WATER-TREE AGING CHARACTERIZATION OF MV XLPE CABLE INSULATION USING TIME DOMAIN SPECTROSCOPY (TDS)

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ABSTRACT

Water-tree degradation of Hydro-Québec's MV XLPE cables was characterized by measuring the residual AC breakdown voltage, the maximum water-tree lengths and the dielectric losses of cable sections removed after 15 to 34 years in service. Contrary to expectations, the XLPE cable insulation for cables in service for 30 years was not severely degraded; the average residual breakdown voltage ranged between 4 and 8 times the service voltage and the maximum water-tree length (bow-tie) was equivalent to only about 30% of the insulation thickness. The dielectric losses measured by Time Domain Spectroscopy (TDS) showed a good correlation with the water-tree degradation, thus demonstrating that this technique can be used as a diagnostic tool for condition-based maintenance of underground lines.

INTRODUCTION

Water-tree aging in XLPE cable insulation has been the subject of numerous papers and theses for the past 30 years. Despite unanimous agreement that the combination of water and electric field in polymeric insulation affects its dielectric performance, there is no clear understanding of the water-tree aging process. Neither proposed aging models nor reported service failure statistics have been very useful for extrapolating the degradation level of the insulation or the remaining life of the cable insulation. Despite this lack of information, the popular belief is that MV XLPE cables reach their end of life after 30 years.

Hydro-Québec has a growing number of MV XLPE underground cables aged 30 or more years. For those cables, three possible maintenance decisions exist: (i) replace systematically all cables aged more than 30 years, (ii) inject silicone fluid for potential rejuvenation or (iii) use a diagnostic method to assess the insulation aging. A condition-based maintenance strategy was privileged and a research project was launched at IREQ to characterize the insulation aging of these cables and to develop an off-line non-destructive diagnostic tool. The MV XLPE cable insulation characterization was performed on cables that were removed after as many as 34 years in service. A test method based on Time Domain Spectroscopy (TDS) was developed as a diagnostic in order to prioritize the underground lines to be maintained or replaced.

EXPERIMENTAL

Three parameters were measured in order to assess the water-tree degradation of MV XLPE insulated cables in service at Hydro-Québec for up to 34 years:

- Residual AC breakdown voltage
- Maximum water-tree lengths (vented and bow-tie)
- Dielectric losses

The residual AC breakdown voltage tests were performed on cable samples approximately 10 m long cut from cable sections removed from the network. Two to five samples were tested per phase for each cable section. The breakdown tests were performed following AEIC test procedures on set-ups consisting of deionized water terminations and AC power supplies (160 kV and 350 kV).

The maximum water-tree lengths for each cable sample were obtained from the visual analysis of a high-resolution scan of 30 slices (600 μm thickness). Before the scan, these slices were stained with a methylene blue solution to enhance the presence of the water trees. The longest bow-tie and vented tree observed on each set of 30 slices were then recorded and associated with the residual breakdown voltage previously measured on that sample.

The off-line non-destructive diagnostic tool used by Hydro-Québec for this study was time domain spectroscopy. The principle is shown in Figure 1. The computer-controlled TDS device developed at IREQ can measure polarization and depolarization currents with a sensitivity of 10 x 10^{-9} A and 1 x 10^{-12} A, respectively. This device has been mounted in a small vehicle for field measurements (Figure 2); a schematic of the TDS circuit is shown in Figure 3.

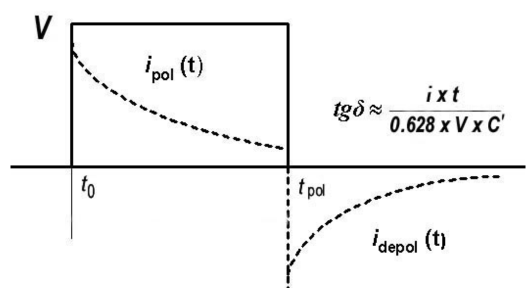

Figure 1: Principle of the time domain spectroscopy

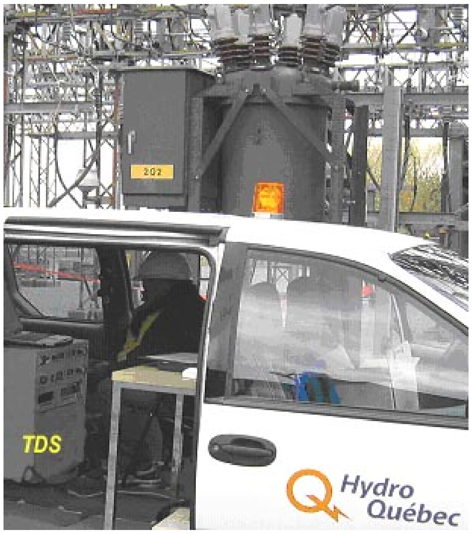

Figure 2: TDS device installed in a small vehicle for field measurements

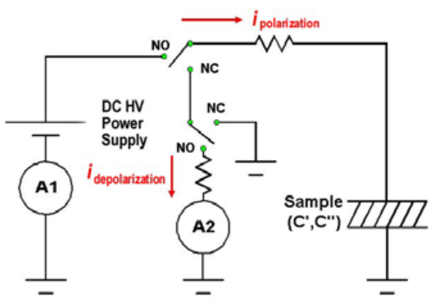

Figure 3: Schematic of the TDS measurements: A1 - multimeter and A2 - electrometer

RESULTS AND DISCUSSION

The data presented in this paper results from the residual breakdown voltage tests and water-tree measurements performed on approximately 45 cable sections removed from service. The TDS data was obtained from measurements performed at IREQ on approximately 40 phases of these 45 cable sections and from field measurements on a total of 18 Hydro-Québec lines.

Residual AC breakdown voltage

More than 330 cable samples of ~10 m were tested for residual AC breakdown voltage following AEIC procedures. The average and standard deviation values of the residual breakdown voltage were calculated for each phase of the various cable lengths; the overall results are presented in Figure 4. In this figure, breakdown values are shown in units of U/U_0 (U_0 = service voltage) in order to compare 15-kV and 25-kV cable lines on the same graph. The average residual breakdown voltage for cables in service for 30 years ranged from 4 to 8 times the service voltage. New cables were also tested for reference: their average breakdown values ranged between 14 to 18 times the service voltage. The observed reduction of the residual breakdown voltage, less than expected, with time is not considered sufficient enough to recommend the cable replacement.

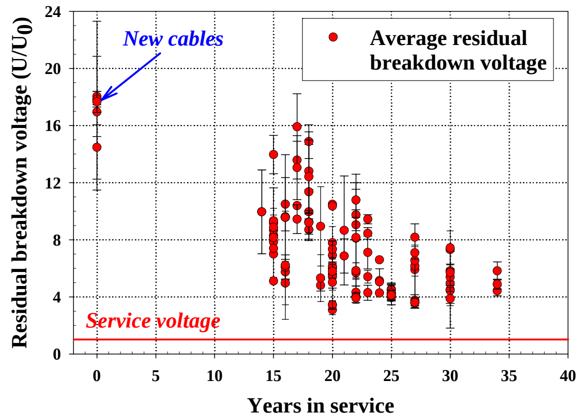

Figure 4: Residual breakdown voltage versus number of years in service

Water-trees

After each breakdown test, a sample of 15 cm of cable was selected for the water-tree analysis. For each cable sample, the longest bow-tie and vented trees observed on the 30 slices were recorded. Approximately 10,000 slices prepared from the 45 cable sections tested were analyzed. The present study clearly revealed that the typical water-tree degradation of Hydro-Québec's MV XLPE cables takes the form of bow-tie trees (Figure 5). The maximum water-tree lengths for vented and bow-tie types are presented in Figure 6 as a function of the number of years in service for each of the cables removed from service. A line corresponding to a water-tree growth rate of approximately 1% of the insulation thickness per year is also shown in Figure 6. From these results, a life expectancy of more than 50 years can conceivably be extrapolated for XLPE cables (with cross-linked shields) that are degraded by bow-tie trees.

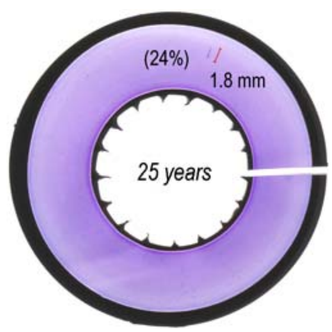

Figure 5: Typical water-tree aging (bow-tie) observed on Hydro-Québec's MV XLPE cables

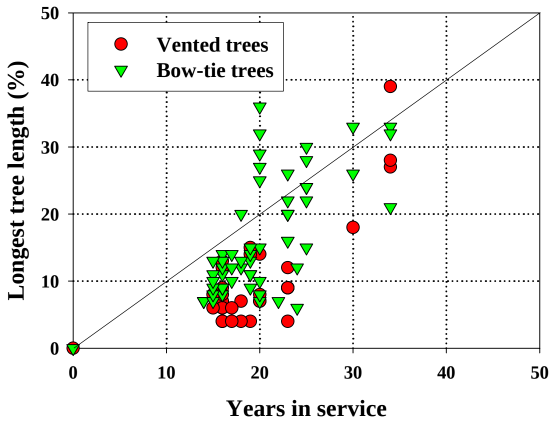

Figure 6: Maximum water-tree lengths (vented and bow-tie) versus number of years in service

An average value of the residual breakdown voltage was calculated for the three phases of a same cable; the values obtained are represented in terms of the longest water tree length in Figure 7 for each type of tree (bow-tie and vented). Although a substantial statistical dispersion is observed, the results clearly show the reduction of residual breakdown voltage values with the longest water-tree lengths [1].

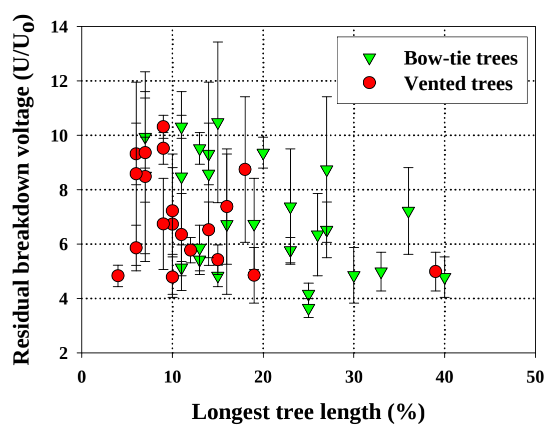

Figure 7: Residual breakdown voltage versus maximum bow-tie tree length

Dielectric losses by TDS

The TDS device developed at IREQ was first used to characterize the dielectric losses in depolarization of XLPE cable lengths without accessories. Once it was confirmed that water-tree aging of XLPE insulation could be characterized by the amplitude of dielectric losses in depolarization, measurements were performed on complete lines. As shown in Figure 3, the TDS device fundamentally performs measurements of polarization and depolarization currents, which can be expressed as a combination of different components [2]:

$$i_{pol}(t) = i_{cap}(t) + i_{abs}(t) + i_{qc}(t)$$
$$i_{depol}(t) = -i_{cap}(t) - i_{abs}(t)$$

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 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 [3]:

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

Cables without accessories

The 40 phases of cable section tested with the TDS at IREQ ranged in lengths from 40 m to 350 m. These cables had been in service between 15 and 34 years at Hydro-Québec. New cables and two aged cables from other utilities were also tested. The measured dielectric losses in depolarization showed a good correlation with water-tree aging, as shown in Figure 8, in the frequency range of 10^{-1} to 10^{-4} Hz. Although different voltage levels and application times were used, the results presented in Figure 8 were obtained for cables subjected to 10 kV_{dc} for 200 s.

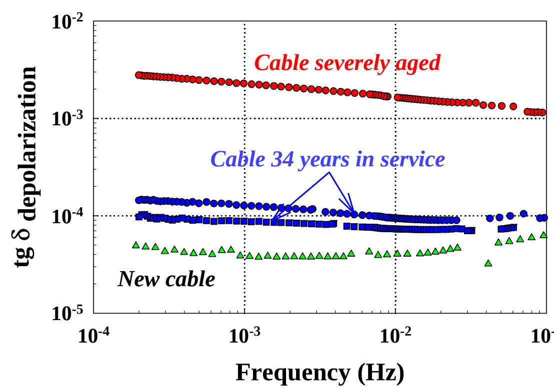

Figure 8: Dielectric losses of cables without accessories for different water-tree length degradation

The cable tagged "severely aged" had no outer screen and had been in service in a European utility. It contained a high density of vented trees growing from the outside, most of them having lengths exceeding 60% of the insulation thickness. TDS measurements showed a strong dependence on the voltage level (non-linearity) for this type of degradation, as observed by Hvidsen *et al* [4]. All the Hydro-Québec cables tested showed lower losses than those of the two phases of the 34-year-old cable (maximum bow-tie tree length being equal to 33% of the insulation thickness) shown in Figure 8.

Hydro-Québec's lines

Field measurements were performed on complete lines ranging from 1.1 km to 8.2 km and with a total of 8 to 45 joints per phase. In order to limit the on-site test time on the three phases to less than 4 h, including the time for set-up, each test voltage was applied for 200 s. The depolarization current was recorded for 500 s after each voltage application (5-10-15 kV). The resulting polarization and depolarization losses at 10^{-3} Hz and for an applied voltage of 10 kV_{dc} were plotted for the different phases of circuits aged 30 years on average (Figure 9). New lines were also tested and the losses for the three phases for one of the lines are presented as a reference. The straight line in Figure 9 corresponds the case of equal depolarization and polarization currents.

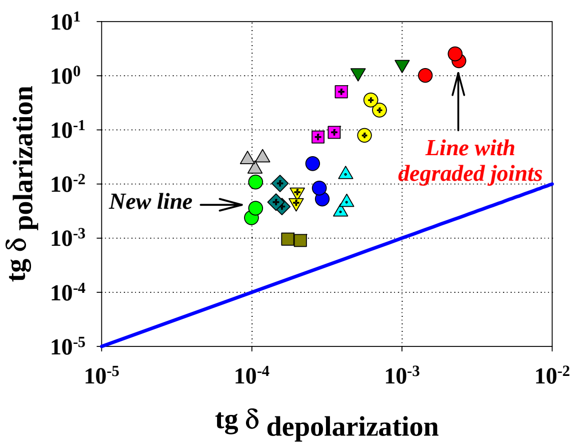

Figure 9: Dielectric loss characterization of underground lines at 10^{-3} Hz

From the field results, it can be seen that some lines present very little scatter between phases while others show significant differences that cannot be explained by normal water-tree aging of the cable insulation, the three phases being expected to present similar depolarization losses. The answer to this discrepancy was obtained from TDS characterization of more than 60 joints recovered from service. Some of these joints showed dielectric losses that were much higher than those of cables alone. In fact, these highly degraded joints could be responsible for the total losses measured on a line. Finally, from preliminary field results, it appears that the more the line-phase losses are located on the right upper side of Figure 9, the higher the probability that these losses originate from a highly degraded joint.

CONCLUSIONS

The statistics obtained from measurements of residual breakdown and maximum water-tree lengths (typically bow-tie) have shown clearly that MV XLPE cables with cross-linked semi-conductive screens were not severely degraded after 30 years in service. According to the results of this study, the life expectancy of these XLPE-insulated cables could be expected to be more than 50 years. Although the water-trees reduce the dielectric performance of cable insulation, the remaining life of lines appears much more dependent on joint degradation or local defects in the cable insulation. Furthermore, field results analysis provided evidence that some cable insulation local defects and some highly degraded joints could be further degraded by repetitive HV impulses used to locate faults ("thumper") [5] and/or by after-repair tests (using AC or DC stress higher than the service voltage).

TDS is an off-line non-destructive diagnostic tool for condition-based maintenance of XLPE cable lines that is limited by neither the length nor the configuration of the circuit. It can be used to assess the normal water-tree aging of XLPE cable insulation but also to pin-point accelerated aging in some joint designs. Measuring polarization and depolarization losses on cables and joints separately was fundamental in setting a preliminary assessment of MV underground lines. Furthermore, non-linearity (dependence on voltage level) and phase discrepancy of losses can also provide information on weak spots of MV underground lines [6]. An expert system is currently under development for the TDS device in order to provide an automatic diagnostic for assessing line degradation.

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