Extraction of Cable Joints Tangent Delta from Bulk Tangent Delta Measurement using HFAC Method

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***Abstract*—Tangent delta measurement is a well-known diagnostic used by many utilities for condition assessment. Guides on field diagnostic testing are well established by North American society through IEEE standards and guideline. Tangent delta, also called loss angle or dissipation factor (δ) measurement, is a diagnostic method of testing underground cables to determine the quality of the cable insulation in which value from the measurement will be used to compute dielectric loss within the cable insulation system. The higher the dielectric loss thus creates higher localized heating which leads to insulation degradation. However, dielectric loss measurement test technique is a global or bulk insulation condition assessment. It gives an overall condition of the complete cable system that includes cable, joints and terminations. A good dielectric loss result thus means that the overall condition of the complete cable system is in good condition whereas such high dielectric loss will just give unhealthy indication of the overall condition of the cable without revealing the weakness component within the insulation system. It is important to distinguish the dielectric loss of cable and its accessories within the system for the ease of maintenance works and such knowledge is an added advantage and greatly needed by the network owner. This paper presents the method of determining the tangent delta of cable joint from the total overall or bulk tangent delta measurement by using higher frequencies (>100Hz) at voltages above 1 kV. In this direct measurement method, the current (I), voltage (V) and phase (θ) were obtained by connecting a linear high voltage probe across the cable cross-section. The phasor diagram is then constructed and by some trigonometric exercises the actual phase across the joint is extracted. Hence, the tangent delta values were calculated.**

Keywords—tangent delta; cables joints; extraction method

I. Introduction

To identify water tree degraded XLPE cables with high moisture content or moisture ingression through poor jointing, diagnostic tests based on dielectric response measurement in either time or frequency domain are used [1, 2]. It is worth to mention that these dielectric response methods had utilized either direct current (DC) or very low frequency (VLF) electrical testing technique. This is due to the fact that DC or VLF has the advantage of less power requirement thus reduce size of the testing equipment to ease mobilization in the field.

In practice, standard laboratory electrical test equipment utilizing power frequency (PF) i.e. 50Hz to 60Hz testing is used. Hence, large static voltage transformer was installed in the laboratory to cater any large capacitance test sample for high voltage testing. These existing dielectric loss or tangent delta diagnostic test methods are bulk assessment techniques that cannot sectionalize or pin point the water tree or any other conductive defect.

In addition, both these tangent delta measurement technique which utilizes standard 0.1 Hz and 50 Hz equipment is not capable to extract the tangent delta values of accessories from the bulk assessment [3, 4, 5]. It can only diagnose the overall condition of the complete cable system that includes cable, joints and terminations. Since medium voltage underground (MVUG) cables in utilities are in service for many years, it is crucial to develop a method to sectionalize or identify the defective components.

This paper presents a new method of High Frequency Alternating Current (HFAC) tangent delta extraction of joints which can be used as an indicative test to pre-determine the condition of joints in the laboratory. The advantage of this method is able to extract the tangent delta values of the joints from the bulk cable. Artificially defective joints were created to give variation in the dielectric loss response and validated using commercial standard onsite VLF and PF tangent delta test method.

II. Type of Test Samples

Cable joints are an integral part of power cable distribution system. The joints are installed as connection between two set of cables. Set of cable with known good insulation condition i.e. tangent delta tested, were connected using artificially created defective jointing condition. The conductors are connected using a connector. The cold shrink integrated joint body with semi-conducting conductor shield, insulation and semi-conducting insulation shield is placed over the connector as shown in Figure 1.

Surface of the cable insulation in between the potential electrode (connector) and ground potential screen (semi conductive insulation shield) were purposely contaminated to facilitate the dielectric loss at the cable joint. Good jointing conditions without any contamination on the cable surface were also created for reference of normal dielectric loss of good joint.

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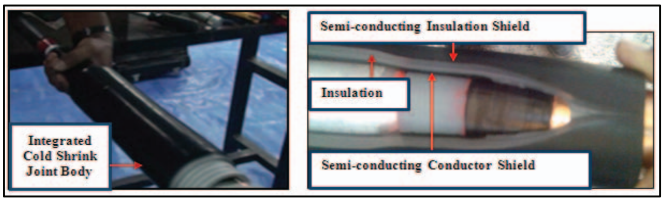


Fig. 1. Integrated cold shrink joint body

Combination of good and defective jointing conditions is crucial to differentiate the responses of tangent delta and for the extraction purposes. For this study, 20 meters of good cable samples with combination of good and defective jointing(s) were prepared and tested.

III. VALIDATION OF TEST SAMPLES

It is known that test samples with defective jointing conditions are prone to having higher tangent delta results. In order to validate these conditions, the test samples were subjected to commercial standard VLF and PF tangent delta equipment. As for reference, solid cable sample (without any joint) of the same length was also tested for comparison. It can be observed in Figure 2 below, the PF tangent delta measurements responded accordingly to the conditions of the samples.

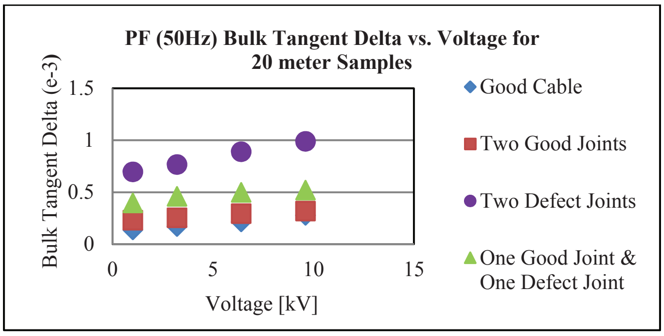


Fig. 2. PF tangent delta test result for 20 meter samples

It can be observed in Figure 3 below, the VLF tangent delta measurements responded accordingly to the conditions of the samples.

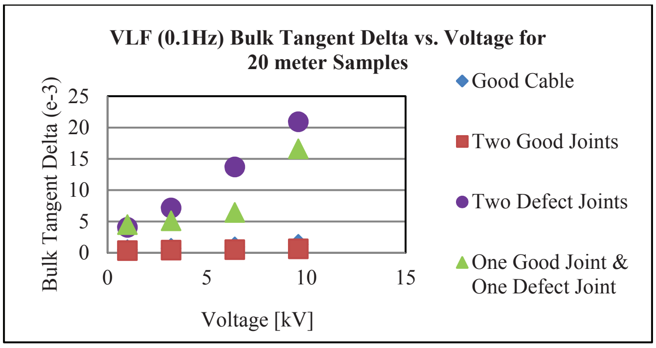


Fig. 3. VLF tangent delta test result for 20 meter samples

The obtained PF and VLF test results above will be used as a reference for the new HFAC test method. It is also noted that the tangent delta using VLF frequency give pronounce response compared to the PF.

IV. HFAC MEASUREMENT TECHNIQUE

A new HFAC tangent delta test method was developed to extract tangent delta results of the tested samples. The equivalent circuit of tangent delta measurement method of a cable is shown in Figure 5 below.

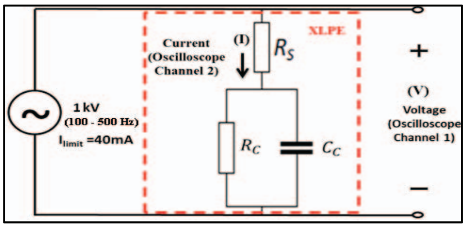


Fig. 5. Equivalent circuit of tangent delta measurement method of a cable

Rs the series resistance of the semi conductive and metallic shield was found to be very small. Hence, the electrical model of the insulation is a model consisting, the R_C and C_C. R_C is the resistive whereas C_C is the capacitive part of the insulation. Tangent Delta is calculated based on the ratio of the current flow in the resistive part to the current flow in the capacitive part of insulation. Higher ratio thus indicates high dielectric loss in the insulation. Hence, tangent delta testing is commonly used as diagnostic method of testing high voltage (HV) electrical equipment to assess the condition of bulk cable insulation. Figure 6 below is representation of loss angle or dissipation factor (δ) in a cable.

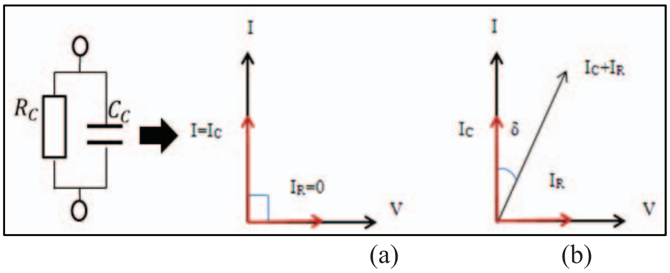


Fig. 6. Representation of loss angle or dissipation factor in a cable as (a) An ideal capacitor or perfect insulator and (b) Capacitor with dielectric loss

R_C = Cable Resistance C_C = Cable Capacitance
I_C = Capacitive Current I_R = Resistive Current
δ = Loss Angle I = Total Current
V = Voltage

Ideally if the insulation of a cable is free from defects, like water trees, electrical trees and moisture, the cable approaches the properties of a perfect capacitor. In a perfect capacitor, the voltage (V) and current (I) are phase shifted by 90 degrees as shown in Figure 5(a). Current through the insulation are purely capacitive current, I_C, which means no resistive current, I_R. If there are defects in the insulation, the resistance of the insulation decreases, resulting in an increase in resistive current through the insulation. It is no longer a perfect capacitor.

Therefore, the voltage (V) and current (I) are no longer shifted 90 degrees as depicted in Figure 5(b). An increasing loss angle (δ) indicates an increase in the resistive current through the insulation, which eventually leads to high dielectric loss. The degree of change of loss angle (δ) represents the tangent delta that depicts the level of ageing in the insulation, which is derived from equations below:

$$Z = Rs + \frac{R_C * \frac{1}{j\omega C_C}}{R_C + \frac{1}{j\omega C_C}} \quad (1)$$

$$Z = Rs + \frac{R_C}{1+\frac{1}{j\omega C_C R_C}} \quad (2)$$

$$(1) = (2) \times \left(\frac{1-j\omega C_C R_C}{1-j\omega C_C R_C}\right)$$

$$Z = Rs + \frac{R_C}{1+\omega^2 C_C^2 R_C^2} - \frac{j\omega C_C R_C^2}{1+\omega^2 C_C^2 R_C^2} \quad (3)$$

$$\frac{V}{I} cos\theta = Rs + \frac{R_C}{1+\omega^2 C_C^2 R_C^2} = imag\theta \quad (4)$$

$$\frac{V}{I} sin\theta = -\frac{\omega C_C R_C^2}{1+\omega^2 C_C^2 R_C^2} = real\theta \quad (5)$$

Since tan θ =real θ / imag θ

$$tan\theta = -\frac{\omega C_C R_C^2}{R_C + Rs(1+\omega^2 C_C^2 R_C^2)} \quad (6)$$

$$tan\theta = -\frac{1}{\frac{1}{\omega C_C R_C} + Rs(\frac{1}{\omega C_C R_C^2} + \omega C_C)} \quad (7)$$

Since $tan\delta = \frac{1}{\omega C_C R_C}$

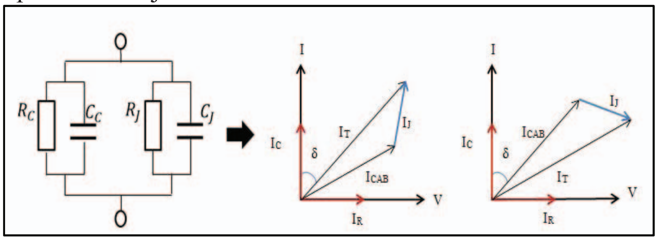
$$tan\theta = -\frac{1}{tan\delta + \frac{Rs}{R_C}(tan\delta + \frac{1}{tan\delta})} \quad (8)$$

Since $R_C >> R_S$

$$tan\theta = -\frac{1}{tan\delta} \quad (9)$$

Z	=	Impedance
R_S	=	Potential Drop which forms a Series Resistance
R_C	=	Cable Resistance
ω	=	Angular frequency ($2\pi f$)
C_C	=	Cable Capacitance
θ	=	Phase between Current and Voltage
V	=	Voltage
I	=	Current
δ	=	Loss Angle

Since the test samples are cable with additional joint component, the representation of loss angle or dissipation factor is depicted in Figure 7 below. The two new components are introduced in a joint which are the resistance of joint R_J and capacitance of joint C_J.



(a) (b)

Fig. 7. Representation of loss angle or dissipation factor in a cable with joint as (a)Displacement current of cable with capacitive joint and (b)Displacement current of cable with resistive joint

If additional joint increases the resistive current of the cable system, Figure 8 below shows trigonometric representations and method use to extract the tangent delta of the joint.

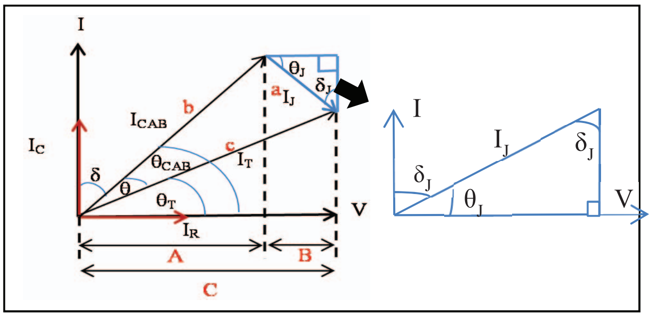


Fig. 8. Trigonometric representations for extraction of joint tangent delta

I_C	= Capacitive Current	I_R	= Resistive Current
I_J	= Joint Current	I_{CAB}	= Cable Current
I_T	= Total Current	θ	= Phase
θ_J	= Joint Phase	θ_{CAB}	= Cable Phase
θ_T	= Total Phase	δ	= Total Loss Angle
δ_J	= Joint Loss Angle		

Basic trigonometric equations are used to extract out the current (I_J) and phase (θ_J) of the resistive joint as follows:

$$I_J^2 = I_{CAB}^2 + I_T^2 - (2 \times I_{CAB} \times I_T \cos\theta) \quad (10)$$

$$\theta = \theta_{CAB} - \theta_T \quad (11)$$

$$cos\theta_{CAB} = \frac{A}{I_{CAB}};\ cos\theta_J = \frac{B}{I_J};\ cos\theta_T = \frac{C}{I_T}$$

Since A + B = C;

$$I_T cos\theta_T = I_{CAB} cos\,\theta_{CAB} + I_J cos\theta_J \quad (12)$$

Hence,

$$\theta_J = cos^{-1}\frac{I_T cos\theta_T - I_{CAB} cos\,\theta_{CAB}}{I_J} \quad (13)$$

$$\delta_J = 180° - 90° - \theta_J \quad (14)$$

In order to perform the calculation, current, I_{CAB} and phase, θ_{CAB} flowing through a good cable was measured as reference. Then, current, I_T and phase, θ_T flowing through the cable with combination of good and defective jointing were subsequently measured. The tangent of the angle delta, δ_J can be calculated to indicate the condition of the joint. Measurement of total current and phase measurement from the conductor to metallic shield through the insulation was done at 1kV voltage and at frequency 100Hz, 200Hz, 300Hz, 400Hz and 500Hz. Figure 9 below shows the HFAC tangent delta test setup. Sinusoidal AC waveform from the waveform generator was fed into the HV amplifier. HV amplifier with 1kV output voltage was applied to the test samples. A clamp current monitor was attached to the HV amplifier output cable to measure the total current flowing through the insulation and HV probe to measure the voltage waveform across the insulation to establish the θ_{CAB} and θ_T.

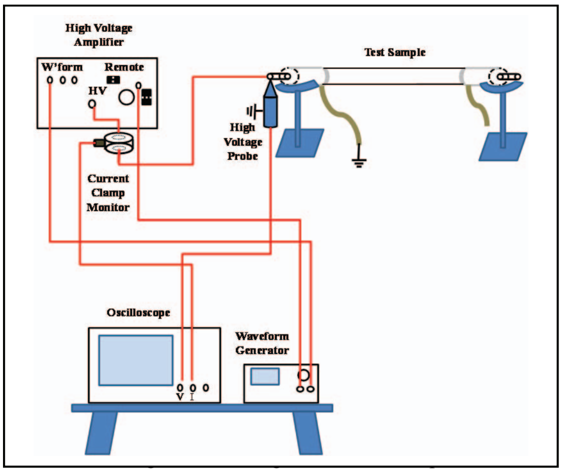


Fig. 9. HFAC tangent delta test setup

V. HFAC MEASUREMENT RESULTS

Tangent delta results of cable joint(s) is extracted from the bulk tangent delta measurement using equations above. Figure 10 shows the extracted tangent delta results for 20 meter test samples.

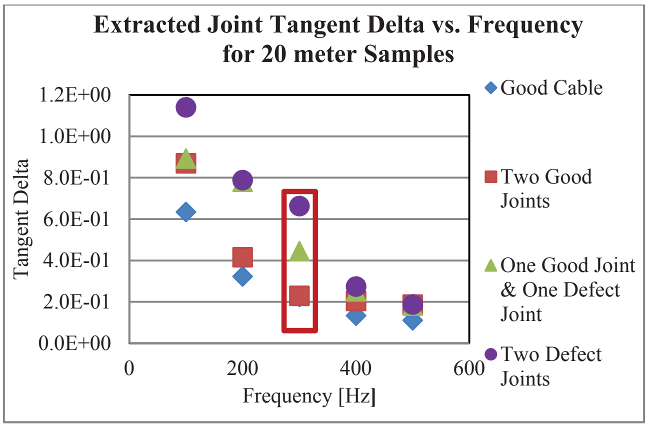


Fig. 10. Extracted joint tangent delta results for 20 meter test samples

Referring to Figure 10 above, the extracted tangent delta results of 20 meter test samples are clearly well discriminated at frequency 300 Hz. The tangent delta results resemble the condition of the joint. The higher the tangent delta of the joint indicates the resistivity of the insulation decreases due to defects in the jointing condition.

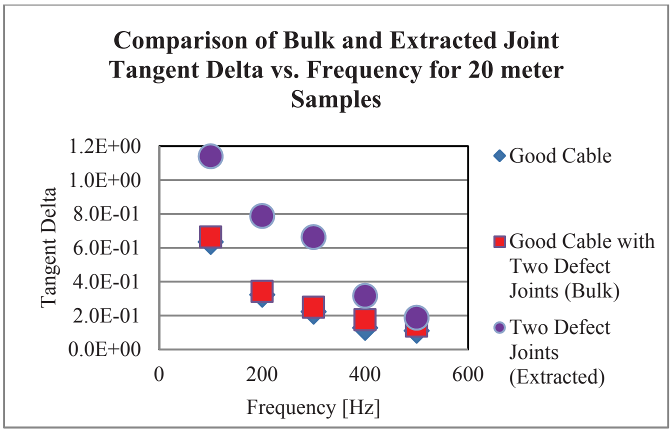


Fig. 11. Tangent Delta of Bulk and Extraction

Referring to Figure 11 above, the bulk tangent delta results of 20 meter test samples with two defect joints is compared with extracted two defect joints. It is visible that the tangent delta of extracted defect joints is higher than the good cable with two defect joints.

VI. CONCLUSION

Existing tangent delta measurement technique of VLF of 0.1Hz or PF 50Hz gives an overall condition of the complete cable system that includes cable, joints and terminations. In this paper, the new HFAC tangent delta test method was established to extract tangent delta of cable joints from the bulk tangent delta measurement. A 20 meter cable and cable with joint(s) were prepared as test samples. Artificially defective jointing conditions were created and installed into the good cable condition to give variation in the dielectric loss response. The defective creations on the test samples were then validated using commercially available VLF and PF tangent delta test method. The VLF and PF tangent delta measurements responded accordingly to the conditions of the samples. Basic trigonometric equations were used to extract out the current and phase of the joint from the measurement results. The extracted tangent delta results of good joints and defective joints are clearly discriminated at frequency 300Hz. The extracted tangent delta is important in order to distinguish the defective component during overall or bulk condition assessment activities. Total replacement of the cable system may be avoided if dielectric loss response is known to be contributed by the joints. Sectionalizing can be done to identify the weak joint. However, further study to establish method to pin point the defective joints within the cable system is of utmost value added to the cable owner in the field so that the rectification maintenance action can be easily and effectively done.

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