CHAPTER 11

Metallic Shield Assessment

Jean Carlos Hernandez-Mejia & Joshua Perkel

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Chapter 4: How to Start

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11.0 METALLIC SHIELD ASSESSMENT

Most US electric utility companies installed thousands of miles of unjacketed, bare concentric neutral cables during the 1960s and 1970s. Analysis of early, unexpected failures revealed issues with neutral corrosion and many utilities decided to add an overall jacket to the cable construction. The jacket serves to protect the metallic shield and cable core from outside elements (moisture, rocks, etc.). Current experience indicates that jackets are effective at reducing moisture ingress and subsequent corrosion of the metallic shield. But a substantial installed population of unjacketed concentric neutral cable remains in service and shield corrosion has led to stray voltage and safety problems as well as cable failures.

As problems due to metallic shield corrosion increase, utilities are faced with making the decision whether to repair or replace these systems. Most diagnostic techniques investigated during CDFI focused on the condition of the dielectric system. This chapter focuses on techniques for assessing the condition of the metallic shield, which is also referred to as the cable neutral.

11.1 Test Scope

The application of cable diagnostic techniques to estimate the condition of the metallic shield of a power cable system is based on the following:

- **Cross Sectional Area Loss:** This condition is usually progressive with time and is due to corrosion. A reduced metallic shield cross sectional area diminishes the cable system capacity to safely carry normal operating and fault currents that may pose a risk to personnel and equipment.
- **Continuity Break:** This condition could be the result of poor workmanship, localized corrosion, or fault current at one location affecting the metallic shield at other locations of the cable system. A cable system with a degraded metallic shield is not able to withstand fault currents it was originally designed to handle and thus the fault current may mechanically and electrically stress degraded locations, resulting in breaks that can go undetected.
- **Loss of Contact with Cable Insulation Shield:** Metallic shield no longer makes good (sufficient) contact with the insulation shield as a result of cable corrosion or insulation shield degradation. A poor electrical contact between the metallic shield and cable insulation shield distorts the designed cable core electric field profile. The distortion may lead to surface arcing, damaging the cable core. While uncommon, mineral deposits at the metallic shield/insulation shield interface can also cause the loss of contact between these components.

The main application for diagnostic techniques for assessing metallic shield integrity is on unjacketed, concentric neutral cables. Figure 1 to Figure 5 show examples of the corrosion problems observed on unjacketed concentric neutral cables.

Figure 1: Unjacketed Concentric Neutral Cable with Corroded Neutral Wires (#14 AWG)

Figure 2: Corrosion of Concentric Neutral Wire Resulting in Loss of Metallic Shield Cross Sectional Area and Contact with Cable Insulation Shield (#14 AWG)

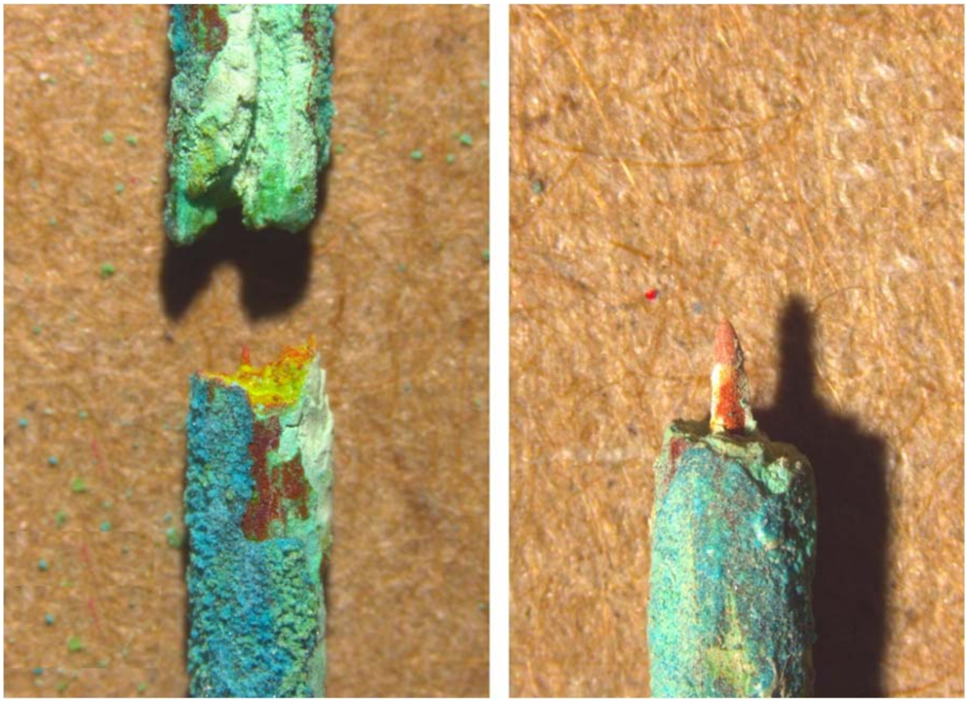


Figure 3: Corrosion of Concentric Neutral Resulting in a Wire Break (#14 AWG)

Figure 4: Metallic Shield Loss of Contact with Cable Insulation Shield Due to Mineralization

Figure 5: Exterior Arcing Due to Corrosion and Neutral Wire Break Causing Degradation to the Cable Core

11.2 How It Works

Two methods are used in field assessments of metallic shields: Time Domain Reflectometry (TDR) and ac resistance (also known as Ω-Check).

The TDR method works much the same way as is described in Chapter 5. A handheld unit sends an energy pulse of as little as 2 ns in width down the cable conductor. Each time this pulse experiences a change in impedance, a portion of the energy is reflected back to the pulse source. Depending on the magnitude and polarity of this reflection, the anomaly causing the impedance change (in the cable conductor or in the neutral) may be characterized. The TDR technique has been used for many years to detect the presence of cable joints and cable system failures, but its use in detecting the presence and relative severity of neutral corrosion is primarily used was initially used by companies involved in cable rejuvenation.

The Ω-Check test method involves measuring the resistance of a neutral path either with or without isolating the cable from the service. The condition of the neutral under test is determined by comparing the measured resistance to the manufacturer published resistance of a new neutral of the same type and configuration.

11.3 How It Is Applied

11.3.1 Time-Domain Reflectometry (TDR)

Typically, this technique is performed offline. A fast rise time, low voltage pulse is applied between the conductor and the metallic shield of a cable system at an elbow or termination. As the pulse travels through the cable system, reflections are produced by discontinuities that change the local impedance. The initial and reflected pulses are displayed against time on an oscilloscope display and interpreted by the operator. The pulse travel time can be converted to distance or location using an assumed velocity of propagation (VoP). An experienced operator can often determine the source (cause) of an impedance discontinuity by the shape and magnitude of the reflected signal. The test duration (including interpretation) is 5-10 min once the TDR and the cable system are connected. Overall advantages and disadvantages of TDR measurements are shown in Table 1.

Table 1: Overall Advantages and Disadvantages of TDR Measurements

Advantages	• Testing is easy to employ. • Test equipment is small and inexpensive. • Test equipment uses low test voltage (much less than U_0). • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Information of location of corrosion or break may be available. • Complete breaks in the entire metallic shield can be clearly identified.
Open Issues	• Unclear whether the test may be performed online. • Detailed knowledge of the cable system construction needed for interpretation. • It is difficult to interpret some impedance discontinuities. • It is difficult to interpret results on tape-shielded cables. • Selecting the pulse width for optimal resolution and distance can be problematic. • Interpreting results on circuits with multiple taps is challenging if not impossible. • Length measurement requires that the start of the TDR pulse be identified, and this can be difficult.
Disadvantages	• Not designed for metallic shield assessment. • Skilled operators are required for testing and post analysis. • There are “blind spots” due to the ringing effect that occurs near the pulse injection end. The length of cable within the blind spot depends on the injection method and pulse width. • Electrical noise may interfere with the low voltage TDR signal. • Successful location of an impedance discontinuity depends on having the correct velocity of propagation for the tested cable system. • Generally only detects significant localized corrosion. • There is no way to determine the cause of “bad” signal responses not related to neutral breaks.

One of the more important issues to note when performing TDR measurements is that the length reading on the TDR unit is related to the cable system conductor length and not the surface distance between the near and far ends of the system under test. This fact causes two challenges that are addressed in detail later in this chapter (see Section 11.6). The first challenge is related to the relationship between how the power cable system was laid underground and its impact for pinpointing an accessory or anomaly. The second is the error in the velocity of propagation, which directly affects the length readings and thus TDR trace interpretation results. An illustration for different power cable system layouts is shown in Figure 6.

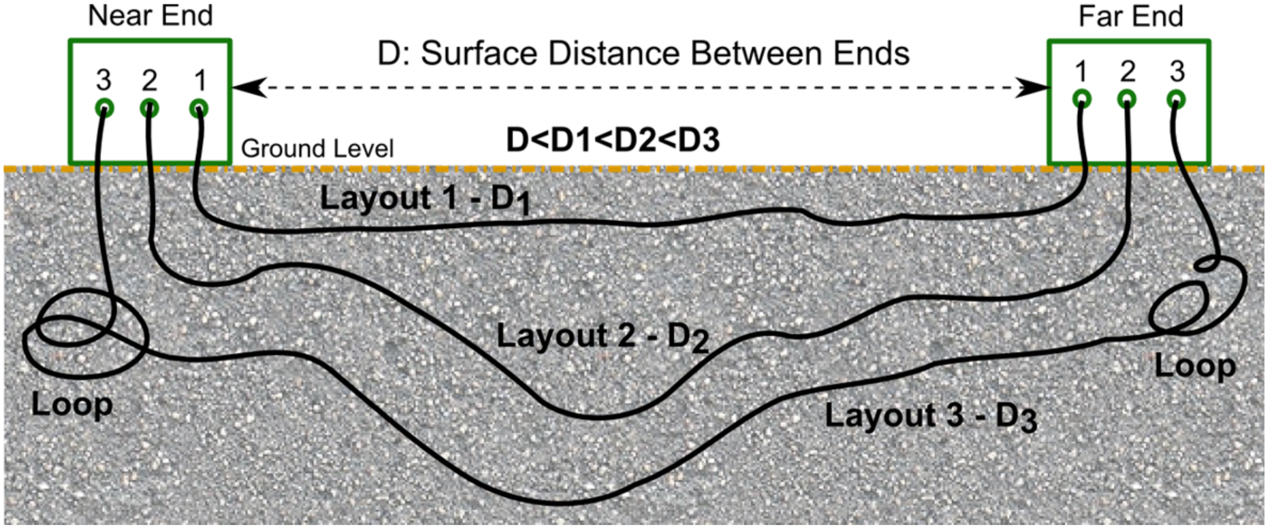


Figure 6: Illustration for Different Path Possibilities for Underground Cable Systems

As shown in Figure 6, there are different paths a cable segment can take between two devices such as transformers or switchgear. The route directly affects the ability of the operator to identify the location above ground. The relationship between the conductor lengths for all layouts (D_1, D_2, and D_3) and the surface distance separation between the ends (D) is also shown in Figure 6. Note that there are also extreme cases that could include loops in the cable system. Obviously, D3 is the worst case scenario since the cable is coiled at both ends.

As indicated, the selected velocity of propagation (VoP), which can be adjusted by the operator, directly affects the distance reading from the TDR and thus will also impact digging location. The VoP depends on the cable geometry and insulation material. Table 2 contains a number of **calculated** VoP's for different cable designs with nominal dimensions. The conductor size and insulation wall affect the VoP by 3-6% and up to 11%, respectively.

Table 2: VoP Guidelines for Different Cable Designs

Conductor Size/ Insulation	Class/ Insulation Thickness	Inductance		Capacitance		Characteristic Impedance Z_0 [Ω]	VoP[1] [%]
		mH/m	mH/ft	pF/m	pF/ft		
1/0[2] AWG XLPE[3]	15 kV/175 mils	171	56	211	69	28	55
	15 kV/220 mils	193	63	178	59	33	57
	25 kV/260 mils	211	69	159	52	36	58
	35 kV/345 mils	244	80	132	43	43	59
1/0[2] AWG EPR[4]	15 kV/175 mils	171	56	257	84	26	50
	15 kV/220 mils	193	63	217	71	30	51
	25 kV/260 mils	211	69	193	63	33	52
	35 kV/345 mils	244	80	160	52	39	53
1,000[2] MCM XLPE[3]	15 kV/175 mils	101	33	505	166	14	47
	15 kV/220 mils	112	37	414	136	16	49
	25 kV/260 mils	121	40	359	118	18	50
	35 kV/345 mils	140	46	284	93	22	53
1,000[2] MCM EPR[4]	15 kV/175 mils	101	33	615	202	13	42
	15 kV/220 mils	112	37	504	165	15	44
	25 kV/260 mils	121	40	437	143	17	46
	35 kV/345 mils	140	46	346	113	20	48

[1]: Velocity of propagation (50% ~ 0.5 ft/ns or 0.16 m/ns)
[2]: Compressed stranded round conductor
[3]: XLPE dielectric relative permittivity of 2.3
[4]: EPR dielectric relative permittivity of 2.8

11.3.2 AC Resistance (Ω-Check)

This test method involves measuring the ac resistance of a cable metallic shield (or neutral path) with or without isolating the cable from the service. The condition of the neutral under test is determined by comparing the estimated ac resistance to the resistance of a new neutral (calculated) of the same type.

This method is primarily used for concentric neutral cable systems where estimates of the neutral resistance have been made. Typically, these segments are installed between two padmount transformers or switching cubicles. However, the test method could also be used for overhead neutrals or shield wires.

The test system injects a 60 Hz current (0-30 A) through the neutral system between the two ends. A portion of injected current returns through the neutral that is being tested and the balance returns through other parallel paths. The device measures the current flowing in the neutral under test, the voltage drop across the neutral and the phase angle between them. It then calculates the resistance of the neutral using following equation.

$$R_n = \frac{V cos\theta}{I} \qquad \textbf{Equation 1}$$

Where:

R_n = Resistance of the neutral under test, Ohms
V = Voltage across the neutral, Volts
I = Current in the neutral, Amperes
θ = Phase angle between V and I, Degrees

In the case of an online test, the unbalanced current may be flowing in the neutral during the test. This current will add/subtract to the test current depending on the phase angles involved. In addition to measuring the resistance of the neutral, the theoretical resistance of a new neutral of the same type, size and length is used for comparison. The theoretical resistance of new neutral is calculated using Equation 2.

$$R_{ref} = \frac{R_s K_1 L}{n} \qquad \textbf{Equation 2}$$

Where:

R_{ref} = Resistance of a new neutral, Ohms
R_s = Resistance of one neutral strand per foot, Ohms
L = Length of the cable, feet
n = Total number of strands in the neutral
K_1 = Lay factor accounting for additional length of spiral neutral strand (the device assumes a lay factor of 1.1)

11.3.2.1 Field Application - Online Test

The main advantage of this method is that the test does not require an outage or switching. However, the operator is required to perform the test by making connections to the neutral system at each end as shown in Figure 7. The equipment requires 120 volts (60 Hz) power supply which typically is obtained from the secondary side of the transformer. For sites consisting of vaults and switching cubicles, the source power must be obtained remotely. The remote source may include a nearby distribution transformer, an exterior house receptacle or a vehicle mounted power inverter (about 2 kW). A portable generator can also be used, if available. During testing, the device continuously changes the polarity of the test current to account for any phase difference between the test current and unbalanced or stray currents that may be flowing in the neutral. However, the test results may be influenced by a source current that has significant harmonic contents. Power sources with clean sinusoidal waveforms are preferred.

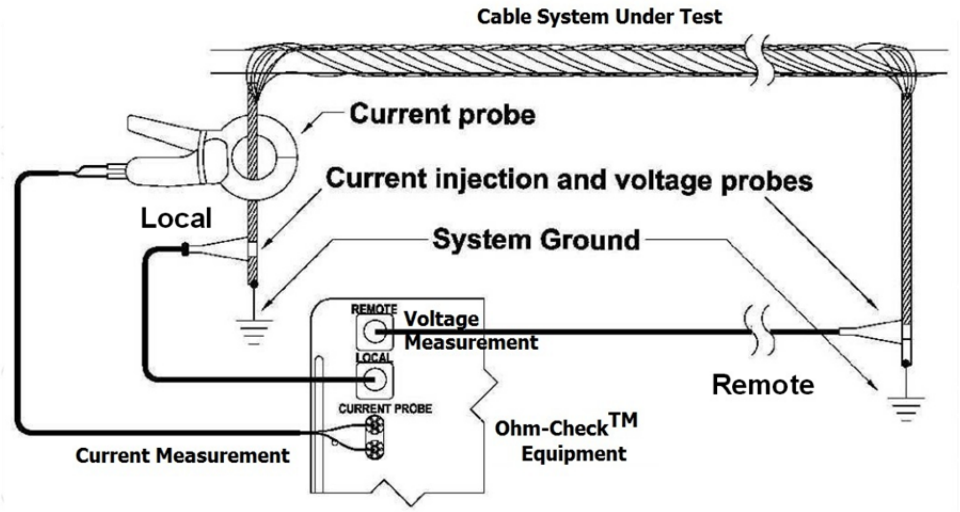


Figure 7: Ω-Check™ Connections for Online or Offline Testing

11.3.2.2 Field Application - Offline Test

For more accurate results, the Ω-Check test should be performed in offline mode. To perform the test in offline mode, the subject cable is disconnected at each end. The test current is injected in the loop formed by the cable conductor and the neutral under test. The main advantage of this application is that the operator does not have to lay the test leads along the cable span. The local and remote test leads from the device are connected only at one end as shown in Figure 8. At the other end the de-energized cable conductor and the neutral are tied together with a short, low-impedance conductor. During offline operation, the system neutral needs to be temporarily disconnected from the cable neutral at the local end (Figure 8). The disconnection of the neutral is not required if the system neutral dead ends on the opposite end of the cable segment.

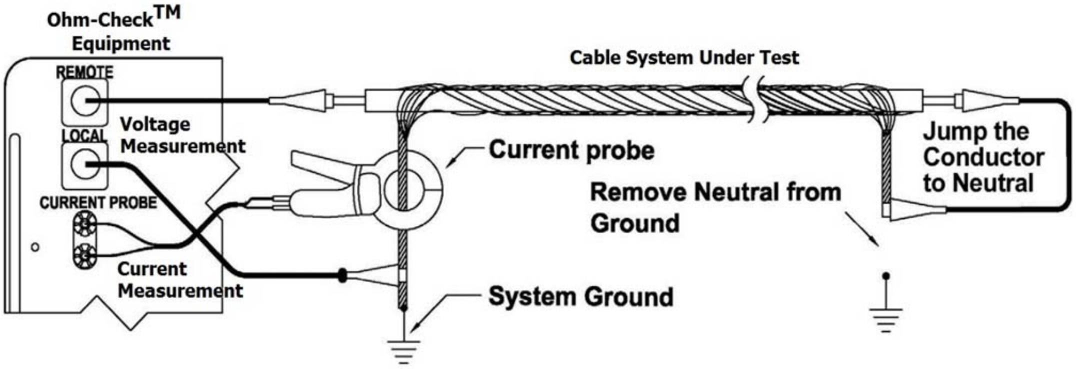


Figure 8: Ω-Check Connections for Offline Testing Using Conductor Back Path

After completing the test connections as shown in Figure 8, the operator turns on the machine and waits for the display to initialize. Unlike online operation, the only information that the operator keys in is the length of 100 ft in the place of span length. For the purpose of keying in, the information regarding neutral is not required. However, the information regarding neutral, cable conductor and cable length is required to compute various resistances external to **Ω**-Check device (see Equation 4).

The test consists of injecting the current in the loop made by the cable conductor and neutral and measuring the current, voltage and phase angle. The **Ω**-Check device then determines the total resistance of the loop as described by Equation Equation 3).

$$R_{n+c+t} = \frac{V\cos\theta}{I\left(\frac{L}{100}\right)}$$ **Equation 3**

Where:

R_{n+c+t} = Measured resistance of the loop (neutral + conductor + termination), Ohms
V = Loop voltage, Volts
I = Loop current, Amperes
θ = Phase angle between V and I, degrees
L = 100 feet

The resistance of neutral under test is externally calculated by using Equation 4).

$$\mathrm{R_n} = \mathrm{R_{n+c+t}} - \mathrm{R_c} - \mathrm{R_t}$$ **Equation 4**

Where:

R_n = Resistance of neutral under test, Ohms
R_c = Resistance of new cable conductor of the same type, size and length as the test conductor (from manufacturer's specifications), Ohms
R_t = Resistance of termination cable at the far end, Ohms (For short termination cable, this resistance can be ignored), Ohms

Other parameters such as the "resistance ratio" or the "% of neutral strands intact" can be determined by comparing against the resistance value of the new neutral wire of the same type and size from Equation 2). Overall advantages and disadvantages of **Ω**-Check techniques appear in Table 3.

Table 3: Overall Advantages and Disadvantages of Ω-Check Techniques

Ω-Check Online	
Advantages	• Specifically designed for metallic shield assessment. • Testing is easy to employ. • Test equipment is small. • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Results are numeric and easy to understand. • Easy to deploy, no expert operator required. • Neutral isolation not required. • Segment does not need to be de-energized for testing. • Detects a wide range of degradation due to corrosion as well as breaks in the neutral. • Immune to high frequency electrical noise on the neutral. • Presence of breaks can be clearly identified (but not located).
Disadvantages	• Requires running a cable to the far end of the tested segment, which can be a challenge for long segment lengths. • Requires an accurate segment length estimate. • The returning current lead and the metallic shield form a loop and thus induced currents may become impact the measurement. • Accurate knowledge of cable metallic shield design is required. • Reference database for neutral resistance is required. • Difficult to apply for metallic shields that are not concentric neutral wires. • Information of location of corrosion or break is not available.
Ω-Check Offline	
Advantages	• Specifically designed for metallic shield assessment. • Testing is easy to employ. • Test equipment is small and inexpensive. • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Numeric easy to understand results. • Easy to deploy no expert operator required. • No risk of failure during test. • Does not require running a cable to the far end of the tested segment. • Induced currents are generally not an issue, which can improve accuracy. • Detects a wide range of degradation due to corrosion as well as breaks in the neutral. • Immune to high frequency electrical noise. • Presence of breaks can be clearly identified (but not located).
Disadvantages	• Requires temporary neutral isolation at far end. • Long lengths are challenging because of long lead length and potential voltage drop issues as well as the uncertainty of the cable conductor resistance if using the cable conductor as the return path.

Table 3: Overall Advantages and Disadvantages of Ω-Check Techniques	
	• Requires an accurate segment length estimate. • Accurate knowledge of cable metallic shield design is required. Reference database is required. • Information of location of corrosion or break is not available. • Difficult to apply for metallic shields that are not concentric neutral wires.
Both Ω-Check Online & Offline	
Open Issues	• Impact of splices and connectors on measurements difficult to establish. • Impact of induced currents for offline procedure is unknown. • Exact lay lengths are generally unknown. • Applicability to EHV, HV including subsea cable systems and armor evaluation is not verified.

11.4 Success Criteria

11.4.1 TDR

Typically, a TDR sends a narrow pulse (2 ns in duration) of approximately 20 V down the cable. Localized changes in impedance like those that would appear because of corroded neutral wires, reflect energy back to the TDR and they appear as positive peaks on the graphical display where corrosion or open neutral conditions exist. A decrease in impedance, below 50 Ω, will cause a negative reflection. After a pulse passes several imperfections it may lose a significant portion of its energy dues to reflection. In this case, a wider pulse (10 ns) must be sent. However, the shorter pulse widths give much cleaner reflections and minimize the blind spot at the near end while the longer pulse widths are able to travel greater distances. On-screen cursors can be adjusted so that the TDR can display the distance along the conductor to the area of interest.

IEEE 1617 – 2007, IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables, addresses TDR testing and adopts a severity approach where the most severe degradation of signal occurs for increasing loss of neutral. The severity of neutral corrosion is divided into four levels. These levels are determined by comparing the peak of the anomaly reflection (+ve) with the far end reflection and any joints in the cable system. There is an implied requirement that a joint should be present in the span. The corrosion levels and how they are defined within IEEE 1617 are listed below:

- **Level-I:** 0%-25% neutral corroded, peak is too small to be recognized.
- **Level-II:** 25%-50% neutral corroded, the +ve peak is less than the splice.
- **Level-III:** 50%-75% neutral corroded, the +ve peak is larger than the splice and smaller than the cable end.
- **Level-IV:** 75%-100% neutral corroded, the +ve peak is larger than magnitude of the reflection at a discontinuity is calculated as the reflection coefficient or ρ. It is calculated as:

$$\rho = \frac{Z_d - Z_o}{Z_d + Z_o}$$ **Equation 5**

Where:

Z_o is the characteristic impedance of the cable and
Z_d is the impedance of a discontinuity.

The value of ρ ranges from 1 (open circuit) to -1 (short circuit). A reflection coefficient of zero indicates there is no reflection. This can only occur if there is no change in impedance. Thus, for the bulk of a cable system, the reflection coefficient is zero along the length since the pulse propagates down the cable with uniform impedance. This process continues along the full length unless there is a change caused by an accessory or neutral discontinuity.

TDR units can generate pulses as much as 100's of microseconds wide or as narrow as 1 nanosecond. For neutral assessment, the pulse width should be as narrow as possible to gain the best spatial resolution while still enabling the pulse to traverse the full circuit length.

11.4.2 Ω-Check

The resistance measured by the Ω-Check device is compared to the theoretical resistance of a new neutral (see Equation 2). This comparison is made available to the user in terms of "resistance ratio, R_n / R_{ref}" or in terms of "% of strands remaining intact" as shown in Equation 6.

$$\%\ \boldsymbol{of\ Strands\ Remaining\ Intact} = \left(\frac{R_{ref}}{R_n}\right)100$$ **Equation 6**

Once the condition of the neutral is determined, a decision to replace the cable can be made on the basis of pre-determined replacement criteria established by the user. Although the cable replacement criteria can vary from one utility to another, it is generally based on short circuit and/or steady-state performance of corroded neutrals. A typical threshold value for replacement used by utilities and cable rejuvenation providers is 50% or less of strands remaining intact.

11.5 Estimated Accuracy

Estimated accuracies are established by comparing test results with actual findings. Therefore, it is not possible to establish accuracies for TDR and Ω-Check as tools to assess the condition of the metallic shield of cable systems. Some of the more important reasons are as follows:

- The amount of TDR and Ω-Check data available is extensive; however, in most cases no follow up is undertaken to determine what in fact happened to these systems.
- TDR and Ω-Check results are not provided in pass/fail terms, but rather as general information concerning the tested cable system.
- When a cable system failure occurs, little or no attention is given to the system's previous

testing or performance history and thus the information and correlation with test data are lost.

11.6 *CDFI* Perspective

Much of the research work within *CDFI* was focused on assessing the condition of the cable system dielectric. However, as the analysis/testing proceeded, it became increasingly clear that the metallic shield impacts diagnostic measurements on the dielectric. As discussed, both the TDR and Ω-Check methods are used for assessing cable metallic shields and like the other diagnostic techniques, they are not without their deployment challenges. The following sections discuss some of these issues.

11.6.1 TDR Based Neutral Assessment

The TDR assessment method involves equipment and set up issues that were not necessarily critical when TDR was only used to identify joints and cable lengths. Figure 9 shows a TDR and impedance grading coupler (left side of Figure 9) that is often used in the field for performing cable metallic shield (neutral) assessment. This figure also shows the commonly supplied TDR leads and their connections. The goal of this arrangement is to inject the “cleanest” signal possible while using a very narrow pulse. Unfortunately, the connection of the TDR unit to the cable system requires great care if meaningful results are to be obtained. Figure 9 shows two connections options. The first utilizes standard leads (right side of Figure 9) while the second is the impedance coupler (left side of Figure 9)

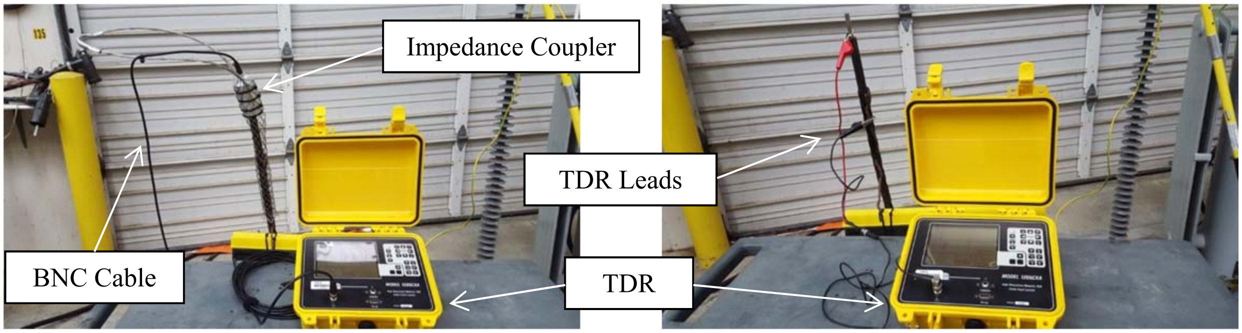


Figure 9: TDR Connections – BNC & Impedance Coupler (left) and BNC & Leads (right)

The impedance grading coupler shown in Figure 9 significantly reduces the magnitude of the reflection resulting from the connection of the TDR to the cable. It is important to note for this device to work on a cable system with elbows, at least one elbow must be removed. This coupler could be used with an indoor or outdoor termination left in place, although the results presented below are for the case of an elbow that is removed. Figure 10 shows an example of signal injection with a TDR with (----) and without (▬) impedance grading. Clearly the large reflection at the connection point is virtually eliminated when impedance grading is employed. As a result, more energy is transmitted to the cable system.

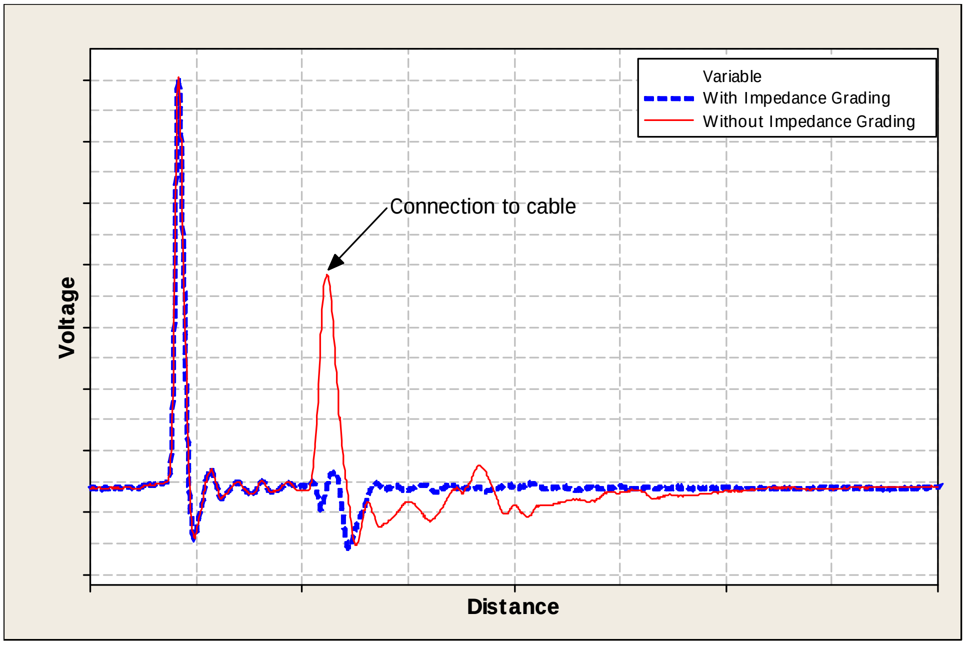


Figure 10: TDR Traces with and without Impedance Grading

By interpreting apparent noise and the reflections in a TDR trace, a trained operator can provide a qualitative assessment of the amount of neutral corrosion and its location within a circuit. The apparent noise on the trace is typically indicates uniform neutral corrosion while the reflections are indications of significant localized neutral corrosion or neutral breaks. As an illustration, Figure 11 shows examples of the types of signals that may be seen in a TDR trace for both uniform and localized corrosion.

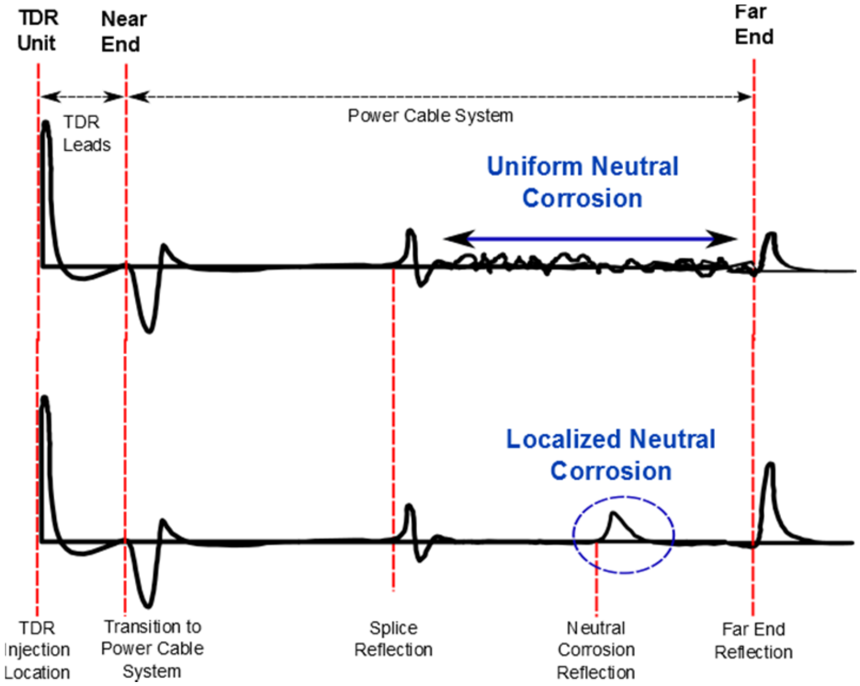
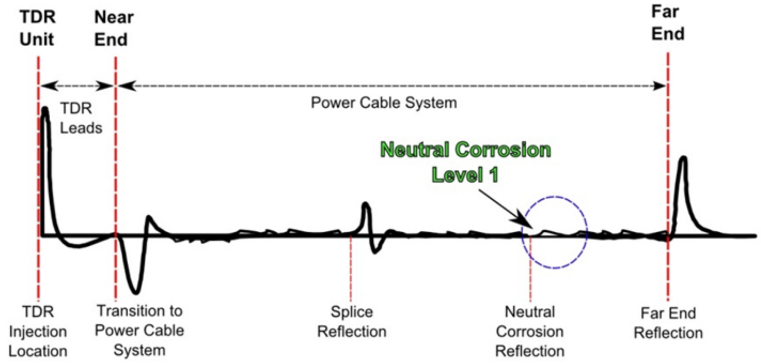
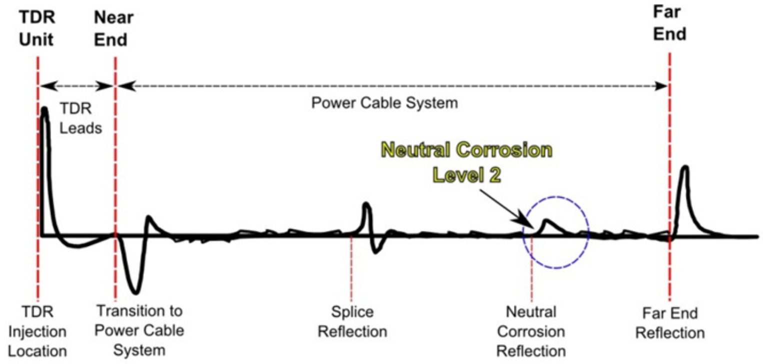


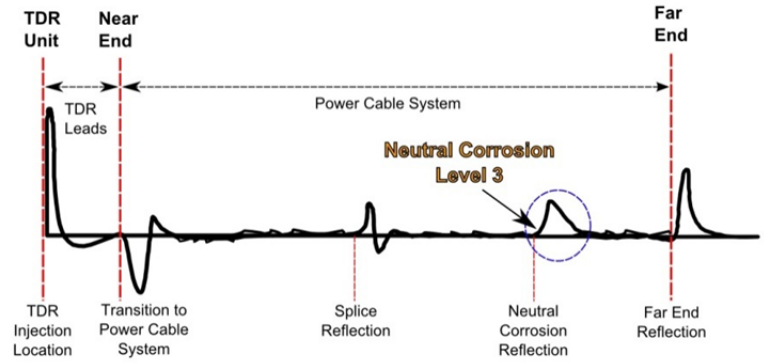
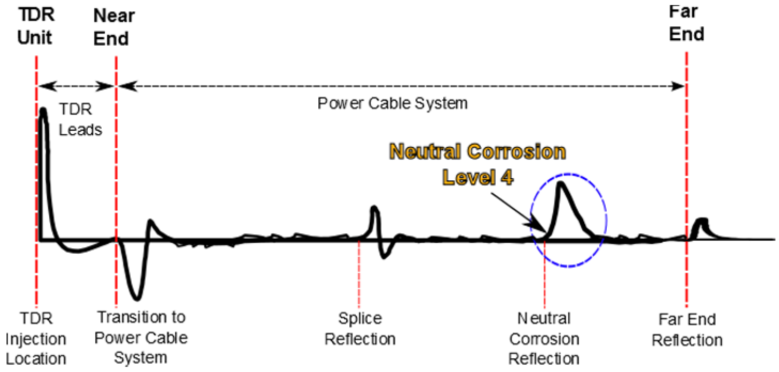
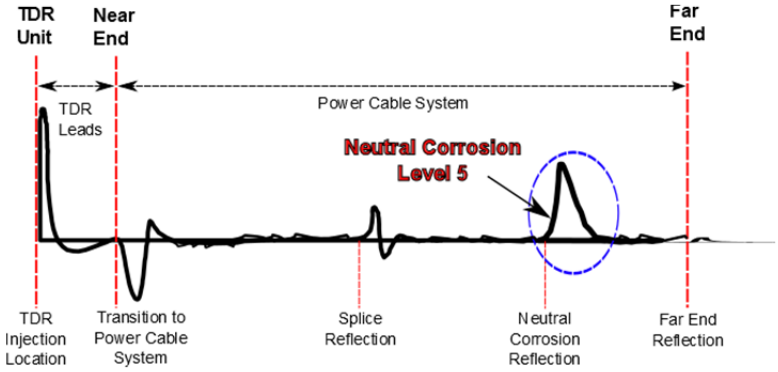
Figure 11: TDR Trace Showing Uniform and Localized Neutral Corrosion

Observe also in Figure 11 that uniform neutral corrosion causes high noise levels in the trace and so the amplitude resolution decreases since smaller reflections cannot be seen in the trace. The noise has the added side effect of reducing the pulse energy such that the far end reflection itself is also lower in amplitude and could be difficult to distinguish from the noise. In the field, both issues could be present in a cable system and one could dominate the other. It is up to the skilled operator to reach a neutral condition assessment.

IEEE 1617 describes how the relative heights of the "bumps" (reflections) in the TDR trace coming from localized neutral issues may be used to assign a condition level to the neutral under test. Instead of expressing the level of corrosion in terms of the percentage of the remaining neutral, IEEE 1617 uses the percentage of wires broken or percent neutral loss. Four levels are considered; however, given the levels, the guide does not provide a prognosis. Guidelines are shown in Table 4. It is unclear in the guide how the correlation of these heights to different degrees of neutral loss was determined.

Table 4: Summary of IEEE Std. 1617 – 2007 Metallic Shield TDR Assessment Levels

Wires Broken	Condition	Illustrated from Assertions in IEEE Std. 1617 – 2007
Level 1 - No recognizable reflections		
0 – 25%	**Good (<< splice reflection)**	
Level 2 – Recognizable reflection but smaller than a splice		
25 – 50%	≤ splice reflection	

<table>
<tr><th colspan="3">Table 4: Summary of IEEE Std. 1617 – 2007 Metallic Shield TDR Assessment Levels</th></tr>
<tr><th>Wires Broken</th><th>Condition</th><th>Illustrated from Assertions in IEEE Std. 1617 – 2007</th></tr>
<tr><td colspan="3">Level 3 – Reflection larger than a splice but smaller than the end of the cable</td></tr>
<tr><td>50 – 75%</td><td>> splice reflection
< end reflection</td><td> </td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Level 4 – Reflection larger than the end of cable reflection</td></tr>
<tr><td>75 – 99%</td><td>> end reflection</td><td> </td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Level 5 – Far end reflection location closer than expected§</td></tr>
<tr><td>100%</td><td>**Bad**</td><td> </td></tr>
<tr><td colspan="3">§ - Not presently described in IEEE Std. 1617 – 2007</td></tr>
</table>

A number of issues exist that are believed to limit the usefulness of the guidelines shown in Table 4:

- Not all cable segments have splice locations that can be used as a reference; guidelines

should be established in order to handle such cases.
- Distance from the TDR unit affects the amplitude of the received reflection – a splice located far away creates a lower amplitude reflection than an identical splice located near the sending end.
- Signal amplitudes depend on several factors – system length, pulse injection method, pulse width, and number of splice locations.

11.6.3 TDR Experimentation at NEETRAC

A 400 ft length of 15 kV XLPE insulated, jacketed cable with six metallic shield wires was modified with switches (two locations approximately 50 ft apart) on each neutral wire so that the effect of different neutral loss conditions could be observed with a TDR. Figure 12 shows one of the locations with the switches in place.

Figure 12: Cable Segment with Switches on Each Neutral Wire

The following figures show measurements that were completed using an impedance grading device as shown in Figure 9. Figure 13 shows the TDR trace for the entire segment with the location of the switch box. The “near end” or injection point is shown on the left while the “far end” is shown in the right of Figure 13. All switches were closed (all neutral wires intact) in this figure.

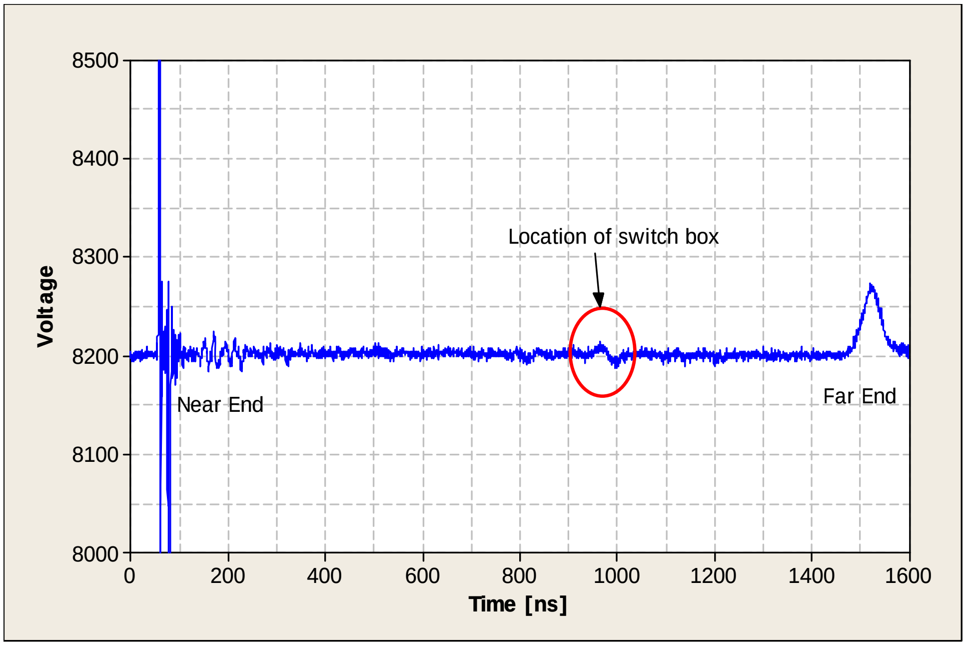


Figure 13: TDR Trace of Full Cable Segment

As switches are opened in the switch box, the size of the reflection generated at switch location increases while the far end reflection decreases in size because more energy is reflected at the switch box location. Figure 14 shows an enhanced view of the TDR trace at the switch box location for different percentages of remaining neutral (66%, 50%, and 17%).

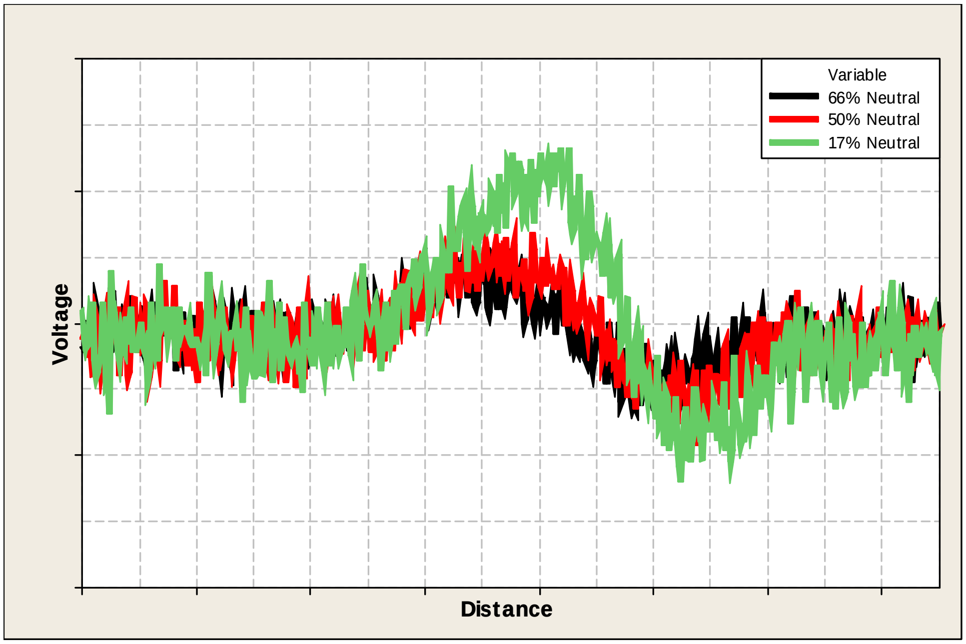


Figure 14: Reflections Resulting from Different Levels of Remaining Neutral for One Cable System (Less Neutral = Larger Reflection)

As Figure 14 and Figure 15 illustrate, the difference between 66% and 50% remaining neutral is difficult to distinguish. However, with only 17% remaining neutral, the difference is quite large as compared to the other two cases. A similar effect can be seen at the far end except the far end reflection reduces as more neutral wires are switched out.

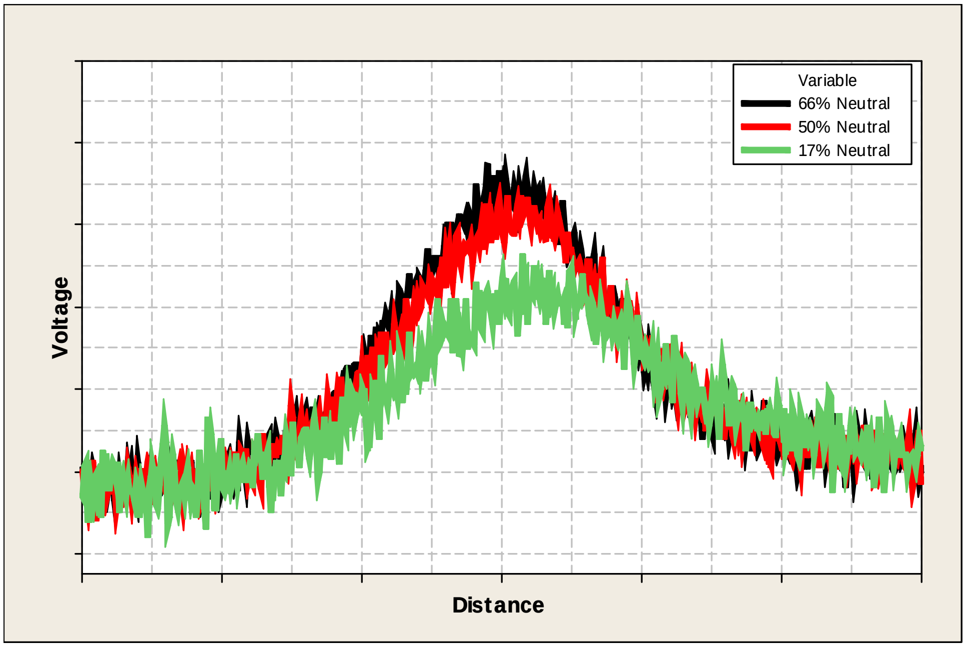


Figure 15: Far End Reflections Resulting from Different Levels of Remaining Neutral for One Cable System (Less Neutral = Smaller Reflection)

As the above figures illustrate, it is possible to see reflections at locations where the metallic shield is, in this case, discontinuous. However, the locations of the switches were known and so it was clear where to look for the changes. This situation would not occur in the field so one must be cautious to keep the above findings in context.

11.6.4 AC Resistance-Based Neutral Assessment

It is estimated that over 1.5 million feet of cable has been assessed using the Ω-Check approach. This approach, however, is not without its own challenges as the test leads must be laid along the segment length if an online test is to be performed (Figure 7). At times, this task can be difficult, particularly for longer spans and for the spans where leads cross the roads. Additionally, there are factors that may influence the accuracy of the test results particularly when the test leads are spread out to connect across the neutral span. A number of such issues exist and are discussed below.

11.6.4.1 Online or Offline Testing

Lay Factor, K_1

The lay factor constant of 1.1 in Equation 2 accounts for the additional length of the neutral strands due to spiraled application of the neutral wires over the cable. For most applications, this factor may range from 1.05 to 1.13, causing some error in the computation of the resistance of a good neutral. In other neutral designs, the lay factor does not apply since longitudinally corrugated tape (LCT) shields (when in good condition) form essentially continuous tubes with corrugations around the cable core. As a result, care must be taken when using Ω-Check to determine the remaining metallic shield since there are no base numbers for the newer shield designs.

Cable Length, L

Similar to the lay factor constant, the length of the cable being tested is used in Equation Equation 2) to compute the resistance of the new neutral for comparison to the measured results. This length should be determined as accurately as possible, though it is often impossible to know precisely the cable route.

Some of the methods used for measurement of length include:

1. installation records, if available;
2. visual inspection of drawings (allow for additional length at each termination);
3. measuring Wheel (allow for additional length at each termination);
4. laser and ultrasonic distance finder (straight line only, allow for additional length at each termination); and
5. Time-Domain Reflectometry.

11.6.4.2 Online Testing

As shown in Figure 7, the online testing requires spreading and connecting the test leads along the cable segment. In some cases, this task is time consuming, especially for longer spans or where the area between the two padmount transformers or switchgear is difficult to access.

Unbalanced Current in the Neutral

Sometimes there is current flowing in the neutral being tested due to unbalanced phase currents (in the case of three phase systems), neutral return current (in the case of single phase systems) and possible stray currents. To minimize the influence of current in the neutral on the measurement, the Ω-Check device may reverse the polarity of the test current and averages the measured current and voltage.

Induced Voltage on Voltage Measuring Lead

During online testing, the current carrying lead and voltage measuring lead run together between the measurement locations. The magnetic loop made by the neutral and the current carrying lead induces voltage on the voltage measuring lead, which may influence the voltage measured across the neutral. Experience has shown that the induced voltage influence on the voltage measuring lead is typically subtractive, indicating somewhat less degraded neutral than actually exists. This could potentially lead to an overly optimistic assessment. To minimize this effect, the test leads should be kept as close to the cable as practical.

11.6.4.3 Offline Testing

Offline tests can be carried out if the cable segment can be de-energized. This helps to alleviate some of the known sources of “interference” as described above.

11.6.5 Comparison of TDR and Ω-Check Data

TDR and Ω-Check data were collated as part of the research work in *CDFI Phase II*. The goal of this analysis was to determine the differences and similarities between these two techniques from the assessment perspective. Both techniques seek to measure/assess the same cable “illness”, but data comparing the two techniques is not available in the literature.

Figure 16 shows the cumulative distribution functions (CDF’s) of remaining neutral for all collated data during the *CDFI* from cable circuits assessed in North America. The TDR assessments were performed according to the conventions in IEEE 1617 – 2007 and are, by definition, based on discrete condition levels (level-based). These levels correspond to different neutral loss ranges and are primarily for unjacketed MV cable systems.

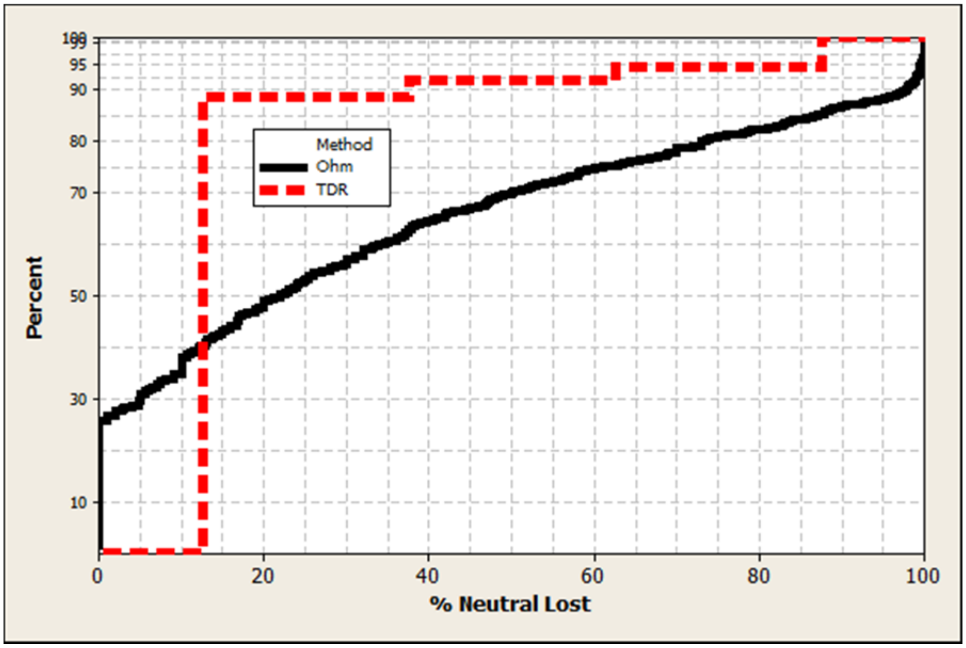


Figure 16: Cumulative Distributions of Ω-Check and TDR Neutral Loss Data [14]

As Figure 16 shows, the data from Ω-Check measurements form a smooth curve since these data are numeric in nature rather than level-based as discussed above. It is useful to compare percentiles as the Ω-Check data appear to paint a more pessimistic picture of the condition of cable neutrals throughout North America. Table 5 shows a comparison of the cumulative distribution percentiles for Ω-Check and TDR. Clearly, there are some significant differences between the estimated neutral loss for the two methods.

Table 5: Comparison of Distribution Percentiles from Figure 16

Neutral Loss [%]	Remaining Neutral [%]	Ω-Check Cum. Percentile [%]	TDR Cum. Percentile [%]
0	100	27	-
< 25	> 75	53	88
< 50	> 50	70	91
< 75	> 25	82	94

As neutral degradation is generally an aging phenomenon, it is worth examining the neutral loss data as a function of cable system age. Figure 17 shows the cumulative distributions for different age classes (top) as well as the corresponding age distribution for circuits with 25% or less remaining neutral (bottom).

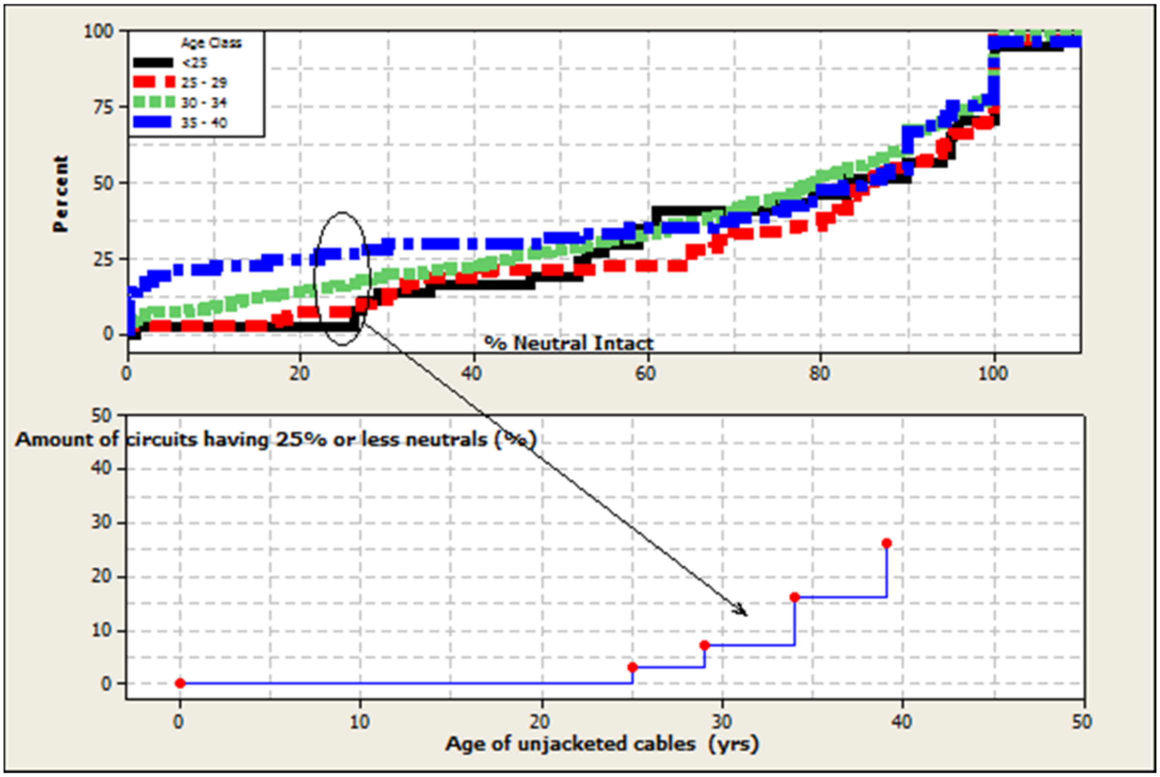


Figure 17: Neutral Integrity as Function of Cable System Age Using Ω-Check Data

Figure 17 illustrates that as unjacketed cable systems approach 35-40 years in service, the likelihood of finding significant neutral corrosion increases significantly. In the case of systems younger than 25 years, the data indicate that none have less than 25% remaining neutral. On the other hand, for systems approaching 40 years of age, there is a 25% chance that an individual segment will have 25% or less remaining neutral.

The industry has tended to refer to 50% loss as a critical threshold for replacement as various safety related issues can arise with additional degradation. Assuming the 50% threshold then for Pass and Not Pass the data in Figure 17 can be re-analyzed. Figure 18 shows the results of re-interpreting the data from Figure 17. This figure shows that systems less than 32 years of age are unlikely to have less than 50% remaining neutral. That percentage increases quite sharply as these cable systems approach 40 years of age – approximately 50% have 50% or less remaining neutral. It is important to note that the data are quite sparse in this age region as most 40 year and older cable systems have been replaced with newer jacketed systems.

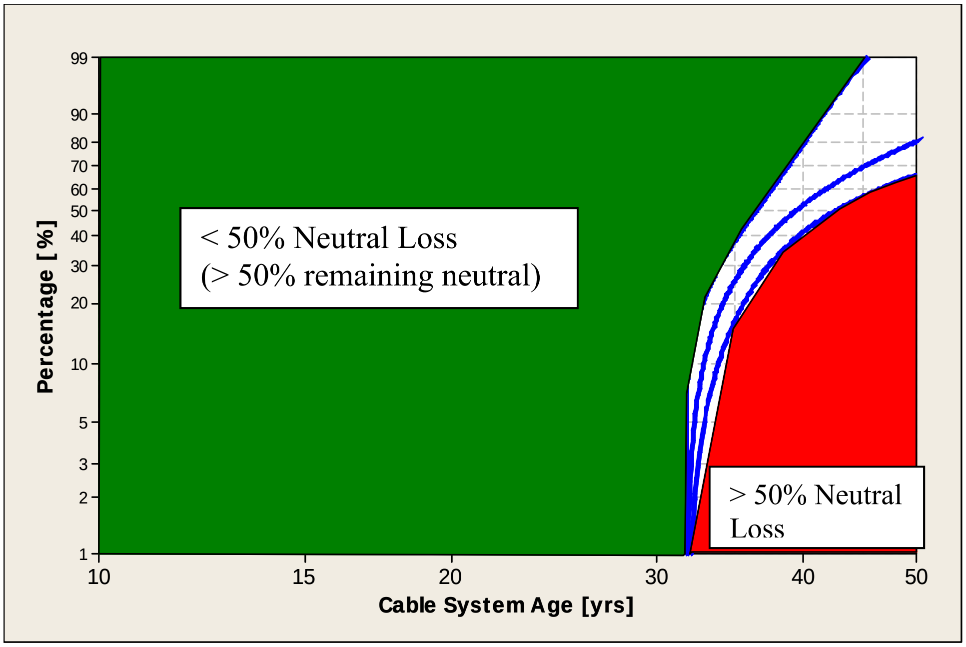


Figure 18: Cable System Neutral Life Expectancy for Full Neutral Cable Systems

Additional Comments

The above use of the 50% remaining neutral (or 50% neutral loss) criterion is commonly used within the industry. The origin of this criterion is not known. It likely evolved as an expedient level from the experience of practitioners for establishing a pass/fail condition assessment for neutral loss. The fact that many unjacketed cables had substantial neutrals with a conductance that was equal to the conductance of the cable conductor (full neutral) also contributed to the choice of 50%. In at least the last 20 years, there has been a move within the industry to reduce the cross sectional area of the metallic shield to reduce circulating current losses, lower cable cost, and enhance the thermal/ampacity performance of the cable. Today's cables may have, when new, as little as a "1/6 neutral" on each phase of a triplex jacketed cable (50% neutral when combined).

This observation presents utility engineers with several questions that currently remain unanswered for the cable system life, chief among them being: *What level of neutral loss should utilities consider as critical for cable systems with "reduced neutral" designs?* In other words: *Is 50% loss for a 1/6 neutral an appropriate threshold?*

The question identified above cannot be addressed with the currently available field data. The vast majority of neutral assessments are not performed on jacketed systems as these systems are believed to have very limited if any corrosion. Although there is some evidence that neutral corrosion can occur on some cable designs, implying that the industry will ultimately need to establish threshold limits based on solid, engineering principals, rather simple expedience.

11.7 Outstanding Issues

11.7.1 TDR

There are a number of outstanding issues for the TDR assessment of metallic shields. These are discussed below.

11.7.1.1 TDR Leads

When using TDR, it is always advisable to be consistent with the TDR leads. When the TDR leads are simply a pair of wires attached to the unit, there is variability in the measurement since the capacitance between leads changes according to how they are placed for the test (see Figure 9). Therefore, using a BNC cable with leads (right side of Figure 9) that are as short as possible is advisable whenever an impedance coupler (left side of Figure 9) is not available.

Another issue for the TDR leads is their length. If short leads are used, the ringing effect at the near end of the cable system might make this portion blurry. The location of the near end is important for accurate location/pinpointing of accessory and anomalies. To overcome this issue and always have a clear position for the near end on the TDR trace, the use of long (15 ft – 50 ft) coaxial (BNC) leads is recommended. In field tests, a length of 30 ft or more has proven useful for achieving a clear near-end signal. Once this length is chosen, it should be used for all tests. Figure 19 shows an illustration for comparing the use of short and long TDR leads.

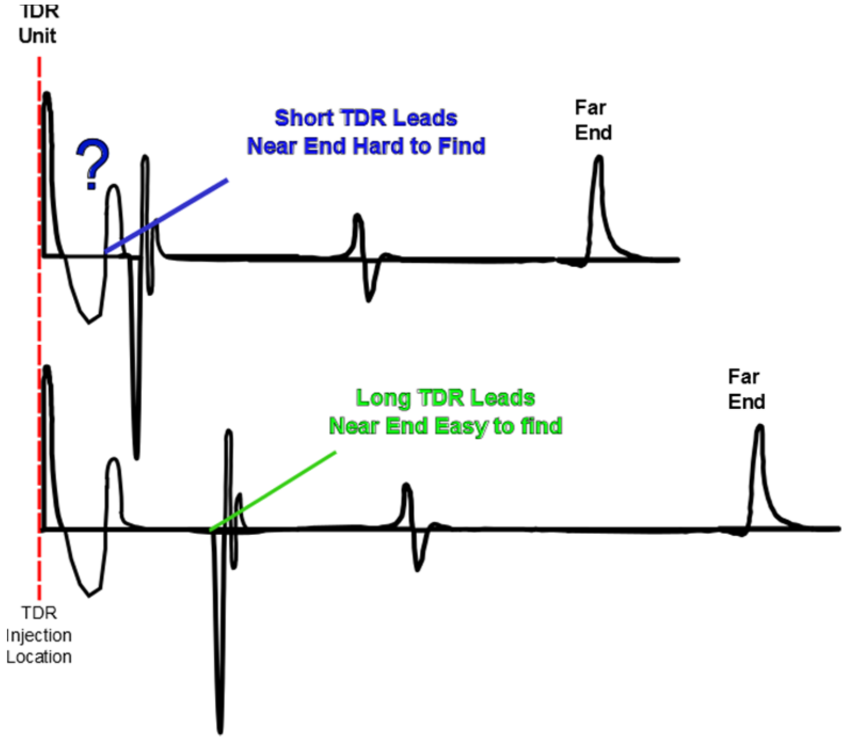


Figure 19: Illustration for Comparing the Use of Short and Long TDR leads

11.7.1.2 Identifying the Far End

Of equal importance to locating the near-end on the TDR trace is the ability to identify the far-end of the cable system. If there is a doubt, comparing TDR traces for the far end grounded and then ungrounded is a useful method. The grounding and ungrounding of the far end produces a polarity reversal for the far-end reflection without affecting any of the other reflections along the cable system. This technique is illustrated in Figure 20 where a comparison between TDR traces for the same cable system for grounded and ungrounded set ups at the far end.

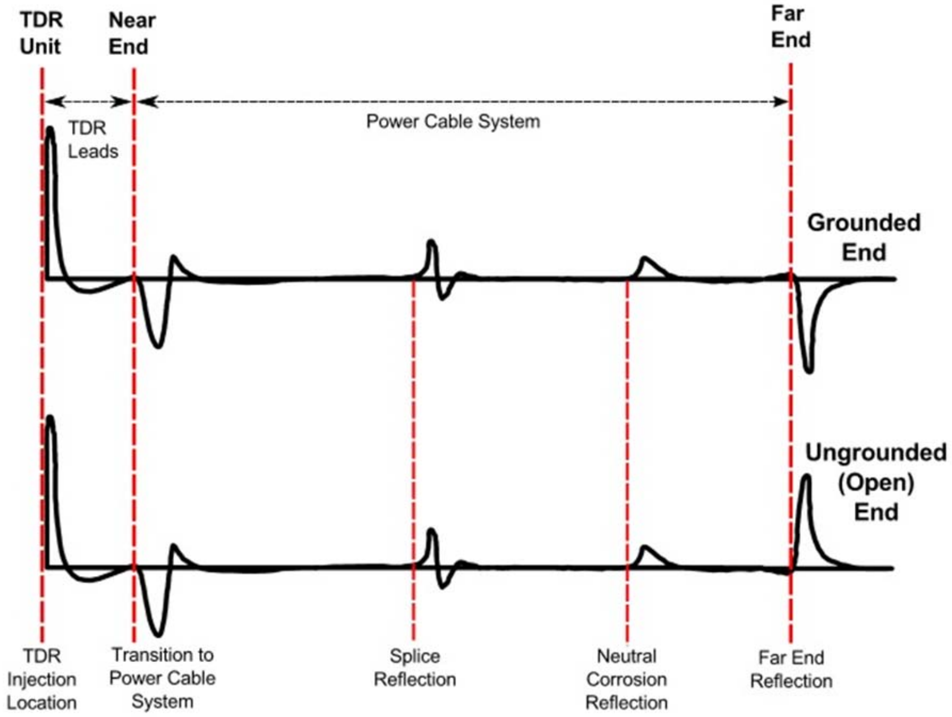


Figure 20: Comparison between TDR Traces for the Same Cable System for Grounded and Ungrounded Far End.

11.7.1.3 TDR "Ghost" Reflections

Even though TDR is a useful tool for diagnosing potential cable system problems, there are some issues when interpreting the TDR trace. One of the key issues is the potential for reflections of reflections (otherwise known as "ghost" reflections) to occur in systems with multiple joints. This can also occur in systems with a single joint located close to the near end of the system.

"Ghost" reflections are signatures that appear on the TDR trace that do not correspond to any actual joint or anomaly present in the system. They are the result of the reflected and re-reflected TDR pulses travelling along the system in both directions, i.e. from near to far end and vice versa. The TDR "ghost" reflections are a function of three variables:

1) the location of joints or anomalies;
2) the number of joints or anomalies; and

3) the difference in characteristic impedance between the joints and cable.

There are a large number of potential situations that could create "ghost" reflections, so it is impossible to cover and understand all of cases. However, an understanding of TDR ghost reflections can be attained through the analysis of basic case studies. This knowledge should lead to improved interpretation in real field scenarios. Six case studies are presented below (see Table 6):

Case 1: Cable system with no splices or anomalies.
Case 2: Cable system with one splice located farther than 50% of the cable system length as measured from the near end.
Case 3: Cable system with one splice located at the exact midpoint of the cable system length.
Case 4: Cable system with one splice located between the near end and midpoint of power cable system length.
Case 5: Cable system with two splices located at arbitrary positions.
Case 6: Cable system with two splices located at arbitrary positions but includes the use of impedance coupling at the near end.

Keeping track of the TDR pulse reflections as they travel back and forth in the cable system is tedious. However, this analysis can be accomplished graphically using bounce diagrams. The bounce diagram is a graphical analysis technique that greatly simplifies the analysis of transients on a "transmission" line and thus provides a tremendous amount of clarity regarding how transients are perceived at any point in the system. (Note that in this case, a "transmission" line is a model for a distributed impedance network that is used to characterize the propagation or transmission properties of signals and not a high voltage power line.) In other words, the bounce diagram provides a pictorial tool showing clearly how incident TDR pulses reflect, transmit, and combine along the length of the cable system over time. To draw a bounce diagram for these different pulses a series of parameters must be considered including:

- The characteristic impedance of the cable used in the cable system.
- Knowledge of the reflection coefficients at the cable system ends, joint, and anomaly locations.
- Number of expected joints in the cable system.
- Expected length of the cable system.

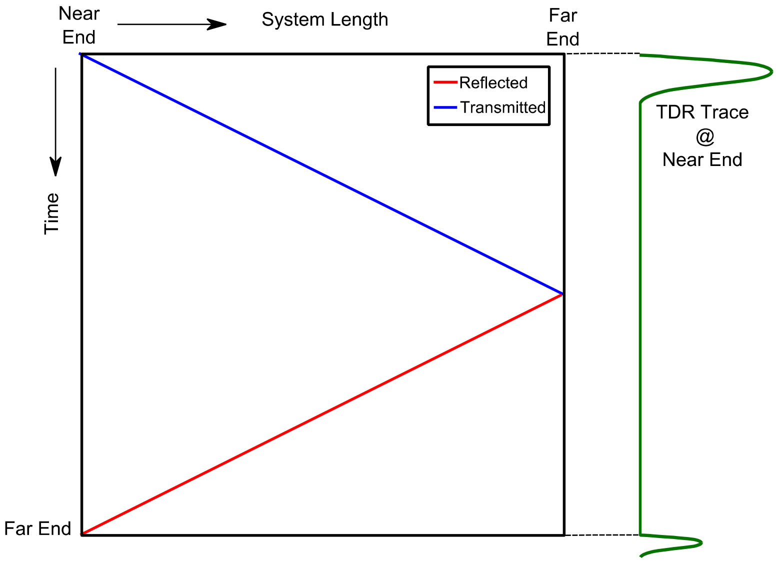
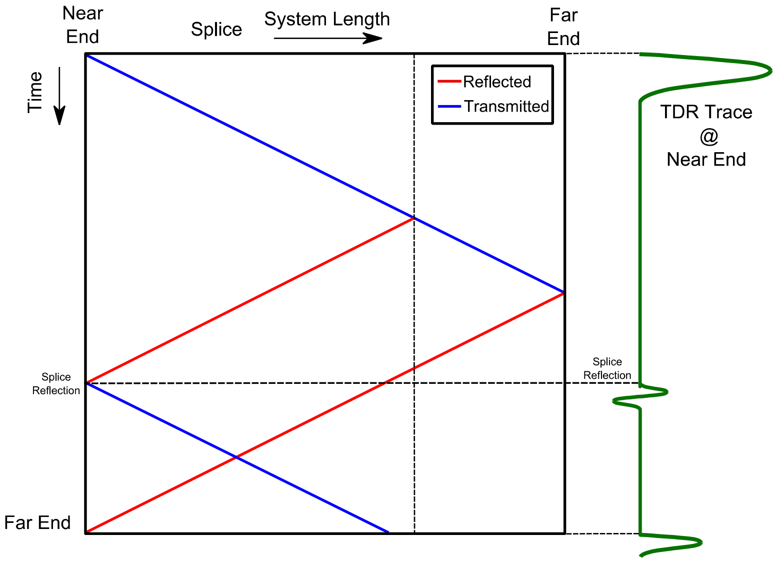
The bounce diagram has the following basic structure:

- X-axis represents the position along the cable system.
- Y-axis represents the elapsed time from the initial injected TDR pulse at the near end.
- Near end is shown on the left side, whereas the far end is shown on the right side of the bounce diagram.
- The initial injected TDR pulse starts at X=0 (near end position) and Y=0 (time zero), and travels to the far end.
- Slopes/gradients represent the velocity of propagation of the TDR pulses through the system; lower gradients equal higher propagation velocities.

Using the above structure and knowledge of the cable system, the following observations generally hold:

- The first reflected TDR pulse occurs at the first joint or anomaly that produces a change on the cable characteristic impedance.
- The amplitudes of the reflected and transmitted TDR pulses decrease as they travel due to the attenuation and dispersion phenomena.
- The TDR trace as seen in the near end can be determined from the bounce diagram by following the vertical line that goes through X=0 (near end position).

The case studies, their corresponding bounce diagram and TDR traces appear in Table 6.

<table>
<tr><th colspan="2">Table 6: Illustrative Case Studies for TDR “Ghost” Reflections</th></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Case 1: Cable System with no Splices or Anomalies</td></tr>
<tr><td>• No TDR “Ghost” reflections observed.</td><td>
</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Case 2: Cable System with One Splice Located Farther than the 50% of the Power Cable System Length as Measured from the Near End</td></tr>
<tr><td>• No TDR “Ghost” reflections observed before the far end reflection.
• “Ghost” reflections arrive after far end reflection and are ignored.</td><td>
</td></tr>
<tr><td colspan="2"></td></tr>
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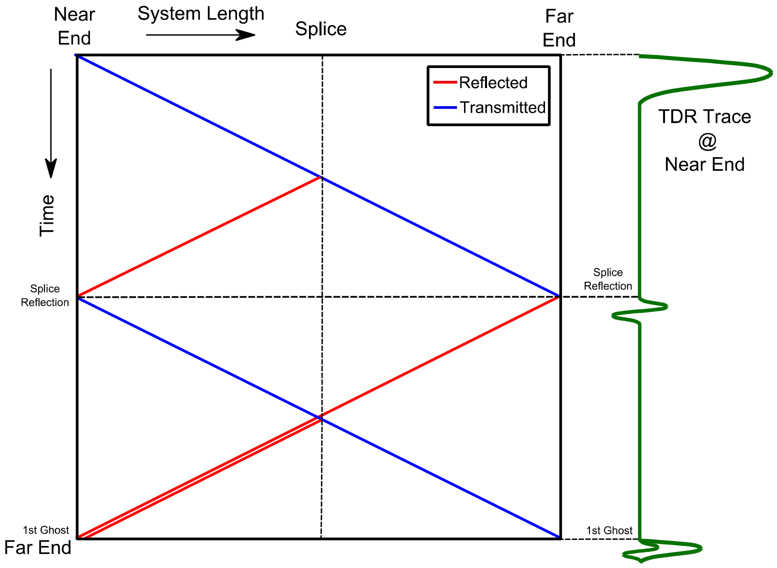
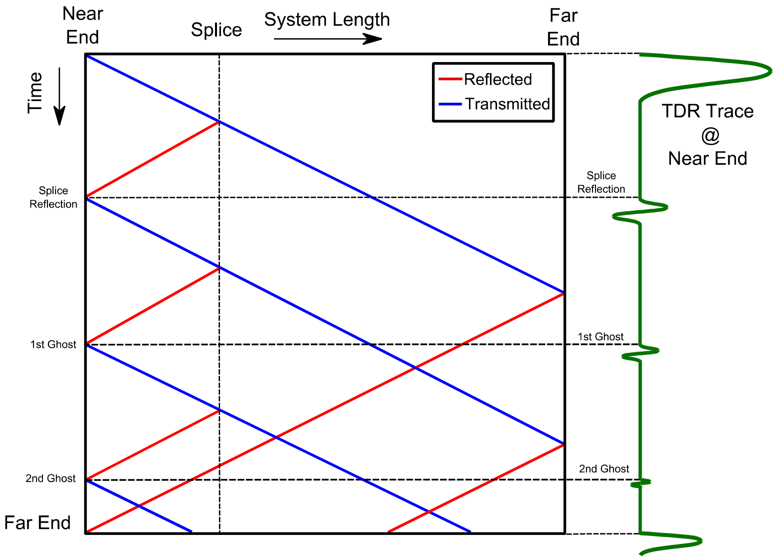
Case 3: Cable System with One Splice Located at the Exact Midpoint of the Power Cable System Length

- No TDR "Ghost" reflections observed before the far end reflection.
- Critical location for splices or anomalies for not having "Ghosts."
- First splice "Ghost" superimposes the far end reflection.



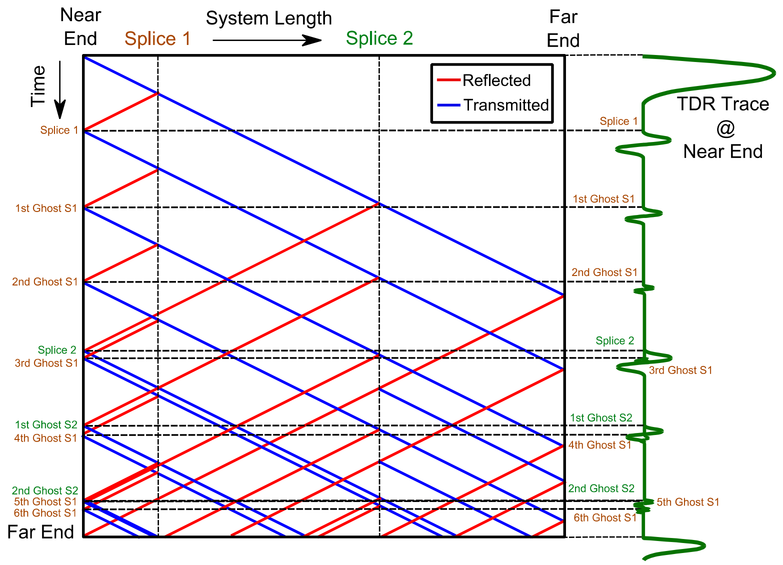
Case 4: Cable System with One Splice Located between the Near End and the Midpoint of the Power Cable System Length

- At least one TDR "Ghost" reflection observed before the far end reflection.
- Generally easy to interpret taking into account the attenuation and dispersion.



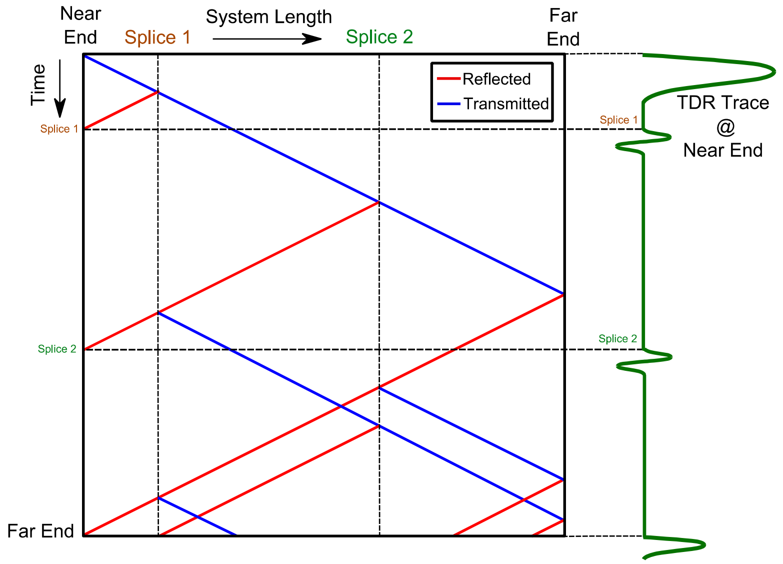
Case 5: Cable System with Two Splices Located at Arbitrary Positions

- At least one TDR "Ghost" reflection observed
- Generally challenging to interpret even by taking into account the attenuation and dispersion



Case 6: Same as Case 5 Considering the Use of Impedance Coupling at Near End

- All TDR pulse reflections are absorbed at the near end.
- No "Ghosts" are observed on the TDR trace before far end reflection.
- The presence of "Ghosts" is still possible depending on splice/anomaly location and separation.



As seen in Table 6, when dealing with TDR "Ghost" reflections, the following points are important:

- The first reflection captured by the TDR unit always corresponds to a joint or anomaly irrespective of where the joint/anomaly is located.
- When one joint or anomaly exists beyond 50% of cable system length, then TDR "ghost" reflections are not an issue. It may, therefore, be advantageous to measure from the other end if there is a doubt.
- The TDR "ghost" reflections start to appear only if the joints or anomalies are located within the first 50% of the cable system length.
- Care must be taken when interpreting TDR traces with "ghost" reflections, since the

"ghosts" might be interpreted as nonexistent joints or additional anomalies.

- The attenuation and dispersion effects as well as spacing between "ghost" reflections can help in the identification.
- The issue can be partially addressed by perfectly matching the cable system characteristic impedance. In this case, any additional reflections from the near end would be absorbed and this could avoid many TDR "ghost" reflections.
- The TDR "ghost" reflections between joints or joints and anomalies are impossible to control and are always present at some level.
- When dealing with "ghost" reflections, it is always advisable to perform a far end TDR deployment; a discussion on far end TDR deployment is contained in the next section.

The TDR "ghost" reflections have been observed in the field, see Figure 21, for a 25 kV WTRXLPE URD cable system approximately 5,211 ft long with two splices. A 100 ns TDR pulse was injected without an impedance matching device. The cable system structure (splice locations) was known beforehand.

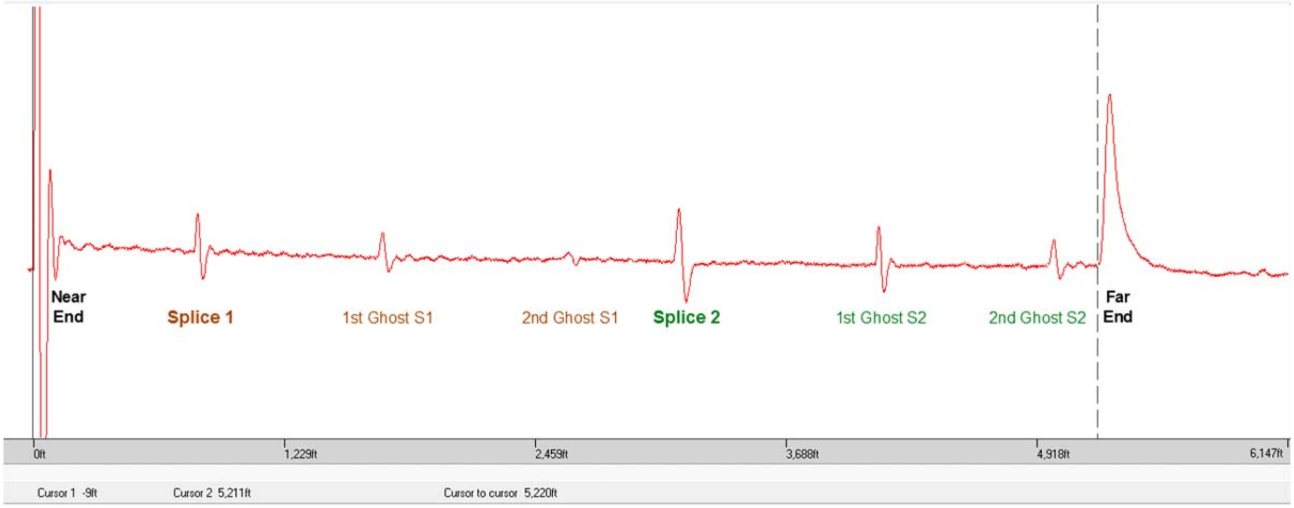


Figure 21: Splice and Ghost Reflections as seen in a TDR Unit from Field Tests of a 25 kV XLPE Cable System with Two Splices (TDR pulse of 100 ns) (See Case 5 in Table 6)

As seen in Figure 21, two "ghost" reflections appear in the TDR trace. The "ghost" reflections can be easily identified in this trace because of the spacing pattern. For example, the distance between "1st ghost S1" and "splice 1" is the same as the distance between "1st ghost S1" and "2nd ghost S1"; conversely, "2nd ghost S1" was more attenuated/dispersed than "1st ghost S1" and "1st ghost S1" more attenuated/dispersed than "splice 1". The same also holds true for "Splice 2" and its "ghost" reflection. In fact, the bounce diagram presented in Table 6 for two splices corresponds to the TDR trace shown in Figure 21; however, the other predicted "ghost" reflections for "splice 1" are not observed in the TDR trace. This is due to attenuation and dispersion that causes them to fall below the noise level and thus making them undetectable by the TDR unit.

The interpretation of the TDR trace shown in Figure 21 is relatively straightforward once some configuration assumptions are made based on known cable system configuration parameters (e.g. standard reel lengths, consistent spacing between "ghost" reflections, other local knowledge, etc.).

Without these assumptions, then an operator could easily conclude that the system has six joints - an erroneous assessment as verified by the utility when they attempted to find the joints.

11.7.1.4 TDR Far End Deployment

In most cases, TDR is only deployed from one end (near end) of the cable system. This is generally enough for determining the system structure and possible existing anomalies; however, in some cases, there is benefit to deploy the TDR test from both ends. It is advisable to repeat TDR measurements from the far end if:

- The far end is not visible on the TDR trace or there is a mismatch between the TDR trace length and the estimated actual length.
- There is doubt about the presence and type of an anomaly.
- There is a need to pinpoint an accessory or anomaly.

Figure 22 shows the near and far end deployment of TDR.

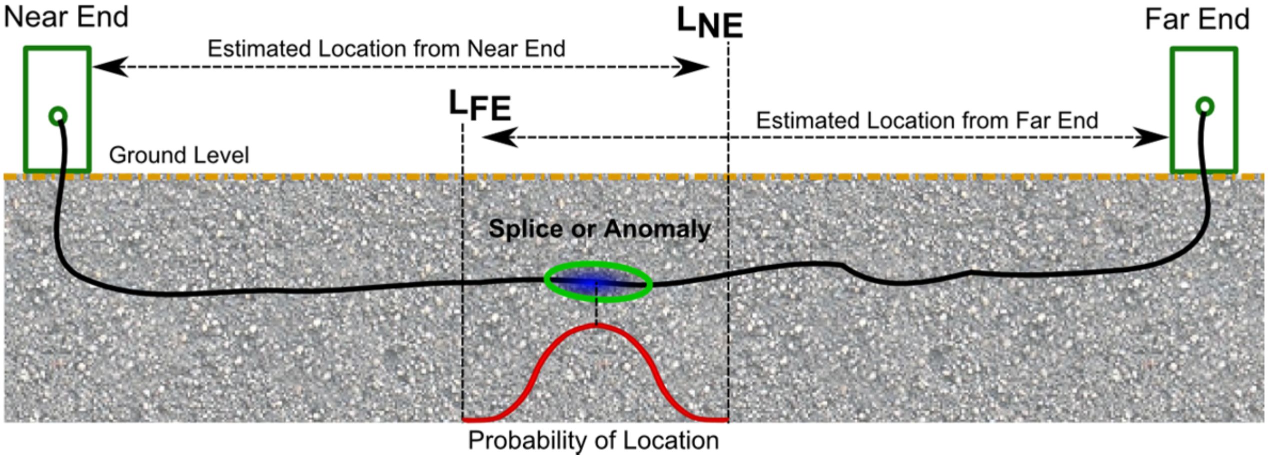


Figure 22: Conundrum for Pinpointing a Splice or Anomaly based on TDR Measurements

As seen in Figure 22, the TDR is deployed from both ends and in each case the joint or anomaly location is over estimated; however, the TDR pinpointing has the advantage that the limits L_{NE} and L_{FE} are identified, the joint would be located with a high degree of certainty between them. In Figure 22, the probability of the location of the splice or accessories occurring between the limits is represented by the red curve. It is important to note that the probability has its maximum at the midpoint of the range established by L_{FE} and L_{NE}; therefore, if digging for repairs is required, this location is the best choice. If the joint or anomaly is not found at that location; then repair crews should start digging in both directions until it is found.

It is important to mention that to increase the accuracy in pinpointing splices or anomalies, the TDR technique can be used in combination with other locating methods. There are several methods to achieve the aim and the previously specified benefits. However, some of them (especially those based on high voltage testing) can diminish the integrity, or even worse, be destructive to the cable system. Some of these might require equipment that is not easy to handle and deploy, or some might involve detection methods that are unfamiliar to the utility cable engineer. There is no question that an understanding of all available methods is essential to maximizing the effectiveness of successfully locating a splice or anomaly; however, such a comprehensive study falls beyond the scope of the research and practical work considered in the *CDFI*.

11.7.1.5 Pinpointing an Accessory or Anomaly

From a financial and reliability perspective, the importance of pinpointing an accessory or anomaly in a cable system is very important, thus knowing the cable system structure with some level of certainty is of great value. As seen in the previous section, the TDR technique, when deployed from both ends, can effectively pinpoint an accessory or anomaly in a cable system. However, there are several factors to consider when maximizing the benefits of the TDR results.

- Influence of the velocity of propagation (VoP): As mentioned earlier, different cables have different VoP's. To assure the most accurate conductor distance measurements, the cable VoP must be determined. Therefore, the CDFI perspective provided in this chapter is only valid if the correct VoP has been selected.
- System layout: The layout is directly related to the conductor length and thus affects the TDR results. Figure 23 is the same as Figure 6 and shows different cable system layouts that could be encountered in the field. Figure 24 shows the corresponding illustrative TDR traces for the different layouts in Figure 23.

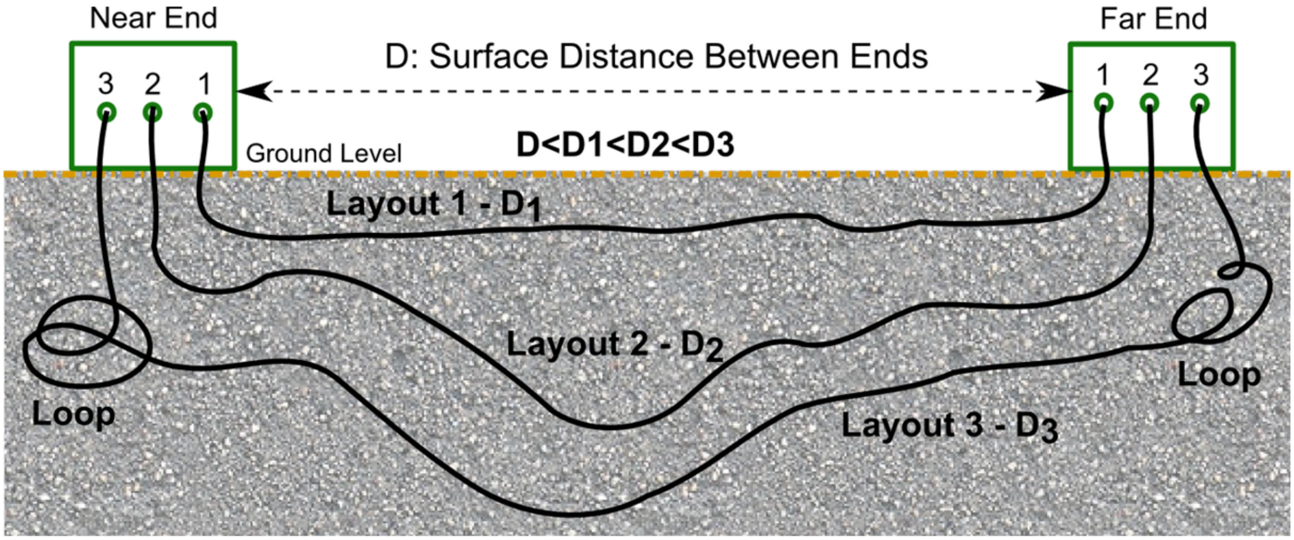


Figure 23: Different Underground Power Cable System Layouts

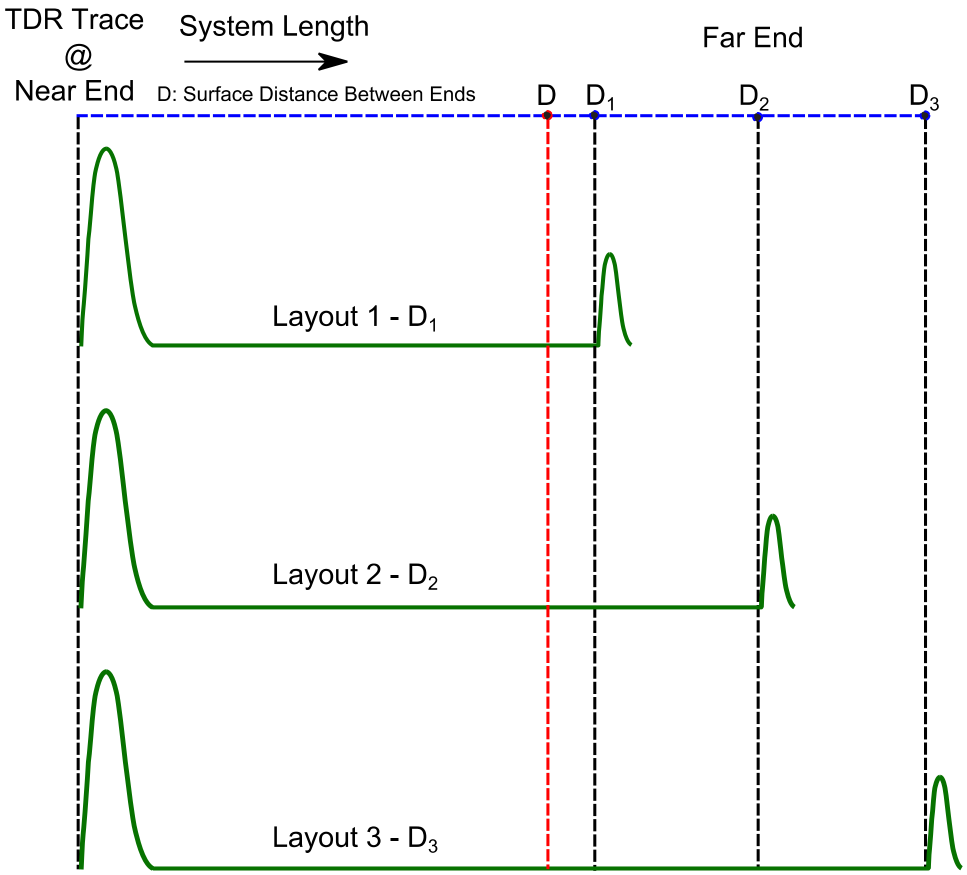


Figure 24: Illustrative TDR Traces for the Different Underground Power Cable System Layouts Shown in Figure 23

As seen in Figure 24, when the correct VoP is used, the estimated distance of the far end, as compared to the surface distance between ends, is always over estimated. This situation intensifies for layouts 2 and 3 as more buried cable and thus conductor length is present. One obvious solution to this issue is to adjust (increase) the VoP up to the level that causes the TDR measured distance to be the same as the surface distance between ends. While this could be a good practice for layout 1 (small difference between D and D_1), it does not work for layouts 2 and 3. It is, therefore, best practice not to assume the cable system follows the shortest path. The VoP has to be determined or estimated according to the cable system under test. Fortunately, basic cable parameters are relatively easy to identify based either on cable markings or utility installation practice.

11.7.1.6 Operator Training

Beyond hardware and software, the success of power cable condition assessment using TDR relies on the skill of the operator. Therefore, an excellent operator training program would provide a higher probability for correctly assessing the cable systems. Training should not be over simplified. Initially the operator must understand the basic concepts of transmission lines and how a high frequency signal travels through them. The concepts of frequency components, attenuation, dispersion, noise coupling, and filtering are also important. The operator must study and develop a command of the TDR unit hardware and software. Next would be learning acquired from the basic accessory or anomaly TDR signatures. Hands-on experience would then become paramount. Tailored solutions appropriate for their specific system would be learned and correlated with the TDR measurements. Finally, heuristic rules and procedures would be developed. This would round out training and should result in the development of a skilled operator.

11.7.2 Ω-Check

11.7.2.1 Application to other Types of Metallic Shield other than Concentric Neutral

The Ω-Check method was initially designed considering only cable systems with bare concentric neutral wires. However, the principles of the technology can be applicable to any other cable metallic shield types. Therefore, problems with copper tape, wire, LCT, other metallic shield types could potentially be identified if proper databases and procedures are developed. This requires an expansion of the capabilities of this diagnostic technology, which is outside the scope of the *CDFI*.

11.7.2.2 Impact of Joints and Connectors on Measurements

The presence of joints and/or connectors in a cable system can influence Ω-Check results, specifically if they pose high resistances at the connection interfaces with the metallic shield. These high resistances may be interpreted as corrosion issues and thus they may lead to incorrect assessment results, though a poor metallic shield connection at a joint is good information to have. It is also important to consider that the likelihood of metallic shield breaks is increased when joints are present in the system.

11.7.2.3 Applicability to EHV, HV Cable Systems Including Subsea Cable Systems and Armor Evaluation

During the last two decades, a considerable increase in the number of EHV and HV cable systems including subsea applications have occurred in the electric power industry. There is no question that over time these systems will start to degrade and eventually fail. Given their importance, diagnostic techniques will be needed to assess all of their elements of these systems, including their metallic shields and even the cable armor, if present. The Ω-Check technology has the potential to be adapted to provide this capability through the development of proper databases and test procedures.

11.8 References

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11.9 Relevant Standards

- IEEE Std. 81 - 2012: *IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Grounding System*.
- IEEE Std. 400 – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*.
- IEEE Std. 1617 – 2007: *IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables*.

11.10 Appendix A

11.10.1 VoP Error in TDR Measurements

It may be thought that variations in VoP would make it almost impossible to locate an accessory or anomaly accurately. Fortunately, there are ways to minimize the error in the VoP when testing, resulting in very accurate distance measurements. The most common technique used to reduce VoP error is to test the system from both ends (TDR dual-ended deployment) to establish two lengths thereby localizing the accessory or anomaly between the two ends. The procedure is as follows:

- Determine the path of the cable system. With a measuring wheel, estimate the length of the cable system being tested. Set the VoP to 50%, test the cable from one end, and record the distance reading to the accessory or anomaly. Next, using the same VoP setting, test from the opposite end of the cable system and also record the distance reading. If the sum of the readings is the length of the cable system that was initially estimated, the VoP is correct and the fault has been located with some good degree of certainty.
- If the sum of the two readings is more than the initial estimated distance, reduce the VoP setting and re-test. This process can be repeated until a match between the computed and estimated distances is found.
- Similarly, if the sum of the two readings is less than the measured distance, increase the VoP setting. This process can be repeated until a match between the computed and estimated distances is found. However in this case, the operator must also consider the possibility of two accessories or anomalies.
- Same results can be obtained mathematically. Take the estimated power cable system length and divide by the sum of the two TDR readings obtained by the tests from each end. This gives the adjustment factor. Then multiply each of the TDR readings by the adjustment factor. These results will be the corrected length readings.