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Condition Monitoring and Fault Detection in Cables using Line Impedance Resonance Analysis

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Abstract

Line Impedance Resonance Analysis is a powerful technique to determine the location of water trees and physical damage in all cables, from LV to EHV. The technique, which uses the concept of frequency-domain reflectometry, was originally developed for nuclear plants and has now been commercialized for practical applications in the field of condition monitoring as well as fault location.

Keywords: Cable Condition Monitoring, Fault Detection, Frequency-domain Reflectometry, LIRA

1. Background

Cable condition monitoring and fault location techniques have come a long way with the help of techniques such as tan delta, partial discharge and TDR. However, there are still significant areas that remain to be resolved. Some of these are :

1. Determination of the location of water trees.
2. Detecting and determining the location of physical damage.
3. Quantification of the workmanship of the joints, especially for HV and EHV cables.
4. A portable, lightweight tool for easy fault-finding.

Nuclear plants especially rely on cables for a variety of functions for safe operation and their reliability as they age is of utmost concern. The Nuclear Energy Agency (a consortium of 19 countries) carried out research on this subject at the Halden Reactor project in Norway and developed the Line Impedance Resonance Analysis (LIRA) technique for meeting all the gaps in the condition assessment of cables. The technology was further validated by studies conducted at EPRI.

2. Theory

Line Impedance Resonance Analysis (LIRA) measures the surge impedance of a cable at a large range of frequencies. The measurement signal can be modified from 100 MHz to 100 kHz, to get the most suitable range for the measured cable which allows analysis of cable lengths ranging from tens of meters to hundreds of kilometers. Theory of electromagnetic wave propagation in transmission lines and the well-known Telegrapher´s Equation is the basis for the underlying LIRA algorithms. In an ideal cable system where the cable geometry and material properties are unchanged throughout the cable length the surge impedance is constant. Discontinuities such as joints, cable damages and defects will change the wave impedance will reflect and influence the incoming signal send from the LIRA equipment.

One central part of the processing algorithms active in LIRA is the resonance frequencies caused by geometric properties and material characteristics. The system identifies these through zero-crossings of the phase of the measured impedance. The physical characteristics of the cable are calculated, including cable capacitance, resistance, inductance as well as characteristic impedance and cable attenuation. The cable impedance can also be visualized as a function of cable length (denoted spot signature) which makes detection and monitoring of suspected cable fault locations.

2.1 Equations Governing LIRA

LIRA method 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

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comparison with the wavelength λ of the electric signal traveling into it. The wavelength is defined as:

$$\lambda = \frac{v}{f} \quad (1)$$

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 behaviour and the circuit impedance (Zin), 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 ≥ λ, 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:

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

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

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 behaviour of a cable when a high frequency signal is passing through it. In transmission line theory, the line behaviour is normally studied as a function of two complex parameters.

The first is the *Propagation Function*

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

Often written as

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

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:

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

The second parameter is the *Characteristic Impedance*

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

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:

$$Z_d = \frac{V_d}{I_d} = Z_0\frac{1 + \Gamma_d}{1 - \Gamma_d} \quad (8)$$

where, Γ_d is the *Generalized Reflection Coefficient*

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

And Γ_L is the *Load Reflection Coefficient*

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

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

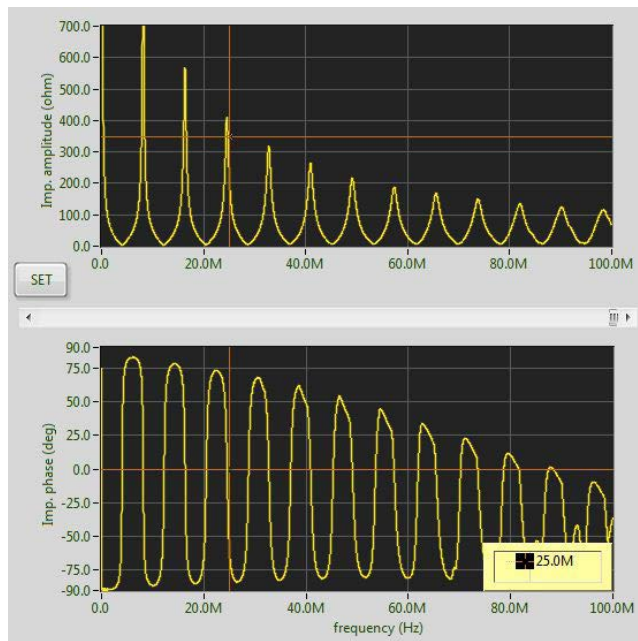


Figure 1. Impedance of an unmatched transmission X line.

From (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 (8), which has the shape of Figure 1.

2.2 LIRA Concepts

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. 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.

From the above, LIRA can assess cables using the following parameters:

1. Spot Signature and DNORM – local degradation along the cable length
2. DeltaG – overall degradation of the cable
3. Balanced Termination Signature (BTS) – condition of the cable terminations

2.2.1 Spot Signature

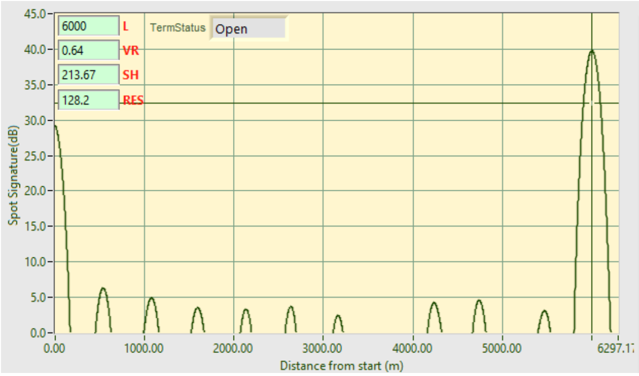


Figure 2. Spot Signature graph of a 6.3 km. cable.

The Spot Signature is used to detect local degradation/failure within the cable. It shows the variations in impedance as a function of the cable length. The impedance gain (dB) can be regarded as a severity indicator. While the initial signal on a new cable is just its characteristic, a significant change in the impedance gain (known as HotSpot) over time at a particular location is indicative of an incipient defect. The Spot Signature can be used to map all joints and bends in a cable, as well as determine its exact length.

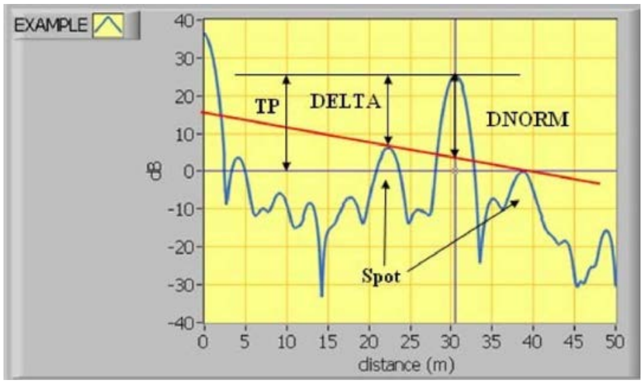


Figure 3. HotSpot assessment with LIRA.

2.2.2 DNORM

To allow assessment of the degree of aging, a parameter called DNORM was developed. Figure 3 visually presents the DNORM concept. Any localized HotSpot produces a mirror image on the other side of the terminal peak (see Figure 3). This is due to a second-order reflection of the damaged section. The second-order spike is like a new spot of the same severity at distance 2L - SL, where L is the cable length and SL is the spot location on the cable.

Since the distance between the two spots is known (after the spot localization), it is possible to draw and calculate the trend line (the red line in Figure 3) that represents how the spike size changes with distance due to the cable attenuation. In DNORM, the spike delta (difference from the Terminal Peak (TP)) is normalized to the TP position,

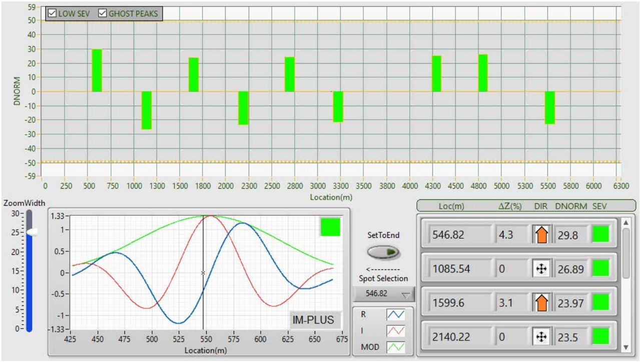


Figure 4. DNORM graph of a 6.3 km. cable

regardless of where the real spot is located. This technique allows the severity of the local conditions to be compared to each other or measurements taken at different times on the same cable to be compared.

Figure 4 shows the DNORM graph of the same cable whose Spot Signature is shown in Figure 2. It can be seen that the DNORM values are both positive and negative (upper graph). This assessment comes from comparing the real and imaginary components of the signal (lower graph) and helps identify whether the defect is due to physical degradation (+ve DNORM) or water ingress (-ve DNORM).

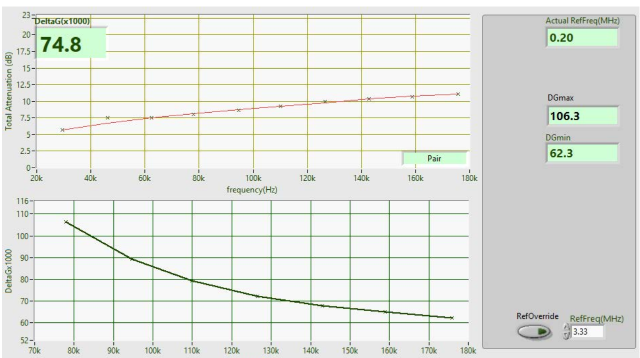


Figure 5. DeltaG indicator.

2.2.3 Global Aging Indicator (DeltaG)

DeltaG is an indicator of the dielectric losses, equivalent to tan delta. It is calculated by an accurate estimation of the attenuation spectrum across the entire applied bandwidth. This attenuation is a factor of the conductor resistance and the dielectric losses and can be calculated if we know the core and shield material, core and shield diameter and the cable temperature.

As the dielectric losses of a cable increase over time, the trend of DeltaG is an excellent indication of aging of the cable insulation. An added benefit is that as the measurements are made at low voltage, the assessment is 100 % non-destructive.

2.2.4 Balanced Termination Signature (BTS)

The Balanced Termination Signature (BTS) is a method to assess the condition of the far-end termination. The BTS function assesses the termination capacitance by analyzing the complex component of the Fourier analysis of the LIRA signature. A change in the capacitance of the termination is usually due to problems such as water ingress and can be easily detected.

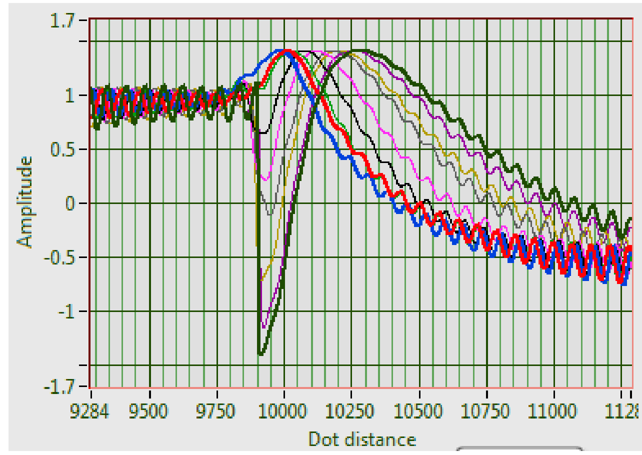


Figure 6. BTS indicator.

3. Operation

The typical LIRA connection set-up is shown in Figure 7. Measurements are usually made between conductor and screen, though they can also be taken between conductor-to-conductor, conductor-to-armour, screen-armour and basically between any two metallic conductors.

The cable can be left connected or can be disconnected at either end. It is required to ground the screen at the far end. In case of multiple cable runs, disconnection is definitely required.

LIRA applies a low voltage (5 V), high frequency sweep of signals into the cable, varying the maximum frequency from 100 kHz to 100 MHz, depending on the cable length. Input of the Phase Velocity Ratio or the cable length is generally required.

The Bandwidth is adjusted manually to achieve a balance between seeing the reflection from the end of the cable and getting a high resolution for each Hot Spot location. Ideally, multiple sweeps are conducted with different frequencies so as to cover all possibilities. Measurements can generally be completed within tens of minutes.

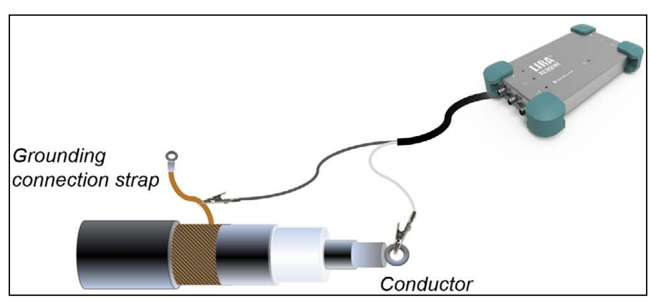


Figure 7. LIRA connection set-up.

4. Case Studies

4.1 Weak Joint in 33 kV Cable - Petrochemicals

VLF Tan Delta (TD) test was performed on a 310 metre, 3-core, 33 kV cable. The cable had been in service for just 5 years. The values measured were extremely high, as seen in Table 1.

Table 1. Initial VLF Tan Delta values

Phase	Tan Delta (x 10-3)	Limit	Δ Tan Delta (x 10-3)	Limit
R	6.0		2.2	
Y	4.0	< 2.0	1.9	< 1.0
B	45		24.7	

As these were of concern, Damped AC Partial Discharge (PD) measurements were performed at 1.5U0 to try and locate the defect. However, the only PD that was detected was at the end-termination and had a very low amplitude (370 pC – see Figure 8).

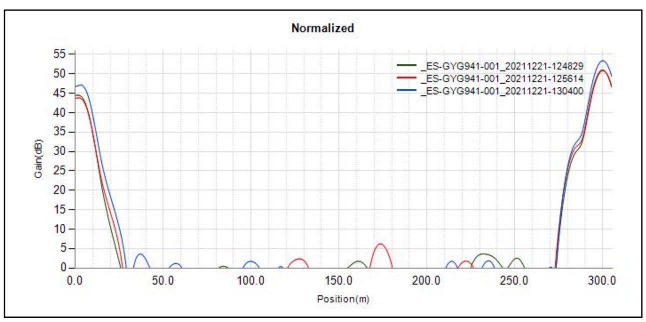


Figure 8. Damped AC PRPD at 1.5U0.

Finally, LIRA measurements were performed, which clearly picked up a defect at 288 metres (see Figure 9). This section of the cable was excavated and a joint found at this location. The same was replaced and the VLF TD as well as the LIRA tests were repeated. The results were now perfect (Table 2).

Table 2. Final VLF Tan Delta values

Phase	Tan Delta (x 10-3)	Limit	Δ Tan Delta (x 10-3)	Limit
R	0.6		0.25	
Y	1.1	< 2.0	0.50	< 1.0
B	0.6		0.13	

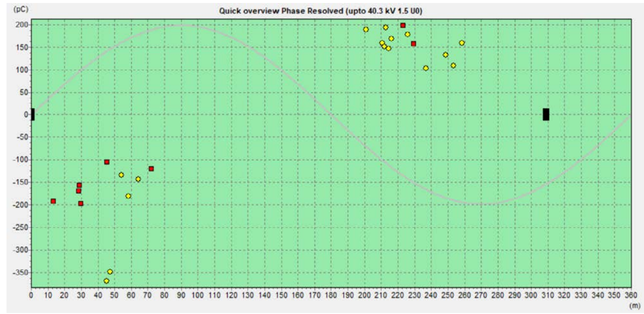


Figure 9. Initial LIRA spot signature.

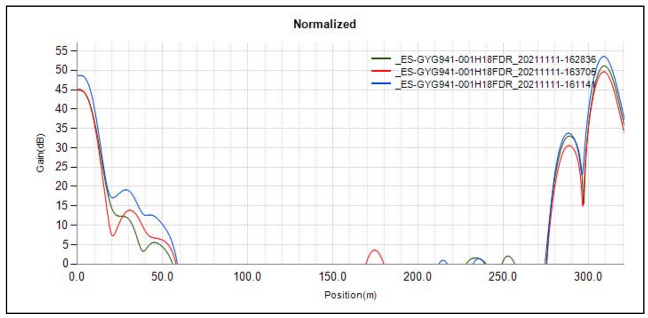


Figure 10. Final LIRA spot signature.

4.2 Failed Joint in 13.5 km, 22 kV Sub-sea Cable – Oil and Gas

A large offshore oil field was drawing power from the central complex using 1-core, 22 kV cables. After 36 years of service, there was a failure in one cable, leading to a lack of redundancy. Several methods were applied to locate the fault, but failed due to the long cable length, lack of accessibility, etc.

LIRA test was then performed to identify the defect location. Measurement was limited to 2 MHz because of the length. For the healthy cables (L1 and L2), the complete cable length was evident, along with all joints. For the failed cable (L3), the signals were unable to travel beyond 3.2 kms (Figure 11). This clearly indicated the defect location.

Cross-checking with installation records confirmed that there was a joint at this location. The same was physically identified and found to be damaged. On replacement, the cable insulation resistance values were excellent and the cable could be re-energized.

A repeat of the LIRA test confirmed that the dB values for the replaced joint were much better than earlier. An added benefit that could be derived from the exercise was that the condition of each joint could now be quantified, as seen from the final DNORM graphs (Figure 12).

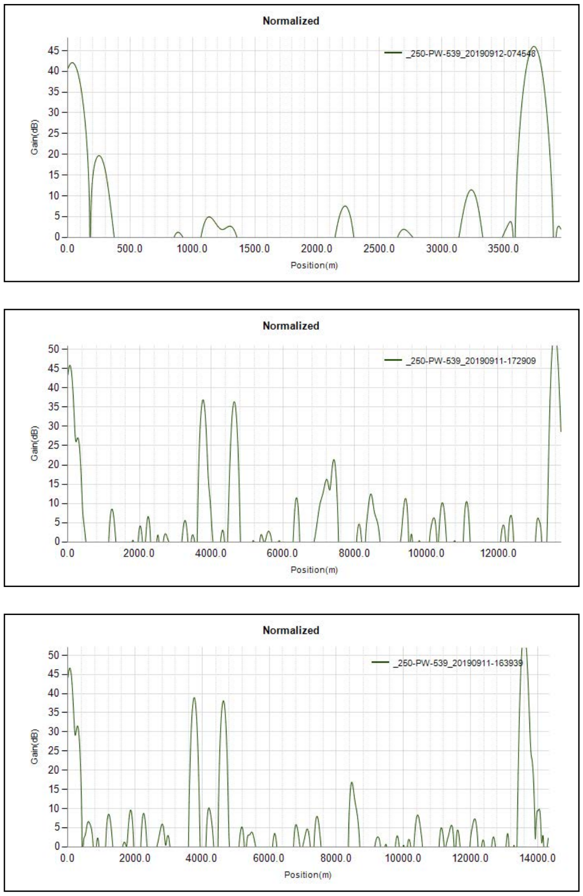
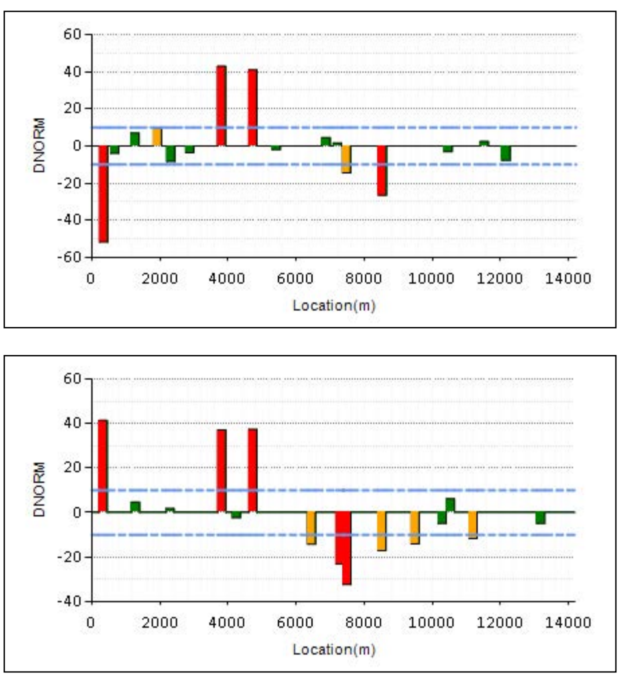


Figure 11. Initial LIRA spot signature.



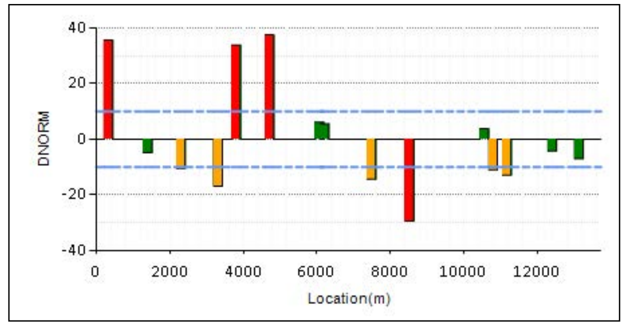


Figure 12. Final DNORM graph quantifying each joint's condition.

4.3 Defective 1.3 km, 4.16 kV Cable - Fertilizer

Fifteen (15) nos. 1-core, 4.16 kV cables had been in service for barely two years. Insulation resistance (IR), VLF tan delta and VLF PD measurements were performed for fingerprinting purposes. No PD was detected, tan delta values were excellent while IR was nominally low for one core (see Table 3).

Table 3. IR and VLF tan delta values

Phase ID	IR	TD Stability	Δ TD	TD at U0
301-A-W01MV -L1	235	< 0.1	0.00	0.01
301-A-W01MV -L2	269	< 0.1	0.00	0.01
301-A-W01MV -L3	506	< 0.1	0.06	0.09
301-A-W02MV -L1	823	< 0.1	0.00	0.02
301-A-W02MV -L2	725	< 0.1	0.00	0.01
301-A-W02MV -L3	632	< 0.1	0.00	0.01
301-A-W03MV -L1	178	< 0.1	0.05	0.01
301-A-W03MV -L2	350	< 0.1	0.00	0.01
301-A-W03MV -L3	452	< 0.1	0.00	0.02
301-A-W04MV -L1	230	< 0.1	0.05	0.05
301-A-W04MV -L2	442	< 0.1	0.00	0.01
301-A-W04MV -L3	885	< 0.1	0.04	0.04
301-A-W05MV -L1	99	< 0.1	0.04	0.04
301-A-W05MV -L2	235	< 0.1	0.00	0.01
301-A-W05MV -L3	220	< 0.1	0.00	0.01

Three months later, there was a failure in the same core which had a slightly low IR value. This was a high resistance fault, capable of withstanding 1 kV.

Because of the nature of the defect, traditional cable thumping and TDR methods struggled to determine the

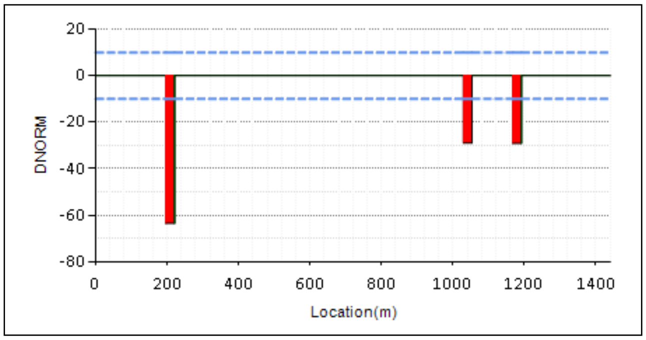


Figure 13. Initial DNORM graph.

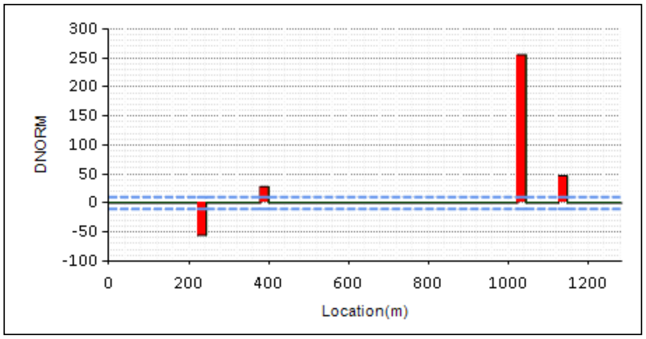


Figure 14. Final DNORM graph - after burn-on-arc.

fault location. LIRA was then brought in, which identified three potential defect locations (Figure 13).

In order to further pinpoint the defect, the cable was subjected to 1 kV for a period of one hour, after which LIRA was repeated. It could be clearly seen that the DNORM amplitude at 1024 metres had shot up, which was thus the point of failure (Figure 14). Replacement of this section enabled the cable to be put back in service.

5. Conclusions

No single technology can assess the health of a cable in totality, nor be able to determine the defect location in every case. A combination of techniques is generally the best approach for this purpose.

LIRA provides a powerful tool to fill the gaps in the traditional condition assessment techniques (tan delta, PD, etc.), viz. the inability to determine the locations of water treeing and physical damage. It also enables condition assessment of LV and control cables, which have hitherto been bereft of any techniques.

Further research work is ongoing to strengthen the correlation between DeltaG and traditional Tan Delta measurements for global degradation assessment as well as to develop termination assessment via BTS.

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