, j, k) - \frac{\sigma(i + \frac{1}{2}, j, k)\Delta t}{\varepsilon(i + \frac{1}{2}, j, k)} \cdot E^{n+1/2}_x(i + \frac{1}{2}, j, k) \]  

\[ + \frac{\Delta t}{\varepsilon(i + \frac{1}{2}, j, k)\Delta y} \cdot [H^{n+1/2}_z(i + \frac{1}{2}, j, k)] \]  

\[ -H^{n+1/2}_z(i + \frac{1}{2}, j, k) \frac{\Delta t}{\varepsilon(i + \frac{1}{2}, j, k)\Delta z} \cdot [H^{n+1/2}_y(i + \frac{1}{2}, j, k + \frac{1}{2})] \]  

\[ -H^{n+1/2}_y(i + \frac{1}{2}, j, k - \frac{1}{2}) \]  

(7)

where \(\varepsilon(i + 1/2, j, k)\) is permittivity of the grid point, and \(\sigma(i + 1/2, j, k)\) is conductivity of the grid point.

The time advancing calculation formula for the electric field, as used in the FDTD method, is described in (7). Other components of the electric and magnetic fields \((E_y, E_z, H_x, H_y, H_z)\) can be calculated in a similar way.

The stability of the numerical solution needs to be considered: Courant stability condition must be satisfied. The time step \(\Delta t\) is determined accordingly:

\[ \Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \]  

(8)

where \(\Delta x, \Delta y, \) and \(\Delta z\) are the spatial lag along the \(x, y,\) and \(z\)-coordinate directions, \(\Delta t\) is the time step, and \(c\) is the maximum propagation speed of electromagnetic waves.

When the stability condition is satisfied, mesh generation is performed on the simulation model of a cable joint in Cartesian coordinates. The simulation must consider the influence of the semiconductor layer of the cable on the propagation of PD signals. At the same time, to reduce the dispersion caused by the FDTD numerical calculation, the simulation model is divided into cuboidal cells. The size of the three-dimensional subdivision unit \(x \times y \times z\) is \(1.4 \times 1.4 \times 10\) (length, width, height, unit mm), and such dimensions satisfy the numerical stability criterion. As shown in Fig. 4, the Yee cell is set such that the numerical and geometric Maxwell equations automatically satisfy boundary conditions at the interface of the composite dielectric inside the cable joint.

### B. THE PULSE SOURCE AND BOUNDARY CONDITIONS

Theoretically, the PD pulse waveform can be considered as symmetric (Gaussian) waveforms in pulse propagation in shielded power cable [18]. Here, a Gaussian pulse function is used for simulating the excitation source of PD from the cable joint. The injection position is located at both ends of the XLPE cable which are connected by the cable joint. The Gaussian pulse energy is relatively concentrated and evenly distributed over a wide frequency, approaching the narrow pulse signal caused by the actual signal source. The time-domain form of the Gaussian pulse function is given by (9):

\[ E(t) = \exp[-\frac{4\pi(t - t_0)^2}{\tau^2}] \]  

(9)

where \(\tau\) is a constant, which determines the width of the Gaussian pulse, and the time of peak value of the pulse appears at \(t_0\). The pulse source is added to the simulation model in the form of voltage. The selected pulse peak value is 1 V. The waveform of the PD pulse source is shown in Fig. 5.

Here, the three-dimensional FDTD simulation model of a cable joint adopts the Perfectly Matched Layer (PML). The PML is a special dielectric layer set in the truncation boundary of the FDTD region, the wave impedance of the layer of dielectric exactly matches the wave impedance of the adjacent dielectric, and the incident wave will pass through the interface (with no reflection) and enter the PML [19], [20].

### V. SIMULATION AND EXPERIMENTAL RESEARCH INTO PD IN A CABLE JOINT

#### A. A THREE-DIMENSIONAL FDTD SIMULATION MODEL OF A CABLE JOINT

A three-dimensional FDTD simulation model of a cable joint is built based on FDTD electromagnetic simulation software. The model, contour, and subdivision diagrams of a
three-dimensional FDTD simulation model of cable joint are shown, respectively, in Figs 6, 7, and 8. The length of the cable and cable joint in the model is 3m and 1m, respectively.

The FDTD algorithm does not accommodate the strong frequency dependence of the permittivity. The dielectric parameters such as semiconducting layer and conductive silicon rubber have frequency dependence, the selection of parameters need to be made an adjustment for the best match between the simulated and measured results for PD signals.

Therefore, partial material properties used for modelling the cable joint are referred to [21], such as semiconducting layer and conductive silicon rubber. The parameters used for cable joint model are shown in Table 2.

### B. SIMULATION ANALYSIS OF PD IN CABLE JOINT

The type of prefabricated insulation defect in cable joints directly determines the fault location of PD and propagation characteristics of PD signals. According to different physical mechanisms and different types of PD caused respectively by electrical tree discharge, surface sliding discharge, air gap discharge, and floating discharge, different PD fault locations are simulated in the three-dimensional model of cable joint.

The propagation characteristics of PD signals in different fault locations are researched. Based on the design principles of aforementioned four types of insulation defect models, nine locations of PD fault are shown in Fig. 9: faults numbered “1” to “9” represent nine locations of PD fault, “1” and “2” denote simulated electrical tree discharge, “3”, “4”, and “5” are surface sliding discharges, “6” and “7” are air gap discharge, and “8” and “9” simulate floating discharges.

The propagation characteristics of PD signals in different fault locations are researched. Based on the design principles of aforementioned four types of insulation defect models, nine locations of PD fault are shown in Fig. 9: faults numbered “1” to “9” represent nine locations of PD fault, “1” and “2” denote simulated electrical tree discharge, “3”, “4”, and “5” are surface sliding discharges, “6” and “7” are air gap discharge, and “8” and “9” simulate floating discharges.

Based on the experimental platform for 110 kV cross-bonded XLPE cable system, both ends of the XLPE cable connected by the cable joint are selected as observation locations, because the measured PD signals caused by the aforementioned insulation defect models are compared in different observation locations, the observations made at each end of the XLPE cable are optimum for comparison of the peak value of PD signals and their polarity characteristics. Observation locations A and B are shown in Fig. 9.
The PD pulse source shown in Fig. 5 is injected into locations “1”–“9” as shown in Fig. 9, the electric field time-varying curves at observation locations “A” and “B” are recorded, and then converted into a voltage time-varying curve by electric field line integral under a specific path. The results are shown in Figs 10–Figs 18, respectively.

The simulation waveforms of propagation characteristics of PD signals are shown in Figs 10 to 18, which indicate that when the aforementioned four types of insulation defects, the polarities of the initial peak and the second peak of PD signals are all positive, but the peak values of PD signals caused by the aforementioned insulation defects are different.

With the increase of simulation time, the peak values of PD signals at the observation location far from PD fault locations present a tendency of constant attenuation, and the peak values of PD signals at the observation location near PD fault locations present a tendency of attenuation at the second peak. The regularity is reflected in Figs 10 to 18.

Locations “1” and “2” are used as fault locations for simulating electrical tree discharge. PD fault location occurs at fault location “1” that is near observation location “A” and far from observation location “B”, the initial peak value of the PD signal is 0.52 V at observation location “B”, with the increase of simulation time, then the peak values present a tendency of constant attenuation; the initial peak value is 0.26 V at observation location “A”, and increase to 0.4 V at the second peak, then the peak values present a tendency attenuation at the second peak. Besides, the initial peak value of the PD signal (location “2”) is 0.52 V at observation location “A”, then the peak values present a tendency of constant attenuation; the initial peak value is 0.26 V at observation location “B”, and increase to 0.4 V at the second peak, then the peak values present a tendency attenuation at the second peak.

Locations “3” to “9” also satisfy the above regularity. Locations “3”, “4”, “5” are used as fault locations for simulating surface sliding discharge. At location “3”, the initial peak value is 0.5 V (“B”); the initial peak value is 0.28 V (“A”), and increase to 0.38 V at the second peak. At location “4”, the initial peak value is 0.48 V (“A”); the initial peak value is 0.29 V (“B”), and increase to 0.36 V at the second peak. At location “5”, the initial peak value is 0.5 V (“A”); the initial peak value is 0.28 V (“B”), and increase to 0.38 V at the second peak.

Locations “6” and “7” are used as fault locations for simulating air gap discharge. At location “6”, the initial peak
value is 1.8 V ("B"); the initial peak value is 1.25 V ("A"), and increase to 1.9 V at the second peak. At location "7", the initial peak value is 1.8 V ("A"); the initial peak value is 1.25 V ("B"), and increase to 1.9 V at the second peak.

Locations "8" and "9" are used as fault locations for simulating floating discharge. At location "8", the initial peak value is 0.33 V ("B"); the initial peak value is 0.19 V ("A"), and increase to 0.3 V at the second peak. At location "9", the initial peak value is 0.33 V ("A"); the initial peak value is 0.19 V ("B"), and increase to 0.3 V at the second peak.

According to the above analysis of peak values of PD signals at location "1" to "9", different locations of PD fault can lead to different peak values. Locations "6" and "7" are set in intermediate positions of insulation, and the peak values of PD signals at observation locations “A” and “B” are significantly larger than those of other PD signals.

The comparison of Figs 10 and 11 indicates that when the PD pulse source is injected at fault locations “1” and “2”, the propagation characteristics of PD signals at observation locations “A” and “B” are symmetrical, PD signals at position “1” (“A”) and location “2” (“B”) or PD signals at position “1” (“B”) and location “2” (“A”) have same propagation characteristics with increase of simulation time and same peak values, because fault locations “1” and “2” are symmetrical, which results in symmetry of the propagation path of PD signals. Similar symmetry regularity applies to the other fault locations shown in Figs 12 and 14, 15 and 16, 17 and 18.

The comparison of Figs 11, 13, and 14 indicates that when a range of simulation time is from 0 to 300ns, with the increase of simulation time, the attenuation velocities of peak values of PD signals at locations “2”, “4” and “5” (“A” and “B”) are different, and in the same time range, the attenuation velocity at location “4” is slower than at location “5”, and attenuation velocity at location “5” is slower than at location “2”; the simulation time (300 ns) at location “4” that the peak value of PD signals decrease to 0 is greater than at location “5” (250 ns), and the simulation time (250 ns) at location “5” is greater than at location “2” (220 ns). Therefore, the closer fault locations inside a cable joint, the slower attenuation of the peak value of PD signals present at observation locations “A” and “B”.

Comparison of Figs 14, 16, and 18 indicates that fault locations “5” and “9” are far from the middle position of the insulation and are distributed on both sides thereof, fault location “7” is in the middle position in the insulation. Based on the above analysis of initial peak values of PD signals (observation location far from PD fault location) or initial peak values and second peak values (observation location near PD fault location), the peak value of PD signals at observation locations “A” and “B” (location “7”) is greater than the peak value of PD signals far from the middle position (locations “5” and “9”).

C. VERIFICATION OF PD IN CABLE JOINT BY EXPERIMENT

The accuracy of the three-dimensional FDTD simulation model of a cable joint is verified based on experimental platform (Fig. 1). An electrical tree discharge model shown in Fig. 3(a) is set in the phase A cable joint of 110 kV cross-bonded XLPE cable system. When phase A applies an AC voltage to 13.8 kV, PD will be produced. A surface sliding discharge model shown in Fig. 3(b) is set in the phase B cable joint of 110 kV cross-bonded XLPE cable system. When phase B applies an AC voltage to 26.7 kV, PD will be produced. The fault location caused by electrical tree discharge (Fig. 3(a)) corresponds to fault location “2” (Fig. 9), and the fault location caused by surface sliding discharge (Fig. 3(b)) corresponds to fault locations “5” (Fig. 9).

PD signals are detected by VHF clamp-on sensors at observation location “A” and “B”, the clamp-on sensors
are installed in cross-bonded cable system shown in Fig. 1, which are set in the same observation locations (Fig. 9). The magnetic core of the clamp-on sensors is Fe-Ni alloy with a bandwidth of 1 to 60 MHz and a gain of 40dB. Propagation characteristics of PD signals caused by electrical tree discharge and surface sliding discharge at observation locations “A” and “B” are shown in Figs 19 and 20, respectively.

In conclusion, the propagation characteristics of PD signals shown in Figs 19 and 20 are similar to the propagation characteristics obtained from simulation analysis. The experimental waveforms of propagation characteristics of PD signals are shown in Figs 19 and 20, which indicate that the polarities of the initial peak measured by the experiment are consistent with the polarities of the initial peak of simulated PD signals; the experimental waveforms of propagation characteristics of PD signals also satisfy the above rules that with the increase of time, the peak values of PD signals at the observation location far from PD fault locations present a tendency of constant attenuation, and the peak values of PD signals at the observation location near PD fault locations present a tendency of attenuation at the second peak. Experimental results showed that the three-dimensional FDTD simulation model of a cable joint can explain the propagation characteristics of PD signals in cross-bonded three-phase XLPE cable systems.

VI. CONCLUSION

According to different types of PD caused respectively by electrical tree discharge, surface sliding discharge, air gap discharge, and floating discharge, different PD fault locations are simulated in the three-dimensional model of cable joint. By comparison with the propagation characteristics of PD signals in different PD fault locations, fault locations relating to different types of insulation defect have relevant propagation characteristics of PD signals, including polarity, peak values, attenuation characteristics and symmetry, which provided the theoretical basis for judging the fault locations and types of PD caused by insulation defects in cable joints.

(1) Based on observation locations at both ends of an XLPE cable connected by a cable joint, the peak value of PD signals at the observation location further from a PD fault location presents a tendency of constant attenuation, and the peak value of PD signals at an observation location near a PD fault location presents a tendency of attenuation at the second peak. Therefore, the difference in attenuation characteristics can be used to determine the fault location of PD defects in a cable joint.

(2) When a PD fault occurs in an intermediate position of insulation, the peak values of PD signals at the observation location are greater than the peak values of PD signals further from this position.

(3) If PD signals monitored at observation locations on each end of an XLPE cable connected by a cable joint are symmetrical, it may be said that the types of insulation defects causing PD faults are similar, and the location thereof is symmetrical, which results in symmetry of the propagation path of PD signals.

(4) If the attenuation velocity of the peak value of PD signals monitored at observation locations at each end of an XLPE cable connected by a cable joint decreases, the PD fault is closer to the inner side of the insulation.

(5) Experimental results showed that propagation characteristics of PD signals are similar to propagation characteristics obtained by simulation analysis: the three-dimensional FDTD simulation model of cable joint can explain the propagation characteristics of PD signals in a cross-bonded three-phase XLPE cable system, which provides subsequent theoretical basis for PD detection, diagnosis of fault types caused by PD, and fault location.
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