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

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Abstract – 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 [1] in the safety aspects of electrical cable system aging in industrial installations. Aging 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 [3,4]. While known to be difficult, advancements in detection systems and computerised data analysis techniques may allow ultimate use of electrical testing to predict future behaviour 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 aging 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

THE LIRA METHOD

The Line Resonance Analysis (LIRA) method has been developed by the Halden Reactor Project in the years 2003-2006 [5] and is based on transmission line theory. 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 comparison with the wavelength λ of the electric signal traveling into it.

When the transmission line length is much lower than the wavelength, 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 $L \geq \lambda$, 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 noise measurements. Figure 1 shows the estimated impedance for a PVC instrument cable 100m long, in the 0-10 MHz range.

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. Some results were achieved with coaxial cables [4]). 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.

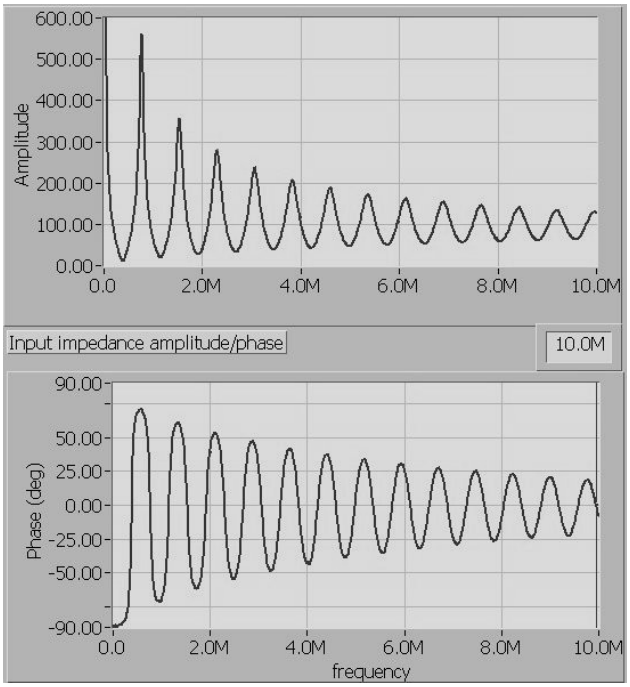

FIGURE 1 IMPEDANCE SPECTRUM OF AN UNMATCHED TRANSMISSION LINE.

One of these possible monitoring techniques is the so called zero-crossing phase monitoring method [3], that can be used to monitor and assess cable global degradation. This method tries to correlate the impedance phase shift from zero (a resonance condition) to the insulation degradation. Although LIRA implements also this technique, it has the following drawbacks:

- Resonance values (and the corresponding zero-crossing conditions) not only depend on the cable electric parameters, but also on the cable length and the reactive component of the connected load. In other words, this technique needs a reference for each tested cable (not just each cable type), from which a zero-crossing deviation can be monitored. This method is effective for continuous real-time monitoring of cable state (for example in aerospace applications), but not for diagnosing degradation in old installed cables.
- It is difficult to discriminate between cable faults (degradation) and load faults (changes in load reactance).

For these reasons, LIRA implements proprietary algorithms for an accurate estimation of the local degradation severity and position (DNORM) and the global cable condition (CBAC).

Global Condition Assessment

Several tests [1,3,4,6,7,8] have shown that global degradation in a cable insulation results in changes in the dielectric capacitance and cable inductance, at some degree. These changes affect the cable attenuation, which can be expressed as:

$$\alpha\ (dB/km) = Kf^{a}\sqrt{\frac{C}{L}} \qquad (1)$$

Where K is constant for a particular cable type and geometry and depends on the D.C. resistance, *f* is the signal frequency, the exponent *a* takes into account the skin effect and ranges between 0.5 and 1, *C* is the dielectric capacitance and *L* the cable inductance. Figure 2 shows an example of LIRA calculated cable attenuation as a function of frequency.

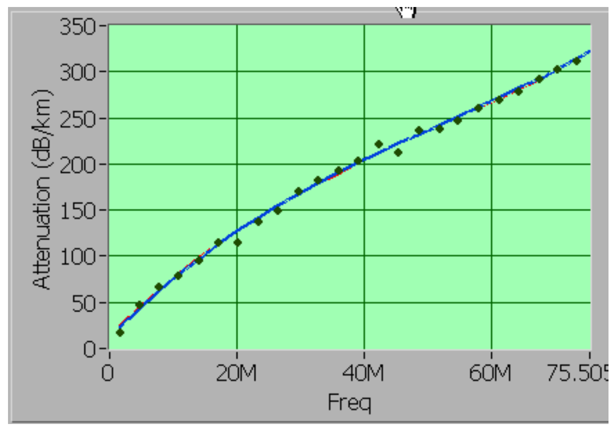

FIGURE 2 CABLE ATTENUATION (ESTIMATED BY LIRA)

Eq. (1) shows that frequency acts as a gain factor in the relation between α and *C/L* and for this reason LIRA uses high frequency attenuation values as the basis for a global condition indicator. High frequency attenuation is estimated by LIRA through a proprietary method called 3rd-harmonic analysis [7].

However, the use of an attenuation figure as it is would not be enough for condition assessment, because of its dependence on the ratio *C/L*. Degradation affects *C* and *L* in a complex way and the shape of its ratio might be non monotonic through the entire cable life. For this reason, LIRA implements a method, sketched in Figure 3, where the contributions from *C* and *L* are isolated, resulting in an indicator sensitive only to *C* (CBAC) and another indicator sensitive only to *L* (CBAL). Since it has been demonstrated that degradation affects *C* at a higher degree than *L*, CBAC is used as a global condition indicator. Note that no attempt is done to estimate directly *C* or *L*: CBAC is calculated through the estimation (using frequency analysis) of:

1. The high frequency attenuation (3rd harmonic analysis)

2. The characteristic impedance Z0
3. The phase velocity VR

Later in this paper some results on EPR and EPDM insulated signal cables are presented.

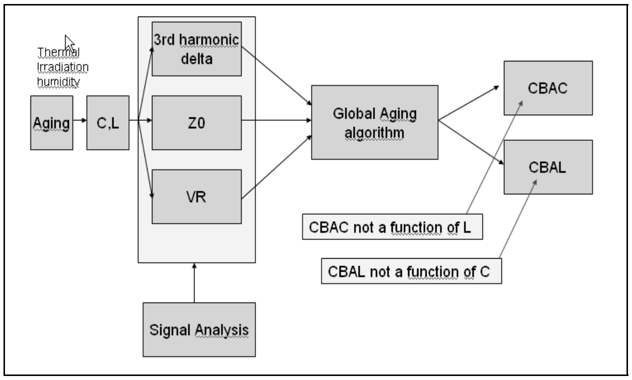

FIGURE 3 GLOBAL CONDITION INDICATOR (CBAC,CBAL) ALGORITHM

Local Degradation Detection

In a program performed in conjunction with EPRI (Electric Power Research Institute), Charlotte, NC from 2006 through January 2007 [7,8], a limited number of crosslinked polyethylene (XLPE) insulated and ethylene propylene rubber (EPR) insulated cables were thermally aged along their entire length to allow evaluation of the ability of LIRA to discriminate between the degrees of aging. These experiments resulted in the development of a condition indicator (DNORM) that can be used to assess local degradation severity, regardless of the cable length and attenuation, for both thermal and mechanical degradation/damage. Later in this paper, some additional results from experiments performed with TECNATOM SA, Spain, and within a research program (PETROMAKS) funded by the Norwegian Research Council (NFR) are presented.

LIRA STRUCTURE

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 spectra. LIRA is composed of several software and hardware modules, as depicted in Figure 4, where the cable (Device Under Test, DUT) is connected to the LIRA modulator.

- The LIRA Generator controls the AWG (Arbitrary Waveform Generator), currently a National Instruments PXI-5422, 200 Ms/s. It supplies a low voltage (1-3V), white noise signal to the system.
- The LIRA Modulator, designed by IFE, produces a reference signal (CH0) and a signal modulated by the cable impedance (CH1). CH0 and CH1 are input to a DSO (Digital Storage Oscilloscope), currently a National Instruments PXI-5124, 200 Ms/s digitizer.
- The LIRA Analyzer, the system kernel, analyses the signals and provides the cable assessment.
- The LIRA Simulator contains a model of the chain *cable->modulator->digitizer* (any cable type and length can be modeled). The simulator can be used to extrapolate results of real experiments and perform *what-if* analysis.

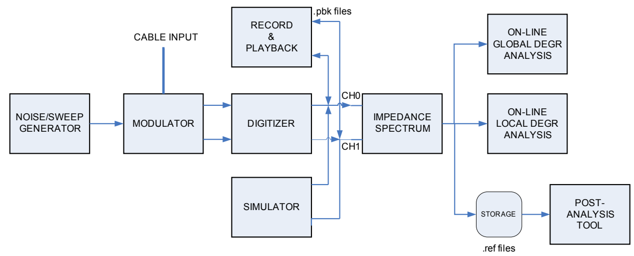

FIGURE 4 LIRA BLOCK DIAGRAM

Figure 5 shows a picture of the system in use evaluating laboratory cable.

FIGURE 5 LIRA R10 DURING A LABORATORY EXPERIMENT.

TECNATOM EXPERIMENT RESULTS (2008)

Experiment Objective

The main objective of this experiment was to evaluate the performance of LIRA on low voltage cables and compare it to other popular CM techniques in fault detection as a consequence of thermal aging and mechanical damage. The other techniques considered in this experiment were:

- Elongation-At-Break (EAB). Used as a reference method to correlate the 3 other techniques to the widely accepted 50% absolute EAB as limiting value (thermal aging).
- The Indenter. It is a local mechanical test that is in use in several power plants. The Indenter has shown a good correlation with EPR, EPDM and PVC insulation types.
- TDR. A method sensitive to changes in the electrical properties of the insulation. TDR is a time domain method used for many years to detect anomalies along electrical wires.

Table 1 shows the specifications of the samples used in this experiment.

TABLE 1 SAMPLE SPECIFICATIONS

Material	EPR	XLPE
Manufacture	PRISMIAN	GENERAL CABLE
Model	RADIFLAM INSTRUMENTACION	XI ANTILLAMA
Insulation	EPDM FIREPROOF	XLPE FIREPROOF
Jacket	AFUMEX + flame screen	Hypalon

Hot Spot Detection

Four XLPE samples were locally aged at increasing severity for a 2m segment centred at 10m. All the samples were 30m long.

Figure 6 shows the 4 TDR traces, where some indication at 10m can be spotted.

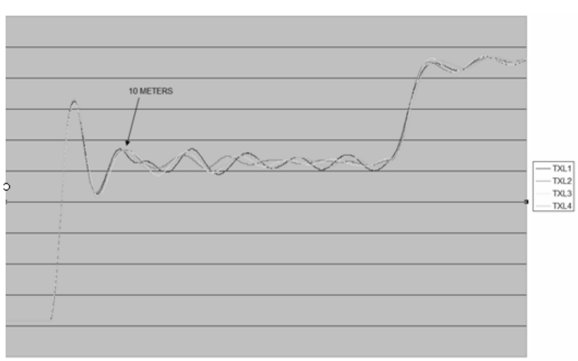

FIGURE 6 HOT SPOT DETECTION USING TDR (XLPE, 4 CASES, SPOTS CENTERED AT 10M)

Figure 7 shows the LIRA signature for the least severe sample. Note the 2 peaks at 9 and 11m, marking the beginning and end of the degraded section. These results are in line with the tests performed at EPRI in 2006-2007, where all the spots were localized correctly, in both EPR and XLPE samples. At that time, however, no comparison with TDR was performed.

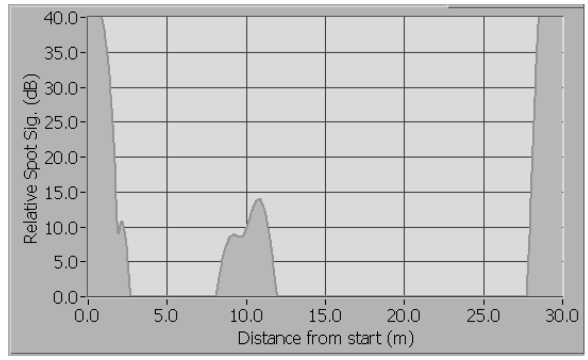

FIGURE 7 HOT SPOT DETECTION USING LIRA (XLPE, LEAST SEVERITY CASE, SPOT CENTERED AT 10M)

Mechanical Fault Detection

Two types of mechanical faults have been tested, as in the 2006-2007 EPRI tests: an insulation cut on both conductors (Figure 8) and a gouge on both conductors (Figure 9).

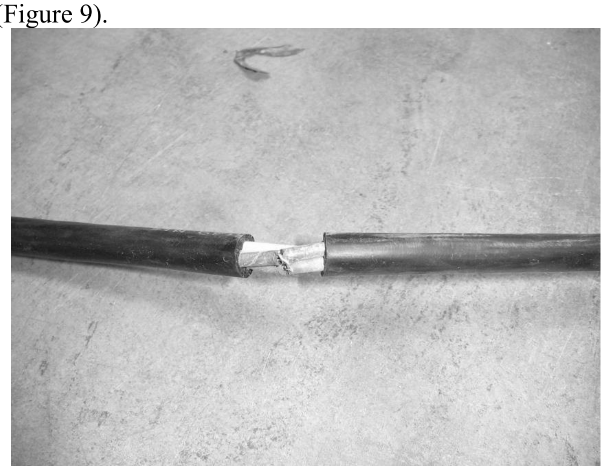

FIGURE 8 INSULATION CUT ON XLPE SAMPLE

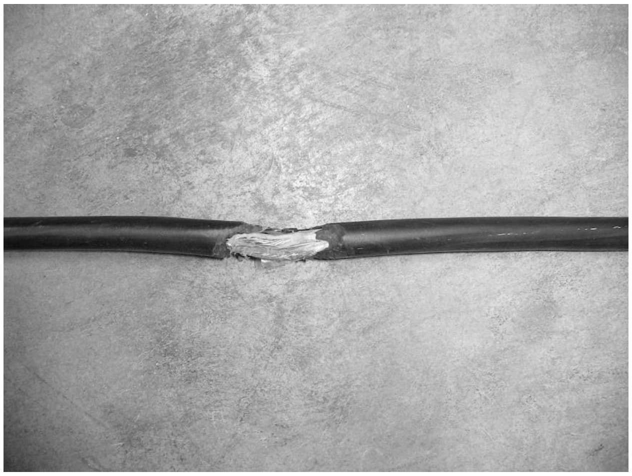

FIGURE 9 INSULATION GOUGE ON XLPE SAMPLE

Figure 10 shows the traces for the TDR measurements (blue trace for the cut, pink trace for the gouge) on the XLPE samples. The diagnosis and localization of the defects is rather uncertain.

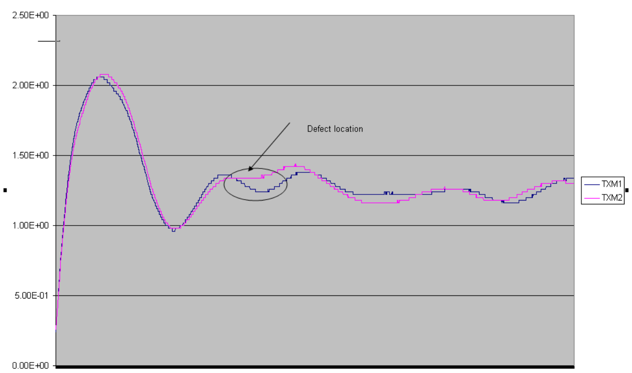

FIGURE 10 CUT/GOUGE DETECTION USING TDR

Figure 11and Figure 12 show the LIRA traces for the cut and gouge, respectively. The area below 0 dB is just noise and should be ignored.

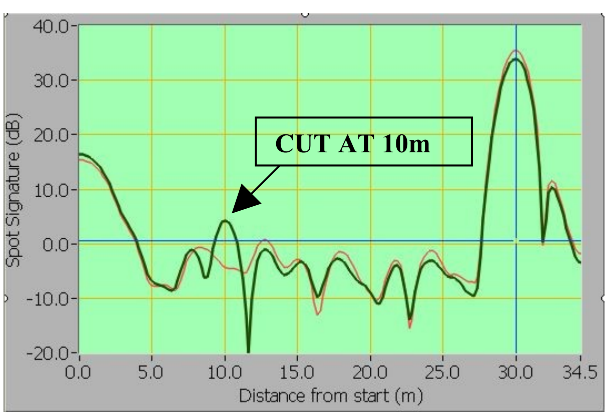

FIGURE 11 CUT DETECTION USING LIRA

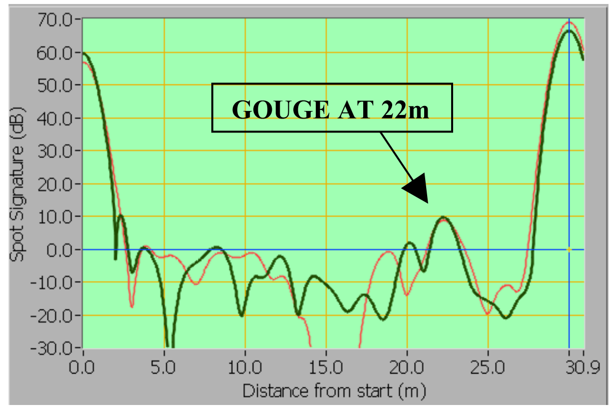

FIGURE 12 GOUGE DETECTION USING LIRA

Global Condition Assessment

3 EPR samples, 20 m long, were aged at 140 °C for 10, 20 and 30 days, producing a thermal degradation equivalent to 20, 40 and 60 years (based on the Arrhenius equation). Figure 13 shows the EAB (Elongation At Break) absolute on the insulation, for the 3 samples and the reference (new) sample.

Figure 14 shows the corresponding CBAC indications from LIRA. The almost linear decreasing trend is due to the fact that thermal aging results in a slight decrease of the dielectric capacitance.

Figure 15 contains the correlation between the EAB indicator and CBAC on the 4 measured samples. It is interesting to see that this correlation is practically linear between 20 and 60 years, which makes easier interpolation and, more important, .extrapolation to the end of life.

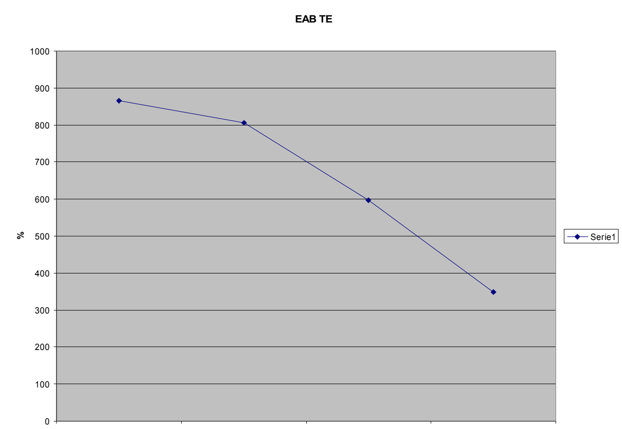

FIGURE 13 EAB MEASUREMENT ON EPR SAMPLES (0,20,40 AND 60 YEARS)

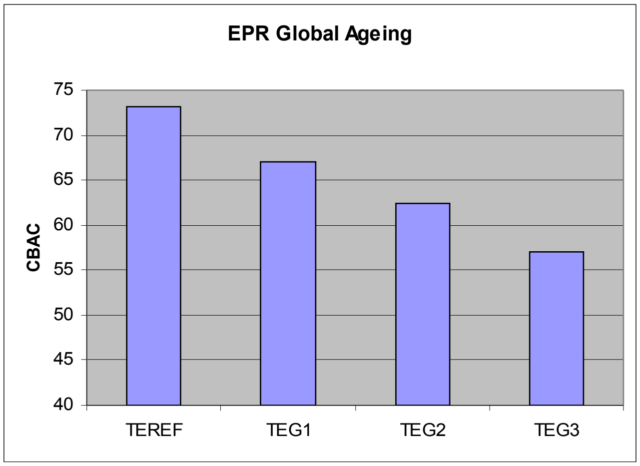

FIGURE 14 LIRA INDICATOR CBAC VS. AGING

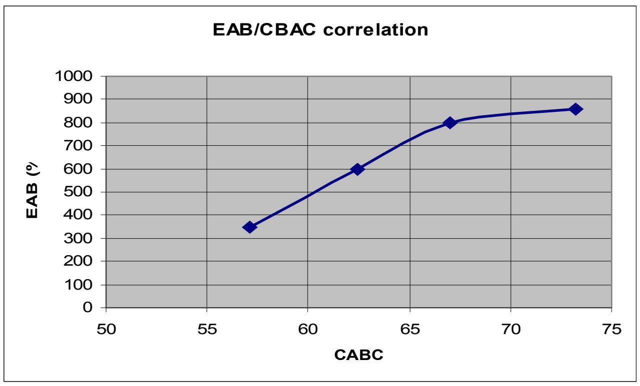

FIGURE 15 CBAC/EAB CORRELATION FOR EPR

Figure 16 shows a new evaluation of the EPR samples used in the EPRI tests (2007), where both CBAC and CBAL have been plotted. It is interesting to note that the initial CBAC value, 72 for the new sample, matches well with the initial value of the TECNATOM EPR samples, although they differ in dimension, geometry and vendor.

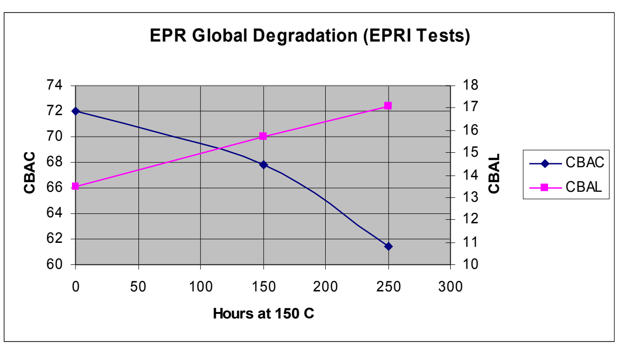

FIGURE 16 CBAC/CBAL VS. AGING, EPR SAMPLES, EPRI EXPERIMENT (2007)

POWER CABLE ASSESSMENT (2008)

In the framework of a program (PETROMAKS) sponsored by the Norwegian Research Council (NFR), 20 samples from three power cable types were tested for mechanical damage detection at increasing severity. They were 30m samples from the TSLF series produced by NEXANS, coaxial, XLPE insulation, aluminium conductor, at different rated voltage and cross section, as specified in Table 2.

TABLE 2 POWER CABLE SPECIFICATION

Cable Type	Rated V	Section	Insulation
A	24 kV	240 mm^2	XLPE
B	24 kV	50 mm^2	XLPE
C	12 kV	50 mm^2	XLPE

Figure 17 shows the structure of cable type A, 24 kV, 240 mm^2.

FIGURE 17 NEXANS POWER CABLE, TSLF SERIES

TABLE 3 LIRA ESTIMATED PARAMETERS

Type	Char. Imp(Ω)	Phase Vel.	C(pF/m)	L(μH/m)
A	20.4	0.590	276	0.12
B	36.4	0.590	155	0.21
C	27.2	0.553	222	0.16

Table 3 shows the electrical parameters for the 3 cable types, as estimated by LIRA. All the values match very well with those provided in the datasheets from NEXANS.

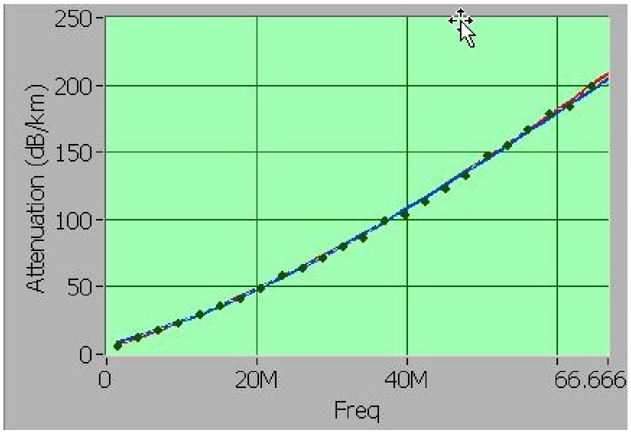

FIGURE 18 LIRA ESTIMATED ATTENUATION, TYPE C

Figure 18 shows the attenuation estimated by LIRA for cable type C. The shape of the curve (a positive second derivative) reflects the high frequency skin effect of these cables, because of the large cross section.

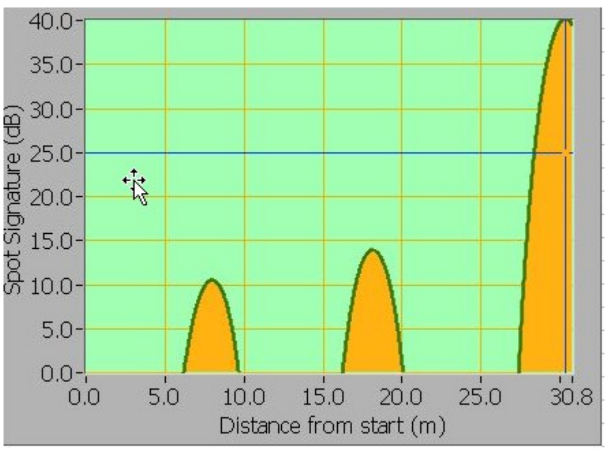

FIGURE 19 CABLE TYPE A, FAULTS AT 8M AND 18M

Mechanical damage was produced on the 20 samples in a controlled way, by removing screen and part of the insulation on one side of the cable, for a length ranging from 5 to 45cm. The aluminium conductor was not exposed and the cable was perfectly operable after the damage. The insulation resistance was unchanged, the environment was dry at ambient temperature.

Figure 19 shows the LIRA detection of two local damages on cable type A. Similar signatures are visible in the tests for cable type B and C.

Figure 20 shows a summary of the findings in the 3 samples of cable type A with local damages at different severity. Although different spike sizes are detectable, it would be difficult to assess a severity condition by observing only the absolute spike height, also because of the influence of the cable attenuation and spot position along the cable.

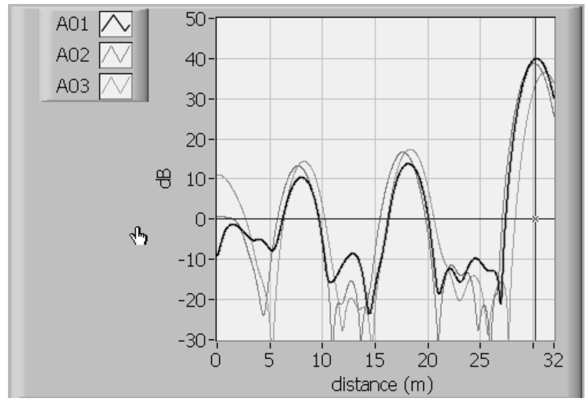

FIGURE 20 DAMAGES AT DIFFERENT SEVERITY, TYPE A

The use of the LIRA DNORM indicator helps to normalize the spot severity, as shown in Figure 21, Figure 22 and Figure 23 for the 3 cable types.

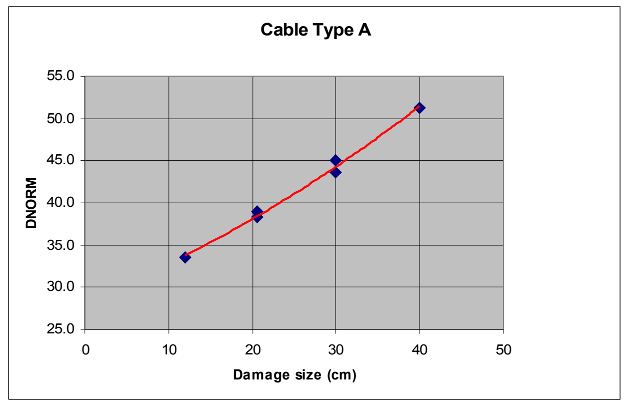

FIGURE 21 SEVERITY ASSESSMENT, TYPE A

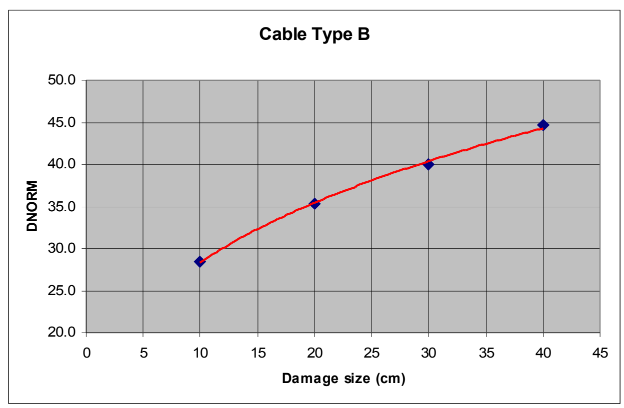

FIGURE 22 SEVERITY ASSESSMENT, TYPE B

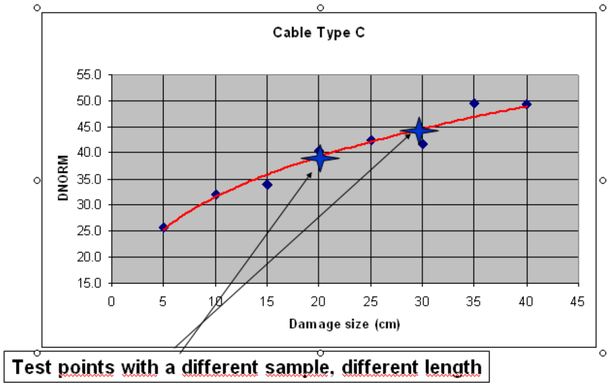

FIGURE 23 SEVERITY ASSESSMENT, TYPE C

Figure 24 shows a summary of the the localization accuracy of the local damages on the 20 tested samples, type A, B and C. The average localization error is 0.23% of the cable length with a standard deviation of 0.08. Same values were achieved with thermal hot spots.

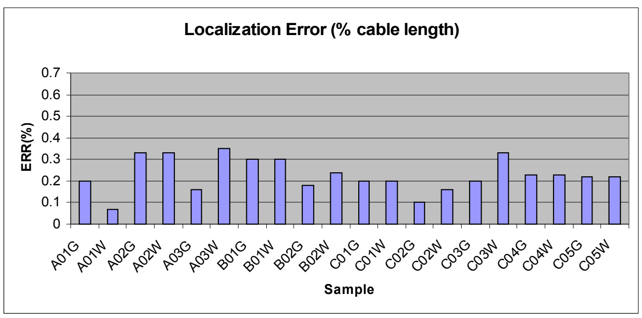

FIGURE 24 LIRA ACCURACY IN SPOT DETECTION

Average ERR(%)	**0.23**
Standard Dev.	**0.08**

CONCLUSIONS

The tests at EPRI in 2006 and 2007 and the tests at Tecnatom in 2008 showed that LIRA could identify localized thermal damage to insulation that had not progressed to the point where the insulation had totally failed. LIRA could locate the damage even though the insulation could still function adequately under normal and accident conditions. These tests indicated that LIRA could identify aging before end of the qualified life. The results indicate that LIRA will be useful in assessing the condition of cables located in conduits that are suspected of having been subjected to localized thermal/radiation aging. Similarly, LIRA could be used to assess cables in trays that are difficult to access. These tests also indicate that LIRA can identify cuts and gouges to one or more conductors of multi-conductor cables, both in signal and power cables. The global thermal aging results with the new CBAC condition indicator verified LIRA's ability to assess the relative degree of aging and a good correlation with the accepted EAB indicator was found for EPR/EPDM insulated cables.

ACKNOWLEDGMENTS

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The experiments at TECNATOM SA, Madrid, were funded by the Halden Reactor Project, Norway.

The tests performed within the PETROMAKS Project were funded by the Norwegian Research Council (NFR) with the contribution from Shell E&P, UK and Norsk Hydro ASA (now StatoilHydro ASA).

The tests described in this paper have been performed using the LIRA 2.2 R10 developed by Wirescan AS (www.wirescan.no).

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