A Guide to Cable Diagnostics – Theory, Practical Aspects & Field Experiences

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ABSTRACT

Diagnostic testing on medium voltage power cables is well established. However, many gaps remain in this field, and end users often wonder what is the right approach to be followed. Defects have been found correctly on numerous occasions but have also been missed from time-to-time. This paper discusses the basic theory of various techniques, how they can be combined to maximize accurate diagnoses and reduce the chances of an incorrect assessment. It will also address common doubts & misconceptions about cable diagnostics.

Keywords

Cable condition monitoring, Fault detection, VLF, Damped AC, Tan Delta, Partial Discharge, Time 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 & TDR. Some excellent guidelines for these are:

1. IEEE 400, 400.1, 400.2, 400.3, 400.4 & 1234
2. IEC 60502, 60840 & 60885-3
3. CIGRE 502 & 841
4. ANSI-NETA Acceptance Testing Specs & Maintenance Testing Specs

These have established that AC Hipot testing alone is insufficient to have a qualitative assessment of cables, which DC Hipot testing is actually harmful. Now that many end-users have decide that they want cable diagnostics, some of the questions that commonly arise are:

1. Is it required to test new cables?
2. How often should cables be tested?
3. Which tests should be performed?
4. Is on-line PD testing sufficient to assess cable health?
5. Can applying over-voltage for doing an off-line PD or a tan delta test degrade the cable?
    a. From what voltage levels is PD testing useful?
6. Is VLF or DAC testing better?
7. Can every single incipient defect be detected?
8. Can we know the remnant life of the cable?

The paper will address each of these questions, along with some other rarer ones:

1. Can we determine the location of water trees?
2. Can we detect & determine the location of physical damage?
3. Can we quantify the workmanship of the joints?
4. Should tan delta be performed on very short-length cables (< 50 metres)?
5. Can we find defect locations in very long cables (over 7-10 kms)?
6. How accurate is the determination of the defect location?
7. Can we know the remnant life of the cable?
8. What is Dielectric Spectroscopy?
9. What is Polarization-Depolarization Current Analysis?

Lastly, we will look at field case studies to see how the combination of multiple test techniques can help overcome the limitations of each technology and derive very accurate assessment of the cable health.

2. BASIC CONCEPTS

2.1 DC HI-POT
2.2 AC HI-POT
2.3 TAN DELTA
2.4 PARTIAL DISCHARGE
2.5 LINE IMPEDANCE RESONANCE ANALYSIS

2.1 BASIC CONCEPTS – DC HI-POT

DC over-potential (Hi-Pot) testing is the easiest method for testing of cables. It can be used for acceptance testing of all types of cables, as well as for maintenance testing of PILC cables. The main idea is to apply a voltage stress on the dielectric to determine its capability to withstand actual stresses during operation. As per IEEE 400.1-2018, the procedure is to apply DC voltage between the conductor & earth, as under:

a) Apply voltage in 5 or more steps

b) Keep first step < 1.8 x rated voltage

c) Hold voltage for 1 min. at each step

d) Hold max. voltage for 15 minutes

e) Keep max. voltage as given in Table 1 (overleaf):

Rated Voltage (kV)	Applied Vol. (kV) – Acceptance Test	Applied Vol. (kV) – Maintenance Test
3.3	28	23
6.6	36	29
11	56	46
22	75	61
33	100	75
66	175	130
132	325	245
220	525	395

Table 1: Test voltages for DC Hi-Pot

Alternatively, IEC 60502-2 (2014) specifies a voltage of four times the rated phase-to-ground voltage (4 x ***U0***) for a period of 15 minutes. This is meant for new cables only.

While there isn't much diagnostic information in the test, ICEA S-94-649 states that it can detect gross problems such as improperly installed accessories or mechanical damage. The basic idea is to use the test for pass/fail purposes only. Some assessment can be done by comparing the leakage currents between phases (or identical cables). It should be within 3 times of each other.

The main advantages of the DC Hi-Pot are small size of test equipment, low cost, and simplicity.

One key point to keep in mind is that DC testing induces space charges in extruded cable insulation (especially old cables), and this can degrade cable life and cause failure when an AC voltage is re-applied. Hence, it should never be used for old XLPE or EPR cables.

2.2 BASIC CONCEPTS – AC HI-POT

AC over-potential (Hi-Pot) testing has a long history within lab & field testing and is considered the most acceptable test for cables. It can be performed using power frequency, VLF and Damped AC power sources. Like a DC Hi-Pot, the main idea is to apply voltage stresses to evaluate the insulation condition.

The test can be performed as a Simple Withstand Test (Pass/Fail) or as a Monitored Withstand Test (where leakage current, tan delta or partial discharge are recorded). The latter gives significant benefits due to the diagnostic information generated. The test voltages are specified differently in different standards. IEC 60502-2 (2014) meant for new cables gives the following options:

a) Apply rated phase-to-phase voltage (***U***) for 15 minutes at a frequency between 20 Hz to 300 Hz.
b) Apply rated phase-to-ground voltage (U_0) for 24 hours at power frequency.
c) Apply thrice the rated phase-to-ground voltage (3 x U_0) for 15 minutes at 0.1 Hz.

For old cables, the standard advises lower voltages but does not specify values.

For VLF (0.1 Hz) testing, a more usable standard is the IEEE 400.2 (2013), which recommends test voltages as follows:

Rated Voltage (kV)	Applied Vol. (kV_{rms}) – Acceptance Test	Applied Vol. (kV_{rms}) – Maintenance Test
5	10	7
8	13	10
15	21	16
20	26	20
25	32	24
28	36	27
30	38	29
35	44	33
46	57	43
69	84	63

Table 2: Test voltages for AC VLF Hi-Pot

If performed as a Simple Withstand Test, the voltage is to be applied for a period of 60 minutes. The only criterion here is that the cable should not fail during the test. If performed as a Monitored Withstand Test, the voltage is to be applied for a period of 30 minutes.

For DAC (20 Hz to 500 Hz) testing, the appropriate standard is the IEEE 400.4 (2015), which recommends test voltages as follows:

Rated Voltage (kV)	Applied Vol. (kV_{peak}) – Acceptance Test	Applied Vol. (kV_{peak}) – Maintenance Test
3	6	5
5	8	6
6	12	10
8	14	11
10	17	14
15	26	21
20	34	28
25	43	35
30	51	41
35	60	48
45-47	75	60
60-69	99	80
110-115	181	145
132-138	187	150
150-161	212	170
220-330	254	204

Table 3: Test voltages for Damped AC Hi-Pot

The voltage should be held for 50 DAC excitations. Like the VLF test, the DAC Hi-Pot too can be a Simple or Monitored Withstand Test. In case of old cables, the no. of excitations should be reduced as may be acceptable to the testing agency and the end-user.

2.3 BASIC CONCEPTS – TAN DELTA

The tan delta test is one of most effective diagnostic tests for cable assessment. It is highly sensitive to water treeing & also has some sensitivity to partial discharges and physical degradation. The measurement can be performed using power frequency, VLF or DAC, of which VLF is the most sensitive.
The core concept of tan delta is explained in the graphs below:

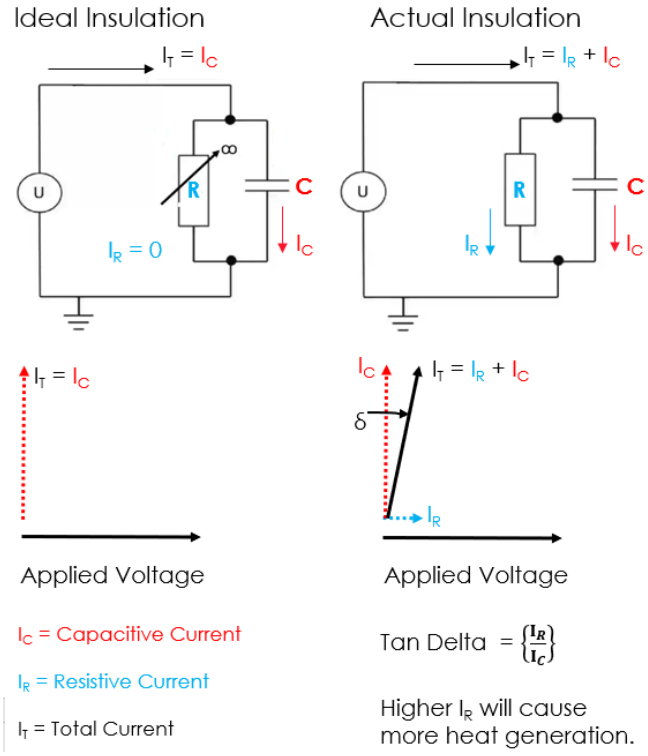


Fig. 1: Tan Delta concept

Tan delta is the ratio of the resistive current to the capacitive current when AC voltage is applied between the conductor and earth (i. e., across the insulation). An ideal insulation would have infinite resistance and thus the resistive current should be zero (thus the tan delta value too would be zero). The only current that would be drawn in such cases would be the capacitive charging current.

As insulation degrades, the insulation resistance would no longer be infinite, and thus some resistive current would flow. In such a situation, the total current would be a vector sum of the resistive & capacitive currents and thus lag the capacitive current by an angle delta (δ). The tangent of this angle delta (i. e. tan δ) would be greater than zero and indicate insulation degradation.

The test is recommended for both new and old cables. The permissible limits under the various standards are:

IEC 60502-2 (2014) for new cables at power frequency:
XLPE – 4 x 10^{-3}
EPR – 40 x 10^{-3}

A more effective way of measuring tan delta is to use a VLF (0.1 Hz) power source and apply voltage in steps. IEEE 400.2 (2013) is the standard to be followed in such cases, which requires measurement of the following parameters:

a) **Tan delta stability** – the std. deviation for the tan delta values when measured every 10 seconds for 1 minute at rated voltage ***U0***.
b) **Delta tan δ** – The difference between the tan delta values at two different voltages (either $2.0U_0 – 1.0U_0$ or $1.5U_0 – 0.5U_0$).
c) **Tan Delta** at ***U_0***.

A big advantage of this standard is that it specifies limits for both new & old cables as well as grades the results instead of just pass/fail. These limits are as under:

Condition Assessment	**Tan δ Stability at U_0**		**Δ Tan Delta**		**Tan Delta at U_0**
(Old XLPE)	**(x 10^{-3})**		**(x 10^{-3})**		**(x 10^{-3})**
North America					
No action required	< 0.1	and	< 5	and	< 4
Further study advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action required	> 0.5	or	> 80	or	> 50
Rest of World (XLPE)					
No action required	< 0.1	and	< 0.6	and	< 1.2
Further study advised	0.1 to 0.5	or	0.6 to 1	or	1.2 to 2
Action required	> 0.5	or	> 1	or	> 2
Rest of World (TR-XLPE)					
No action required	< 0.5	and	< 1.5	and	< 8
Further study advised	0.5 to 1	or	1.5 to 3	or	8 to 10
Action required	> 1	or	> 3	or	> 10

Table 4: Limits for VLF Tan Delta – Aged XLPE

Condition Assessment	**Tan δ Stability at U_0**		**Δ Tan Delta**		**Tan Delta at U_0**
(Old EPR)	**(x 10^{-3})**		**(x 10^{-3})**		**(x 10^{-3})**
North America					
No action required	< 0.1	and	< 5	and	< 35
Further study advised	0.1 to 1.3	or	5 to 100	or	35 to 120
Action required	> 1.3	or	> 100	or	> 120
Rest of World					
No action required	< 0.5	and	< 4	and	< 10
Further study advised	0.5 to 1	or	4 to 10	or	10 to 80
Action required	> 1	or	> 10	or	> 80

Table 5: Limits for VLF Tan Delta – Aged EPR

Condition Assessment	Tan δ Stability at U$_0$		Δ Tan Delta		Tan Delta at U$_0$
(Old PILC)	(x 10^{-3})		(x 10^{-3})		(x 10^{-3})
North America					
No action required	< 0.1	and	-35 to +10	and	< 85
Further study advised	0.1 to 0.4	or	-35 to -50 or +10 to +100	or	85 to 200
Action required	> 0.4	or	< -50 or > +100	or	> 200
Rest of World (XLPE)					
No action required	< 0.5	and	-20 to +20	and	< 50
Further study advised	0.5 to 1	or	-20 to -50 or +20 to +50	or	50 to 100
Action required	> 1	or	< -50 or > +50	or	> 100

Table 6: Limits for VLF Tan Delta – Aged PILC

Condition Assessment	Tan δ Stability at U$_0$		Δ Tan Delta		Tan Delta at U$_0$
(New XLPE)	(x 10^{-3})		(x 10^{-3})		(x 10^{-3})
No action required	< 0.1	and	< 0.8	and	< 1.0
Further study advised	> 0.1	or	> 0.8	or	> 1.0
Action required	> 1.3	or	> 100	or	> 120

Table 7: Limits for VLF Tan Delta – New XLPE

Tan delta measurements can also be carried out using a Damped AC power source, in which case the IEEE 400.4 (2015) standard is applicable. Herein, test voltage is applied in steps upto the maximum voltage specified in Table 3. There are no absolute limits specified in the standard, and assessment is primarily by comparing identical cables or trending the same cables over time.

While all three methods – power frequency, VLF & damped AC can be used to measure tan delta, VLF is the recommended method as the low frequency measurement is far more sensitive to water treeing as compared to the other methods.

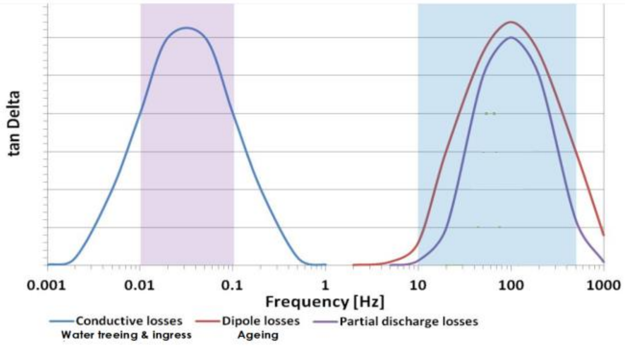


Fig. 2: Tan Delta sensitivity to frequency

2.4 BASIC CONCEPTS – PARTIAL DISCHARGE

Partial discharge is the localized breakdown of insulation that does not find a path to ground.

PDs are small electric sparks that occur in defects in the insulation, or at interfaces or surfaces, or between a conductor & a floating metal component (not connected electrically to the HV conductor nor to the ground conductor). The discharges do not bridge the insulation between conductors, and the defects may be entirely within the insulation, along interfaces betn. insulating materials (joints) or along surfaces (terminations).

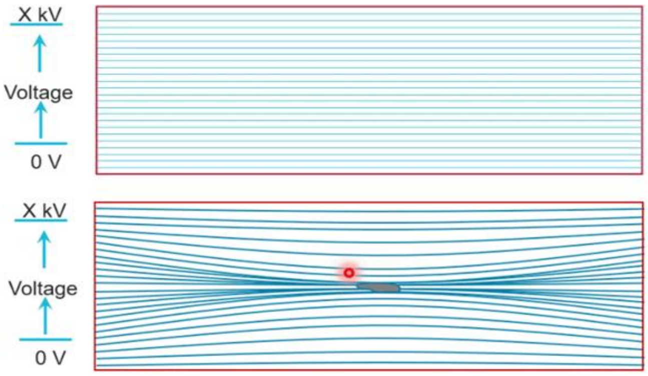
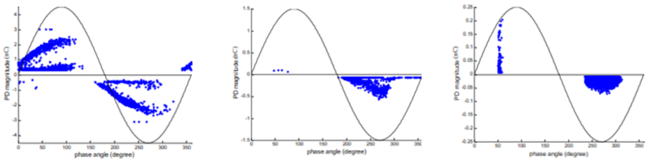


Fig. 3: Concentration of electrical stress lines in the presence of a void

The presence of a void or an impurity in the insulation causes a concentration of the electrical field lines. This increased stress along with the lower dielectric strength of the void significantly increases the chances of an electrical breakdown.

Measurement of PD is important because initiation of PD activity (for XLPE) or a rapid rise in PD activity (for PILC) is a precursor to imminent failure. In addition, the analysis of the partial discharge patterns (PRPD) helps understand the nature of the defect while the analysis of the PD pulse shapes helps identify the weak spots. This is very useful to determine the severity, likelihood of failure and the section of the cable to be repaired.



Void discharge Surface discharge Corona

Fig. 4: PRPD patterns for different defects

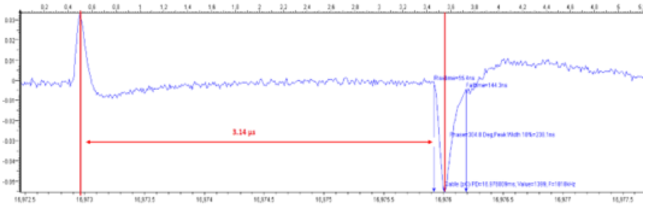


Fig. 5: PD pulse shape showing the defect location

Partial discharges can be measured both on-line and off-line. The off-line measurements can be conducted using power frequency, VLF or DAC voltage sources. On-line PD measurements can be done with several sensors, such as high frequency current transformers (HFCT), transient earth voltage sensors (TEV), flexible magnetic couplers (FMC), etc. Each of these have their own advantages & disadvantages, that need to be taken into consideration during measurements. Off-line PD measurements are usually done using capacitive couplers.

Some of the standards that govern partial discharge measurements and analysis are IEC 60885-3 (2015), IEEE 400.3 (2006) and IEEE 400.4 (2015). The first one is for off-line PD measurements at power frequency, the second one covers all types of PD measurements on cables while the last one is for DAC-based testing. All these cover testing & interpretation procedures. However, no limits are specified. A very useful reference is hence the OISD 137 (2016), which does give limits for PD amplitude as well as PD Inception & Extinction Voltages (PDIV & PDEV).

Result	**PD Category - High**	**PD Category - Low**	**Remarks**
PDEV < 1.0 U_0	Bad cable	Bad cable	Replace immediately
PDIV < 1.0 U_0	Bad cable	Bad cable	Replace immediately
PDIV < 1.3 U_0 & PDEV > 1.0 U_0	Bad cable, replace immediately	Good cable, re-test after 12 months	
PDIV > 1.3 U_0 & PDEV > 1.0 U_0	Some concern, re-test after 6 months	Good cable, re-test after 24 months	
PDIV > 2.0 U_0 & PDEV > 1.0 U_0	Some concern, re-test after 24 months	Very good cable	

Table 8: Limits for PD Inception & Extinction Voltages (OISD 137 – power frequency or VLF)

PILC PD Level (pC)	**XLPE PD Level (pC)**	**Assessment**	**PD Category**
0 – 3000	0 – 250	OK - discharge within tolerable limits	Low
3000 – 6500	250 – 350	Some concern - monitoring recommended	
6500 – 10000	350 – 500	Significant concern - regular monitoring recommended	High
> 10000	> 500	Severe concern – locate, then repair or replace	

Table 8: Limits for PD Amplitude (OISD 137 – power frequency or VLF)

2.5 BASIC CONCEPTS – LINE IMPEDANCE RESONANCE ANALYSIS

Line Impedance Resonance Analysis (LIRA) is a technique that uses frequency domain spectroscopy to detect changes in the cable impedance as a function of its length. As a cable is homogenous (except for joints & terminations), any change in the impedance is symptomatic of degradation. The most common types of defects that can be detected by LIRA include moisture ingress, overheated conductors, physical damage and defective joints. One unique benefit of LIRA is the ability to test LV, MV, HV & EHV cables.

LIRA is performed by injecting low voltage, high frequency signals (100 kHz to 100 MHz) between the conductor and earth. These signals travel along the cable, and some portions get reflected from wherever there are impedance changes. While the impedance change is very low, the use of high frequencies such that the wavelength of injected signals is lesser than the length of the cable, the impedance changes are amplified by resonance.

LIRA measures the complex impedance of the cable over a wide frequency spectrum:

$$\vec{Z}(f) = Re + Im$$

The discrete values make up an impedance vector consisting of:

- Frequency
- Impedance real part
- Impedance imaginary part

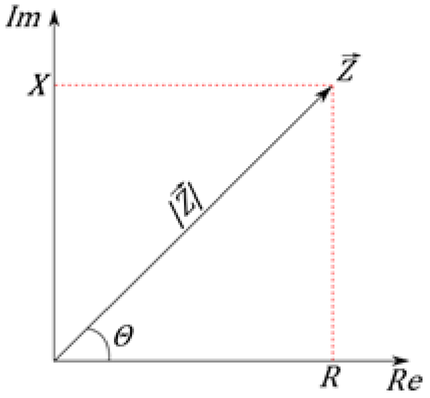


Fig. 6: Cable complex impedance representation

This vector is used to calculate the impedance amplitude and phase:

$$|\vec{Z}| = \sqrt{R^2 + X^2}$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right)$$

When both these values are plotted as a function of frequency, we get the resultant LIRA graphs shown in Figure 7.

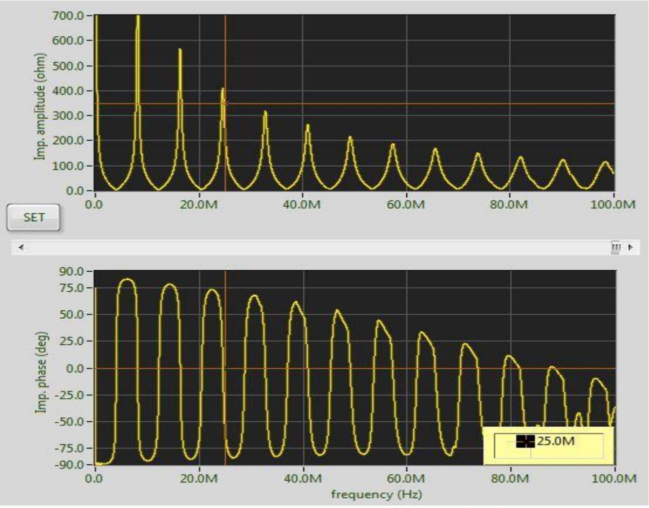


Fig. 7: LIRA shows resonance at specific frequencies

As any assessment of the cable condition is dependent on the change in impedance, the best way to quantify discrete sections of the cable is to compare the reflected signal from each section to the injected signal. The resultant signal gain is plotted on a log (dB) scale as a function of the length to assess the condition.

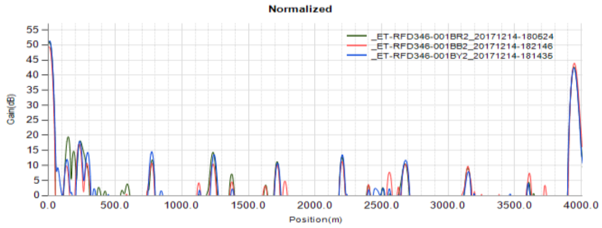


Fig. 8: LIRA Gain plot shows impedance change at each joint as well as other weak spots

In addition, it is also possible to exclude the injected signal and assess whether the change in impedance (as compared to the remaining cable) is positive or negative – referred to as the DNORM value. This is very useful as a high positive DNORM value would indicate physical damage/ overheating whereas a high negative DNORM value would indicate moisture ingress/ water treeing.

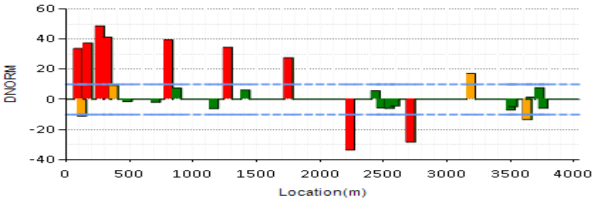


Fig. 9: DNORM plot showing +ve & -ve changes

LIRA is relatively a new technology and been referenced in the CIGRE 825 (2021) standard. One of the key benefits of LIRA is that it is performed at a low voltage (9 V) and hence poses no danger to the cable being tested. Another practical benefit is that cable disconnection is not required (unlike tan delta & PD), and hence testing is much faster and more convenient.

3. ANSWERS TO BASIC QUESTIONS

3.1 Is it required to test new cables?

Yes, testing of new cables is highly recommended. Field experiences show that many defects occur during cable laying & splicing. Identifying them in time prevents infant failures as well as those later in operation. In addition, having baseline test data from new cables is also very helpful when assessing later test results.

The ANSI-NETA Acceptance Testing Specifications for Electrical Equipment (2021) recommends the following tests:

a) Dielectric Withstand – DC or AC
b) Tan Delta – power frequency, VLF or DAC
c) Insulation Resistance
d) Partial Discharge – on-line, power frequency, VLF or DAC

3.2 How often should cables be tested?

The recommended interval for testing cables depends on the current condition of the cable as well as its importance. The ANSI-NETA Maintenance Testing Specifications for Electrical Equipment (2019) recommends the following:

		RECOMMENDED TIME FOR NEXT TEST		
CABLE CONDITION →		POOR	AVERAGE	GOOD
CABLE RELIABILITY REQUIREMENT	LOW	3 yrs	6 yrs	7 ½ yrs
	MEDIUM	1 ½ yrs	3 yrs	4 ½ yrs
	HIGH	9 mnths	1 ½ yrs	2 ¾ yrs

Table 10: ANSI recommended time intervals

For the above table, the importance of the cable is to be decided by the end-user, whereas the cable condition is based on the previous test results.

3.3 Which tests should be performed?

There are two approaches to this question. One way is to refer the standards. ANSI-NETA MTS (2019), IEEE 400 (2012) and CIGRE 825 (2021) specify the various tests to be performed. As a minimum, the following should be considered:

a) Insulation Resistance
b) Tan Delta (VLF preferred, DAC acceptable)
c) Partial Discharge if the voltage is 11 kV or above

Depending on the cable condition, previous history and its criticality, the following additional tests are to be considered:

a) LIRA
b) Dielectric spectroscopy
c) Monitored hi-pot with PD
d) Polarization-Depolarization Current
e) Ampacity calculations

3.4 Is on-line PD testing sufficient to assess cable health?

There isn’t a very clear answer to this, but typically NO. PD testing is good for detecting voids & some joint defects. However, it cannot detect water treeing, moisture ingress or physical damage. Tan delta (and sometimes LIRA) are required as complements.

The sensitivity of the on-line PD measurement also depends greatly on the sensor used. HFCTs have high sensitivity but require access to the cable’s earth strap (which connects the screen to ground). In many cases (especially 6.6/ 11/ 22 kV cables), this strap is not accessible. Alternatives such as FMC, EMI, TEV & capacitive foil sensors exist, but all of these are usually effective only for short cable lengths.

Thus, if a defect is detected by on-line PD testing, the assessment is generally correct. However, there are many defects that could be missed. Hence, it is best used as a screening tool or to monitor a PD defect that has already been detected.

3.5 Can applying over-voltage for doing an off-line PD or a tan delta test degrade the cable?

This can happen though it is very rare. IEEE 400.2 (2013) states that 1 % to 2 % of cables can fail during an over-voltage test. IEEE 400.4 (2015) states that test excitations should be kept low to reduce chances of failure.

We have experienced such failures in 8-10 cases out of the over 8,000 cables that we have tested. For this reason, we recommend limiting the test voltage to **1.5U_0** rather than **2.0U_0** for old cables (e. g. 29 kV for a 33 kV cable). The over-voltage will not degrade healthy cables.

3.6 From what voltage levels is PD testing useful?

IEEE 400 recommends PD testing for cables above 5 kV. In our experience, we have never seen PD activity in 6.6 kV cables and very rarely in 11 kV. PD does indeed happen at the terminations for these voltages and can be easily detected using on-line techniques.

3.7 Is VLF or DAC testing better?

Both methods have their own advantages & disadvantages. The final choice really depends on availability and site conditions. Benefits of both are:

DAC:

a) More similarity with power frequency, hence, replicates real-life PD activity better.
b) Double-ended solutions are available, hence determining PD locations in long length cables is easier.

VLF:

a) Limits are specified by IEEE for both old & new cables.
b) Much more sensitive to water treeing.
c) Results of non-identical cables can be compared as frequency does not change.
d) Voltage is uniform for all cycles (no DC component).

3.8 Can every single incipient defect be detected?

Unfortunately, the answer to this is often NO. It is usually not possible to perform all the possible tests due to time or commercial constraints. In addition, there are specific situations wherein PD, tan delta & LIRA can all miss out on a defect. Some of the reasons why this can happen are:

a) Excessive signal attenuation due to cable length, or shield corrosion
b) High background noise
c) The trade-off between using a high enough voltage to excite PD and low enough to not damage the cable can cause some misses.

4. ANSWERS TO ADVANCED QUESTIONS

4.1 Can we determine the location of water trees?

Yes, it is possible to find the location of water trees. This requires a combination of VLF tan delta & LIRA measurements. A high tan delta value combined with the absence of PD is a clear indication of water treeing. LIRA should be performed in such cases. The location at which a high negative DNORM value is observed is where the water treeing/ ingress has occurred.

4.2 Can we detect & determine the location of physical damage?

Yes, using a similar approach as above. The combination of a high tan delta value with a high positive DNORM value will indicate the location of the physical damage.

4.3 Can we quantify the workmanship of the joints?

Yes, in two ways. Every single joint will have a change in impedance as far as LIRA is concerned. Hence, the Signal Gain or the DNORM value for each joint is a quantification of its workmanship. In the EU, it is common to perform LIRA for all EHV cables to verify joint quality.

In the case of EHV cables that have cross-bonding, it is also possible to take PD measurements at each joint to detect voids within it (remember that LIRA is good for water ingress & physical damage, but not voids).

4.4 Should tan delta be performed on very short-length cables (< 50 metres)?

Tan delta is defined as the ratio of resistive current to capacitive current while applying AC voltage across the insulation. In the case of short length cables, the capacitive current is low while the surface leakage current (which is resistive in nature) is high. Hence, the measured tan delta values will be very high, even though the cable is perfectly healthy. Trending these values does not serve any benefit.

For this reason, such short cables are often not tested. The only way to overcome this problem is to use a guard circuit that can eliminate the surface leakage current. The guarding must be at both the cable ends to be effective. We have had practical experience where the tan delta values dropped from over (200 x 10^{-3}) to (0.2 x 10^{-3}) with such guarding. Thus, tan delta should be performed on short length cables only if guarding is possible.

4.5 Can we find defect locations in very long cables (over 7-10 kms)?

The answer to this is yes, but it is much more difficult and not always guaranteed. There are three possible scenarios:

Case 1 – EHV cables with cross-bonding
In this case, the cross-bonding point is accessible at the link box for PD sensors. Measurements can be taken in sections, making the effective test length much shorter. LIRA too can be used for other types of defects. Localization is thus possible.

Case 2 – MV cables with water treeing/ damage
In this case, LIRA is very effective, especially when the normalization technique is used. Further accuracy can be achieved by taking measurements from both ends.

Case 3 – MV cables with PD
Finding the location for PD activity in long length cables remains the most challenging aspect for any analyst. Both IEC & IEEE (400.4) have acknowledged this aspect.

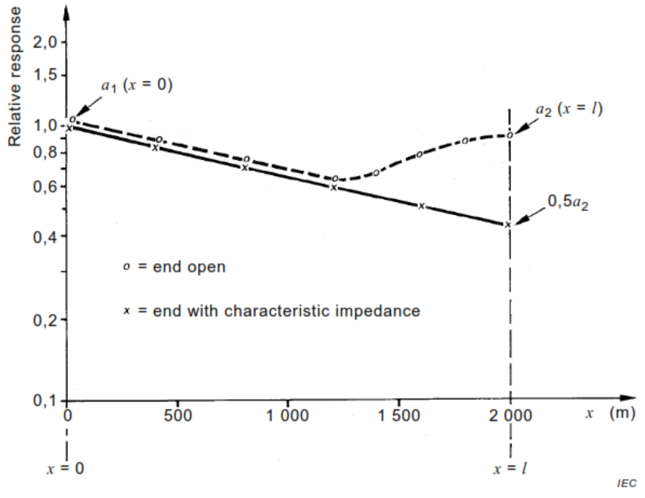


Fig. 10: IEC 60885-3 (2015) shows the PD pulse attenuation along the cable length

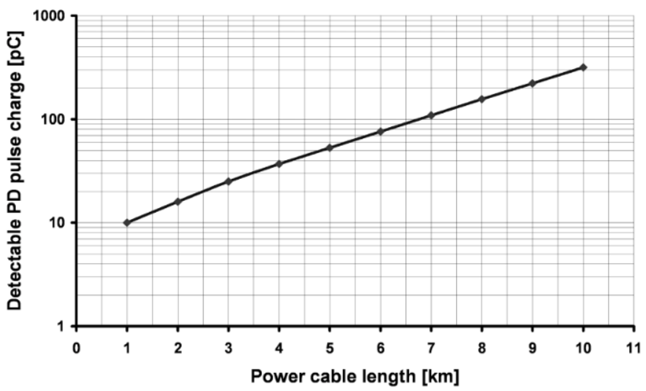


Fig. 11: IEEE 400.4 (2015) shows the reduction in sensitivity with increase in cable length

Figure 11 is most interesting. It shows that a PD sensor that can detect as low as 10 pC at a distance of 1 km. would only be able to detect PD over 300 pC at 10 km. This is a hundred-fold reduction in sensitivity. As a cable is likely to fail well before it reaches 1000 pC of discharge, this would not be useful. An even bigger challenge is to find the reflection of the PD signal, which is critical to determine the location.

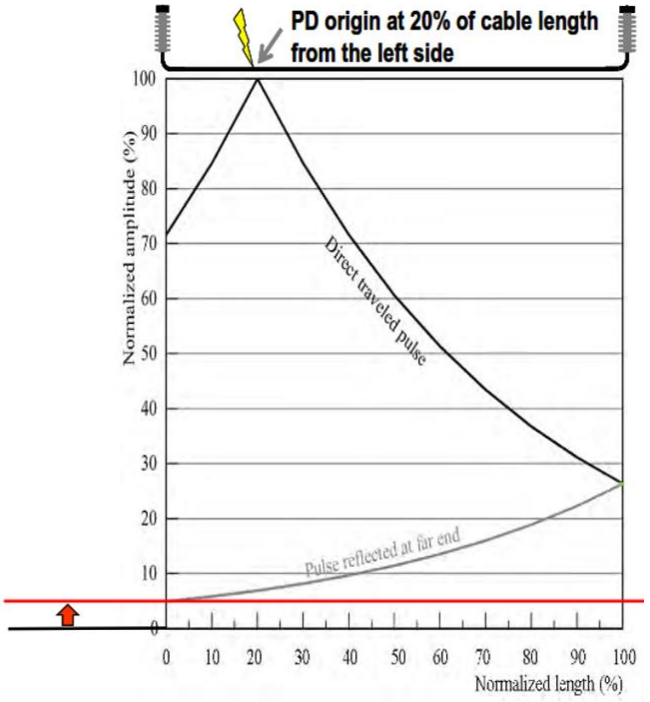


Fig. 12: Single-ended PD detection

In the example shown in Figure 12, the direct PD pulse is about 72 % in amplitude, but the reflected pulse is only 5 %. Thus, having a PD sensor (coupling capacitor) at one end would make it very difficult to determine the location of the PD activity.

This can be significantly improved by using PD sensors SIMULTANEOUSLY at both ends and have them communicate with each other using GPS.

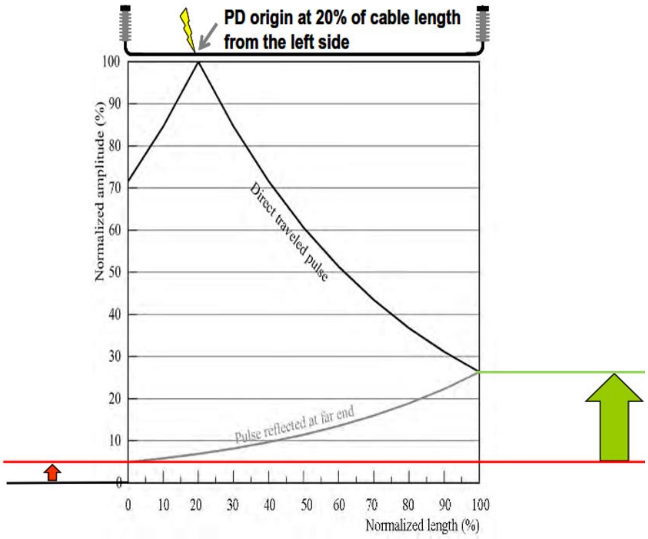


Fig. 13: Double-ended PD detection

In Figure 13 above, we have used two coupling capacitors together – one at each end. The reflected signal is now about 26 %. There is thus a 21 % increase in measurement sensitivity.

Our practical experience with cables is that it is not possible to determine the PD location in cables over 3 kms. In length using a single-ended PD coupler. Simultaneous double-ended measurement is the only solution in such cases. Double-ended PD measurement devices are now commercially available with DAC and the same is being explored for VLF also.

4.6 How accurate is the determination of the defect location?

The determination of the defect location is done using PD & LIRA techniques (depending on the type of defect). Both technologies require the signal return speed of the cable to accurately calculate the defect location. This can vary from as low as 75 mtrs/µsec for PILC to as much as 90 mtrs/µsec for XLPE. However, these are only thumb rules, and the exact speeds differ from OEM to OEM.

Wherever the signal return speed is known exactly (from OEM datasheet), the calculation accuracy of the defect location is as high as 0.1 % (the only error comes from the small change of the speed in the joints). When the return speed is not known, the calculations are done based on the thumb rules, and the accuracy can be off by as much as 5 %.

Knowing the exact location of the joints can help in improving the accuracy, as defects as most likely to be in one of them and the length can be calibrated accordingly.

4.7 Can we know the remnant life of the cable?

Residual Life Analysis (RLA) is one of the most misused terms in electrical testing. While the various technologies can identify defects and assess their severity, cable life depends on many other factors such as soil resistivity, ambient temperatures, Ampacity, load flow, etc.

Thus, it is not possible to arrive at an accurate calculation of the remnant life. A much better approach is to use the ANSI-NETA guidelines for frequency of repeating the tests.

However, some estimation of life can be done IF the diagnostic techniques discussed in this paper are combined with Ampacity, load flow studies and mechanical tests (compressive modulus, elongation-at-break, etc.).

4.8 What is Dielectric Spectroscopy?

Dielectric Spectroscopy is an off-line test method wherein high voltage (several kV) is applied between the conductor and earth, the test frequency varied in steps from 0.01 Hz to 10 Hz and the tan delta values are measured at each step.

When we measure tan delta at VLF (0.1 Hz) and get high values, these can be due to conduction losses or polarization losses. The issue is primarily with shorter cables (see Question 4.4). Conduction losses are not of much concern, whereas polarization losses would indicate water trees. By measuring tan delta over a range of frequencies and comparing over time, we can distinguish between the two effects (see below).

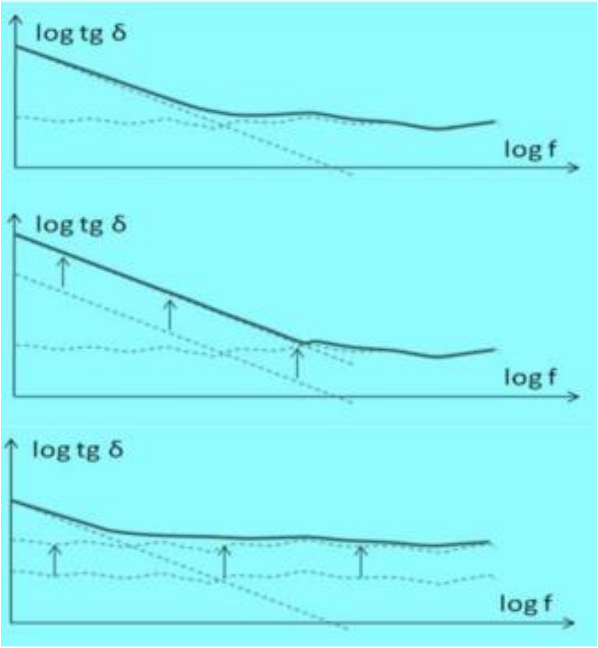


Fig. 14: Top graph is normal, middle shows conductive losses and bottom shows water treeing

To an extent, this test is less popular because of the ease and location determination capability of the LIRA test. However, it remains a very effective test to verify the condition of short cables.

4.9 What is Polarization-Depolarization Current Analysis?

This is a technique explained in IEEE 400 (2012) where the cable is charged using a low DC voltage for a fixed time and then discharged through a ground resistor for the same period. The charging & discharging currents measured continuously, and the resultant graphs analyzed to determine overall degradation.

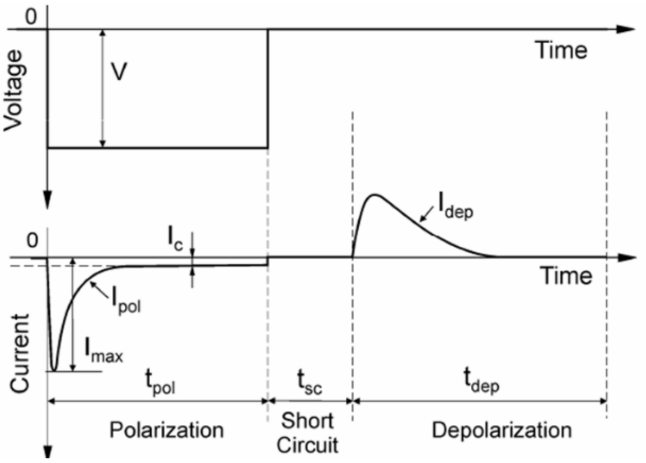


Fig. 15: Typical PDCA graphs

While many of papers have been published on this technique, clear guidelines or standards are not available. Hence, it has not gained much popularity.

5. CASE STUDIES

5.1 Weak joint in 33 kV cable - (slightly low IR, very high tan δ, no PD, high DNORM)

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 11.

Phase	IR (GΩ)	Tan Delta (x 10^{-3})	Limit	Δ Tan Delta (x 10^{-3})	Limit
R	85	6.0	< 2.0	2.2	< 1.0
Y	110	4.0		1.9	
B	19	45		24.7	

Table 11: Initial VLF Tan Delta values

As these were of concern, Damped AC 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 16).

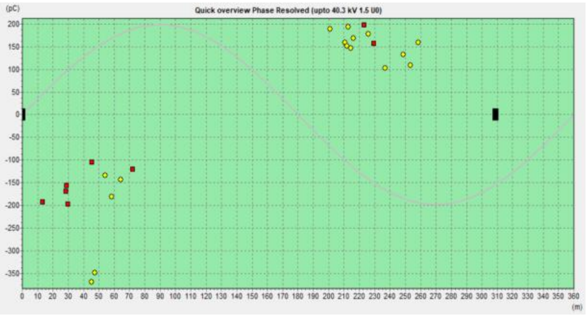


Fig. 16: Damped AC PRPD at 1.5U0

Finally, LIRA measurements were performed, which clearly picked up a defect at 288 metres (see Fig. 17). This section of the cable was excavated & a joint was found at this location. The same was replaced & the VLF TD as well as LIRA tests were repeated. The results were now perfect (Table 12).

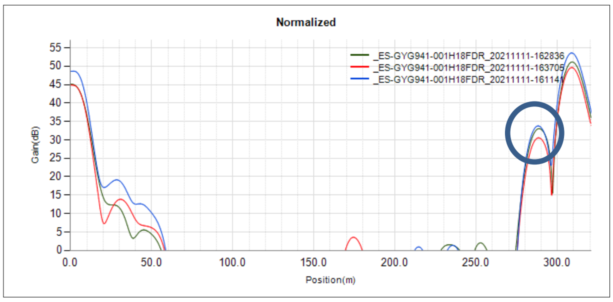


Fig. 17: Initial LIRA Spot Signature

Phase	IR (GΩ)	Tan Delta (x 10^{-3})	Limit	Δ Tan Delta (x 10^{-3})	Limit
R	222	0.6	< 2.0	0.25	< 1.0
Y	103	1.1		0.50	
B	109	0.6		0.13	

Table 12: Final VLF Tan Delta values

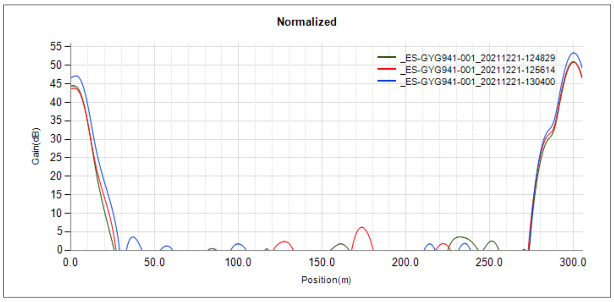


Fig. 18: Final LIRA Spot Signature

5.2 Weak joint in 35 kV cable - (slightly low IR, very high tan δ, high PD)

VLF tan delta (TD) test was performed on a 1.4 km, 3-core, 35 kV cable. The cable had been in service for over 20 years. The values measured were extremely high, as seen in Table 13.

Phase	IR (GΩ)	Tan Delta (x 10^{-3})	Limit	Δ Tan Delta (x 10^{-3})	Limit
R	42	2.1	< 2.0	3.9	< 1.0
Y	93	1.2		49	
B	80	1.7		4.6	

Table 13: Initial VLF Tan Delta values

As these were of concern, VLF partial discharge (PD) measurements were performed at 1.5U0 to try and locate the defect. PD was detected in a section at 670 metres from the test end.

Phase	Peak PD (pC)	Inception Voltage	Extinction Voltage	Location (metres)
R	5480	$1.1U_0$	$1.0U_0$	Near end
Y	5510	$1.1U_0$	$1.0U_0$	670
B	4940	$1.1U_0$	$1.0U_0$	673

Table 14: Initial VLF PD values

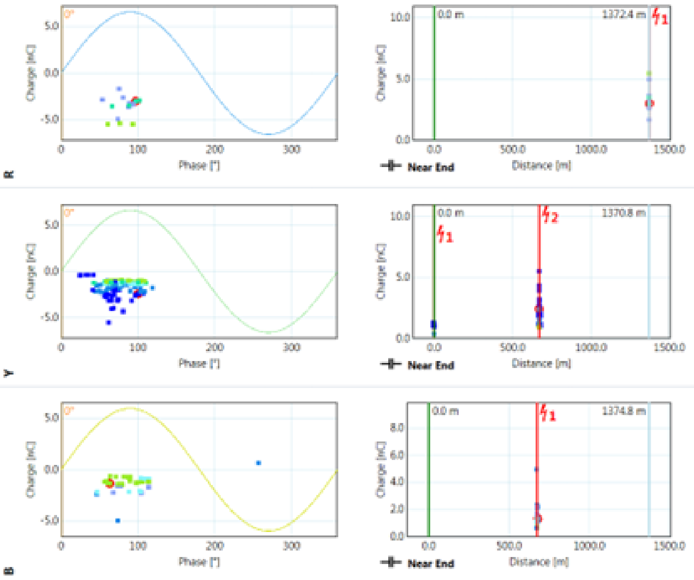


Fig. 19: PD graphs

The section at 670 metres was excavated and a joint was found there. It was in a poor condition and on the verge of failure. Had this occurred, an entire production line would have been down for several days. The joint was replaced and the cable re-tested; all results were excellent.

Fig. 20: Defective joint

Phase	IR (GΩ)	Tan Delta (x 10^{-3})	Limit	Δ Tan Delta (x 10^{-3})	Limit
R	62	0.1	< 2.0	0.3	< 1.0
Y	72	0.0		0.0	
B	164	0.0		0.4	

Table 15: Final VLF Tan Delta values

5.3 Weak section in 33 kV cable - (high IR, high tan δ, very high PD)

VLF tan delta (TD) & PD tests were performed on a group of 180 metre, 1-core, 33 kV cables. These had been in service for 21 years. The IR values were excellent, while the tan delta values were high but not alarming. However, the cause of concern was the detection of PD in one phase only.

Phase	IR (GΩ)	Tan Delta (x 10^{-3})	Δ Tan Delta (x 10^{-3})	Peak PD (pC)
R	603	0.2	1.2	-
Y	561	0.3	4.1	1230
B	620	0.1	0.7	-

Table 16: VLF Tan Delta & PD values

The greater concern was that the PD activity was located at 68 metres from the test end (i. e. within the cable), and there were no joints. Due to operational exigencies, the cable was re-energized without any repairs. It failed 24 hours later, at the same location where the PD was detected.

Fig. 21: Failed section

5.4 Failed joint in 13.5 km, 22 kV sub-sea cable (high Signal Gain & DNORM)

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 was then performed to identify the defect location. For the healthy cables (L1 & 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 22). This clearly indicated the defect location.

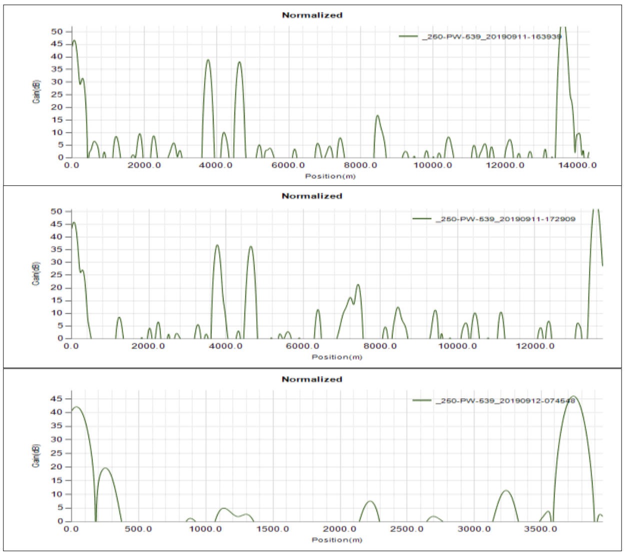


Fig. 22: LIRA Spot Signature – before repair

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 was that the condition of each joint could now be quantified, as seen from the final DNORM graphs (Figure 23).

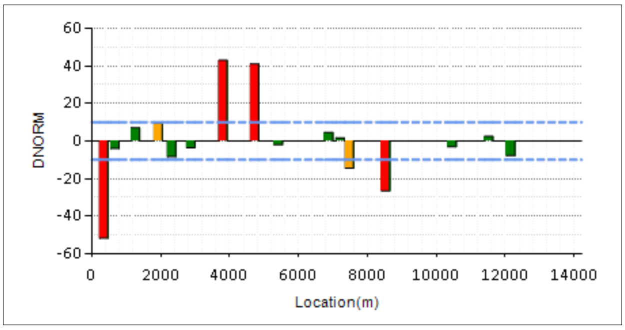


Fig. 23: DNORM graph quantifying each joint's condition

6. CONCLUSIONS

a) Many technologies are available to assess cable health. All of these are effective but not infallible.

b) The use of multiple technologies in conjunction significantly increases the reliability of the assessment.

c) Identifying locations of incipient defects in long length cables is highly challenging.

d) PD testing is effective but not going to detect all types of defects.

e) Cable life estimation is an approximation, not an exact science.

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