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DIAGNOSTIC TESTING OF MV ACCESSORIES BY TIME DOMAIN SPECTROSCOPY (TDS)

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ABSTRACT

A Time Domain Spectroscopy (TDS) measuring device developed at IREQ was used to assess the dielectric losses of joints recuperated from service. Analysis of the dielectric losses in polarization and depolarization of various types of joints suggests at least two different aging mechanisms: (i) global slow degradation of the insulation by water treeing and (ii) local degradation on specific joint designs. Also, the dielectric losses of joints do not correlate with the number of years in service and one advanced degraded joint alone could explain all the losses measured on one phase of a line.

KEYWORDS

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

INTRODUCTION

Dielectric spectroscopy is a powerful diagnostic tool for studying electrical insulation and, in particular, for water-tree degradation of XLPE cable insulation [1-3]. Two methods can be used to measure the dielectric losses: Time Domain Spectroscopy (TDS) and Frequency Domain Spectroscopy (FDS). With the TDS method, the losses are measured both in the polarization and depolarization modes while with the FDS method they are only measured in the polarization mode. If water-treeing is the only degradation process of the polymeric insulation, then polarization or depolarization losses can provide an assessment of the global aging. However, if one cable or joint is plagued with a local defect that "shunts" the insulation, the resulting quasi-conduction current measured in the polarization mode will completely overshadow the contribution of the global losses. In such a case, the TDS method allowing measurements in depolarization mode offers a clear advantage over the FDS method, since only the global aging contributes to the depolarization losses.

When dielectric spectroscopy is used for the diagnostic testing of underground lines, the total losses measured are the result of the combined contributions of cable sections, joints and terminations on each phase [4]. It is thus fundamental to determine the respective contribution of each component in order to assess the water-tree aging of the XLPE cable insulation.

This paper presents TDS results obtained on 71 joints recuperated from service together with TDS results on new joints, for reference. From the analysis of the results obtained by the systematic characterization of joints by TDS, two aging mechanisms are proposed. The results of a line simulation with cables and joints recuperated from service, in order to assess the respective contribution of the components to the dielectric losses, are also presented.

EXPERIMENTAL

TDS is a non destructive and efficient method for measuring dielectric losses of polymeric insulation; the principle is shown in Figure 1. Dielectric losses are calculated in the low-frequency range between 10^{-1} Hz and 10^{-4} Hz from the measured polarization and depolarization current values.

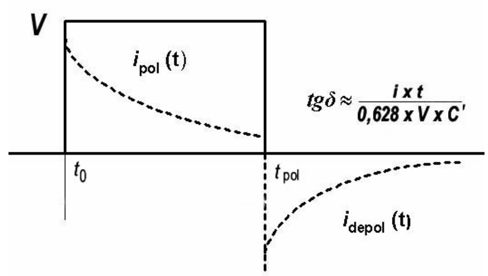

Figure 1: Principle of the Time Domain Spectroscopy measurements

The computer-controlled laboratory version of the TDS device developed at IREQ can measure currents as low as 1×10^{-12} A both in polarization and depolarization. The sensitivity of this laboratory version is better than the TDS field device in the polarization mode, since the samples are grounded through the electrometer. A schematic of the TDS circuit and a photo of the set-up used to characterize all joints are shown in Figures 2 and 3 respectively.

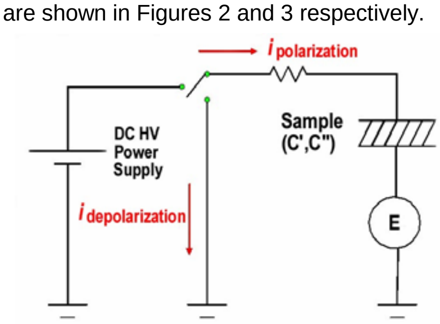

Figure 2: Schematic of the TDS measurements in ungrounded mode: E = electrometer

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Figure 3: TDS device (ungrounded) developed at IREQ and used for joint characterization

RESULTS AND DISCUSSION

The joints were tested following two slightly different protocols: (i) screening TDS tests at lower voltages to identify the most advanced degraded joints and (ii) standard TDS tests to compare the losses with those measured in the field. All the results presented in this paper are dielectric losses obtained at 5 kV_{DC} except for those of the line simulation, which were performed at 15 kV_{DC}. The test conditions are summarized in Table 1.

Table 1: Test conditions

Test	Time		DC Voltage
	Polarization	Depolarization	
	(s)	(s)	(kV)
Screening	200	500	1-3-5
Standard	200	500	5-10-15

As shown in Figure 2, the TDS device fundamentally performs measurements of polarization and depolarization currents, which can be expressed as a combination of different components [5]:

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

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

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

The absorption current (*abs*) is the component that relates the most to the water-tree degradation level and is obtained directly from the depolarization current measurements. In order to compare the degradation level of samples of different capacitance and rated voltage, the dielectric losses ($tg\ \delta$) need to be calculated. The TDS device automatically calculates $tg\ \delta$ using the Hamon approximation [6]:

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

Results of the polarization and depolarization currents measured with the TDS on a severely aged and a new joint are presented in Figures 4 and 5 respectively.

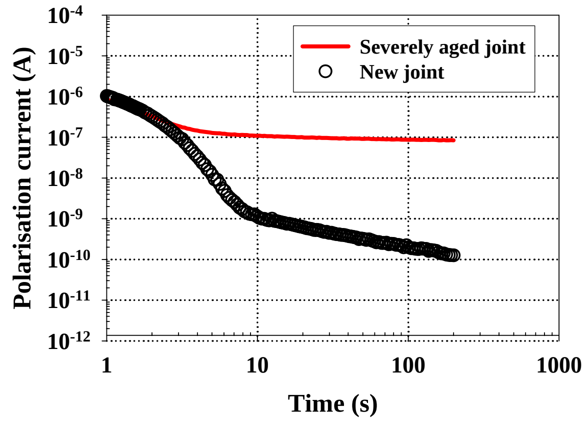

Figure 4: Time dependence of the polarization current for a new and a severely aged joint as measured with the TDS device

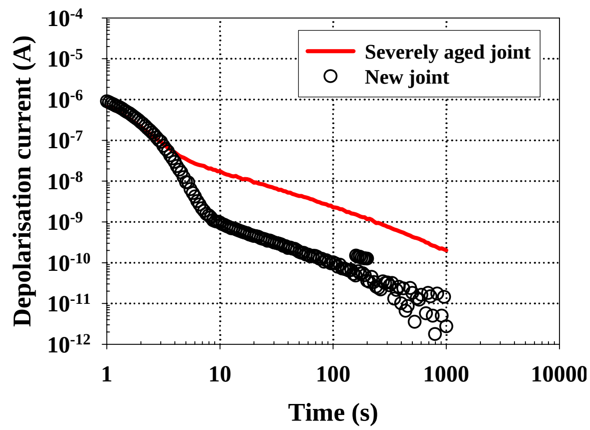

Figure 5: Time dependence of the depolarization current for a new and a severely aged joint as measured with the TDS device

These two cases illustrate the different universal relaxation processes described by Joncher [7], except for the first ten seconds where the current is driven by the capacitive (RC) contribution of the circuit. In polarization mode (Figure 4), a charge carrier process dominates the current component of the severely aged joint (hot spot). In such a case, the measured quasi-conduction current results from a local degradation in the joint. For the new joint, the polarization current results from the combination of dipolar and interfacial polarization. The dipolar process will generally dominate for short times while interfacial polarization dominates for long times. These two processes result from the presence respectively of permanent dipoles and different dielectric materials contained in the insulating material. In the depolarization mode (Figure 5), the current result only from the combination of dipolar and interfacial depolarization for the two joints.

The water-tree aging phenomenon can be explained as an increase in polarizability associated with space charges accumulation (interfacial polarization) and not from the water itself [8]. The water-tree degradation can be seen as an increase in the degraded insulation volume over time. This phenomenon had been confirmed by depolarization current measurements on dry and hydrated cables [9].

Aged and new joints

TDS measurements were performed at IREQ on a total of 71 joints recuperated from service (after up to 34 years) and on seven new joints of different types, Table 2. A total of 58 joints were recuperated from the same line (PBR-201) after the decision was made to completely replace the 5-km line after 30 years in service. Prior to dismantling, TDS measurements were performed on the three phases of that line and the dielectric losses obtained were later compared to those of cable sections and of the joints recuperated from that same line [4]. The other 13 joints tested were recuperated from other lines following a reported diagnostic of hot spots by infrared imaging. Not every one of these 13 joints presented hot spots but, according to Hydro-Québec practice, when one joint is identified as such, all three joints of the line in that manhole are replaced.

Table 2: List of joints tested with the TDS

Type of joint	Aged samples	Service location	New sample(s)
A	17	PBR-201	2
B	3	PBR-201	-
C	20	PBR-201	1
D	10	3 from PBR-201 7 from other lines	1
E	15	PBR-201	1
F	6	IREQ	-
G	-	-	2
Sub-total	**71**		**7**
Total	**78**		

In order to compare the different state of aging between joints recuperated from service, polarization and depolarization losses at 10^{-3} Hz were plotted on a graph. The results obtained on the 78 joints, listed in Table 2, are presented in Figure 6 in terms of the imaginary capacitive component *C"* which can be expressed as:

$$C'' \approx \frac{i \times t}{0.628 \times V} \qquad (4)$$

The *C"* plots allow a better comparison between joints instead of *tg* δ since the capacitance is strongly dependent on the joint design geometry. The preliminary analysis of the dielectric losses (*C"*) in polarization and depolarization of all joints recuperated from service suggest at least two aging mechanisms: (i) global slow degradation of joint insulation by water treeing [10, 11] and (ii) local degradation for specific joint designs. In Figure 6, the dotted line represents the trend of the global (water-tree) aging while the joints that showed hot spots (some specific design) are shown in the ellipse. A dotted line showing the global-aging trend was arbitrarily drawn for the joint insulation parallel to the theoretical limit represented by the solid line. The theoretical limit relates to the case where the depolarization and polarization currents are equal (considering that, in any case, $I_{pol} \geq I_{depol}$). The global-aging trend of joints was set empirically but the physical significance originates from the increase in the polarizability of the dielectric from water treeing.

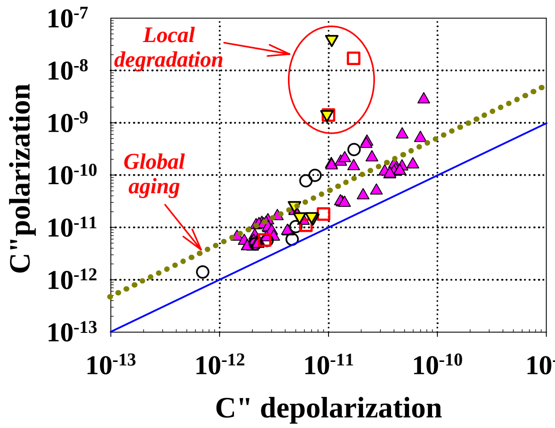

Figure 6: Dielectric losses at 10^{-3} Hz and 5 kV of all the joints measured with the TDS device

The *C"* analysis also showed that insulation degradation is not correlated to the time in service and that there could be a substantial difference in dielectric losses between different joints installed on the same line, several aged joints presenting dielectric losses similar to new ones.

Specific joint designs

The joints recuperated from service were of six different designs. Although their losses in general seem to follow the same global-aging trend, some joint designs are more susceptible to local degradation which can lead to hot spots. The losses specific to each joint design are presented in Figures 7 to 12. Apart from joint types B and F (taped), the dielectric losses of new joints are always included as reference. Joints referred to as type A are commonly used for replacement after a joint failure or hot-spot diagnostic. The TDS dielectric losses of type A joints present two clusters of points that correspond to two different joint designs, Figure 7.

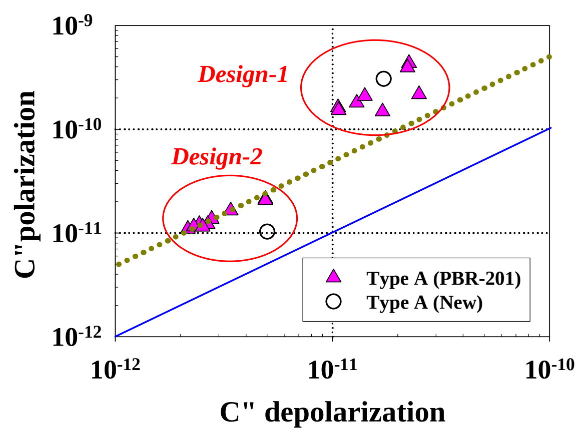

Figure 7: Dielectric losses at 10^{-3} Hz and 5 kV of 17 type A joints recuperated from the PBR-201 line

Only three type B joints were recuperated and no new joint was available as a reference, Figure 8. However, these joints are the same design as type E and their dielectric losses are similar.

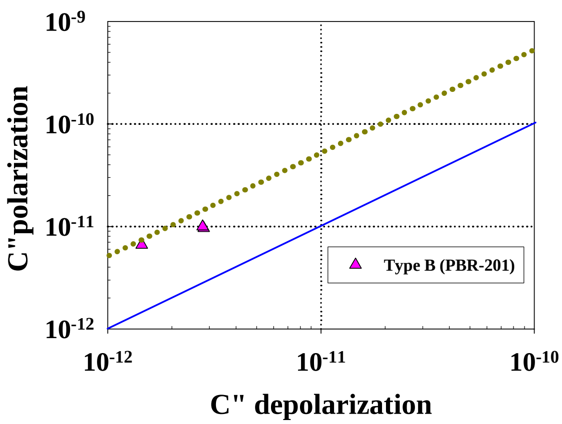

Figure 8: Dielectric losses at 10^{-3} Hz and 5 kV of three type B joints recuperated from the PBR-201 line

Of all joints recuperated from the PBR-201 line, type C are those with the highest TDS losses, Figure 9. The type C joint presenting the highest losses was subjected to AC voltage and was diagnosed with a hot spot by infrared imaging. Two type D joints from different lines were diagnosed with a hot spot following an infrared-imaging routine test in the field. Once the joint with the hot spot had been replaced, together with those on the other two phases, they were sent to IREQ for further investigation. The TDS results for all the type D joints are presented in Figure 10 where it can be seen that the polarization losses of the two hot-spot joints are 2 to 3 orders of magnitude higher than those of joints with normal global aging. The other joints show a global-aging trend parallel to the theoretical limit line.

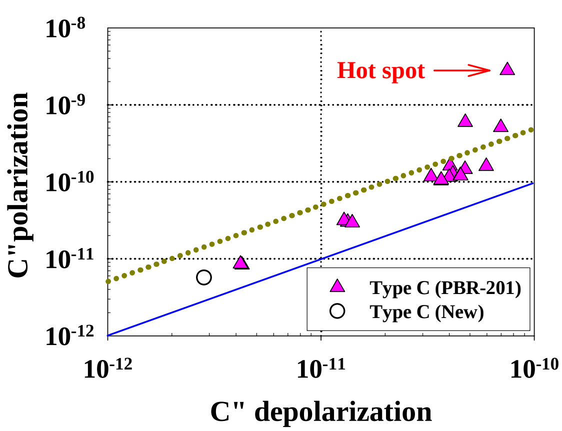

Figure 9: Dielectric losses at 10^{-3} Hz and 5 kV of 20 type C joints recuperated from the PBR-201 line

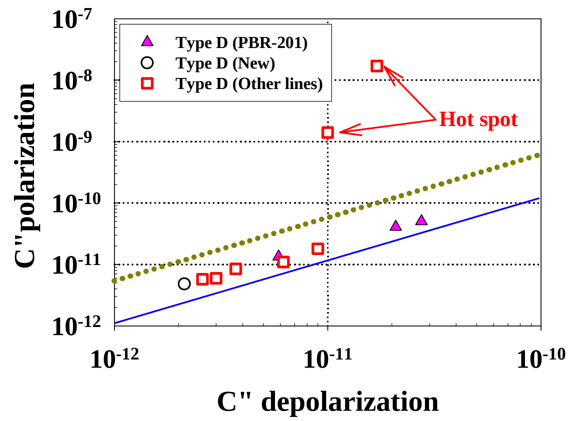

Figure 10: Dielectric losses at 10^{-3} Hz and 5 kV of three type D joints recuperated from the PBR-201 line, together with five type D joints from other lines

Type E joints exhibit losses very close to the reference new joint, Figure 11. The observed scatter of the results is minor and the very low losses suggest that these joints experience a slow global aging in service.

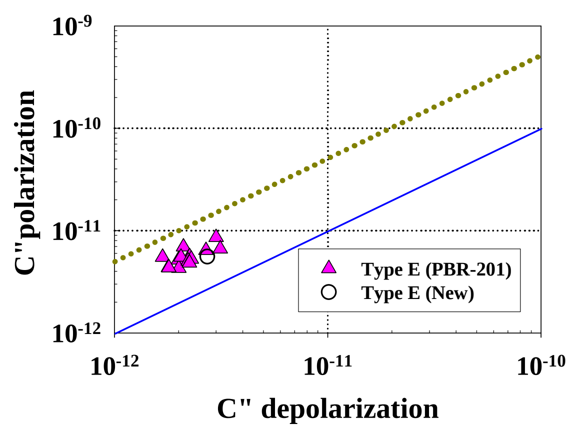

Figure 11: Dielectric losses at 10^{-3} Hz and 5 kV of 15 type E joints recuperated from the PBR-201 line

The type F joints were taped and had been in service at the IREQ site for 34 years: they were replaced after hot spots on some joints had been diagnosed. The resulting losses for six of these joints are presented in Figure 12, but no reference (new joint) is provided since the technology had been replaced many years previously and required skilled personnel. It is interesting to note that, apart from the two joints with hot spots, the others show very little aging.

The systematic characterization of joints recuperated from service suggests that joints affected with advanced local degradation (hot spots) could well make a dominating contribution to the dielectric losses of a whole line. According to the actual state of knowledge and experience, in such a case, the field measurement response would presumably be wrongly interpreted as a severely degraded cable [12, 13].

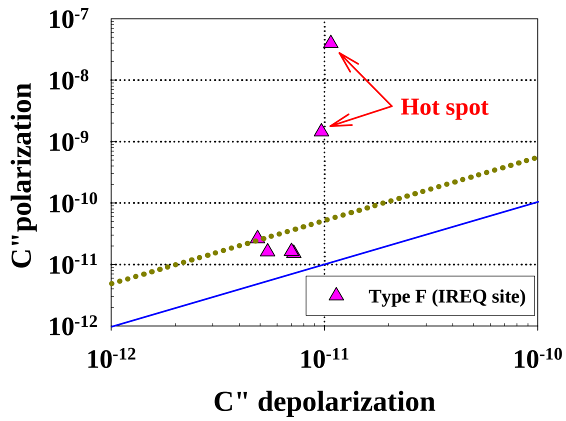

Figure 12: Dielectric losses at 10^{-3} Hz and 5 kV of six type F joints recuperated from the IREQ site

Cable and joint contribution analysis

In order to confirm the major contribution to the dielectric losses of some joints with advanced insulation degradation, a line simulation was performed at IREQ. Standard TDS measurements were performed on ~200-m-long cable section (3 phases) on a reel (recuperated from the network) and eight joints: two new ones and six presenting various degrees of degradation, Figure 13.

The cable and joint components were first characterized individually and, once the tests were completed, the different combinations of components were tested together. The measured and calculated dielectric losses (at 10^{-3} Hz) in polarization and depolarization for the different combinations are shown in Table 3. The calculated values were obtained from a modified expression of equation 3 (at t = 100 s):

$$tg\ \delta_{comb.} \approx \left(\frac{160}{V}\right) \times \sum_{j=1}^{n} i_j \Big/ \sum_{j=1}^{n} C_j' \qquad (5)$$

where n is equal to the total number of components for each combination. In combinations of components numbered #2 to #9, only one cable phase (C-1ϕ) was tested with the joints (J) while for the #10 combination, the three phases (C-3ϕ) of the cable section were tested simultaneously with all eight joints.

The evolution of the measured and calculated dielectric losses (at 15 kV and 10^{-3} Hz) for the different combinations is presented in Figure 14 together with those measured on the three phases of a Hydro-Québec line. The TDS dielectric losses of the three phases (3ϕ) of this line, presented as a reference in Figure 14, are considered to be representative of a line with degraded joints [4].

It can also be seen in Figure 14 that the cable alone (#1) presents the lowest losses and that the addition of new and moderately degraded joints results in an increase in the polarization and depolarization losses (#2 to #9). The point corresponding to the number #9 combination is the one with the addition of a joint that was diagnosed with a hot spot as the type C one shown in Figure 9. It is interesting to note that the last combination (#10) in Table 3 corresponds to a ~600-m line (the three phases connected together) and that the losses are simply divided by a factor of 3 due to the capacitance increase. However, even in that case the total current of the all combination results only from the last joint (J8) added. The dielectric losses of this simulated line with a "weak link" can then be expressed as:

$$tg\ \delta_{\#10} \approx \frac{160 \times i_{advanced\ degraded\ joint}}{V \times C_{line}'} \qquad (6)$$

Figure 13: Set-up of cables and joints used for the line simulation measurements

Table 3: Measured and calculated dielectric losses for a ~200-m line simulation with eight joints

Combinations		Tg δ (at 10^{-3} Hz)			
		Measured		Calculated	
		depol.	pol.	depol.	pol.
1	C-1 ϕ	5.4×10^{-5}	1.7×10^{-4}	5.4×10^{-5}	1.7×10^{-4}
2	C-1 ϕ + 1 J	6.7×10^{-5}	1.9×10^{-4}	6.4×10^{-5}	1.9×10^{-4}
3	C-1 ϕ + 2 J	9.1×10^{-5}	2.9×10^{-4}	9.3×10^{-5}	2.5×10^{-4}
4	C-1 ϕ + 3 J	1.8×10^{-4}	4.4×10^{-4}	1.9×10^{-4}	4.6×10^{-4}
5	C-1 ϕ + 4 J	2.2×10^{-4}	4.5×10^{-4}	2.3×10^{-4}	5.4×10^{-4}
6	C-1 ϕ + 5 J	6.2×10^{-4}	1.9×10^{-3}	6.1×10^{-4}	2.0×10^{-3}
7	C-1 ϕ + 6 J	7.2×10^{-4}	3.1×10^{-3}	6.9×10^{-4}	3.2×10^{-3}
8	C-1 ϕ + 7 J	9.2×10^{-4}	8.8×10^{-3}	1.0×10^{-3}	1.0×10^{-2}
9	C-1 ϕ + 8 J	4.2×10^{-3}	20	4.0×10^{-3}	20
10	C-3 ϕ + 8 J	1.4×10^{-3}	6.2	1.4×10^{-3}	6.7

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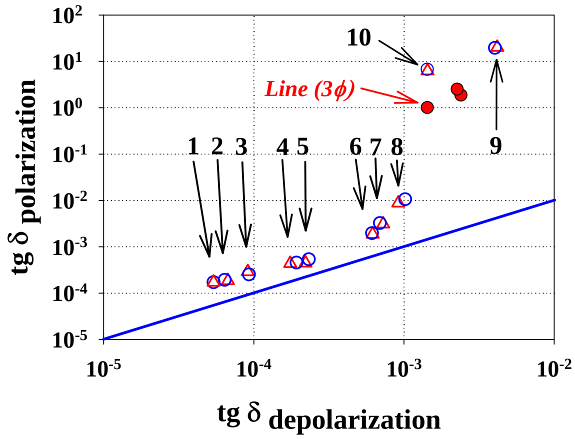

Figure 14: Evolution of the measured and calculated losses of a cable with different accessories (Δ: measured, o: calculated)

CONCLUSION

The TDS characterization of 58 joints recuperated from the same line that was dismantled after 30 years in service showed that the insulation degradation of joints is not correlated to the time in service. Some of the joints from this line had dielectric losses similar to new ones and different aging distribution levels were observed between the five types of joint.

A preliminary TDS characterization of the dielectric losses (*C"*) in polarization and depolarization of all joints recuperated from service suggest at least two different aging mechanisms: (i) global slow degradation of joint insulation by water treeing and (ii) local degradation for specific joint designs.

The major contribution to the dielectric losses of some joints with advanced insulation degradation was confirmed by performing a line simulation at IREQ by testing with the TDS ~200-m long cable sections on a reel and eight joints (two new ones and six presenting various degrees of degradation), with the TDS. This line simulation clearly confirmed the dominant contribution of advanced joint degradation to the dielectric losses.

The most important advantage of the Time Domain Spectroscopy approach is that it measures the depolarization losses, not only the polarization losses. This difference is fundamental if global aging (depolarization) is to be distinguished from local degradation, which is predominant when it originates from accessories [13]. The TDS method offers other advantages such as compactness and the fact that neither the length nor the configuration of the circuit limits the measurements.

Another parameter that characterizes insulation degradation is the nonlinearity of the TDS losses with the applied voltage [1, 12]. In this study, only joints affected by hot spots (detected by infrared imaging in the manhole) showed a clear nonlinearity in the polarization and depolarization modes. Preliminary measurements on terminations also showed a nonlinearity behavior either in polarization or depolarization depending on the phase from which they were recuperated.

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