Measurement of Cable System Losses using Time Domain and VLF Techniques

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1. VLF and TDS Principles

2. Correlation between Tan $\delta$ measurements at VLF and TDS
   2.1 New cables
   2.2 Joints
   2.3 Field aged cables

3. Neutral issues for VLF

4. Effect of polluted terminations

5. “Arithmetic” of Tan $\delta$ at VLF and TDS (overview)

6. Conclusions
Dielectric losses - Tan δ

- The cable insulation system is represented by an equivalent circuit.
- It consists of two parameters; a resistor and a capacitor [IEEE Std. 400].
- When voltage is applied to the cable, the total current will be the contributions of the capacitor current and the resistor current.

\[
\tan(\delta) = DF = \frac{I_R}{I_C} = \frac{1}{\omega RC}
\]
Dielectric losses - VLF principle

- Frequency domain
- In this case, performed in AC (sine wave) "VLF" (0.1 Hz to 0.02 Hz)
- Derived from the phase angle difference between $I$ and $V$
Dielectric losses - TDS principle

- **Time domain**
- Based on current measurements under DC voltage
- Dielectric losses derived from the current contributions using Hamon approximation

**Principle**

\[
\begin{align*}
\text{Voltage} & \quad \text{Current} \\
V & \quad i_{\text{pol}}(t) \\
\text{time} & \quad t_0, t_{\text{rel}}, t_{\text{rel}} \\
\text{Dielectric loss} & \approx \frac{i \times t}{0.528 \times V \times C} \\
i_{\text{pol}}(t) & = i_{\text{cap}}(t) + i_{\text{abs}}(t) + i_{\text{qc}}(t) \\
i_{\text{depol}}(t) & = -i_{\text{cap}}(t) - i_{\text{abs}}(t)
\end{align*}
\]

**Schematic of TDS device**

(Grounded config.)

**Sensitivity**

- **M**: Multimeter \(10 \times 10^{-9} \text{ A} \)
- **E**: Electrometer \(1 \times 10^{-12} \text{ A} \)
1 – VLF and TDS Principles

IREQ's TDS system

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>Grounded</th>
<th>Ungrounded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol</td>
<td>Depol</td>
<td>Pol</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Electrometer</td>
<td>Electrometer</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Sensitivity</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>( \sim 10 \times 10^9 \text{ A} )</td>
<td>( \sim 1 \times 10^{12} \text{ A} )</td>
<td>( \sim 1 \times 10^9 \text{ A} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXPERIMENTAL PROCEDURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltage</td>
</tr>
<tr>
<td>( \text{kV} )</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>2.9 - 5.8 - 8.7</td>
</tr>
</tbody>
</table>

![Graph showing voltage and time]
Dielectric losses - TDS principle

- Example of current measurement

\[ i_{\text{pol}}(t) = i_{\text{cap}}(t) + i_{\text{abs}}(t) + i_{\text{qc}}(t) \]
\[ i_{\text{depol}}(t) = -i_{\text{cap}}(t) - i_{\text{abs}}(t) \]
Dielectric losses - TDS principle

• Application of the Hamon approximation
1 – VLF and TDS Principles

Tan δ : VLF vs TDS

**VLF**
- Frequency domain
- Sinusoidal waveform
- Computed from a phase difference
- Tan δ at different frequencies requires different tests
- Monitored withstand

**TDS**
- Time domain
- DC waveform
- Estimated using the Hamon approximation
- One test at a particular test voltage provides Tan δ at different frequencies
- Monitored withstand
1 – VLF and TDS Principles

VLF & TDS Laboratory Setups
2 – Correlation between \( \tan \delta \) measurements at VLF and TDS

2.1 New cables - TR-XLPE

[Diagram: DIELECTRIC LOSSES (\( \tan \delta \)): VLF vs TDS]

Cable: TR-XLPE New 200 f (Neetrac)
2 – Correlation between \( \text{Tan } \delta \) measurements at VLF and TDS

2.1 New cables - EPR
2 – Correlation between $\tan \delta$ measurements at VLF and TDS

2.2 Joints - PIT3-C1

![Graph showing correlation between $\tan \delta$ measurements at VLF and TDS for Joint: PIT3-C1 (Neetrac)]
2 – Correlation between $\tan \delta$ measurements at VLF and TDS

2.2 Joints - PIT3-C2
2 – **Correlation between Tan δ measurements at VLF and TDS**

2.3 Field aged cables - S-1-3
2 – Correlation between \( \tan \delta \) measurements at VLF and TDS

**Correlation \( \tan \delta \) - VLF vs TDS**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Values at 0.02 Hz and Uo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Aged Cable</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

Other includes:
- Non-aged cables, field-aged joints and cable-joint combinations.

![Graph showing correlation between \( \tan \delta \) at VLF and TDS](image-url)
Correlation between Tan δ measurements at VLF and TDS – Interim Conclusions

• Good correlation between Tan δ from VLF and Tan δ from TDS for samples not evolving during test.

• Spectrums seem to complement each other.
3 – *Neutral Issues for VLF*

- **Insulation Shield**
- **Cotton Pads**
- **Neutral Strap**

![Image of testing end](image1)

![Image of neutral issues](image2)
3 – Neutral Issues for VLF
3 – Neutral Issues for VLF

EPR with Good neutral connection

DIELECTRIC LOSSES (tan δ): VLF vs TDS

Cable: EPR(2) New 80 f (Neetrac) Good neutral connection with insul. shield
3 – **Neutral Issues for VLF**

EPR with **Bad** neutral connection

![Graph of Dielectric Losses vs Frequency](image)

**Cable:** EPR(2) New 80 f (Neetrac)  
**BAD neutral connection with insul. shield**
It is normal practice in the field to thoroughly clean terminations. Insufficient cleaning can occur but is readily spotted by divergent behavior of the capacitance, loss and voltage dependence. Nevertheless there was an academic interest to investigate the magnitude of this effect on the cable system loss.
4 – Effect of highly polluted terminations

Normal clean test terminations prior to pollution

Polluted test terminations
4 – *Effect of polluted terminations*

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Tan-delta [1e-3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33 (U_0)</td>
<td>0.33 Uo 0.67 Uo 1.0 Uo</td>
</tr>
<tr>
<td>0.67 (U_0)</td>
<td>VLF of 0.1 Hz</td>
</tr>
<tr>
<td>1.0 (U_0)</td>
<td>Termination flashover</td>
</tr>
</tbody>
</table>

Condition
- Clean
- Polluted - Dry
- Polluted - Humid
- Polluted - Wet
Effect of polluted terminations

Failure channel

Highly polluted surface
TR-XLPE cable system without splive
5 – "Arithmetic" of Tan δ at VLF and TDS (Overview)

Joint PIT3-C1 alone
TR-XLPE system cable PLUS Joint PIT3-C1
As measured directly:

DIELECTRIC LOSSES (tan δ): VLF vs TDS

- 2.5 kV VLF
- 5.5 kV VLF
- 8.7 kV VLF
- 2.5 kV TDS (core)
- 5.5 kV TDS (core)
- 8.7 kV TDS (core)
- 2.5 kV TDS (deck)
- 5.5 kV TDS (deck)
- 8.7 kV TDS (deck)

C" measurement (direct)
5 – "Arithmetic" of Tan $\delta$ at VLF and TDS

TR-XLPE system cable PLUS Joint PIT3-C1

As calculated by sum of individual contributions:

![DIELECTRIC LOSSES (tan $\delta$): VLF vs TDS](image)
6 – **Conclusions**

- Good correlation between $\tan \delta$ from VLF and $\tan \delta$ from TDS for samples not evolving during test.
- Spectrums seem to complement each other.
- Polluted terminations influence cable system loss measurements.
- TDS seems less perturbed by neutral issues than VLF.
- “Arithmetic” of cable system loss works for TDS as well as for VLF.