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Snapback Device Studies Using Multilevel TLP and Multi-impedance TLP Testers

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Abstract - Standard 50-ohm TDR TLP systems do not accurately measure the clamp voltage and minimum holding currents of snapback ESD protection structures. Two methods are presented that can accurately determine device operation at the turn-on point. Multilevel TLP generated with charge lines is contrasted with 100-to-1000-ohm TDRT for snapback parameter determination.

I. Background and Purpose

Two approaches will be described that can provide improved device characterization of snapback performance: Multilevel Transmission Line Pulser (MLTLP) and Multi-Impedance Transmission Line Pulser (MITLP). This paper describes how to add capability to a Transmission Line Pulser (TLP) system to these techniques to accurately determine the turn-on characteristics of a device under test (DUT). Multilevel TLP test has been demonstrated [1] using two two solid-state pulse generators to produce a two level TLP pulse. In this work a standard 50-ohm time domain reflection (TDR) TLP system was modified to generate a multilevel pulse shape that can characterize the turn-on or "snapback" response of a DUT.

The MLTLP concept uses a stair-stepped two level pulse that begins with high enough voltage to turn on the protection structure, and later drops to a range that tests the DUT at low currents both above and below the holding point. The MLTLP waveforms in this work were produced by modifying the charge line of a traditional TDR TLP system, which will be described.

The TLP system configuration can be converted from TDR to Time Domain Transmission and Reflection (TDRT) by cabling and software changes. TDRT has a 100-ohm delivery impedance, and can be modified by adding resistance in the ground path to increase the impedance. This is called High-Z TDRT [2] and impedances impedance above 100 ohms can be produced. MITLP can be implemented using High-Z TDRT impedances and repeating the TLP measurement with increasing impedance. With increasing impedance the DUT currents are reduced to a level where the DUT fails to conduct even though adaquate voltage is applied. This limiting case displays the desired DUT performance.

The MLTLP and MITLP using High-Z TDRT obtain similar information on low current DUT operation. Both techniques provide a full description of device operation at low currents, but each has its own operational details and advantages.

The MLTLP technique can be extended many stair-steps and even to simulate Human Body Model (HBM) pulses and provide HBM stress levels for some DUTs. While the familiar short circuit load waveform meeting all the ESD Assoc. specifications for HBM, can be produced and delivered to a DUT, the pulse delivery impedance is 50 ohms. This results in DUT stress that diviates from HBM when DUT impedance is large compared to 50 ohms but not large compared to 1500 ohms, the output impedance of an HBM pulser.

II. Multilevel TLP Tester Design

MLTLP can be built from a standard TDR configured TLP system which is diagrammed in Figure 1. The goal of producing a two level pulse is accomplished by charge line modification. The charge line is broken into two sections, as shown in Figure 2, connected by a resistor. This resistor determines the amplitude ratio between the first pulse level and the second level.

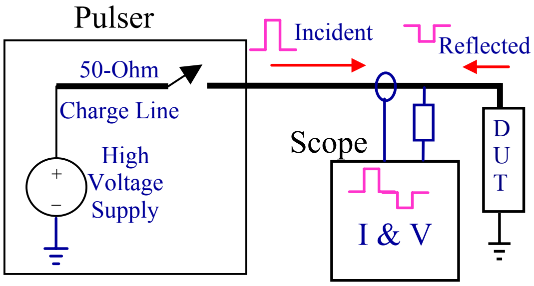

Figure 1: 50 ohm impedance TDR TLP Configuration

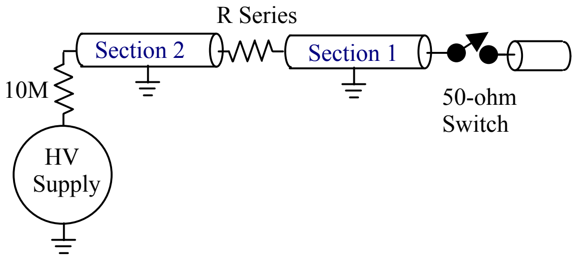

Figure 2: MLTLP Pulser with Two-Section Charge Line

Before the 50-ohm switch of Figure 2 is closed, both sections of the charge line are initially at the output voltage of the supply, V_0. Before the switch is closed the output line is discharged to 0 volts. When the switch is closed, the charge line and the output cable on both sides of the switch are forced to the same voltage, and since both cables have impedance of Z_0, that common voltage is $\frac{V_0}{2}$. An outgoing pulse of $\frac{V_0}{2}$ is generated, and the charge line pulse of $-\frac{V_0}{2}$ superimposed upon the static voltage V_0 is sent down the charge line toward the high voltage supply. When that pulse reaches the R Series resistance, a voltage reflection occurs and another pulse is generated that propagates back toward the output cable. The magnitude of this pulse can be determined by the familiar formula of the reflected voltage at an impedance discontinuity when going from impedance Z_1 to impedance Z_2:

$$V_{Reflected} = V_{Incident}\frac{Z_2 - Z_1}{Z_2 + Z_1} = -\frac{V_0}{2}\cdot\frac{(R + Z_0) - Z_0}{(R + Z_0) + Z_0} =$$

$$-\frac{V_0}{2}\cdot\frac{R}{2Z_0 + R},$$ where R is the series resistance placed into the charge line and Z_0 is the cable impedance. This reflected voltage is superimposed with the previous voltage in the cable and the new voltage is

$$V_2 = V_1 + V_{Reflected} = \frac{V_0}{2} - \frac{V_0}{2}\frac{R}{2Z_0 + R} = \frac{V_0}{2 + R/Z_0}.$$

In summary, the first voltage level is one-half the high voltage supply output and the second level is reduced from the first by a factor of $\frac{2}{2 + R/Z_0}$.

Using a 332 ohm resistor separating the charge line sections, the pulses of Figure 3 are generated with $V_2 = \frac{V_1}{4.3}$. The down and back round trip propagation time of section 1 of the change line determines the first pulse level duration. Section 2 of the charge line should be at least half as long as section 1 so that reflections from its far end will not interfere with the second level pulse measurement.

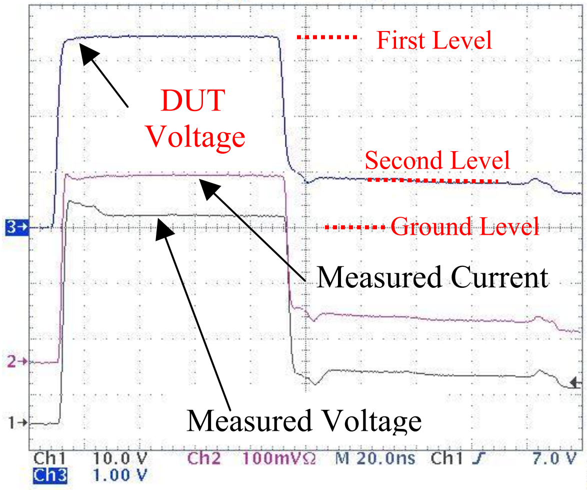

Figure 3: Multilevel TLP Pulses

Using these MLTLP pulses, TLP measurements are made using TDR-O which overlaps the incident pulse from the pulser and the reflected pulse from the DUT. The voltage and current waveform pairs of Figures 4 though 6 show the three ranges of operation with the two level pulses. The two steps in rise and fall of the voltages and the current spikes in Figure 4 are the result of the imperfect overlap of incident and reflected pulses. A small delay between these pulses results from the round trip transit time from the measurement probes to the DUT. As there is no current measured in the stable regions of either the pulses of V_1 or V_2 in lower part of Figure 4, these voltages were insufficent to caused the DUT to be turned on. Figure 5 shows when V_1 has reached sufficient voltage to cause the DUT to turn on, or snapback, but the current supplied by the voltage level V_2 is insufficient to keep the DUT on. This can be seen by the drop in current even though the level 2 voltage is almost the same as the clamped voltage measured during the first half of the pulse. Note that the current observed during the V_2 time period is actually negative. This is not a measurement error, and will be discussed in section IV.

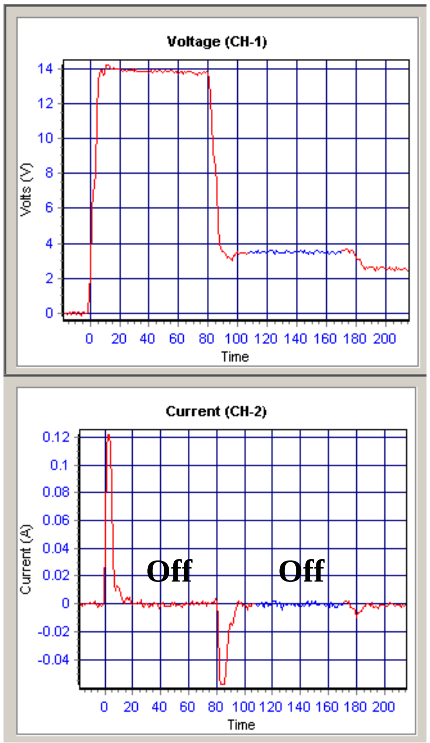

Figure 4: MLTLP Voltage and Current Waveform Pairs with voltages low so that neither pulse level causes DUT to conduct

The third region of operation is when the pulses are great enough to keep the DUT conducting during both pulse periods as shown in Figure 6. Here the current during the first pulse level is above 700 mA and decreases to 80 mA during the second period. Note that the voltage is clamped to a lower voltage during the second half of Figure 6 than in Figure 5 when the DUT had turned off; the I-V curve shows this as a snapback. We have see that the current data is easier to interpret than the voltage data in identifying these three regions of operation.

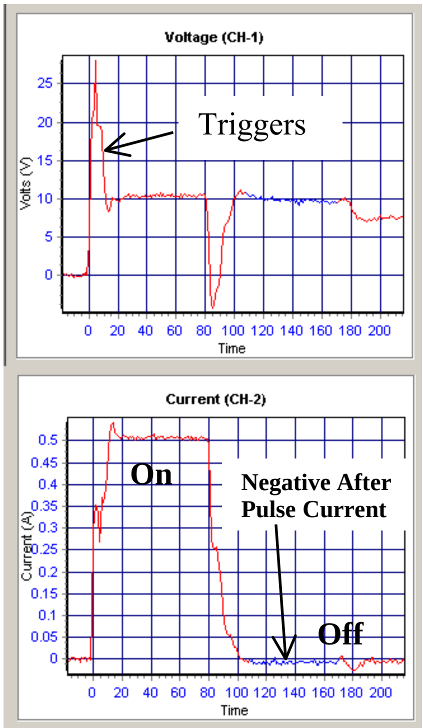

Figure 5: MLTLP Voltage and Current Waveform Pairs for the conditions where the DUT is On for the first half, the Off

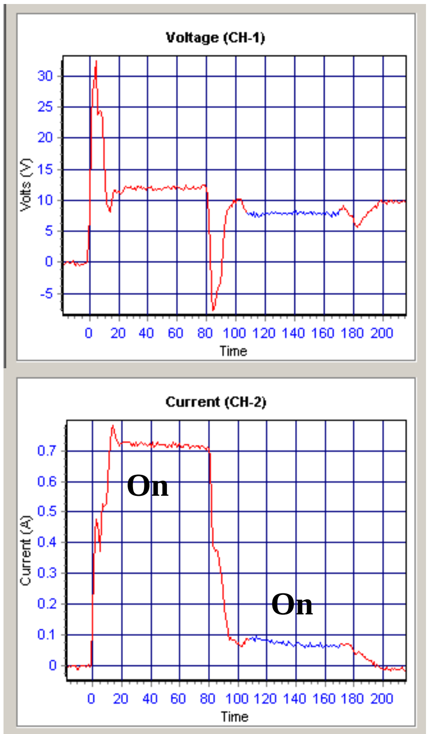

Figure 6: MLTLP Voltage and Current Waveform Pairs for the condition where the DUT is On for the entire pulse

While we focus on the second period of the MLTLP pulse, we can also analyze the data from the first period that can provide a standard I-V curve. Thus, we can make two measurements on each pulse, reporting the standard snapback measurement and low current operation in one measurement sequence. This can be important if the DUT stress levels are increased to where they induce permanent damage.

III. Multi-Impedance TLP Tester Design

In all TLP testers, the system pulse driving impedance restricts the voltage-to-current ratio of stress pulses delivered to the DUT. Different TLP configurations [2,3] provide different driving impedances, even though all may be built with 50-ohm cables. The TDRT configuration [3] can be modified by adding a resistor in series with the DUT [4] as shown in Figure 7. This allows any impedance above the basic 100-ohm impedance of TDRT to be realized. Delivery impedance of a High-Z TDRT system, $Z_{TLP} = R_{HI\text{-}Z} + 2\ Z_0$, where $R_{HI\text{-}Z}$ is the resistor in series with the DUT transmission path to the scope and Z_0 is the common cable impedance. The DUT voltage, V_D, is measured as the difference of voltages at the ends of the DUT. Two scope channels measure the DUT voltage and current in a TDR-O mode, and this measures the voltage (and current) at the "pulse-end" of the DUT, V_P. The "ground-end" voltage of the DUT, V_G, is determined by measuring the transmitted pulse at a third scope channel, V_3.

$$V_D = V_P - V_G = V_P - V_3 \cdot \left(1 + \frac{R_{HI-Z}}{R_S}\right),$$ where R_S is approximately 50 ohms, the scope channel input resistance.

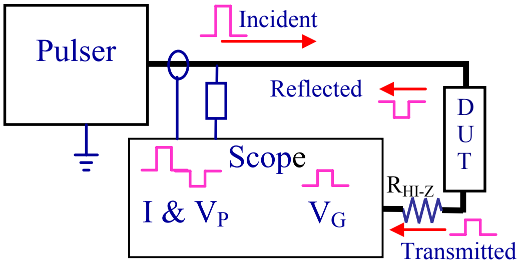

Figure 7: ≥ 100 ohm impedance TDRT TLP Configuration

The TLP I-V curve is made by plotting the DUT current as a function of DUT voltage with increasing TLP stress pulses. The difference between the I-V curves taken with difference Z_{TLP} is that the points have different ratios of current to voltage (or more percisely, current to the voltage dropped from the open circuit voltage). The stress pulses can be described as being the TLP voltages with an open circuit DUT. The I-V curve for an open circuit is increasing points, the stress voltages on the horizontal voltage axis. When the DUT conducts, the DUT voltage is reduced from the stress voltage by $I_{DUT} \cdot Z_{TLP}$. This is often refered to as being on the TLP "load line". As the TLP pulse delivery impedance increases the load lines become flatter (smaller slope) and more stress voltage is needed for a given DUT current. The DUT current after snapback is reduced with increasing impedance showing more of the operation and lower currents. Staying on the load line, the current increase when snapback occurs, ΔI, is proportional to the drop in voltage, $\Delta V_{SB} \approx V_{t1} - V_{On\text{-}Min}$, the difference in voltage before and after snapback. $\Delta I \approx \Delta V_{SB}/Z_{TLP}$.

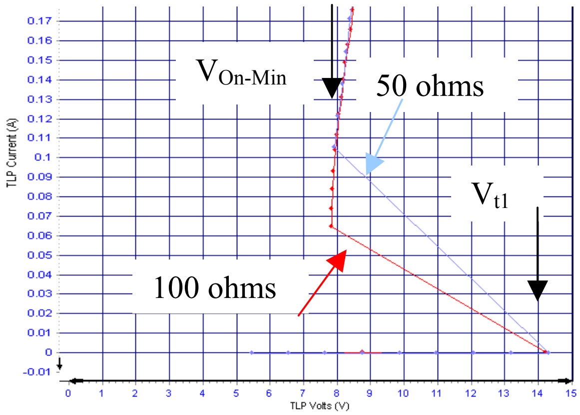

Figure 8: 50-ohm TDR and 100-ohm TDRT Showing Load Line Differences

The effect of increasing impedance is illustrated in Figure 8. Snapback occurs above 14V and drops to 8V (ΔV_{SB} is about 6V, smaller steps in TLP stress pulse increases allow better ΔV_{SB} determination). The increase in DUT current for a 50-ohm TLP system is about 6/50=120mA. With 100-ohm TLP the increase of current is 6/100=60mA. The DUT operation between 60 and 120 mA can be seen with 100 ohm Z_{TLP}, but not with 50 ohms. If we continue to increase Z_{TLP} by increasing $R_{HI\text{-}Z}$, more and more of the DUT I-V curve will be displayed until the limit of holding current is reached.

IV. Measurements with Multilevel TLP Tester

A single commercial device was used to compare these low current measurements. A Texas Instruments SN74LS688N comparator I.C. is tested with positive pulses delivered to input pin 17 with package ground pin 10 grounded. Results are displayed in Figures 9 through 11. Figure 9 demonstrates an advantage of MLTLP, two I-V curves are generated from one measurement set. The red line is data from the first level pulse which agrees with a standard 50-ohm TDR-O measurement. We see the DUT performance from 120 mA and above. The blue line is from the same set of measurements using the second pulse level by changing the location of the measurement window (shown as the blue area in Figure 4). The DUT operation below 120 mA shows the holding voltage is 7.8V and the minimum holding current is 45 mA. The small negative resistance range in the 45 to 60 mA is commonly seen in many devices. It appears that as the current is increased from just above the turn on point threshold, the clamping voltage drops.

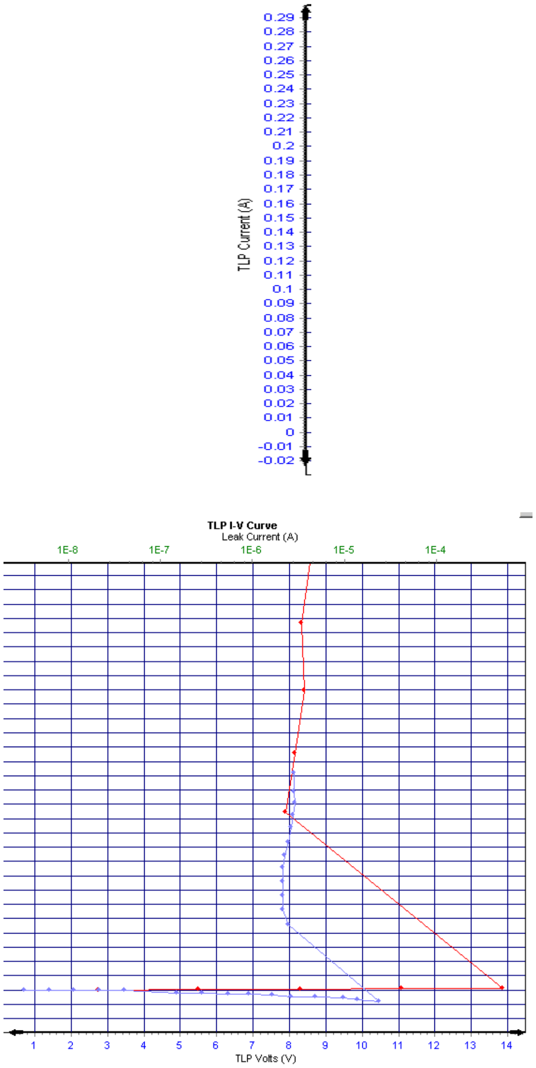

Figure 9: MultiLevel TLP and Standard TDR, both Curves from Same Pulses, Measured with Different Time Windows

However, we also see a negative current drift that begins when the first level of the MLTLP pulse reaches the DUT turn-on voltage, V_{t1}. Figure 10 shows this in more detail; a -0.7mA per volt drift is displayed when $V_1 > V_{t1}$. This appears to be charge stored in the device by the first pulse level current being discharged during the second level time period. This charge could effect the low current measurements as 7 mA is a significant fraction of the 45 mA $I_{On\text{-}Min}$.

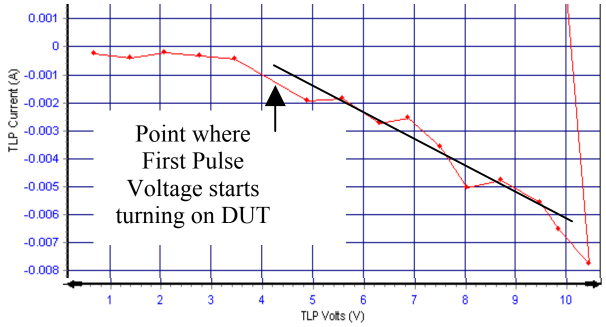

Figure 10: Negative Current Drift During Second Pulse due to First Pulse Amplitude

V. Measurements with Multi-impedance TLP Tester Design using High-Z TDRT

Increasing the pulse delivery impedance clearly shows more low current response as shown in Figure 11. The blue line is from 100-ohm TLP (using $R_{HI\_Z} = 0$). V_{t1} is displayed at 14 volts same as with 50-ohm TLP, and the operation from 60 mA and above are shown on this I-V curve. The red curve is data with 500-ohm TLP (using $R_{HI\_Z} = 400$). Operation from 28 mA to 60 mA is displayed and both curves agree above 60 mA. The voltage is seen to exceed Vt1 and be noisy.

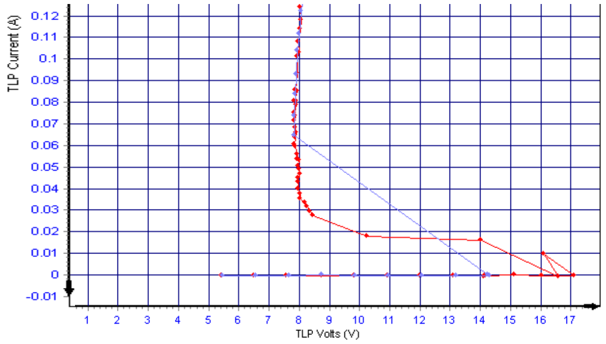

Figure 11: 100-ohm (Blue) and 500-ohm (Red) High-Z TDRT

At high impedances, when the pulse voltage just exceeds V_{t1}, a region of instability is entered where the protection structure tries to turn on but the delivery impedance prevents sufficient current flow to allow the device to remain on. Oscillations, like in Figure 12, cause noise in the measurement, and points of low current and voltage exceeding V_{t1} and other somewhat random points with current below the holding current are recorded. Once adequate current is provided stable operation is obtained. At this point the holding current and voltage is recorded.

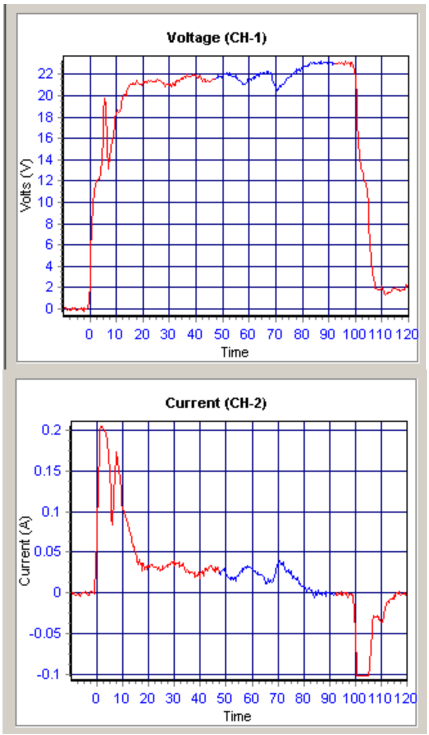

Figure 12: DUT oscillation at 22.5 V 500-ohm pulse response

Once the entire operating region has been displayed, increasing the delivery impedance further does not provide more information as shown in Figure 13.

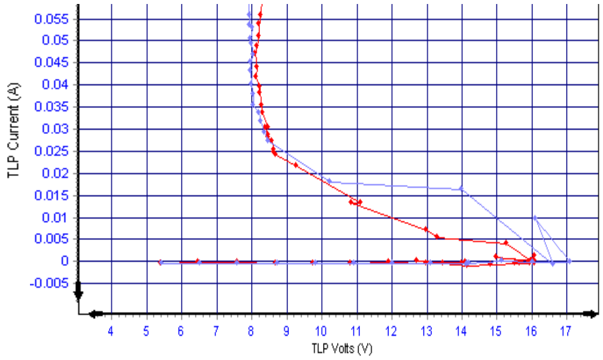

Figure 13: 500 (Blue) and 1000-ohm (Red) Hi-Z TDRT

The region of negative resistance after snapback (from 20 to 60mA) is observed just as in MLTLP. However, lower currents are seen with high-Z TLP compared with the MLTLP.

Figure 14 shows an issue with high impedance testing: the DUT input capacitance causes longer settling times as the TLP driving impedance is increased. This makes the measurement more sensitive to proper measurement window positioning, and error in the measurement may occur with noise increasing with impedance.

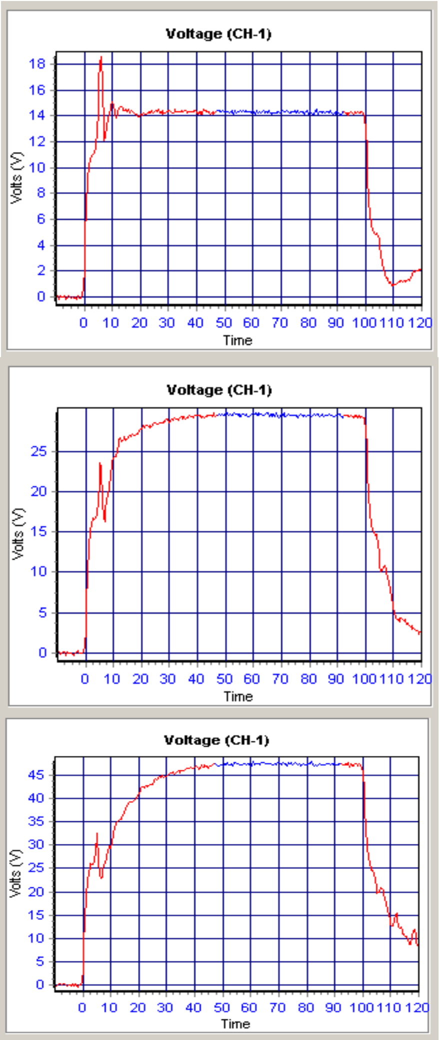

Figure 14: 100-ohm at 20 V; 500-ohm at 30V; 1000-ohm at 46 V

VI. MLTLP Generating a Decaying Pulse

In section II we built a Multilevel TLP system that worked with two levels. Data can be extracted from each level. More information can be obtained with more levels, using a pulse that first exceeds V_{t1} and then decreases in many small steps. Theoretically, a complete I-V curve could be constructed from one pulse with each level providing a data point. Figure 15 shows a schematic of a TLP system that produces an exponential decaying pulse. The round trip propagation time of the charge line, which normally determines the entire pulse width, now fixes the step temporal width. R_{Series} limits the amount of current in the pulse and thus the pulse voltage amplitude.

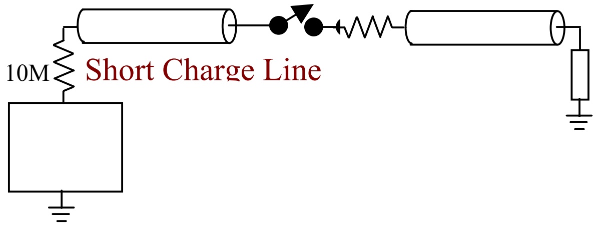

Figure 15: MLTLP Design for Decaying Pulse

When the 50-ohm switch in Figure 15 is closed the pulse is initiated. The current flowing out of the charge line passes through both the series resistor and the output cable. With both the charge line and the output cable having impedance Z_0, the drop in voltage in the charge line equals the initial output pulse voltage, $V_1 = \dfrac{V_0}{2 + R_{Series}/Z_0}$, where V_0 is the initial charge line voltage. The section of the charge line by the switch drops from V_0 to V_1 and this pulse of $-V_1$ propagates back toward the 10M resistor. When the pulse hits the 10M resistor it is fully reflected in phase by the almost open circuit, and this pulse of $-V_1$ travels back toward the switch. Upon reaching the switch some of the pulse is transmitted through R_{Series} and the output pulse is reduced. There is also another reflected pulse produced going back down the charge line. The reflections continue back and forth in the charge line until all the energy stored in the charge line has been discharged into the output cable. Since the amplitudes of negative pulses echoing in the charge line are proportional to the magnitude of the existing output level, the resultant waveform is approximately exponential. The output pulse decays in steps of twice the charge line propagation time, and a simple low pass filter can control the initial rise time and smoothes the transition between steps.

Figure 16, shows the oscillograph of a decaying MLTLP pulser driving a DUT. At the beginning of the pulse (Blue trace), the DUT conducts the pulse current (Green trace), and clamps the voltage (Black trace). When the MLTLP pulse has decayed to almost the clamping voltage, the current through the DUT has decayed to almost zero and the protection structure turns off. Then the DUT voltage equals the decaying TLP voltage. This action is the same as the DUT response to an HBM pulse.

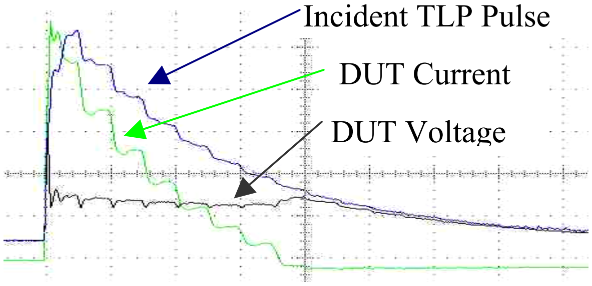

Figure 16: Decaying TLP driving a Protection Device

VII. MLTLP Generating an HBM Pulse

By selecting the charge line length and series resistance placed at the switch, we can produce a decaying exponential waveform similar to an HBM pulse. Figure 17 models this concept. It is not surprising that if we use a meter of cable (about 100 pF of cable capacitance) and a series resistor of approximately 1500-Z_0 ohms we will have a waveform that meets the HBM standard for a short circuit load. Figure 18 shows this circuit produces a 1 ampere current pulse that meets the HBM specifications [8] for rise time, ring, decay time, etc. The one operational concern with this circuit is that the change line requires high voltage: 8KV/ampere of DUT current. This is 5.3 times the voltage needed for a standard HBM pulse generator for the same short circuit current. This is largely because of the –20 dB attenuator used to attenuate reflections from the load and provide a relatively constant load impedance for the charge line discharge. Reducing the attenuation to –6 dB can bring the charging voltage to the same level as a standard HBM pulser, but the waveform will suffer some distortions. These distortions can be minimized with a long output cable because the pulse will decay before the reflections arrive at the DUT.

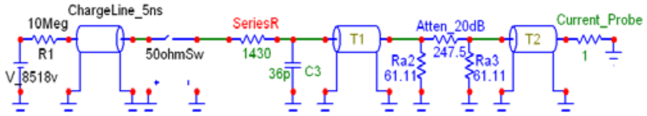

Figure 17: MLTLP Design for Decaying Pulse

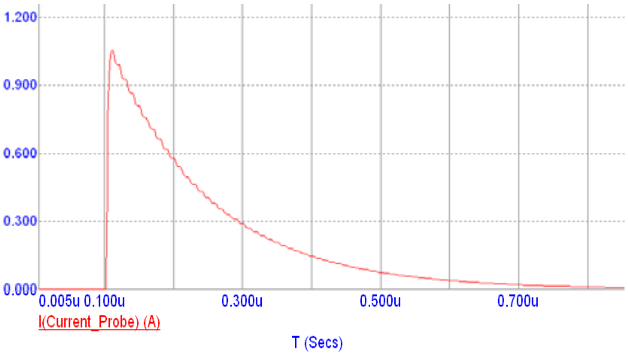

Figure 18: Spice Model of MLTLP Simulating HBM Short Circuit Response

The main question is: Can MLTLP produce a true HBM pulse? The answer is no. However, this MLTLP has a very similar stress on many types of DUTs as shown in Figure 14. Due to its 50-ohm delivery impedance, the MLTLP pulse does not fully replicate HBM. The circuit of Figure 19 is the same HBM-like MLTLP but with a 500-ohm load. The transient response of this circuit is shown in Figure 20. The wave shape is almost unchanged, but the peak current is reduced by a factor of about 10.8 (approximately (500+50)/50). This fails to meet the 500-ohm load test of the HBM standard test method.

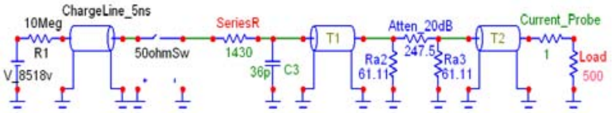

Figure 19: MLTLP Design for Decaying Pulse

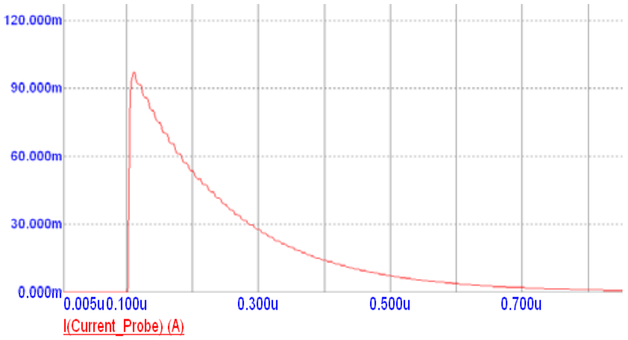

Figure 20: MLTLP Design for Decaying Pulse

VIII. Conclusions

Straightforward modifications of a TLP system can provide either Multilevel or Multi-Impedance TLP to overcome the absence of low current measurements with 50-ohm TDR TLP. Both techniques can be implemented with minor hardware changes, but both could require some software features: the MLTLP needs flexible measurement windowing, while the MITLP requires calibration for high impedance TDRT. Such software features are available from TLP vendors.

Both techniques have been demonstrated to provide useful information. The performance differences between these techniques are summarized in Table 1. The MLTLP has a negative current drift during second pulse as a function of first pulse amplitude as a drawback. This may limit the lowest current measurements and effect accuracy when measuring some DUTs. MITLP, while requiring multiple scans, provides better sensitivity measuring 20 mA smaller currents (25 to 45 mA range) after turn-on with the DUT used in this paper, as shown in Figure 21. The basic results of the two measurement techniques strongly agreed as demonstrated by the overlap of the common measurement regions of their I-V curves.

Table 1: MLTLP and MITLP Comparison

	MLTLP	**MITLP**
Pros	Standard and Low Current measurements made with 1 scan	More complete low current measurements
Cons	Stress of 1st pulse level has residual effects during 2nd level measurement as shown by negative current drift before snapback	Multiple scans needed with difference impedances. V_{t1} can only be measured at low impedances
	Measurements at lowest currents are limited	Settling times increase with impedance
		High impedance curves have a noisy region

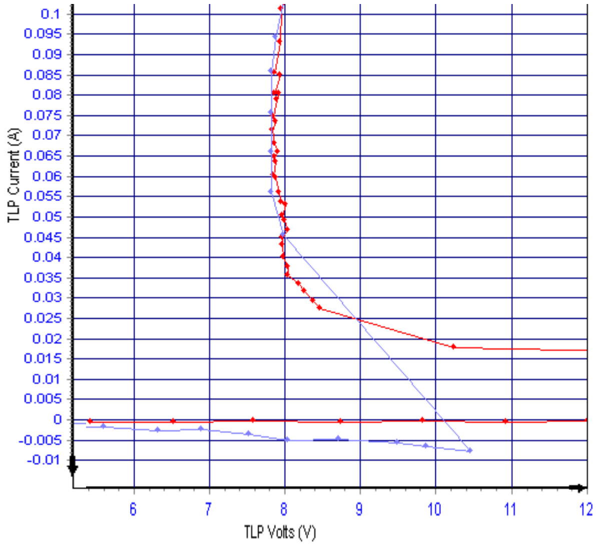

Figure 21: 500-ohm HI-Z TDRT and MLTLP Level 2 data

It has been asserted [1] that

> "While using a TLP system with high impedance (e.g. 500 or 1k Ohm) could yield accurate measurement of the holding point, it requires higher charging/driving voltages, high voltage cables, higher attenuations and losses in the cables, etc., thereby complicating the measurement procedure and degrading the pulse shapes. Thus, it is required to pre-select a TLP system having an appropriate load line depending on the snapback curve of the device to be tested, to accurately determine all the IV points, especially the holding point One could also use a measurement setup with tunable load line specifications…"

The traditional Current Source 500-ohm TLP system [3] requires more voltage than the High-Z TRDT [4] for the same DUT current [2]. Thus, using High-Z TDRT addresses some of the concerns raised above. All testing described herein used a standard commercial TLP system available with a high impedance option and did not require any special high voltage components nor special software. The choice of impedance, as long as it was sufficiently high, was not found to be critical; 500 and 1000 ohm High-Z TRDT yielded the same results. Two or three MITLP scans can provide all the information available from this technique. The tunable load line that was suggested [1,4] proved to be useful. Therefore, the issues using MITLP have been largely overcome.

The custom charge lines used for generating MLTLP pulses are simple to construct and were easy to install on the same tester.

The use of MLTLP to duplicate HBM performance is limited by its delivery impedance not being 1500 ohms. However, for DUT circuits of low impedance in the region of interest, which includes common ESD protection circuits, the current waveforms mimic HBM tester waveforms and therefore the stress effects of MLTLP should correlate closely with HBM.

IX. References

[1] T. Daenen, et.al., “Multilevel Transmission Line Pulse (MTLP) Tester”, pp. ,ESD Assoc. Symposium, 2004

[2] E. Grund, “Comparisons of Transmission Line Pulser Configurations”, Proceedings of 8th ESD Forum of the Interessengemienschaft Electro Static Discharge e.V., Munich Germany, Dec. 2003, pp 87-99.

[3] ESD Assoc. Standard Practice. ESD DSP5.5.1-2003, “Electrostatic Discharge Sensitivity Testing, Transmission Line Pulse (TLP), Component Level”, 2003.

[4] Grund and Gauthier, “TLP Systems with Combined 50 and 500 ohm Impedance Probes and Kelvin Probes”, EOS/ESD Symposium Proceedings, pp. 354-363, 2003

[5] S. Voldman, et.al., “Standardization Of The Transmission Line Pulse (TLP) Methodology of Electrostatic Discharge”, EOS/ESD Symposium Proceedings, pp. 372-381, 2003

[6] T. Maloney and N. Khurana, “Transmission Line Pulse Technique for Circuit Modeling and ESD Phenomena”, EOS/ESD Symposium Proceedings, pp. 49-54, 1985

[7] H. Hyatt, et.al., “TLP Measurements for Verification of ESD Protection Device Response”, EOS/ESD Symposium Proceedings, pp. 111-121, 2000.

[8] ESD Assoc. Standard Test Method ANSI/ESD STM 5.1-2001, “Electrostatic Discharge Sensitivity Testing, Human Body Model (HBM), Component Level”, 2001.