Wire System Aging Assessment and Condition Monitoring Using Line Resonance Analysis (LIRA)

Paolo F. Fantoni

IFE Halden Reactor Project, P.O. Box 173, Halden, 1751, Norway, Paolo.Fantoni@hrp.no

Gary J. Toman

Electric Power Research Institute, 1300 WT Harris Blvd, Charlotte, North Carolina, 28262 USA, Gtoman@epri.com

Abstract – This paper describes a method for wire system condition monitoring, developed at the IFE Halden Reactor Project, which is based on Frequency Domain Reflectometry. 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 some results achieved in field experiments on signal cables for nuclear installations, in USA and Europe.

I. INTRODUCTION

There is a continued interest worldwide [1] in the safety aspects of electrical wire (cable) system aging in industrial installations. Aging of a wire 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 wire system can lead to unavailability of equipment important to safety and compromise public health and safety.

In the USA, the NRC published in May 2003 the Regulatory Issue Summary (RIS) 2003-09 [2], where it reported the conclusions of qualification tests on I&C cables. Here also particular concern was posed on cables status assessment needs when extending the plant life and the need to have reliable qualification methods for LOCA and post-LOCA conditions. Basically, the NRC concluded that current I&C wire system qualification methods provide a high level of confidence that the installed cables will perform adequately during design basis events, as required by 10 CFR 50.49. However some LOCA test failures indicate that in certain conditions the accepted conservatisms in the qualification tests are less than expected. Moreover, no single monitoring techniques were found adequate to detect reliably I&C cable failures. Two recommendations stand up among others:

- Environment conditions should be monitored during plant operation, to ensure that they do not exceed those applied for the qualification tests.
- A combination of condition monitoring techniques is suggested, to overcome the limits existing in each single method.

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.

II. 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 by its length in comparison with the wavelength λ of the electric signal traveling into it. The wavelength is defined as:

$$\lambda = {}^{v}\!/_{f} \tag{1}$$

where v is the speed of the electric signal in the wire (also called the *phase velocity*) and f the frequency of the signal.

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 (Z_{in}), 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.

The voltage V and the current I along the cable are governed by the following differential equations, known as the *telephonists equations*:

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V \qquad (2)$$

$$\frac{d^2I}{dz^2} = (R + j\omega L)(G + j\omega C)I \qquad (3)$$

where R is the conductor resistance, L is the inductance, C the capacitance and G the insulation conductivity, all relative to a unit of cable length.

These four parameters completely characterize the behavior of a cable when a high frequency signal is passing through it. In transmission line theory, the line behavior is normally studied as a function of two complex parameters. The first is the *propagation function*

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad (4)$$

often written as

$$\gamma = \alpha + j\beta \qquad (5)$$

where the real part α is the line *attenuation constant* and the imaginary part β is the *propagation constant*, which is also related to the phase velocity and wavelength through:

$$\beta = \frac{2\pi}{\lambda} = \frac{\omega}{v} \qquad (6)$$

The second parameter is the *characteristic impedance*

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (7)$$

Using (4) and (7) and solving the differential equations (2) and (3), the line impedance for a cable at distance *d* from the end is:

$$Z_d = \frac{V(d)}{I(d)} = Z_0 \frac{1 + \Gamma_d}{1 - \Gamma_d} \qquad (8)$$

Where Γ_d is the *Generalized Reflection Coefficient*

$$\Gamma_d = \Gamma_L e^{-2\gamma d} \qquad (9)$$

and Γ_L is the *Load Reflection Coefficient*

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (10)$$

In (10) Z_L is the impedance of the load connected at the cable end.

From eqs, (8), (9) and (10), it is easy to see that when the load matches the characteristic impedance, $\Gamma_L = \Gamma_d = 0$ and then $Z_d = Z_0 = Z_L$ for any length and frequency. In all the other cases, the line impedance is governed by eq. (8), which has the shape of Figure 1.

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 wire 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.

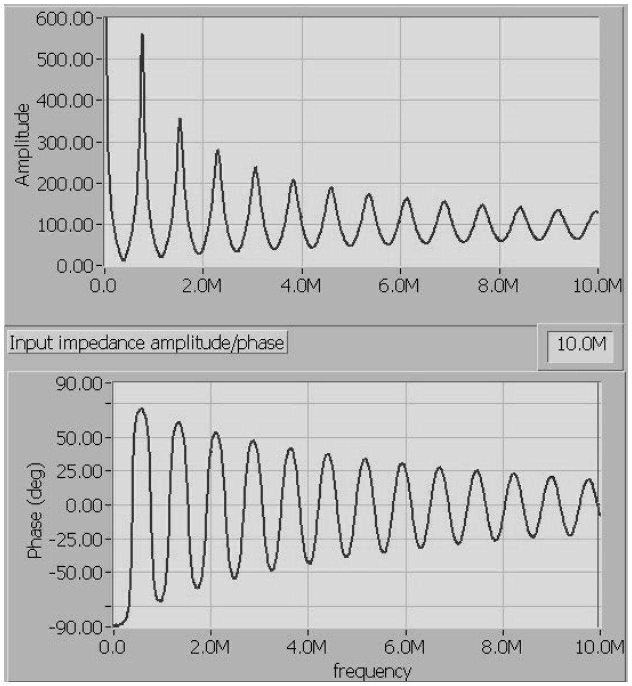

Fig. 1. Impedance of an unmatched transmission line.

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) do not depend only 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 a custom algorithm for an accurate estimation of the phase velocity (up to 4 significant digits), which is a function of C and L, but is completely independent by the cable length and load.

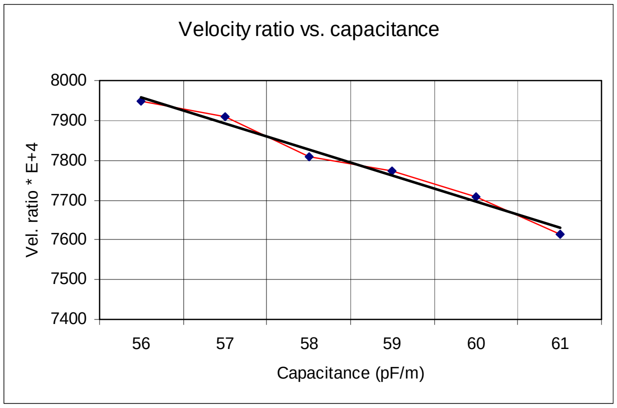

Fig. 2. Phase velocity ratio vs. cable capacitance.

A condition indicator CI for the cable global condition is then expressed by:

$$CI = g\left[f(v)\right] \tag{11}$$

Where f represents the correlation between phase velocity and capacitance (Figure 2 is an example, where the phase velocity is expressed as its ratio to the light speed in vacuum) and g is the correlation function between insulation state and capacitance change, for a specific cable type.

Evaluation of the correlation function g is under development in a co-operation between EPRI and IFE and first results are expected in November 2006.

Hot spots due to localized high temperature conditions and local mechanical damage to the insulation are detectable by LIRA through a proprietary algorithm starting from the line impedance spectra. The next chapter shows some results achieved in 2005 and 2006 at EPRI (Electric Power Research Institute), Charlotte, NC and in the framework of the NKS project (Nordic Countries Nuclear Safety Research).

II.A. LIRA structure

LIRA is composed of several software and hardware modules, as depicted in Figure 3, 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, which analyses the signals and provides cable assessment.
- The LIRA Simulator. It 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.

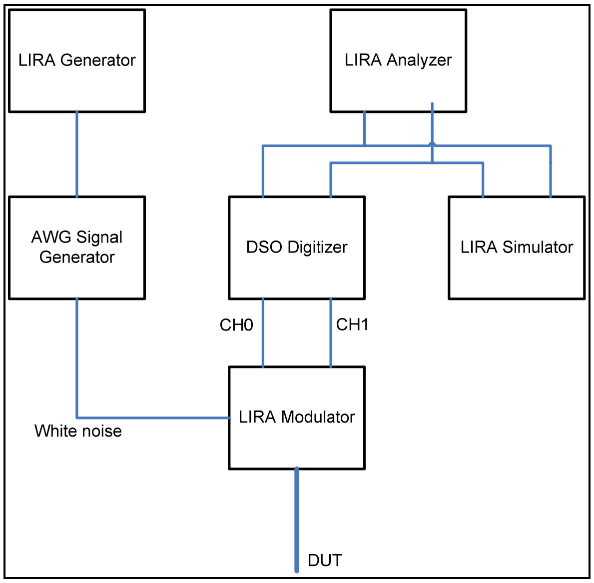

Fig. 3. LIRA Block Diagram.

Fig. 4. LIRA during the EPRI experiment, May 2006.

III. EXPERIMENT RESULTS

III.A. EPRI Tests

These tests were performed in September 2005 and May 2006 at the EPRI facility in Charlotte, NC. A final test session is planned for the beginning of November 2006.

III.A.I First Experiment (September 2005)

The objective of the first experiment was to verify the LIRA capability to detect hot spots in different conditions on EPR[1] and XLPE[2] low voltage cables. A total of 10 specimens had gone through accelerated thermal aging to simulate various degrees of bulk and local degradation.

The main concern of these tests was whether LIRA could identify localized thermal aging (0.5 m) of a cable that was significant but less than that which would cause cracking of the insulation. One specimen of each cable type had been thermally aged essentially to the end of its qualified life and another to approximately 66% of its qualified life. The XLPE cables were 18.3 m long and the EPR cables were 16.8 m long. LIRA was able to find all of the localized hotspots and identified changes in the propagation ratio for cables that were aged along their entire length but to less severe conditions.

Figure 5 shows the successful detection of a hot spot at 9m in a new EPR cable (LIRA indicated localized damage at 9.01m). The significance of the results is that LIRA can identify significant localized aging of cables that were installed in conduits. Detection of thermally damaged insulation that is still intact is not possible with current commercially available electrical tests.

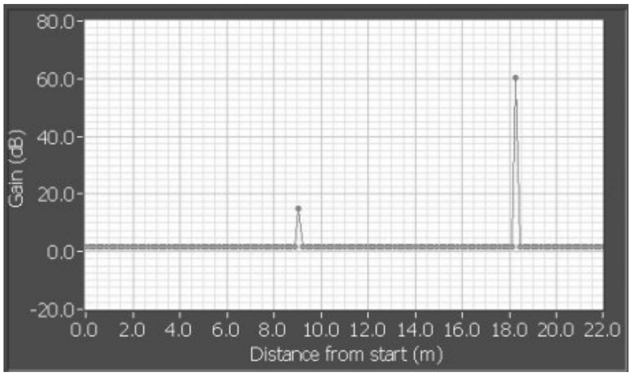

Fig. 5. Hot spot signature for the EPR cable. (Hot spot at 9.1 m, termination at 18.3 m)

The cables in this test were 16.8 to 18.3 m in length and the signal bandwidth was 50 MHz (because of the hardware used at that time). Cables that short would require a much higher bandwidth of 150-200 MHz to avoid large blind areas at the beginning and end of the cable. For this reason, LIRA was not able to detect hot spots close to the terminations. In spite of this, the preliminary experiment was quite successful and

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[1] Ethylene propylene rubber insulated with chlorosulfonated polyethylene conductor and overall jacket

[2] Crosslinked polyethylene insulation with chlorosulfonated overall jacket

demonstrated that bulk and localized thermal degradation affects the cable electrical properties and can be detected by LIRA with high sensitivity.

III.A.II Second Experiment (May 2006)

The objective of the second experiment was twofold:

- Verify the LIRA capability to detect localized insulation damage (cuts and gouges), both in dry and wet conditions.
- Perform initial measurements on new cables before exposing them to bulk and local thermal degradation (accelerated aging), to derive a correlation between LIRA bulk and local condition indicators and the actual degradation state.

Several specimens of EPR and XLPE low voltage, 2 and 3 wire cables (all new), 30.5m long, were tested with LIRA. Some were damaged to simulate cuts and gouges to one or more conductors.

Figure 6 shows an example of cuts to 2 of the conductors of an XLPE specimen at 24m. Figure 7 shows the LIRA signature with the damage indication, for both dry and wet environments. The input signal bandwidth was 100 MHz (200 Ms/s[3]).

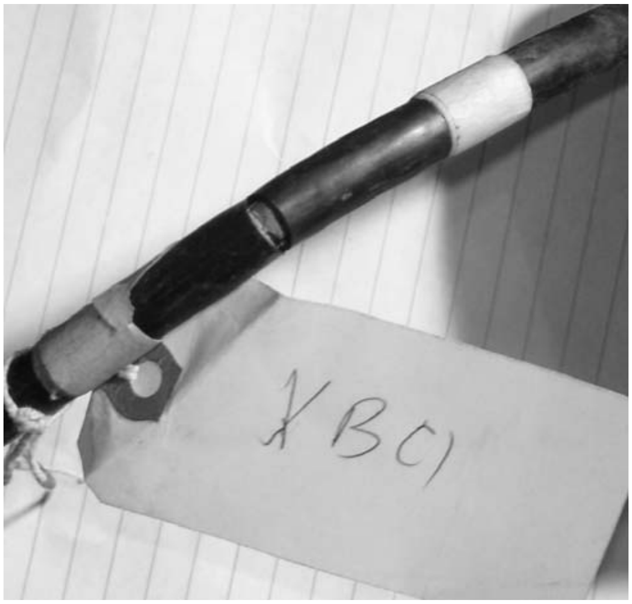

Fig. 6. XLPE 2-wire insulation cut. (wide cut to outer jacket with cut to conductor of each individual).

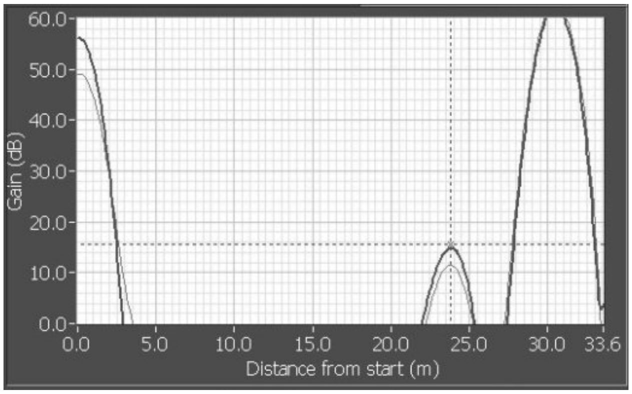

Fig. 7. XLPE 2-wire insulation cut detection at 24m, wet (thick line) and dry conditions. (length = 30.5 m)

Figure 7 shows a slightly higher peak under wet conditions than dry (about +5 dB), a result that is supported by the theory.

Table 1 shows the main electrical parameters of this cable in dry conditions, as estimated by LIRA.

TABLE 1. Electrical Parameters for XLPE specimen

Phase Velocity Ratio	0.6133
Characteristic Impedance	93 Ω
Line Attenuation at 2MHz	15 dB/km

Figure 8 shows an example of gouge on a XLPE specimen. The gouge left two conductors partially uncovered.

Fig. 8. Gouge through the outer jacket and through the XLPE insulation of two conductors.

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[3] Ms/s = mega samples/second

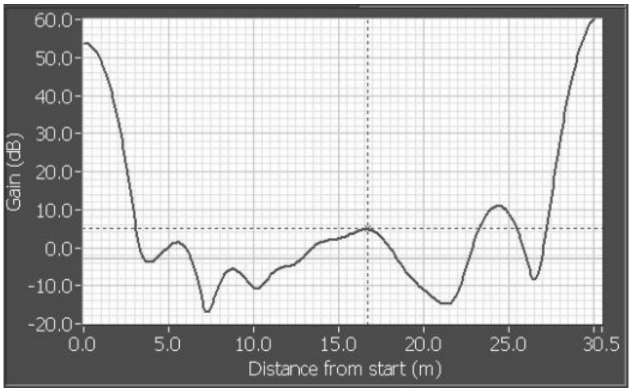

Fig. 9. LIRA detection of the gouge in shown in Fig. 8 at 24 m under dry conditions.

Figure 9 gives the LIRA detection of the spot at 24m. The lower peak at about 17m is a second smaller gouge inflicted on the cable during the testing session.

Fig. 10. Gouge on EPR specimen.

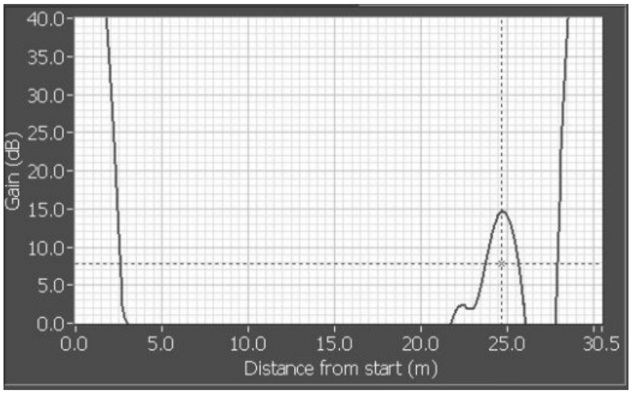

Fig. 11. LIRA detection of the gouge in Fig. 10.

TABE 2. Electrical Parameters for EPR specimen.

Phase Velocity Ratio	0.5188
Characteristic Impedance	81 Ω
Line Attenuation at 2MHz	30 dB/km

Figure 10. shows a gouge produced on a EPR specimen with the LIRA result shown in Fig. 11.

Table 2 presents the main parameters for the EPR specimen, as estimated by LIRA.

III.A.III Third Planned Experiment (Nov. 2006)

A third experiment session will take place in Charlotte at the beginning of November 2006, when the accelerated aging process is completed. A new measurement set on the cables will be performed and compared with the initial measurements of May. The result of this work will be a correlation between bulk and local LIRA condition indicators and the degradation state of the specimens. These tests will help determine if the degree of aging can be determined by LIRA testing.

III.B. NKS Tests

These tests were performed at Ringhals NPP (Sweden) during the outage of June 2006, in a collaborative work between IFE and Vattenfall AS in the framework of the NKS 2006 project [6].

The experiment was conducted on four low-voltage, triaxial (2 wires, inner shield, outer shield), PVC insulated cables, 142m long. The cables are named A, C, E and G, where G is the spare cable. The 4 cables have been in operation for more than 20 years. Cables A, C and E were terminated at the far ends with high impedance ionization chambers. Cable G was open at the end. The inner and outer shields were open at both ends.

After a first measurements on the four cables, one of them, cable G, was disconnected at the containment penetration and partially extracted from the conduit and then reinserted. After this procedure, a new measurement on cable G was taken to determine if any damage occurred to the insulation/jacket as a consequence of this movement.

Figure 12. shows cable G signature before disconnection at the penetration. The penetration mark is visible at 105m.

Figure 13 shows the relocation effect of the first part of the cable (up to the penetration) in comparison to the test before removal and reinsertion. As visible from the overlaid signatures, no significant change had occurred as a consequence of the cable relocation.

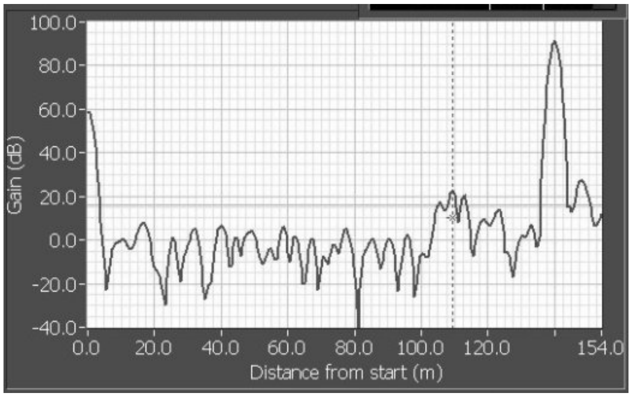

Fig. 12. PVC cable with containment penetration signature at 105.7m.

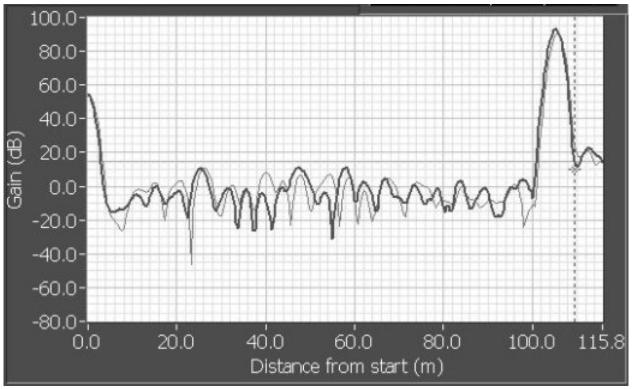

Fig. 13. Cable signature after disconnection at 105.5m, before (thin line) and after (thick line) relocation.

Table 3 shows the electrical parameters of the cables tested at Ringhals NPP.

TABLE 3. Electrical Parameters for the triaxial cable

Phase Velocity Ratio	0.7940
Characteristic Impedance	75 Ω
Line Attenuation at 1.5MHz	4.7 dB/km

Although there was no cable degradation or fault to be detected in this test, the interesting part of this experiment was to verify that LIRA was capable to operate efficiently in a real environment on installed cables.

Figure 14 shows the line impedance spectra as measured during the test, in the range 0-4 MHz. Figure 15. shows how well the LIRA simulation engine can predict a cable behavior.

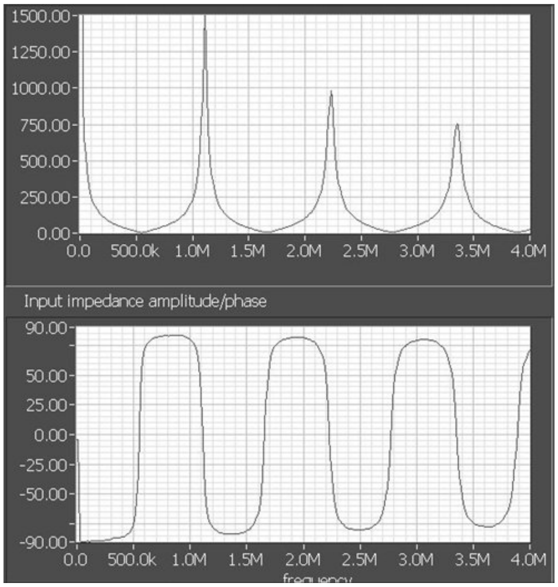

Fig. 14. Impedance Measurement of the 105.5m triaxial cable (after disconnection).

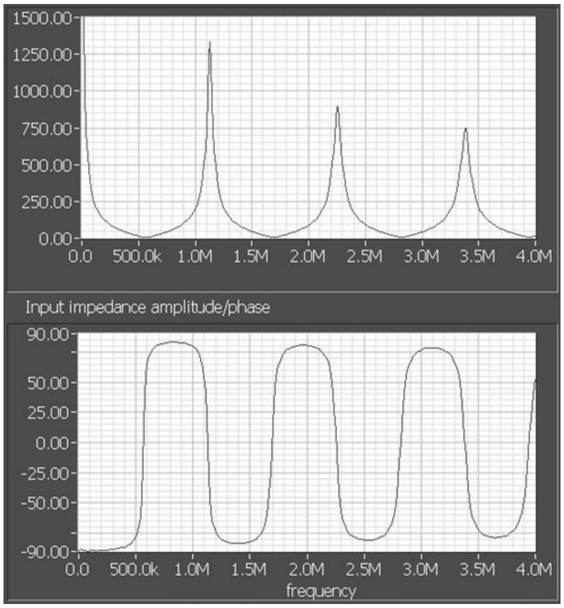

Fig. 15. Impedance Measurement of the 105.5m cable using the LIRA simulation model.

IV. CONCLUSIONS

The initial tests at EPRI in September 2005 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. The May 2006 EPRI tests indicate that LIRA can identify cuts and gouges to one or more conductors of multi-conductor cables. In-plant tests or simulation thereof may be necessary to determine if cuts and gouges to a single conductor can be identified under plant conditions. The remaining tests that will be performed at EPRI will help determine if LIRA can be used to determine the degree of thermal damage that has occurred to a cable.

The tests of the Ringhals triaxial cables showed that LIRA could function in nuclear power plant environments. The tests showed that the noise in the plant did not adversely affect the LIRA system and, in these limited tests, that the LIRA radio frequency signals did not adversely affect the plant.

ACKNOWLEDGMENTS

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The NKS tests were performed in a collaborative work between IFE and Vattenfall AS and funded by the Nordic Nuclear Safety Research (NKS).

The tests described in this paper have been performed using the LIRA engine ver. 3.0 developed by IFE, implemented in a software/hardware product by Wirescan AS (www.wirescan.no).

REFERENCES

[1] P.F. FANTONI, "*NPP Wire System Aging Assessment and Condition Monitoring: State-Of-the-Art Report*" Halden Reactor Project (HWR-746) (2004).

[2] "*Environment Qualification of Low Voltage Instrumentation and Control Cables*", US NRC RIS 2003-09, 2003

[3] D. ROGOVIN and R. LOFARO, "*Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in NPP*" USNRC (NUREG/CR-6904) (2006)

[4] K.S. CHANG-LIAO, T.K. CHUNG, H.P. CHOU, "Cable Aging Assessment by Electrical Capacitance Measuring Technique" *Proc. NPIC&HMIT 2000,* Washington D.C., Nov. 2000, (2000).

[5] P.F. FANTONI, "*Wire System Aging Assessment and Condition Monitoring: The Line Resonance Analysis Method (LIRA)*" Halden Reactor Project (HWR-788) (2005).

[6] P.F. FANTONI and A. NORDLUND, "*Wire System Aging Assessment and Condition Monitoring (WASCO)*" Nordic Nuclear Safety Research (NKS-130) (2006).