Concepts for market-based MV cable operations and maintenance using insulation parameters measurements

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***Abstract*—A variety of measurement techniques can be used for estimating of the dielectric properties of cables. These techniques can include both methods for general evaluation of the cable insulation status, as well as methods for localization of insulation changes. Using a combination of these techniques, the cable operator can define a specific program for cable maintenance and prioritize replacement of cables or cable sections that have deteriorated most. Dielectric is used for evaluating the overall status of water-tree induced deterioration of the insulation by measuring the loss tangent as a function of voltage levels and frequency. Time Domain Reflectometry (TDR) is used as method for localization of water-treeing in medium voltage (MV) power cables. The main challenge when applying TDR is that reflections from cable joints, bending and other discontinuities are usually significantly larger than signals attributable to insulation deterioration. A novel measurement sequence is used to detect the latter signals that is utilizing the nonlinear characteristics of water-treed cross-linked polyethylene (XLPE).**

Keywords—cable insulation, measurement techniques, diagnostic methods, cable replacement, cable operations, XLPE, dielectric spectroscopy, time domain reflectometry (TDR)

I. Introduction

Breakdown strength of XLPE insulated cables can be decreased by water trees [1]. Dielectric spectroscopy has been developed as method for identifying the presence of water trees and estimating the level of insulation deterioration [2]. A particular aspect is dielectric spectroscopy gives an estimate of the insulation status. On the other hand, often water trees affect only particular sections along the cable length. Identifying and replacing only these affected cable sections would be more cost effective.

This paper presents a combination of two measurement techniques. The first is dielectric spectroscopy as a function of frequency and voltage levels where the overall status of the cable insulation is evaluated. The second measurement procedure is based on TDR that uses measurements prior, subsequent and during the application of high AC voltages to localize sections of the cable affected by water-treeing. High voltage stresses would induce parameter changes in the cable section affected by water trees, which can subsequently be localized by TDR. During this measurement procedure geometric discontinuities, that also cause reflections localizable by TDR, would not be affected by the voltage application and thus could be distinguished in the analysis.

The remaining of this paper is organized in the following way. Section 2 presents the high frequency properties of power cables and their relevance for TDR localization. In Section 3 the concept for localization of water-tree induces insulation changes is presented. Section 4 contains a description of the developed TDR measuring system. Section 5 presents the measurement results and the signal processing needed for the localization analysis. Water-tree content analysis, verifying the TDR measurements, is described in Section 6. Sections 7 and 8, contain Discussion and Conclusions, respectively.

II. TDR Measurements on Power Cables

A. High frequency cable properties

To conduct TDR measurements on a power cable, its high frequency properties must be well known and understood. MV power cables can be described as a transmission line with a propagation constant $\gamma(\omega)$ and characteristic impedance $Z_c(\omega)$ which can be represented as

$$\gamma(\omega) = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} = \sqrt{zy}$$
$$Z_c(\omega) = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} = \sqrt{\frac{z}{y}} \tag{1}$$

where the distributed line parameters are inductance L (H/m), capacitance C (F/m), resistance R (Ω/m) and conductance G (S/m). z is the unit length series impedance and y – shunt admittance. The attenuation constant α (Np/m) and phase constant β (rad/m) are the real and imaginary parts of the propagation constant γ (m^{-1}). Using the above the phase velocity ν (m/s) is then

$$\nu = \omega/\beta = 2\pi f/\beta \tag{2}$$

Measurement techniques for MV power cables characterization have been previously presented in [3] – [4].

B. High frequency cable modeling

Measurement techniques have also been developed for high frequency characterization of the semi-conducting screens [6] – [8]. Fig. 1 presents a typical MV power cable design.

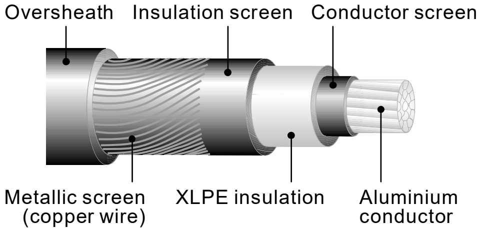

Fig. 1. MV power cable design.

Measurements techniques and modelling of the semiconducting insulation and conductor screens revealed

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that high frequency signals are significantly attenuated when propagating along the cable length, which effect is mainly due to the properties of the semiconducting screens [6] – [8].

C. Field measurements on power cables

TDR detects reflections from cable joints, bending and other discontinuities that are usually significantly larger than signals attributable to insulation deterioration, Fig. 2.

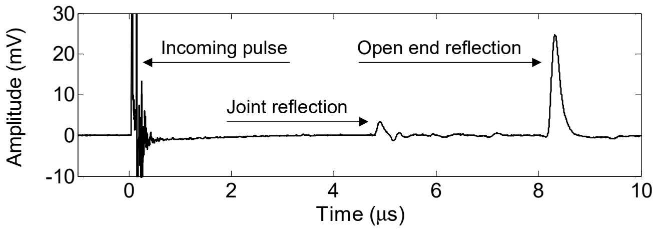

Fig. 2. Example of multiple reflections in TDR measurements on distribution class power cables.

The installation of MV power cables can vary. Depending if the cable is directly buried or placed in ducts means that the surrounding conditions can be differ significantly. It has been established that not only changes in the cable geometry and insulation, but also variations in the surrounding medium would affect the TDR measurements, Fig. 3.

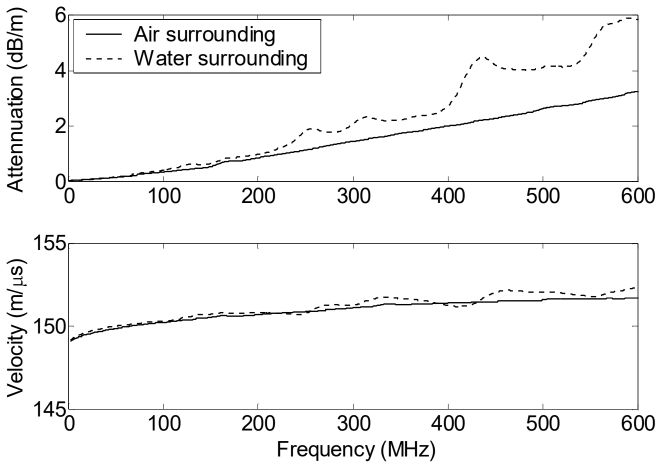

Fig. 3. Measurements of the attenuation constant (α) and velocity (v) conducted when air and water are surrounding the MV power cable.

The effect is most prominent above 70 MHz and influences predominantly the attenuation constant. The cause of the phenomenon has been attributed to the spiralization of the metallic screen, [9].

III. Concept for Localization of Insulation Degradation

A. Differential TDR measurements

To identify signals attributable to water-treeing induced deterioration and separate them from all other influences a measurement procedure is proposed. The measurement technique is utilizing the voltage dependent properties of the water trees [2]. For a water-treed insulation the complex relative permittivity, increases with the applied voltage and is also changed by the extended application of high voltages [1], Fig. 4. Voltage application, on the other hand, does not affect the parameters of cable joints, bending and other discontinuities and reflections from these will remain unchanged. Therefore, two sets of TDR measurements will be studied. One compares TDR reflections signals prior and subsequent to the application of high voltages, recording any hysteresis effect. The other evaluates TDR results performed at the zero crossing (0°) and the top (90°) of the applied voltage, thus analyzing for voltage nonlinearities, Fig. 5.

By comparing the measurements in each set reflection from discontinuities unaffected by the application of voltage will remain constant and thus extracted. The remaining differences between the signals can be attributed to the changes in the XLPE insulation. The procedure is therefore called *Differential TDR*.

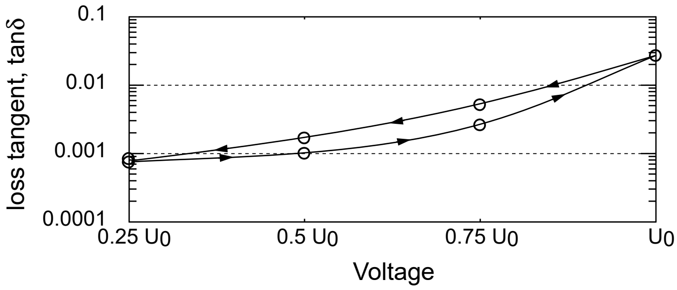

Fig. 4. Tanδ measurements on a water treed cable at voltages up to the service voltage U_0 at 1 Hz. The observed voltage dependence of the loss tangent confirms the effect of water treeing. By repeating, subsequently, the measurements at identical voltage levels one observes a hysteresis type of effect that is indicative for significantly deteriorated insulation.

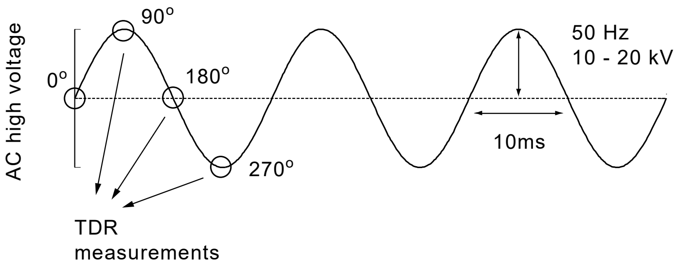

Fig. 5. TDR measurements performed while applying AC high voltages.

IV. Measuring System

A system has been designed for TDR measurements while applying high AC voltages, Fig. 6. An important feature of the on-line system is that TDR measurements have to be synchronized with the applied AC voltage. The reason is that the sinusoid voltage, with a period in the range of millisecond, will be seen as a DC offset for the TDR measurement, which is with durations in the range of microseconds, Fig. 5.

Therefore, the TDR signal should be synchronized to the AC phase, to estimate the voltage stress on the insulation at the time of the TDR measurement. By performing TDR at the top or the zero crossing of the AC voltage, the insulation is characterized at the minimum and, respectively, the maximum of the applied voltage stress. Phase-locking is achieved by synchronization of the pulse generator (PG) triggering with the HV AC supply. The PG and measurement equipment are connected to the high voltage side through coupling capacitors. Additional circuits for sensitive equipment protection and filtering of the AC voltage frequency can also be added. The sinusoid voltage source is connected through a HV amplifier with a maximum output of 20 kV_{peak}. The PG produces a signal with amplitude of up to 1000 V.

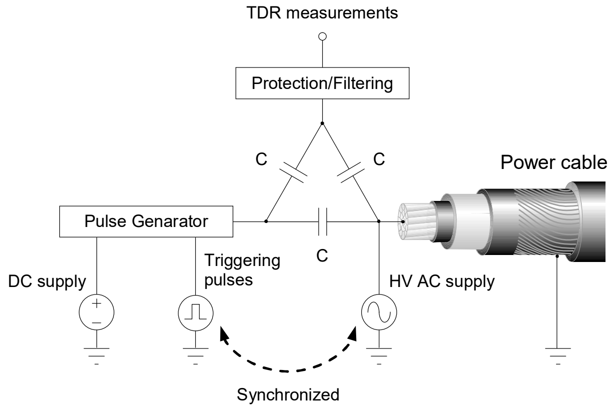

Fig. 6. Measurement system for performing TDR phase-locked to the applied high voltage.

The produced by the PG signal can be seen in Fig. 7 (a). It should be noted that the time domain signal shape, defined by the pulse width and rise-time, is designed for frequency content up to approximately 70 MHz, Fig. 7 (b). The reason for this is the influence of the surrounding medium for the frequencies above this threshold.

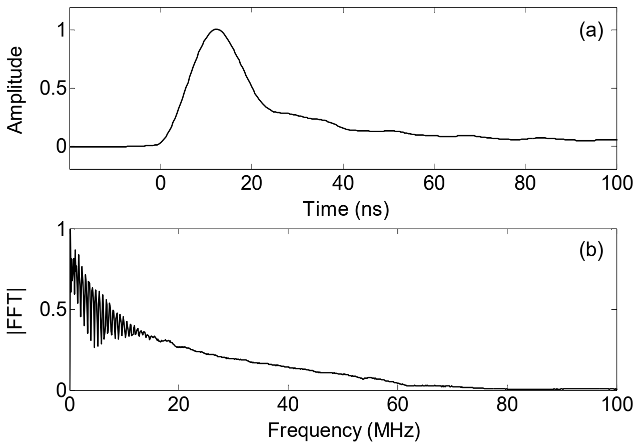

Fig. 7. The pulse generator signal output (a) and frequency content (b).

V. Measuring Results and Signal Processing

Each of the following TDR measurements is lowpass filtered up to 70 MHz to exclude the influence of artifacts. It is also of key importance to apply averaging to the TDR measurements. In the presented case each measurement is the mean value of 512 signals. Thus, the effect of noise and PG instability is reduced significantly and measurements of signals in the range of *1 mV* is possible even in field conditions with significant electromagnetic pollution.

This concept is demonstrated by differential TDR measurements prior and subsequent to the application of high voltages. The measurement procedure starts with a TDR measurement, then followed by applying high AC voltages (up to U_0) for approx. 30 min. AC voltages with frequencies between 0.1 and 10 Hz are used. The cable is briefly short circuited afterwards. Then a new TDR measurement is performed. The signal from the second TDR measurement is subtracted from the initial one, thus canceling out signals from the cable geometrical discontinuities, Fig. 8.

A. Cable 1 localization measurements

After calculating the differential TDR signal, Fig. 8, one can observe a change in the signal subsequent to the application of high voltage at around 7 µs.. The disturbance in the beginning of the differential TDR signal can be attributed to calculational artifacts.

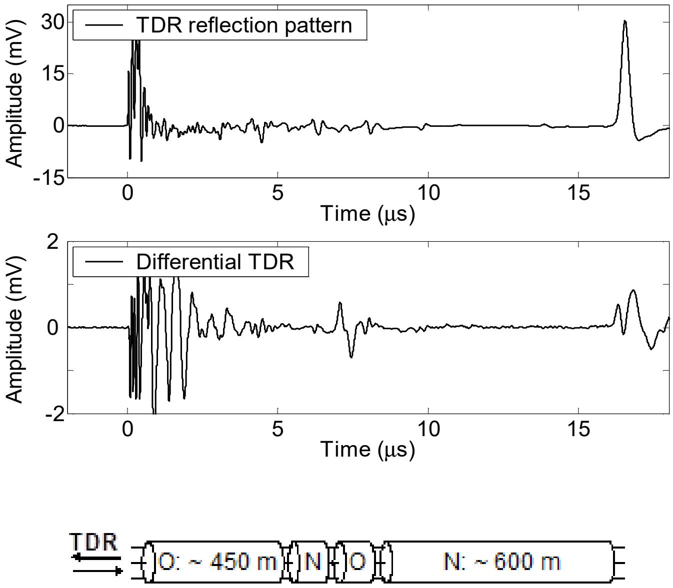

Fig. 8. (upper measurement) TDR on a MV XLPE cable in operation for over 30 years (Cable 1). (lower graph) Differential TDR signal calculated by subtracting the measurement signal prior and the one after the application of AC high voltages. New (N) and old (O) cable parts are shown at the bottom of the Figure.

The signal at the end of the differential signal is caused by the change in the propagation time which is estimated to be $\Delta t = 0.02$ µs. Considering the wave propagation speed of 147 m/µs, the observed signal at around 7 µs corresponds to approx. 450 – 500 m from the cable end from which the measurements are conducted, Fig. 8 *bottom drawing*. That matches the position where water tree deterioration caused several breakdowns and were the reason for a partial cable section replacement that is designated as (N)

B. Cable 2 localization measurements

Fig. 9 shows a measurement on a 170 m long 24 kV XLPE water-tree deteriorated cable before and after the application of high voltages. Sections in Cable 2 denoted with *A* are from the 1970s and section *B* – a new cable from 2002. Measurements from both sides are performed for precise mapping of the cable profile. Reflections from the joints to section *B* are at 1.4 µs and 2.0 µs for measurements from side (I). The corresponding positions for side (II) measurements are at 0.4 µs and 1.0 µs.

Differential TDR did not produce a specific deteriorated insulation region that was pinpointed by the technique. That led to the conclusion that the cable was evenly deteriorated along most of its length.

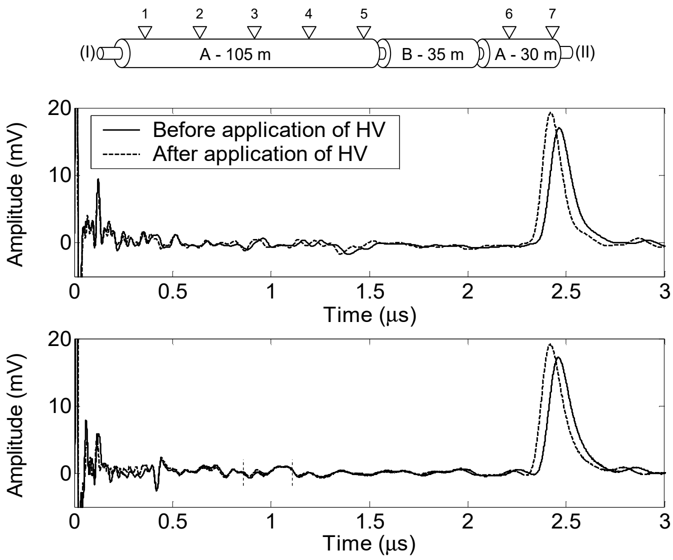

Fig. 9. TDR measurements from both sides (Cable 2).

VI. Dielectric spectroscopy

A. Dielectric spectroscopy measurements

The water-tree deterioration has been verified by dielectric spectroscopy measurements. The voltage dependence and increased losses at repeated measurements at the same voltage level are an indication of significant water tree deterioration [2], Fig. 10.

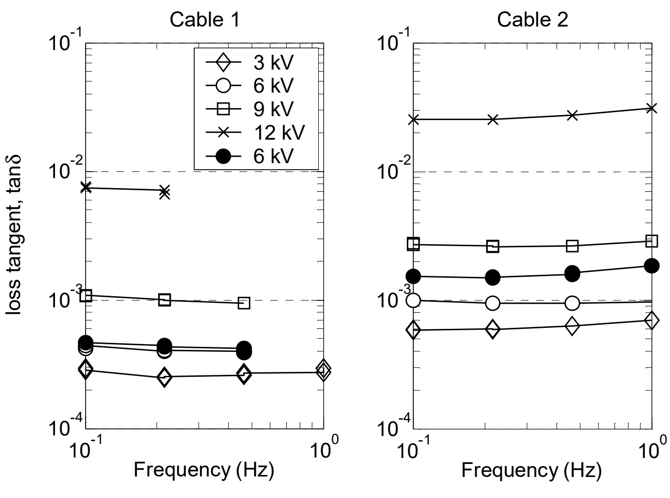

Fig. 10. Tanδ for Cables 1 and 2. Significant voltage dependency can be observed in both cases which is indicative of water tree ageing.

Cable 1 reveals lower deterioration but taking into account that more than half of the cable length is unaged. Cable 2 is showing higher deterioration confirmed by the fact only 1/5 of the cable are newly replaced.

B. Water tree analysis

Samples from Cable 2 were taken from 7 points along the cable length (Fig. 8). Water tree analysis showed an even deterioration with water tree lengths corresponding to breakdown strengths of approx. $2.5U_0$ [1], Table 1.

Table 1. Water tree analysis results.

	Water tree density (cm^{-2})	Longest water tree (%)	Shape (l/w)
1	49.3	80.4	5.9
2	44.1	81.4	6.4
3	31.1	79.2	5.4
4	47.0	77.1	5.7
5	45.7	76.7	5.7
6	11.1	70.1	5.4
7	88.7	75.0	5.1

Only in section 6 and 7 the densities of the water trees differed notably.

Thin and long water trees with a high density were predominant (Fig. 11 *left*) and have previously been also observed in this type of cable design [1]. Trees of lengths exceeding 80% of the insulation thickness and considerable width have also be found, Fig. 11 *right*.

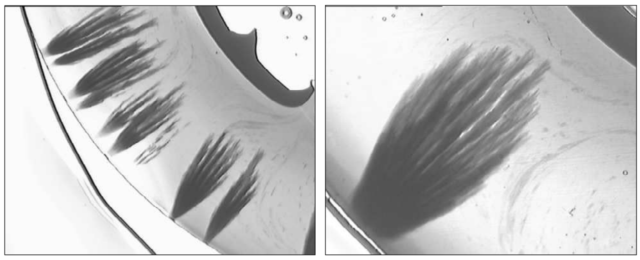

Fig. 11. Example of water trees found by the destructive analysis.

VII. Discussion

Water trees increase the high frequency ε' and ε'' of the insulation [10] – [12]. In this investigation the changes in $Z_c(\omega)$ caused by the application of high voltages are due to a decrease in ε'. A proposed explanation can be found using the results from which identified build up of charges at the tips of the water trees [13]. This phenomenon results in a reduced charge mobility and respectively reduced ability to to follow the high frequency signals contained in the TDR pulse.

This could result in a lower high frequency ε'. It is proposed that this phenomenon is observed when performing phase-resolved TDR measurements, e.g. at 0° and 90° of the HV AC. It should also be noted that phase-resolved TDR measurements at 10 Hz of the applied HV AC are presented here. Measurements have been performed at 1 and 3 Hz as well, with no detectable difference in results. The lack of frequency dependence on the charge build-up has also been observed for heavily water-treed insulation in [13].

The precision of the localization is defined by the upper frequency of measurements which is 70 MHz with a corresponding wavelength of 2 m. However, for distribution class cables with lengths in range of several kilometers, the frequency content of the TDR signal can be further decreased due to the high signal attenuation. Therefore, a precision of localization within the 5 to 7 m range can be expected in practice.

VIII. CONCLUSIONS

Dielectric spectroscopy and TDR have been used as non-destructive techniques for estimation of the general condition, and additional localization of water-tree deteriorated parts of the MV power cables. The techniques are based on the effects of voltage nonlinearity of the insulation characteristics when they are affected by water-treeing. Dielectric spectroscopy could identify which, from the two cable samples, is more affected by insulation deterioration. Additionally, *Differential TDR* measurements localize the deteriorated region in one of the samples, in the presence of large reflections from geometric irregularities. The combination of the two diagnostic techniques could thus be used to identify which cables should be prioritized for replacement and if the whole, or only part of the cable needs to be replaced.

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