CHAPTER 5

Time Domain Reflectometry (TDR)

Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

Users are strongly encouraged to consult the link below for the most recent release of Chapter 4:

Chapter 4: How to Start

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

This document was prepared by Board of Regents of the University System of Georgia by and on behalf of the Georgia Institute of Technology NEETRAC (NEETRAC) as an account of work supported by the US Department of Energy and Industrial Sponsors through agreements with the Georgia Tech Research Institute (GTRC).

Neither NEETRAC, GTRC, any member of NEETRAC or any cosponsor nor any person acting on behalf of any of them:

a) Makes any warranty or representation whatsoever, express or implied,
   i. With respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
   ii. That such use does not infringe on or interfere with privately owned rights, including any party’s intellectual property, or
   iii. That this document is suitable to any particular user’s circumstance; or
b) Assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if NEETRAC or any NEETRAC representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process or similar item disclosed in this document.

DOE Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

Copyright of this report and title to the evaluation data contained herein shall reside with GTRC.

Reference herein to any specific commercial product, process or service by its trade name, trademark, manufacturer or otherwise does not constitute or imply its endorsement, recommendation or favoring by NEETRAC.

The information contained herein represents a reasonable research effort and is, to our knowledge, accurate and reliable at the date of publication.

It is the user's responsibility to conduct the necessary assessments in order to satisfy themselves as to the suitability of the products or recommendations for the user's particular purpose.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

5.0 TIME-DOMAIN REFLECTOMETRY (TDR)

5.1 Test Scope

A time-domain reflectometer locates and characterizes changes in impedance in a cable system. These changes can be caused by:

- faults (shorts)
- joints (splices)
- open connections
- taps in the cable system
- deteriorated neutrals
- water ingress into insulation material or joints
- bad (high resistance) connectors
- Any other type of anomaly affecting the characteristic impedance of the system.

5.2 How It Works

A TDR works like radar. A fast rise time pulse is injected into the cable system at one end (near end). As the pulse travels down the cable, any change in the characteristic impedance (impedance discontinuities) will cause some of the incident signal to be reflected back towards the source. The reflected pulse components will be positive or negative depending on whether the impedance is greater or less than the cable's characteristic impedance. The initial pulse and the reflection are plotted against time on the instrument display, like an oscilloscope. Since the instrument can be calibrated to determine the speed of the pulse in the cable, the conductor distance to the end of the system can be determined.

This information can also be used to locate discontinuities indicated by reflected pulses. In addition, the shapes of reflected pulses on the instrument display help the operator to determine the nature of the discontinuity.

The 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 1**

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, implying that the cable system terminates at impedance equal to the characteristic impedance of the tested system.

5.3 How It Is Applied

Typically, this technique is performed offline. A fast rise time, low voltage pulse is applied between the conductor and the insulation shield of a cable system at an elbow or termination. As the pulse travels through the cable system, reflections are produced by discontinuities and changes in system impedance. The initial and reflected pulses are displayed against time on an oscilloscope type display and interpreted by the operator. Since the velocity of propagation (VoP) of the TDR pulses is known or can be estimated, the time can be converted to distance or location. An experienced operator can often determine the source (cause) of an impedance discontinuity by the shape and magnitude of the reflected signals.

The test duration (including interpretation) is between five and ten minutes once the TDR and the cable system are connected.

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 (less than U_0). • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires maintaining accurate data. • Locates areas of the cable system with impedance related problems.
Open Issues	• The ability to perform the test online is unclear. • Proper interpretation of TDR data may require the history of cable system construction. • The test voltage of a low voltage TDR may not be high enough to detect some dielectric imperfections. • 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. • Length measurement requires that the start of the TDR pulse be identified, this can be difficult.
Disadvantages	• Skilled operators are required for testing and post analysis. • Blind spots due to the ringing effect occur at the near end where the pulse is injected. The length of cable within the blind spot depends on the injection method and width of the pulse. • Electrical noise may interfere with the low voltage TDR signal. • Successful location of an impedance discontinuity depends on having the correct velocity of propagation in combination with the underground cable system layout.

However, one of the more important issues when performing TDR measurements is to understand that the length reading on the TDR unit is uniquely 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 on *CDFI* Perspective). The first challenge is related to the relationship between how the cable system was arranged underground and how that affects precisely locating an accessory or anomaly; secondly, the error on the velocity of propagation that directly affects the length readings and thus TDR trace interpretation results. An illustration for different underground cable system layouts appears in Figure 1.

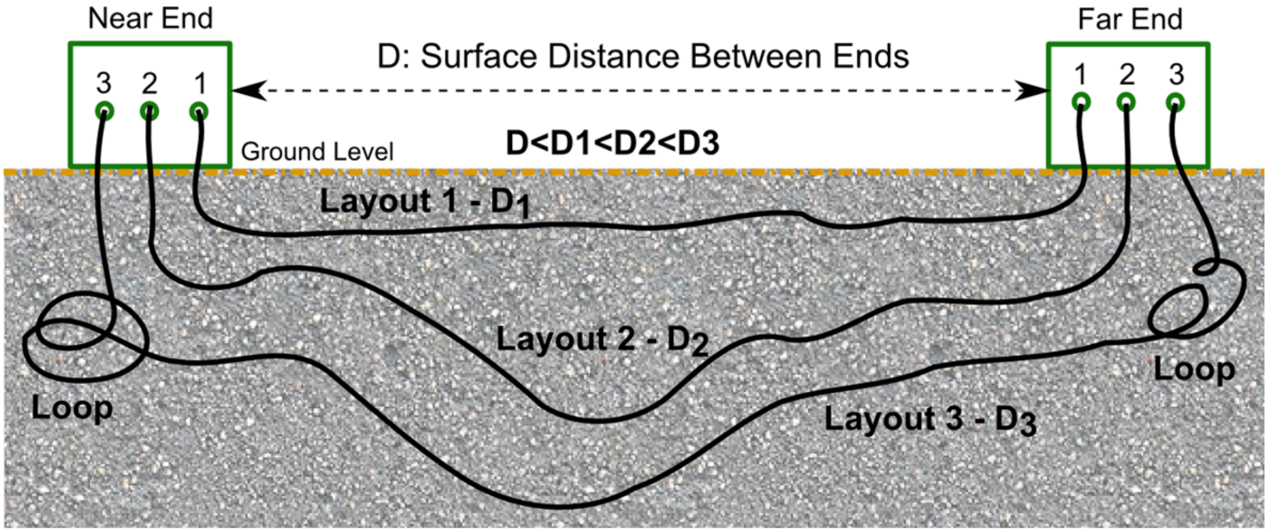


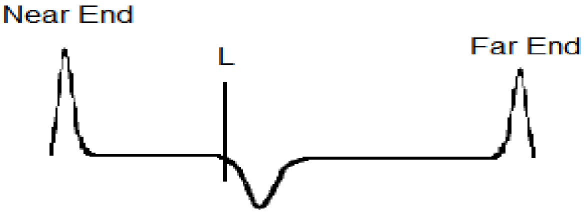
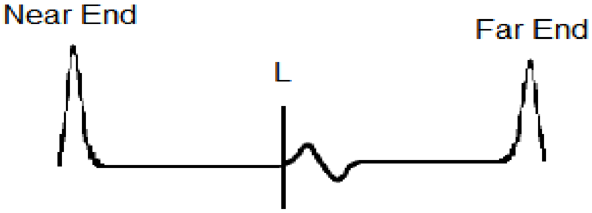
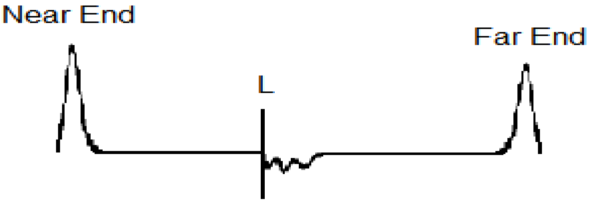
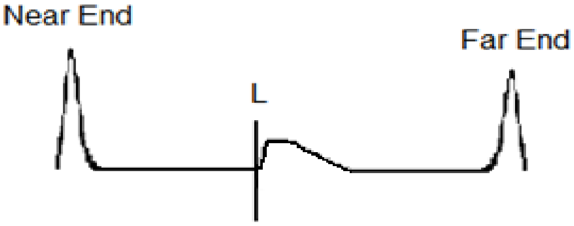
Figure 1: Illustration for Different Underground Cable System Layouts

As observed in Figure 1, there are different ways in which a cable system can be configured underground which directly affects the conductor length and thus the TDR results. The relationship between the conductor lengths for all layouts (D_1, D_2, and D_3) and the separation surface distance between ends (D) appears in Figure 1. Figure 1 figure also illustrates an extreme case where loops could be included in the cable length that could be left under the base of a switchgear cabinet, for example.

5.4 Success Criteria

Typical waveforms and their interpretation appear in Table 2. The actual appearance of the waveforms varies and will not exactly match those shown in references. Therefore, there are no unified success criteria for TDR testing.

Table 2: Cable System Conditions Distinguishable using TDR [1]

Case	TDR
Uniform cable system with no joints.	
Uniform cable system with no joints and shorted conductor at distance L from Near End.	
Cable system with a joint at a distance L from Near End.	
Cable system with a wet joint at a distance L from Near End.	
Cable system with water ingress at a distance L from Near End.	
Cable system with localized corroded neutrals at a distance L from Near End.	

5.5 Estimated Accuracy

The amount of TDR data needed to compare test results and actual findings is insufficient to calculate accuracies. In addition, most TDR results are not provided in pass/fail terms, but rather as general information concerning the tested cable system.

5.6 *CDFI* Perspective

Research shows that TDR is a useful tool for diagnosing potential cable system problems. It is an easy and fast way to scan a cable system, associated accessories (joints and terminations), and anomalies that affect the system characteristic impedance. TDR is especially valuable during field measurements where portability is essential and cable systems are often long. TDR has been used here to obtain preliminary data on the cable system to be tested, *i.e*. length and number of splices. It is also used as a diagnostic tool providing an initial condition assessment of the cable system, *i.e*. neutral condition, possible water ingress, and others.

A TDR unit typically uses very low power. Because of the non-destructive nature and usefulness of the data provided, it is highly recommended that it be performed prior to any other diagnostic test. The TDR may even provide some information for hybrid cable systems. While the distances/locations would not be correct for some of the system, the number of joints would still be measurable. Unfortunately, branch systems present an additional challenge that has yet to be overcome for the TDR.

During the *CDFI* project a considerable amount of knowledge has been accumulated regarding the use of TDR as a useful tool for diagnosing potential cable system problems. As with any diagnostic tool, accurate data interpretation maximizes the value of the resulting data. Thus, a variety of issues addressing TDR deployment and applicability have been found, analyzed, and understood, they include:

- Examination of the waveform/trace to understand the tested system characteristics and identify anomalies.
- Comparison the length of one phase of a cable system against a companion phase.
- Importance of understanding the cable system characteristic impedance and velocity of propagation.
- Relevance of the TDR pulse width and amplitude.
- Practices used for TDR pulse injection.
- TDR for condition assessment of cable system neutral.
- The role of TDR leads.
- Identification of the cable system far end.
- TDR dual-ended deployment.
- Operator training.

All these issues are discussed in detail in the following sections and they represent the main contribution of the *CDFI* to the TDR measurements for condition assessment of cable systems.

5.6.1 Diagnosis via Waveform Analysis

Interpreting the signal to provide an accurate TDR condition assessment requires experience. TDR traces with similar condition assessments can look different from the examples shown here, even if the cable system is the same type and length. During one series of field tests, a failure occurred at a splice after testing a PILC feeder cable in an area that had experienced several failures. Upon examination, water was found in the splice. Evidence of the water appears in the TDR trace for that cable (Figure 2). The length of the cable system tested and a rough estimate location of the water ingress given by the TDR correlated with both the actual length and the failure site location.

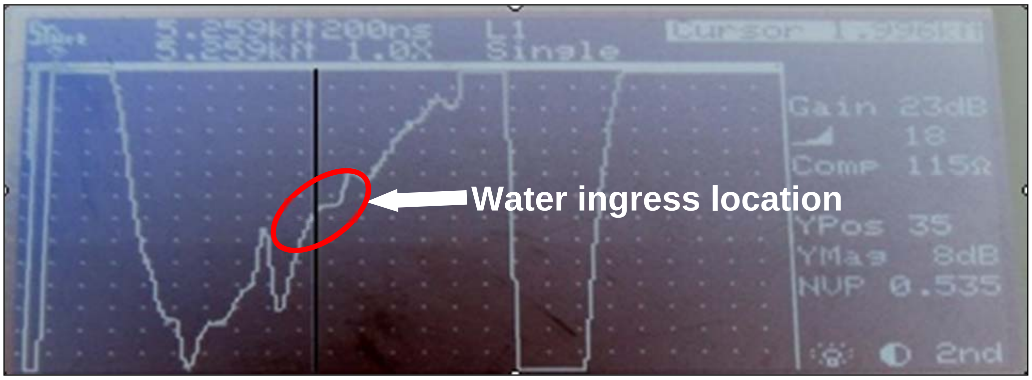


Figure 2: TDR Trace - Moisture in Splice

During another series of field tests performed on PILC cable systems, a significant change in the characteristic impedance of the cable insulation was detected at a specific location using a TDR test. Figure 3 shows a sharp negative peak on the TDR trace indicating the location of the change in insulation impedance. Examination of the cable system in that area found the manhole full of water with signs of oil leakage.

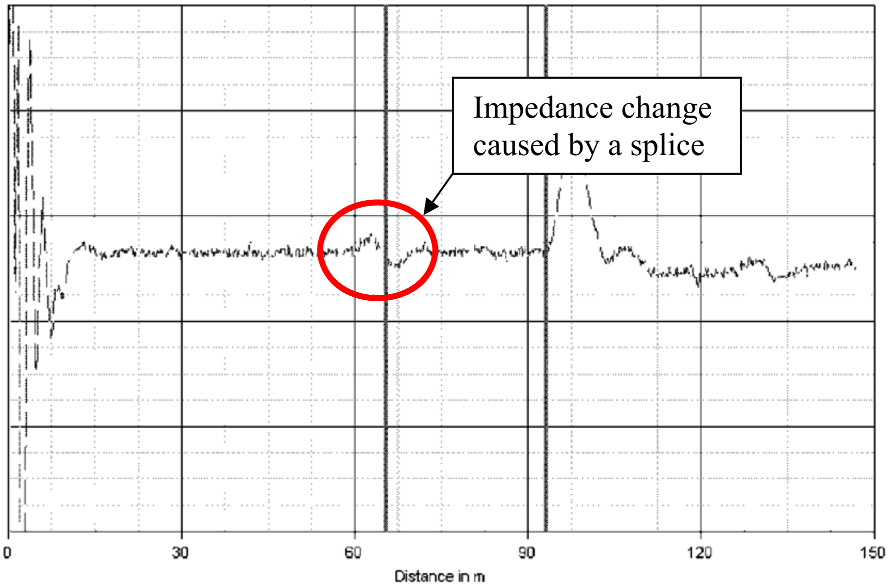


Figure 3: TDR Trace – Significant Change in Cable System Impedance

Anomalous reflections on adjacent phases of three-phase cable systems suggest additional investigation. Figure 4 shows an example of how measurements made on an XLPE cable system are used to assess the overall characteristics of a tested cable system. The solid circles indicate a splice location while the open circles indicate anomalous reflections.

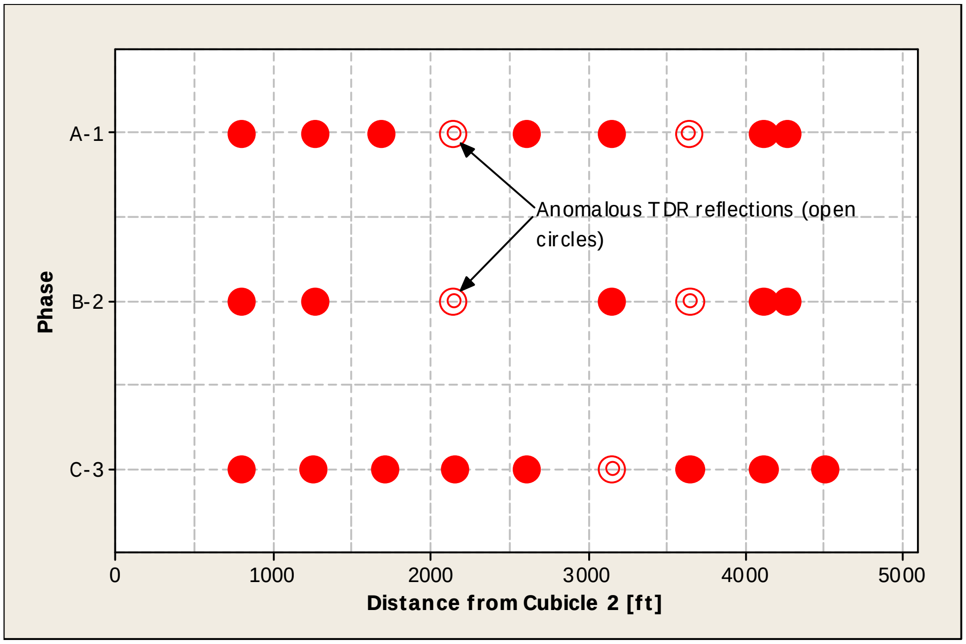


Figure 4: Example of Anomalous TDR Reflections on Adjacent Phases

5.6.2 Diagnosis Via Length Comparison

Length comparisons are especially useful (and simple) on three-phase circuits since the length of the phases are nearly identical. Measurements made from both ends of the system are effective for identifying single or multiple breaks in the neutral wires. As an illustration, consider a three-phase cable system with a neutral wire metallic shield as shown in Figure 5.

Figure 5: Three-Phase Section under Test Using TDR

The TDR length results for all phases measured from Location 1 appear in Table 3. Phases A and B measure nearly identical lengths at approximately 1,500 ft. while Phase C measures only 690 ft.

Table 3: TDR Results from Location 1

Phase	Length [ft]
A	1,500
B	1,503
C	690

The TDR results clearly indicate a break/discontinuity in the Phase C metallic shield (neutral wires). A TDR measurement from Location 2 will determine if there are multiple breaks. Table 4 shows the results of these measurements.

Table 4: TDR Results from Location 2

Phase	Length [ft]
A	1,500
B	1,503
C	380

Comparing the Phase C measurements from Table 3 with Table 4 it is apparent that there are multiple (at least two) neutral wire breaks since the sum of the measured lengths is only 1,070 ft. Had the two lengths summed to approximately 1,500 ft then there is only a single break.

5.6.3 Characteristic Impedance (Z_0) and Velocity of Propagation (VoP)

When TDR pulses travel through a cable system, the system is modeled as a transmission line. In electrical engineering, a transmission line is a specialized tool design to withstand certain operating voltage and carry alternating low frequency (60 Hz) current (powers systems applications) or high frequency signals (communications applications).

A cable system is modeled as a transmission line by using an equivalent circuit of passive elemental components; the schematic representation of the equivalent circuit model appears in Figure 6.

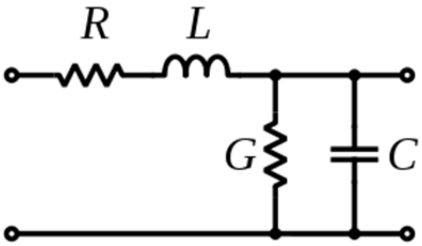


Figure 6: Per Unit Length Transmission Line Equivalent Circuit Model

The transmission line model in Figure 6 represents the transmission line as an infinite series of two-port elementary components each representing an infinitesimally short segment of the transmission line. They are as follows:

- The distributed resistance *R* of the conductor and the neutral is represented by a series resistor (expressed in Ω per unit length).
- The distributed inductance *L* (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (expressed in H per unit length).
- The capacitance *C* between the conductor and the neutral is represented by a shunt capacitor (expressed in F per unit length).
- The conductance *G* of the insulation and semicons between the conductor and the neutral is represented by a shunt resistor (expressed in S per unit length).

The model consists of an infinite series of the elements shown in Figure 6, and that the values of the components are specified per unit length so the picture of the component can be misleading. *R*, *L*, *C*, and *G* may also be functions of frequency. However, it is generally assumed that they do not change with frequency. These quantities can also be known as the primary electrical cable system parameters. A series of useful constants can be derived from these parameters such as propagation constant, attenuation constant, phase constant, velocity of propagation and others. The constants are used depending on the type of diagnostic technology deployed and thus, in some cases, knowing the cable system parameters is essential.

The TDR is an extremely accurate instrument. However, if cable system parameters and constants are in error, they might cause incorrect data interpretation. For the specific TDR case, knowing the parameters or propagation constants is imperative: they are necessary for any analysis of TDR signals.

The more important constants for TDR are the characteristic impedance (Z_0) and the velocity of propagation (VoP), the characteristic impedance is used for TDR pulse injection settings; the TDR device should have the same characteristic impedance as the cable system in order to improve the pulse energy transfer from the TDR to the system; this is not a simple task and thus it is discussed later in this Chapter in detail.

In contrast, the VoP is used to characterize the cable system structure and pinpoint the locations of joints and possible anomalies present in the system. One way to minimize error in pinpointing is to use the correct VoP of the cable system under test. The VoP is a specification of the cable indicating the speed at which high frequency signals travel down the cable system. Different cables have different VoPs. In order to assure the most accurate distance measurements, the cable VoP must be determined.

The VoP is generally defined in terms of the speed of light in a vacuum (~1 ft/ns), which accounts for reference as 100%. All other signals would travel through the cable system at slower speeds, e.g. a cable system with a VoP of 85% would transmit a TDR pulse signal at 85% of the speed of light (0.85 ft/ns). Knowing the VoP of a cable system is the most important factor when using a TDR for accessory or fault location. The instrument can be calibrated to the particular cable system by entering the correct VoP.

The VoP number of a cable is determined by the insulation dielectric material, operating temperature, and age; however, as a rule of thumb when the VoP is unknown, it can be assumed to be approximately 50% (0.5 ft/ns). Typically, the VoP of the cable system under test will be listed in the cable manufacturer catalog or specification sheet. If not, one approach is to compute it from the cable parameters (L and C) or simply measure or estimate the length of the cable system and change the TDR VoP setting until the display shows at the far end the same distance reading as the measured/estimated length. A partial listing of typically used MV cable types with their inductance, capacitance, characteristic impedance (Z_0), and VoP appears in Table 5.

Table 5: Important Cable Constants for TDR

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

5.6.4 Relevance of TDR Pulse Amplitude and Width

Cable systems have an impulse response that distorts the original injected TDR pulse signal as it travels through the system. The distortion is caused by several types of cable system losses which are frequency dependent. The longer the cable system is, the greater the distortion [2-6]. The physical processes that characterize the losses are well known and defined; they are skin effect, dielectric loss, reflection and radiation [6]. In a simple manner, these physical processes can be represented by two major sources of TDR pulse distortion: attenuation and dispersion.

To understand the sources of distortion, the typical parameters of a TDR pulse must be introduced. The typical parameters of a TDR pulse are its amplitude and width. On the one hand, the amplitude is defined as the peak amplitude of the TDR pulse; in other words, it is the maximum magnitude that the TDR pulse reaches independently of its shape. On the other hand, the pulse width is generally defined as the difference in time between those points in the TDR pulse that have amplitude of 50% of the peak amplitude. The amplitude and width of a TDR pulse are illustrated in Figure 7.

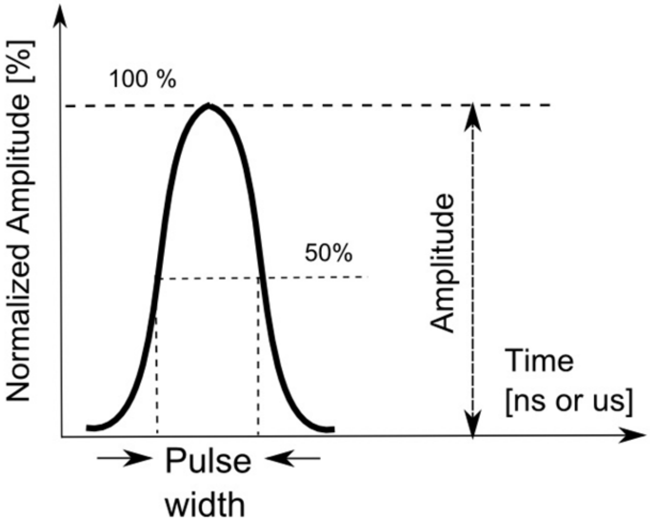


Figure 7: Typical Parameters of TDR Pulse

The TDR pulses are generated by the TDR unit as fast pulses having fast rise and decay times with a width that generally ranges from a few nanoseconds to hundreds of nanoseconds. When the TDR pulses travel along the cable system, the system behaves as a lossy transmission line; therefore, it can be modeled in this way. The lossy line behavior causes the TDR pulses to change their shape as they travel along the system. The change in their shape is due to two mayor important effects: (1) change in pulse shape due to loss of energy (attenuation) and (2) change in pulse shape due to different travel speeds for different frequencies without any energy loss (dispersion). In addition, spurious pulses will appear that are introduced by reflections of TDR pulses at the system ends and splices. The attenuation and dispersion are discussed in more detail in the next paragraphs.

Attenuation: While traveling along lossy transmission lines, TDR pulses lose energy. This energy loss is a function of the distance traveled by the pulse and its frequency components. In a cable system, the attenuation is due to losses in the bulk insulation and propagation through the resistance of the conductor, neutral, and semiconductive jackets. Normally, attenuation increases with frequency; energy losses may be significant for frequencies of the order of a few megahertz. As a consequence, fast TDR pulses can only travel short distances (because of their high frequency components) before they are attenuated to a level at which they are hidden by the induced background noise. Therefore, as the length of the cable system increases slower TDR pulses have to be used to overcome the cable system attenuation. Figure 8 shows the relationship between attenuation per unit length and TDR pulse width for a 300 ft of 33 kV, 630 mm^2, XLPE cable. Note in Figure 8 that faster pulses show higher attenuation magnitudes.

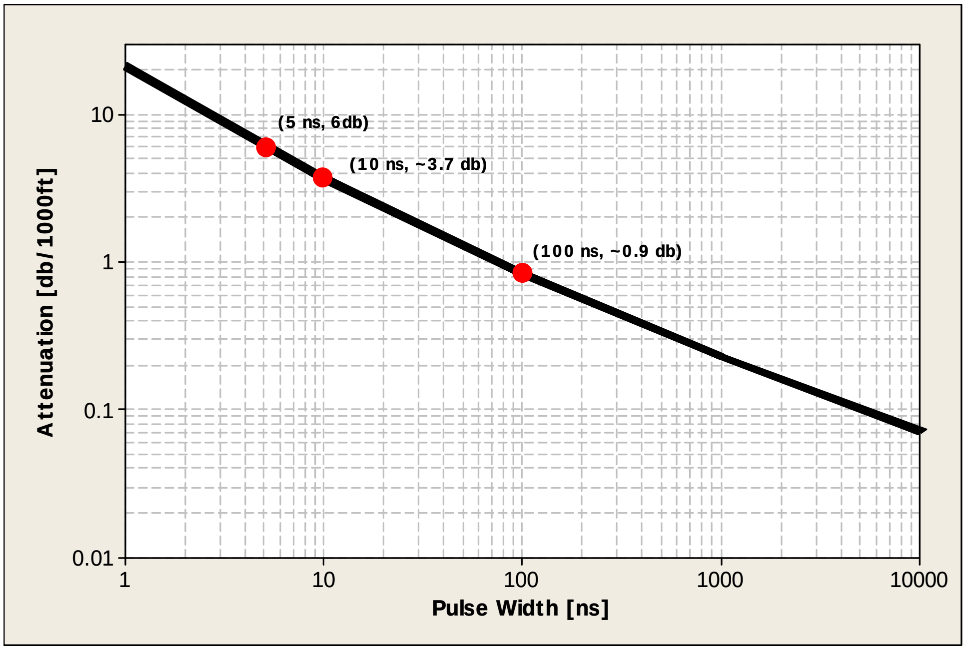


Figure 8: Calculated Attenuation as a Function of TDR Pulse Width for 300 ft of 33 kV, 630 mm^2, XLPE Cable [2]

Knowing the attenuation per unit length versus the TDR pulse width can provide useful information regarding how far a TDR pulse can travel through the cable system before reaching a specific level of attenuation. Using the example in Figure 8, several observations follow:

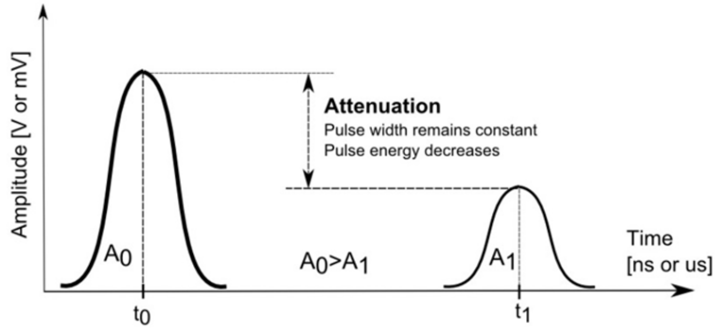
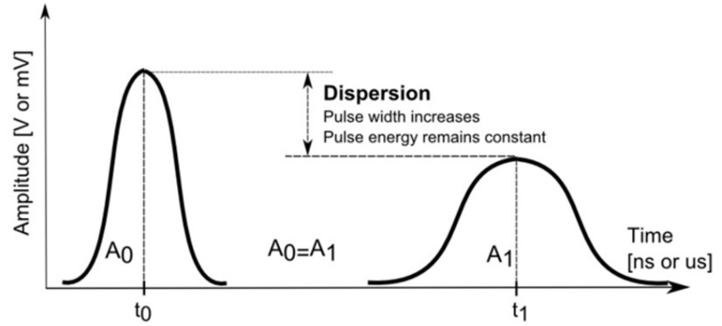
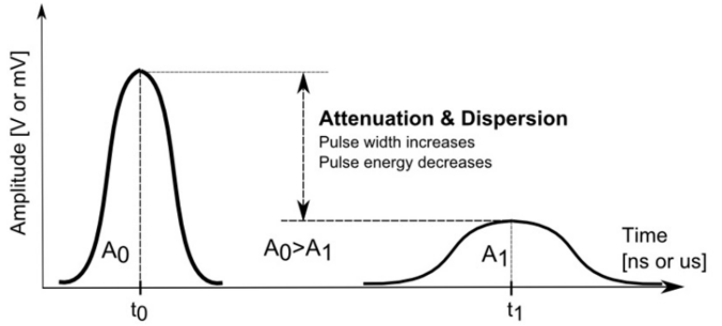
- A 5 ns TDR pulse has an attenuation of 6 dB/1000 ft, which means the pulse has to travel 1,000 ft to show 50% of its initial amplitude.
- Similarly, a 10 ns TDR pulse has an attenuation of approximately 3.5 dB/1,000 ft, which means the pulse has to travel approximately 1,700 ft to show 50% of its initial amplitude.
- Additionally, a 100 ns TDR pulse has an attenuation of approximately 0.9 dB/1,000 ft, which means the pulse has to travel up to approximately 6,700 ft to show 50% of its initial amplitude.

Even though the attenuation information is useful; generally, it cannot be considered alone. The TDR pulse distortion due to attenuation and dispersion is always present. In some cases, the dispersion would dominate the attenuation (low loss); and in other cases, the attenuation would dominate the dispersion (high loss). In the context of cable systems, both attenuation and dispersion are systemic and must be analyzed on a case by case basis.

Dispersion: As mentioned before, a TDR pulse is composed of different frequencies that travel along the cable system at different speeds. This change in speed causes distortion known as dispersion. The distortion can be seen as a phase shift of each of the individual frequency components of the TDR pulse and is a function of the distance traveled by the pulse and its frequency component profile. Dispersion distorts TDR pulses regardless of whether the system is lossy or not. This can affect the accuracy of locating splices and possible anomalies.

As a rule of thumb, it can be understood that attenuation causes the loss of frequency content of the TDR pulses while they are distorted and spread out in time due to the dispersion effect. Table 6 presents the cases on how a TDR pulse is distorted by attenuation, dispersion, and both.

Table 6: Overall Advantages and Disadvantages of TDR Measurements

Observations	Case
Attenuation: • Reduced amplitude. • Constant pulse width. • Reduced energy.	
Dispersion: • Reduced amplitude. • Increased pulse width. • Constant energy.	
Attenuation & Dispersion: • Reduced amplitude. • Increased pulse width. • Reduced energy.	

The performance of the TDR technique for diagnosing cable systems can be best comprehended by the concept of resolution. Resolution, in the context of engineering, is generally defined as the act or process of separating into constituent or elementary parts. TDR is not an exception. Specifically, for TDR two types of resolution should be considered when performing tests.

Resolution in TDR is basically the ability of the TDR system (the TDR system includes the hardware, software, and skilled operator) to identify very small changes in the characteristic impedance (Z_0) of the cable system, and that these small changes become visible as reflections in the display of the TDR unit. The resolution can also be defined as the ability to identify two closely spaced changes in the characteristic impedance as having separate reflections (in common words, two “bumps” in the TDR display instead of one). Therefore, the two types of resolution that should be considered are: amplitude and time resolution; it is desirable that a TDR system exhibit both good amplitude and time resolution.

Amplitude Resolution (Range): Refers to the ability of the TDR system to display a reflection signal from an accessory or abnormality that produces a small variation of the reflection coefficient. When there is a good amplitude resolution, very small characteristic impedance discontinuities along the cable system length can be displayed by a TDR system. A discontinuity causing a reflection signal that is smaller than the displayed background noise is difficult to observe. Displayed noise is therefore a good reference to use in comparing the amplitude resolution of various TDR systems. To improve the amplitude resolution, the displayed noise can be filtered or TDR waveforms can be acquired and then averaged.

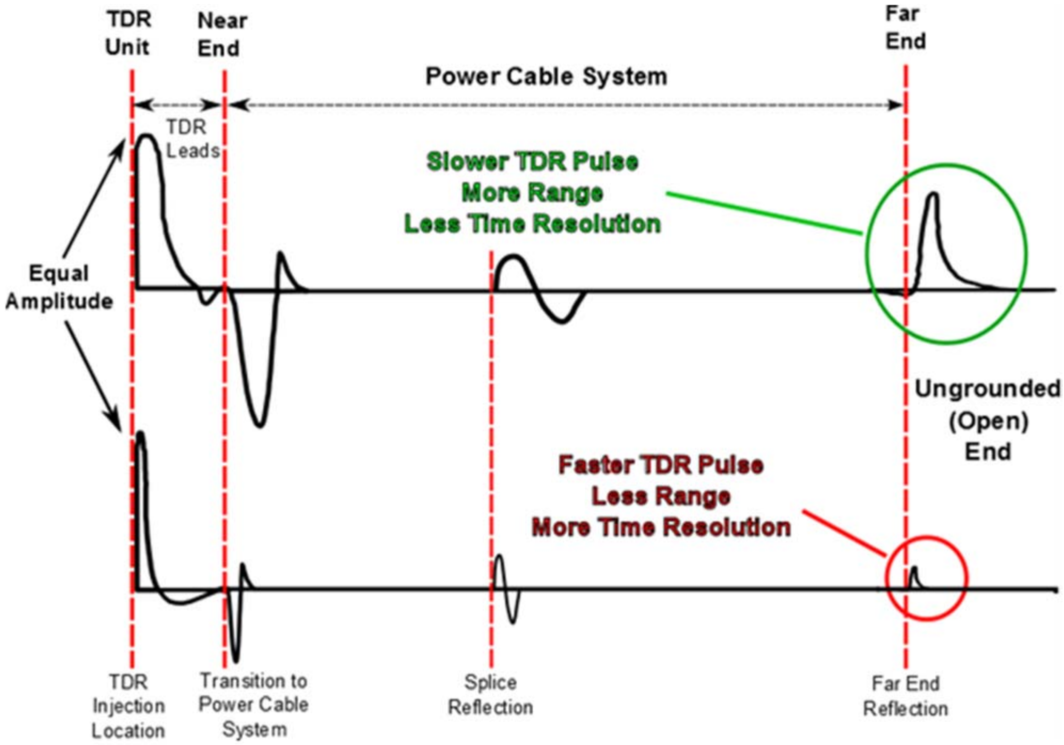


Figure 9: Illustration of Amplitude Resolution (Range) for TDR Systems

Thus, the amplitude resolution of a TDR system may then be defined as: the minimum change in the characteristic impedance that is equivalent to the displayed background noise amplitude without any filtering or averaging of the TDR acquired waveforms. The amplitude resolution can also be understood as the range of the TDR pulse, the range in the case refers to the distance that the TDR injected pulse or reflection is able to travel before it gets attenuated and dispersed to the background noise level. An illustration of the amplitude resolution concept (range) appears in Figure 9.

Time Resolution: Refers to the ability of a TDR system to distinguish between two point anomalies that are located very close together. The time resolution is then defined as the minimum time spacing (can also be seen as cable system length) of two similar anomalies which give rise to a distinguishable valley between the two displayed reflections [6]. An illustration of the time resolution concept appears in Figure 10.

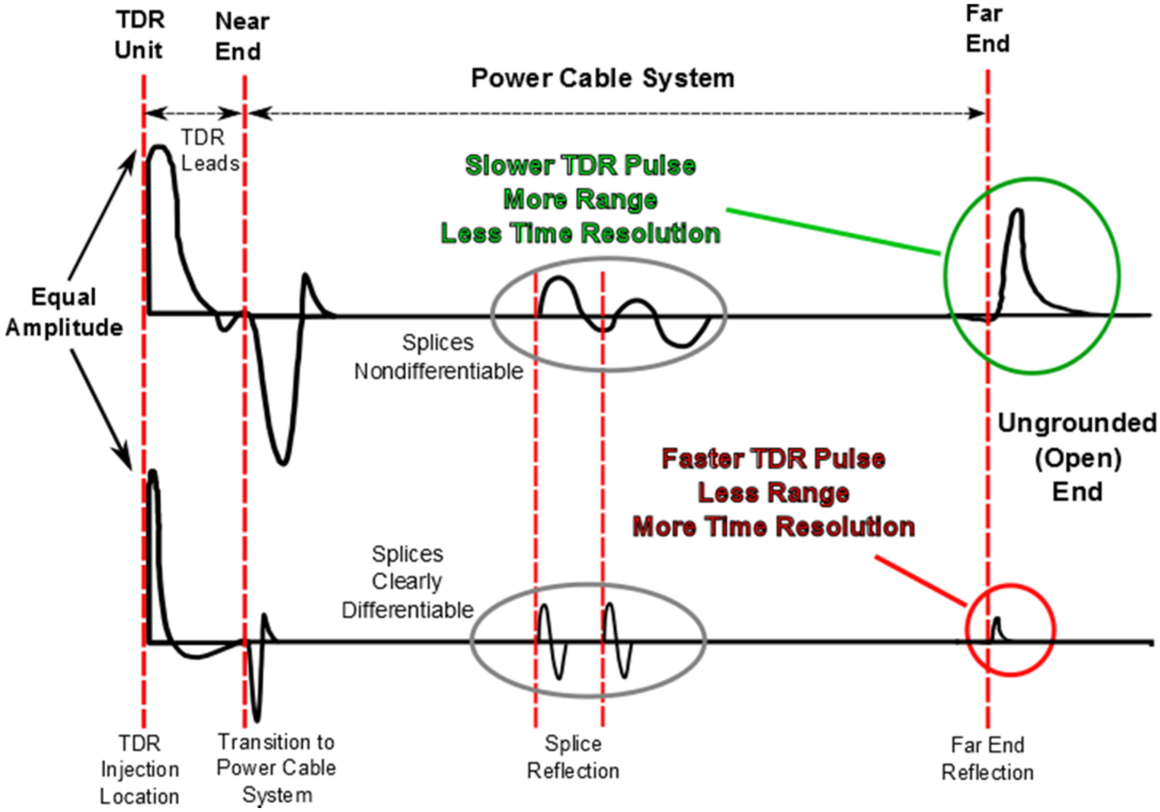
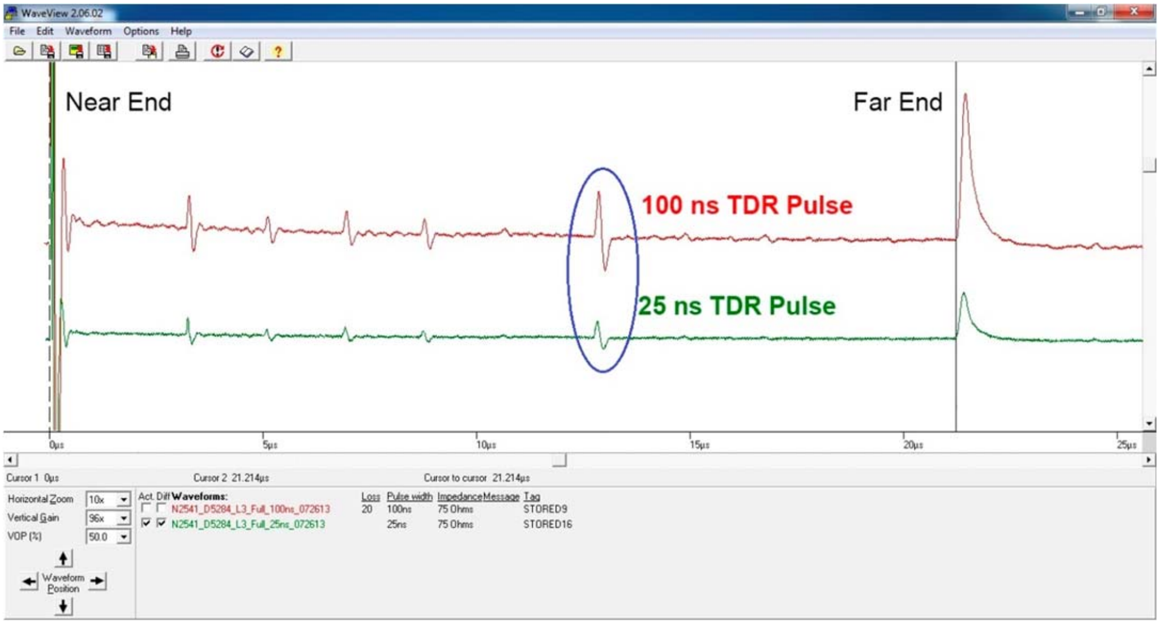


Figure 10: Illustration of Time Resolution for TDR Systems

A comparison between TDR traces taken in the field for a 25 kV, approximately 5,000 ft, XLPE, jacketed cable systems, appears in Figure 11; pulse widths of 100 ns and 25 ns have been considered. In Figure 11, the red and green traces correspond to the 100 ns and 25 ns TDR pulse widths respectively. The amplitude of injected TDR pulse at the near end is kept constant.



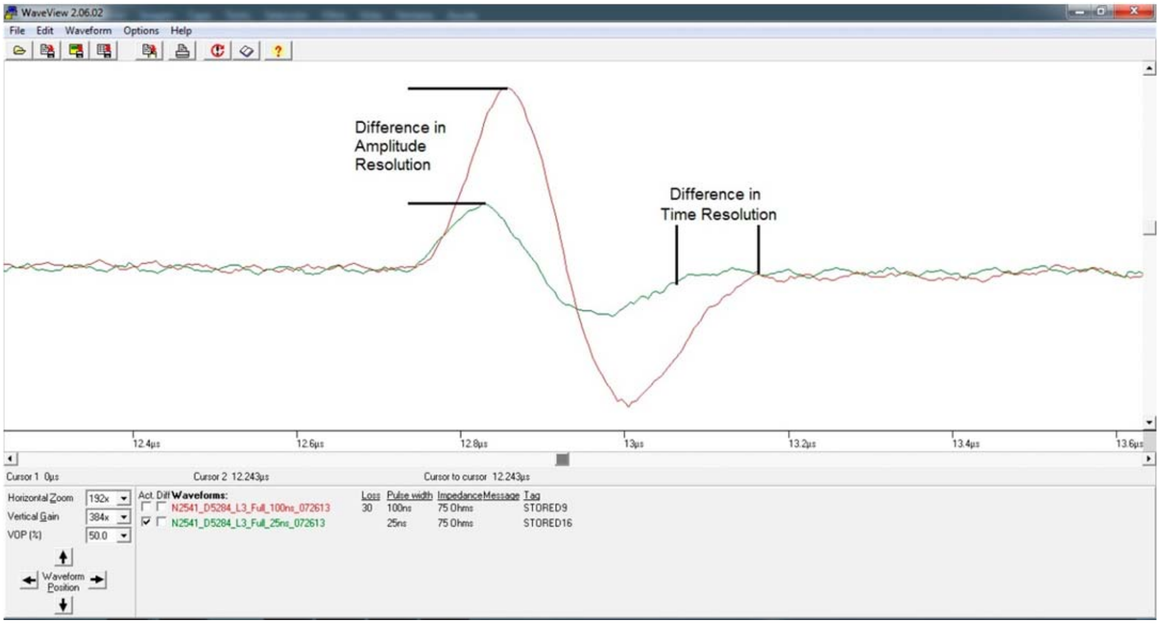
Cursor 1 0µs
Cursor 2 21.214µs
Cursor to cursor 21.214µs

Horizontal Zoom 10x
Vertical Gain 96x
VOP (%) 50.0

Act.	Diff	Waveforms:	Loss	Pulse width	Impedance	Message	Tag
☐	☐	N2541_D5284_L3_Full_100ns_072613	20	100ns	75 Ohms		STORED9
☑	☑	N2541_D5284_L3_Full_25ns_072613		25ns	75 Ohms		STORED16

Figure 11: Comparison between TDR Traces from Field Tests of a 25 kV XLPE Cable System for 100 ns and 25 ns TDR Pulses

As observed in Figure 11, both TDR traces indicate that there are five noticeable splices in the system. Also note that the amplitude resolution decreases with faster TDR pulses. However, as mentioned before, faster TDR pulses not only affect the amplitude resolution but also the time resolution. To show the influence of the TDR pulse width on both resolutions in a real cable system, a closer look at the splice reflection circled in blue in Figure 11 is considered and presented in Figure 12.



Cursor 1 0µs
Cursor 2 12.243µs
Cursor to cursor 12.243µs

Horizontal Zoom 192x
Vertical Gain 384x
VOP (%) 50.0

Act.	Diff	Waveforms:	Loss	Pulse width	Impedance	Message	Tag
☐	☐	N2541_D5284_L3_Full_100ns_072613	30	100ns	75 Ohms		STORED9
☑	☐	N2541_D5284_L3_Full_25ns_072613		25ns	75 Ohms		STORED16

Figure 12: Changes in Amplitude and Time Resolutions in TDR Field Tests

Figure 12 shows that there are issues when dealing with amplitude and time resolutions of TDR systems as follows:

- Dispersion and attenuation affect both resolutions.
- When the amplitude resolution is improved by sending wider TDR pulses through the cable system, then the time resolution is compromised, i.e. more time for the 100 ns TDR pulse compared to the 25 ns TDR pulse.
- On the contrary, when the time resolution is improved by sending narrower TDR pulses through the cable system, then the amplitude resolution is compromised, i.e. less amplitude for the splice reflection for the 25 ns TDR pulse compared to the 100 ns TDR pulse.

The two last issues are based on the assumption that the amplitude of the sent TDR pulses remains constant. Thus, to overcome this situation, modern TDR systems provide a means of adjusting the amplitude in addition to the width of the pulses; which provides another degree of freedom to the skilled operator. However, in a real case, the operator would have to compromise amplitude or time resolution to find an optimal point for condition assessment using the TDR technique. A conceptual map of the relationship between amplitude and time resolutions appears in Figure 13.

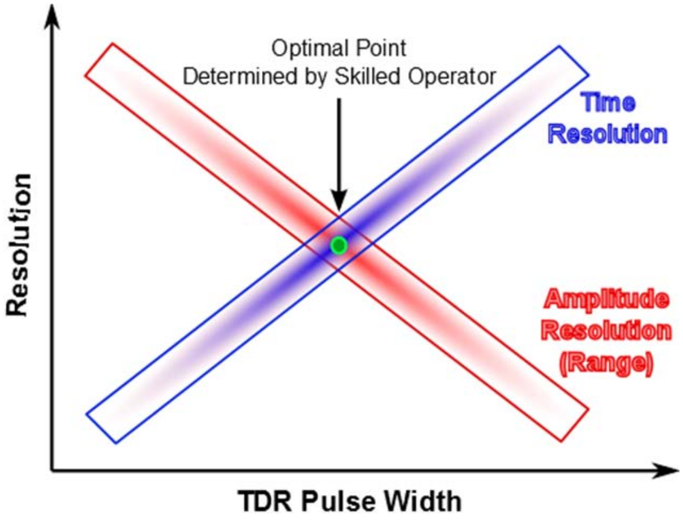


Figure 13: Conceptual Map of the Amplitude (Range) and Time Resolution Relationship

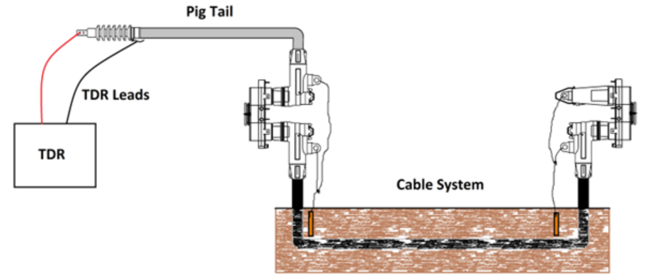
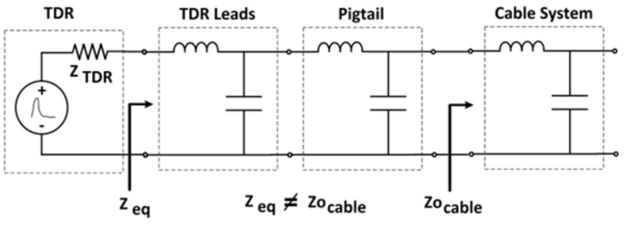
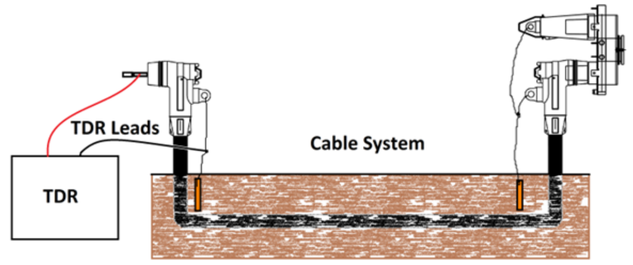
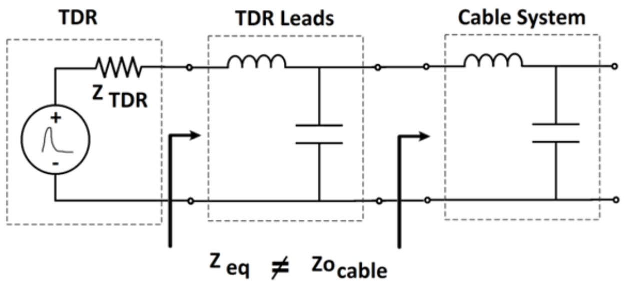
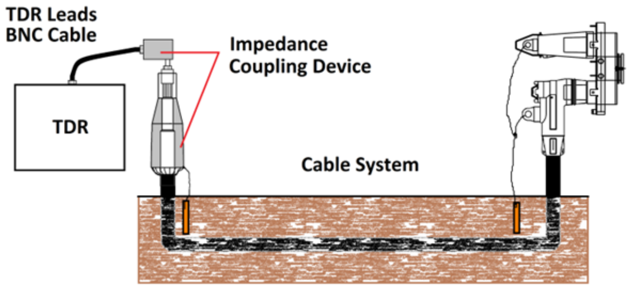
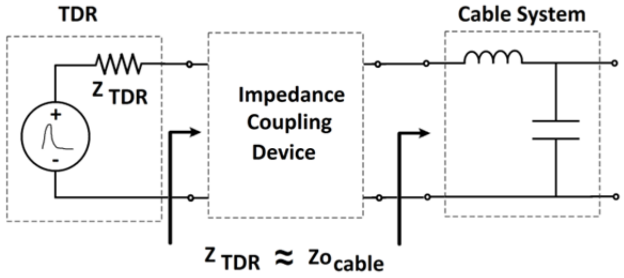
5.6.5 Importance of TDR Pulse Injection

Research shows there are several ways to inject a TDR pulse into a cable system. The main reason for having different pulse injection practices relies on that TDR systems and leads have different characteristic impedance than the cable systems they test. Thus, two issues arise and have to be considered here, they are as follows:

- Initial reflections are expected at the transition point to the cable system; this would cause the TDR pulse energy that is effectively injected into the cable system to be compromised. A reduction in the effectively injected energy of the TDR pulse diminishes both amplitude and time resolutions which consequently adversely affects the possibility of achieving a condition assessment.

- The initial reflection at the transition point would also travel back and forward to the TDR unit, which results in a '"ringing" effect on the TDR trace. The ringing effect is observed on the TDR trace beyond the near end position and thus does not allow any resolution at the near end of the cable; i.e. TDR signature of cable anomalies cannot be established. Therefore, when the ringing is present, the TDR system is "blind" for the first few tens of feet after the near end position; this situation spans up until the TDR trace stabilizes to reference.

Table 7 shows the known practices for TDR pulse injection, the typical deployment and equivalent circuit showing the transition points and characteristic impedance changes are also presented.

<table>
<tr><th colspan="2">Table 7: Known Practices of TDR Pulse Injection</th></tr>
<tr><th>Typical Deployment§</th><th>Equivalent Circuit</th></tr>
<tr><td colspan="2">Common Practice/Simplest Approach</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Better Practice/Approach</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Best Practice/Most Comprehensive Approach</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">§: Far end can also be a termination</td></tr>
</table>

As seen in Table 7, the known practices for TDR pulse injection to a cable system are classified as common, better, and best practices. The ordering here is established by considering the level of ringing for each case, the common practice has the highest level of ringing and the best practice has the lowest.

The common practice considers injecting the TDR pulse through the TDR leads (leads can also be BNC (Bayonet Neill-Concelman) cables) and a pigtail; thus, it has two impedance changes, from the TDR to the pigtail and from the pigtail to the system as seen in the equivalent circuit. This practice is preferred by the utilities since accessories are not removed, and if a follow-up high voltage test is to be deployed after TDR, then only the TDR unit is removed.

To reduce the ringing, the better practice considers injecting the TDR pulse directly into the elbow (or termination). In this case, there is only one transition point from the TDR unit to the cable system. If a high voltage follow-up test is to be deployed, then the pigtail has to be reconnected, which in some cases can be time consuming due to the particular utility's switching policies.

The ringing is driven to its minimum value by the best practice. For this case, the elbow or termination is removed and an impedance coupling device is used to match the cable system characteristic impedance. The impedance coupling device works on the basis that it is possible to change the dimensions of a transmission line without giving it a reactive nature or changing its characteristic impedance. If, for instance, a bigger conductor is used in the impedance coupling device, even though the inductance per unit length is changed (reduced), increasing the spacing proportionately between the conductor and the metallic shield will also reduce the per unit length capacitance and thus the characteristic impedance could remain unchanged, this approach is known as geometrically based impedance coupling (see Figure 14). The changes in the physical dimensions of the geometrically based impedance coupling device are made gradually over a short distance (short relative to the highest frequency wavelength of the TDR pulse spectrum) in order to avoid a sudden change in the characteristic impedance at the transition.

Another possible way of coupling the cable system impedance is to use a network that couples the impedance between the TDR and the system (see Figure 14). This approach has the advantage that the network can be fine-tuned to match as best as possible the system impedance while the geometrical based impedance coupling device is limited to a particular cable size and power system voltage.

As mentioned before, the best practice requires the near end accessory to be removed which adds testing time. The removed accessory is generally replaced by a new one and then a follow-up high voltage test can be deployed.

It is important to mention that in most cases a perfect impedance coupling is not possible; however, practice has shown that the ringing effect can be diminished to an acceptable level thus improving TDR pulse energy transfer to the cable system and amplitude and time resolutions along the full system length. The impedance coupling device is also known as an impedance match (or matching) device; however, as the impedance is never completely matched the term coupling is more suitable for describing such a device. Figure 14 shows the different types of TDR pulse injection using impedance coupling devices.

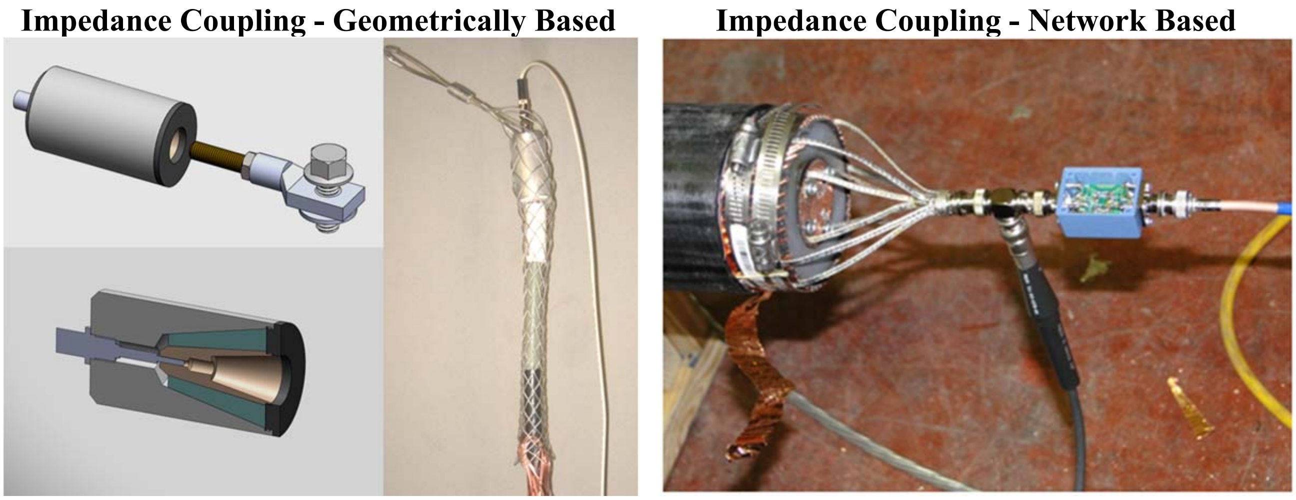


Figure 14: Different Types of TDR Pulse Injection using Impedance Coupling Devices

Figure 15 shows an illustrative example for comparison between two TDR traces, one for injection with TDR leads and pigtail, and the other one for injection with an impedance coupling device.

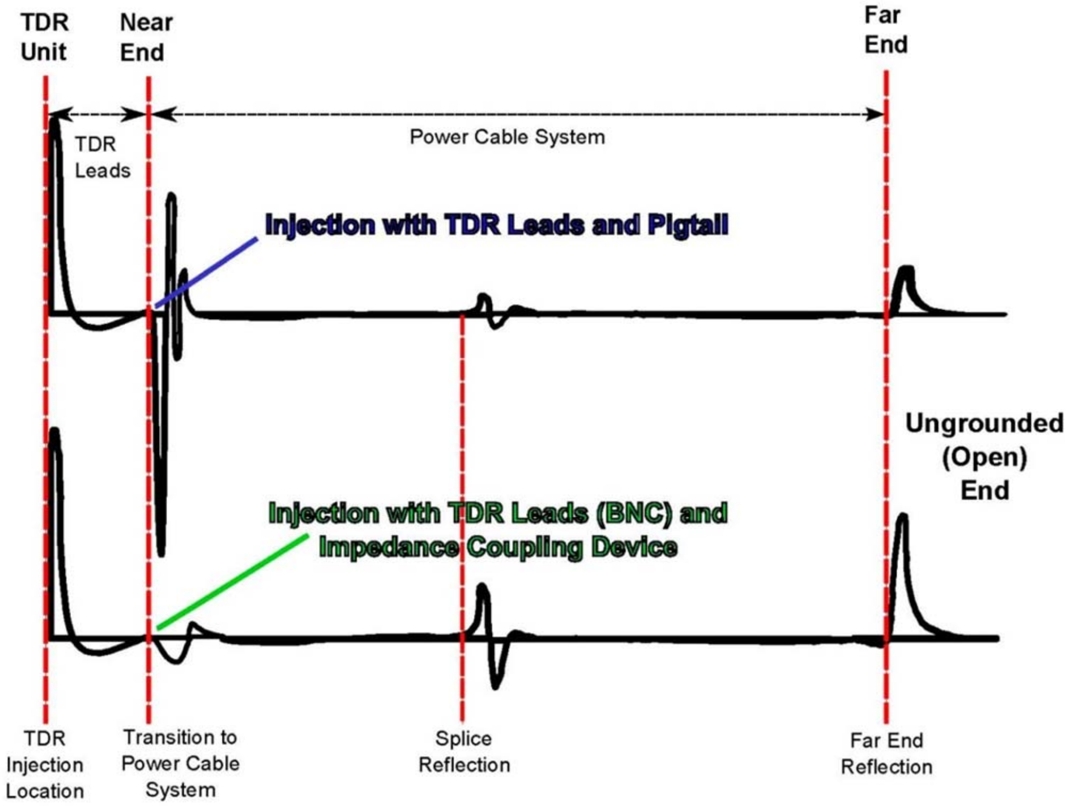
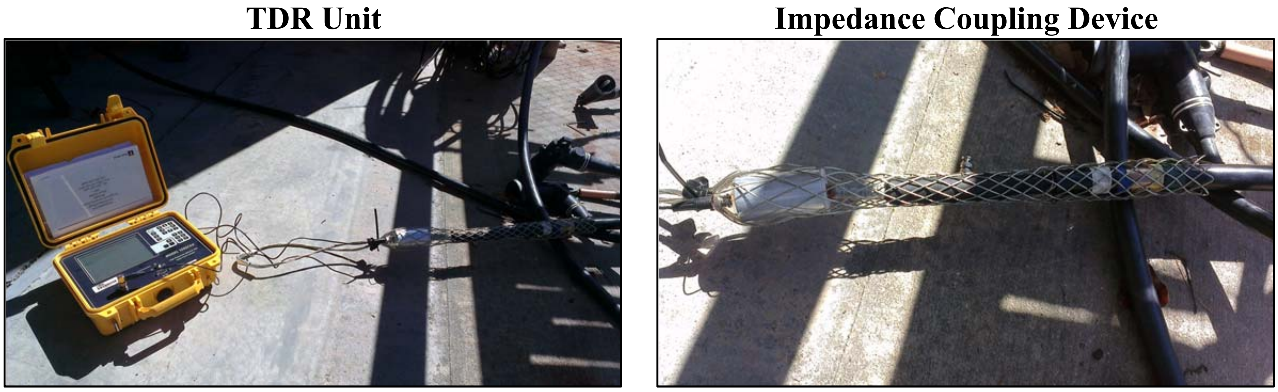


Figure 15: Illustrative Comparison between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device

As seen in Figure 15, when an impedance coupling device is used, then the ringing effect at the transition point to the cable system is reduced and the TDR pulse energy that is injected into the system is higher; this is represented by the better amplitude resolution of the splice and far end reflections.


TDR Unit

Impedance Coupling Device

Figure 16: Test Setup for Comparison of Laboratory Measurements between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device.

To test the concept of TDR pulse injection using an impedance coupling device, laboratory research was undertaken. The laboratory setup appears in Figure 16 and the results are shown in Figure 17. In this case, a geometrically based impedance coupling device is used. The cable is a conventional 15 kV, 1/0, jacketed, XLPE cable.

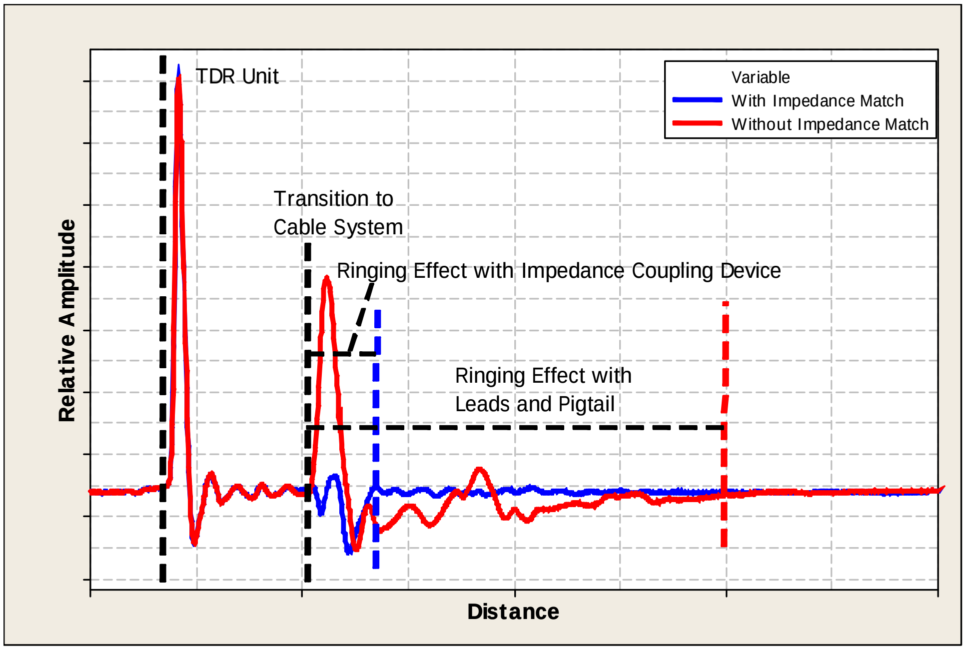


Figure 17: Results for Comparison of Laboratory Measurements between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device

As seen in Figure 17, the impedance coupling device minimizes the ringing effect at the transition point to the cable and thus increases the energy transferred to the system improving the amplitude and time resolutions.

5.6.6 TDR Based Cable Neutral Assessment.

TDR systems can also be used to detect neutral issues; in fact, cable injection providers routinely use them as a means of providing a condition assessment on the neutral prior to injection [2-4]. The neutral condition is imperative before deciding whether to inject a cable system.

A trained operator can provide a qualitative assessment of the amount of neutral corrosion and its location within a circuit by interpreting apparent noise and the reflections in a TDR trace. The apparent noise is correlated with uniform neutral corrosion while the reflections are correlated with localized neutral corrosion or neutral breaks [8-10]. Figure 18 shows examples of the types of signals that may be seen in a TDR trace for both uniform and localized corrosion.

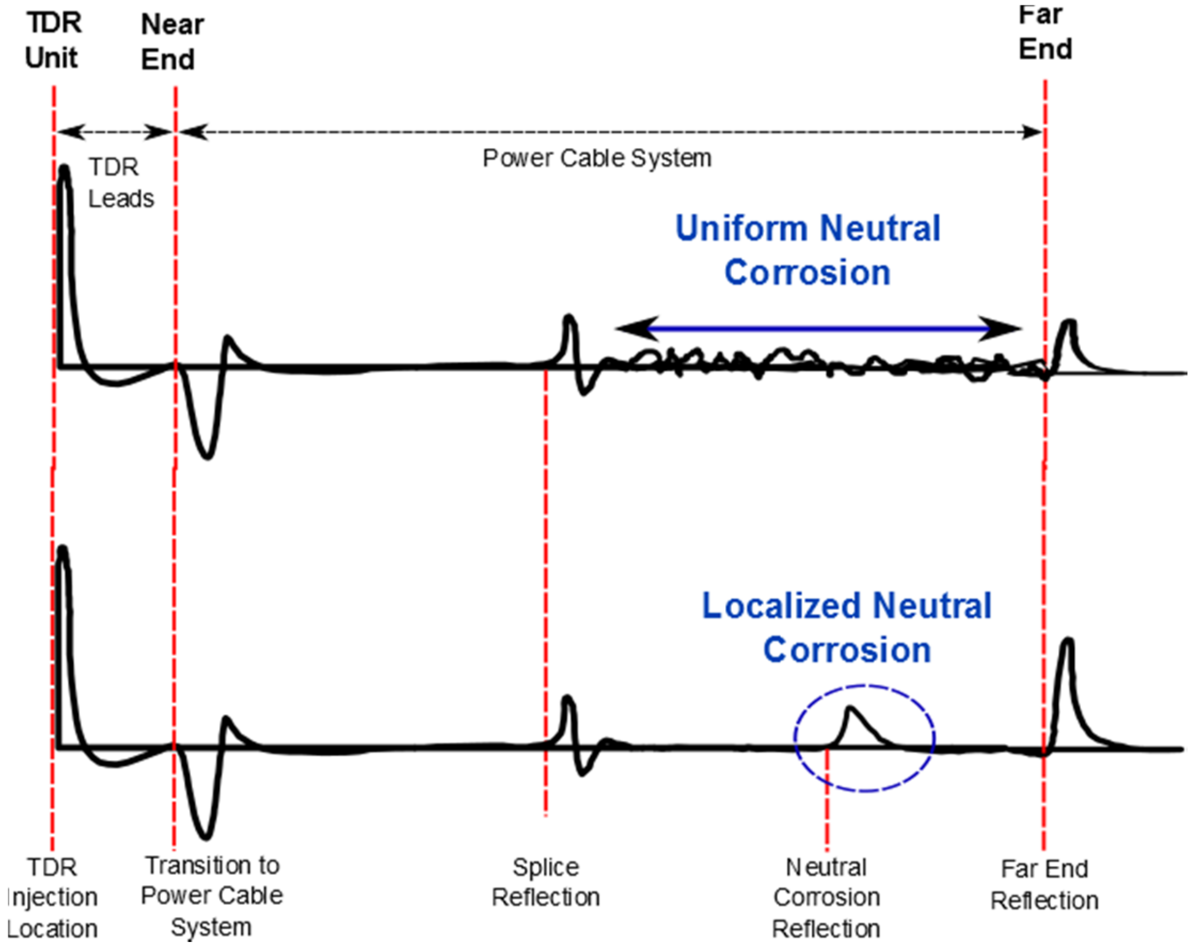


Figure 18: TDR Trace Showing Uniform and Localized Neutral Corrosion Issues

Observe also in Figure 18, that uniform neutral corrosion causes the amplitude resolution to decrease as the reflection from the far end is in this case considerably less than the case of localized neutral corrosion. In a real scenario, both issues could be present in the cable system and one could dominate the other, then it is up to the skilled operator to reach a neutral condition assessment. However, in all cases both types of neutral corrosion are treated as no pass, i.e. the cable system cannot be injected and remedial action must be planned for the future.

Therefore, the *CDFI* perspective regarding cable systems neutral condition assessment via TDR considers either "Good" or "Poor" classes. Alternatively, it has been proposed [7] that the relative heights of the "bumps" in the TDR trace coming from localized neutral issues may be used to assign a condition level to the neutral under test. In fact, this claim is the basis for corrosion categories for detection and evaluation of corrosion of concentric neutral wires presented in the IEEE Std. 1617 [7] (Table 1). The claim appears to be based on practical experience and no literature exists quantifying the issue. Thus, this claim has been proven in laboratory research by performing TDR on a cable system with concentric neutral in which the neutral wires can be switched in and out progressively at a specific location. The actual location at which the neutral wires can be switched in and out appears in Figure 19 and the correlation between the percentage of remaining neutral and amplitude of the reflected TDR pulses appears in Figure 20.

Figure 19: Cable System with Concentric Neutrals in Which Neutral Wires Can Be Switched In and Out Progressively

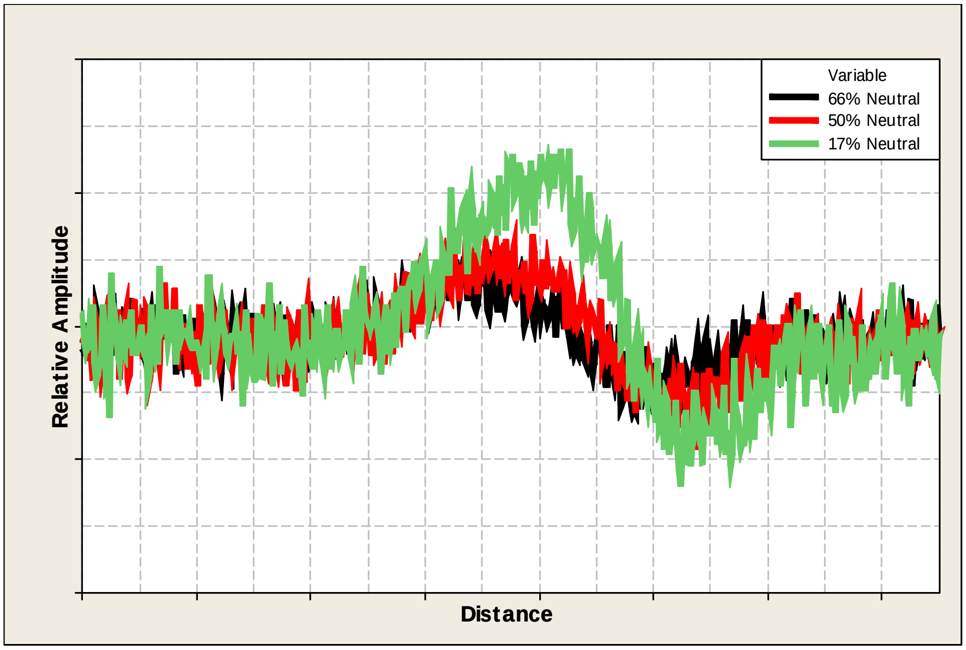
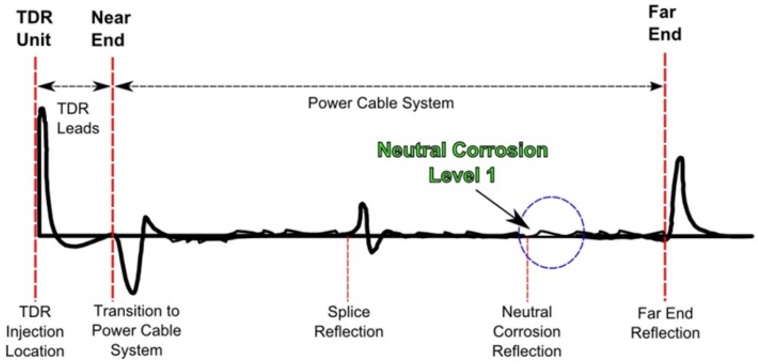
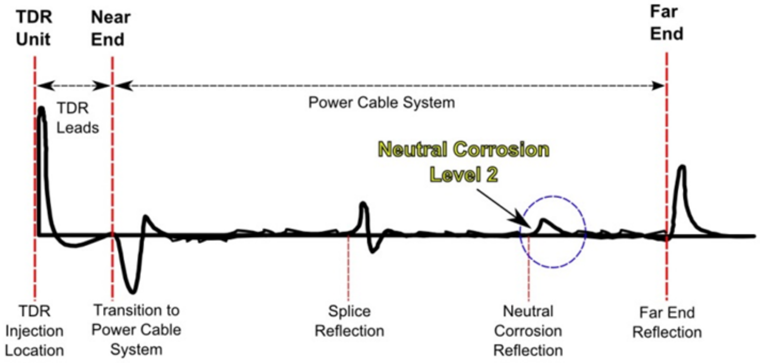
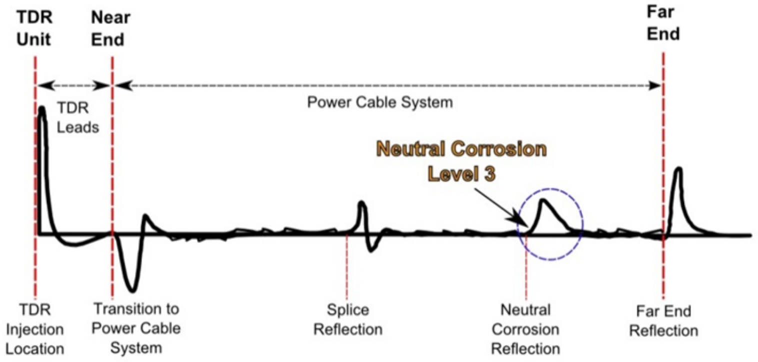
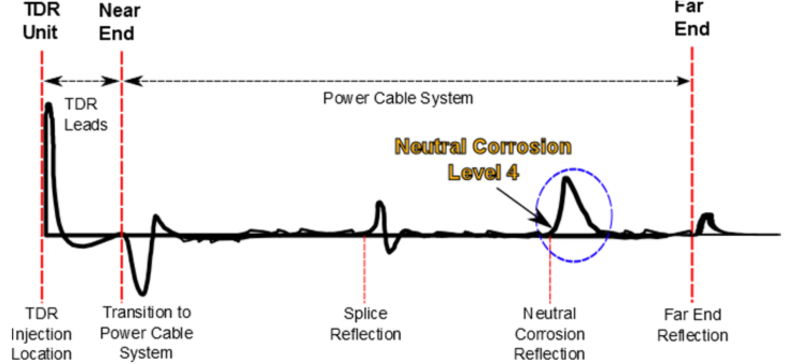
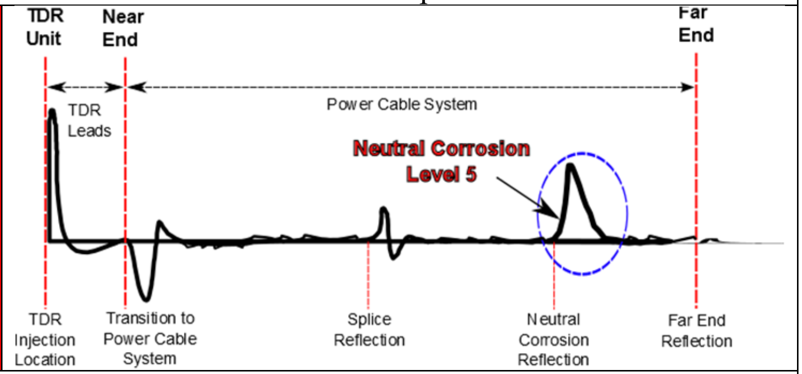


Figure 20: Correlation between Percentage of Remaining Neutral Wires and Amplitude of Reflected TDR Pulses

In Figure 20, there is no question that the percentage of remaining neutral is correlated to the TDR reflection pulse amplitude; small differences are observed between the 50% and 66% while the 17% can be clearly distinguished from both. Thus, the amplitude of the reflected TDR pulse can be used to estimate the level of localized neutral corrosion.

Instead of expressing the level of corrosion in terms of the percentage of the remaining neutral the IEEE Std. 1617 [7] uses the percentage of wires broken or percentage of neutral loss, four levels are considered; however, given the levels, the standard does not provide a prognosis for the condition of the cable system. Guidelines for these levels are provided in IEEE Std. 1617 and appear here in Table 8.

Table 8: Summary of IEEE Std. 1617 [7] Metallic Shield TDR Assessment Levels		
Wires Broken	**Condition**	**Illustrated from Assertions in IEEE Std. 1617 [7]**
Level 1 - No recognizable reflections		
0 – 25%	🟩 **Good**	
Level 2 – Recognizable reflection but smaller than a splice		
25 – 50%	🟩	
Level 3 – Reflection larger than a splice but smaller than the end of the cable		
50 – 75%	🟧	

<table>
<tr><td colspan="3">Level 4 – Reflection larger than the end of cable reflection</td></tr>
<tr><td>75 – 99%</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 [7]</td></tr>
</table>

Within the *CDFI*, a number of issues that might limit the usefulness of the guidelines shown in Table 8 are:

- Not all cable systems have splice locations usable for reference; guidelines should be established to handle such cases.
- Distance from the TDR unit affects the amplitude of the received reflection – a splice located far away has lower amplitude than one located near the sending end.
- Signal amplitudes depend on several factors – system lengths, pulse injection method, pulse width, etc.

Hopefully, these issues will be reviewed during the next update of IEEE Std. 1617 [7]. However, as mentioned before, for purposes of the testing performed in most systems, the five levels in Table 8 are condensed into “Good” and “Poor”. Generally, a “Poor” condition will lead to a full system replacement.

Correlation between Percentage of Remaining Cable Neutral Wires and Age

During *CDFI Phase II*, approximately 500 TDR tests have been performed on a variety of cable systems including URD and transmission. If the age of the cable system is known, then the neutral condition assessment based on TDR measurements in conjunction with the age can be used to estimate the change in the percentage of the remaining neutral wires vs. age of the cable system.

Once this information becomes available, it is extremely useful for asset management. For instance, the utility cable engineer can then more ably manage the cable system by taking into account the statistical probabilities of neutral degradation during a given time frame.

Unfortunately, when determining the change in the percentage of the remaining neutral wires in tandem with their ages, the complete dataset of approximately 500 TDR tests cannot be used. Only those TDR tests that showed neutral corrosion with documented cable ages were considered; accordingly, approximately 100 cable systems met these criteria. Between those that are considered, the condition assessment of the neutral wires is set at the 50% for class separation; i.e. if the percentage of remaining neutral wires is less than 50%, then the system is considered to have a "Poor" neutral and thus it is classified as a "Fail". In contrast, if the percentage of the remaining neutral is greater than 50 %; then, the cable system is considered to have a "Good" neutral and it is classified as a "Pass." It is important to note two issues about the threshold level for the percentage of remaining neutral, they are as follows:

- Due to the nature of the statistical analysis, the threshold level is not a definite value and thus has a confidence interval related to a probability that the value is accurate.
- A value of 50% is considered here; however, it can be adjusted to another level according to the utility requirements, heuristic rules learned with time, correlation between classification and performance, and simply because of evolution of the database.

The correlation between percentage of remaining neutral wires and age appears in Figure 21. The information presented in Figure 21 can also be understood as a probabilistic predictive model for neutral corrosion based on TDR measurements.

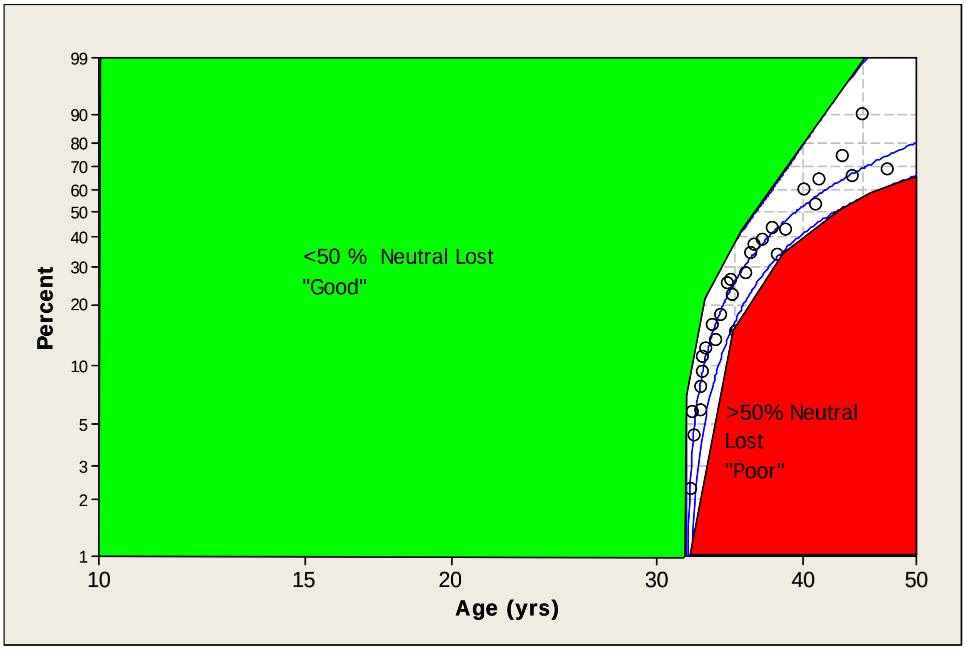


Figure 21: Research Showing the Correlation between Percentage of Remaining Cable Neutral Wires and Age

In Figure 21, the "Good" neutral condition is represented by the green area and the "Poor" neutral condition is represented by the red one. The confidence intervals are also shown and represent the 95% confidence level. Another important issue to note is that there is a threshold age level of approximately 30 years before a cable system reaches any neutral loss. Figure 21 also shows that the correlation between neutral condition and age is not linear and the percentage of cable affected increases rapidly after the age threshold level. This can be better understood by looking at Table 9 which contains information extracted from Figure 21 of the mean percentage of remaining cable neutral wires as a function of age.

Table 9: Percentage of Lost Cable Neutral Wires as a Function of Age

Age [yr]	Mean Percentage [%]
30	< 1
35	27
40	54
45	70
50	80

As seen in at Table 9, research shows that it takes on average 40 years to lose approximately 50% of the neutral wires and 50 years for an 80% loss.

5.7 Outstanding Issues

5.7.1 Connection 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 measurements since the capacitance between leads changes according to how they are placed for the test. Therefore, using BNC TDR leads with as short as possible transition wires is always advisable.

Another issue for the TDR leads is their length. If short leads are used, the ringing effect at the near end of the system might make that location challenging. The location of the near end is important for accessory and anomalies location and pinpointing. Therefore, to overcome this issue and always have a clear position for the near end, the use of long leads is recommended. In field tests, a length of 30 ft. has shown to be a good choice as at that length the leads have a low attenuation and dispersion and perform well in most cases. In addition, the same length and thus leads must be used for all tests. In this case, comparisons between different tests become possible because the attenuation and dispersion due to leads is equal. Figure 22 shows an illustration for comparing the use of short and long TDR leads.

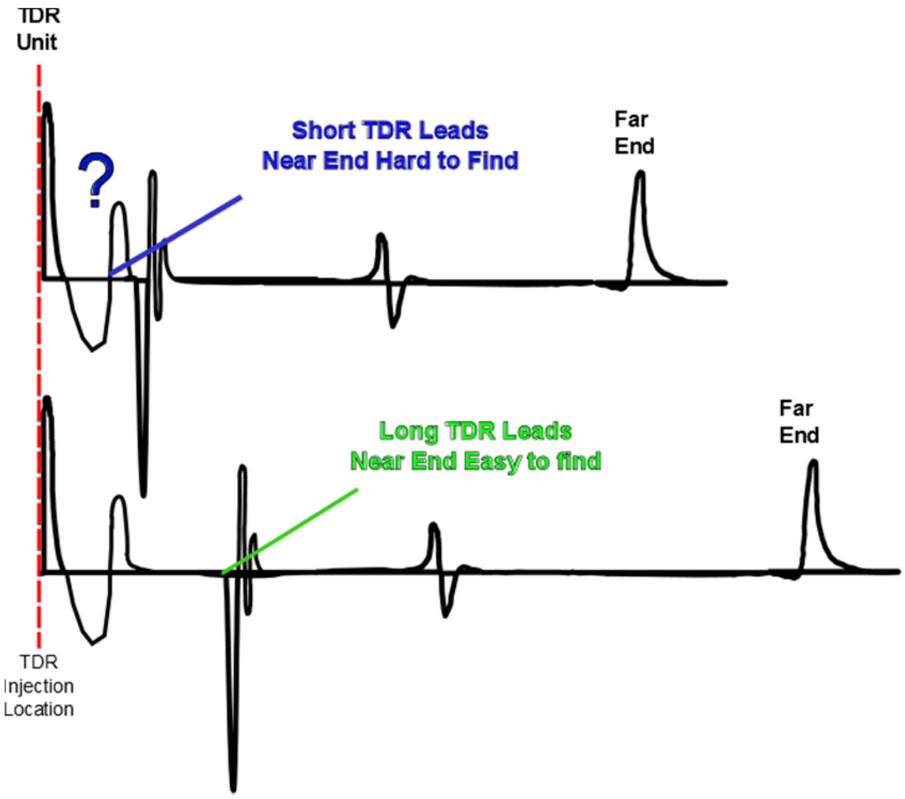


Figure 22: Illustration for Comparing the Use of Short and Long TDR leads

5.7.2 Identifying the Far End

If there is doubt about the far end location on the TDR trace, a good practice for identifying it is to simply compare the TDR traces for the conditions of grounded and ungrounded far end. In this case only the far end reflection is affected by changing polarity, not amplitude. This situation is illustrated in Figure 23 where a comparison between TDR traces for the same cable system for grounded and ungrounded far end is presented.

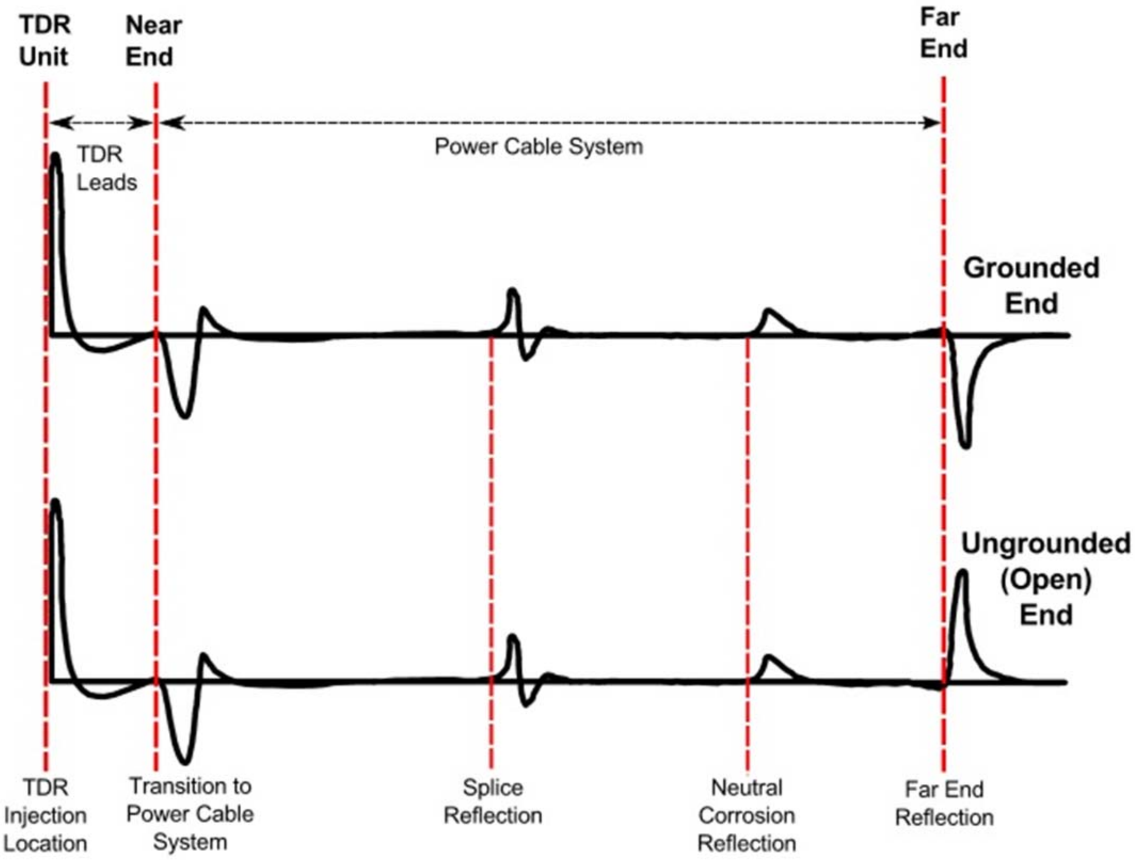


Figure 23: Comparison between TDR Traces for the Same Cable System for Grounded and Ungrounded Far End.

5.7.3 "Ghost" Reflections

Even though TDR is a useful tool for diagnosing potential cable system problems, there are some issues when interpreting the TDR trace. If the issues are not understood and addressed, they can lead to confusing results that do not correspond to the actual condition of the cable system under test. In particular, the issues are related to what it is called here TDR "Ghost" reflections.

The TDR "Ghost" reflections are signatures that appear on the TDR trace that do not correspond to any splice or anomaly present in the system. They are the result of the reflected and transmitted TDR pulses travelling along the system in both directions, i.e. from near to far end and vice versa. The TDR "Ghost" reflections depend on three variables: 1) the location of splices or anomalies, 2) the number of splices or anomalies, and 3) how they affect the cable characteristic impedance. Thus, the TDR "Ghost" reflections are pervasive with hundreds to thousands of possible combinations when considering all possible cable system configurations, splice and anomaly types, and operating conditions.

The extensive nature of the TDR "Ghost" reflections makes it impossible to cover and understand all of the possible cases. However, a better understanding of TDR "Ghost" reflections can be attained through the analysis of basic case studies. This knowledge would hopefully lead to improved TDR trace interpretation in real field testing scenarios. . Six case studies are presented here (see Table 10):

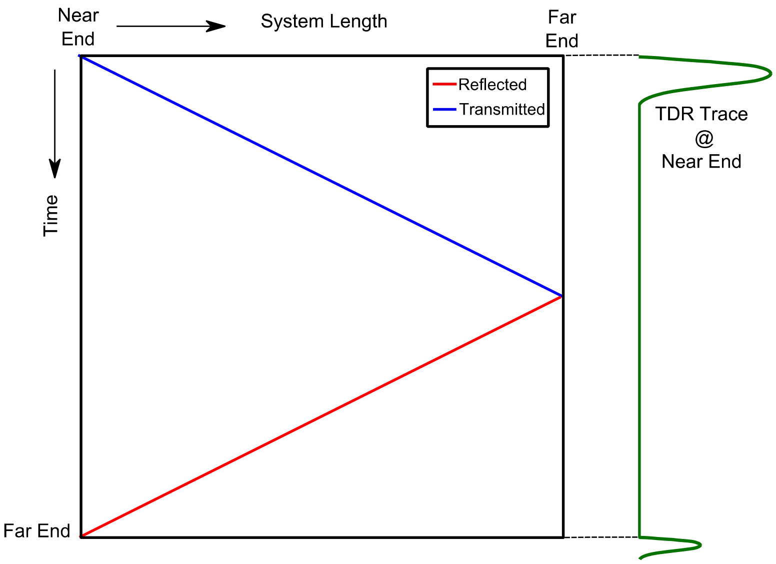
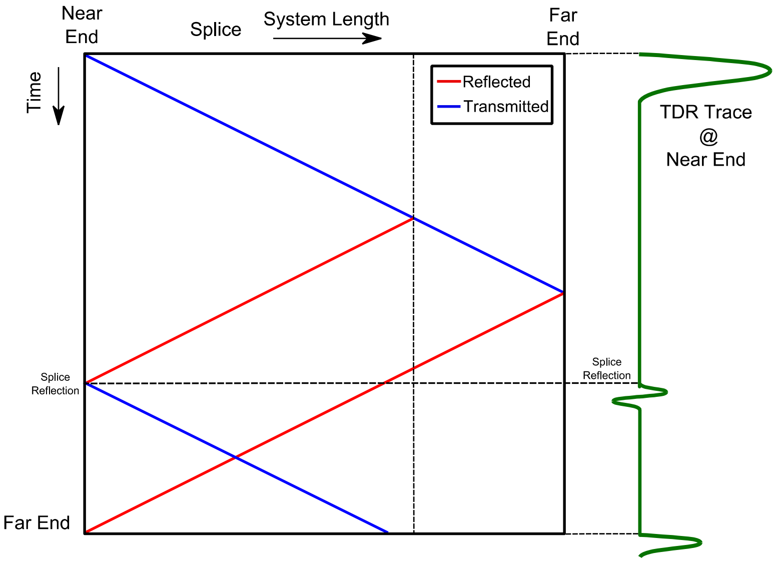
- **Case 1:** Cable system with no splices or anomalies.
- **Case 2: C**able system with one splice located farther than 50% of the cable system length as measured from the near end.
- **Case 3:** Cable system with one splice located at the exact midpoint of the cable system length.
- **Case 4:** Cable system with one splice located between the near end and midpoint of cable system length.
- **Case 5:** Cable system with two splices located at arbitrary positions.
- **Case 6:** Same as Case 5; however, it considers the use of impedance coupling at the near end.

Keeping track of the TDR pulse reflections and refractions as they travel back and forth on the cable system is tedious. However, this analysis can be accomplished graphically by the use of bounce diagrams. The bounce diagram is a graphical analysis technique which 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. In other words, the bounce diagram provides a pictorial tool showing clearly how incident TDR pulses reflect, refract, and combine along the length of the cable system over time. To draw a bounce diagram for the initial incident, reflected, and transmitted TDR pulses, a series of parameters and facts must be considered. Therefore, prior to interpreting the bounce diagram, some cable system parameters must be estimated and facts established including:

- The characteristic impedance of the cable used in the cable system.
- Knowledge of the reflection coefficients at the cable system ends and splice or anomaly locations.
- The horizontal axis (X-axis on the bounce diagram) represents the position along the cable system.
- The vertical axis (Y-axis on the bounce diagram) represents the elapsed time from the initial injected TDR pulse at the near end.
- The bounce diagram is a zigzag line that clearly shows the progress of TDR pulses as they travel and get reflected and transmitted through the cable system.
- The 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.
- The first reflected TDR pulse occurs at the first splice 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.

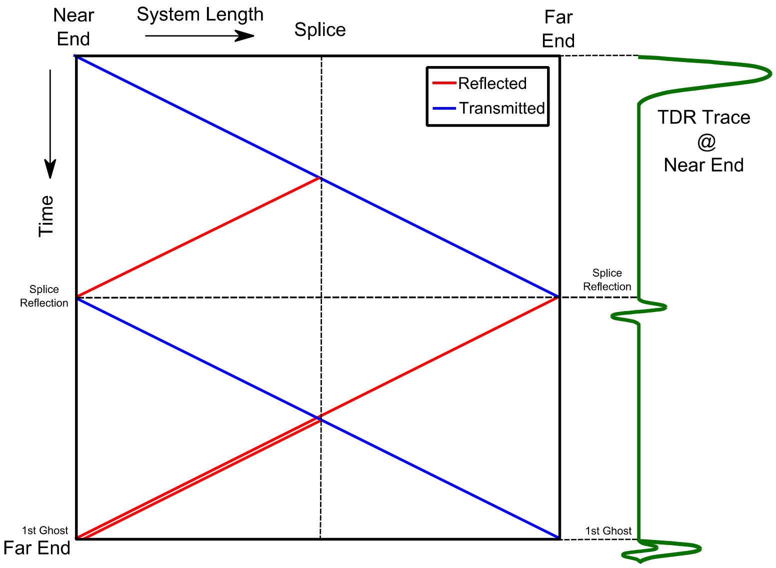
- The TDR trace as seen in the near end can be determined from the bounce diagram by following the vertical line that goes through X=0 (near end position).
- Slopes/gradients represent the velocity of propagation of the TDR pulses through the system; lower gradients equal higher propagation velocities.

The case studies, their corresponding bounce diagram and TDR trace appear in Table 10.

<table>
<tr><th colspan="2">Table 10: Illustrative Case Studies for TDR “Ghost” Reflections</th></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">Case 2: Cable System with One Splice Located Farther than the 50% of the 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 discounted.</td><td>
</td></tr>
</table>

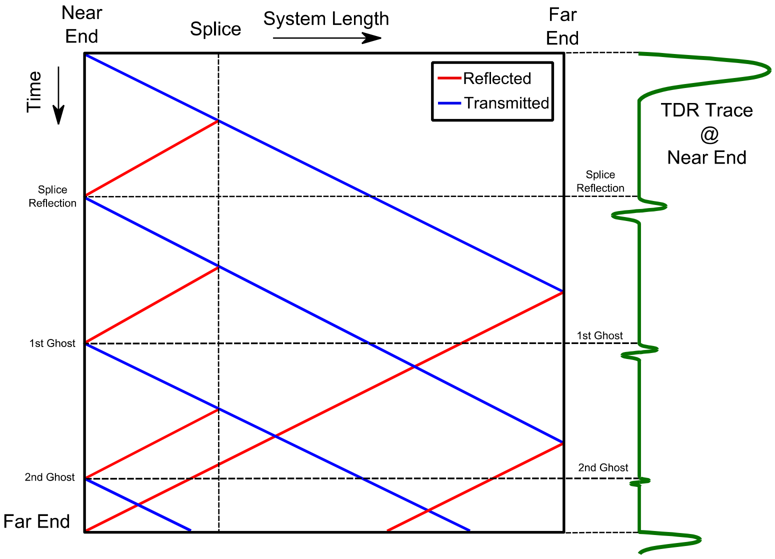
<table>
<tr><th colspan="2">Table 10: Illustrative Case Studies for TDR “Ghost” Reflections</th></tr>
<tr><td colspan="2">Case 3: Cable System with One Splice Located at the Exact Midpoint of the Cable System Length</td></tr>
<tr><td>

- 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.

</td><td>


</td></tr>
<tr><td colspan="2">Case 4: Cable System with One Splice Located between the Near End and the Midpoint of the Cable System Length</td></tr>
<tr><td>

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

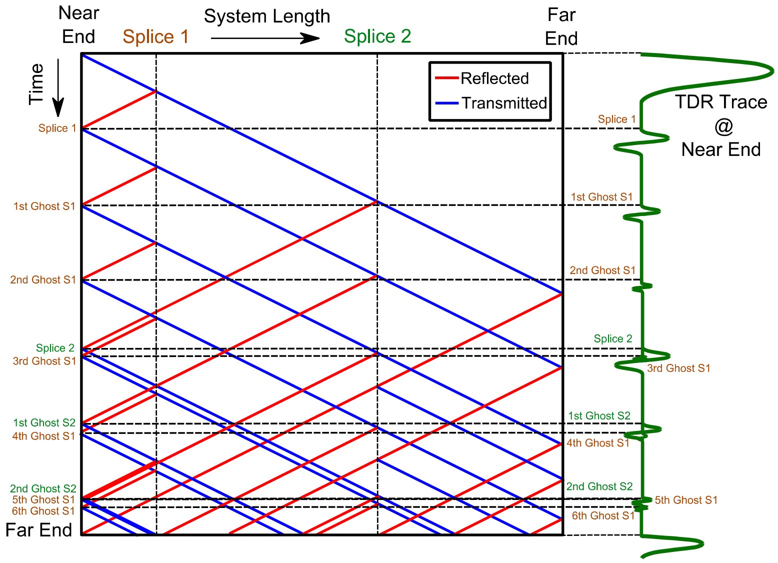
</td><td>


</td></tr>
</table>

<table>
<tr><th colspan="2">Case 5: Cable System with Two Splices Located at Arbitrary Positions</th></tr>
<tr><td>

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

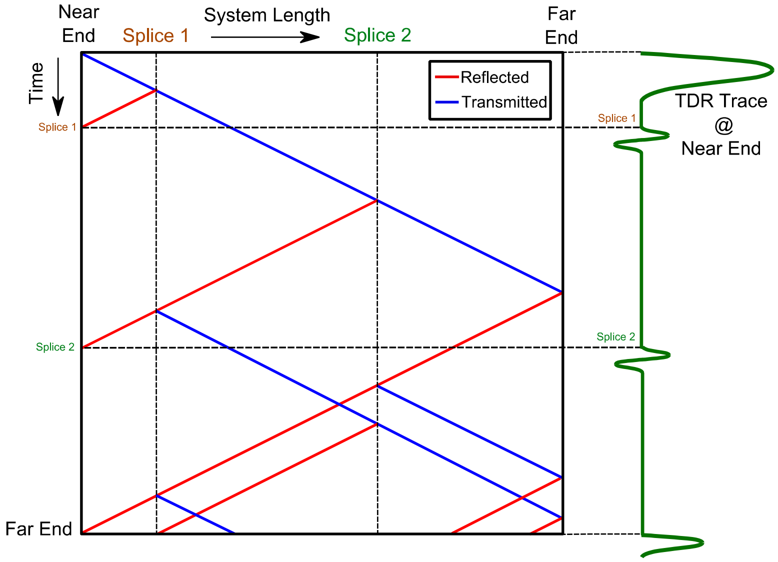
</td><td>



</td></tr>
<tr><th colspan="2">Case 6: Same as Case 5 Considering the Use of Impedance Coupling at Near End</th></tr>
<tr><td>

- 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.

</td><td>



</td></tr>
</table>

As seen in Table 10, when dealing with TDR “Ghost” reflections, the following points are important:

- The first reflection captured by the TDR unit always corresponds to a splice or anomaly irrespective of where the splice/anomaly is located.
- When one splice or anomaly exists beyond 50% of cable system length, then TDR “Ghost” reflections are not an issue.
- The TDR “Ghost” reflections start to appear only if the splices 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 splices or additional anomalies.

- The attenuation and dispersion effects as well as spacing between “Ghosts” can help identify TDR “Ghost” reflections.
- The issue can be ameliorated by having a better TDR pulse injection and impedance coupling device. In this case, the impedance match between the TDR unit and cable system would absorb all the reflections coming back from splices or anomalies at the near end; therefore, potentially avoiding many TDR “Ghosts”.
- The TDR “Ghosts” reflections between splices or splices and anomalies are impossible to control and are always present at some level; however, the magnitude of their presence depends on the number of splices or anomalies, their relative locations,, and the length of the cable system.
- 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 24, for a 25 kV WTRXLPE URD cable system of approximately 5,211 ft. and with two splices. A TDR pulse of 100 ns was injected without an impedance matching device. The cable system structure (splice locations) was known beforehand.

Figure 24: 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)

As seen in Figure 24, two “Ghosts” for each splice are visualized in the TDR trace. The “Ghosts” can be easily identified here because of the correlation between the spacing between them and their respective splice and also their attenuation and dispersion. For example, the distance between “1st Ghost S1” and the “Splice 1” is the same as the distance between “1st Ghost S1” and “2nd Ghost S1”; conversely, “2nd Ghost S1” is more attenuated and dispersed than “1st Ghost S1” and “1st Ghost S1” more attenuated and dispersed than “Splice 1”. The same also holds true for “Splice 2” and its “Ghosts”. In fact, the bounce diagram presented in Table 10 for two splices corresponds to the TDR trace shown in Figure 24; however, the other predicted “Ghosts” for “Splice 1” are not observed on the TDR trace. This is due to the attenuation and dispersion they suffer causing 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 24 has been relatively straightforward, this is because the cable system configuration could be postulated and thus a correlation can be made between the expected TDR "Ghost" reflections and the observed TDR trace. In a more realistic case, if the system structure is unknown, then an operator unaware of this issue could conclude that the system has six splices - a completely erroneous assessment. A well-trained operator, before reaching a TDR condition assessment, would have to correlate the TDR trace with different possible scenarios and choose the one that best represents the situation observed on the TDR trace; this is when the bounce diagram is most valuable.

5.7.4 Far End Deployment

In the common case, TDR is only deployed from only 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 when the TDR is deployed from both ends. Therefore, 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 estimated and actual lengths.
- There is doubt about the presence and type of an anomaly.
- There is a need to pinpoint an accessory or anomaly.

5.7.5 Pinpointing an Accessory or Anomaly

From a financial and power quality perspective, the importance of pinpointing an accessory or anomaly in a cable system is increasing; knowing the cable system structure with some level of certainty is becoming imperative. This is because faults that occur in any part of the system may often engender severe economic losses. A more accurate knowledge of the cable system structure would facilitate inspections, maintenance, and repairs; yielding a more reliable and secure system by reducing outage times, revenue losses, and repair crew costs.

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 VoP: As mentioned earlier, different cables have different VoPs. To assure the most accurate conductor distance measurements, the cable VoP must be determined. Therefore, the *CDFI* perspective shown here 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 25 is the same as Figure 1 and shows different underground cable system layouts. Figure 26 shows the corresponding illustrative TDR traces for the different layouts in Figure 25.

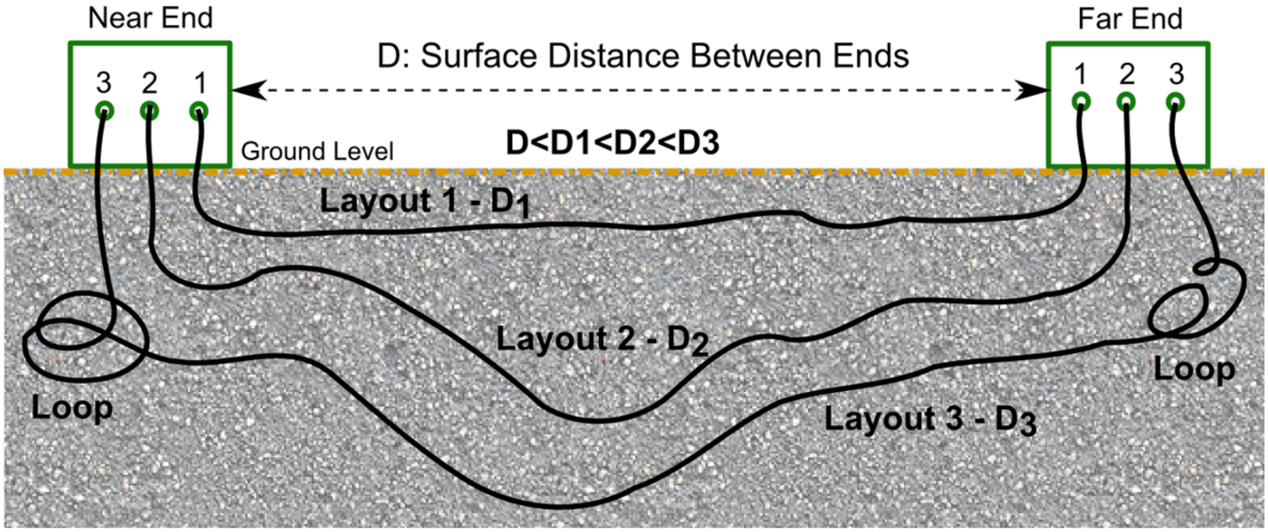


Figure 25: Different Underground Cable System Layouts

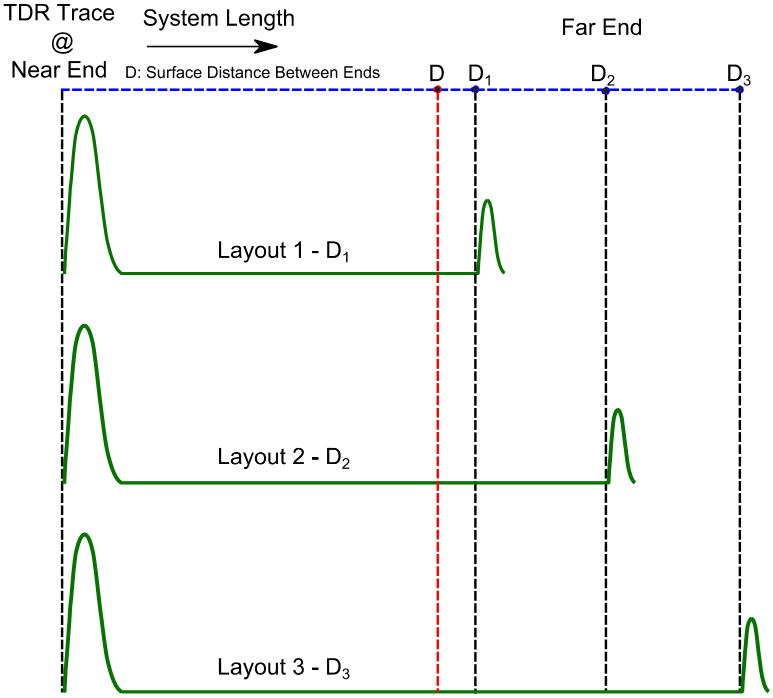


Figure 26: Illustrative TDR Traces for the Different Underground Cable System Layouts Shown in Figure 25

As seen in Figure 26, 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 affects the TDR unit. It may be thought; that this overestimation issue can be solved by adjusting (increasing) 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. In addition, because of the uncertainty regarding the precise cable system layout, adjusting the VoP to match the surface distance between ends is not a good practice and should be avoided. The VoP has to be determined or estimated according to the cable under test.

This situation imposes an issue which is a conundrum for pinpointing a splice or anomaly on a cable system based on TDR measurements. This is illustrated in Figure 27.

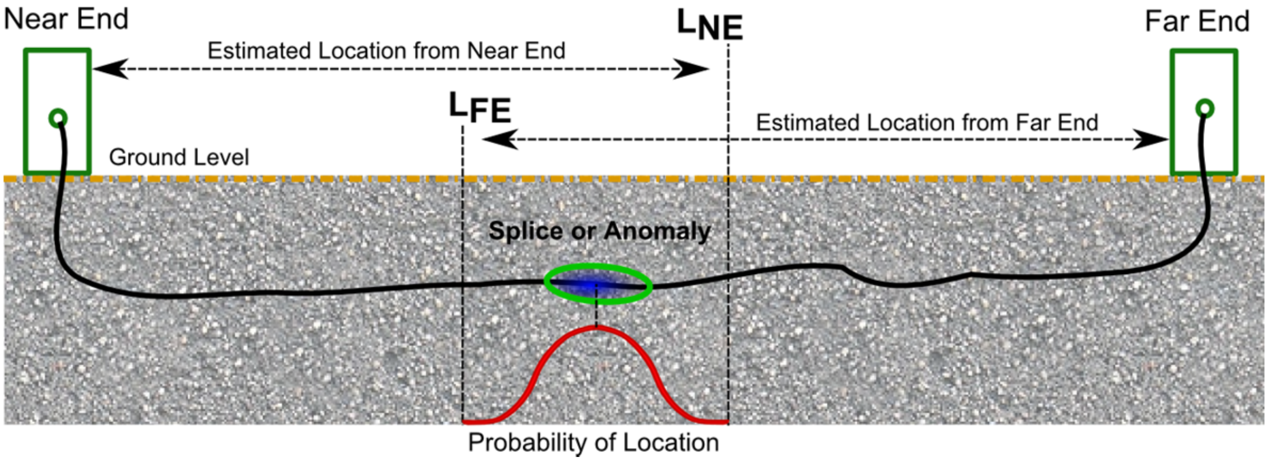


Figure 27: Conundrum for Pinpointing a Splice or Anomaly based on TDR Measurements

As seen in Figure 5, the TDR is deployed from both ends and in each case the splice or anomaly location is over estimated; however, the TDR pinpointing has the advantage that the limits L_{NE} and L_{FE} are identified, the splice or accessory would be located with a high degree of certainty between them. In Figure 27, the probability of the location of the splice or accessories occurring between the limits is represented by the red curve; 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 splice or anomaly is not found at that location; then repair crews should start digging in both directions until it is found. This is the best practice when using TDR to find splices or anomalies on an underground cable system.

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 more, 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 here.

5.7.6 Operator Training

Beyond hardware and software, the success of cable system 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 a trivial process. 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.

5.7.7 VoP Error

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 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.

5.8 References

1. User's Manual – SebaKMT TDR, Model Easyflex Com.
2. N.H. Rahim, I.S. Chairul, S. Ab-Ghani, M.S. Ahamadkhiar, N. Abas, and Y.H.Molfhayoob, "Simulation of TDR circuit for the analysis of wave propagation in XLPE cable model," Proceedings of the IEEE International Conference on Power Energy (PEcon), Dec. 2012, pp. 796-801.
3. NOVINIUM©, "Novinium rejuvenation instructions: power cables, inspect & pinpoint," Version 20130212, 2013, pp. 1-17.
4. W. Stagi, W. Chatterton, "Cable rejuvenation – past, present and future," International Conference on Insulated Power Cables, JICABLE-2007, 2007, paper No. C-7214.
5. O.E. Morel, "The role of time domain reflectometry in cable systems diagnostics," UtiliX Corporation, presented in the IEEE-PES Insulated Conductor Committee (ICC), Fall 2011, Denver, 2011.
6. J.A. Strickland, "Time domain reflectometry measurements," Tektronix Measurement Concepts, 2013.
7. IEEE, "IEEE guide for detection, mitigation, and control of concentric neutral corrosion in medium-voltage underground cables," IEEE Std. 1617-2007, Feb. 2008
8. K. Abdolall, G. Halldorson, and D. Green, "Condition assessment and failure modes of solid dielectric cables in perspective," IEEE Transactions on Power Delivery, Vol. 17, No.1, pp. 18-24, Jan. 2002.
9. S. Boggs, "Failure mechanisms of shielded power cable related to high ground shield resistance and/or insulation of neutral wires from the ground shield," IEEE Transactions on Power Delivery, Vol. 17, No. 2, pp. 295-301, Apr. 2002.
10. J. Hanck and G. Nekoksa, "Research to develop guidelines for cathodic protection of concentric neutral cables," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No.7, pp. 1878-1887, July 1982.

5.9 Relevant Standards

- IEEE Std. 1617 – 2007: *IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables*.