EMP Measurement Notes

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Specifying and Testing Cables for EMP Measurements

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Abstract

This note describes the time domain parameters of transmission lines and compares these parameters to the more commonly used frequency domain parameters. Methods for testing transmission lines for transient response are described. While the note is particularly oriented to transmission lines, the principles discussed also apply to systems intended for the measurement of transient signals.

I. Introduction

The parameters that are commonly quoted for the specification and testing of components and systems for the transmission and measurement of transient signals do not necessarily result in acceptable characteristics. The purpose of this note is to point out the advantages of new methods of specifying and testing transmission lines for transient signals. The principles discussed also apply to the specification and testing of systems for transient signal analysis.

II. Frequency Domain Parameters

The characteristics of transmission lines have been conventionally specified and measured in the frequency domain. The important frequency domain parameters are: (1) characteristic independence, (2) voltage standing wave ratio, (3) attenuation, (4) crosstalk and (5) phase shift. Each of these parameters is dependent upon the frequency of measurement to some degree, and therefore the specification of these parameters must include the frequency band in which the transmission line is to operate.

Although the characteristic impedance of a transmission line is nearly always specified, it is rarely measured directly. Accepted practice is to measure the capacitance and propagation velocity of the line and calculate the impedance. The general formula for the impedance, Z_o, of a transmission line is

$$Z_o = \left[\frac{R + j\omega L}{G + j\omega C}\right]^{1/2}$$

where R is the series resistance of the line per unit length, G is the shunt conductance of the dielectric per unit length, ω is the radian frequency, L is the series inductance of the line per unit length, and C is the shunt capacitance of the line per unit length.

If the ratio of R to L is equal to the ratio of G to C the line is "distortionless" and the impedance can be expressed as

$$Z_o = (L/C)^{1/2}$$

If R and G are very small compared to $j\omega L$ and $j\omega C$, respectively, the line is "lossless" and the impedance can be expressed as

$$Z_o = (L/C)^{1/2}$$

Note that since the impedance is a ratio of per-unit-length parameters the impedance is not a function of length.

The propagation velocity, v, of a transmission line can be expressed as

$$v = (LC)^{-1/2}$$

By substitution the impedance expression becomes

$$Z_o = 1/Cv$$

In practice the conditions for a lossless or distortionless transmission line are seldom met so this method of impedance measurement is an approximation valid only over a narrow band of frequencies. Greater accuracy can be obtained by measuring impedance using a slotted line technique, but the most common practice is to measure VSWR and assume that if VSWR is within tolerance then the impedance must be within tolerance. The frequency dependence of impedance is slight in the bands where coaxial cables are used.

The VSWR of a transmission line is the expression of the ratio of voltage maxima to voltage minima in the standing waves on the line. The standing waves result from an impedance mismatch causing a portion of the signal to be reflected back toward the sending end of the line. Since the wavelength and propagation velocity of a given continuous wave signal is the same in either direction, the incident and reflected waves add together to form waves whose peak values vary with distance but do not propagate. These are standing waves. The VSWR is the ratio of the voltage maximum to the voltage minimum along the standing wave. The value of the standing wave ratio can be related to the magnitude of the discontinuity but it cannot give any information concerning the location or nature of the discontinuity. In the case of multiple discontinuities, the VSWR of a transmission line is frequency dependent. With the proper spacing (in wave lengths) a series of discontinuities can give the appearance of one very large discontinuity. Since braided coaxial cable is manufactured by rotating machinery, there are usually some sort of small cyclic imperfections in the cable due to periodicity in the machinery. Thus, there is usually one or more frequencies where a given cable has a high VSWR. This makes it very important to state the frequency band of interest when specifying VSWR for a coaxial cable.

The attenuation of a transmission line is the fraction of energy dissipated in the line during transmission. Attenuation is usually expressed in decibels per unit length. The factors contributing to transmission line attenuation are dielectric conductance or V^2G losses and conductor resistance or I^2R losses. The dielectric conductance in most coaxial cables is very low and is not normally considered. The conductor resistance of cables is proportional to the square root of the frequency. This is known as the skin effect. As a result, the attenuation of a coaxial cable is proportional to the square root of the frequency except at very high or very low frequencies. At high frequencies the dielectric conductance becomes a more important factor.

These frequencies, however, are beyond the useful frequency range of coaxial cables for polyethylene and other common dielectrics. At low frequencies the attenuation approaches the D.C. resistance of the cable and thus loses its frequency dependence. The attenuation of a cable is usually specified and measured at the upper limit of the frequency range of interest.

The crosstalk of a transmission line is measured by transmitting a signal down the line into a termination and measuring the radiation signal. The crosstalk of a coaxial cable is an expression of the shielding efficiency of its outer conductor. The shielding efficiency of an outer conductor is dependent upon conductor thickness at lower frequencies and upon the braid coverage at higher frequencies. In the frequency range from 50 to 200 MHz, the shielding efficiency of most coaxial cables is relatively constant.

The phase shift of a transmission line is dependent upon the length of the line in wavelengths. The electrical length, and thus the phase shift, varies with frequency and with the velocity of propagation. Except for the lossless transmission line, the propagation velocity is frequency dependent. However, in modern coaxial cables, the phase error due to the frequency dependence of the propagation velocity is insignificant except for frequencies well below 1 MHz and then only for extremely long lines.

As has been discussed, the parameters of interest in the frequency domain are valid only over a certain band of frequencies and when specifying these parameters the frequency band of interest must also be specified. In the case of nuclear test instrumentation, the practice has been to derive the Fourier components of the expected wave form and to use these frequencies to set the band pass of the systems. In some cases, this practice results in specifications that are too rigid for economical procurement. For example, the specification of VSWR over such a band might include a frequency with a high VSWR due to periodicity in the cable. Since the use of the cable involves a non-repeating transient, a VSWR specification is unnecesarily rigid and costly. In other cases, specifications in the frequency domain may be too lax for a pulse system. For example, specifying the attenuation in such a band could result in the delivery of a cable that is within attenuation specifications but with a pulse distortion that is severe.

Even though all parameters in the frequency domain can be related to parameters in the time domain, it is best to specify and test in the domain of interest. As with any other scientific endeavor, test conditions should attempt to duplicate operational conditions. Transient signals are most conveniently described in the time domain. Thus, the transmission line that carries transients may be considered to be working in the time domain.

III. Time Domain Parameters

There are several things that a transmission line can do to a transient. These means of deterioration are the cable parameters that are specified and measured in the time domain. The important time domain parameters are: (1) pulse reflection coefficient, (2) pulse distortion coefficient, (3) crosstalk, (4) time delay and (5) pulse amplitude response. Note the similarity between these and the frequency domain parameters. The first is an input characteristic and the remainder are transfer functions.

The pulse reflection coefficient is a measurement of the percentage of the input that is reflected back toward the source. The pulse reflection coefficient is specified for a given input impedance. The reflection can be caused by two things: the impedance of the transmission line may not be matched to the impedance of the source or termination; or there may be an impedance discontinuity along the line. The existence of discontinuities along the line will result in reflections arriving at the source for each discontinuity. The shape of the reflected pulse indicates the nature of the discontinuity and the round trip time required for the pulse to return to the source indicates the location of the discontinuity.

An effective method for testing a transmission line for impedance discontinuities is to drive the line with a fast rise step function and measure the reflections with an oscilloscope. The step function can be approximated by using a square wave generator whose period is at least four times the transit time of the transmission line. A high impedance probe is inserted across the line at the input. The oscilloscope is calibrated so that centimeters of deflection are directly correlated to percent reflection. This technique of measuring the pulse reflection of a transmission line is called Time Domain Reflectometry (TDR). The amplitude of the reflected pulse is related to the size (in ohms) of the discontinuity. The shape of the reflected pulse indicates whether the discontinuity is resistive, capacitive, or inductive. In a manner similar to radar the time lag between the incident and reflected pulses indicates the location of the discontinuity. The use of TDR techniques gives the experimenter the nature and location of each discontinuity in the transmission line. For this reason, TDR is far superior to VSWR measurement especially when the projected application of the line is pulse transmission.

The pulse reflection coefficient is the only input characteristic of a transmission line that is considered when specifying and testing in the time domain. All other characteristics of importance are transfer characteristics. The first of these is the pulse distortion of the transmission line. A transmission line can distort a pulse through any of a multitude of mechanisms. Perhaps the most important mechanism is the amplitude distortion of a pulse due to higher attenuation of those portions of the pulse related to high frequencies, primarily the rise time. This type of distortion is directly related to the attenuation vs frequency characteristic of the transmission line. Pulse distortion is measured qualitatively by comparing input and output. A quantitative measurement of pulse distortion can be obtained by measuring the output of a transmission line when the input is an "ideal" step function and calculating the line's transfer function from this data. Using the results, a high pass filter can be constructed to compensate for the high frequency attenuation and thus reduce the pulse distortion. This reduction in distortion is accomplished at the expense of amplitude response for a passive compensator.

There is little that can be added to what has already been said about crosstalk. The methods of measuring crosstalk in the time domain do not differ from the methods used in the frequency domain. However, if the application of the line is to be pulse transmission, then the line should be tested with a transient approximating the expected data pulse.

When a single transmission line is used to transmit information from point A to point B the time delay is relatively unimportant. However, if the transmission line is to be used as a delay line, or if more than one channel of information is to be transmitted from point to point, the time delay becomes very important. Two cables of the same construction can have a variation in delay per unit length of as much as 2 percent. Therefore, in applications where data is to be transmitted over more than one transmission lines and in applications where cables are to be used as delay lines the transit times of the cables must be accurately measured. One method of measuring the transit time of a cable is to terminate the cable in a short circuit and measure the location of the short circuit by TDR techniques. Instruments are available that are capable of measuring the transit time of a cable to within 0.1 percent.

The pulse amplitude response of a transmission line is of importance if it is nonlinear or if the amplitude of the input pulse is so low that the attenuation of the line will lower the amplitude of the signal to the noise level. The pulse amplitude response of a transmission line varies with line length and pulse width. The variation with pulse width is related to the fact that the narrow pulses have more Fourier components in the higher frequency portion of the spectrum. The pulse amplitude response to narrow pulses is therefore related to the pulse distortion of the transmission line and does not vary linearly with pulse width. Compensation through the use of a high pass filter, as is done with pulse distortion, does not help in the case of pulse amplitude because the peak amplitude of the output is affected in the latter case. The pulse amplitude response of a given cable cannot be compensated for. If improvement is needed, either a different cable must be selected or the data pulse must be sufficiently amplified so that the attenuation becomes unimportant.

By specifying and testing transmission lines in the time domain, the manufacturer and the user have a common basis of understanding of the requirements for the application of the product. This understanding will often result in the user obtaining a cable that is closely matched to his needs at the minimum possible cost.

IV. Time Domain Testing of Transmission Lines

Testing a transmission line in the time domain requires the application of techniques somewhat different from the techniques used in frequency domain testing. The most important time domain testing technique is Time Domain Reflectometry (TDR). TDR is relatively new to the coaxial cable field but has been used in other types of transmission lines for several years. In particular, telephone and power companies have used TDR to locate breaks in their lines. By measuring the time required for a pulse to return after being reflected from an open circuit, the repair crew could determine the location of the damage to within a few hundred yards. The accuracy of this one-dimensional radar was limited by the rise time of the pulse generator used. With the advent of fast rise pulse generators, this technique has been made practical for the testing of coaxial cables. A person who is proficient in TDR techniques can determine the impedances, discontinuities, losses, risetime and electrical length of a cable using a single test setup.

The impedance of a cable is determined by comparing it with a section of cable whose impedance is precisely known. The standard is usually a section of precision air line. The output of the TDR pulse generator is fed through the standard, to the test sample. If the impedance of the test sample is different from the impedance of the standard a portion of the input pulse will be reflected at the transition from the standard to the test sample. The size of the reflected pulse is related to the difference in impedance. The polarity of the reflected pulse is related to direction of the impedance difference. A positive reflection indicates that the test sample has a higher impedance than the standard. The impedance of the test sample (Z_r) is related to the impedance of the standard (Z_o) by

$$Z_r = Z_o \left(\frac{1 + r}{1 - r}\right)$$

where r is the fraction of the incident pulse that is reflected at the transition. Figure 1 is an example of an impedance measurement.

Discontinuities are found using the TDR as a one dimensional radar. Modern TDR systems have a rise time on the order of 0.15 nanosecond. Solid dielectric cables have a propagation velocity of approximately 20 centimeters/nanosecond. Therefore, a discontinuity along a transmission line can be located by its reflection to within $\pm$ 3 cm.

The nature of the discontinuity can be determined by the shape of the reflection. If the step response of a simple circuit with resistances, capacitances, and inductances is recalled it becomes obvious that the reflection from any type of discontinuity will have a signature unique to that type of discontinuity. Consider, for example, discontinuities at the termination of a cable. A resistive discontinuity will have a step rise and fall. A series R-L discontinuity will have a step rise (initial open) followed by an exponential decay. A shunt R-C discontinuity will have a negative going step rise (initial short) followed by an exponential rise. A shunt R-L will have a step rise corresponding to the resistance, followed by an exponential decay to zero (or short circuit). A series RC will have a step rise corresponding to the resistance, followed by an exponential rise to open circuit.

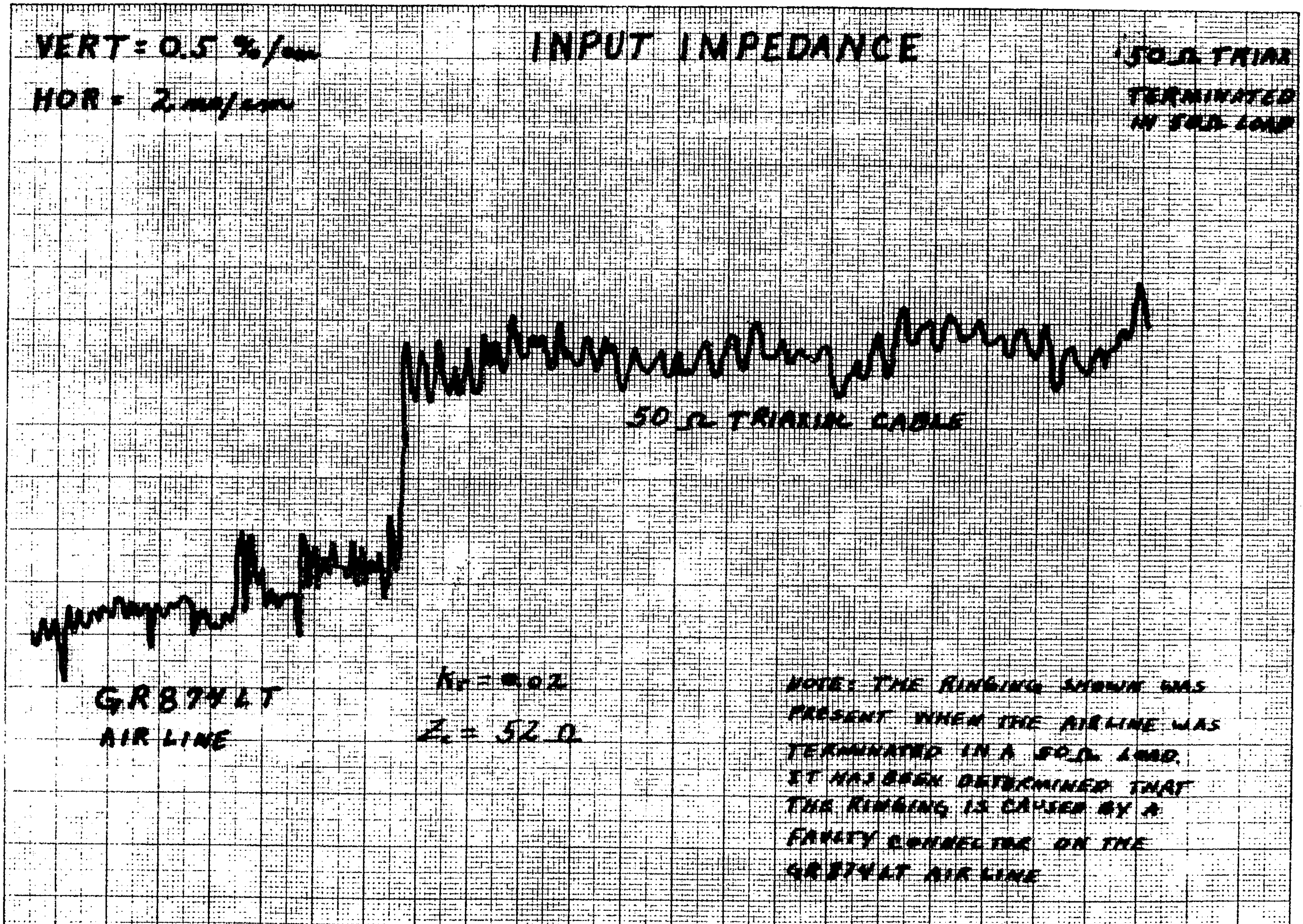
If the experimental conditions are ideal, the time constant of the exponentials can be measured and the actual value of the elements of the discontinuity can be calculated. In practice, however, the distortion of the input step is severe enough that an accurate measurement of the time constant of a discontinuity is very difficult. If the magnitude of the discontinuity is enough to jeopardize the signal, it can be "tuned out" by adding suitable "loading elements" to cancel the effect of the discontinuity. If the discontinuity is not accessable for loading, the line is cut and spliced removing the bad section.

The losses of the cable can be easily measured using the TDR setup. If a cable is terminated in a short circuit the entire step will be reflected. This reflected step will cancel the incident step. At the sampling point the reflected step will exhibit the losses due to two transitions through the cable one as the incident and one as the reflected. Figures 2 and 3 are samples of cable losses as shown by TDR.

The DC loss of the cable or the pulse amplitude response will be one half of the difference in amplitude between the incident and reflected pulses. The risetime degradation or pulse distortion of the cable for a fast rise input pulse will be 0.707 times the observed rise time of the reflection. The electrical length or propagation time of the cable is simply half the time between the arrival of the incident pulse and the arrival of the reflected pulse.

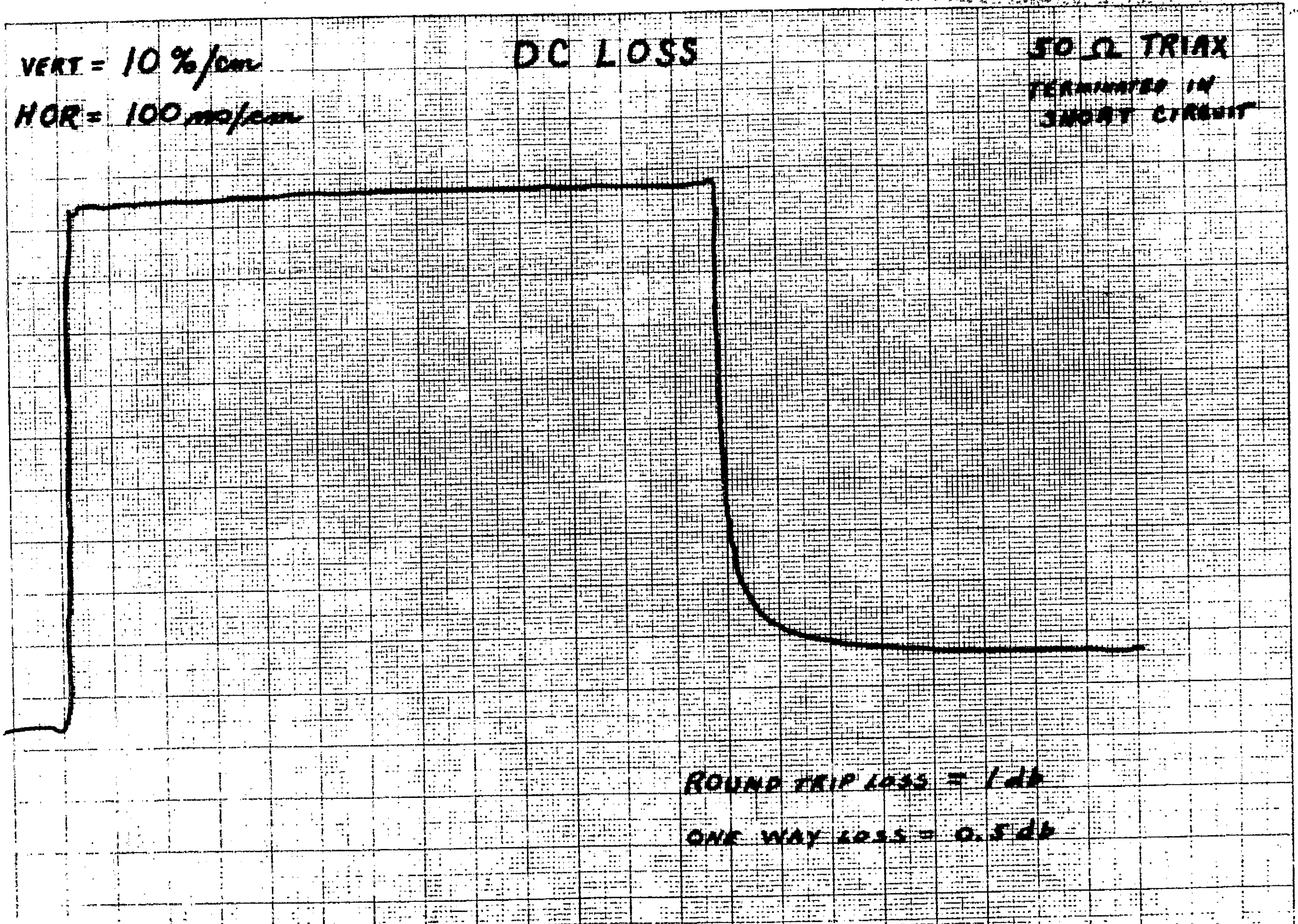
V. Summary

It has been shown that time domain testing is superior to frequency domain testing when the cable is intended for transient signals. Time domain testing is also useful in conjunction with frequency domain testing for cables intended for continuous wave transmission. For example, a TDR test can be used to locate a discontinuity that is causing a high VSWR. In general, it is best to combine the two types of measurement. This will give a comprehensive set of specifications and tests that will cover many applications.



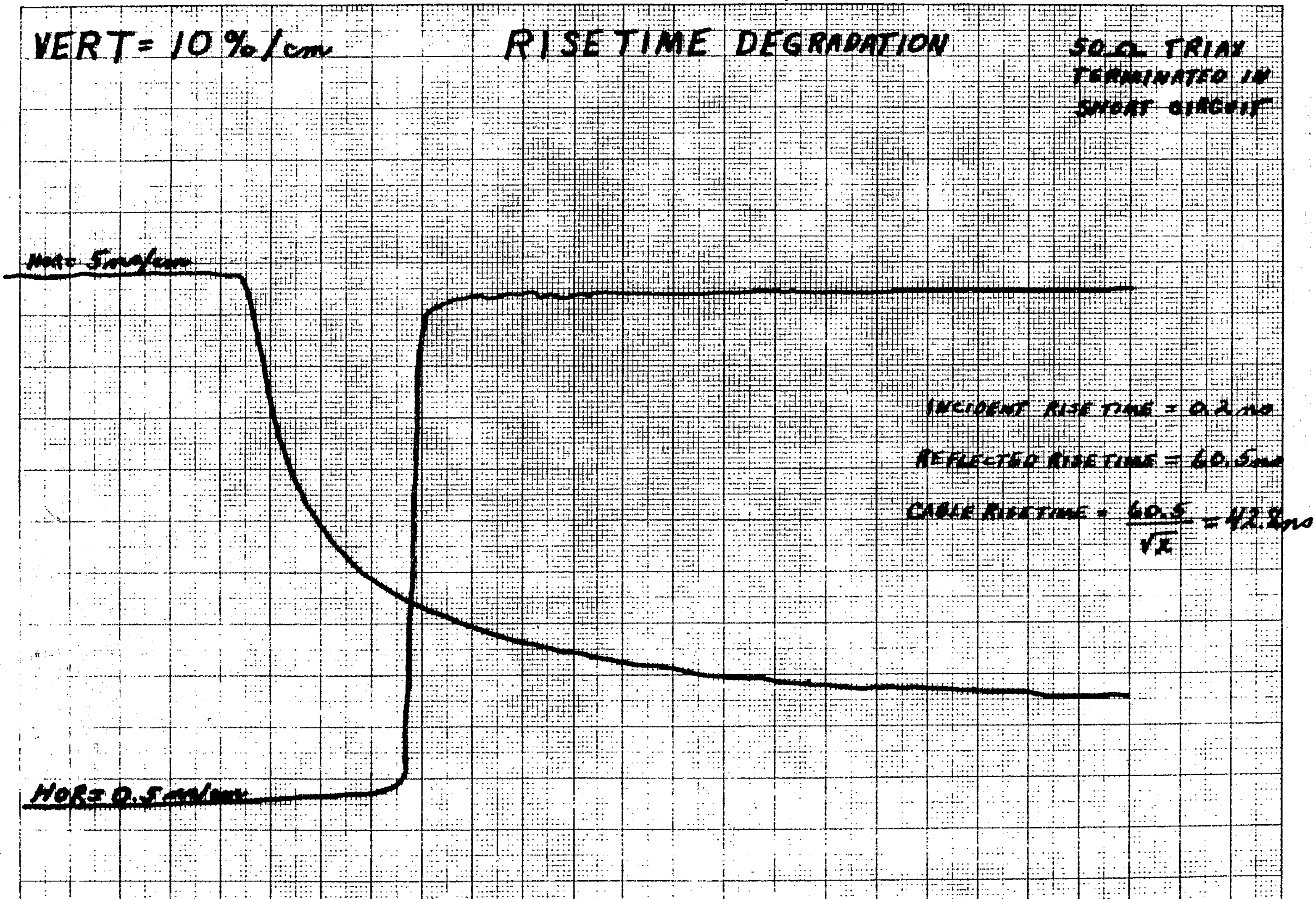
VERT = 0.5 %/cm
HOR = 2 ns/cm
INPUT IMPEDANCE
50 Ω TRIAX
TERMINATED IN 50 Ω LOAD
50 Ω TRIAXIAL CABLE
GR874LT AIR LINE
$Z_c = 52\ \Omega$
NOTE: THE RINGING SHOWN WAS PRESENT WHEN THE AIRLINE WAS TERMINATED IN A 50 Ω LOAD. IT HAS BEEN DETERMINED THAT THE RINGING IS CAUSED BY A FAULTY CONNECTOR ON THE GR874LT AIR LINE

FIGURE 1



VERT = 10 %/cm
HOR = 100 ns/cm
DC LOSS
50 Ω TRIAX
TERMINATED IN
SHORT CIRCUIT
ROUND TRIP LOSS = 1 db
ONE WAY LOSS = 0.5 db

FIGURE 2



VERT = 10%/cm
RISETIME DEGRADATION
50 Ω TRIAX
TERMINATED IN
SHORT CIRCUIT
HOR = 5 ns/cm
INCIDENT RISE TIME = 0.2 ns
REFLECTED RISETIME = 60.5 ns
CABLE RISETIME = $\frac{60.5}{\sqrt{2}}$ = 42.8 ns
HOR = 0.5 ns/cm

FIGURE 3