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ADVANCEMENTS IN CONDITION MONITORING OF ELECTRICAL CABLES USING LINE RESONANCE ANALYSIS (LIRA)

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Abstract ï This paper describes a method for cable system condition monitoring, developed initially at the IFE Halden Reactor Project and then further developed at Wirescan AS, which is based on transmission line theory and resonance analysis. This method resulted in the development of a system called LIRA (LIne Resonance Analysis), which can be used on-line to detect local or global changes in the cable electrical parameters as a consequence of insulation faults or degradation. This paper presents the latest results achieved in field experiments on signal and power cables.

INTRODUCTION

There is a continued interest worldwide in the safety aspects of electrical cable system degradation [1,2]. Degradation of a cable system can result in loss of critical functions of the equipment energized by the system, or in loss of critical information relevant to the decision-making process and operator actions. In either situation, unanticipated or premature aging of a cable can lead to unavailability of equipment important to safety and compromise public health and safety.

Current techniques to evaluate aging properties of electric cables include electric properties tests. While known to be difficult, advancements in detection systems and computerized data analysis techniques may allow ultimate use of electrical testing to predict future behavior and residual life of cables. The following describes the current results and development of a system (LIRA) and its progress in being able to determine the degree of cable degradation through electrical testing. LIRA has gone through extensive tests since 2005 with low, medium and high voltage cables, both in laboratory tests and in-situ experiments and it has been used in service assignments since 2007.

The LIRA (Line Resonance Analysis) technology is a cable condition assessment, cable fault location and cable aging management system that works in frequency domain through advanced algorithms. LIRA is based on the transmission line theory, and calculates and analyse the complex line impedance as a function of the applied signal for a wide frequency band. It detects and locate changes in the cable impedance and makes it possible to perform fault location and cable condition monitoring on I&C, low, medium and high voltage cables even in inaccessible challenging environments. The applied frequency band is a 5V signal, and is harmless to the cable.

LIRA will detect and locate local degradations in the cable, which is specific to certain sections of the cable and caused by mechanical stress and damages, or by heat-induced oxidation and radiation. It will also detect global degradation in the cable, which is applicable for the entire cable, and is caused by general aging, influenced by external and internal environmental conditions.
This paper presents the current technology at the base of this system, together with some interesting results on installed cables.

THE LIRA METHOD

The Line Resonance Analysis (LIRA) method has been developed by the Halden Reactor Project in the years 2003-2006 [4] and then further developed by Wirescan AS and it is based on transmission line theory [5-13]. A transmission line is the part of an electrical circuit providing a link between a generator and a load. The behavior of a transmission line depends on its length in relation to the wavelength of the electric signal traveling into it.

When the transmission line length is much lower than the wavelength (ə), as it happens when the cable is short and the signal frequency is low, the line has no influence on the circuit behavior and the circuit impedance, as seen from the generator side, is equal to the load impedance at any time.

However, if the line length and/or the signal frequency are high enough, so that *Length* Óə, the line characteristics take an important role and the circuit impedance seen from the generator does not match the load, except for some very particular cases.

LIRA includes a proprietary algorithm to evaluate an accurate line impedance spectrum from high frequency measurements.

Line impedance estimation is the basis for local and global degradation assessment. Tests performed with

LIRA show that thermal degradation of the cable insulation and mechanical damage on the jacket and/or the insulation do have an impact on C and at a lesser degree on L. Direct measurement of C (and L) would not be effective because the required sensitivity has the same magnitude of the achievable accuracy, due to the environment noise normally present in installed cables (especially for unshielded twisted pair cables, see FIGURE 1. Some results were achieved with coaxial cables [3]). LIRA monitors C variations through its impact on the complex line impedance, taking advantage of the strong amplification factor on some properties of the phase and amplitude of the impedance figure, as shown in FIGURE 2.

Hot spot damage due to localized high temperature conditions and local mechanical damage to the insulation are detectable by LIRA through use of a proprietary algorithm starting from the line impedance spectrum.

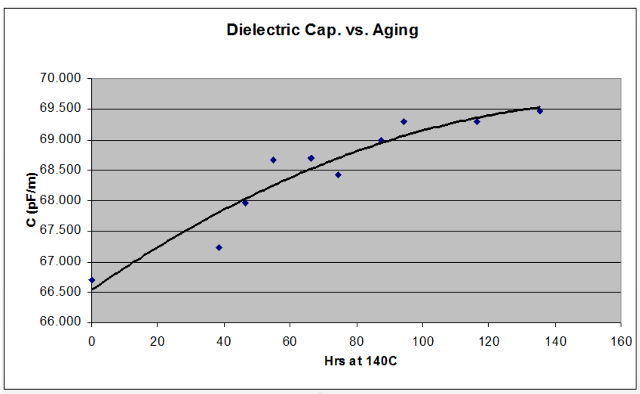

FIGURE 1 Dielectric capacitance vs. ageing

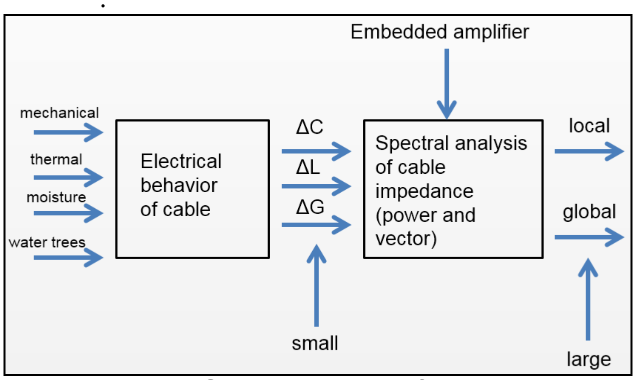

FIGURE 2 LIRA workflow

TERMINATION ASSESSMENT

The Termination Assessment algorithm (BTS) is based on the Fourier transform of the cable impedance spectrum, at the maximum bandwidth allowed by the applied maximum frequency.

While the output of the Fourier analysis for the LIRA signature is a power spectrum, for the BTS analysis the complex output is preserved. The ratio between the difference of the imaginary and real component of the transformation function (also called the BTS signature function) has a significant diagnostic value and it is bounded between +sqrt(2) and ï sqrt(2).

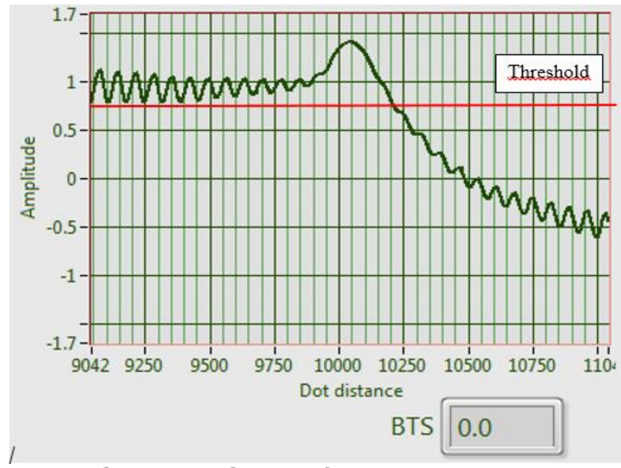

FIGURE 3 BTS graph for a good termination

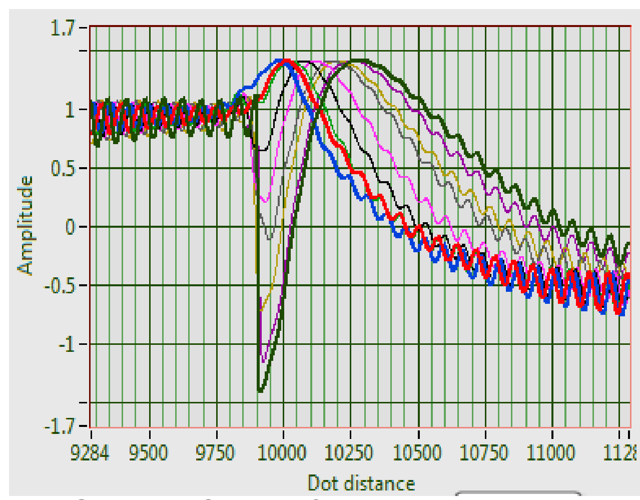

FIGURE 4 BTS graphs for damaged terminations

FIGURE 3 shows the result of the BTS assessment for a good cable termination, where the trace is bounded above the threshold line. FIGURE 4 shows the BTS trace behavior when water penetrates the into the cable termination, at different increasing levels. FIGURE 5 shows the corresponding BTS indicator trend.

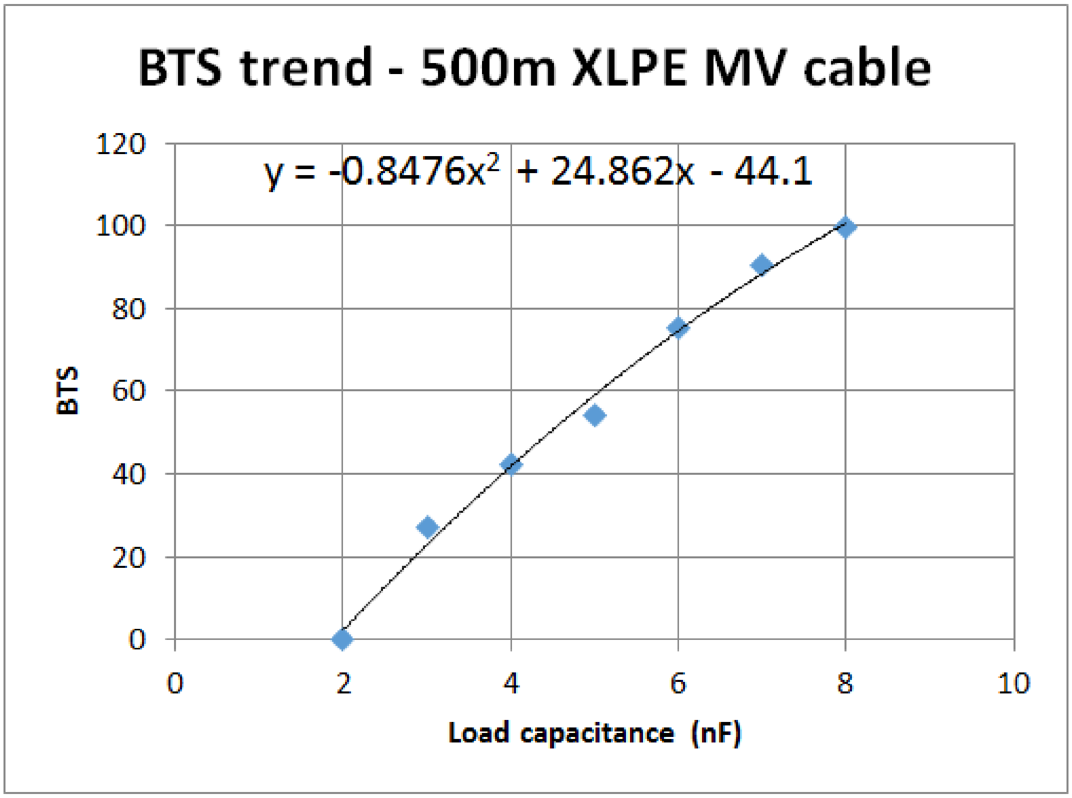

FIGURE 5 BTS trend with increasing load capacitance

GLOBAL AGEING ASSESSMENT (DeltaG)

DeltaG is the LIRA indicator for global cable degradation and it is correlated to the well known Tanŭ indicator, also known as dissipation index.

The DeltaG algorithm is based on the calculation of the cable attenuation in a frequency range from 0 to approximately one third of the full applied bandwidth.

The attenuation is the result of two factors, one correlated to the conductor resistance (including the skin factor) and one correlated to the energy dissipation through the insulation (sensitive to ageing):

$$\propto = K1 \times \sqrt{f} + K2 \times f$$

K1 and K2 can be accurately estimated using a non linear regression algorithm. DeltaG is derived from K2.

Calculation of DeltaG requires the knowledge of the following parameters:

1. Cable length
2. Core material
3. Core diameter
4. Core temperature
5. Cable structure (twisted pair, coaxial)

About cable length, LIRA can estimate this parameter, when unknown, if other parameters like velocity ratio (VR) are known.

FIGURE 6 shows the steps performed by LIRA to estimate DeltaG

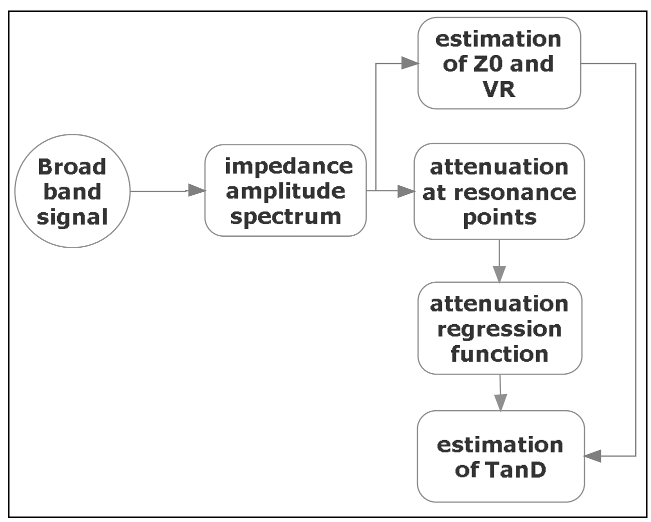

FIGURE 6 DeltaG workflow

An example of DeltaG estimation is shown in FIGURE 7**.**

The LIRA DeltaG for thermal ageing degradation in nuclear installations is currently under assessment at Pacific Northwest National Laboratory (PNNL), USA.

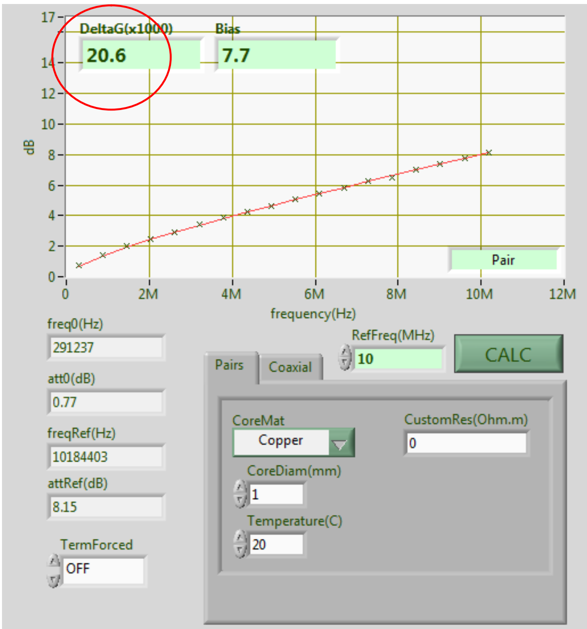

FIGURE 7 DeltaG assessment

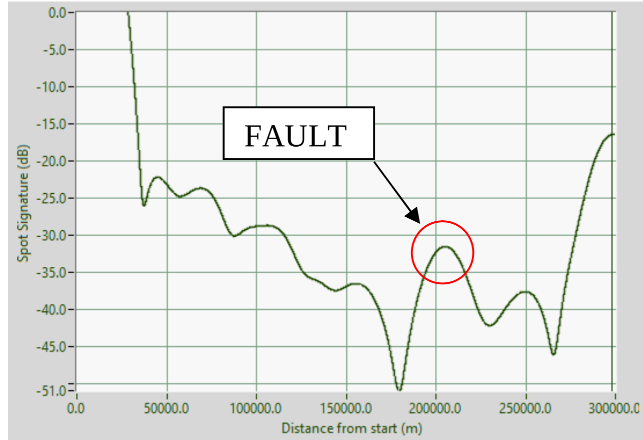

FIGURE 9 Fault localization in a 300 km HV cable

RECENT CABLE ASSESSMENTS

This section presents some cases of cable fault identification recently performed with LIRA. LIRA is currently used for cable degradation assessment in the nuclear, T&D and subsea field, on I&C, medium and high voltage cables with polymer and paper insulation.

FIGURE 8 shows the LIRA signature for an 8 km medium voltage subsea cable failed in service in a windfarm. The fault location is clearly visible, just before the joint.

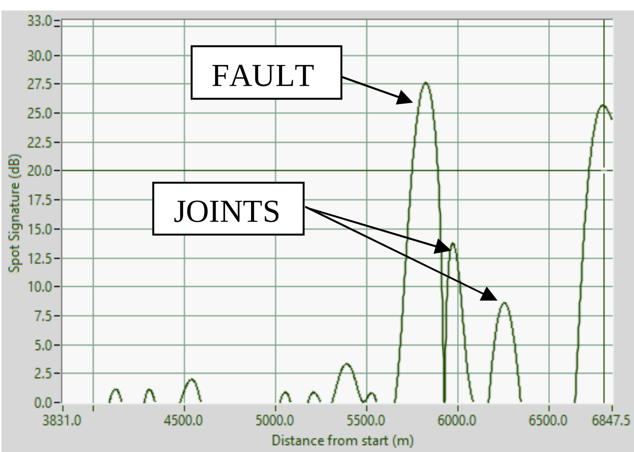

FIGURE 8 Fault localization close to a joint

FIGURE 9 and FIGURE 10 show the signatures taken from both cable ends, for a 300 km HVDC subsea cable, failed in service. Because of the high attenuation, due to the large cable length, this was a very challenging case. The fault location is clearly visible from both ends.

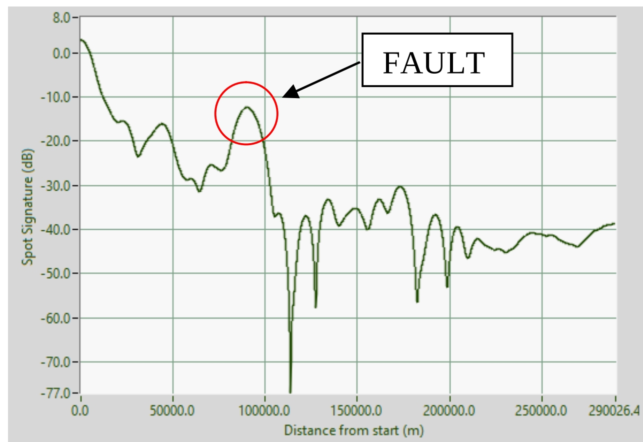

FIGURE 10 Fault localization in a 300 km HV cable (from other end)

FIGURE 11 shows the measurements of a 132 kV AC export cable, 34 km long. These measurements have been performed before (red trace) and after (yellow trace) a failure that occurred at the end of 2013. The failure was clearly identified and localized at 2500 m. After inspection, the failure position error was less than 0.3 %.

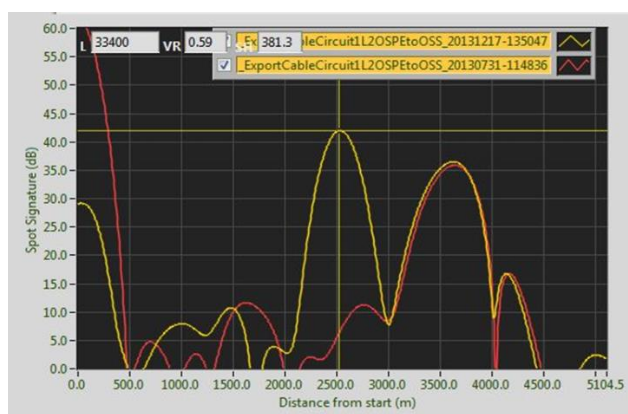

FIGURE 11 Short localization in a MV cable

CONCLUSIONS

LIRA is a frequency domain system for condition monitoring of electrical cables. This paper shows some laboratory and field cases where LIRA was used to successfully detect locations where the cable insulation was degraded because of thermal, electrical or mechanical stress.

The system is currently in use in several organizations for assessing the conditions of installed signal, medium voltage and high voltage cables.

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