CONDITION ASSESSMENT OF MEDIUM VOLTAGE UNDERGROUND CABLES BASED ON TANGENT DELTA AND PARTIAL DISCHARGE MEASUREMENTS

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ABSTRACT
The suitability of 0.1 Hz VLF tangent delta (TD) and three different partial discharge (PD) measurement methods for condition assessment and commissioning measurements of MV underground cable systems were studied. On-site measurements were conducted in MV networks of 12 Finnish distribution network operators (DNOs) on a total of 100 three phase cable systems of different ages and 5 different cable types. Based on the TD measurement results the limits given in IEEE Std400.2-2013 seem too high for Finnish cable systems. No clear correlation between the PD and TD measurement results or the age of the cable and TD was observed. It could be concluded that the measurements complement each other revealing different degradation mechanisms. TD measurement does not reliably reveal the presence of PD and thus, for cable commissioning, PD measurement is recommended.

INTRODUCTION
Condition assessment (CA) of MV cables is becoming increasingly important as a considerable part of city networks is coming to the end of its planned lifetime. With a reliable condition assessment method the replacement of old cables could be made based on the cable condition and not on age. Thus, considerable cost savings could be achieved in network investments by extending the lifetime of still well-performing cables and in interruption costs by replacing the most degraded cables in time before they fail.

Various measurement methods are available for condition assessment of underground cables. Tangent delta (TD, also known as dissipation factor or loss angle) measurement and partial discharge (PD) measurement are among the most well known and versatile ones. Research results and practical experience of the methods has been reported in several studies [1-3] and there are service providers offering these measurements as a commercial service to DNOs. Recently, also standards have been published to support the preferred implementation of the measurements and interpretation of the measurement results [4]. For example, IEEE Std400.2 – 2013 considering VLF tangent delta measurements defines three condition classes for cables (“no action required”, “further study advised” and “action required”) and sets limits for each class for the three different tan-delta parameters defined in the standard. The main aims of this paper are to study the suitability of these limits to Finnish cable systems and to compare the suitability of VLF tangent delta and different PD measurement methods to CA of MV cables.

CABLES STUDIED
On-site measurements were conducted in MV networks of 12 Finnish DNOs on a total of 100 three phase cable systems of different ages and different cable types. The total length of the cables was 44.6 km and the DNOs were located around the country including both city and rural DNOs. The cable types studied are presented in Table 1.

Table 1. Cables studied.

<table>
<thead>
<tr>
<th>System voltage [kV]</th>
<th>Cable type</th>
<th>Installation years</th>
<th>Number of cables [pcs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Paper-oil</td>
<td>Hochstadter *)</td>
<td>1967-1989</td>
<td>15</td>
</tr>
<tr>
<td>10 Paper-oil</td>
<td>Belted</td>
<td>1966-1990</td>
<td>9</td>
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<tr>
<td>10 Paper-oil</td>
<td>Belted</td>
<td>1950-1972</td>
<td>7</td>
</tr>
<tr>
<td>10 XLPE</td>
<td>Single core</td>
<td>2012</td>
<td>1</td>
</tr>
<tr>
<td>20 XLPE</td>
<td>Single core</td>
<td>1985-2015</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>100</td>
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</tbody>
</table>

*) belted with separate shield around each core

TD AND PD MEASUREMENT METHODS
Four different measurement methods were used. Two of them were off-line methods: 0.1 Hz VLF tangent delta measurement and PD measurement using DAC (damped AC) method. These measurements were conducted on all the studied 100 cables. Two of the methods were on-line PD measurements: HFCT (high frequency current transformer) method and Pry-Cam, which is based on measuring electromagnetic field around the cable. These measurements were conducted on approx. half of the cables. Off-line measurements were conducted by disconnecting the cable from the network by the disconnectors at both ends of the cable, i.e. halves of the disconnectors were also connected to the cable measured.

VLF tangent delta measurement
VLF tangent delta measurements were conducted according to IEEE Std400.2 – 2013 at 0.1 Hz frequency at
Voltage levels of 0.5 $U_0$, 1.0 $U_0$ and 1.5 $U_0$, where $U_0$ is the normal operating voltage of the cable. The principle of tangent delta measurement is presented in Figure 1 showing an equivalent circuit of the cable insulation and the capacitive and resistive current through it.

![Equivalent circuit of the cable insulation and phasor diagram of the currents considered in TD measurement](image1.png)

**Figure 1.** Equivalent circuit of the cable insulation and phasor diagram of the currents considered in TD measurement [1].

Tangent delta can be calculated from these current components according to Equation (1) below:

$$\tan\delta = \frac{1}{\omega R C} = \frac{I_R}{I_C}$$  \hspace{1cm} (1)

The advantage of the VLF method compared to e.g. power frequency and DAC methods is better sensitivity and accuracy due to the lower capacitive current through the insulation studied. The disadvantage of tangent delta measurement compared to e.g. partial discharge measurement is that it gives a single reading for the whole insulation i.e. it cannot locate the deteriorated spot or region of the cable.

**Off-line DAC PD measurement**

The basic principle of a DAC PD measurement system is presented in Figure 2. The cable insulation (one phase at a time) is charged with a DC voltage and then connected in parallel with an inductor forming a resonant circuit where the voltage oscillates at a frequency determined by the cable capacitance and inductor inductance. Due to the circuit losses, the amplitude of the voltage decays in time.

![Principle of DAC PD measurement system](image2.png)

**Figure 2.** Principle of DAC PD measurement system [3].

Compared to VLF PD measurement DAC method is more efficient due to the higher frequency of the test voltage (typically some hundreds of Hz), which allows collecting an adequate number of PD pulses for the analysis in shorter time. In principle, the decaying voltage amplitude also allows the determination of PD extinction voltage with a single measurement. A drawback of the DAC method is that the test voltage frequency depends on the cable capacitance, which may have some effect on the results.

**On-line PD measurements**

The HFCT measurement is based on measuring the PD current pulses flowing in the cable conductor and cable screen. The measurement system consists of three HFCTs installed around the necks of the cable terminations of each phase (or around the ground straps) and an oscilloscope to record the PD pulses occurring in the cable. The bandwidth of the HFCTs used was approx. 70 kHz…18 MHz (-3 dB). A fourth HFCT and a signal generator was used before the actual PD measurement to inject a pulse into the cable to determine the propagation velocity of the PD pulses in the cable for TDR (time domain reflectometry) calibration. This improves the accuracy of PD location.

![HFCT measurement system](image3.png)

**Figure 3.** HFCT measurement system [6].

Pry-Cam measurement is based on measuring the electromagnetic field generated by the PD pulses. The measurement system consists of a camera shaped measuring unit having a sampling rate of 200 MS/s and bandwidth of 100 MHz and an iPad, which is used to control the measurement and to visualize the results. The measurement is conducted one phase at a time.

![Pry-Cam measuring unit and iPad](image4.png)

**Figure 4.** Pry-Cam measuring unit and iPad [6].
TAN-DELTA MEASUREMENT RESULTS

Four different tan δ parameters were considered in this study: TD (tan δ), DTD (delta tan δ or tan δ tip-up), TDTS (tan δ temporal stability) and TUTU (tip-up of tan δ tip-up). At each test voltage level 10 tan δ measurements were conducted and TD is calculated as the mean of these tan δ values. DTD represents the voltage stability of tan δ and it is calculated according to Equation 2 below. TDTS is calculated as the standard deviation of the 10 measured tan δ values at a single voltage level. These three tan δ parameters are defined also in [4]. In [5] TDTS was found to have the best correlation with the breakdown voltage (and aging) of the cable. The fourth parameter studied, TUTU, has been suggested e.g. in [1] to improve TD diagnostics and it is calculated according to Equation 3:

\[
DTD = TD(1.5U_0) - TD(0.5U_0) \quad (2)
\]

\[
TUTU = (TD(1.5U_0) - TD(1.0U_0)) - (TD(1.0U_0) - TD(0.5U_0)) \quad (3)
\]

TUTU provides a measure of the degree of nonlinearity of the voltage dependence of tan δ. A value of 0 corresponds to a completely linear voltage dependence whereas a high TUTU value indicates a steeper increase of tan δ above the normal operating voltage of the cable, which may be a symptom of deterioration of the insulation.

The empirical cumulative distribution functions (CDF) of the tan δ parameters of the 20 kV cables studied are presented in Figures 5 and 6. The blue vertical lines in the figures represent the limit between the condition classes “no action required” and “further study advised” defined in IEEE Std400.2 – 2013. In the standard the limit is based on the 80 % percentile of the CDF while the limit for the class “action required” is based on 95 % percentile of the CDF. Generally, the limits given in the standard seem too high for Finnish cables. Thus, new limits presented in Tables 2 and 3 were calculated for Finnish cables based on the data acquired in this study.

No clear correlation between the age of the cable and the tan δ parameters were found in case of paper-oil cables [6], which shows also in Figure 8 later in this paper. Thus, the assessment of the cable condition and replacement need should be based on measurements and not on the cable age. In case of 20 kV XLPE cables the variations of the parameters were somewhat higher in old cables compared to new ones, but this is more likely to be attributed to the cable accessories and the switchgear than the cable itself.
In XLPE cables, tan δ of the cable insulation is so low that the imperfections in terminations and joints have a larger impact on the tan δ parameters than in the case of paper-oil cables. In Finland the first XLPE cables were installed so late that the water-tree problems associated with the first XLPE cable generations have been practically absent.

### APPLICABILITY AND DIAGNOSTIC RESULTS OF TD AND PD METHODS

For the comparison of the applicability and diagnostic results of different methods 34 cables were measured with all the four methods (TD, off-line PD, HFCT and Pry-Cam). The diagnostic results of these measurements are presented in Table 4. As the table shows, the correlation between TD and PD measurements is relatively weak and it was observed that even a relatively high PD level in a cable (several nC) did not necessarily manifest itself in the TD measurement.

Based on these observations, TD measurement is not a reliable tool for detecting partial discharges in cable insulation. Thus, PD measurement should be preferred in commissioning measurements, where the aim is to detect installation errors, which often cause PD. However, it may be useful to acquire also a TD fingerprint of the cable system for comparison and trending in later measurements.

Figure 7 presents an example of the PRPD (phase resolved partial discharge) patterns measured from one cable with all three PD measurement methods. As the figure indicates, there are some differences in the patterns, which may be attributed to different measurement bandwidths and measuring principles, but the PD in phase L3 at both half-cycles was detected with all methods. Due to the quick and easy implementation, Pry-Cam measurement seems a good tool for preliminary screening of the potentially problematic cables, while off-line PD measurement is best suited to in-depth study and location of the PD. HFCT measurement can be used for both, although it is not as easy and quick to use as Pry-Cam.

### Table 2. Figures of merit for the assessment of service-aged paper-oil and PE-based insulations based on [4] and this study (20 kV cables).

<table>
<thead>
<tr>
<th>Condition assessment</th>
<th>TDT at U0 [10^{-3}]</th>
<th>DTD (1.5U0-0.5U0) [10^{-3}]</th>
<th>TD at U0 [10^{-3}]</th>
<th>TUTU [10^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kV paper-oil</td>
<td>IEEE This study</td>
<td>IEEE This study</td>
<td>IEEE This study</td>
<td>IEEE This study</td>
</tr>
<tr>
<td>No action required</td>
<td>&lt; 0.1 &lt; 0.15 and &lt;35</td>
<td>-3.4...2.5 and &lt;85 &lt;15</td>
<td>and -</td>
<td>0.2...1.4</td>
</tr>
<tr>
<td>Further study advised</td>
<td>0.1...0.4 0.15...0.75</td>
<td>8.5...3.4 or 2.5...6.3</td>
<td>85...200 15...29</td>
<td>1.4...3.5</td>
</tr>
<tr>
<td>Action required</td>
<td>&gt; 0.4 &gt; 0.75</td>
<td>85...200 15...29</td>
<td>or &lt; -0.6 or</td>
<td>&lt; 3.5</td>
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### Table 3. Diagnostic results of 34 cables measured with all four studied measurement methods.

<table>
<thead>
<tr>
<th>Cable type</th>
<th>Diagnosis</th>
<th>TD</th>
<th>Off-line PD</th>
<th>HFCT</th>
<th>Pry-Cam</th>
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<tr>
<td>XLPE</td>
<td>Single core 403 1991</td>
<td>&lt;100</td>
<td>&lt;15</td>
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<td>Paper-oil</td>
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<td>&gt;1.5</td>
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<tr>
<td>Paper-oil</td>
<td>Hofstätter 580 1983</td>
<td>&gt;100</td>
<td>&gt;1.5</td>
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CABLE FAILURE AFTER MEASUREMENTS

One of the 10 kV paper-oil insulated belted cables failed during normal operation a few weeks after the TD and PD measurements. A breakdown occurred in phase L1 approx. 32 m from one end of the cable. Figure 8 presents the DTD and TDTS measured from the failed cable a few weeks before the failure in comparison to the other measured cables of the same type. The DTD parameter is clearly higher in all the phases than in most of the other cables. TDTS in phase L1 exceeds the “further study advised” limit given in IEEE Std400.2 – 2013, but there are even higher values in two other cables of the same type, which are still in operation.

The PD activity and level was also relatively high in all phases in the failed end of the cable. The PDs incepted at 0.7 U₀ and the maximum PD magnitudes at U₀ were in the order of 1.3...2.7 nC depending on the phase. Overall, the cable was in a relatively poor condition. On-line PD measurements were not conducted on this particular cable.

DISCUSSION AND CONCLUSIONS

Based on the results TD measurement is a relevant tool for condition assessment of, especially, paper-oil cables, but the limits given in IEEE Std400.2 – 2013 may need to be revised for Finnish cables. For commissioning measurements, PD measurement seems to be the best tool. In condition assessment, TD and PD measurements complement each other by revealing different problems and insulation degradation mechanisms.

According to the DNOs, cable faults often occur at sites where e.g. lots of construction activities or other abnormal stresses have occurred during the cable life-cycle. Additional gains could be achieved in condition assessment of underground cables by utilizing big data analytics to analyze e.g. load and other operational data of the cables and data available from data sources outside the DNOs (e.g. related to other infrastructure construction projects).

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