Condition Monitoring of Electrical Cables Using TDR and Line Resonance Analysis (LIRA)

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Paolo Fantoni
Wirescan AS

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Paolo F. Fantoni
Consultant, Wirescan AS
1777, Halden, Norway
pff@wirescan.no

Dan Beverly, Brent Shumaker, Chris Campbell
Analysis and Measurement Services Corp.
Knoxville, TN, USA
bshumaker@ams-corp.com

Abstract

Early fault detection of electrical cable is an important issue in industrial installations, both for safety and performance considerations. This paper presents the results of laboratory experiments on fault detection of low voltage cables using two emerging techniques: Time Domain Reflectometry (TDR) and Line Resonance Analysis (LIRA).

Keywords: condition monitoring, reflectometry, LIRA, electrical cables

Introduction

The interest of safety aspects of wire systems aging (especially those wire systems used for control and instrumentation) is increasing worldwide because of their impact on several industrial fields, like power generation, transportation and defense. Although the environment conditions and degradation mechanisms of installed cables can be different from target to target, the negative consequences of wire failures, both from a safety and performance standpoint, are so important that almost all the countries in the industrialized world have some research project in progress in this area.

In the nuclear field, where cables are normally qualified before installation for an expected life of 40 years, there are a number of issues that are not completely solved today. These issues include:

- The effect of the particular adverse environment conditions (high radiation, humidity and temperature), especially during and after a Design Basis Accident (DBA).
- Extending the plant life after 40 years involves the requirement to assess and qualify the cable conditions for a longer time.
- Many cable condition monitoring techniques do exist today, but none of them is considered accurate and reliable enough for all the cable materials in use and conditions. In addition to that, only few of them are non-destructive techniques and are applicable in situ.
- Accelerated aging techniques, for qualification purposes under DBA conditions, are often not conservative and should be complemented with reliable condition monitoring methods.

An important issue is the assessment of the condition of installed cables that have been exposed for a long time (more than 30 years) to relative high temperature and gamma radiation (the condition of cables inside the reactor containment). Several techniques have been proposed to monitor and identify cables that are close to the end of their qualified life. The purpose of this work was to evaluate two well known techniques in detecting localized damage due to thermal and mechanical stresses. These techniques are the Time Domain Reflectometry (TDR) and the Line Resonance Analysis (LIRA). TDR is well known technique based on the measurement of a reflection, together with the elapsed time, caused by a damage along the line. LIRA (© Wirescan AS) is an emerging technique based on the evaluation of electrical properties and their trends with the aging conditions. The TDR measurements have been performed by AMS Corp. on 3 samples of low voltage cables, while the LIRA measurements have been performed by IFE using the LIRA equipment provided by Wirescan AS.

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. 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*:

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

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

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*

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

often written as

$$\gamma = \alpha + j\beta \tag{5}$$

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:

$$\beta = \frac{2\pi}{\lambda} = \frac{\omega}{v} \tag{6}$$

The second parameter is the *characteristic impedance*

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

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:

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

Where Γ_d is the *Generalized Reflection Coefficient*

$$\Gamma_d = \Gamma_L e^{-2\gamma d} \tag{9}$$

and Γ_L is the *Load Reflection Coefficient*

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{10}$$

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 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.

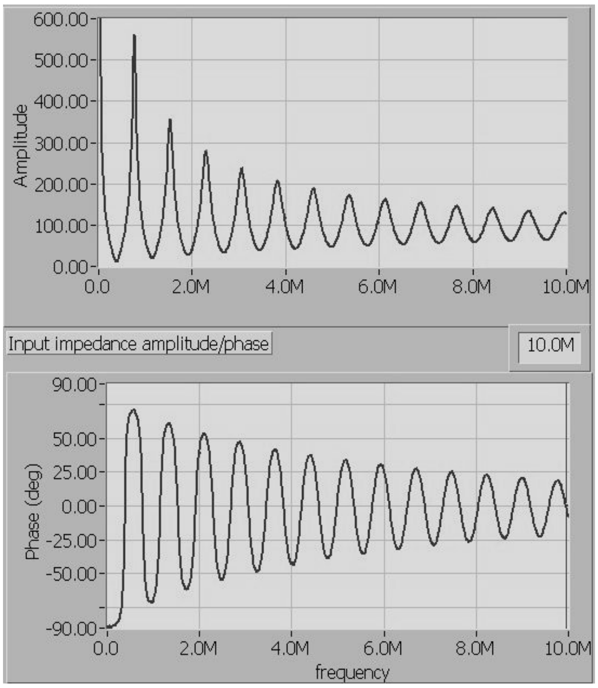

Fig. 1. Impedance of an unmatched transmission line.

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) 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 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.

Test Description and Results

Three low power cables, 30m long, were prepared for testing with TDR and LIRA. The test cables with the different type and position of the spot damages are described in Table 1.

Table 1 Cable samples with damage type and position

Cable #7		**m**
Length		29,43 (96.5ft)
Known Faults #8	**From (T) m**	**ft**
Smash with hammer	9.14	30
Butt splice	14.8	48.5
Extreme bending	23.3	76.4
Vice grip squeeze	26.4	86.6
Cable #8		**m**
Length		29,66 (97.3ft)
Known Faults #8	**From (T) m**	**ft**
Butt Splice	14.33	47
Shield burn	23.47	77
Jacket burn	26.52	87
Cable #9		**m**
Length		29,90 (98ft)
Known Faults #9	**From (T) m**	**ft**
Jacket cut	10.67	35
Butt splice	14.63	48

The cables have been prepared for the tests by AMS Corp. in their laboratory in Knoxville, TN.

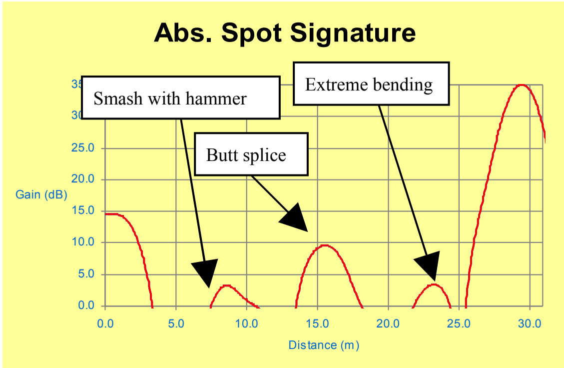

Figure 3. LIRA signature on Cable 7

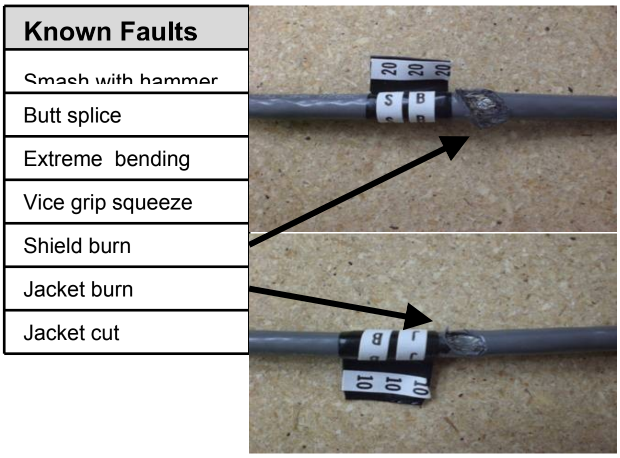

Figure 2 Fault types on the cables

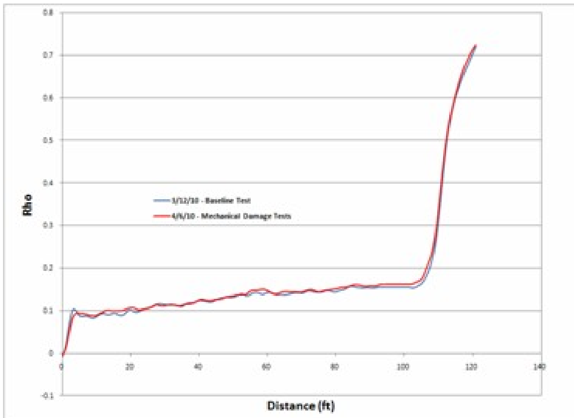

Figure 4. TDR signature on Cable 7

The following figures show the TDR results performed by AMS Corp. and the LIRA results. With TDR, eleven measurements for each cable sample were conducted, one between each conductor, each conductor and the shield, and the shield to ground. For each cable, a baseline measurement, before the damage, was performed (shown in blue in Figures 4, 7 and 10) and then another measurement after the damage. Difference plots are shown in Figures 5, 8 and 11.

Figures 3, 6 and 9 show the LIRA results performed by Wirescan AS, Norway. All the measurements were performed using one conductor and the shield. Four measurements for cable sample were conducted, one for each conductor.

The cables before damage were not available for LIRA baseline measurements, so the LIRA analysis and results are based on one shot measurements on the damaged cables and no difference plot was possible to draw.

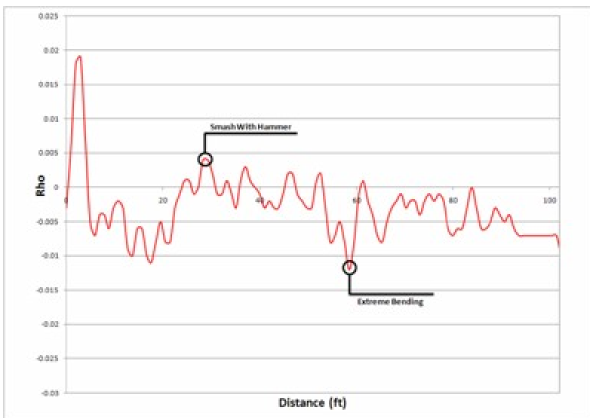

Figure 5. Relative signature on Cable 7, TDR

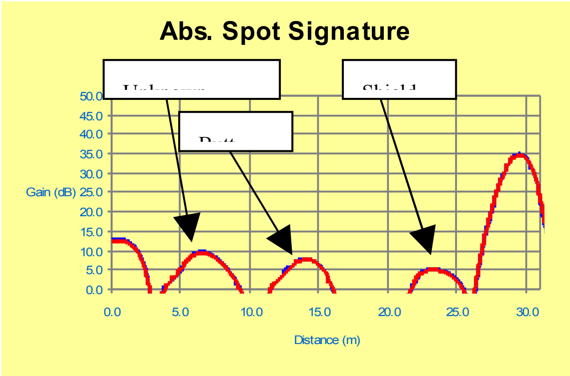

Figure 6. LIRA signature on Cable 8

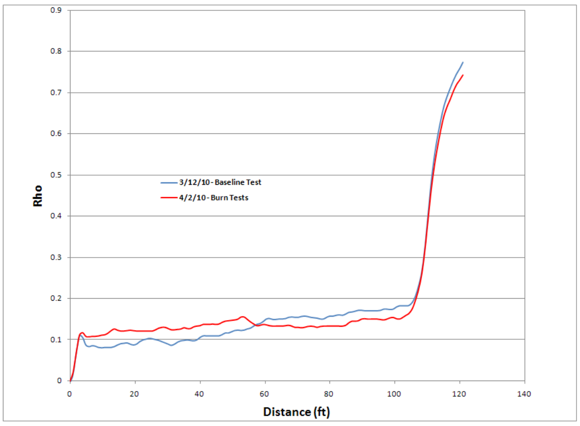

Figure 7. TDR signature on Cable 8

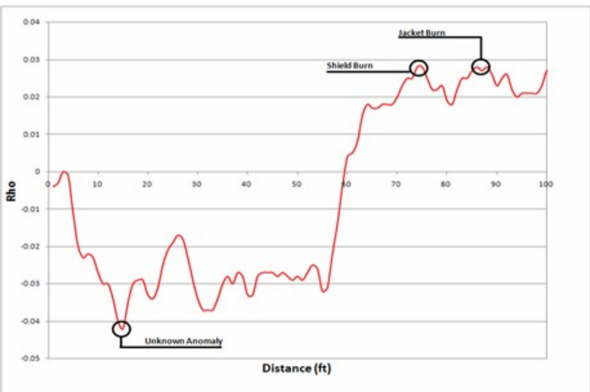

Figure 8. Relative signature on Cable 8, TDR

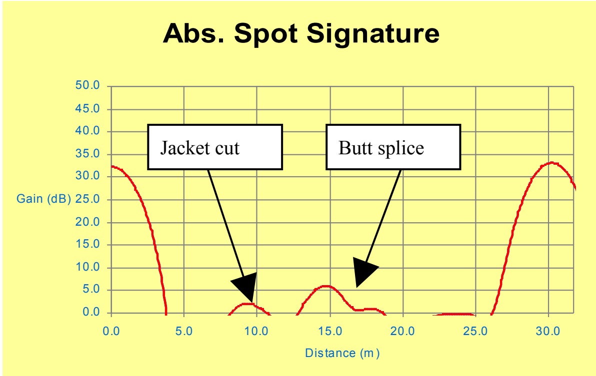

Figure 9. LIRA signature on Cable 9

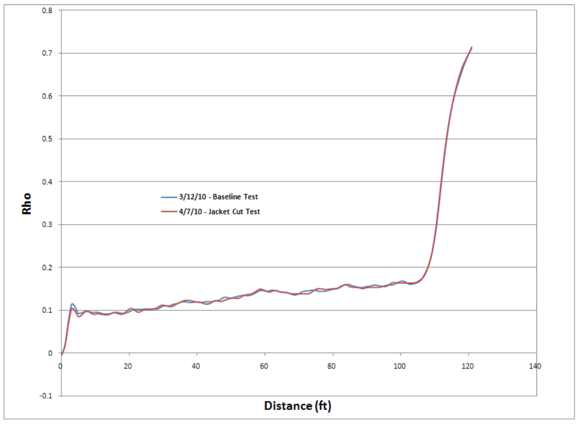

Figure 10. TDR signature on Cable 9

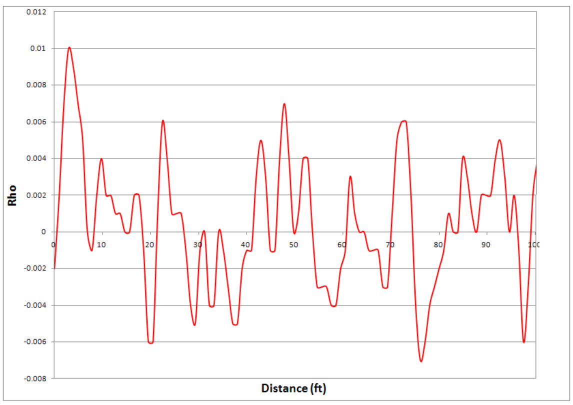

Figure 11. Relative signature on Cable 9, TDR

Discussion of Results

The TDR traces and TDR difference plots were able to pinpoint the location of several of the faults created on the cables. The portion of Cable 7 that was hit with a hammer was detected along with the section that experienced an extreme bend. These results can be seen in Figure 5.

The shield and jacket burn were both detected on Cable 8 and can be seen in Figure 8. Also, an unknown anomaly was discovered in the TDR difference plot. TDR was unable to detect jacket cut that was made in Cable 9.

LIRA was able to detect the point that experienced the smash with a hammer, the butt splice and the extreme bend. These results can be seen in Figure 3. Neither cable testing techniques were able to detect the vice grip squeeze. LIRA is unable to detect the vice grip squeeze due to the termination shadow it produces. Detection of features close to the termination would require higher bandwidth using LIRA. The LIRA system discovered both of the burns created on Cable 8 along with the unknown anomaly just as TDR. However, LIRA was able to detect the butt splice that is in Cable 8, whereTDR did not. These results can be seen in Figure 6. The jacket cut and the butt splice were detected in Cable 9 by the LIRA equipment and can be seen in Figure 9.

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