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The Electromagnetic Field Simulation and Analysis for the Characteristics of EM Wave in 10kV XLPE Cable Joints

***Abstract**. A 10kV cross-linked polyethylene (XLPE) cable joint simulation model was established, in which the electromagnetic wave resulted from partial discharge (PD) was simulated by Finite Integration Technique (FIT). Factors influencing the electric field intensity and energy loss of UHF signals were analyzed. The simulation results indicate that quasi-TEM is the main propagation mode of EM wave, UHF signal intensity is related with the detection distance and the original PD pulse waveform.*

***Streszczenie.** Zbadano połączenie 10 kV kabli z izolacją polietylenową. Może tam powatwać fala elektromagnetyczna jako rezultat wyładowania niezupełnego. Przeanalizowano natężenie pola elektrycznego i straty energii. Stwierdzono, że quasi-TEM (linia długa) jest głównym sposobem prppagacji flai elektromagnetycznej. (**Symulacja pola elektromagnetycznego w połączeniu 10kV kabla w izolacji polietylenowej**)*

Keywords: XLPE Cable Joint, Partial Discharge, Ultra High Frequency, FIT
Słowa kluczowe: połączenie kablowe, ;pole elektromagnetyczne, wyładowania niezupełne.

Introduction

The occurrence of PD in XLPE cables is associated with the generation of electromagnetic pluses. The pulse width is less than 1 ns and the bandwidth is over 1 GHz[1]. The ultra high frequency (UHF) method, capturing these pluses from discharge sites by antenna sensors, is used more and more frequently in the on-site PD detection of XLPE cables. Compared with traditional measurements, it has better behavior on anti-interference and high precision on defect detection and location[2-4].

XLPE cable joint is composed of conductor, isolation layer, semiconducting layer, metal shielding and stress cone. When XLPE cables joint is in operation, the electric stress concentrates on the discontinuous interfaces between metal shielding, conductor and semiconducting layer. After a period time of running, the XLPE cable joint has a high risk of intrusion by dust, particle, water bubble and other contaminants, which will cause PD activity, develop electrical tree between conductor and insulating layer and lead to breakdown eventually. So it is of great significance to study the characteristic of the electromagnetic field in complicated shielding structure of cable joints [5-6], such as waveguide propagation mode, transmission attenuation, signal intensity.

In this paper, the 10kV XLPE cable joint simulation model with artificial defect was designed. The finite integration technique (FIT) method is applied to calculate the electromagnetic field intensity distribution and influential factors on electromagnetic signals, which are the propagation modes, the impact of detection distance on signal attenuation and the relationship of the original PD pulse waveform and cumulative energy of signals. The simulation result provides theoretical instruction to the application of UHF PD detection method on XLPE cable joints.

Model description

The cable joint simulation model is a 10kV XLPE prefabricated joint made for 70 mm² conductor as shown in Fig.1(a). The joint consists of a connector covered by conductive silicon rubber, a silicon rubber bushing with stress cone in it and the outer copper screen. The cables being connected are of a structure including the conductor, isolation layer, semiconducting layer and metal shielding. An axial cross section is shown in Fig.1 (b).

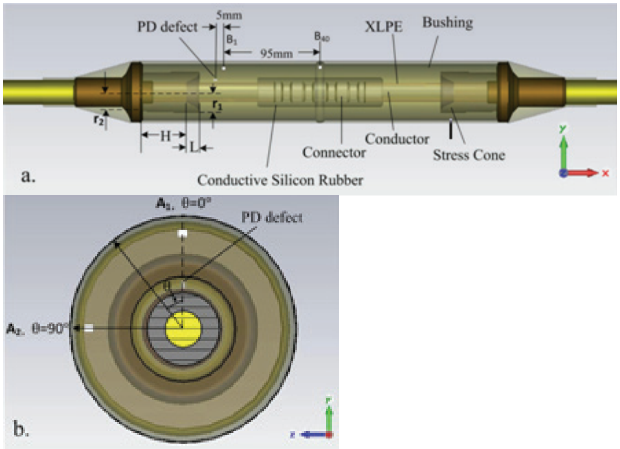

Fig.1. 3D model of 10kV XLPE cable joint

To reduce the electric stress, semiconducting tapes are used on the place between metal shielding and semiconducting layer of the cable, lapping 15 mm respectively. Both ends of the bushing, in contract with metal shielding of the cable, are also lapped with the semiconducting tapes (30 mm respectively). The conductors of two cables are combined as an entirety to simplify calculation. The main structural parameters are presented in Table 1. The length parameters given below are unilateral data, which are symmetric with centreline of the model.

Table 1. Main structural parameters of the cable joint model

Components	Property			
	length(mm)		radius(mm)	
Conductor	350		4.5	
Silicon rubber bushing	180		25	
	length(mm)		thickness(mm)	
Isolation layer	306.5		4.5	
Semiconducting layer	190		1	
Metal shielding	145		1	
	H(mm)	L(mm)	r1(mm)	r2(mm)
Stress cone	52	16	10	7

When the conductivity of stress control material $\gamma \geq 10^{-5}$ S/m, intensity of surface field would be less than 10 kV/cm and considerably lower than the electric field intensity, which comes out of the ionization in the air. Accordingly, the relative permittivity of stress cone ε is set to be 30 and γ is set to be 0.0002 S/m to ensure the best matching between the simulated model and real cable joints. In addition, the relative permittivity of conductive silicon rubber ε is set to be 90 and γ is set to be 0.5 S/m. For XLPE, ε is set to be 2.25 and $\gamma$is set to be 0 S/m.

As is shown in Fig.1 (a), PD excitation source is located in the interface of XLPE and silicon rubber, with the depth of 2 mm. A Gaussian-shaped current pulse is injected into it to simulate PD defect and its time domain expression is as shown below :

(1) $$i(t) = I_0 e^{-4\pi(t-t_0)^2/\tau^2}$$

where: I_0 – current pulse peak, t_0 – pulse peak time , τ – pulse width

Fig.2 shows the Gaussian-shaped pulse injected into excitation source of the model, where t_0 = 1.2 ns, τ = 1 ns, I_0 = 10 mA, referring to the time domain behaves very similar to PD in cable joints.

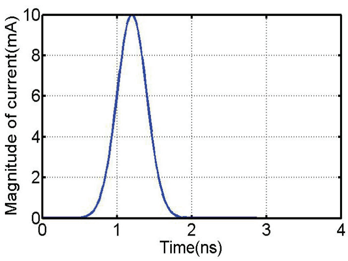

Fig.2. Excitation signal in time domain applied to the model

Propagation modes of EM wave in cable joints

Considering that cable joints in the reality contain several components with irregular shape such as stress cone and metal connector, and moreover the diameter of the cavity varies in different part, it could not be regarded as ideal coaxial waveguide and the propagation of electromagnetic wave from PD in it is rather complex.

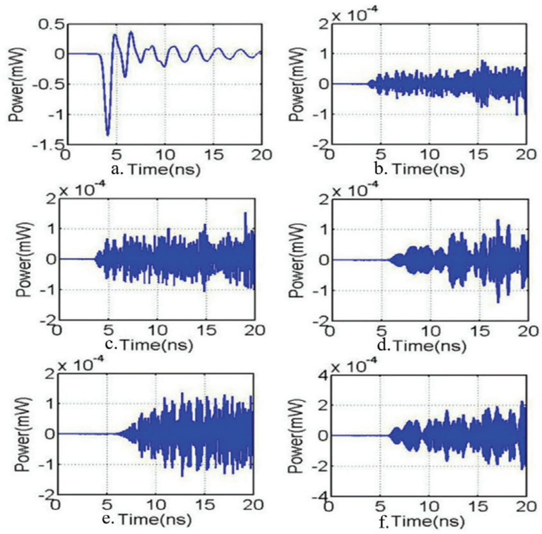

Fig.3. Power of EM signal from PD in different propagation modes

To study the characteristics of PD signals in cable joints, the distribution of propagation modes is discussed firstly. A waveguide port is placed at the right end of the model to receive output signals. The PD signal power in different propagation modes are given in Fig.3.

It can be seen that the power of signals in high-order modes received by the port is far less than that in quasi-TEM mode (Fig.3 (a)), it indicates that EM wave from PD in the cable joint mainly propagates in quasi-TEM mode and the high-order modes (Fig.3 (b-f)) have little influence on propagation of the PD pulse. Additionally, it is proved by experiments that EM waves in quasi-TEM mode have dispersion and its longitudinal field component change with the operating frequency f, when f < 5000 MHz, it could be treated as TEM mode approximately; and when f > 5000 MHz, the dispersion should not be neglected, otherwise a gross error would be engendered if still taking it as TEM mode, which has no dispersion. As the frequency components in the model excited by transient input of the Gaussian-shaped pulse is in the range of 0-1500 MHz, the propagation mode of EM wave from PD in the cable joint could be calculated approximately as TEM mode. The cross-section distribution of electric field in quasi-TEM mode is shown in Fig.4.

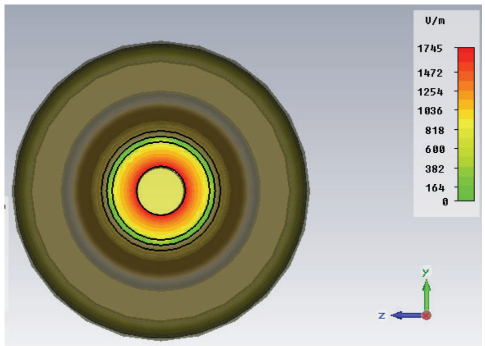

Fig.4. Electric field distribution in quasi-TEM mode

The electric field in TEM mode has only radial component, perpendicular to the extend direction of the cable. Therefore it can be inferred that the field component amplitude, detected at the same location, would vary widely in different directions. To justify this inference, two probes are placed at A1 and A2 (see Fig.1 (b)), with angle of 0°and 90° respectively to PD excitation source. The field intensity in direction x, y, and z at the two locations is shown in Fig.5. It is found that the electric field intensity in direction x is very slight both at A1 and A2, and values of radial component(y-component at A1 and z-component at A2) are much greater than the longitudinal one (x-component). This exactly coincides with the conclusion above.

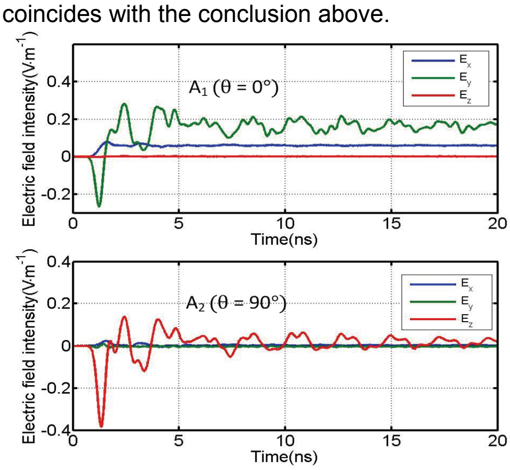

Fig.5. Intensity of field components at A1 and A2

Attenuation characteristics of EM wave in cable joints

It is known that the signal intensity of EM wave attenuates when propagating in the cable joints. There are several reasons that could explain such phenomenon [7]. For example, there is severe signal loss when EM wave travels along the lossy medium such as silicon rubber and the loss also occurs in the part where the structure is discontinuous. As a result, cumulative energy of PD pulse received by the probe would vary widely with different detection distances.

To research the attenuation characteristics of EM wave in cable joints, 40 probes are placed at B1, B2 … B40 (see Fig.1 (a)) with the same Y-value. The angle between probes and PD excitation source is 0° and the spacing is 5 mm. By varying the distance from 5 mm to 200 mm and calculating the cumulative energy of PD signals in 20ns, the exponential dependency of energy is revealed as shown in Fig.6. A clear decline with the increase of distance on the whole can be seen, yet when magnifying the curve partly, it is found that induced energy increases in the range of B8 to B28 , which are exactly above the conductive silicon rubber, and the curve is symmetric with respect to the centerline of the model. This can be explained with an effect of reflection inside the silicon rubber bushing between conductive silicon rubber and outer screen. In consequence, orientation for PD source is the first step to demarcate PD capacity with UHF signals and the results should be modified according to different distances.

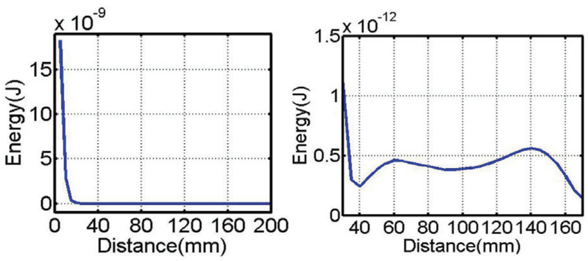

Fig.6. Cumulative energy with detection distance variation (t =20 ns)

It can be seen from the time domain expression of Gaussian-shaped pulse that the waveform is determined by pulse amplitude and width [8]. To simulate the effect of PD pulse waveform to UHF detection signals, five Gaussian-shaped pulses with the same pulse width 1 ns are injected into the PD excitation source. Their amplitudes are 10 mA, 20 mA, 30 mA, 40 mA and 50mA (as shown in Fig.7).

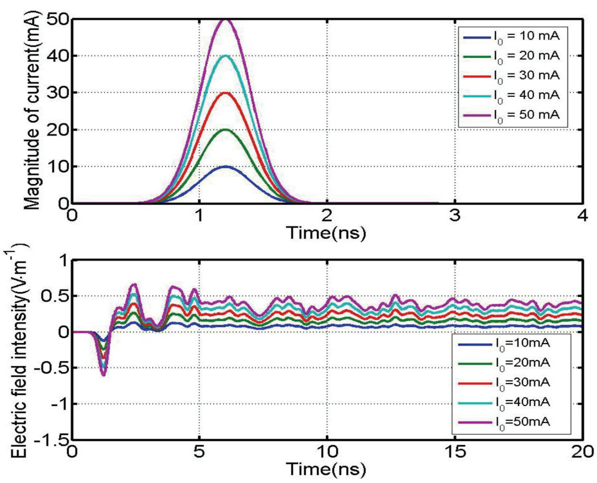

Fig.7. Electric field intensity with pulse amplitude variation

The distribution of electric field got by the probe which is located at B3 is shown in Fig.7, demonstrating that the character of the curves is similar and the electric field intensity increases along with the raise of pulse amplitude. Fig.8 presents the cumulative energy of 10 PD signals with pulse amplitudes from 5 mA to 50 mA and it reveals that the induced energy increases with the rising amplitude of PD pulse. The cumulative energy is related to the integrated square of pulse amplitude according to the calculation formula, therefore it should be in direct proportion to the squared amplitude of excitation pulses. As is shown in Fig.8, the energy curve coincides with the variation trend of function $y = 0.973\times10^{-14}x^2$ in general.

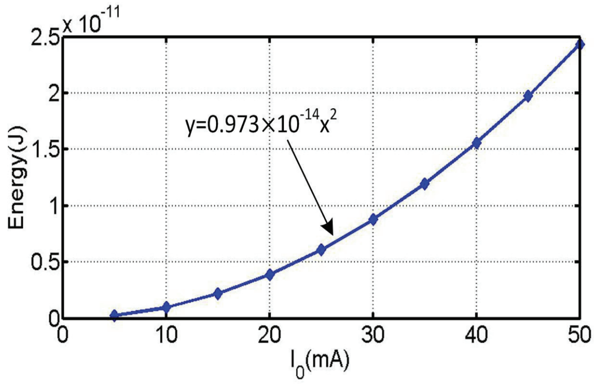

Fig.8. Cumulative energy with pulse amplitude variation

As the pulse width is not a constant in reality when PD activity occurs in the cable joint, five different PD pulses originating from the same source location are simulated as shown in Fig.9. These pulses have amplitude I_0 = 10mA and pulse width τ = 0.2, 0.4, 0.6, 0.8 and 1 ns. Detection probe is still placed at B3. Fig. 10 shows the electric field intensity and induced energy of the PD signals with pulse width variation in 20 ns. Comparing the results derived from the simulation, it can be found that the field intensity and energy of signals are getting higher when the pulse waveforms steepen.

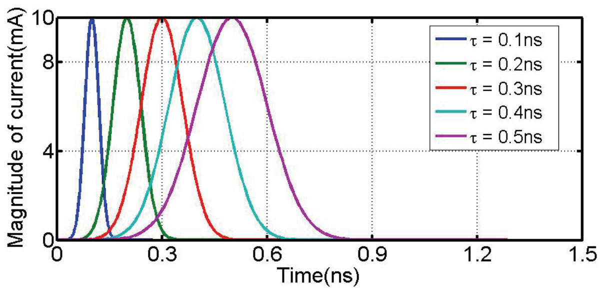

Fig.9. Excitation signals in time domain with pulse width variation

For the discussion above, a consequence can be concluded that UHF detection signals are influenced by the original PD pulse waveform. Though it is quite difficult to demarcate PD capacity by UHF method with the effect of detection distance and other influencing factors, detection results are still useful in revealing the severity level of the PD activity in cable joints.

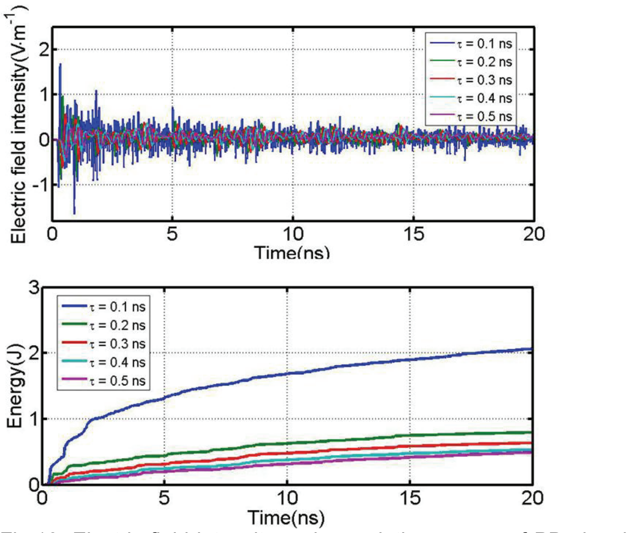

Fig.10. Electric field intensity and cumulative energy of PD signals with pulse width variation

Conclusion

EM wave from PD in the cable joint mainly propagates in quasi-TEM mode and radial component of the electric field is always much greater than longitudinal one in any detection position;

Cumulative energy of EM wave from PD has a clear decline with the raise of distance, while slightly increases when locating the detection position inside the silicon rubber above conductive silicon rubber.

Electric field intensity and cumulative energy of UHF signal get higher when the amplitude of original PD pulse increases, and induced energy is in direct proportion to the squared pulse amplitude.

The sharper the original PD signal is, the more energy of UHF signal is induced.

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