IDENTIFYING CABLE DISORDERS WITH ON-VOLTAGE TIME DOMAIN REFLECTOMETRY

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ABSTRACT
In this paper a diagnostics technique is presented for localization of degraded regions along a cross-linked polyethylene (XLPE) insulated power cable. The diagnostics would help to develop a strategy for condition based maintenance of old XLPE power cables. A design of the diagnostics system and results of measurements performed on two power cables are presented. The measurements data is processed in order to localize the degraded insulation regions. The sensitivity of the diagnostics is investigated in terms of signal attenuation along the cable.

KEYWORDS
Diagnostics, Cross-linked polyethylene (XLPE) insulated power cable, sensitivity, signal attenuation.

INTRODUCTION
Most interruptions in the power distribution grid are caused by power cable failures (Bertling, L. 2002). Diagnostics of power cables are an important technique used to detect progressive deterioration of cable insulation. The aim of using diagnostics is to achieve a strategy for condition based maintenance of old and aged cables, where good enough cables are kept but bad cables are replaced.

XLPE insulated power cables suffer from the insulation degradation called water-treeing, Figure 1**.** Nevertheless the water trees are regarded as an insulating material but their breakdown strength is reduced (Steennis, 1990). In a research carried out by Werelius, (2001) it was shown that dielectric spectroscopy diagnostics could be used to detect and estimate the severity of water-tree degradation of the power cable insulation. The dielectric spectroscopy diagnostics provide information about the whole length of power cable condition. However the water-treeing can be a local phenomenon, where only the specific cable regions are affected. In order to localize the degraded regions Time Domain Reflectometry (TDR) diagnostics for power cables was developed. TDR is a technique similar to pulse-radar. It is implemented by injecting a pulse into the cable and measuring the reflections along the cable. The reflections arise due to joints and also due to small irregularities in the cable itself. On-voltage TDR diagnostics are performed on the cable energized with an external High Voltage (HV) source. Application of the HV is used as a differentiating parameter in the on-voltage TDR diagnostics as the HV stress affects dielectric properties of the water-trees. On-voltage TDR has a potential to be developed to an on-line TDR where the diagnostics are performed on the power cable in operation (Dubickas, 2005).

Figure 1: Water-trees in the field-aged power cable's insulation.

TIME DOMAIN REFLECTOMETRY (TDR)

Time domain reflectometry is implemented by injecting a short duration voltage pulse V_i with a fast rise time into the power cable with the characteristic impedance Z_0, refer to Figure 2. Joints along the cable have different characteristic impedance than the cable. Also the irregularities along the cable itself cause small local changes in the cable's characteristic impedance. Therefore, due to changes of the characteristic impedance along the cable the reflections V_r arise and are measured with a high speed oscilloscope.

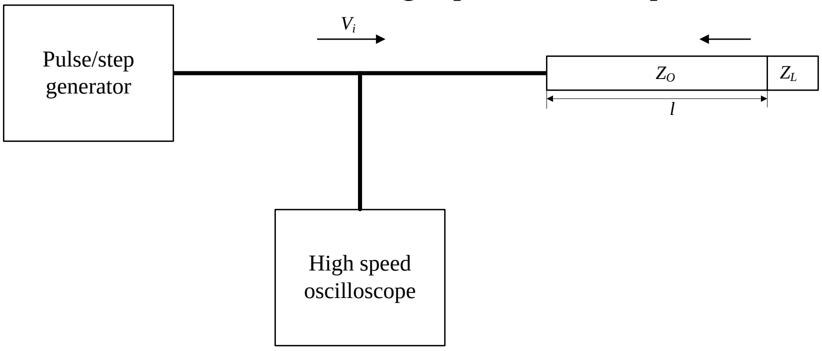

Figure 2: Basic TDR system.

The ratio of the reflected voltage wave and the incident voltage wave is defined as the voltage reflection coefficient and can be expressed as:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_O}{Z_L + Z_O} \qquad \text{.....................(1)}$$

The reflected voltage wave V_r will propagate back to the measuring system and will be recorded by the high speed oscilloscope after a travelling time t_r. Knowing the wave propagation velocity $\boldsymbol{v}$ in the transmission line the distance, $\boldsymbol{l}$ to the discontinuity can be obtained as:

$$l = v\frac{t_r}{2} \qquad \text{...................... ..(2)}$$

ON-VOLTAGE TDR

On-voltage diagnostics are performed on the cable disconnected from the grid. The name on-voltage emphasizes the fact that the cable during the diagnostics is energized with a low frequency (1-10 Hz) HV. The frequency is limited by the maximal current the HV source can generate, as the capacitive current in the energized cable is proportional to the frequency. The HV applied to the cable is used as a differentiating parameter to detect and localize the water trees, which have the voltage dependent dielectric properties.

DIFFERENTIATING PARAMETER IN THE DIAGNOSTICS

The permittivity of water-treed insulation is voltage dependent (Werelius, 2001). It was observed that the high frequency real part of permittivity of water-treed insulation ε' (V) decreases when the HV is applied. A possible explanation to this is that charges are trapped in the tips of the water trees during the application of high voltage stresses with charge build-up varying with the phase of the applied voltage. This effect could reduce the mobility of charges and their ability to follow the high frequency field of the TDR pulse. Therefore the TDR pulse propagation velocity, equation (3), is higher in the water-treed section of the cable when the cable is energized with HV. It allows us therefore to use the non-linearity of ε' (V) of the water trees as a differentiating parameter for the diagnostics.

$$v \approx \frac{1}{\sqrt{\mu\varepsilon'(V)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

METHODOLOGY

Measuring system:

The pulse generator produces pulses of 100 ns duration, 20 ns rise time, and the amplitude of the pulses can be selected up to 1000 V. The pulse generator is synchronized with the HVAC supply unit, refer to figure 3, and the pulses are sent to the cable through the coupling capacitors at the specified positions of the applied HVAC: 0°, 90°, 180° and 270° (Dubickas, 2004). According to equation (3) the pulses sent at the phases 90° and 270°, when the amplitude of the applied HVAC is maximal will propagate faster than the pulses sent at 0° and 180°, when the HVAC crosses zero potential. Due to the velocity variations a time shift appears between the reflections of the pulses sent at (90°, 270°) and (0°, 180°). The reflections are filtered and measured through a high frequency probe with x100 attenuation factor with a digital high speed oscilloscope using averaging function in order to reduce the influence of the noise and the pulse generator fluctuations.

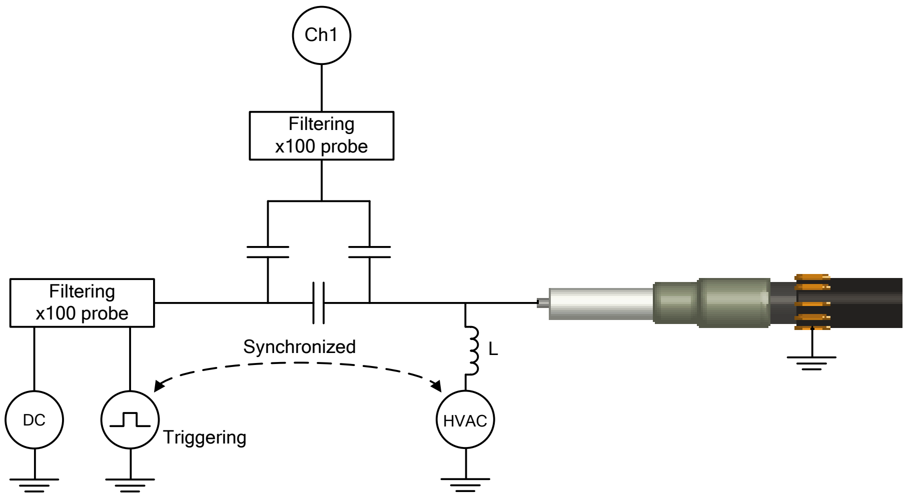

Figure 3: On-voltage TDR system.

MEASUREMENT OBJECTS:

The diagnosed cables are XLPE insulated, field-aged and therefore water-tree deteriorated that was confirmed by the dielectric spectroscopy measurements. The cables have tape and graphite insulation screen. The cables with such design are known as the first generation power cables. The description of the cables is presented in Table 1.

Table 1: Description of the cables diagnosed with on-voltage TDR.

	Voltage rating (kV)	Length (m)	Description	Location
Cable 1	24	110	XLPE insulated, first generation, field-aged	Laboratory
Cable 2	12	1280	XLPE insulated, first generation, field-aged	On-site

MEASUREMENT RESULTS

Cable 1

During the diagnostics the cable was energized with 6 kV, 10 Hz HVAC. The pulses of 100V amplitude were injected through the coupling capacitors at different phase positions of the HVAC. The measurement results are presented in Figure 4. The first and the last pulses are the injected pulse and the reflection from the open end of the cable respectively. The oscillations during 0.1-0.6 µs are generated in the LC circuit composed of the coupling capacitors and the inductive loop formed by the capacitors connection to the cable.

The locations from 1 to 2 are magnified in the Figure 5. Considering a pulse propagation velocity of v = 150 m/µs and time taken for the reflected wave to travel back to the measuring system from positions 1 and 2 as t_1 = 1µs and t_2 = 1.42µs, the distance to the positions 1 and 2 was estimated from equation 2 as follows:

$$l_1 = \frac{t_1 v}{2} = \frac{1.0\times10^{-6}\times150\times10^{6}}{2} \approx 75m \quad \text{and} \quad l_2 = \frac{t_2 v}{2} = \frac{1.42\times10^{-6}\times150\times10^{6}}{2} \approx 107m$$

Examining the magnified signal in Figure 5 a time shift of 20 ns was noticed between the reflections of the pulses sent at (90°, 270°) and (0°, 180°), that indicates the presence of water trees in the cable.

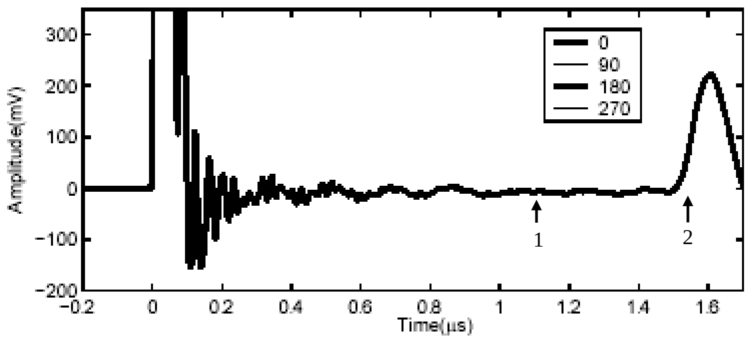

Figure 4: On-voltage TDR measurements on Cable 1.

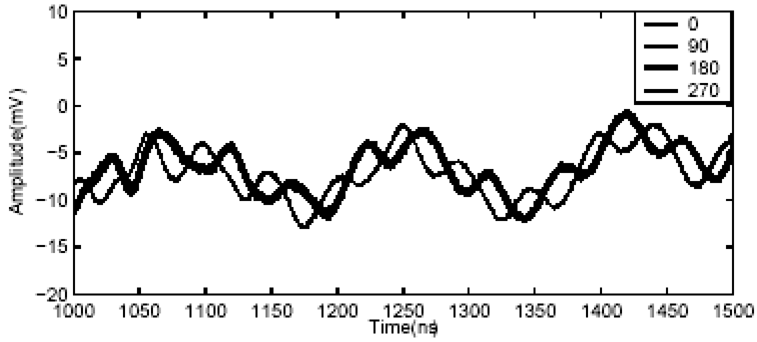

Figure 5: Magnified section of the signal in Figure 4

Cable 2

During the diagnostics the cable was energized with 2 kV, 1 Hz HVAC. The pulses of 100 V amplitude were injected through the coupling capacitors at different phase positions of the HVAC.

The measurement results are presented in Figure 6. The locations 1 and 2 are magnified in the Figure 7 and Figure 8. Considering typical pulse propagation velocity in the power cable of v = 150 m/μs and the time taken for the reflected wave to travel back to the measuring system from positions 1 and 2 as t_1 = 422μs and t_2 = 725μs respectively, the distance to the positions 1 and 2 was estimated from equation 2 as follows:

$$l_1 = \frac{t_1 v}{2} = \frac{4.24\times10^{-6}\times150\times10^{6}}{2} \approx 318m \qquad \text{and} \qquad l_2 = \frac{t_2 v}{2} = \frac{7.25\times10^{-6}\times150\times10^{6}}{2} \approx 544m$$

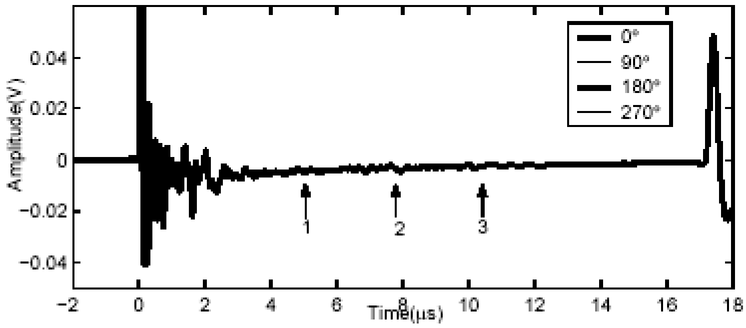

Figure 6: On-voltage TDR measurements on Cable 2.

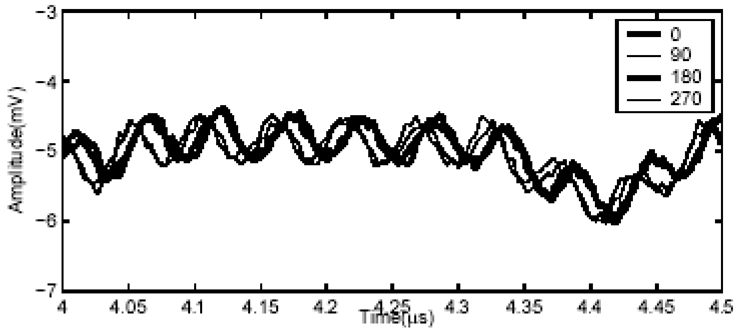

Figure 7: Magnified location 1.

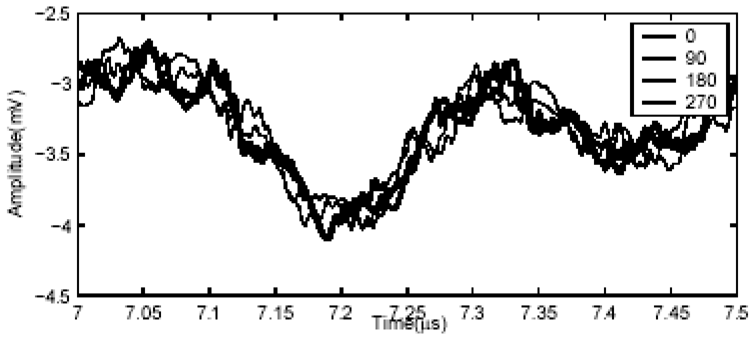

Figure 8: Magnified location 2.

From the measurements at location 1, in Figure 7, a time shift of 19 ns between (90°, 270°) and (0°, 180°) reflections was noticed indicating water-trees presence in this section of the cable. The water trees are present in the cable section between locations 1 and 2 as well as the time shift is increased to 25 ns, refer to Figure 8.

The high frequency components of the propagating pulse in the cable are attenuated by the semiconductive layers of the cable. The pulse at the location 3 is highly attenuated, and the time shift between the reflections could not be distinguished.

PULSE ATTENUATION STUDIES

The time shift can only be observed if reflections contain frequency components above 20 MHz, when on-voltage TDR diagnostics are performed by injecting the pulse at different phases of the applied HVAC (Papazyan, 2005). Simulations were performed in order to investigate the pulse attenuation at different lengths of the power cable. The propagation of the measured on-voltage TDR pulse is simulated in the high frequency model of the power cable (Mugala, 2004). The modeled cable is a one phase, 7/12 kV 1x95/25LT type. The simulated reflections from the cable's open end are presented in Figure 9. The length of the cable in these simulations correspond to 0 m, 100 m, 200 m, 300 m, 400 m and 500 m.

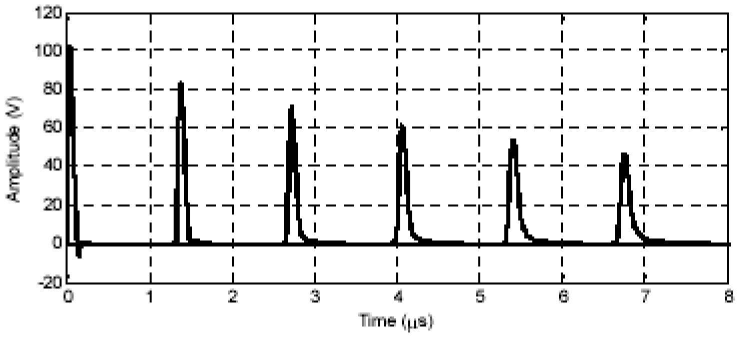

Figure 9: Simulated pulse reflections from the open end of the cable. The lengths of the cable used in simulations: 0 m, 100 m, 200 m, 300 m, 400 m and 500 m.

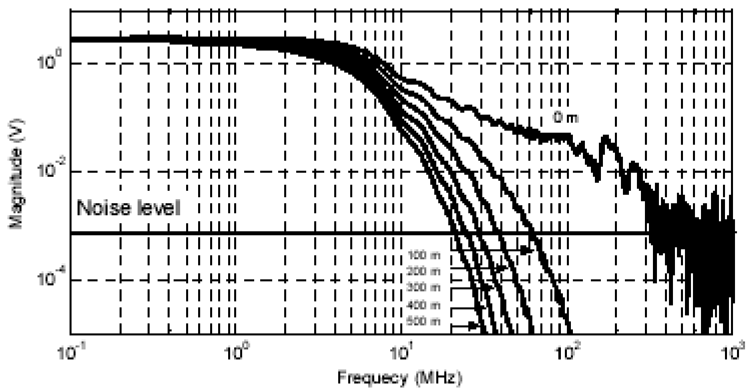

Figure 10: Spectrum of the reflections in Figure 9.

The spectrum of the reflections is presented in Figure 10. The noise level was present as the pulse used for simulations was actually measured. Strong attenuation of the signal's high frequency components can be noticed. As an example 20 MHz component of the reflection from 100 m long cable open end is attenuated by 60%, while 30 MHz component is attenuated by 80%, compared with the spectrum of the initial pulse. While the frequency components above 20 MHz are below the noise level of the reflection from the open end of the 500 m long cable.

LOCALIZING PULSE VELOCITY VARIATIONS

As mentioned before the pulse velocity in water-tree deteriorated cable sections will increase when the pulse is sent on top of the applied HVAC (90°), compared to the pulse sent at zero crossing (0°). Examining the time shift variations between the 0° and 90° reflections the local velocity values along the cable can be obtained using the calculation procedure described by Papazyan (2005). In the calculation procedure the pulse velocity at 0° was considered to be constant along the cable and equal to v =150 m/µs. The obtained local velocity profiles in Cable 1 and Cable 2 are presented in Figure 11 and Figure 12 respectively.

The beginning of the TDR signal is disturbed by the oscillations produced in the previously mentioned LC circuit. Therefore the local velocity profiles could be extracted only from 0.65 µs and 3 µs for Cable 1 and Cable 2 respectively. The connection of the coupling capacitors to the Cable 2 had higher inductance as the measurements were performed on-site, that resulted a longer duration of the oscillations.

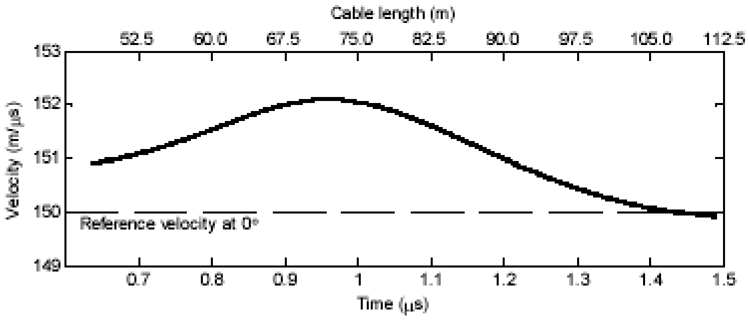

Figure 11: Local velocity profile of Cable 1.

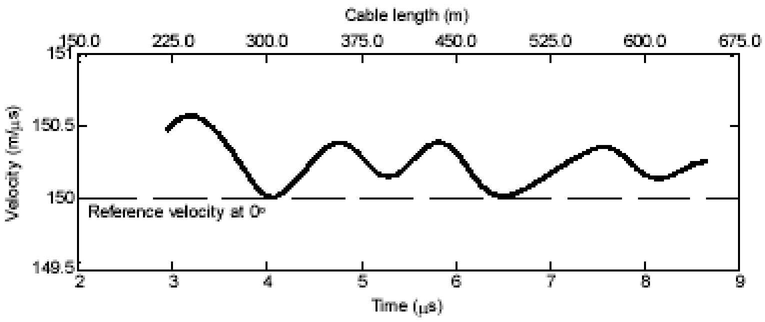

Figure 12: Local velocity profile of Cable 2.

The extraction of the remaining local velocity profile part from 8.5 µs of Cable 2 is limited by the pulse attenuation in the cable. The velocity profile in Figure 11 indicates the water-tree presence in the cable part from 50 m to 90 – 100 m. The observed velocity minimum at the end of the cable can be explained by the fact that the cable ends of 3 m and 15 m are inside of the laboratory while the rest of the cable is left outside. The cable part outside is subjected to humidity and water-trees can refill, while cable ends are in warm and dry surrounding that causes water-trees to dry. Therefore velocity minimum from 90-100 m to 110 m can be explained by the presence of dry water trees in this cable part.

The local maximums in Figure 12 indicate water-tree deteriorated sections of the cable, while local minimums indicate lower water tree density or non-deteriorated sections of the cable. However in order to verify the results a water-tree analysis of the cable samples is needed. The obtained maximal increase in the local velocity corresponds to a decrease in ε' of 2.6% in Cable 1 and 0.8% in Cable 2.

CONCLUSIONS

The on-voltage TDR diagnostics were performed on two cables in an attempt to localize the water-tree degraded insulation regions. The strong attenuation of the pulse along the cable limited the on-voltage TDR diagnostics sensitivity. The pulse propagation in the cable was simulated, and spectrums of the reflections at different cable lengths were investigated. For this particular cable model it was found that the frequency components required for water-tree detection (f > 20 MHz) are below the noise level of the reflection from 500 m long cable open end.

The local velocity variations were observed in the cables indicating water-tree degraded regions. The velocity variations correspond to ε' changes of 2.6% and 0.8% in Cable 1 and Cable 2 respectively. The obtained local velocity profile of the Cable 1 corresponds well to the fact that the part of the cable is situated outside the laboratory enabling water-trees to refill and the cable part of 15 m inside the laboratory where the water-trees are considered to be dry.

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