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TIME DOMAIN SPECTROSCOPY (TDS) AS A DIAGNOSTIC TOOL FOR MV XLPE UNDERGROUND LINES

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ABSTRACT

A Time Domain Spectroscopy (TDS) measuring device has been developed at IREQ as a diagnostic tool to assess the water-tree aging of MV XLPE underground cables. The diagnostic is based on the dielectric losses obtained by TDS measurements in polarization and depolarization. The results of TDS measurements on a total of 15 Hydro-Québec's lines show that the dielectric losses do not correlate with the number of years in service and losses are mainly due to joint degradation.

KEYWORDS

MV XLPE cables and accessories, water-tree aging, diagnostic tool, dielectric spectroscopy in the time domain

INTRODUCTION

The demand by electrical power utilities for condition-based maintenance and for diagnostic tools to assess the degradation of underground cable system insulation is increasing. With the growing number of assets aged 30 years or more, there is also a need to prioritize in which order underground lines should be maintained or replaced.

In the case of MV XLPE underground cable systems, the insulation is prone to water-tree degradation unless it has a water barrier to prevent water infiltrating. Although every one agrees that water treeing will potentially affect the dielectric performance of the insulation, there is no clear understanding of how it will affect the expected material lifetime. The models developed to date are not useful and the reported failure statistics are too insufficient to be able to extrapolate the degradation level of the insulation and the remaining life of the cable insulation because they cannot take into account the so-called TEAM (temperature, electric stress, ambient conditions, mechanical stress) factors. The lack of reliable diagnostic methods available to characterize global insulation aging also complicates the replacement decision.

In order to assess the water-tree degradation of Hydro-Québec's MV XLPE underground cable system, a project was launched at IREQ to determine the potential of Time Domain Spectroscopy (TDS) as a diagnostic tool. The TDS measuring device developed at IREQ was used to assess the water-tree aging on more than 25 cable sections that had been removed after being in service between 15 and 34 years. The tests performed on cables between 40 m and 350 m long (without accessories) showed a good correlation between the global (water-tree) aging and the amplitude of the dielectric losses in depolarization [1]. Once this correlation was well established, field measurements were taken on 15 Hydro-Québec lines (ranging from 1.1 km to 8.2 km and 8 to 45 joints). The results obtained on these lines showed that the dielectric losses do not correlate with the number of years in service. In several cases, lines commissioned more than 30 years ago even showed dielectric losses close to those of new lines. These results are in good agreement with those obtained from residual breakdown voltage and maximum water-tree length measurements on approximately 45 cable sections recuperated from the network. Indeed, contrary to what was expected, the minimum residual breakdown voltage for cables in service for 30 years ranged as high as between four to eight times the service voltage and the maximum water-tree length (bow-tie) was approximately equivalent to 30% of the insulation thickness [1].

Following the TDS field measurements on lines, several cable sections were recuperated (when feasible) and sent to IREQ for further investigation (residual breakdown voltage, water-tree length and TDS losses). Investigating the TDS dielectric losses on these particular cable sections provided key data for getting a proper interpretation of line losses. In fact polarization and depolarization losses measured on underground lines are the result of a combination of losses coming from cable sections, joints and terminations. Previous studies showed that the contribution of the accessories could be significant, even to the point of dominating that of the cable sections [2-4].

EXPERIMENTAL

TDS is an off-line, non-destructive and efficient method for measuring dielectric losses of polymeric insulation. The principle is shown in Figure 1. The dielectric losses are calculated in the low-frequency range between 10^{-1} Hz and 10^{-4} Hz from the polarization and depolarization current values measured with the TDS device. The computer-controlled TDS device developed at IREQ can measure polarization and depolarization currents with a sensitivity of 10×10^{-9} A and 1×10^{-12} A, respectively. The circuit is schematized in Figure 2.

A field version of the TDS device developed at IREQ was installed in a small vehicle, Figure 3. TDS measurements are performed by applying the voltage to the line terminations either in outdoor (indoor) substations or directly to the pole at the transition between overhead and underground lines, Figure 4.

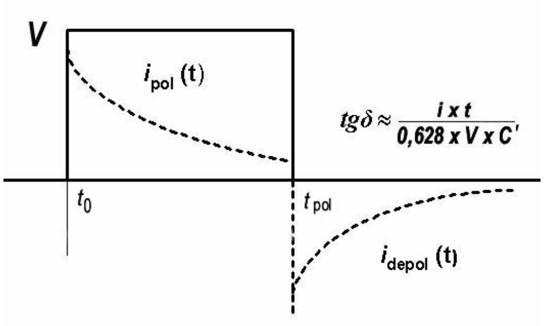

Figure 1: **Principle of the Time Domain Spectroscopy measurements**

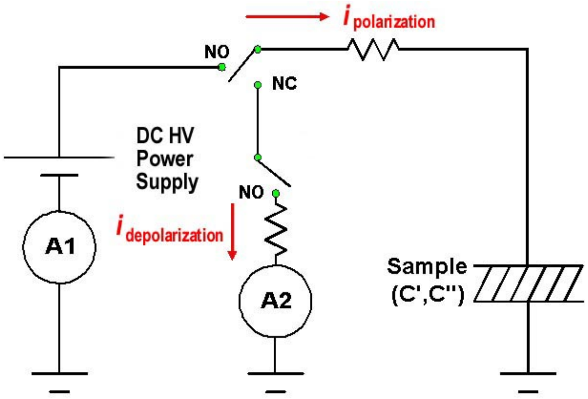

Figure 2: **Schematic of the TDS measurements in the grounded mode: A1 = multimeter and A2 = electrometer**

Prior to any TDS measurement, the capacitance of each phase of the line is measured in order to calculate the dielectric losses. Also, the initial condition of each phase in terms of residual charge is verified by performing a TDS measurement with no voltage applied (0 V). Performing the on-site test on the three phases of a circuit using the test conditions summarized in Table 1 takes approximately 4 h, including the time for set-up.

Table 1: **Standard test conditions**

DC Voltage	Time	
	Polarization	Depolarization
(kV)	(s)	(s)
0	0	200
5-10-15	200	500

RESULTS AND DISCUSSION

The TDS device developed at IREQ was first used to characterize the dielectric losses in depolarization of XLPE cable lengths without accessories. Dielectric loss measurements were performed with the TDS device on approximately 45 phases of cable sections ranging from 40 m to 350 m long that had been in service up to 34 years. The measured dielectric losses in depolarization showed a good correlation with global (water-tree) aging. Typically, the depolarization losses (*tg* δ) of all cable sections tested with the TDS device were less than 1.5 x 10^{-4} at a frequency of 10^{-3} Hz [1]. Such low values of depolarization losses suggest that the XLPE cable insulation is, at most, moderately degraded by water trees. This moderate global aging was also confirmed by the characterization of the residual breakdown voltage and the water-tree lengths.

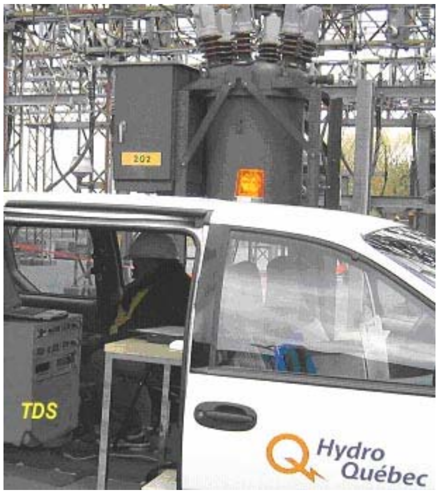

Figure 3: **TDS device installed in a small vehicle for field measurements**

Figure 4: **Connector used for the TDS measurement in the field**

The minimum residual breakdown voltage for cables in service for 30 years ranged between four to eight times the service voltage and the maximum water-tree length (bow-tie) was approximately equivalent to 30% of the insulation thickness [1]. Although the presence of water trees was confirmed in the XLPE insulation, these cables were considered in good condition [5,6]. That analysis also clearly revealed that the typical water-tree degradation of Hydro-Québec's MV XLPE cables takes the form of bow-tie trees, in agreement with reported studies on XLPE cables with fully bonded insulation screens [7].

The correlation between the dielectric losses measured with the TDS in depolarization mode and the global degradation can be explained by looking at the different current components involved. The measured polarization and depolarization currents (Figure 2) can be expressed as a combination of different components [8]:

$$i_{pol}(t) = i_{cap}(t) + i_{abs}(t) + i_{qc}(t) \tag{1}$$

$$i_{depol}(t) = -i_{cap}(t) - i_{abs}(t) \tag{2}$$

where: *cap = capacitive*, *abs = absorption*, *q.c. = quasi-conduction*

The absorption current (*abs*) is the component that relates the most to the global degradation level and is obtained directly from the depolarization current measurements. In order to compare the degradation level of cables or lines of different lengths and rated voltage, the dielectric losses ($tg\ \delta$) need to be calculated. The TDS device automatically calculates $tg\ \delta$ using the Hamon approximation [9]:

$$tg\delta \approx \frac{i \times t}{0.628 \times V \times C'} \tag{3}$$

TDS measurements on lines

Once it was confirmed that the amplitude of dielectric losses in depolarization could characterize global aging of XLPE insulation, TDS measurements were then performed in the field on 15 of Hydro-Québec's 25-kV distribution lines. The shortest line was 1.1 km long with eight joints and two terminations per phase while the longest line was 7.7 km long with 45 joints and nine terminations per phase. The field TDS measurements on lines were generally performed after a cable section (or joint) was replaced following a fault on the line.

The corresponding dielectric losses obtained with the TDS device in polarization and depolarization in the frequency range between 10^{-2} Hz and 10^{-4} Hz are presented for each line in Figures 5 and 6 respectively. Three of those lines were new and had been tested just before being energized. The slight difference in the dielectric losses of new lines can be explained by the different types of joints installed [10]. In Figures 5 and 6, only the phase showing the maximum dielectric losses is presented for each line.

A clear advantage of the TDS method is that measurements are limited neither by the length nor the configuration of the line. However, two limitations remain for the application of such a method for performing dielectric loss measurements in the field. The first limitation, imposed by long lines, resides in the more pronounced capacitive (RC) contribution, which overshadows the losses in the frequency range between 10^{-2} Hz and 10^{-3} Hz, Figure 7. The second limitation relates to the presence of a quasi-constant current associated with the residual charges left, in some cases, by the application of repetitive voltage impulses (thumper) during fault-location testing. If this current is greater than the loss currents, it will hinder the aging assessment of the line with the TDS device.

The dielectric losses presented in Figures 5 and 6 show a significant scatter between new lines and aged ones. The higher ratios (at 10^{-3} Hz) between the minimum and maximum dielectric losses of lines are approximately 30 and 3000 in depolarization and polarization respectively. This substantial difference in the ratios between new and the most degraded lines can be explained by the dominant contribution of the quasi-conduction current ($i_{q.c.}$) in the polarization mode. Indeed in such a case, the dielectric losses are basically representative of an advanced local degradation and not of global aging.

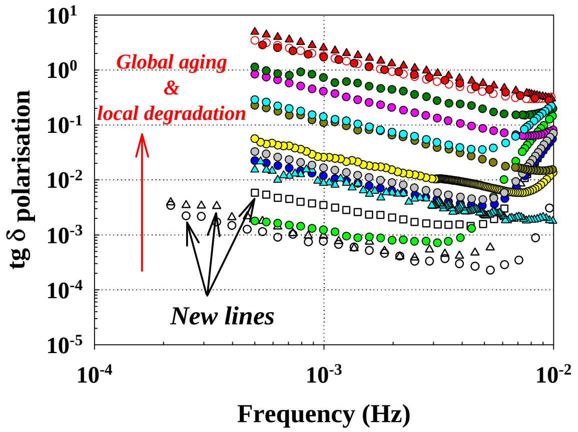

Figure 5: **Dielectric losses in polarization of typical underground MV XLPE cable lines measured with the TDS device**

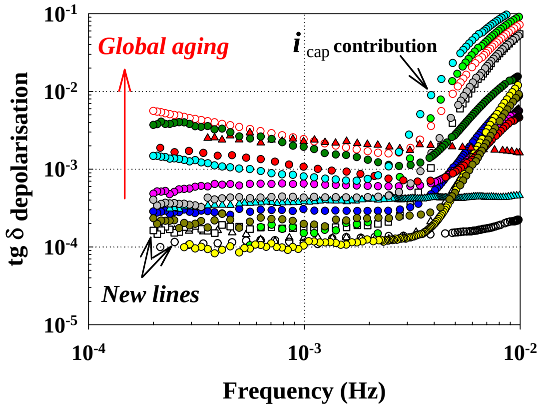

Figure 6: **Dielectric losses in depolarization of typical underground MV XLPE cable lines measured with the TDS device**

TDS measurements on line PBR-201

Just before the total replacement of a 5.4-km line with 30 joints per phase (PBR-201) that had been in service for 30 years, TDS measurements were performed on each phase. The rationale for replacing this line was the belief that the XLPE cable insulation had completely degraded after 30 years and, also, that this line had experienced some joint and cable section replacement in the past. A total of 58 joints (out of 90, i.e. 3 x 30 per phase) and three cable sections were recuperated and brought to IREQ for further investigation (residual breakdown voltage, water-tree lengths and TDS losses). The dielectric losses in polarization and depolarization of the PBR-201 line and of the three recuperated cable sections are presented in Figures 7 and 8 respectively.

Again, in Figures 7 and 8, only the phase showing the maximum dielectric losses is presented for the PBR-201 line. The difference between the dielectric losses of the line and those of the cable sections (ratio of $tg\ \delta > 100$ in polarization and $tg\ \delta > 10$ in depolarization) can be explained by the dominant contribution of advanced joint degradation [10].

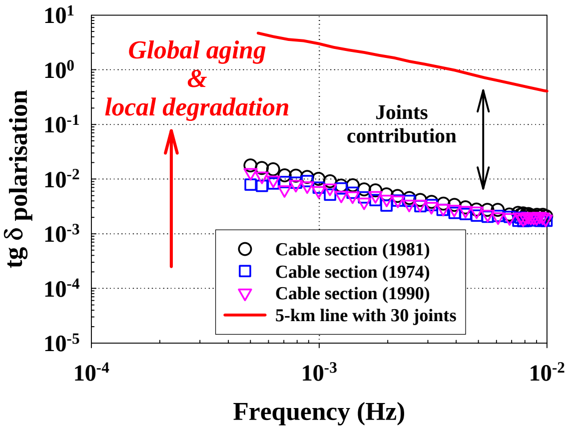

Figure 7: **Dielectric losses in polarization of one phase of the PBR-201 line with the corresponding losses of three different cable sections recuperated from this line after dismantling**

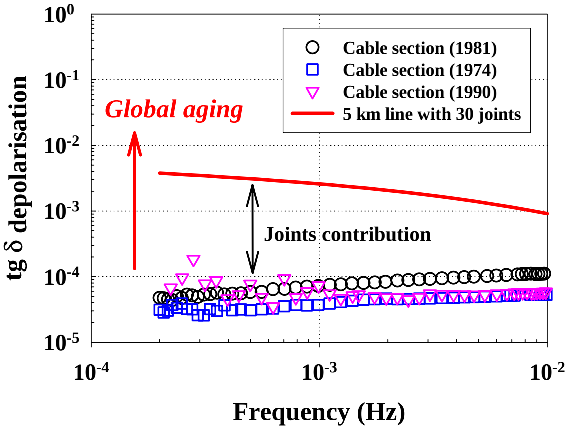

Figure 8: **Dielectric losses in depolarization of one phase of the PBR-201 line with the corresponding losses of three different cable sections recuperated from this line after dismantling**

Proposed TDS diagnostic

The global aging, and thus the depolarization losses, of the components (cable sections and accessories) of each phase of a line are assumed to be similar since they experience the same so-called TEAM factors. However, the results of the study on joints [10] clearly showed that if, on one phase of a line, only one joint presents an advanced local degradation, its dielectric losses will dominate those of the cable sections and other joints on this phase. Consequently, in such a case, significant differences will be observed between phases. An example of global and local degradation is well illustrated for the three phases of the RNC-286 line, Figure 9. In this case, the depolarization losses are equal for each phase, confirming the same global aging, while polarization losses are not equal, indicating different advanced local degradation on each phase.

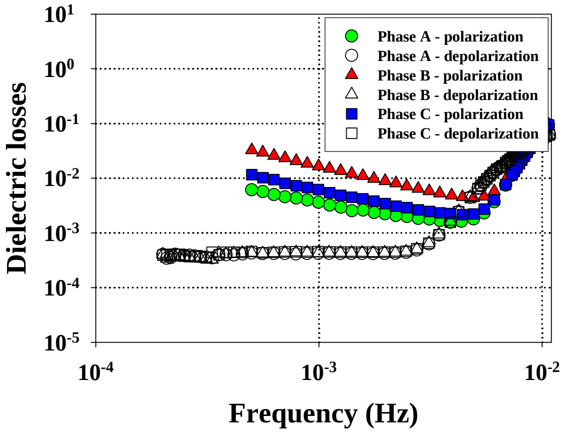

Figure 9: **Comparison of the dielectric losses in polarization and depolarization of phases A, B and C of the RNC-286 line**

The proposed TDS diagnostic takes into consideration the particularly good sensitivity of the polarization mode to detect advanced local degradation and the strong dependence of the depolarization losses with global aging. To assess the global aging and local degradation, the proposed TDS diagnostic first compares:

- relative values of the dielectric losses between lines;
- dielectric losses between phases of the same line.

The results of polarization and depolarization losses measured with the TDS device (at 10^{-3} Hz) on the three phases of a selection of lines are presented in Figure 10. The dielectric losses of three new lines are shown together with those of lines that were in service between 25 and 30 years. The solid line shown in Figure 10 corresponds to the theoretical limit, which relates to the case where the depolarization and polarization currents are equal (considering that in any case $I_{pol} \geq I_{depol}$).

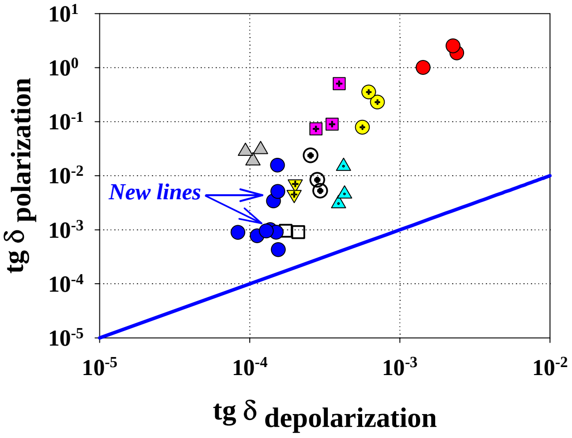

Figure 10: **TDS diagnostic development of MV XLPE lines (at 10^{-3} Hz)**

It can be seen in Figure 10 that, after more than 25 years in service, some of the lines had dielectric losses similar to new ones and that these lines present a small scatter of the

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depolarization losses of the three phases. The other lines show dielectric losses that are distributed towards the top right corner of the graph as their degradation increases. According to this observation, a priority list of lines for maintenance or replacement can be established quite simply by representing the dielectric losses measured with the TDS device on such a graph. Also, a "good condition" diagnostic of a line (cables and joints) can be set when depolarization and polarization losses present small differences between phases and reasonable levels. A "degraded joint" diagnostic can be set when polarization losses are high and depolarization losses of the three phases are different (as is the case for the three points at the top right corner). Such a diagnostic of joint degradation is based on the systematic TDS characterization of joints and cable sections without accessories that was performed at IREQ [10]. All these cables and joints were recuperated from Hydro-Québec's network and most of them were part of lines previously characterized with the TDS device.

In the TDS diagnostic of XLPE insulated cables sections (without accessories) recuperated from the network, shown in Figure 11, it can be seen that all cable sections show depolarization losses below ~1.5 x 10^{-4} (at 10^{-3} Hz). In the graph, the polarization loss values (triangles) are only valid for the cables tested with a TDS device operated in an ungrounded configuration [10]. For other cables (circles), the polarization values are wrongly high since the current measurements were limited for the lowest values by the sensitivity limit of the multimeter.

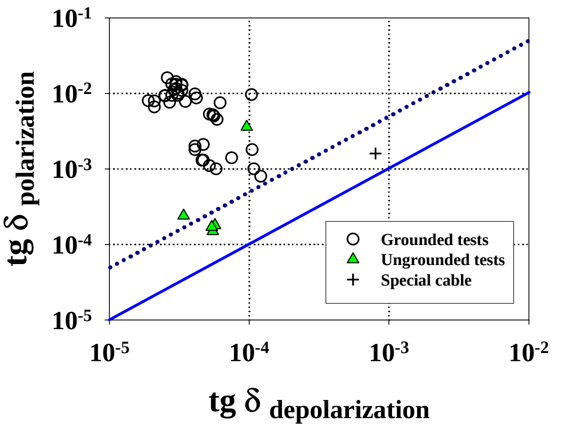

Figure 11: TDS measurement on cables without accessories at IREQ (at 10^{-3} Hz)

A cable that had been in service at a European utility was also tested with the TDS device. The cable contained a high-density of vented trees growing from the outside, most of them with lengths exceeding 60% of the insulation thickness. Not only did this cable (tagged ‘special’) present the highest losses of all cables tested but these losses also showed a strong dependence with the voltage level (nonlinearity) [11].

The TDS diagnostic of all cable sections recuperated from a line previously tested with the TDS is presented in Figure 12. The dotted vertical line (at ~1.5 x 10^{-4} in depolarization) clearly shows that the degradation measured on lines always exceeds that measured on corresponding cable sections.

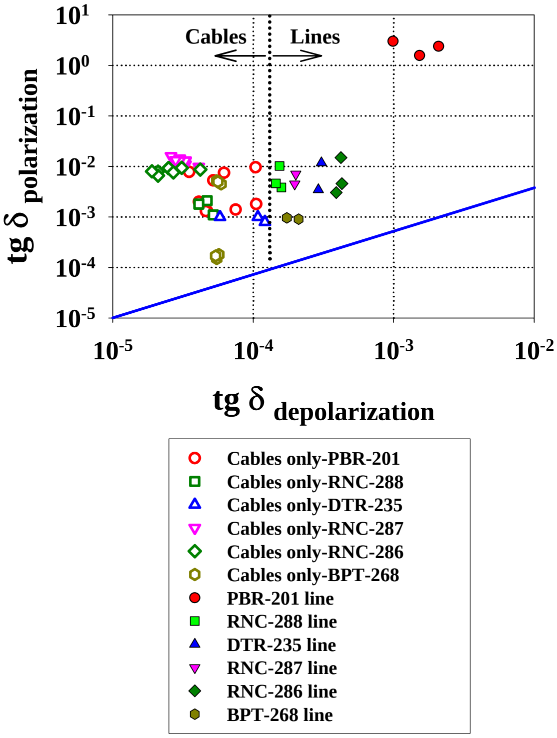

Figure 12: Dielectric losses of cables without accessories tested at IREQ and the corresponding losses of the lines from which they were recuperated (at 10^{-3} Hz)

This difference in the dielectric losses provides an indication of the dominant contribution of global aging and advanced local degradation of joints to the overall dielectric losses measured on lines. According to the results presented in Figure 12, the contributions of joints that experience advanced local degradation clearly appear dominant in the case of line PBR-201. In order to confirm the dominant nature of the contribution of such joints plagued with advanced insulation degradation, a line simulation was performed at IREQ [10]. Standard test conditions (Table 1) were used to assess the individual and combined losses of a cable section on a reel (~200-m) and eight joints: two new ones and six presenting various degrees of degradation. This line simulation clearly confirmed the dominant contribution of advanced joint degradation on the dielectric losses. In such a case, the line dielectric losses can then be expressed (at 10^{-3} Hz) as equivalent to those of the "weak link":

$$tg\ \delta_{line} \approx \frac{160 \times i_{advanced\ degraded\ joint}}{V \times C'_{line}} \qquad (4)$$

Nonlinearity effects

A preliminary analysis of the dielectric losses with the applied voltage was made on some "highly degraded" lines (i.e. line showing high values and significant differences of dielectric losses between phases). As observed on individual cables and joints affected by high local degradation, the dielectric losses in polarization and depolarization are nonlinear, i.e. they depend on the applied voltage [4,12].

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Normally, for sound insulation, the dielectric losses are independent of the applied voltage [11]. This nonlinear voltage dependence (at 5 kV, 10 kV and 15 kV) is shown for phase B of line PBR-201, Figure 13. All the cable sections recuperated from this line and all other cables systematically showed a linear behavior when tested with the TDS device at three different voltages, 5-10-15 kV. Similar linear behavior was also observed for joints affected only by global aging [10]. This leads to conclude, in terms of diagnostic, that the phase B of line PBR-201 had joints affected by advanced local degradation.

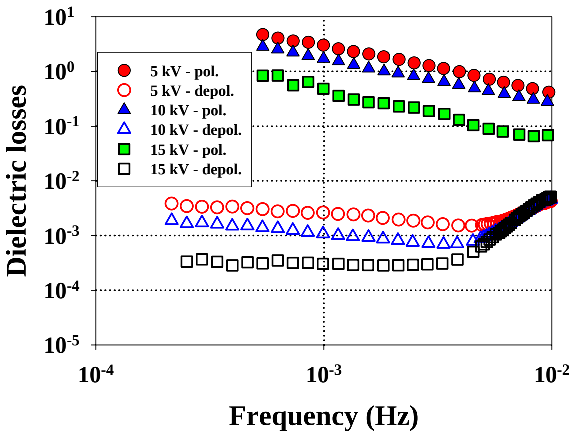

Figure 13: Nonlinearity of the dielectric losses in polarization and depolarization of phase B of line PBR-201

CONCLUSION

The depolarization losses of cable sections measured with the TDS device showed a good correlation with the global (water-tree) aging of the XLPE cable insulation. Preliminary results of polarization losses measured with a TDS device operated in an ungrounded configuration also showed a good correlation with global aging. The statistics obtained from TDS measurements on cable sections (without accessories) together with residual breakdown voltage and maximum water-tree lengths measurements have clearly shown clearly that MV XLPE cables with cross-linked semi-conductive screens were not severely degraded after 30 years in service.

The TDS measurements on lines in service for 25 to 30 years showed that the global aging can be assessed by the depolarization losses. The higher polarization losses measured on some lines can be explained by the dominant contribution of advanced local degradation in some joint designs. The characterization of the cable sections recuperated from lines previously tested with the TDS systematically revealed losses values being much lower than those measured on associated lines. The systematic TDS testing of joints recuperated from service confirmed that the difference in the dielectric losses between lines and cables alone could be explained by the joint contributions.

The TDS diagnostic proposed in this paper is based on a proper understanding of the individual contributions to the dielectric losses of cables and joints. The aging assessment and the maintenance prioritization of a pool of designated lines can be established by considering:

- relative values of the dielectric losses between lines;
- dielectric losses between phases of the same line;
- nonlinearity of the dielectric losses with the applied voltage.

TDS can be described as an off-line non-destructive diagnostic tool for condition-based maintenance of XLPE cable lines that is limited neither by the length nor the configuration of the circuit. It can be used to assess the global (water-tree) aging of XLPE cable insulation and, also, to pinpoint accelerated aging of some joint designs.

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