

# 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.

System voltage [kV]	Cable type		Installation years	Number of cables [pcs]
	Insulation	Construction		
10	Paper-oil	Hochstädter *)	1967-1989	15
10	Paper-oil	Belted	1966-1990	9
10	Paper-oil	Belted	1950-1972	7
10	XLPE	Single core	2012	1
20	Paper-oil	Hochstädter *)	1964-1992	35
20	XLPE	Single core	1985-2015	33
			Total	100

\*) 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.

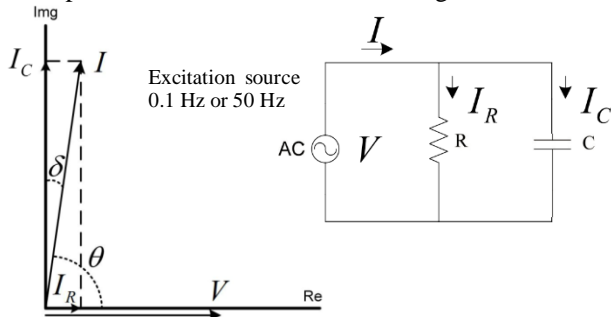


Figure 1. Equivalent circuit of the cable insulation and phasor diagram of the currents considered in TD measurement [1].

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

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

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.

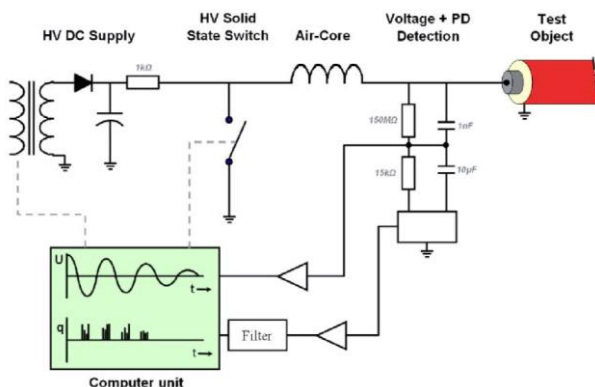


Figure 2. Principle of DAC PD measurement system [3].

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.

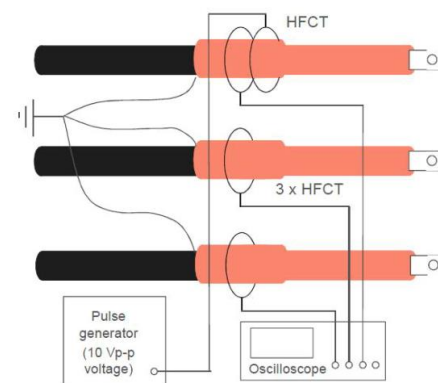


Figure 3. HFCT measurement system [6].

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.

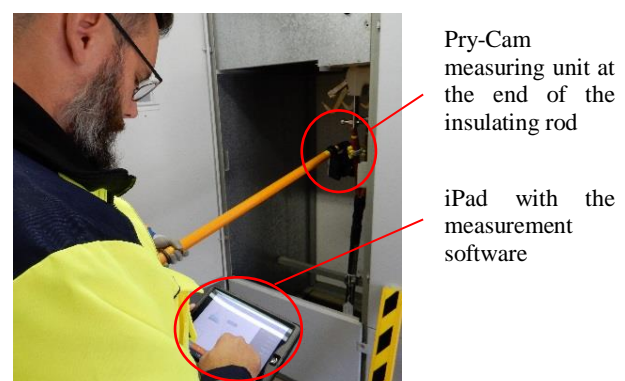


Figure 4. Pry-Cam measuring unit and iPad [6].

## TAN-DELTA MEASUREMENT RESULTS

Four different  $\tan \delta$  parameters were considered in this study: TD ( $\tan \delta$ ), DTD (delta  $\tan \delta$  or  $\tan \delta$  tip-up), TDTS ( $\tan \delta$  temporal stability) and TUTU (tip-up of  $\tan \delta$  tip-up). At each test voltage level 10  $\tan \delta$  measurements were conducted and TD is calculated as the mean of these  $\tan \delta$ -values. DTD represents the voltage stability of  $\tan \delta$  and it is calculated according to Equation 2 below. TDTS is calculated as the standard deviation of the 10 measured  $\tan \delta$  values at a single voltage level. These three  $\tan \delta$  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:

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

$$TUTU = \frac{(TD(1.5U_0) - TD(1.0U_0)) - (TD(1.0U_0) - TD(0.5U_0))}{TD(1.0U_0) - TD(0.5U_0)} \quad (3)$$

TUTU provides a measure of the degree of nonlinearity of the voltage dependence of  $\tan \delta$ . A value of 0 corresponds to a completely linear voltage dependence whereas a high TUTU value indicates a steeper increase of  $\tan \delta$  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  $\tan \delta$  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  $\tan \delta$  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.

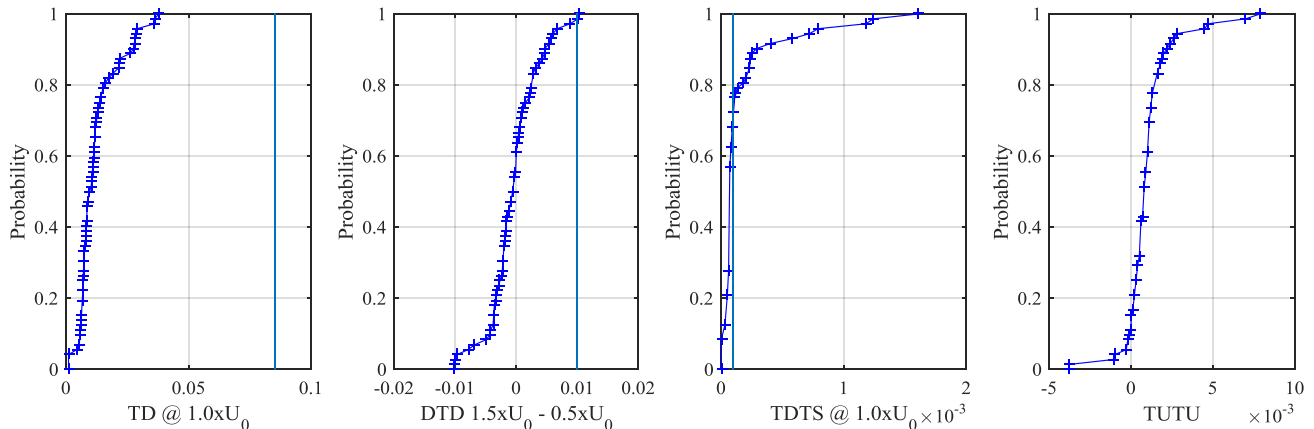


Figure 5. Cumulative distribution functions of the  $\tan \delta$  parameters of the studied 20 kV paper-oil cable systems.

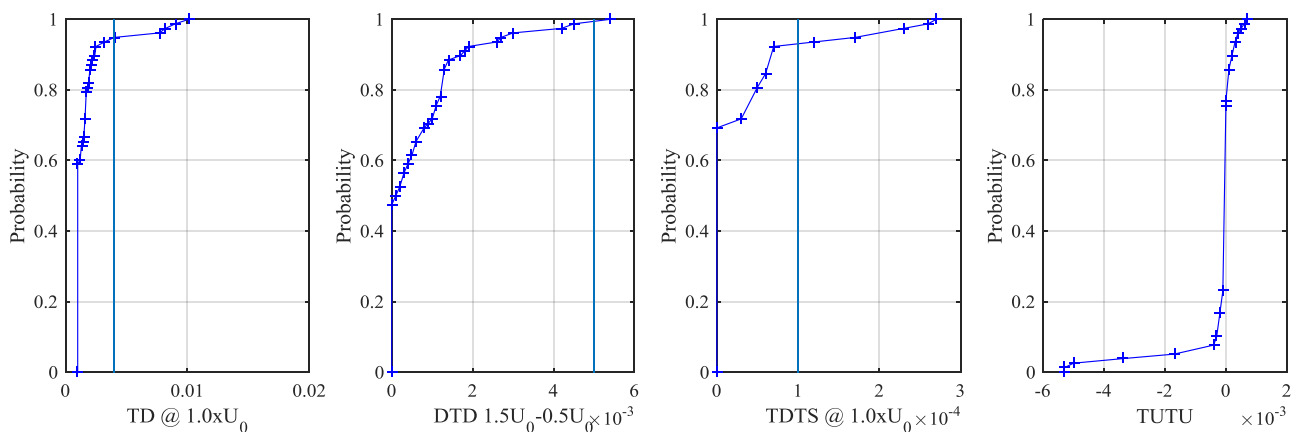


Figure 6. Cumulative distribution functions of the  $\tan \delta$  parameters of the studied 20 kV XLPE cable systems.

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).

Condition assessment	TDTS at $U_0$ [ $10^{-3}$ ]			DTD ( $1.5U_0-0.5U_0$ ) [ $10^{-3}$ ]			TD at $U_0$ [ $10^{-3}$ ]			TUTU [ $10^{-3}$ ]	
20 kV paper-oil	IEEE	This study		IEEE	This study		IEEE	This study		IEEE	This study
No action required	<0.1	<0.15	and	-35...10	-3.4...2.5	and	<85	<15	and	-	0.2...1.4
Further study advised	0.1...0.4	0.15...0.75	or	-50...-35 or 10...100	-8.5...-3.4 or 2.5...6.3	or	85...200	15...29	or	-	1.4...3.5
Action required	>0.4	>0.75	or	<-50 or >100	<-8.5 or >6.3	or	>200	>29	or	-	<-0.6 or >3.5

Condition assessment	TDTS at $U_0$ [ $10^{-3}$ ]			DTD ( $1.5U_0-0.5U_0$ ) [ $10^{-3}$ ]			TD at $U_0$ [ $10^{-3}$ ]			TUTU [ $10^{-3}$ ]	
20 kV XLPE	IEEE	This study		IEEE	This study		IEEE	This study		IEEE	This study
No action required	<0.1	<0.048	and	<5	<1.2	and	<4	<1.7	and	-	-0.15...0.03
Further study advised	0.1...0.5	0.048...0.17	or	5...80	1.2...2.7	or	4...50	1.7...4.5	or	-	-1.9...-0.15 or 0.03...0.35
Action required	>0.5	>0.17	or	>80	>2.7	or	>50	>4.5	or	-	<-1.9 or >0.35

In XLPE cables,  $\tan \delta$  of the cable insulation is so low that the imperfections in terminations and joints have a larger impact on the  $\tan \delta$  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 3. Diagnostic results of 34 cables measured with all four studied measurement methods.

$U_0$ [kV]	Cable type				Diagnosis			
	Insulation	Construction	Length [m]	Year of installation	TD	Off-line PD	HFCT	Pry-Cam
5.8	XLPE	Single core	2080	2012	Green	Yellow	Green	Green
5.8	Paper-oil	Hofstädter	495	1972	Green	Green	Green	Green
5.8	Paper-oil	Hofstädter	516	1977	Green	Green	Green	Green
5.8	Paper-oil	Hofstädter	346	1981	Green	Green	Green	Green
5.8	Paper-oil	Hofstädter	400	1989	Green	Green	Green	Green
5.8	Paper-oil	Belted	293	1950	Green	Red	Green	Green
5.8	Paper-oil	Belted	816	1962	Green	Red	Green	Green
5.8	Paper-oil	Belted	581	1963	Green	Red	Green	Yellow
5.8	Paper-oil	Belted	722	1964	Yellow	Green	Green	Yellow
5.8	Paper-oil	Belted	207	1972	Red	Green	Green	Green
11.6	XLPE	Single core	403	1991	Yellow	Green	Green	Green
11.6	XLPE	Single core	293	1992	Yellow	Green	Green	Green
11.6	XLPE	Single core	560	1992	Yellow	Green	Green	Green
11.6	XLPE	Single core	305	1993	Red	Green	Green	Green
11.6	XLPE	Single core	300	1995	Green	Green	Green	Green
11.6	XLPE	Single core	364.3	1995	Green	Green	Green	Green
11.6	XLPE	Single core	450	1995	Green	Green	Green	Green
11.6	XLPE	Single core	569	1996	Green	Green	Yellow	Yellow
11.6	XLPE	Single core	460	2001	Yellow	Green	Green	Red
11.6	Paper-oil	Hofstädter	356	1968	Yellow	Red	Yellow	Yellow
11.6	Paper-oil	Hofstädter	342	1973	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	200	1974	Red	Green	Green	Green
11.6	Paper-oil	Hofstädter	650	1974	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	200	1976	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	328	1977	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	270	1979	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	311	1979	Red	Yellow	Green	Green
11.6	Paper-oil	Hofstädter	155	1983	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	207	1983	Green	Yellow	Green	Green
11.6	Paper-oil	Hofstädter	300	1985	Green	Green	Green	Green
11.6	Paper-oil	Hofstädter	513	1990	Green	Green	Green	Yellow
11.6	Paper-oil	Hofstädter	617	1990	Green	Green	Green	Green
11.6	Paper-oil	Hofstädter	380	1992	Yellow	Green	Green	Green
11.6	Paper-oil	Hofstädter	525	1971	Green	Red	Yellow	Red

Green	No action required
Yellow	Further study advised
Red	Action required

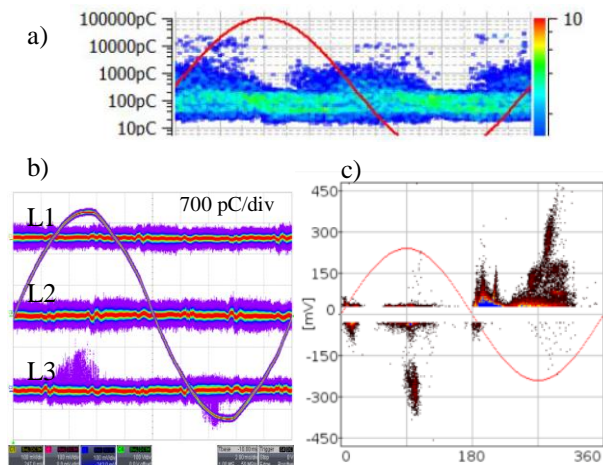


Figure 7. PRPD patterns of a 20 kV paper-oil insulated cable measured with (a) off-line DAC (L3), (b) on-line HFCT (all phases) and (c) Pry-Cam (L3) methods.

### 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.

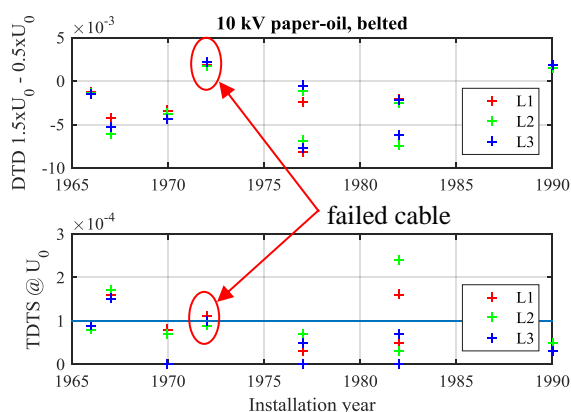


Figure 8. DTD and TDTS parameters of the failed cable in comparison to other cables of the same type and IEEE Std400.2 – 2013 “further study advised” limit (blue line).

The PD activity and level was also relatively high in all phases in the failed end of the cable. The PDs inception at  $0.7 U_0$  and the maximum PD magnitudes at  $U_0$  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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