CONDITION ASSESSMENT OF XLPE MV CABLE JOINTS BY USING AN INSULATION TESTER

Henrik ENOKSEN
SINTEF Energy Research - Norway
henrik.enoksen@sintef.no

Espen EBERG
SINTEF Energy Research - Norway
espen.eberg@sintef.no

Sverre HVIDSTEN
SINTEF Energy Research - Norway
sverre.hvidsten@sintef.no

Ole Johan HATLEN
BKK - Norway
ole-johan.hatlen@bkk.no

Eva A. ROGNSVAAG
BKK - Norway
Eva.Rognsvag@bkk.no

ABSTRACT

Condition assessment of water treeing in medium voltage XLPE cable insulations by tan δ measurements is well established. If a measured cable section has one or more joints with low insulation resistance, the assessment of the complete cable link can be difficult as the tan δ is significantly higher for the joints than for the cable insulation. This paper describes a simple method based on using an insulation tester to reveal if joints with low resistance are present in the cable link. Measurements have been performed on cable samples taken from service after more than 20 years due to high tan δ values and partial discharges located in the cable. The joints were characterized in the laboratory by time domain dielectric response and dielectric spectroscopy. It has been shown that both the polarization and depolarization currents should be used during the assessment to provide robust evaluation criteria to distinguish the response of a low resistance joint from heavily water treed cable insulations avoiding misinterpretation of the cable condition. This method should be used before applying any other diagnostic equipment.

INTRODUCTION

In Norway it has been observed that many medium voltage (12 and 24 kV) cable sections with one or several heat shrink joints have a very low insulation resistance. This is especially observed for XLPE cables installed in the 80s, which constitutes a significant amount of the installed cables in the network. The low resistance values can typically be in the range of 0.1 – 10 GΩ making condition assessment of the cable sections not feasible by using very low frequency (VLF) tan δ testing at 0.1 Hz [1]. Moreover, the presence of low resistance joints can likely lead to misinterpretation of the cable condition. Even though the cable itself is in good condition, the assessment based on the on-site diagnostic testing can conclude that the cable is severely water tree degraded. The diagnostic criteria enclosed with the diagnostic equipment do likely not take the challenge of joints into account.

The main purpose of this paper is to propose a methodology to be able to distinguish the response of a severely water tree degraded cable from a cable with no water trees but with a heat shrink joint with low resistance. This work includes measurements on cable joints removed from service. The methodology is mainly based on measurements using a simple DC insulation tester.

THEORY

When applying a DC voltage across the cable insulation, the conductivity of the insulation and the dielectric displacement will contribute to the displacement (polarization) current, expressed by

$$\boldsymbol{J}(t) = \sigma \boldsymbol{E}(t) + \frac{d\boldsymbol{D}(t)}{dt} \tag{1}$$

where σ is the conductivity, $\boldsymbol{E}$ is the electric field, and $\boldsymbol{D}$ is the electric displacement field of the insulation [2]. After some time, all the molecules are polarized and thus the dielectric displacement current vanishes. At this point, there is only a steady state conductive current flowing through the insulation.

When the cable insulation is short-circuited, the polarized molecules will relax to their original orientation/position. Consequently, a new current will flow in the opposite direction of that of the polarization current. However, as the applied voltage is zero during this period, there is no contribution from the conductivity. This current is called the depolarization current. A typical behavior of the polarization and depolarization currents is shown in Figure 1.

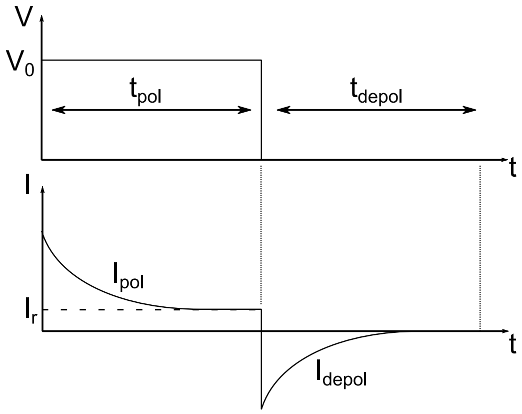

Figure 1: Illustration of polarization (I_{pol}) and depolarization (I_{depol}) currents as a function of time.

Expressing Eq. (1) in frequency domain, and assuming that the permittivity is complex, yields

$$\boldsymbol{J}(\omega) = (\sigma + \omega\epsilon'')\boldsymbol{E}(\omega) + j\omega\epsilon'\boldsymbol{E}(\omega) \tag{2}$$

where ω is the frequency, and ϵ' and ϵ'' are the real and imaginary parts of the permittivity, respectively. The loss tangent is defined as

$$\tan\delta = \frac{C''(\omega)}{C'(\omega)} = \frac{\sigma + \omega\epsilon''}{\omega\epsilon'} \tag{3}$$

where C' and C'' are the real and imaginary part of the test object's capacitance [2]. It is essentially the ratio between the resistive part and the capacitive part of the cable. If the test object is a long cable with a joint, the resulting loss tangent can be calculated as

$$\tan\delta = \frac{C''_{cable} + C''_{joint}}{C'_{cable} + C'_{joint}} \tag{4}$$

If the cable is much longer than the joint, then $C'_{joint} \ll C'_{cable}$, and if the cable insulation is XLPE, then $C''_{cable} \ll C''_{joint}$. Consequently, Eq. (4) can be approximated as

$$\tan\delta \approx \frac{C''_{joint}}{C'_{cable}} \tag{5}$$

EXPERIMENTAL WORK

Test object

This work includes on-site measurements on a 469 m long 24 kV three-phase wet designed XLPE insulated power cable (U_0=12 kV) that was installed in 1985. After the on-site measurements, a 30 m long section was removed for further on-site measurements and characterisation in the laboratory. It was important to not mechanically strain the cable section during the removal and therefore a mechanical support was carefully attached to the cable during the handling. At the centre of the removed cable a heat-shrink joint was present. Each of the joints was immediately covered with aluminium and plastic foils to prevent any moisture to escape from or diffuse into the joint materials. For practical reasons, the cable section used in the laboratory was reduced to 2.5 m with the joint positioned at the centre of the section.

Diagnostic testing in service

Partial discharges (PDs) and the dielectric loss tangent were measured at voltages from 6 kV to 25 kV using commercially available VLF equipment (0.1 Hz). After testing in service, the 30 m long cable was removed from service. Then, additional on-site PD measurements were performed on the removed section.

Diagnostic testing in the laboratory

Water tree examination

Ten 20 cm long cable sections with removed strippable insulation screens were immersed in 90°C water for one month. Afterwards, the pieces were visually checked for very long (bridging) vented water trees.

Dielectric spectroscopy

The loss tangent was measured at RMS voltages 2.5/√2, 5/√2, 6, and 12 kV. The first two magnitudes were chosen in order to make direct comparisons with the results with the DC polarization and depolarization current measurements. The latter two voltages were selected to compare the results from the laboratory and service measurements. The voltage frequencies range from 0.01 to 100 Hz. After the measurements at 5/√2 kV, a second measurement at 2.5/√2 kV was performed to examine the reproducibility of the measurements (hysteresis). The same was done at 6 kV after 12 kV. PD free terminations and guard electrodes were installed prior to the laboratory measurements.

Time domain dielectric response measurements

Two different measurement setups were used to perform time domain dielectric response measurements. First, a conventional DC insulation tester was used. Here, the polarization and depolarization currents were measured at 0.5, 1, 2.5, and 5 kV for 10 and 5 minutes, respectively. Another measurement was performed at 2.5 kV after 5 kV to check for hysteresis. A guard electrode was used to remove spurious surface currents. Then, the measurements were repeated with a more sensitive experimental setup including a stable high voltage DC source and a picoamperemeter. The purpose of these measurements was to examine the accuracy of the currents measured with the insulation tester. Figure 2 shows the measurement circuit for the latter setup. The measurement circuit of the insulation tester is principally the same. During these measurements, the joint was placed inside a plastic tube covered with aluminium foil connected to ground which shields the measurement electrode from outside noise.

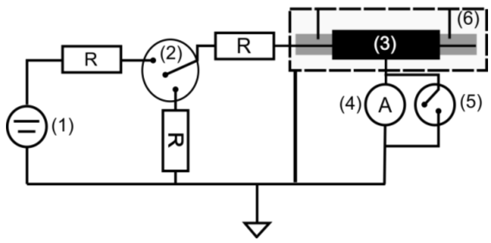

Figure 2: Illustration of experimental setup. (1) FUG 65 kV HVDC source, (2) 70 kV HV switch, (3) cable joint, (4) Keithley 6485 picoamperemeter, (5) 6 kV HV switch, and (6) aluminium covered tube connected to ground. The resistors, R, are 50 MΩ.

RESULTS AND DISCUSSION

Diagnostic testing in service

The measurements in service were performed at 0.1 Hz and are summarized in Table 1 and Table 2.

Table 1: PD results before and after removing the cable from service. The cable length before removal is 469 m, while it is 30 m after removal. U_0 = 12 kV. Note that the phases are labelled differently before and after removal.

Phase	PD before [pC]		PD after [pC]	
	U_0	$2U_0$	U_0	$2U_0$
F1	0	0	100-200	1000-2000
F2	0	500-1200	500-1600	3000-9000
F3	150-300	200-700	0	0

Table 2: Loss tangent results before removing the 469 m long cable from service. Results are taken from measurements at 0.1 Hz.

Phase	tan δ $[10^{-3}]$, 6 kV	tan δ $[10^{-3}]$, 12 kV
F1	18.9	27.1
F2	11.4	17.8
F3	12.7	20.7

High numbers and magnitudes of partial discharges were measured for the 469 m long cable. The loss tangent measurements were stopped at 12 kV (U_0) due to very high values. Due to the partial discharges and the high loss tangents, a 30 meter long cable section was removed with the discharge site at the centre of this section. Partial discharges were re-measured on the 30 m section. Again, the PDs were located at the centre of the cable where it was observed that a joint was positioned. The magnitudes were even higher than before removal. The lower magnitudes before removal are likely due to the attenuation and dispersion of the much longer cable.

According to the procedure issued by the manufacturer of the equipment, the tan δ results indicated that all phases were severely water-treed. However, the presence of a low resistance joint can also cause very high loss tangents [1], and thus lead to wrong conclusions about the complete cable. The joint could likely be the cause of both the partial discharges and the high dielectric loss tangents.

Note that the phases were not labelled when the cable was removed from service. Hence, it is not possible to compare directly the results obtained from service with the results obtained in the laboratory.

Diagnostic testing in the laboratory

When removing the outer sheath of the cable, it was observed that the joints had likely experienced overheating as visible deformations were seen on the joint body surfaces.

Table 3: Loss tangent results from the laboratory. Results are taken from measurements at 12 kV and 0.1 Hz.

Phase	tan δ $[10^{-3}]$	Corrected tan δ $[10^{-3}]$
L1	99.6	30.3
L2	472	144
L3	256	77.9

Water tree examination

The visual examination of the cable sections showed no visible large bridging water trees. Consequently, this indicates that the cable was most likely not severely water tree degraded.

Dielectric spectroscopy

The loss tangent values measured in the laboratory are even higher than those measured in service. Table 3 shows the loss tangent for all phases measured at 12 kV at 0.1 Hz. Note that these measurements are performed on the joints only. Hence, a corrected value is calculated with Eq. (5) to account for the cable length (469 m) present when measuring in service. When calculating this value it is assumed that the cable has low losses, as expected for moderately service aged XLPE cables of this design [2, 3]. Figure 3 shows the loss tangent as a function of frequency for different voltages for phase L2. The other two phases show similar frequency and voltage dependencies, although with lower magnitudes as observed in Table 3.

The great increase in the loss tangents at low frequencies indicates that the conductivity of the joint is large, see Eq. (3). This is most likely caused by high water content in the joint [4]. One possible reason for obtaining much higher loss tangents in the laboratory than in service, even after correcting for the cable length, could be presence of condensed water at interfaces in the joint. In any case, these results strongly indicate that the joint is the cause of the high loss tangents measured in service. Hence, there is no indication of severe water tree degrading in the cable.

The dotted lines of Figure 3 show the second measurements of 2.5/√2 kV and 6 kV performed after 5/√2 kV and 12 kV, respectively. These results indicate slight hysteresis in the loss tangent. In the case of bridging water trees, the hysteresis should be significantly larger [3].

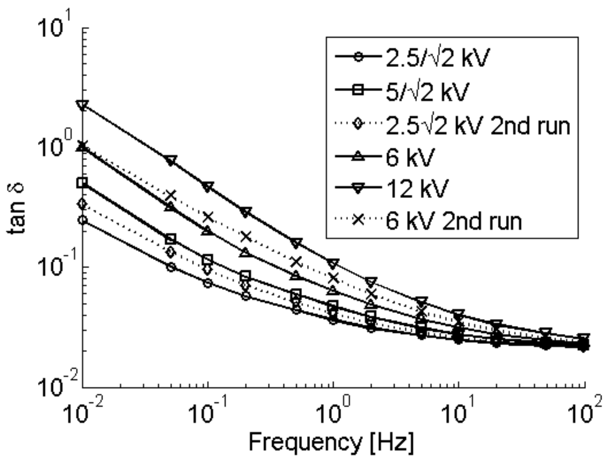

Figure 3: Loss tangent as a function of frequency for different voltages for phase L2 measured in the lab.

Time domain dielectric response measurements

Figure 4 and Figure 5 show the polarization and depolarization currents, respectively, for phase L1 at 500 V and 5 kV measured with the insulation tester and the laboratory setup. Results for voltages 1 kV and 2.5 kV, and the other two phases are not shown, though the measurements at these voltages show similar magnitudes. As instrumental current transients from the insulation tester disturb the measurements during the first 30 seconds, these are omitted. It is observed that the difference between the currents measured by the two setups is very small and can for practical purposes be neglected in this range.

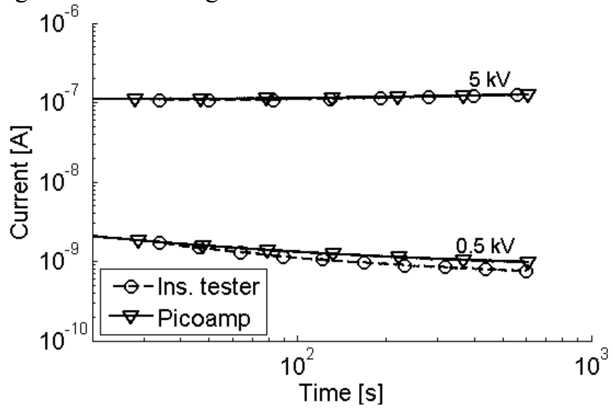

Figure 4: Polarization currents measured with a picoamperemeter (solid lines with downwards triangles) and the insulation tester (dashed lines with circles) for phase L1 at 0.5 kV and 5 kV.

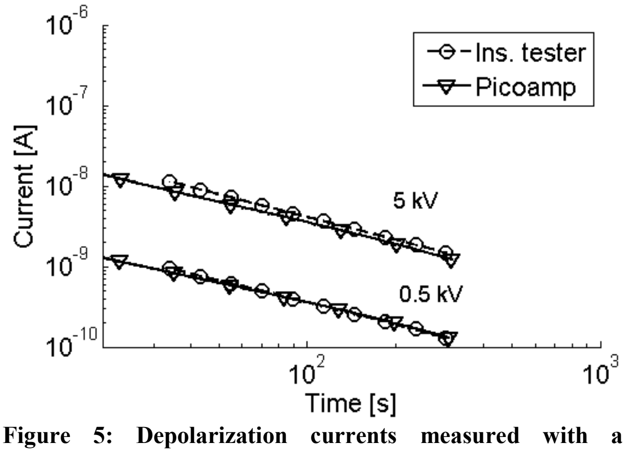

Figure 5: Depolarization currents measured with a picoamperemeter (solid lines with downwards triangles) and the insulation tester (dashed lines with circles) for phase L1 at 0.5 kV and 5 kV.

According to theory, the polarization current should relax to a steady conductive current after the polarization processes are diminished, see Eq. (1). The measured polarization current magnitudes are however very large compared to the depolarization currents even after short times and low voltages. This indicates a large contribution from the conductivity of the joint. The origin of the low resistance (high conductivity) could be increased moisture content of the joints [4]. Another reason can be an increase in the conductivity induced by overheating causing material oxidation. Moreover, the currents at 5 kV display an unstable oscillatory behavior for L2, and for L1 and L3 the currents increase with time as shown in Figure 6. This may be caused by movement of condensed water located at the interfaces between the different parts of the joint.

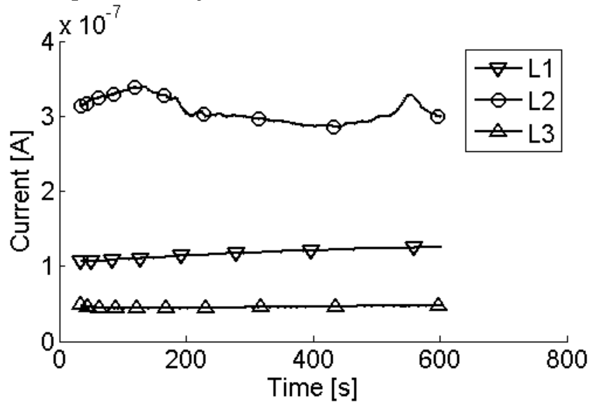

Figure 6: Polarization currents measured with the insulation tester for all phases at 5 kV shown at a linear scale.

Figure 7 shows that the polarization currents have a significant voltage dependence. It has previously been shown that high water content in the joint materials will make the conductivity voltage dependent [4] as indicated in Figure 4. Hence, it is likely that this joint has absorbed a significant amount of moisture during its service.

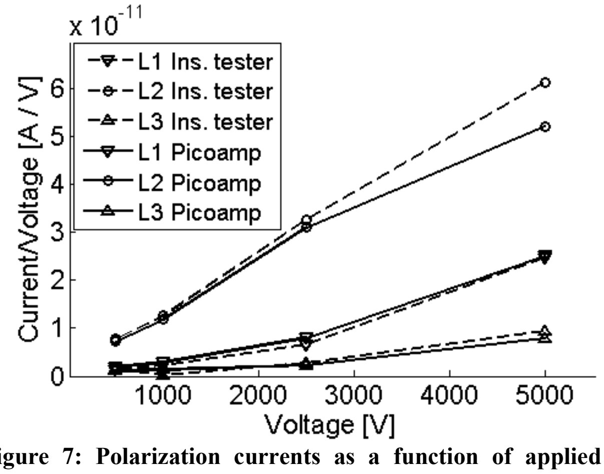

Figure 7: Polarization currents as a function of applied voltage for all three phases (L1 downwards triangles, L2 circles, and L3 upwards triangles). The currents are normalized with respect to the applied voltage and each data point is the average value of the data taken from the last two minutes of measuring. The dashed and solid lines denote insulation tester and picoamperemeter, respectively.

Figure 8 shows that the depolarization current is much less dependent on voltage than the polarization current. If a high number of long vented water trees were present, the depolarization current would likely be voltage dependent [5].

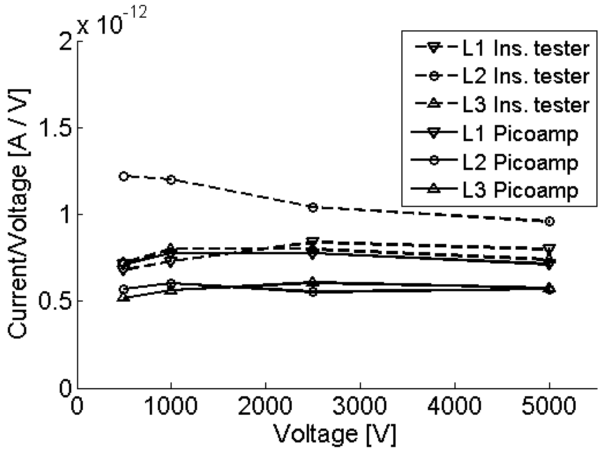

Figure 8: Depolarization currents after 100 seconds as a function of applied voltage for all three phases (L1 downwards triangles, L2 circles, and L3 upwards triangles). The currents are normalized with respect to the applied voltage. The dashed and solid lines denote insulation tester and picoamperemeter, respectively.

The initial measurements of the loss tangent indicated that the cable was heavily water-treed due to the high values shown in Table 2. Figure 9 shows the polarization and depolarization currents measured at 2.5 kV, then 5 kV, and then at 2.5 kV again for phase L2. The other phases show the same behavior. Note that only 0.5 m of the cable on each side of the joint is included in these measurements. Still, if the cable had been severely water tree degraded, this cable length should have contained enough water trees to yield a significant hysteretic effect as expected from heavily water tree degraded cables [3]. However, only a slight hysteresis is observed. This corresponds to the slight hysteresis observed in Figure 3. Hence, the cable is probably not severely water tree degraded. It is more likely that the low resistance joints are the cause of the large loss tangents, rather than water trees bridging the insulation.

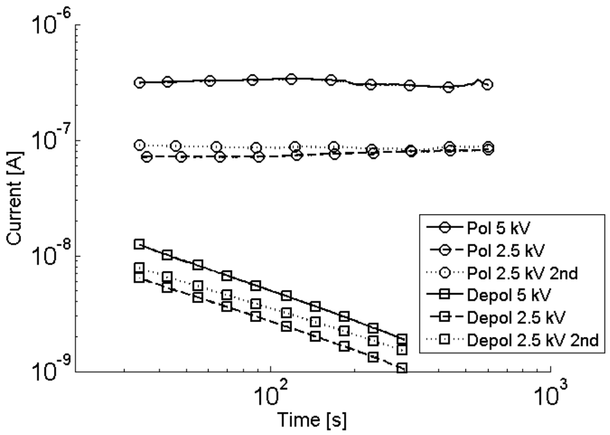

Figure 9: Polarization and depolarization currents for phase L2 at 2.5 kV first run, 5 kV, and 2.5 kV second run, denoted by dashed, solid, and dotted lines, respectively. Polarization and depolarization currents are denoted by circles and squares, respectively.

CONCLUSION

This paper indicates that a simple insulation tester provides useful information when assessing the condition of a MV XLPE cable system with joints. It is an easy and efficient method of separating heavily water tree degraded cables from cable systems where a joint is causing high loss tangents. This method should be used before applying any other diagnostic equipment.

From the results in this work it can be concluded that:

- The insulation tester provides sufficient accuracy and resolution to be used in MV XLPE cable links.
- By using reliable evaluation criteria, an insulation tester can e.g. reveal if a joint is the cause for high tan δ values of the complete cable link avoiding misinterpretation of the condition.
- Example of such a criterion could be the non-linear (voltage dependent) polarisation currents, and linear depolarisation currents as measured for the joint.
- The results can also be used to decide if more advanced diagnostic methods (PD or tan δ) should be applied afterwards.
- More work must be performed to establish robust and reliable evaluation criteria for the insulation tester that can be used during the condition assessment.

Acknowledgements

The work has been performed as a R&D-project in the framework of Norwegian Federation of Utilities (Energy Norway). Both Norwegian utilities and cable industry have contributed to and sponsored the work. The authors would like to express gratitude for their support and permission to publish the work.

REFERENCES

[1] S. Hvidsten, and J. T. Benjaminsen, 2002, "Diagnostic Testing of MV XLPE Cables with Low Density of Water Trees", *Conference Record of the 2002 IEEE International Symposium on Electrical Insulation*, pp.108-111.

[2] A. K. Jonscher, 1983, *Dielectric Relaxation in Solids,* Chelsea Dielectrics Press, London, United Kingdom, 45.

[3] CIGRE Working group D1/B1.20, "Non-Destructive Water-Tree Detection in XLPE Cable Insulation" TB-493, April 2012.

[4] F. Mauseth, K. D. Hammervoll, and S. Hvidsten. "Dielectric properties of service aged medium voltage XLPE cable joints", *Solid Dielectrics (ICSD), 2010 10th IEEE International Conference on*, pp. 1-4.

[5] T. Heizmann, and W.S. Zaengl, "Influence of ageing on depolarization currents in polymer-insulated medium-voltage cables", *Electrical Insulation and Dielectric Phenomena (CEIDP). 1991 Annual Report. Conference on*, pp. 324-329