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On-site Insulation Tests for MV cable using Very Low Frequency and Damped AC Techniques

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Abstract. MV cables are vital components in urban power networks. Several insulation test techniques are proposed for guaranteeing the operation of MV cables. In this paper, two kinds of off-line testing techniques are introduced, namely Tanδ measurement using VLF and PD detection using DAC. Firstly, the operation principle of each technique is introduced. Then, a simulation model was built in Simulink platform to demonstrate the operation processes of detecting the defects in the cable. At last, an on-site case using both VLF and DAC techniques is introduced for presenting the functions of different techniques.

Keywords: MV cable; insulation aging; partial discharge; DAC; VLF.

1. Introduction

Cross-linked polyethylene (XLPE) insulated medium voltage (MV) cables are widely used in the urban electric power distribution networks and industrial power supply[1]. Though the reliability and stability of XLPE MV cable have been greatly improved compared with that of overhead lines, many unpredictable factors can still lead to outages[2]. The aging process and partial discharge are the main factors among them[3].

The aging process of XLPE insulation can be divided into several types according to the corresponding induce factors, such as, electrical aging (partial discharge, electric tree, et.al), thermal aging, stress aging, water-tree and so on[4]. No matter which way causes the aging process, the XLPE material is deteriorated, the energy loss increases, and the insulation performance decreases, eventually leading to change of bulk properties of MV cable. As for partial discharge (PD), it is the electric conduction of a local area within or on the surface of the XLPE insulation. It is usually caused by tiny defects in the cable or its accessories introduced in the manufacture process or on-site installation process[5]. PD will not directly lead to XLPE insulation breakdown, but gradually deteriorate the cable insulation in an electric, thermal and chemical way[6]. Therefore, PD detection is regarded as an effective tool to evaluate the condition of cable insulation and gains its popularity in on-site test field.

As a result, there are two types of on-site tests for fully assessing the condition of MV cable insulation during commissioning test and routine maintenance. One to detect changes in the bulk properties indicative of the overall condition of XLPE insulation and another to pinpoint the local tiny defects[7]. The dielectric loss factor (tangent delta, Tan δ) is a common used parameter to estimate the bulk aging condition of the XLPE insulation. Tan δ is usually obtained under a very low frequency (VLF) high voltage, typically at a 0.1Hz sinusoidal voltage, though there may be some other types of waveform, such as square wave, cosine-rectangular wave[8-11]. The Tan δ values at different time, of different phases and under different voltages are adopted to evaluate the degradation of cable insulation. PD signals would propagate towards to both directions along the cable, leading to a time lag of the sampling signal at the testing side. That means a time domain reflectometry (TDR) algorithm can be used to locate the defect generates the PD pulses. As for

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on-site PD test method, damped AC (DAC) is the most popular technique due to its effectiveness, portability and ease of use[12,13].

Though Tan δ under 0.1Hz VLF voltage and PD under DAC voltage are used to evaluate the insulation characteristics of MV cable from different perspectives, they are also related to a certain extent. For example, an aged cable with water-trees would not generate PDs but the Tan δ value would exceed the criterial limit. Furthermore, Tan δ would generally increase when PD occurs. Thus, in this paper, the on-site testing case of a 10-kV XLPE insulated MV cable using both diagnostic method is analyzed to interpret this kind of phenomenon.

2. Principle of DAC and VLF

2.1 VLF testing

Since DC voltage applied on the XLPE insulation would lead to space charge accumulation, VLF withstand test is recommended instead. The VLF withstand voltage could be sinusoidal, cosine-rectangular or trapezoidal, shown in Fig.1[14]. The frequency of VLF voltage ranges from 0.01Hz to 1Hz. In fact, 0.1Hz VLF voltage is typically favored. Due to the frequency characteristics of VLF, the power demand is much smaller than operation frequency of 50Hz, leading to small size and light weight of the equipment.

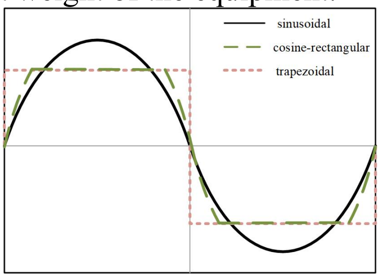

Figure 1. Waveforms of VLF test.

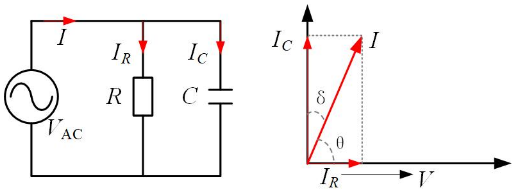

Figure 2. Equivalent circuit of Tan δ test and its phasor diagram.

When conducting VLF sinusoidal voltage withstand test, the Tan δ is usually obtained simultaneously. A typical impedance model of MV cable insulation can be described as in Fig.2. The Tan δ value is obtained under an AC excitation voltage and from the phase difference between the voltage waveform and the corresponding current waveform. According to the phasor diagram, the Tan δ value can be expressed as in equation (1).

$$\tan\delta = \frac{I_R}{I_C} = \frac{1}{\omega RC} \tag{1}$$

The insulation resistance R of the cable will decrease with the process of aging. That means, the Tan δ value increases during the aging process of cable. Besides, according to the research results, the changes of insulation aging characteristic are more visible at lower frequencies than operation frequency[15].

2.2 DAC testing

DAC voltage is generally generated by either DC-charge method or resonance-based method[16,17]. The regular DC-charge DAC technique is taken as an example and the operation diagram is depicted in Fig.3.

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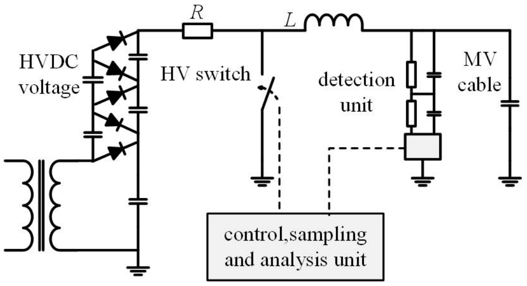

Figure 3. Structure of DAC test system.

The operation procedures of PD detection using DAC technique is described as following: A HV DC voltage is generated and applied on the MV cable under test, through a protective resistor and an inductor. When the cable is charged to the target voltage level, the HV switch which is usually made up of semi-conductive power electronic components, turns to conduction condition. The MV cable discharges through the inductor. Then the voltage applied on the cable transits into a damped AC voltage due to the resonant principle and the loss of the resistance of inductor windings. Within the DAC periods, the PD activities from the defects are generated and can be detected by the detection unit.

The frequency of DAC voltage generally ranges from 30Hz to 500Hz, within which the PD characteristics are similar to that under 50Hz. This frequency is determined by the capacitance of the MV cable under test and calculated by the following equation.

$$f_{\mathrm{DAC}} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Since the DAC test is conducted at one end of the cable, the TDR algorithm can be adopted to locate the defects that generate PDs. The PD location can be pinpointed by the following equation.

$$L_{\mathrm{PD}} = L_{\mathrm{c}} - v \cdot \Delta t / 2 \tag{3}$$

in the above, LPD is the distance of defect from the detection end, Lc is the total length of the cable, v is the velocity of the PD pulse propagating in the cable, Δt is the time lag between the pulse directly propagate to the end and after reflecting by the other end.

3. Simulation of defects

According to the PD generation mechanism, a simplified simulation model was built by Simulink, as shown in Fig.4. The distributed parameter lines are used to simulate a single-phase MV cable. A three-capacitor model is built to simulate the PD generation process. The upper capacitor is paralleled with a voltage controlled switch. When the voltage across the upper capacitor exceeds the threshold value, the switch is closed and the capacitor is thus short circuited. Therefore, the PD signal is generated by the on and off actions of the switch. At the cable end near the HV source, a PD detection circuit is added to sample filter the components in power frequency and sample the PD signals. At the other cable end, a resistor with large resistance value is used to simulate the open circuit condition.

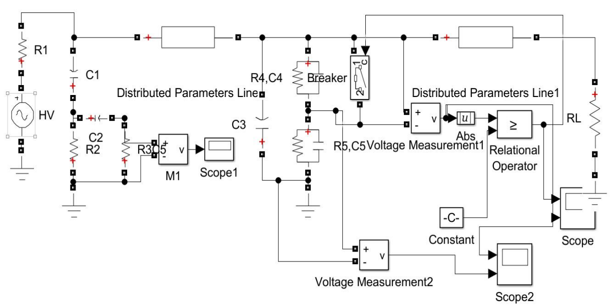

Figure 4. Simulation layout in Simulink.

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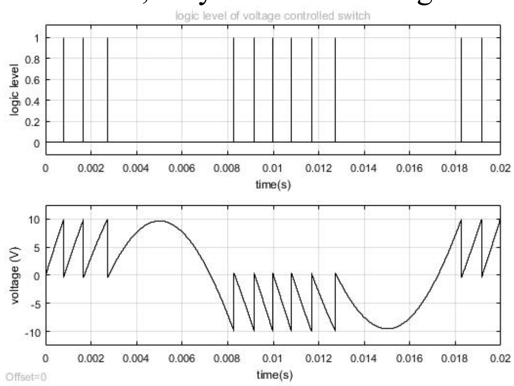
In a particular case, the total length of the cable is 1km and the defect is set at the position 300m from the HV source end. The HV source is set as sinusoidal voltage with a max peak value of 8.17kV and frequency of 50Hz. The threshold value of the voltage-controlled switch is set as 10V. The main parameters, such as resistance, inductance and capacitance per unit length of the distributed parameters line in this simulation case is shown in Table 1.

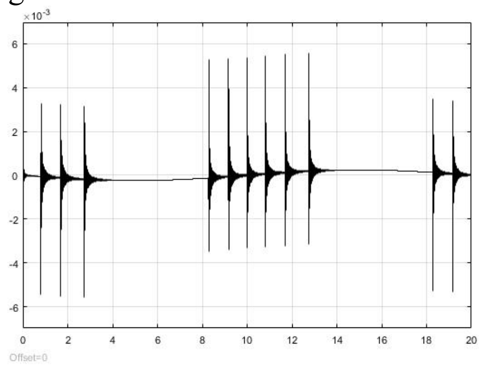
Table 1. Parameters in the simulation.

Components		Values
Distributed parameters line	r1	0.1Ω/km
	l1	2.3×10-5H/km
	c1	1.5×10-6F/km
	length	0.3km
Distributed parameters line	r1	0.1Ω/km
	l1	2.3×10-5H/km
	c1	1.5×10-6F/km
	length	0.7km
HV source		max8.17kV,50Hz
PD coupling capacitance C1		2nF
Protective resistance R1		0.1Ω
Load resistance RL		100MΩ

When applying the maximum voltage 8.17kV, the voltage controlled switch changes its states according to the logic level shown in Fig.5. Besides, the PD detection results from R3 are also shown in Fig.5.From the logic signal of the voltage controlled switch, it is obvious that the switch closes for 7 times. It is also verified from the PD signals from the detection unit shown in Fig.5(b). When magnifying the pulses in Fig.5, it is quite clear that the time lag of the pulses detected at the source position is equal. Due to the ideal condition in the simulation, there exist lots of reflection pulses. Therefore, only the first time lags of each PD signal are considered.



(a)the control logic level of voltage controlled switch and the voltage waveforms across the capacitance C4



(b)The simulation reuslts of PD detection signals from resistance R3

Figure 5. The waveforms from the simulation results

The corresponding PD defect locations according to equation (3) are depicted in Fig.6. The results show that the PD location 'dots' are clustered in one dot. For better presentation of the PD location results, the PD magnitudes are multiplied by a random coefficient. The clusters show the defect is at the point 300meter away from the HV source end and it is in consistent with the actual simulation layout. As a comparison with the HVAC condition, the HV source is changed to a DAC voltage. The corresponding simulation results are shown in Fig.7. The frequency of the DAC voltage is 200Hz and its waveform is shown in Fig.7(a). From Fig.7(b), it is obvious that the damped AC voltage triggers the voltage controlled switch only within the first five cycles. From Fig.7(c), the PDs are found in accordance with the Fig.7(b). It should be noticed that DAC voltage should be high enough to generate PDs due to the damp characteristics that the voltage in the later

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cycles are weak. In fact, on-site PD detection for MV cable using DAC technique counts the first 3 to 4 cycles of DAC voltage.

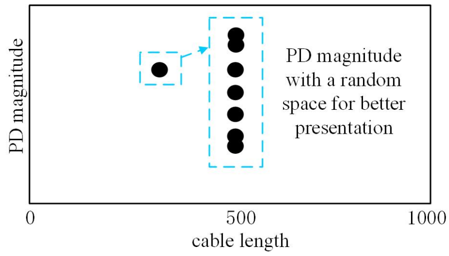
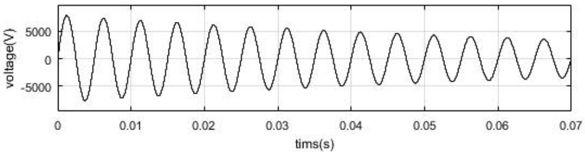
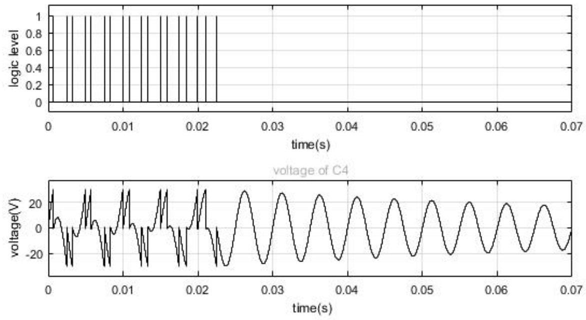


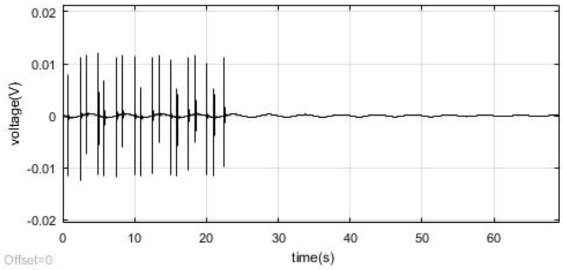
Figure 6. The location result of simulation.



(a) the DAC voltage waveform.



(b) the control logic level of voltage controlled switch and the voltage waveforms across the capacitance C4



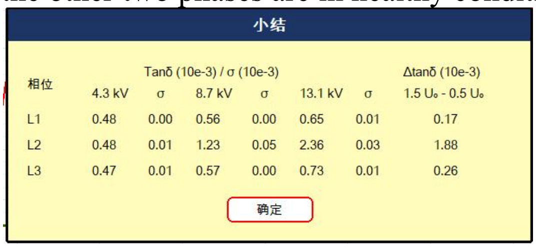
(c) The simulation reuslts of PD detection signals from resistance R3

Figure 7. The waveforms of DAC simulation results

4. On-site test case

For an XLPE insulated 10kV cable, typed YJV22-8.7/10, on-site Tan δ test under VLF and PD test under DAC voltage are conducted. The length of the cable is 0.85km and there are 3 joints.

In an off-line routine test, withstand test using VLF system manufactured by Megger is conducted with Tan δ measurement. The VLF voltage applied on the cable is 0.5U0, U0 and 1.5U0. The Tan δ value result is shown in Fig.8. From this figure, it can be seen that Tan δ of phase B exceeds the critical limit and the other two phases are in healthy condition.



小结

相位	Tanδ (10e-3) / σ (10e-3) 4.3 kV	σ	8.7 kV	σ	13.1 kV	σ	Δtanδ (10e-3) 1.5 U₀ - 0.5 U₀
L1	0.48	0.00	0.56	0.00	0.65	0.01	0.17
L2	0.48	0.01	1.23	0.05	2.36	0.03	1.88
L3	0.47	0.01	0.57	0.00	0.73	0.01	0.26

确定

Figure 8. Tan δ measurement results exported from the VLF system

It is deduced that there must be some aging issues with phase B. However, the factors leading to the aging issues are not clear. Therefore, a DAC PD testing was carried out then, as shown in Fig.9.

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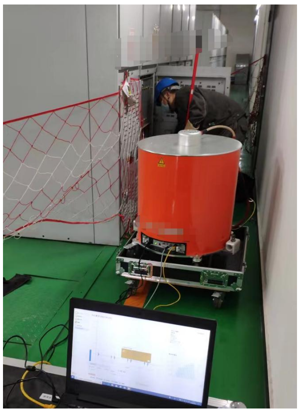

Figure 9. DAC PD testing

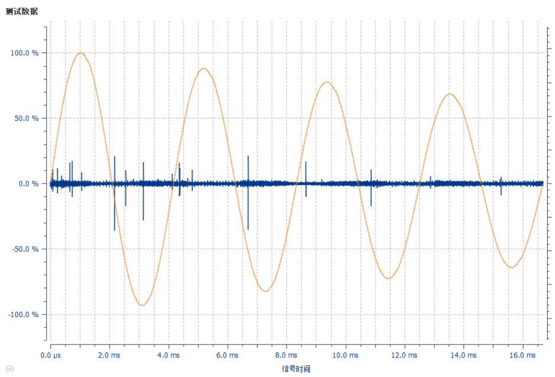

Figure 10. DAC voltage and PD signals.

According to the DAC testing standard, the maximum charged voltage is set as, 0U0 once,0.5 U0 once, 1U0 once, 1.1U0 once, 1.3U0 once, 1.5U0 for three times, 1.7U0 for three times, 1U0 once and 0U0 once in order. When the applied voltage reaches 1.7U0, PD signals with the maximum magnitude over 1000pC are detected. The corresponding DAC voltage and PD signals are shown in Fig. 10.

The corresponding location of defect is calculated and the PD location map is depicted in Fig.11. The result indicates that there are insulation problems at the joint near 400m from the testing side. A maintenance was made to dissect this joint and finally some discharge traces were found on the surface of insulation screen.

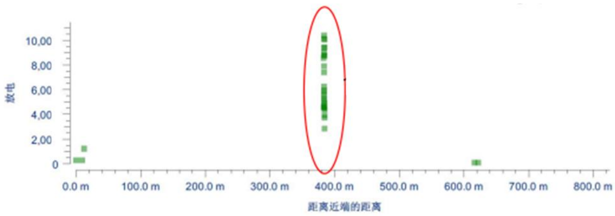

Figure 11. PD location map.

5. Conclusion

In this paper, two kinds of on-site insulation testing techniques were introduced. VLF withstand test with Tan δ value monitoring is effective to evaluate the bulk aging properties of the cable. Meanwhile, PD detection by DAC testing is generally used to locate the PD defects. A simulation by Simulink platform is made to show how VLF and DAC work. At last, an on-site testing case using VLF and DAC techniques are demonstrated. The Tan δ obtained by VLF testing indicated that the cable insulation is suffering from aging problems. PD detection shows that this defect is in the joint which is near 400m away from the testing side. In a word, comprehensive testing techniques should be adopted for better estimating the MV cable insulation condition.

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