

CONTROLLED IMPEDANCE AND TIME DOMAIN REFLECTOMETRY (TDR)

As the speed of Electronic Circuits increases the demand on Printed Wiring Board (PWB) performance has expanded as well. At high speeds the PWB traces behave more like transmission lines rather than interconnects. In order to optimize system performance and signal transfer, the Characteristic Impedance of the transmission line (PWB circuit) and the Impedance of the circuit load must be matched.

Impedance is described as the resistance offered by an electronic circuit to an AC signal. Impedance can be described in two fashions: 1) circuit Impedance "Z" (load); 2) Characteristic Impedance "Z₀" (transmission line). Circuit Impedance is the resultant interaction between the resistive, capacitive, and inductive portions of the electronic circuit. Both the capacitive and inductive portions of circuit impedance are dependent upon the frequency of the AC signal applied to the circuit. Electronic circuit impedance (Z) can be expressed as:

$$|Z| = \sqrt{R^2 + (2\pi fL - 1/5\pi C)^2}$$

R = DC Resistance

C = Capacitance

L - Inductance

f = Signal Frequency

Characteristic Impedance is defined as the ration of voltage to current of a wave moving down a transmission line. The resistive element a transmission line is typically small enough where it does not play a significant part in the Characteristic Impedance (see figure 1). For a lossless line Z₀ can be expressed by:

$$Z_0 = L/C$$

C = Capacitance/unit length

L = Inductance/unit length

Circuit designers typically attempt to match the characteristic Impedance of a transmission line/trace to that of the load which terminates the line. This will maximize the signal transfer to the load. When there is a mismatch between Z₀ and Z, or anomalies in the transmission line/trace a portion of the signal reflects back down the line toward the source. This reflection will dampen and attenuate the signal headed into the load.

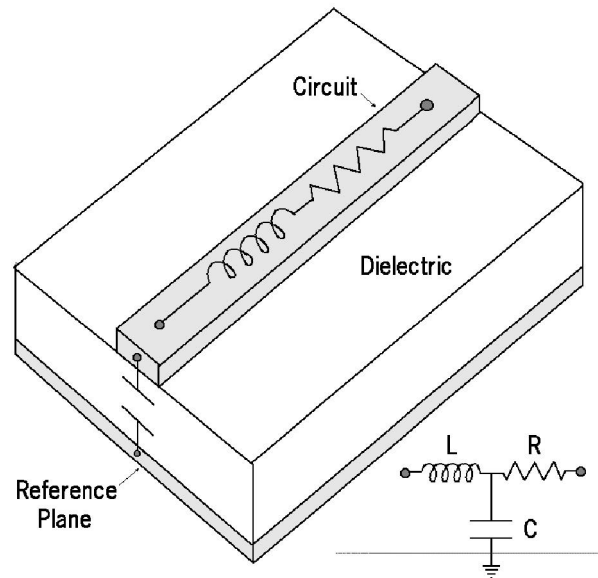


FIGURE 1

Time Domain Reflectometry (TDR) is a technique employed to derive the Characteristic Impedance (Z₀) of a transmission line/trace. TDR techniques derive and do not directly measure Characteristic Impedance. The derived Z₀ is only an approximation of the actual Characteristic Impedance. The measurement accuracy of Z₀ from a TDR cannot be traced to a referee standard at NIST (National Institute of Standards Technology) due to the manner in which it is derived. TDR instruments utilize a pulse generator and an oscilloscope in a system that is best described as "closed loop radar". As a pulse from the generator starts down the test path, it begins to charge the inductive and capacitive portions of the transmission line with current flowing in accordance with actual impedance (see equation 2 & figure 1). When that initial point in the pulse encounters a change in Z₀ some of its' energy is sent back toward the signal source. This action is called Reflection, and is the basis for TDR measurement techniques. The oscilloscope portion of the TDR test system measures both the voltage of the pulse as it leaves the generator (V_{incident}), as well as those reflected back from the circuit under test (V_{reflected}). All TDR measurements are based on the ratio of incident to reflected voltage. This ratio is called the reflection coefficient (ρ) and is defined as:

$$\rho = V_{\text{reflected}}/V_{\text{incident}}$$

The magnitude of, as well as the time lapse between pulse transmission and reflection are a function of the magnitude of, and distance to a Z_0 change. An unknown Z_0 is derived by characterizing the magnitude of ρ from the trace under test and comparing it to the ρ from a known Reference Impedance (Z_{ref}). This can be expressed as:

$$Z_0 = Z_{ref} (1 + \rho)/(1 - \rho)$$

Z_0 = unknown characteristic impedance

Z_{ref} = known (reference) impedance

ρ = measured reflection coefficient

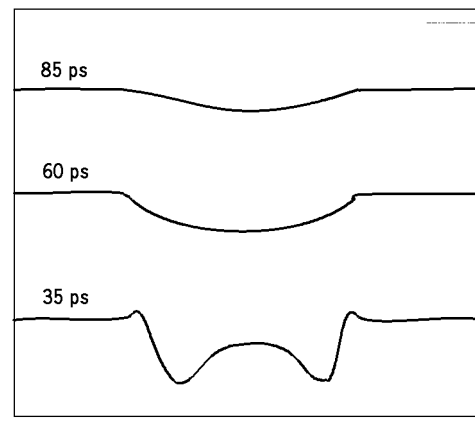
While modern test instruments make it easy to complete the mathematics of the calculation, there are several issues that must be considered when trying to achieve high accuracy and repeatable measurements.

As the difference between the Z_0 of trace under test and the system increases, the accuracy and repeatability of the measurement decreases. Other areas which can decrease accuracy and repeatability are cable and interconnection quality, test probe configuration, test probe application force, variation in manual positioning of test cursors, inadvertent reversal of signal and ground connections, quality of reference impedance, varying means for calculating results, and ambient environmental conditions.

To distinguish small anomalies on the test trace it is important to have an adequately small pulse rise time in your test system. This system rise time determines the smallest impedance discontinuity that the TDR can measure, and it is associated with the pulse rise times generated by the pulse generator, the oscilloscope, and the test setup (wiring, probes, static switch, etc.). This pulse rise times can be calculated by observing the amount of time a pulse takes to go from 10% to 90% of its' final magnitude in each of the system components. The system rise ($t_{r\ system}$) can then be approximated by:

$$t_{r\ system} \approx \sqrt{(t_{r\ step\ gen})^2 + (t_{r\ sampler})^2 + (t_{r\ test\ setup})^2}$$

If a circuit anomaly is small in respect to system rise time, its' reflection will not accurately represent its' impedance, and in extreme cases many not be distinguishable at all. As the system rise time increases, the ability of the system to distinguish between anomalies which are close together lessens (see figure 2). This relationship can be demonstrated by the formula:



System Rise Times; Reflection v.s. Distance

FIGURE 2; Two Discontinuities 2mm apart on GF PWB trace.

$$d_{min} = (c/\sqrt{\epsilon_r} (t_{r\ system}/4))$$

d_{min} = minimum distinguishable distance between discontinuities

c = speed of light

ϵ_r = relative dielectric constant of insulator

Test probes and probing techniques can induce a tremendous amount of error into the TDR measurement. Exceptional probes and probing techniques are critical to the accurate characterization of reflection coefficient. There have been several recent advances in test probe design which demonstrate a very stable 50Ω impedance in a spring loaded tip configuration. Interconnection of the test set up must be accomplished with high quality, stable 50Ω cables preferably with SMA connector ends. These cables and connectors are necessary to eliminate unwanted losses, attenuations, and reflections in the test setup. To make accurate ρ measurements from the reference standard, a coaxial air line of at least 10 cm in length is required. High quality connectors should be used to connect this reference standard to the test system.

TDR instrumentation is very susceptible to static discharge. A PWB trace can store enough energy to damage the TDR sampling heads. It is therefore recommended that a static protection switch be inserted into the test setup. This switch should ground the entire test setup until after the probe has been attached to the test trace. This will allow the trace to discharge its' stored energy prior to testing.

It now becomes obvious that a standardized method for performing TDR measurements must be followed if there is going to be any correlation of measurement between test sites. IPC-TM-650, method 2.5.5.7 "Characteristic Impedance and Time Delay of Lines on Printed Wiring Boards by TDR" provides a detailed standard by which TDR testing can be accomplished. IEC 1189-3E07 is comparable to the IPC test method, and should be published within the year. These methods are accepted worldwide, and should become the standard for TDR measurement.

There are currently two TDR techniques. utilized for measuring Z_0 . They are both thoroughly described in the IPC test method mentioned above: 1) Stored Reference Method; 2) In-Situ Method.

The Stored Reference method saves the reflection coefficient (ρ) from the reference impedance standard in the TDR's memory, and then compares it to the ρ of the trace under test. This method allows test setups where it is not particle to have the reference standard within the test system during measurement. The down side to this techniques is that any drift in the test instrumentation is not accounted for, and will cause variation in the Z_0 calculation.

The In Situ method utilizes the reference impedance standard as part of the test setup. This provides a measurement of the reference impedance's ρ with every test. This method dramatically reduces the affect that instrumentation drift has on the accuracy of the calculations. The down side to this technique is that the reference standard increases the cable length and interconnections, thereby increasing system rise time.

The most reliable and repeatable way to gauge the characteristic Impedance of traces on a PWB is to test a representative coupon (see figure 3). The test coupons should be included either within the PWB, or on the periphery of the PWB panel. This coupon should adequately simulate the design of the traces in question (i.e. trace geometry, dielectric spacing, reference planes). To obtain accurate TDR measurements this test trace should also be between 6 & 12 inches in length. It should be terminated with plated through holes (0.02" - 0.04"). These test coupon must also contain an access hole to the Reference Plane. this access hole must be located 0.02" away from the test circuit access hole providing for easy connection to the new styles of high frequency test probes.

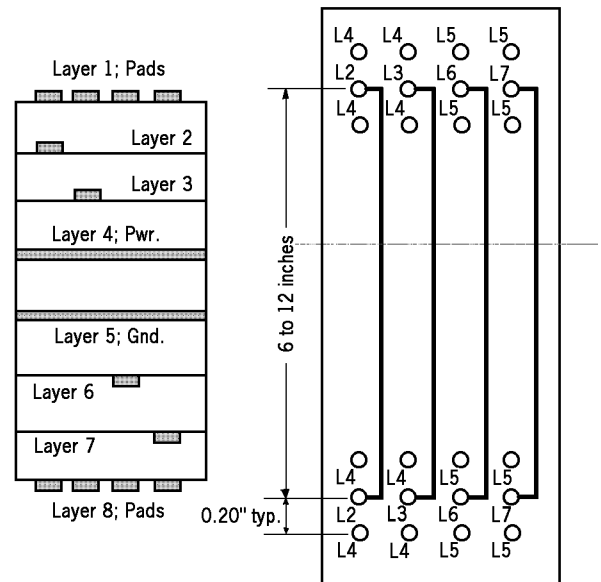


FIGURE 3: Sample TDR Test Coupon

Each test provides a wealth of information, and the utilization of this data must be carefully considered. All measurements are based upon a waveform which is captured over time by the instrumentation. Each waveform contains between 512 and 2048 bits of data collected by the TDR. Each bit of data is a ρ reading at a specific instant in time. The TDR samples the waveform very rapidly, and displays a composite of these readings onto the TDR's monitor. The first decision which must be made is how many individual pulses will be averaged before the waveform is stored for analysis.

For example, if a ten pulse average is chosen, each bit of data in the waveform will be read ten times, and the average of these 10 readings will be stored as the "waveform" into the TDR's memory (see figure 4). Once the waveform is stored into the instruments working memory, the decisions must be made on how to handle this data.

Manual manipulation of the data stored in the TDR allows an operator to take the average of points in any area of the waveform. The test cursors are typically set at the beginning and end of the areas highlighted in figure 4, carefully staying within the undisturbed region of the waveform. This gives an average magnitude for the ρ of the baseline, reference, and test trace. It does not give any information about the maximum, minimum, or standard deviation of individual waveform bits form the circuit under test. This information can be invaluable, especially if there is a single anomaly or large deviations within the test trace. It is therefore recommended that the waveform be transferred to a computer (via RS-232 or GPIB) for further computational analysis.

There are also other instruments available which can define Characteristic Impedance. A portable metallic cable TDR provides single point measurement with a display of the characteristic waveform. This unit has the advantage of easy setup and measurement, and relatively low equipment cost. It's drawbacks include a slow instrument pulse rise time (~200 p.s.), and a relatively low accuracy when making absolute measurements. The measurement accuracy can be improved by using a reference impedance in the test setup, and measuring the differential ρ between the reference and the unknown. The instrument rise time limits the anomalies, and the distance between anomalies which can be resolved (see figure 2 & equation 6). As in any single point measurement setup, it is difficult to obtain an accurate average of an unknown characteristic impedance. This is especially true if there is a large variation on the test trace.

Another inexpensive way to interpret characteristic impedance is with a capacitance meter. Since capacitance comprises most of magnitude of Z_0 in a PWB trace, the measurement of capacitance at a given frequency will typically correlate to the average characteristic impedance from that trace. This method of measurement has many obvious drawbacks, and is not accurate enough to use for reporting Z_0 . It does have tremendous potential as a process control tool, and can be utilized by certain point to point electrical testers.

The accurate measurement of Characteristic Impedance is a best difficult to obtain. The result from testing are easily misinterpreted, and test that can be incorrectly manipulated. The instrumentation, software, and test procedures do exist whereby accurate, repeatable measurements can be made. An understanding of the limitations of test instrumentation, test setup, and data manipulation is critical in obtaining consistent results.

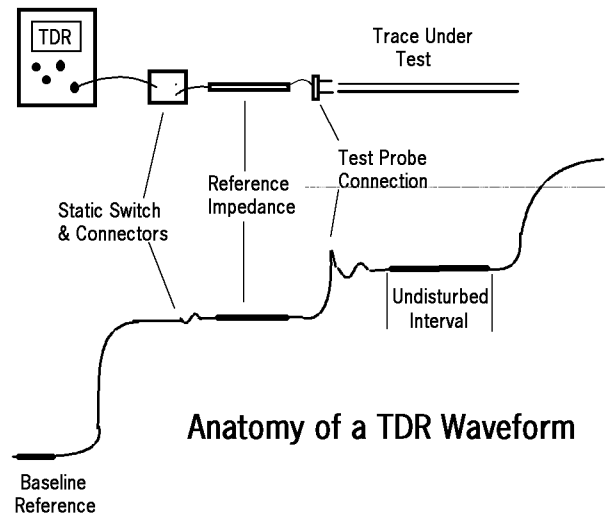


FIGURE 4: In-Situ Test Setup