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Research Article

High Frequency Tan Delta Measurement Method for 132kV Transmission Underground Cables

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Abstract: Tangent Delta is a measurement technique to investigate cables insulation strength. Current techniques utilize Very Low Frequency (VLF) at 0.1 Hz and power frequency at 50 Hz. However, high voltages are required, thus requiring larger space and cost. Proposed method of tangent delta testing utilizes High frequency Low voltage diagnoses. The phase between the current and the voltage is utilized to determine the tangent delta (tan δ). The aim of this study is to develop a low voltage high frequency tangent delta measurement method and test if it can discriminate manufactured 132 kV good conditioned cable sample from defect induced cables with void, scotched and contamination in its insulation. Impurities are clearly discriminated using this method. Comparison of Tangent Delta of cables manufactured simultaneously in good condition and defect induced is performed using High Frequency Tangent Delta method and in 50 Hz conventional method to validate the effectiveness of the measurement technique. The High Frequency AC setup utilizes a small testing environment which can sample small lengths with minimum 1 m length of cable. The small lengths will result in the reduction of total capacitance of the cable but using High Frequency induces high electric stress on XLPE layer thus resulting in measureable dielectric current.

Keywords: 132 kV Cables, dissipation factor, HFAC, high frequency, tangent delta, XLPE

INTRODUCTION

Current Tangent Delta measurement techniques utilize Very Low Frequency (VLF) at 0.1 Hz and power frequency at 50 Hz. On the contrary, high voltages are required, thus requiring larger space and cost. This method of tangent delta testing utilizes High frequency Low voltage diagnoses and discriminates good cables from faulty ones (Gudmundsdottir *et al*., 2010). Hence, this technique is more economical to assess dielectric insulation condition for any lengths of transmission cables in the laboratory.

Electromagnetic studio simulation (EM simulation) was used to study the contribution of void on the electric field distribution. Comparison between a good insulation and a void induced insulation is made. Cable Suite simulation was used to simulate the sufficiency of dielectric current obtained to confirm the validity of the experimental setup.

Following stage was the development and setup of the high frequency tan delta measurement system. This consists of the acquiring and setting up of the current monitor, high voltage probe, high-speed high-voltage power amplifier, function/arbitrary waveform generators and a screen cage in the lab.

Parallel to the setup is the preparation of the good and defective cables. Contamination and void embedded in the insulation of the cable were manufactured to simulate a intermittent controlled defect. Scotched cables were manufactured to represent a severe defect. Factory acceptance test was conducted on the good and defective cables to discriminate the cables. The 132 kV 400 mm^2 XLPE cable samples were then subjected to High Frequency Tangent Delta testing. Discrimination of intermittent and gross defective cables from good cables is clearly visible with good sensitivity.

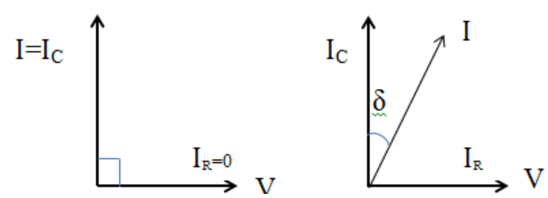

Fig. 1: Equivalent circuits of (a) an ideal capacitor and (b) capacitor with dielectric loss

Figure 1a shows the phase shift for a perfect capacitor. Ideally Current leads Voltage by 90° resembling that only pure capacitive current is present. Figure 1b shows that current and voltage are no longer shifted 90°. This is due to the presence of the resistive current through the insulation because the resistivity of the insulation has degraded (Fothergill *et al*., 2011; Ponniran and Kamarudin, 2008; Hernandez-Mejia *et al*., 2009). This may be the result of impurities like

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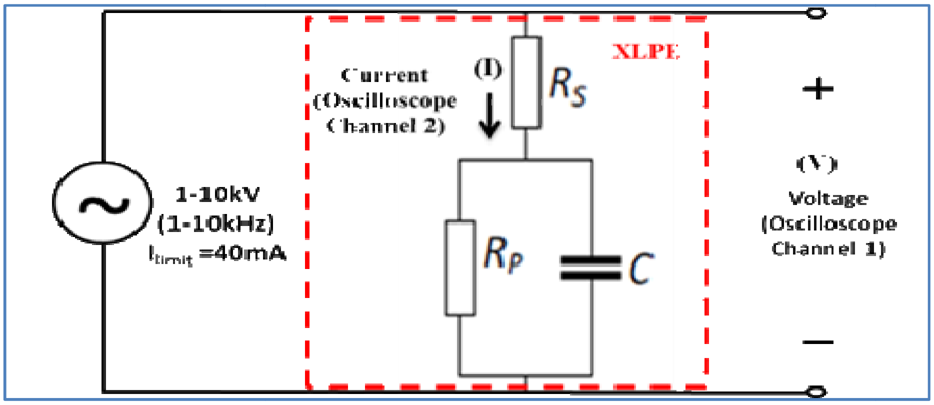


Fig. 2: Equivalent circuit of tan delta measurement method of a cable

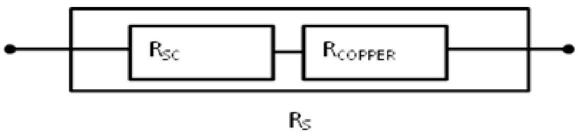


Fig. 3: Equivalent modal of R_S

voids, contamination or scotching effects on the insulation.

The degree of change of phase shift, θ represents the tan delta that depicts the level of aging in the insulation. The equivalent circuit of tan delta measurement method of a cable is shown in Fig. 2.

R_P represents the resistance of the cable insulation and C is the capacitance. Impurities in the insulation reduce the resistance of the insulation thus increasing resistive current through the insulation (Ponniran and Kamarudin, 2008).

A series resistance R_S with the cable insulation is formed due to a potential drop across the cable. This is influenced by the increase of frequency as displacement current increase as well. R_S is the combination of R_{SC} (series resistance of semiconductor) and R_{COPPER} (series resistance of copper i.e., metallic sheath and core) as shown in Fig. 3 above. Since R_{SC} is much larger than R_{COPPER} therefore $R_S \approx R_{SC}$ (Hernandez-Mejia *et al.*, 2009; Phung *et al.*, 2008; Martí, 1988).

Hence, this study is to develop new technique for the measurement of tan delta at Low Voltage High Frequency (LV-HF) for 132 kV XLPE cable. The study will provide an alternative means to practically and effectively measure the tan-delta of high voltage power cable. This method of tangent delta testing utilizes High frequency Low voltage will be able to and discriminates good cables from faulty ones. Hence, this technique is more economical to assess dielectric insulation condition for any lengths of transmission cables in the laboratory.

METHODOLOGY

In this project, the research methodologies are as Fig. 4 below:

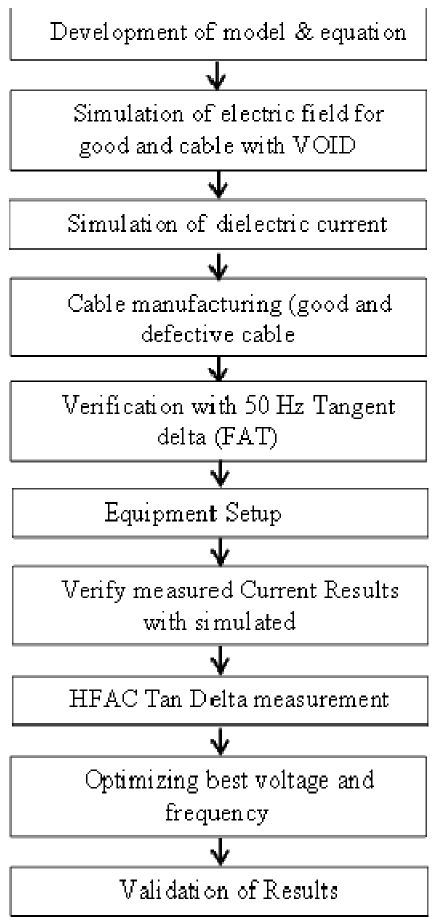


Fig. 4: Methodology

Tangent delta equation: From Fig. 2, equivalent impedance of cable is:

$$Z = Rs + \frac{Rp * \frac{1}{j\omega C}}{Rp + \frac{1}{j\omega C}} \tag{1}$$

$$Z = Rs + \frac{Rp}{1 + \frac{1}{j\omega CRp}} \tag{2}$$

$$(3) = (2) \times \left(\frac{1-j\omega CRp}{1-j\omega CRp}\right)$$

$$Z = Rs + \frac{Rp}{1+\omega^2 C^2 Rp^2} - \frac{j\omega CRp^2}{1+\omega^2 C^2 Rp^2} \tag{3}$$

The resistance and reactance components are separated:

$$\frac{V}{I} cos\theta = Rs + \frac{Rp}{1+\omega^2 C^2 Rp^2} = imag\theta \tag{4}$$

$$\frac{V}{I} sin\theta = -\frac{\omega CRp^2}{1+\omega^2 C^2 Rp^2} = real\theta \tag{5}$$

Since tan θ =real θ / imag θ

$$tan\theta = -\frac{\omega CRp^2}{Rp+Rs(1+\omega^2 C^2 Rp^2)} \tag{6}$$

$$tan\theta = -\frac{1}{\frac{1}{\omega CRp}+Rs(\frac{1}{\omega CRp^2}+\omega C)} \tag{7}$$

Since $tan\delta = \frac{1}{\omega CRp}$

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

Since Rp>>Rs

$$tan\theta = -\frac{1}{tan\delta} \tag{9}$$

where,

Z = Impedance
R_s = Potential drop which forms a series resistance
R_p = Resistance of the cable insulation
ω = Angular frequency (2πf)
C = Capacitance
θ = Phase between current and voltage
V = Voltage
I = Current
δ = Dissipation angle

RESULTS AND DISCUSSION

Field and dissipation current simulation (CST EM and CABLE): For the simulation, the Electromagnetic

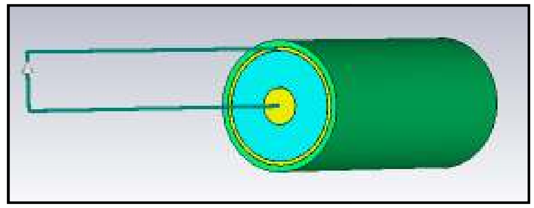


Fig. 5: The cable model for the electric field simulation

Computer Simulation Technology Studio (CST EM) was used to model to perform electric field simulation.

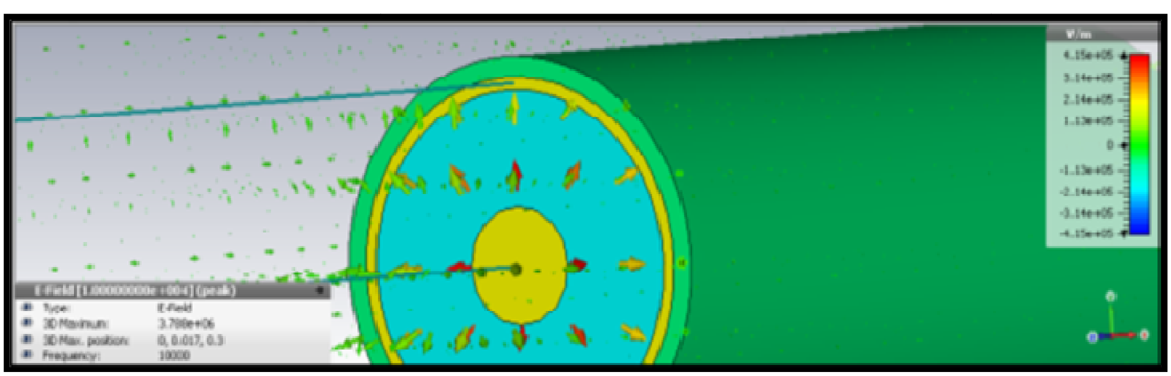
The cable 3D model is shown in Fig. 5 above. The structure in the model was created based on all the characteristics of 132 kV cable. The properties of the cable and the boundary conditions were pre-set and then a voltage source inserted between the core and sheath as the excitation source. The arrow indicates the oscillating voltage source. The applied source voltage is 1kV voltage and 10 kHz frequency. The outer sheath is grounded.

Two cases for the electric field vector and scalar plots were simulated which are cable without air void and cable with air void (as discussed below). This simulation was performed to show the effect of the electric field and localized perturbation by the presence of void. Figure 6a and b shows the electric field vector and scalar plots for the cable with no air void.

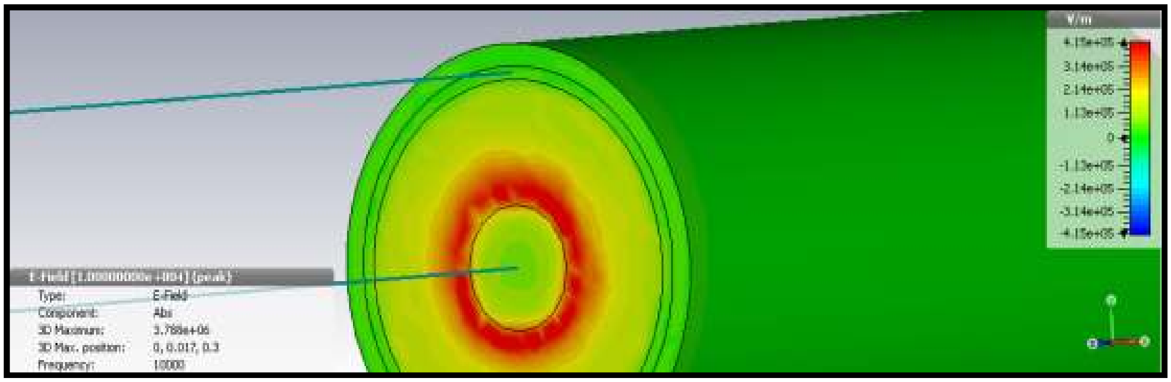
Cable with no air void: The results show clear azimuthal field uniformity. Figure 7 below shows that the field exhibits inverse relationship in which the field gradually decreases towards the sheath.

Cable with air void: Figure 8a and b shows the electric field vector and scalar plots for the cable with air void. The void has 1 mm in diameter and located about 20 mm from the center of the core.

The results clearly show that the electric field distribution is perturbed due to the presence of the air void. A localized hot spot is also clearly visible in the scalar plot as shown in Fig. 8b at the location of the void. In order to depict this, the electric field vs radial



(a): Electric Field 3D Vector Plot without air voids



(b): Electric Field 3D Scalar Plot without air voids

Fig. 6: Electric field vector and scalar plots for the cable with no air void

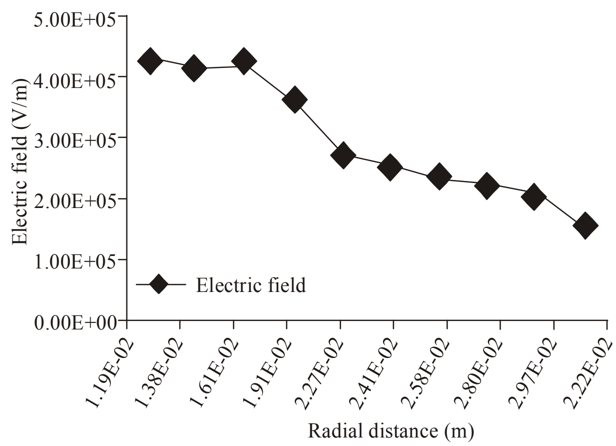


Fig. 7: The plot of electric field vs. radial distance for the cable with no air void

distance in Fig. 9 explicitly shows the electric field magnitude actually peaked at about 2 cm from the core thus justifying effect of the void on electric field distribution.

Cable suite simulation for charging current: Cable suite setup is shown in Fig. 10 below.

The comparison of current results at power frequency is shown in Fig. 11a and High Frequency is shown Figure 11b to d. The results for 132 kV from 10 to 100 Hz represents power frequency meanwhile results at 2, 6 and 10 kV, represents High Frequency simulation.

Figure 11, it is shown that the charging current for 2 kV, 6 kV, 10 kV at 1 kHz is 1.53, 4.36 and 7.20 mA and is comparable with 132 kV 50 Hz which is 10.5 mA. From the simulation results, it seems that 1kV 10 kHz seem to be in good agreement with 132 kV 50 Hz. Nevertheless, this simulated result is verified with laboratory experiment.

132 kV Sample preparation: Four types of 132 kV 400 mm^2 Cu XLPE cable samples were prepared by cable manufacturer. The cable samples consist of the following:

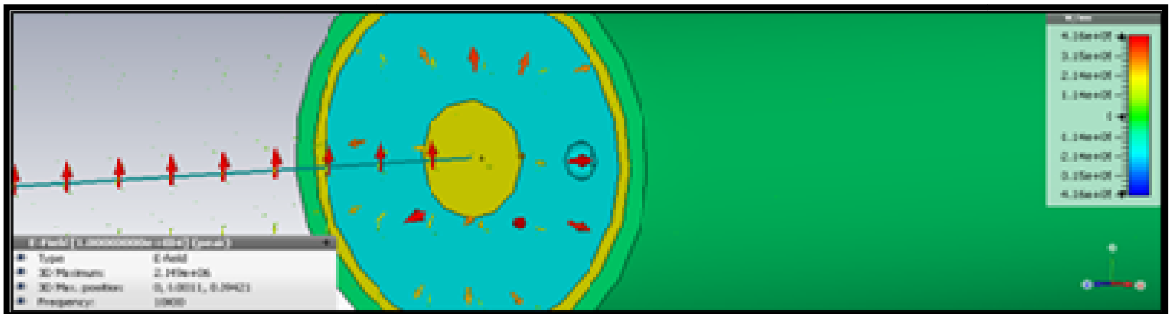
Good cable preparation: The head is where 3 extruded layers are combined. Nitrogen is introduced as inert gases to reduce the chances or corrosion at high temperatures during curing.

Scotched cable preparation: Temperature of Zone 4 to 6 of Extruder 3 for outer semiconductor extrusion is ramped to 150°C to create a scotching effect as shown in Fig. 12.

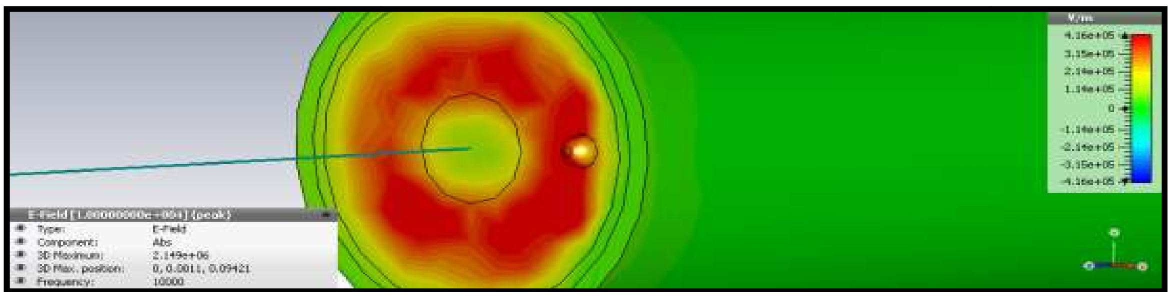
Void cable preparation: The pressure of the XLPE extrusion curing oven has been reduced from 10 to 4 bars to introduce void in the XLPE region.

Contaminated cable preparation: Parameters are the same as good cable but filter is changed to 20 holes per cm² type to create to allow wood ash contamination to be positioned into XLPE extruder as shown in Fig. 13.

The Tangent Delta measurement using conventional 50 Hz was conducted as Factory Acceptance Test. Figure 14 shows that the order of



(a): Electric Field 3D Vector Plot with air void



(b): Electric Field 3D Scalar Plot with air void

Fig. 8: Electric field vector and scalar plots for the cable with air void

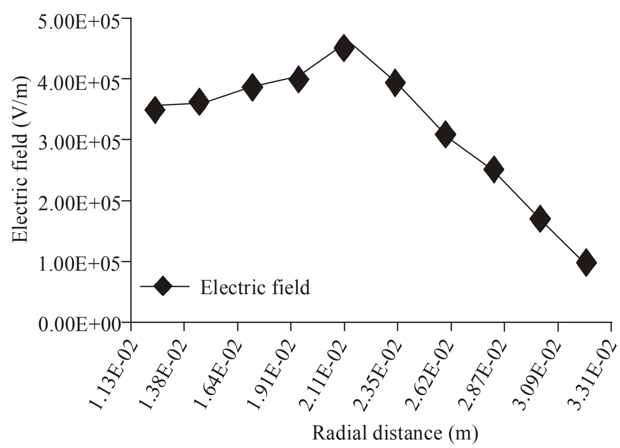


Fig. 9: The plot of electric field vs radial distance for the cable with air void

Tangent Delta with Scotched being the worst followed by Contamination Void and Good.

HF EXPERIMENT SETUP

The laboratory test was carried out using the newly developed tan delta measurement method. The setup is shown in Fig. 15 and 16.

The equipment for HF Tan Delta Test consists of:

- High voltage power amplifier
- Current monitor
- High voltage probe
- Oscilloscope
- Waveform generator
- Screen cage
- 132 kV 400 mm² single core cable (1 m length)

Figure 17a to c shows the current vs. frequency for 2 kV, 6 kV and 10 kV.

Based on the figures above, at 2kV, scotched cable is clearly differentiated from the rest. The dissipated current measured for 2 kV, 6 kV and 10 kV for the 132 kV 400 mm² cable shows good<contamination<void <scotching. At 6 and 10 kV, defect cables are clearly discriminated from good cable. However, current reaches amplifier limit of 40 mA for 6 and 10 kV when

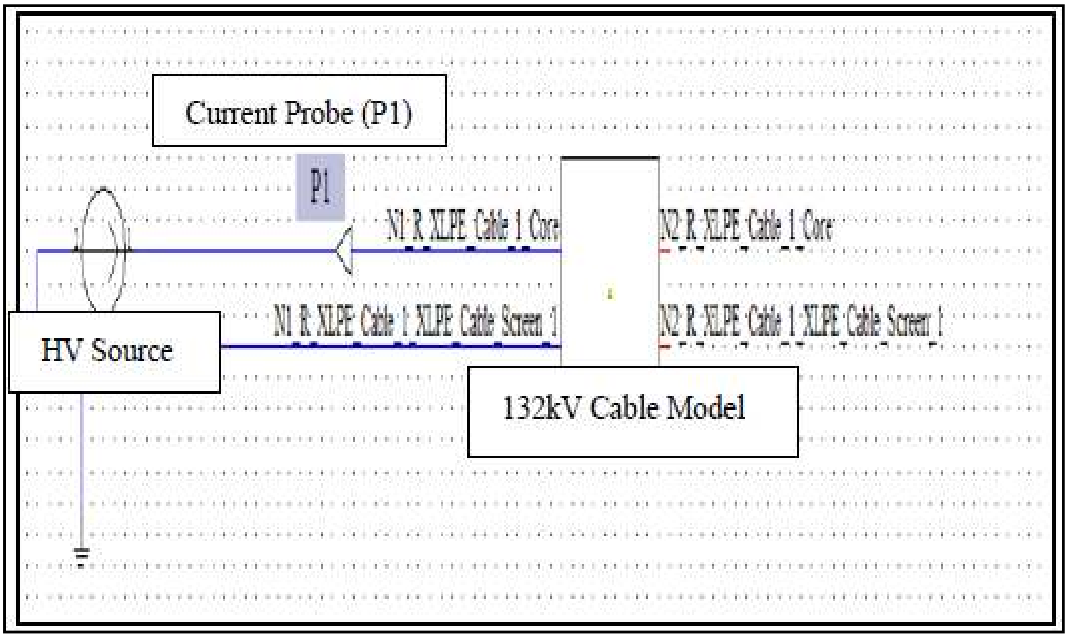


Fig. 10: Circuit diagram for simulation using CST cable

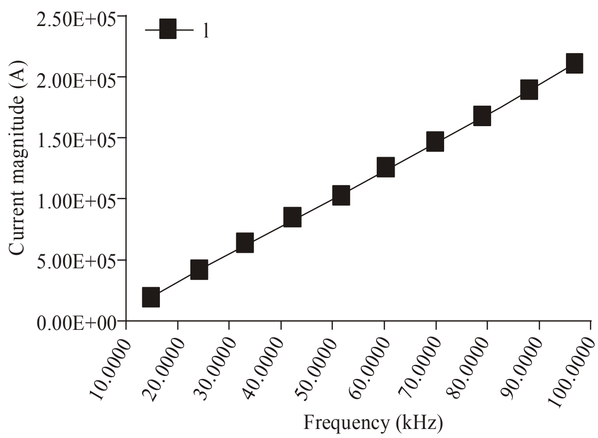


Fig. 11a: Current vs. frequency results for 132kV from 10 to 100 Hz

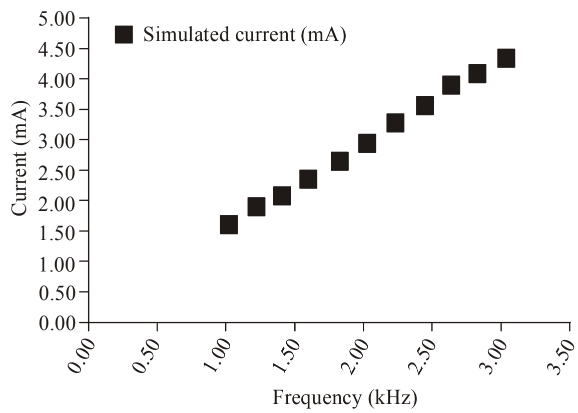


Fig. 11b: Current vs. frequency results for 2kV from 1 to 3 kHz

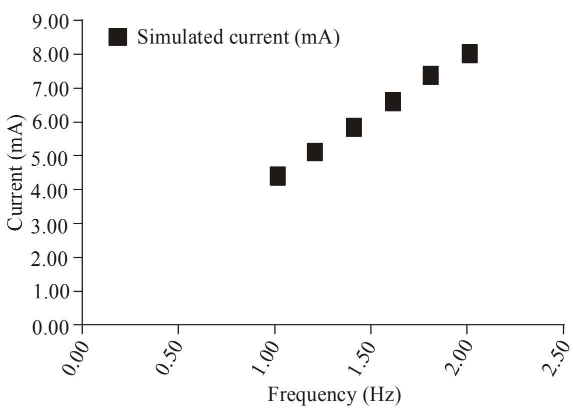


Fig. 11c: Current vs. frequency results for 6kV from 1 to 2 kHz

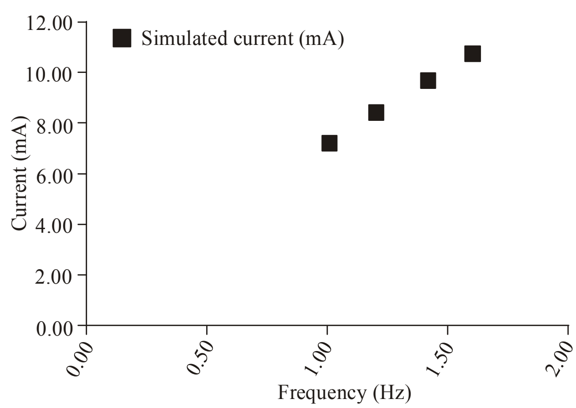


Fig. 11d: Current vs. frequency results for 10kV from 1 to 1.6 kHz

(a) (b) (c)

Fig. 12: (a): Good semicon layer; (b): Scotched semicon layer; (c): Scotched XLPE layer

Fig. 13: Wood dust particle inserted into machine to create contaminated cable

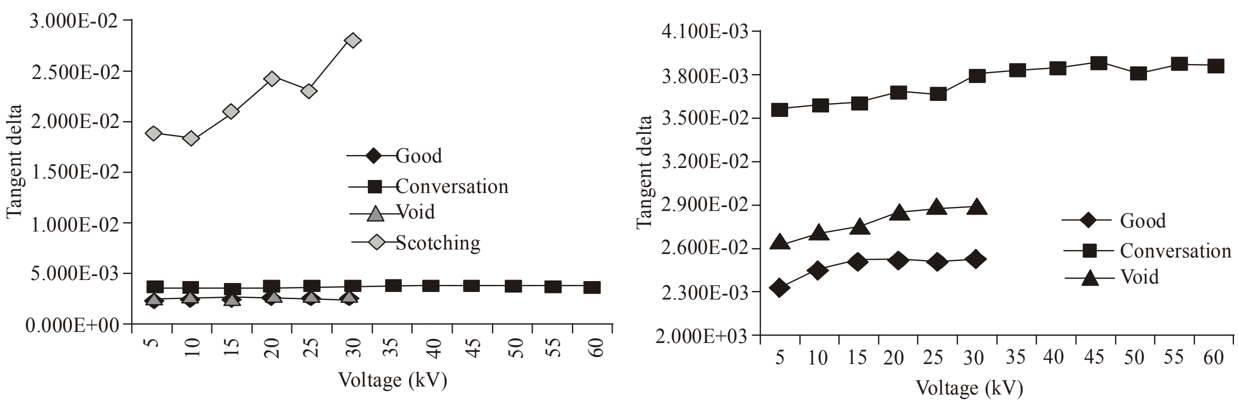


Fig. 14: (a and b) Tangent delta 50 Hz results (FAT)

Fig. 15: Laboratory setup for HF tan delta measurement system

using scotched cable (signal clipping), therefore the test could not be continued for scotched cable at 6 kV and 10 kV.

Figure 18 shows the Current vs. Frequency simulated vs. measured for (a) 2kV (b) 6kV (c) 10kV good cables.

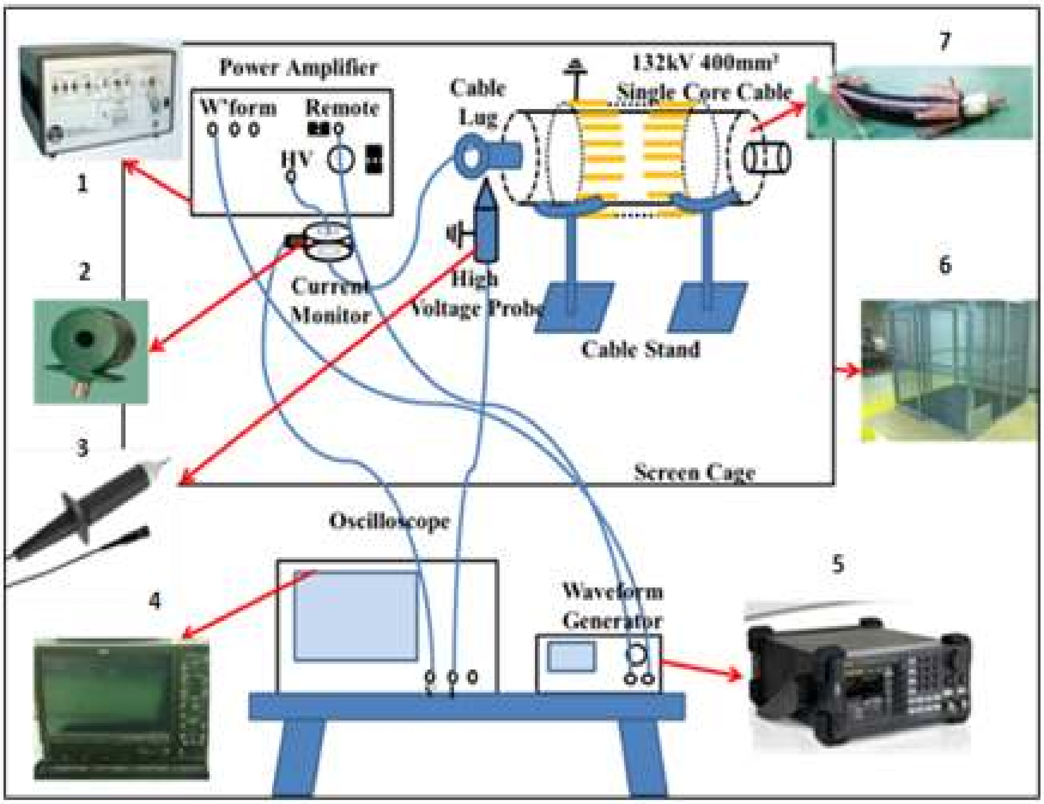


Fig. 16: Equipment setup

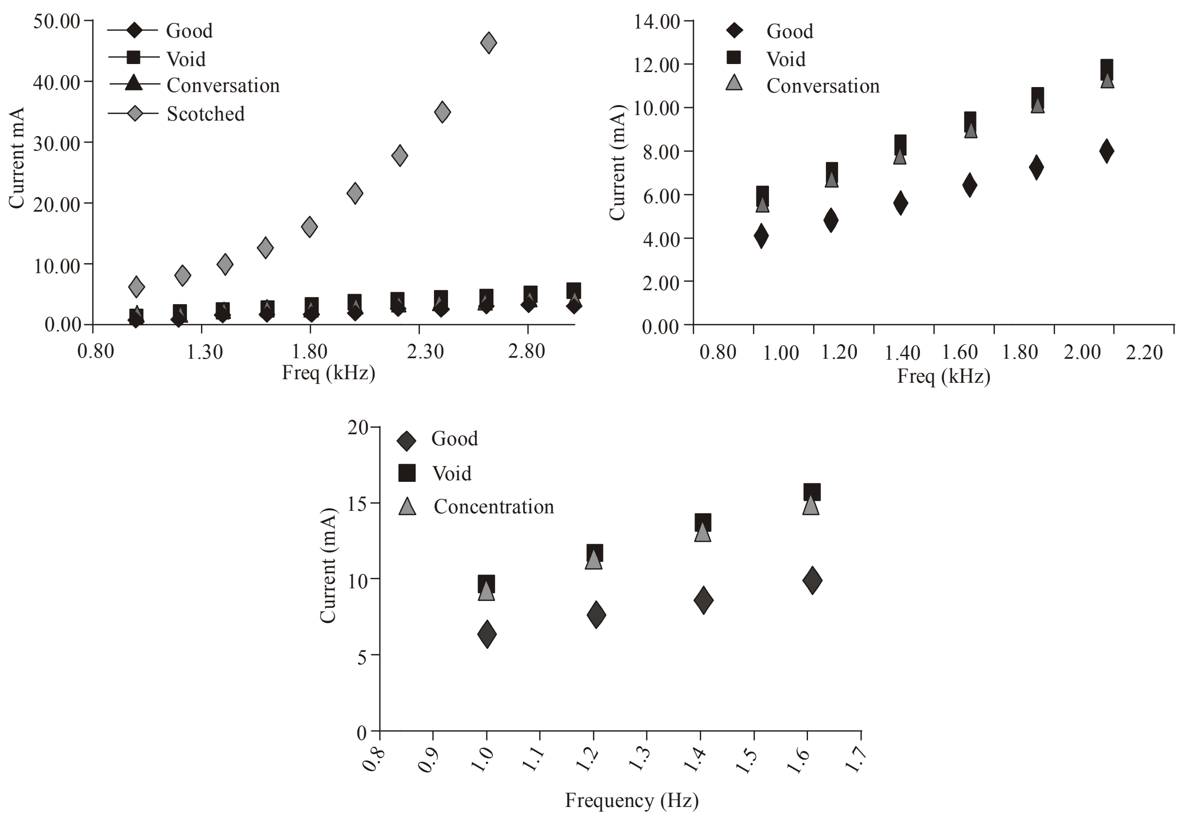


Fig. 17: Current vs. Frequency for; (a): 2kV; (b): 6kV; (c): 10 kV

The measured current and simulated current are very close to each other for good cable comparison.

Figure 19a to c shows the tan delta vs. frequency for 2, 6 and 10 kV, respectively.

At 6 kV and 10 kV, defect cables are clearly discriminated from good cable. The scatter plot for tan delta 1 kHz at 6 kV and 10 kV able to discriminate tangent delta value of contamination>void>good cable samples.

The newly developed HF tan delta measurement method able to discriminate tan delta value of contamination>void>good cables at 6 kV and 10 kV. The best resolution of tan delta between all the cables is clearly seen at 6kV at 1 kHz as shown in Fig. 20.

50 Hz tan delta test was performed at 5 kV and 10 kV. Whereas, HF tan delta (1 kHz) was performed at 2, 6, 10 kV, respectively. Based on Fig. 21, at 50 Hz tan delta values are poorly discriminated between all the cables at 5 kV and 10 kV. At 1 kHz tan delta values are clearly discriminated between all the cables at 6 kV and10 kV. Discrimination is much better using HF tan delta measurement method developed.

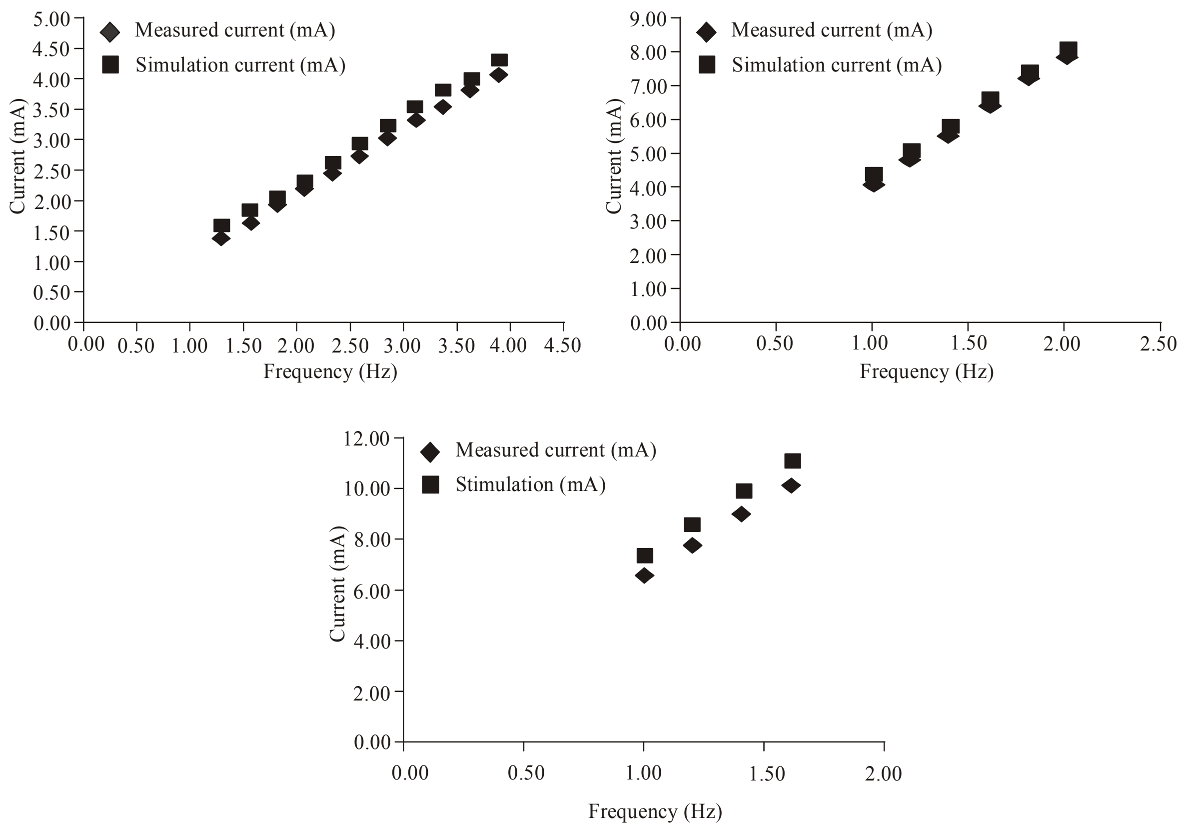
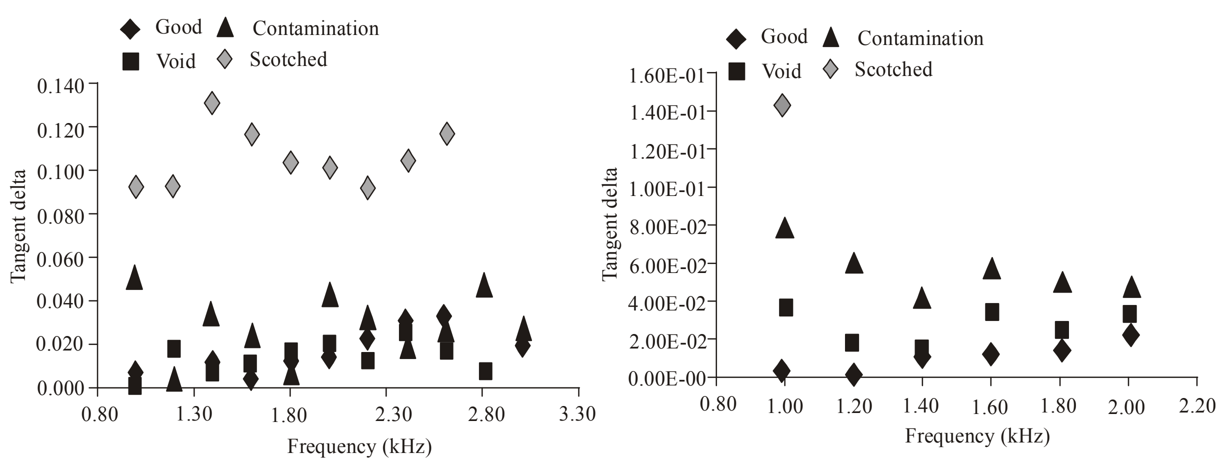


Fig. 18: Current vs. Frequency simulated and measured for; (a): 2kV; (b): 6kV; (c): 10kV good cables



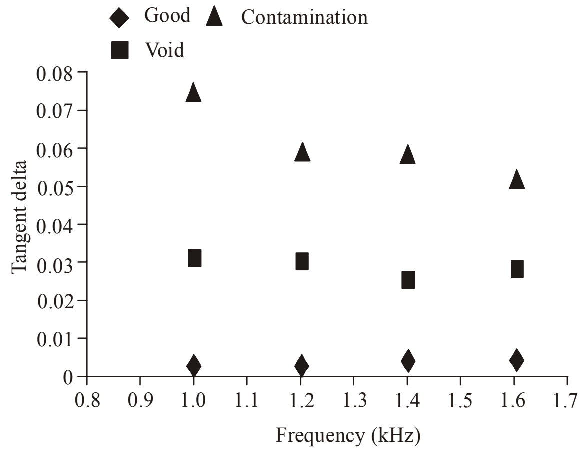


Fig. 19: Tan Delta vs. Frequency for (a): 2kV; (b): 6kV; (c): 10kV

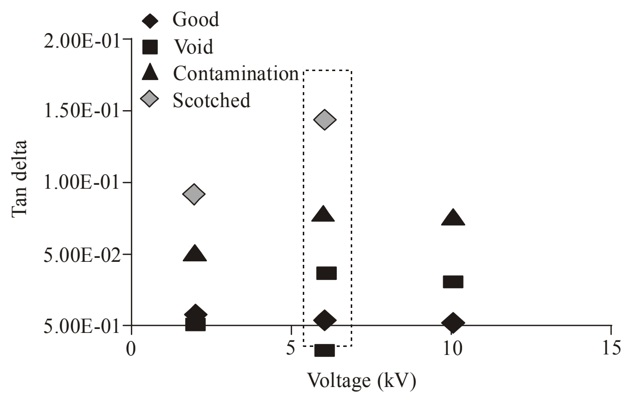


Fig. 20: Tan delta vs voltage at 1kHz

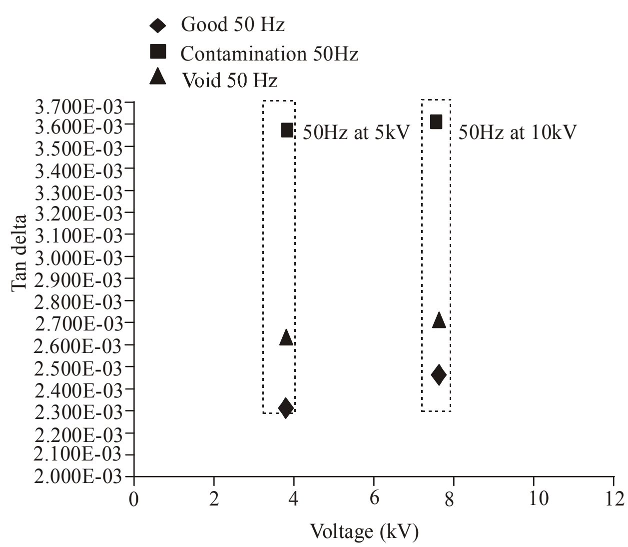


Fig. 21: Tan delta vs. voltage at 50 Hz

CONCLUSION

The 132 kV good conditioned cable sample and several types of defect were manufactured and tested using the new developed high frequency tangent delta system.

These cable samples were tested with the newly developed low voltage high frequency tangent delta measurement method. The new tangent delta measurement proves that phase shift angle by charging a small capacitance cable of 1 m length can be used to obtain tangent delta.

Measurements for 132 kV cable are attainable using frequency range of 1-5 kHz and applied voltage ranging from 1 kV-10 kV. The optimum was found to be at 1 kHz. At 6 kV and 10 kV, defect cables are clearly discriminated from good cable. The scatter plot for tan delta 1 kHz at 6 kV able to discriminate tangent delta value of contamination>void>good cable samples.

Thus this newly developed HF tan delta measurement system can be used as an indicative test to pre-determine the condition of 1 m cable in the laboratory. By developing a correlation method, the tan delta results in HF can be correlated to 50 Hz tan delta values in the future.

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