Computer-Based Electronics Training System

Transmission Lines in Communication Systems
FACET®

Courseware Sample

36970-F0

Order no.: 36970-00
First Edition
Revision level: 02/2015

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Printed in Canada

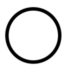
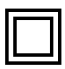
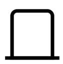
ISBN 978-2-89289-842-2 (Printed version)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2005
Legal Deposit – Library and Archives Canada, 2005

Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
~	Alternating current
	Both direct and alternating current
3~	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

Table of Contents

Introduction

The Transmission Lines circuit board provides students with the theory and measurement skills required to implement and test transmission lines into real-world designs. The student first learns the principles and operational characteristics of transmission lines. The student then learns how to conduct transmission line measurements under transient (step testing) conditions, and sinusoidal steady-state conditions. Finally, the student acquires a valuable foundation in the theory and practice of time domain reflectometry (TDR) and impedance matching and transformation.

The circuit board uses two RG-174 coaxial cables of 24 meters (78.7 feet) each, that can be used alone or connected end-to-end. Each line has five probing points that permit observation and measurements of the signal along the entire length of the line, using an oscilloscope.

Two generators are provided to study the line behavior: a step generator that produces 50-kHz voltage steps for transient behavior testing, and a signal generator that produces a sinusoidal voltage of variable frequency (5 kHz - 5 MHz) for steady-state behavior testing. Each generator has several BNC outputs providing different output impedances.

A load section, consisting of a configurable network of resistors, inductors, and capacitors, permits connection of different load impedances to the receiving end of each line.

The circuit board may be used in the F.A.C.E.T. base unit, or as a stand-alone unit:

– When used in the FACET base unit, the course can be performed through the interactive computer-based learning (CBL) format. Moreover, faults can be inserted into the circuits to allow the student to develop troubleshooting capabilities.
– When used as a stand-alone unit, the course is performed in a conventional way by using the provided Student and Instructor Guides.

Courseware Outline

TRANSMISSION LINES IN COMMUNICATION SYSTEMS

Introduction

Installation of the Circuit Board and Insertion of Faults

Unit 1 Characteristics of Transmission Lines

The different types of transmission lines used. Equivalent circuit of a transmission line. Characteristic impedance, impedance mismatch, attenuation, and distortion. Transient behavior of transmission lines terminated by different resistive load impedances.

Ex. 1-1 Introduction to the Transmission Lines Circuit Board

Familiarization with the various sections of the Lab-Volt TRANSMISSION LINES circuit board. Thevenin equivalent of an electrical linear circuit. Determining the voltage across a load connected to a generator, using the Thevenin equivalent and the voltage divider rule.

Ex. 1-2 Velocity of Propagation

Measuring the velocity of propagation of a signal in a transmission line, using the step response method. Determining the relative permittivity of the dielectric material used to construct this line, based on the measured velocity of propagation.

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Behavior of a transmission line terminated by various resistive load impedances, when voltage steps are launched into the line. Measuring the characteristic impedance of a line, using two different methods: with a variable load resistor, or through measurement of the rising edge of the launched step.

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Courseware Outline

TRANSMISSION LINES IN COMMUNICATION SYSTEMS

Unit 2 Transmission Line Measurements Under Transient (Step Testing) Conditions

Distributed inductance and capacitance of a line, and how they relate to characteristic impedance and velocity of propagation. The voltage reflection diagram. Transient behavior of transmission lines terminated by complex load impedances. Using time-domain reflectometry (TDR) to locate and identify discontinuities (impedance changes) along a line.

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Measuring the distributed capacitance and distributed inductance of a line, in order to infer its characteristic impedance and velocity of propagation.

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Ex. 2-3 Transient Behavior of a Line Terminated by Complex Load Impedances

Step response signal of a line terminated by various complex (inductive or capacitive) load impedances.

Ex. 2-4 Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

Using techniques based on time-domain reflectometry (TDR) to detect and locate discontinuities (impedance changes) along transmission lines.

Ex. 2-5 Troubleshooting

Locating and identifying the nature of discontinuities (faults) introduced by your instructor along the transmission lines of the circuit board, using time-domain reflectometry.

Courseware Outline

TRANSMISSION LINES IN COMMUNICATION SYSTEMS

Unit 3 Transmission Line Measurements Under Sinusoidal (Steady-State) Conditions

Electrical length, standing waves, and voltage standing wave ratio (VSWR). Parameters related to the transfer and loss of power in transmission lines: insertion loss, return loss, and mismatch loss. The Smith Chart and its various uses. Impedance transformation and matching with quarter-wavelength (λ/4) line sections.

Ex. 3-1 Standing Waves and Voltage Standing Wave Ratio (VSWR)

Creation of standing waves on transmission lines. Characteristics of a standing wave based on the nature of the impedance mismatch at the origin of this wave. Measuring the voltage standing-wave ratio (VSWR) on a line.

Ex. 3-2 Effects of Attenuation on the VSWR

Definition and calculation of important parameters related to the transfer and loss of power in mismatched transmission lines: insertion loss, return loss, and mismatch loss. Calculation of the VSWR in a lossless line in terms of the reflection coefficient at the load. Effect that attenuation has on VSWR measurements in lines that are lossy.

Ex. 3-3 The Smith Chart, Resonant Lines, and Impedance Transformation

How the input impedance of a mismatched line varies as a function of the electrical length of the line. Resonant lines. The Smith Chart and how it is used to determine the input impedance of a line that is not terminated by its characteristic impedance. Using quarter-wavelength (λ/4) line sections to perform impedance transformation and matching.

Appendices
- **A New Terms and Words**
- **B Step Response Signal For Various Load Impedances**
- **C The Voltage Reflection Diagram**
- **D Graph for Plotting the Standing Waves on the Trainer Transmission Lines**
- **E The Smith Chart**

Bibliography

Sample Exercise

Extracted from

Transmission Lines

in Communication Systems

Exercise 2-4

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

EXERCISE OBJECTIVES

In this exercise, you will learn how discontinuities along transmission lines are detected and located, using techniques based on time-domain reflectometry (TDR).

DISCUSSION

Time-Domain Reflectometers (TDR's)

A **discontinuity** is a change in impedance along a transmission line. Discontinuities can be due, for example, to broken conductors, loose connectors, shorted conductors, sheath faults, mismatched load, etc.

If, for example, the two conductors of a twisted-pair line are spaced apart at some point along the line, this will create an impedance discontinuity at that point and, therefore, a reflection. Similarly, if the dielectric of a coaxial line is crushed at some point along the line, the impedance discontinuity at that point will create a reflection.

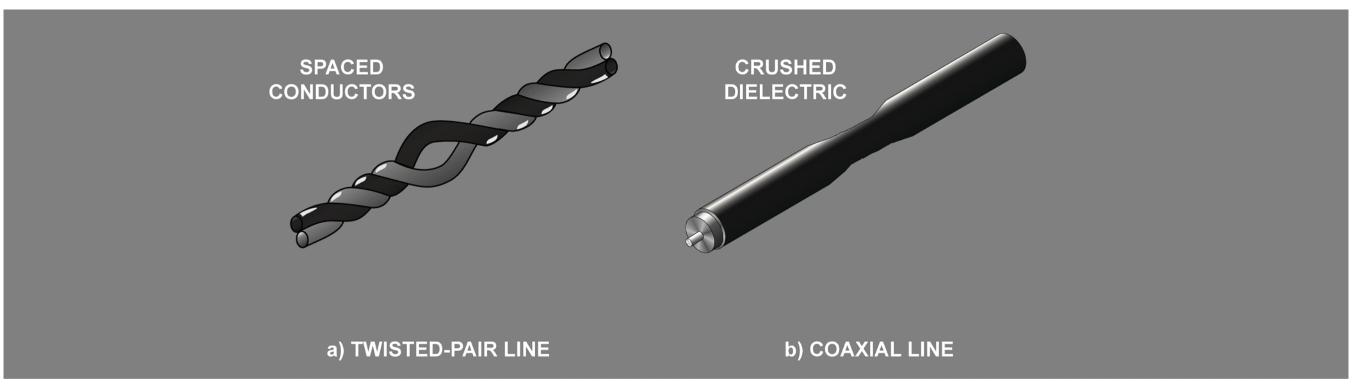

Figure 2-70. Discontinuities along a twisted-pair line and a coaxial line.

A **time-domain reflectometer** is an instrument used to detect and locate discontinuities along transmission lines. A TDR consists of a step generator and a high-speed oscilloscope combined in a single unit, as Figure 2-71 shows.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

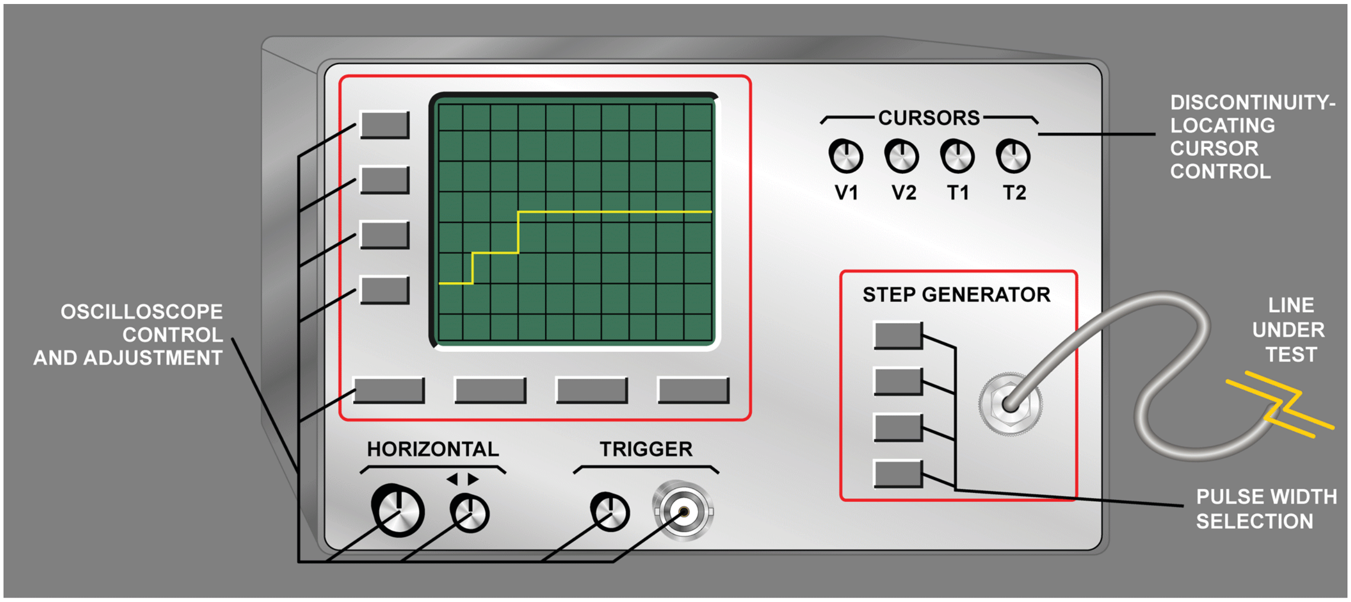

Figure 2-71. A time-domain reflectometer.

To detect and locate discontinuities, a TDR uses the same technique as bats or radars: the echo technique.

- The step generator launches a pulse into the line under test.
- When the pulse encounters a discontinuity along the line, or a mismatched load at the end of the line, part of the pulse energy is reflected back to the TDR for display on the oscilloscope.

The signal displayed by the TDR is, therefore, the algebraic sum of the incident pulse voltage and reflected voltage. The TDR signal is often called the **signature** of the line, because it reveals the presence and nature of discontinuities, if any.

Examples of TDR Signals

Figure 2-72 shows a TDR signal for a coaxial line that is free from discontinuity, but that is terminated by a load whose impedance does not match the characteristic impedance of the line. The signal shows the beginning of the launched pulse.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

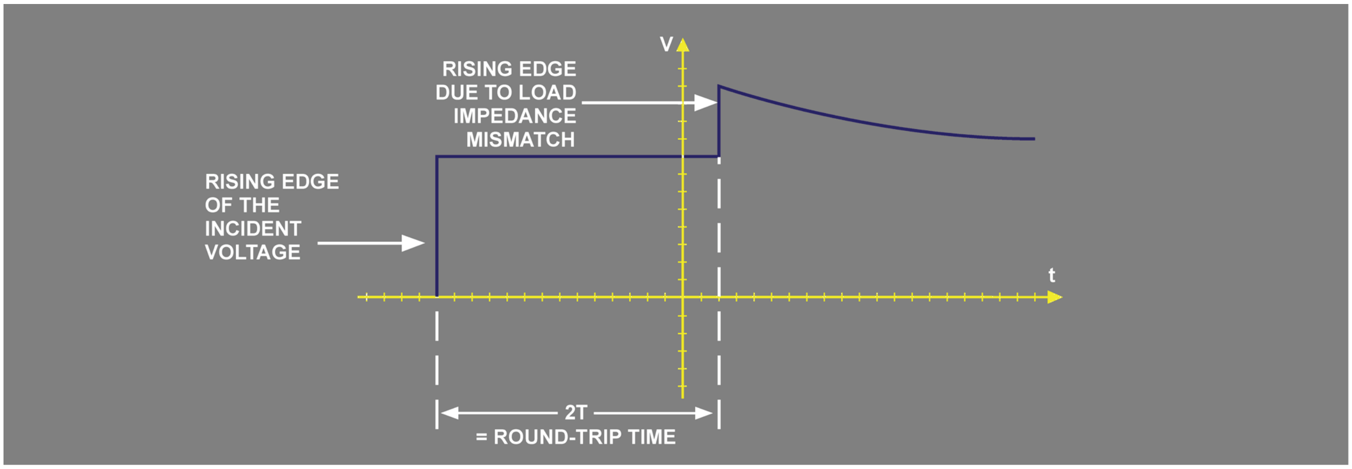

Figure 2-72. TDR signal for a coaxial line terminated by a load whose impedance does not match the characteristic impedance of the line.

In that particular case, the actual length of the line can easily be determined, using the steps below.

- The time between the rising edge of the incident voltage and the leading or falling edge that follows it, due to the impedance mismatch at the load, is measured on the TDR oscilloscope.
- The measured time, equal to the round-trip time, 2T, is then converted to length, using the equation below:

$$l = \frac{v_P \cdot 2T}{2}$$

where l = Length of the line (m or ft);
v_P = Velocity of propagation of the pulse in the line (m/s or ft/s);
$2T$ = Round-trip time, i.e. time taken by the launched pulse to travel from the TDR to the receiving end of the line and back again to the TDR (s).

Discontinuities cause voltage transients of different shapes that add up to or subtract from the voltage in the TDR signal. For example, Figure 2-73 shows a TDR signal for a coaxial line that has two discontinuities:

- a warped area that compresses the inner conductor of the line, creating a partial open circuit (increase in the resistance) of this conductor;
- a crushed area that creates a complete short circuit across the inner and outer (shield) conductors of the line.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

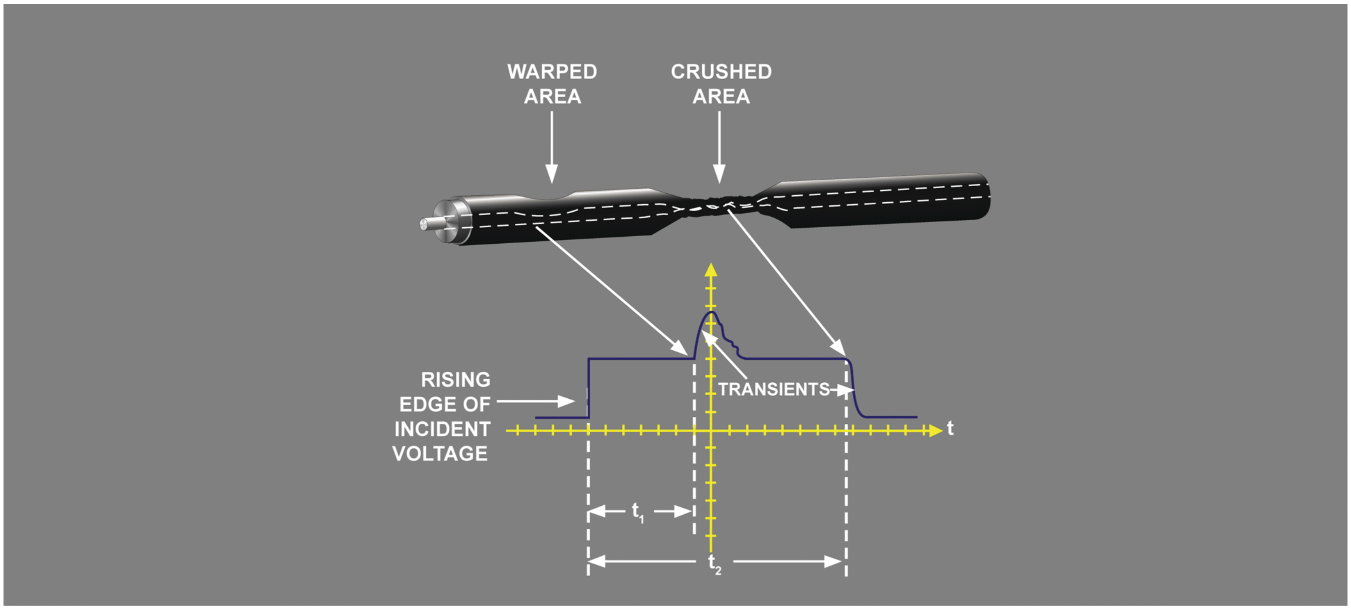

Figure 2-73. TDR signal for a line that has two discontinuities.

The distance from the TDR to a discontinuity can easily be determined by measuring, on the TDR oscilloscope, the time between the rising edge of the incident voltage and the rising or falling transient caused by the reflecting discontinuity. The measured time can then be converted to distance, using the formula below:

$$D = \frac{v_P \cdot t_n}{2}$$

where D = Distance from the TDR to a given discontinuity (m or ft);
v_P = Velocity of propagation in the line (m/s or ft/s);
t_n = Time taken by the launched pulse to travel from the TDR to the discontinuity and back again to the TDR (s).

The formula indicates that the distance from the TDR to a discontinuity varies in direct proportion to the transit time to the discontinuity.

The shape of a rising or falling transient in the TDR signal indicates the nature of the discontinuity that causes this transient: purely resistive, mostly inductive, or mostly capacitive. Moreover, the magnitude of the transient reveals how significant the discontinuity is. The greater the magnitude of the transient, the more severe the discontinuity. The nature and severity of the transient both give clues to the probable cause(s) of the fault.

TDR's normally have a selectable pulse width. The larger the pulse width, the farther the pulse can travel along a line and, therefore, the longer the line length that can be tested. However, the narrower the pulse, the better the detection of discontinuities located near the TDR or near each other. Consequently, when testing a line, the shortest pulse width should be selected first to make sure that discontinuities located a short distance from the TDR will not go undetected. The line can then be tested again by using larger pulse widths.

Nowadays, digital TDR's are available that use digital techniques to automatically provide information on the location and magnitude of the major discontinuities on a digital readout.

Procedure Summary

In this procedure, you will measure the length of a line by using time-domain reflectometry.

PROCEDURE

Measuring the Length of a Line by Using Time-Domain Reflectometry

☐ 1. Make sure the TRANSMISSION LINES circuit board is properly installed into the Base Unit. Turn on the Base Unit and verify that the LED's next to each control knob on this unit are both on, confirming that the circuit board is properly powered.

☐ 2. Referring to Figure 2-74, connect the STEP GENERATOR 50-Ω output to the sending end of TRANSMISSION LINE A, using a short coaxial cable. Connect the receiving end of TRANSMISSION LINE A to the sending end of TRANSMISSION LINE B, using a short coaxial cable. Leave the BNC connector at the receiving end of TRANSMISSION LINE B unconnected. This places the impedance of the load at the receiving end of the line made by TRANSMISSION LINEs A and B connected end-to-end in the open-circuit condition (∞ Ω).

Using an oscilloscope probe, connect channel 1 of the oscilloscope to the sending end of the line [that is, to the 0-meter (0-foot) probe turret of TRANSMISSION LINE A]. Connect the STEP GENERATOR 100-Ω output to the trigger input of the oscilloscope, using a coaxial cable.

The connections should now be as shown in Figure 2-74.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

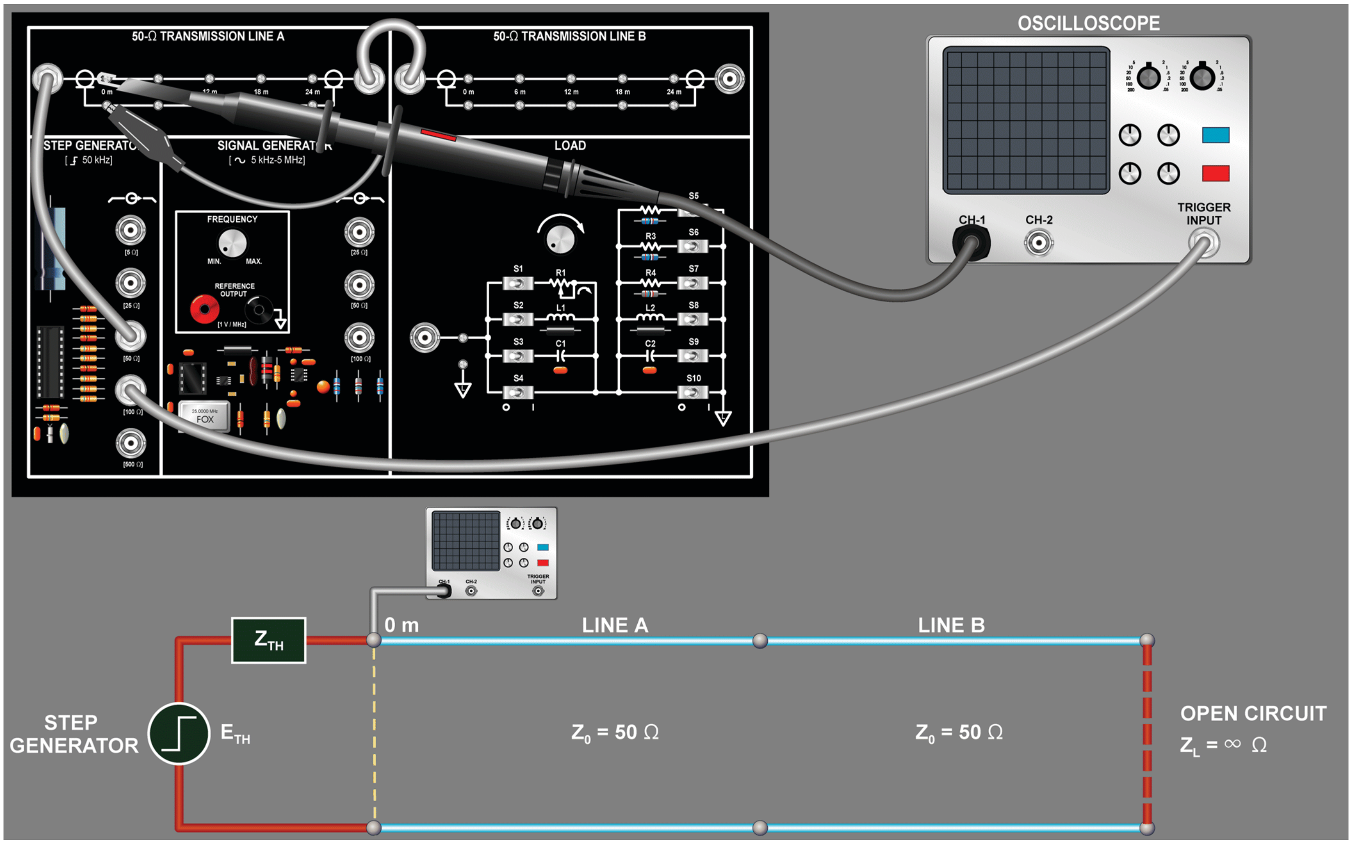

Figure 2-74. Measuring the length of a line by measuring time-domain reflectometry (TDR).

☐ 3. Make the following settings on the oscilloscope:

Channel 1	
Mode	Normal
Sensitivity	0.2 V/div
Input Coupling	DC
Time Base	2 µs/div
Trigger	
Source	External
Level	0.3 V
Input Impedance	1 MΩ or more

☐ 4. On the oscilloscope, observe the step response signal at the sending end of the line.

Since the receiving end of the line is in the open-circuit condition, a reflected voltage adds up to the voltage in the step response signal, as Figure 2-75 shows. Is this your observation?

☐ Yes ☐ No

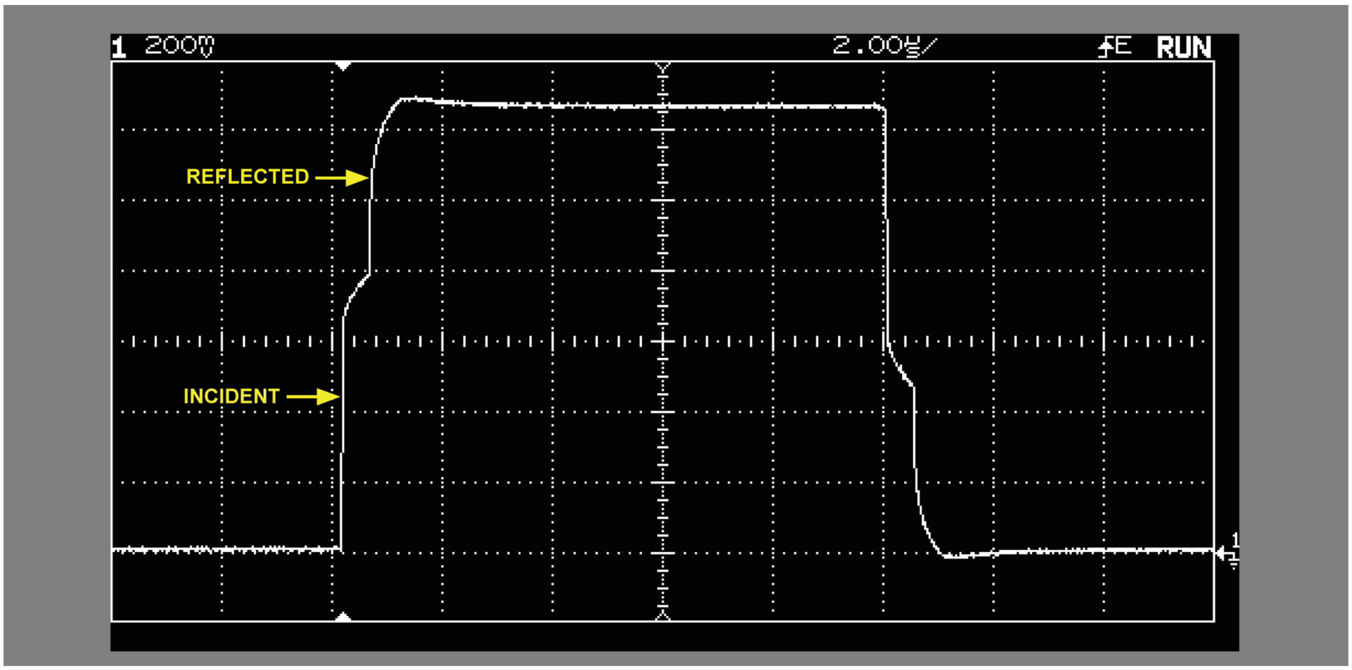

Figure 2-75. Step response signal when the receiving end of the line is left unconnected.

☐ 5. Decrease the oscilloscope time base to 0.1 µs/div in order to be able to see the initial rising edge of a pulse more distinctly, as Figure 2-76 shows.

Measure the time 2T (round-trip time) separating the rising edge of the incident voltage from the rising edge that follows it, due to the impedance mismatch at the load.

2T = ______ $\cdot 10^{-9}$ s

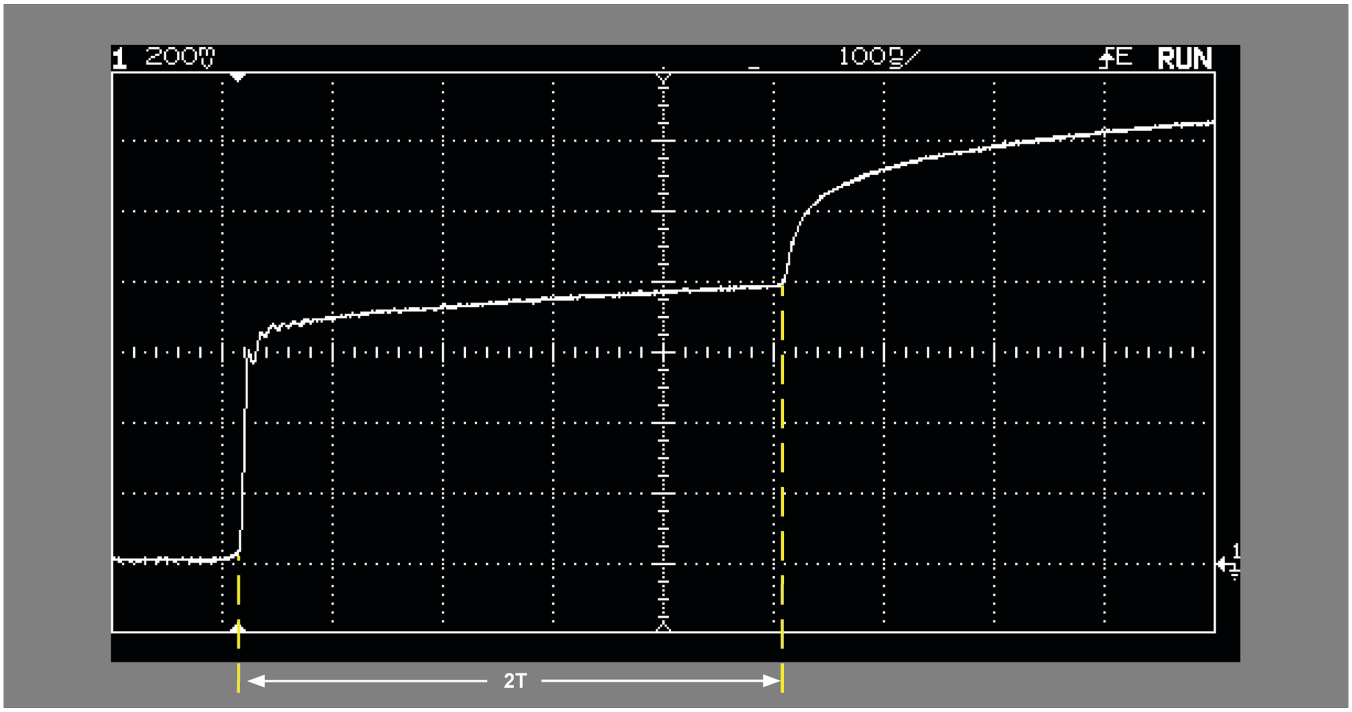

Figure 2-76. Measuring time 2T with TRANSMISSION LINEs A and B connected end-to-end.

☐ 6. Based on the time 2T measured in the previous step, and on a velocity of propagation, v_P, of $2.0 \cdot 10^8$ m/s or $6.5 \cdot 10^8$ ft/s, (i.e., 66% of the velocity of light in free space), calculate the length of the line made by TRANSMISSION LINEs A and B connected end-to end, l_{AB}.

$$l_{AB} = \frac{v_P \cdot 2T}{2}$$

l_{AB} = ______ m (or ft)

Is the obtained length near the theoretical value of 48 m (157.4 ft) [that is, the total line length made by TRANSMISSION LINEs A and B connected end-to-end]?

☐ Yes ☐ No

☐ 7. Reduce by half the length of the line. To do so, remove the coaxial cable between the receiving end of TRANSMISSION LINE A and the sending end of TRANSMISSION LINE B. Leave the BNC connector at the receiving end of TRANSMISSION LINE A unconnected.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

☐ 8. Set the oscilloscope time base to 0.05 μs/div.

As Figure 2-77 shows, measure the time 2T (round-trip time) separating the rising edge of the incident voltage from the rising edge that follows it, due to the impedance mismatch at the load.

$2T = \_\_\_\_\_\_ \cdot 10^{-9}$ s

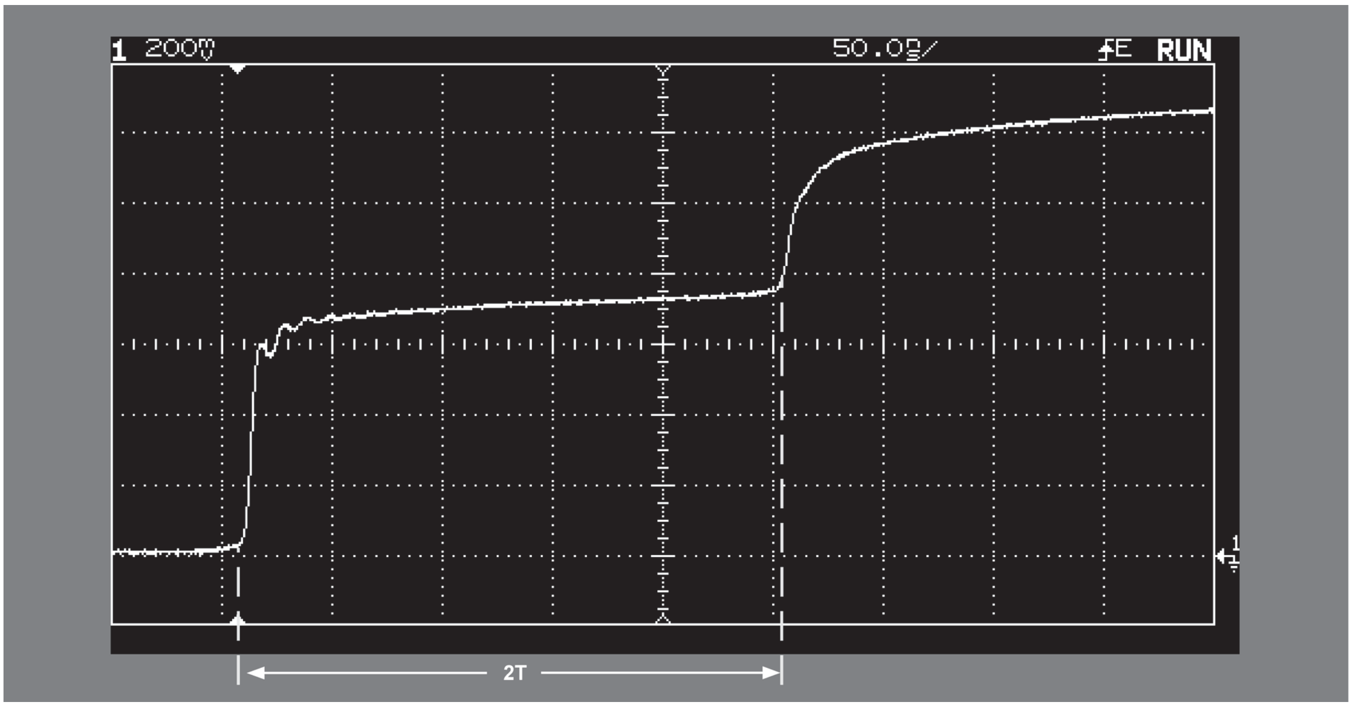

Figure 2-77. Measuring time 2T with a single line.

☐ 9. Based on the time 2T measured in the previous step, and on a velocity of propagation, v_P, of $2.0 \cdot 10^8$ m/s, or $6.5 \cdot 10^8$ ft/s (i.e., 66% of the velocity of light in free space), calculate the length of TRANSMISSION LINE A used alone, l_A.

$$l_A = \frac{v_P \cdot 2T}{2}$$

$l_A = \_\_\_\_\_\_$ m (or ft)

Is the obtained length for a single line, l_A, approximately half the length previously measured when both lines A and B were connected end-to-end, l_{AB}?

☐ Yes ☐ No

☐ 10. Set the oscilloscope time base to 2 μs/div.

☐ 11. Using a coaxial cable, connect the receiving end of TRANSMISSION LINE A to the BNC connector at the LOAD-section input.

Place the impedance of the load at the receiving end of TRANSMISSION LINE A in the short-circuit condition (0 Ω). To do so, set the toggle switches in the LOAD section in such a way as to connect the input of this section directly to the common (i.e. via no load), and observe what happens to the step response signal (see Figure 2-78).

From your observation, when the load impedance is changed from the open- to the short-circuit condition, the polarity of the reflected voltage

a. changes from positive to negative, causing this voltage to add up to the voltage in the step response signal.
b. changes due to a change in the nature of the load mismatch, causing this voltage to subtract from the voltage in the step response signal.
c. remains unchanged, since the nature of the load remains unchanged.
d. changes from negative to positive, due to a corresponding reversal of polarity of the reflection coefficient at the load.

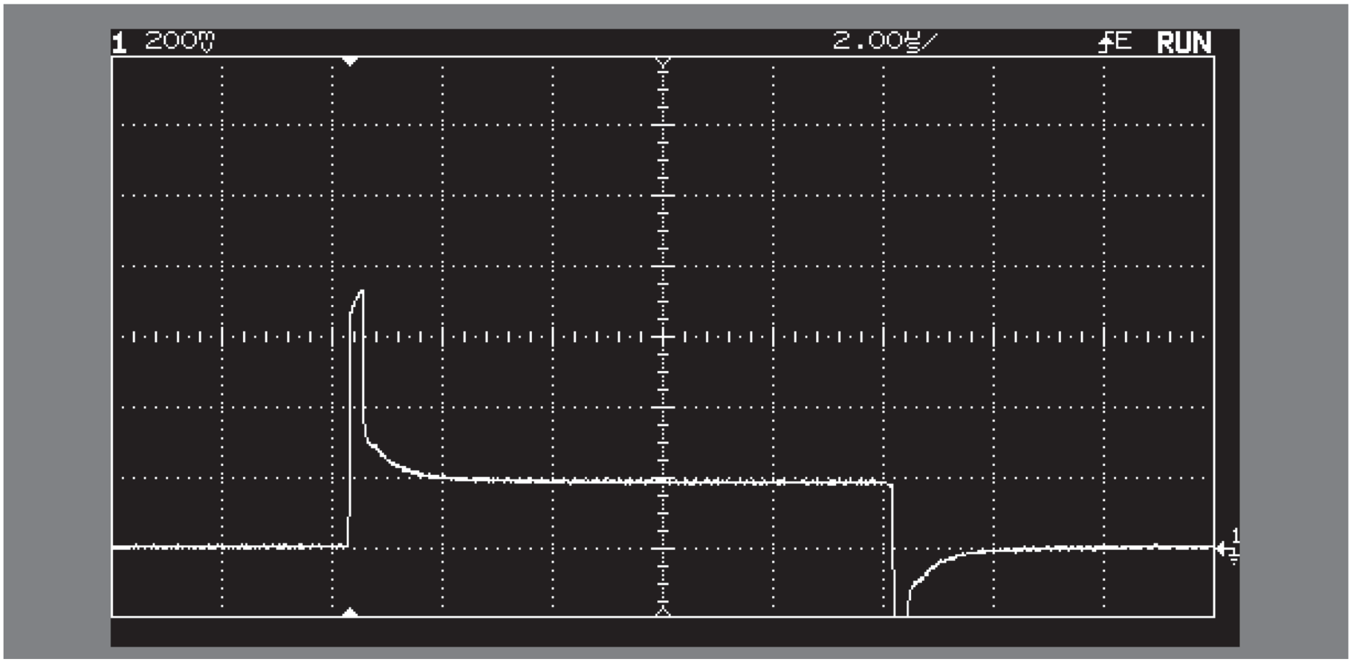

Figure 2-78. Step response signal when the load impedance is in the short-circuit condition.

☐ 12. Turn off the Base Unit and remove all the connecting cables and probes.

CONCLUSION

- A time-domain reflectometer (TDR) is an instrument that uses the echo technique to detect, locate, and determine the nature of discontinuities along transmission lines.

- To operate, a TDR launches pulses into the line under test and displays a step response signal, or signature, that reveals the presence and nature of discontinuities, if any.

- The distance from the TDR to a discontinuity can be determined by measuring, on the TDR oscilloscope, the time separating the rising edge of the incident voltage from the rising or falling transient caused by the discontinuity, and then converting this time to distance by using a simple equation.

- The shape and magnitude of a transient in the TDR signal indicate the nature and severity of the discontinuity that causes this transient.

Detection and Location of Discontinuities on a Line by Using Time-Domain Reflectometry (TDR)

REVIEW QUESTIONS

1. To determine the length of a line, using a time-domain reflectometer (TDR),

   a. the impedance of the load at the end of the line must be perfectly equal to the characteristic impedance of the line.
   b. the velocity of propagation must be divided by the round-trip measured with the TDR oscilloscope.
   c. the round-trip time must be measured with the TDR, and the velocity of propagation must be known.
   d. the transit time to any other discontinuity must be measured with the TDR.

2. The magnitude of a rising or falling transient in the TDR signal

   a. is independent of the distance to the discontinuity that causes this transient when the line is lossy.
   b. indicates whether the nature of the discontinuity is purely resistive, capacitive, or inductive.
   c. varies in reverse proportion to the voltage reflected from the discontinuity.
   d. reveals how great the impedance mismatch that causes this transient is.

3. When using a TDR that has a selectable pulse width,

   a. the selection of larger pulse widths can permit the detection of discontinuities located near the TDR that would otherwise go undetected.
   b. it is recommended that the line be tested with the narrowest available pulse width first.
   c. it is recommended that the line be tested with the largest available pulse width first.
   d. the selection of narrower pulse widths can permit the testing of longer line lengths.

4. A short circuit across the inner and outer (shield) conductors of a lossy coaxial line causes

   a. a rising voltage transient to occur in the TDR signal.
   b. a falling voltage transient to occur in the TDR signal.
   c. the voltage in the TDR signal to double.
   d. the voltage in the TDR signal to fall to 0 V.

5. An open circuit of the inner conductor of a lossy coaxial line causes

   a. a falling voltage transient to occur in the TDR signal.
   b. a rising voltage transient to occur in the TDR signal.
   c. the voltage in the TDR signal to double.
   d. the voltage in the TDR signal to fall to 0 V.

Other Sample

Extracted from

Transmission Lines

in Communication Systems

Unit Test

1. The harmonics of a rectangular signal having a period of 0.5 µs are

   a. even multiples of 5 MHz.
   b. odd multiples of 2 MHz.
   c. even multiples of 2 MHz.
   d. odd multiples of 5 MHz.

2. The velocity of propagation of a signal in a transmission line can be determined by using

   a. a high-impedance oscilloscope probe connected to the sending end of the line and a step generator connected to the receiving end of the line.
   b. a simple formula, if the time required for a voltage step to travel to the receiving end of the line and back to the sending end is known.
   c. the step response method, provided that the load impedance perfectly matches the characteristic impedance of the line.
   d. a step generator and a high-impedance oscilloscope probe connected to the receiving end of the line.

3. When a voltage step is launched into a lossy line whose series losses are predominant,

   a. the high frequency components contained in the voltage steps make the line temporarily appear as a simple RC network.
   b. the incident and reflected steps will first rise to a certain level and then decrease gradually.
   c. it is not possible to measure the time separating the incident and reflected steps.
   d. the line will appear as a simple LC network from the perspective of the load.

4. Theoretically speaking, the characteristic impedance, Z_0, of a transmission line corresponds to the input impedance, Z_{IN}, of a

   a. line whose load impedance is in the short-circuit condition (0 Ω).
   b. line terminated with a purely resistive load.
   c. particular length of line.
   d. line of infinite length.

5. According to Thevenin's theorem,

   a. the Thevenin impedance Z_{TH} is the impedance seen at the two terminals of the circuit to thevenize, when the voltage source of this circuit is replaced by an open circuit.
   b. the Thevenin voltage E_{TH} is determined by measuring the short-circuit voltage at the two terminals of the circuit to thevenize.
   c. the Thevenin equivalent circuit consists of a voltage source, E_{TH}, and an impedance in parallel with this source, Z_{TH}.
   d. any electrical linear circuit seen at two terminals can be represented by a Thevenin equivalent circuit.

Unit Test (cont'd)

6. The eye-pattern method of evaluating signal quality

   a. provides an eye-pattern display, the width of the eye opening indicating the degree of distortion.
   b. requires that a pseudo-random audio signal be applied to the vertical input of an oscilloscope.
   c. provides a display of the frequency components of the signal as a function of time.
   d. is used with low-speed data transmission systems.

7. In a transmission line, a signal travels at a velocity that

   a. is directly proportional to the relative permittivity of the dielectric material used to construct the line.
   b. is null if the impedance of the load at the receiving end is in the open-circuit condition (∞ Ω).
   c. usually increases as the diameter of the line conductors is decreased.
   d. is relatively less than $3.0 \cdot 10^8$ m/s, or $9.8 \cdot 10^8$ ft/s.

8. The skin effect causes the

   a. current density across the line conductors to remain uniform if the signal frequency is increased.
   b. resistance to current flow of the line conductors to decrease as the signal frequency is increased.
   c. current density to concentrate near the surface of the line conductors at low signal frequencies.
   d. attenuation per unit length to increase as the signal frequency is increased.

9. The step response method can be used to determine the characteristic impedance of a transmission line

   a. by connecting a purely resistive load to the receiving end of the line and adjusting the load resistance until no reflected voltage appears in the step response signal.
   b. by connecting a resistive load having half the input impedance of the line and measuring the voltage of the rising edge of the incident step in the step response signal.
   c. through measurement of the voltage of the rising edge of the reflected step in the step response signal.
   d. provided that the receiving end of the line can be made accessible for connection to a specific load.

Unit Test (cont'd)

10. When the load impedance is purely resistive and lower than the characteristic impedance of the line, the voltage of the reflected step is

    a. of negative polarity, so that it subtracts from the voltage of the incident step when it gets back to the sending end of the line.
    b. equal to the voltage of the incident step, so that it cancels out this step when it gets back to the sending end of the line.
    c. of positive or negative polarity, depending on the extent of the mismatch between the load and line impedances.
    d. of positive polarity, so that it adds up to the incident step when it gets back to the sending end of the line.

Instructor Guide Sample

Extracted from

Transmission Lines

in Communication Systems

EX. 2-4 DETECTION AND LOCATION OF DISCONTINUITIES ON A LINE BY USING TIME-DOMAIN REFLECTOMETRY (TDR)

ANSWERS TO PROCEDURE STEP QUESTIONS

☐ 4. Yes.

☐ 5. $2T = 486 \cdot 10^{-9}$ s

☐ 6. l_{AB} = 48.6 m (159.4 ft)

Yes.

☐ 8. $2T = 243 \cdot 10^{-9}$ s

☐ 9. l_{A} = 24.3 m (79 ft)

Yes.

☐ 11. a. Incorrect. The reflected voltage subtracts from the voltage in the step response signal.
b. Correct.
c. Incorrect. The polarity of the reflected voltage changes from positive to negative, reflecting the change in load condition.
d. Incorrect. The polarity of the reflected voltage changes from positive to negative, due to a corresponding reversal of polarity of the reflection coefficient at the load.

ANSWERS TO REVIEW QUESTIONS

1. a. Incorrect. An impedance mismatch must exist at the load to permit measurement of the round-trip time on the TDR oscilloscope.
b. Incorrect. The length of the line is directly proportional to both the velocity of propagation and the round-trip time.
c. Correct.
d. Incorrect. Only the round-trip time must be measured with the TDR. Choose a different answer.

2. a. Incorrect. The magnitude of the transient decreases as the distance to the discontinuity increases, due to attenuation.
   b. Incorrect. The nature of the discontinuity is revealed by the shape of the transient.
   c. Incorrect. The magnitude of the transient varies in direct proportion to the voltage reflected from the discontinuity.
   d. Correct.

3. a. Incorrect. The selection of larger pulse widths can prevent the detection of discontinuities located near the TDR.
   b. Correct.
   c. Incorrect. The selection of wider pulse widths can permit the testing of longer line lengths.
   d. Incorrect. The narrowest available pulse width should be used first.

4. a. Incorrect. This situation would occur, for example, in the case of a complete or partial open circuit of one of the conductors of the coaxial line.
   b. Correct.
   c. Incorrect. This situation would occur, for example, in the case of a complete open circuit of one of the conductors of a lossless coaxial line.
   d. Incorrect. The resistance of the lossy coaxial line causes the voltage reflected from the discontinuity to be attenuated as it travels back to the generator.

5. a. Incorrect. This situation would occur, for example, in the case of a complete or partial short circuit across the inner and outer (shield) conductors of the coaxial line.
   b. Correct.
   c. Incorrect. The resistance of the lossy coaxial line causes the voltage reflected from the discontinuity to be attenuated as it travels back to the generator.
   d. Incorrect. This situation would occur, for example, in the case of a complete short circuit across the inner and outer (shield) conductors of a lossless coaxial line.