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Analysis of XLPE Cable Health Assessment Parameters under Various Test Voltages by PDC Method

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Abstract: **Cross-linked polyethylene (XLPE) has been widely used as an insulation material in power cables because of its superior electrical characteristics. The measurement of polarization and depolarization current (PDC) is a classical method used to study the health states of XLPE cables. This paper studied the effects of test voltage on the PDC measurement results and assessment parameters calculated results. The PDC tests of one new and one old cable were carried out under 2kV to 6kV with an interval of 1kV. The assessment parameters such as insulation resistance (IR), polarization index (PI), dielectric absorption ratio (DAR), dielectric loss tan δ, and ageing factor were calculated and analyzed. The results show that with the increase of test voltage, all the assessment parameters are almost independent to the test voltage for the new cable. However, for the old cable, the IR, DAR, and PI values decrease, and tan δ increase with test voltage.**

Keywords: **Polarization and depolarization currents, XLPE cable, Test voltage, Insulation resistance, Dielectric loss.**

I. INTRODUCTION

XLPE has been widely used as an insulation material in power cables due to its excellent electrical, mechanical, and chemical properties [1-3]. However, XLPE insulated cables degrades with time due to electric fields, temperature, and environmental moisture interactions. It is necessary to have proper maintenance diagnostic for XLPE cables for checking the health of the insulation before the occurrence of any complete failure.

The dielectric response technology represented by the PDC (polarization/depolarization current) method has gradually been applied to the insulation diagnosis of XLPE cables. The PDC method has many advantages, such as its simplicity, easy to employ, automated, convenient operation, and massive informativeness [4-6]. By analyzing the PDC test results, information about conduction and polarization, such as insulation resistance (IR), polarization index (PI), and dielectric absorption ratio (DAR) can be obtained directly. Furthermore, some guidelines for those parameters have been studied to diagnose the aging state of XLPE insulation [7].

Besides, the dielectric parameters in the frequency domain can be calculated by the PDC based on the conversion methods such as the extended Debye model [1,2,4,8]. The dielectric loss factor in the frequency domain and ageing factor have been calculated for evaluating the XLPE insulation health [2,4,9]. Traditional experience shows that the conversion method of the time-frequency domain is applied effectively in the low-frequency range [9-11]. The dielectric loss factor at 0.1Hz is an essential value to assess the cable insulation health states, and its guideline has been published in IEEE standard [12].

However, the effects of test voltages on the assessment parameters results of XLPE cable insulation are seldom reported. Studying the effects of test voltages through the acquisition and data analytics of assessment parameter results can provide more accurate guidance for cable insulation health state diagnosis.

This paper introduces the calculation methods assessment parameters obtained by PDC results. Next, the PDC tests are carried out on 6.6kV copper conductor XLPE insulated cables under the test voltage from 2kV to 6kV with an interval of 1kV. Finally, according to the PDC test results, the IR, PI, DAR, aging factor, and dielectric loss (tanδ) are calculated to analyze the effects of test voltages on those parameters.

II. FUNDAMENTAL THEORY

A. *Polairzation Index (PI) and Dielectric Absorption Ratio (DAR)*

Because of the sensitivity of insulation resistance measurements to temperature, moisture, and other factors, the trending of insulation resistance over time compared to a baseline value can be somewhat unreliable. Therefore, a better choice for data trending would be the polarization index (PI) and dielectric absorption ratio (DAR), independent of the environment condition and only dependent on the cable insulation property.

Polarization Index (PI) is the ratio of a 10-minute time-resistance reading divided by a 1-minute time-resistance reading, as (1).

$$PI = \frac{U}{I_{10m}} \Big/ \frac{U}{I_{1m}} = \frac{I_{1m}}{I_{10m}} \tag{1}$$

Where I_{1m} and I_{10m} are the polarization currents at 1 min and 10 min, respectively.

Dielectric absorption ratio (DAR) is the ratio of a 60-second time-resistance reading divided by a 30-second time-resistance reading, as (2).

$$DAR = \frac{U}{I_{1m}} / \frac{U}{I_{0.5m}} = \frac{I_{0.5m}}{I_{1m}} \tag{2}$$

Where $I_{0.5m}$ is the polarization currents at 0.5 min.

B. *Dielectric Loss (Tan δ)*

At present, the extended Debye model shown in Fig. 1 with its known circuit elements can be used for all kinds of transformations.

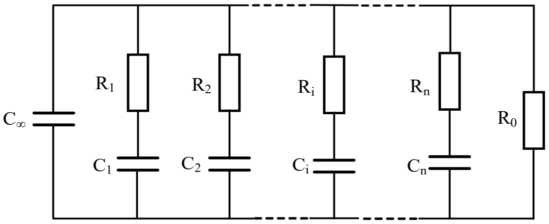


Figure 1. Equivalent circuit to model any linear dielectrics [3-6,8,9]

The introduction of the circuit elements of the equivalent circuit is in the following: C_∞ is the capacitance of the cable insulator representing the electronic, ionic, and dipolar polarization processes (quick polarization processes), and R_0 is the leakage resistance of the cable. The still unknown elements R_i, C_i with their corresponding time constants $\tau_i = R_i \times C_i$ represent the dynamic behavior of polarization and depolarization processes. Those parameters can be calculated by fitting the polarization current with (3).

$$I_{pol}(t) = I_0 + \sum_{i=1}^{n} a_i \cdot \exp\left(-\frac{t}{\tau_i}\right) \tag{3}$$

Where,

$$a_i = \frac{U_C}{R_i} \qquad i = 1,2,3 \ldots \text{n} \tag{4}$$

For the equivalent circuit in Fig. 1, the complex capacitance $C(\omega)$ can now be calculated according to (5) from its complex admittance, $C(\omega)$ as:

$$C(\omega) = \frac{Y(\omega)}{i\omega} = C_\infty + \frac{Y(\omega)}{i\omega R_0} + \sum_{i=1}^{n} \frac{C_i}{1+i\omega R_i C_i} \tag{5}$$

The real and imaginary parts of C(ω) are then given as

$$C'(\omega) = C_\infty + \sum_{i=1}^{n} \frac{C_i}{1+(\omega R_i C_i)^2} \tag{6}$$

and

$$C''(\omega) = \frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{\omega R_i C_i^2}{1+(\omega R_i C_i)^2} \tag{7}$$

Finally, $\tan\delta(\omega)$ can be calculated from:

$$\tan\delta(\omega) = \frac{\frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{\omega R_i C_i^2}{1+(\omega R_i C_i)^2}}{C_\infty + \sum_{i=1}^{n} \frac{C_i}{1+(\omega R_i C_i)^2}} \tag{8}$$

C. *Ageing Factor*

Based on the explanation of three branch Debye model, the aging factor A is introduced in reference [2, 4] as a judgement parameter to describe the ageing state of cable insulation quantitatively. The ageing factor A is defined by (9),

$$A = Q(\tau_3)/Q(\tau_2) \tag{9}$$

where,

$$Q(\tau_2) \approx a_1\tau_1 + a_2\tau_2\left(1 - \frac{1}{e}\right) + a_3\tau_3\left(1 - e^{-\frac{\tau_2}{\tau_3}}\right) \tag{10}$$

$$Q(\tau_3) \approx a_1\tau_1 + a_2\tau_2\left(1 - e^{-\frac{\tau_3}{\tau_2}}\right) + a_3\tau_3\left(1 - \frac{1}{e}\right) \tag{11}$$

In this paper, the branch number of the extended Debye model is chosen to be three for use in calculating tan δ and the ageing factor.

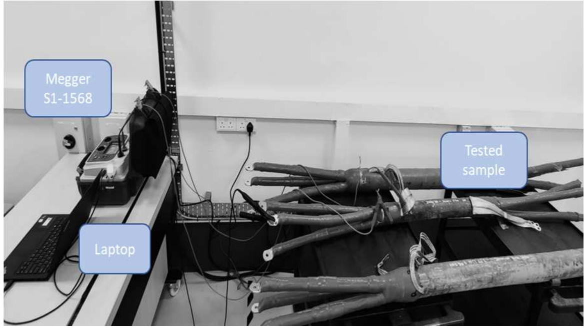
III. EXPERIMENTAL PROCEDURE

In this paper, an old and a new XLPE cable each were measured for studying the effects of test voltage on the assessment parameters. The specifications of the tested cable samples are given in Table I.

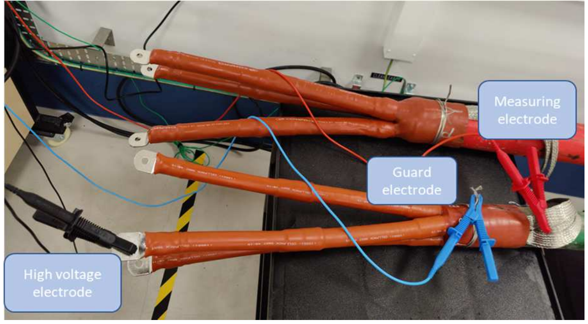
TABLE I
SPECIFICATIONS OF TEST CABLE

Property	Cable	Cable
Insulation Material	XLPE	XLPE
Type	old	new
Length(m)	2.3	2.3
Thickness (mm)	2.8	2.8
Rated Voltage (kV)	6.6	6.6

Before the PDC test, the tested cables were short-circuited to earth for 48 hours to discharge all the remaining charges. The tested voltage is from 2kV to 6kV with an interval of 1kV, and the polarization and depolarization time is 1000s. The test equipment is Megger S1-1568, which is commonly used in a field testing. The actual photograph of the test circuit for the PDC test is shown in Fig. 2.



(a) Measurement circuit



(b) Wire connection method

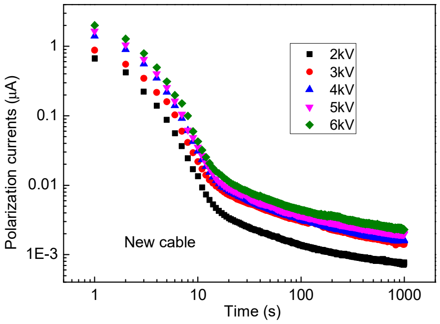
Figure 2. The connection of cable sample

As shown in Fig. 2, the high voltage electrode is connected to the conductor, and the measuring electrode is connected to the grounded wire of the cable. To avoid the leakage current insulation surface, the blue wire (guard wire) is connected to the bare wire wrapped between the conductor and the grounded wire of cable. All the experiments were done at the SP Group – NTU Joint Laboratory at Nanyang Technological University.

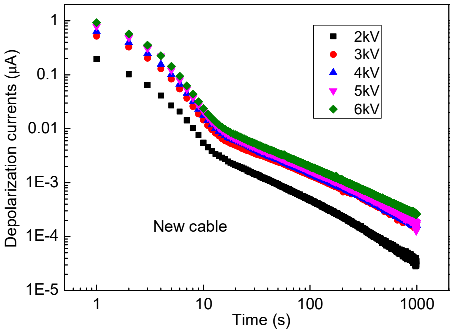
IV. RESULTS AND DISCUSSION

A. *Polarization and Depolarization currents*

The PDC test results of new and old cables under different test voltages are shown in Fig. 3 and Fig. 4.

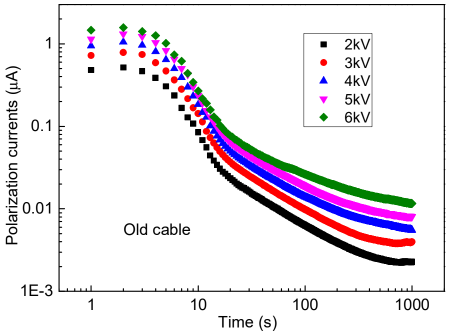


(a) Polarization currents

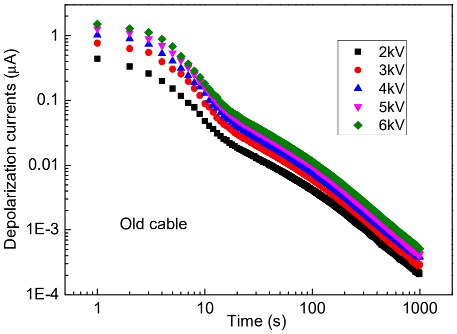


(b) Depolarization currents

Figure 3. Polarization and depolarization currents of new cable under different voltages



(a) Polarization currents



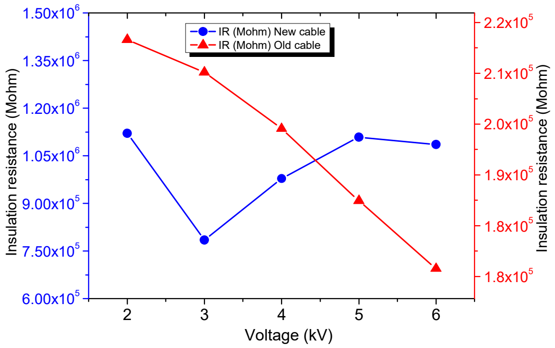
(b) Depolarization currents

Figure 4. Polarization and depolarization currents of old cable under different voltages

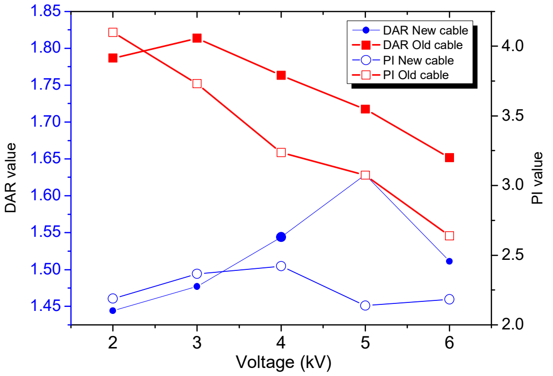
From Fig.3 and Fig. 4, it could be known that the polarization and depolarization currents increase with the test voltage for both new and old cables, especially when the test voltage up to 6kV for the old cable. In addition, the trend of all the PDC curves can be divided into two sections where the breakpoint is around 10s. The beginning section may be mainly caused by the test equipment response, which is inconsistent with the latter section describing the behaviour of test samples. The tanδ and ageing factor in the following context is calculated using the measured currents after 10s. This is to avoid the effects of test equipment on the calculation results.

B. *IR, DAR and PI*

Based on the PDC results, the IR values at 1min are extracted to study the effects of test voltage, as shown in Fig. 5(a). Meanwhile, the PI and DAR are calculated by using equations (1) and (2), respectively, as shown in Fig. 5 (b).



(a) IR value



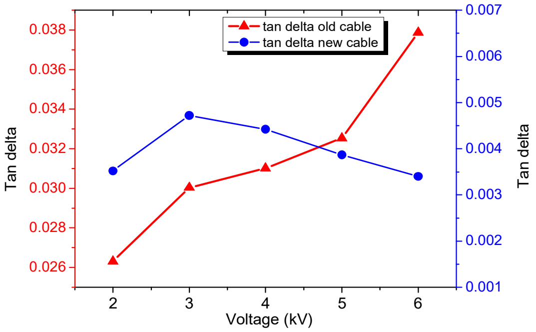
(b) DAR and PI value

Figure 5. IR, DAR, and PI value of new and old cable under different voltages

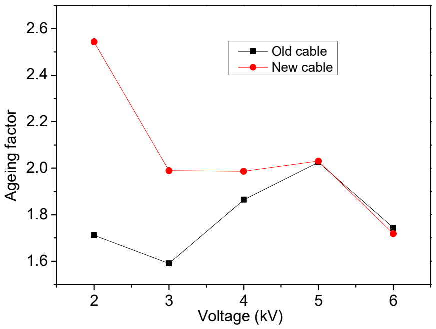
From Fig. 5, all the three parameters IR, DAR, and PI three parameters decrease with the test voltage for the old cable. But for the new cable, these three parameters show an irregular variation with test voltage. One of the reasons for this irregular variation maybe is that the temperature (23-25 °C) or humidity (70-75%) in the test room change when doing the test under different voltage. Another reason maybe is that there is some degree of unrepeatability of dielectric behavior of XLPE insulation under DC electric field [13].

C. *Tan δ and Ageing Factor*

By using (8), tan δ value variation with frequency is calculated based on curve fitting on polarization current test results. The tan δ value at 0.1Hz is extracted to analysis the effects of test voltage on tan δ, as shown in Fig. 6 (a). Because the 0.1Hz tan δ value has been applied to evaluate the insulation ageing state; indicator on extend of water trees [10,12]. Furthermore, the ageing factor is calculated by using (9) based on the curve fitting on depolarization current results.



(a) Tan δ value



(b) Ageing factor value

Figure 6. Tan δ and ageing factor value of new and old cable under different voltages

From Fig. 6(a), the tan δ value at 0.1Hz increases with test voltage for old cable. However, for the new cable, the tan δ value at 0.1Hz is far less than that of the old cable and changes little within the test voltage. These results are consistent with the trending IR value variation with test voltage since the lower IR value of insulation cause more conduction loss. From Fig. 6(b), the ageing factor also has no relation to the test voltage for both the new and old cables.

The analysis of all the assessment parameters IR, DAR, PI, tan δ and the test voltage has large impact on the cable health except the ageing factor for old cable. For the new cable, the test voltage almost has no effect on assessment parameters. The reason is that the conductivity of XLPE in the old cable shows nonlinearity increase with the test voltage, such as exponential, power and hyperbolic sine function [14]. This causes the IR value decreasing and the tan δ increasing.

V. CONCLUSION

This paper analyzed the effects of test voltage on the assessment parameters calculated by the PDC results. The new cable is less affected, while the old cable is more affected by the test voltage. The IR, DAR, and PI values of the old cable decrease with test voltages, and the tan δ increases with test voltages. These results indicate that the test voltage is a crucial factor influencing the results of the IR and other calculated assessment parameters used to assess the cable health. Further research will be carried out to determine correct test voltage to be used. Otherwise, it could be challenging to obtain a unified guideline.

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