A Unique Approach to TVS Characterization

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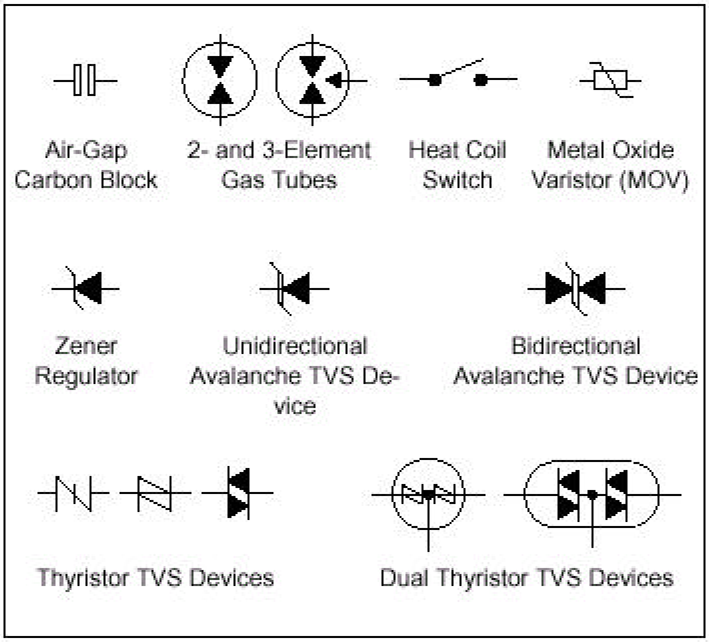

Courtesy of ON Semiconductor Zener/TVS Device Data Book

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A Unique Approach to TVS Characterization

Abstract

In real-world conditions, the occurrence of a plurality of transient voltages is capable of dissipating significant power in circuit protection devices. In order to understand how Transient Voltage Suppressors, TVS, devices perform up to their rated power, techniques and equipment have been developed to characterize the effects of multiple industry-standard pulses being applied to TVS devices under controlled and monitored conditions. This study defines and demonstrates the TVS clamping voltage shifting that occurs during and immediately after transients are applied. It is envisioned that manufacturers of TVS devices, and circuit designers who use these devices, will find this information useful in increasing the level of transient voltage protection.

A. Background / Introduction

As electronic products find broader applications, the need to protect becomes ever more important due to our dependence on maintaining proper circuit operation and data integrity. Generally, the push is for higher speed devices, which pushes the operating voltages way down resulting in devices ever more sensitive to electrical overstress conditions. Although transient disturbances can corrupt data on a temporary basis, Transient Voltage Suppressor, or TVS, devices main use is to prevent or at least limit costly permanent physical damage of electronic circuitry. In order to improve transient protection in both existing and new applications, a better understanding of TVS characteristics would be beneficial. This study will address a unique and useful method of characterization applicable to TVS protection devices of all kinds. In particular, a case study of several silicon TVS devices will be presented.

The market for TVS devices of all kinds is expected to grow at a compound annual rate of 5.7% in the period from 2000 to 2007. "The unbundling of utility operating units has diminished customer confidence in the industry's ability to deliver reliable power. At the same time, customer downtime costs are rising and power quality is becoming a critical concern. Customers want assurance that they'll receive high-quality power." [1] With this in mind, the TVS market would be expected to have the following components:

- Increased Competition
- Pressure for Lower Prices
- Enhanced Performance
- Decreasing Package Size
- Integrated Transient Protection
- New Products

To deal with these market pressures, it is even more important to fully understand how to analyze TVS devices under meaningful current surge conditions utilizing new methods to duplicate various real-world situations.

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[1] Sara M. Bradford, "Market Trends in Transient Protection, Power Conditioning, and Batteries", Power Quality, January 2002

This table shows a number of the many different standards are used to simulate real-world transient events in different applications.

Standard	Voltage	Waveform	Current	Waveform	Application
IEEE-472	4,500V	10/1000 uS	17A		Protective relays
ANSI C37 90.1	2,500V	1.25MHz / 6 uS			Static relays
IEC TC 102D	6,000V	1.2/50 uS			Remote-control receivers
IEC 255	5,000V		12 A		Static relays
IEC TC 41	1, 2.5 kV		25 A		Static relays
IEC 801-4, IEC 61000-4-4	5,000V	1.2 / 50 uS	3,000 A	8 / 20 uS	Industrial process control
	5,000V	0.5 uS / 100 KHz			
	4,000V	5 / 50 nS			
ANSI C62.41 CAT. B	6,000V	1.2 / 50 uS	3,000 A	8 / 20 uS	LV ac power circuits
CAT. B	6,000V	5 uS / 100 KHz	500 A		
CAT. C	6,000V	5 uS / 100 KHz	200 A		
CCITT IX K17	3 - 5 kV	10 / 700 uS			Repeaters
K20		100 / 700 uS			
K15		10 / 700 uS			
FTZ 4391 tv1 (Gmy)	2,500V				Telephone / microphone
FCC Sec. 86.302	2,500V	2 / 10 uS	1,000 A		Telecom power line
PTT 692.01 (Swiss)	4,000V	1.0 / 50 uS			Telecom exchange
EIA PM-1361	2,500V	2 / 10 uS	1,000 A	2 / 10 uS	Telecom terminals
	1,000V	10 / 1000 uS	200 A	10 / 1000 uS	DP interface
	1,500V	10 / 1000 uS	400 A	10 / 1000 uS	
UL-4978	1,000V	10 / 1000 uS	10 A		Data communication
UL-1459					
MIL-STD.704A	50V	45 nS	29 Vdc		Std. telephone equipment
	425V	30 nS	270 Vac		Aircraft electrical power
	600-200V	10 - 50 uS			
MIL-STD704D	100V	50 nS			Military vehicles
MILSTD-1275	32V	200 nS			
MIL-STD1757	1,000 KV/uS	1.2 / 50 uS	200 kA	< 500 uS	Aerospace vehicles
DODSTD-1399,Sec.300					Shipboard ac power
440V	2,500V	1.2 / 50 uS	400 Vac	500 A	
115V	1,000V	1.2 / 50 uS	115 Vac	200 A	

Source: “**AJTVS - The Forgotten Component In Circuit Design”** by David W. Hutchins
Published in EMC Test & Design, March/April 1992

As can be seen from the table, identifying the transient events and standards to be used can be a complex task. Plus the standards are subject to being updated and expanded as new applications are considered. For example, early in the electronics industry, most transients were generated from external sources such as lightning and power line switching. In current times, with the advent of switching power supplies, battery operation and redundant/hot swap equipment over 60% of transient events are now generated locally or even internally.

The automotive industry is presenting an especially challenging market for transient protection and certainly almost all transients can be considered locally generated. Initially, the Load Dump standard was developed to handle the transients due to the switching of increased electrical loads present in today's cars. In the near future as the electrical loads continue to grow, 14/42 volt dual voltage systems will soon be presenting even new transient conditions to be considered in all automotive designs.

"Increasing electrical power consumption is straining the existing 12-V supply system of current vehicles. At some point in the not-too-distant future, manufacturers will have to change to a higher voltage to support improved emissions, safety, and new vehicle options. With the increased growth in vehicle loads (4%/year for the past two decades and about 100 W per year for the last five years)..."[2]

<u>With all these items in mind, the need for a very flexible current surge tester is evident.</u>

B. The Scope of this Study

The goal of this study is to utilize the standardized waveforms and adapt them to provide even more information by analyzing the shifting in the TVS clamping voltage. As previously stated, although silicon TVS are presented, the concepts are applicable to all types of TVS devices in general, both active and passive. Adapting the standardized current waveforms involve digitally combining standard current waveforms and biasing the TVS devices with programmable currents before and after the transient pulse. The voltage across the TVS is then digitally stored and analyzed. While the method described could generate arbitrary current waveforms up to several hundred amperes, industry-standard waveforms will be used for the bulk of this effort.

At this point it would be appropriate to address why current transients are used in this study instead of voltage transients. Configuring the TVS in a shunt protection network, it is basically either off in normal operation or it turns on during the transient event. Although the initial transient may be either voltage or current externally, the TVS's performance is based on it's transient current carrying capacity and it's ability to clamp its terminal voltage within specified limits. The key design specifications for any TVS device are also all current-based as shown:

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[2] Randy Frank, Tim Phillips, Ryan Zahn, "Increases in future automobile voltages will directly and indirectly affect semiconductor devices in every automotive electronic system.", ON Semiconductor, SAE Convergence 2000: An Electronics Showcase

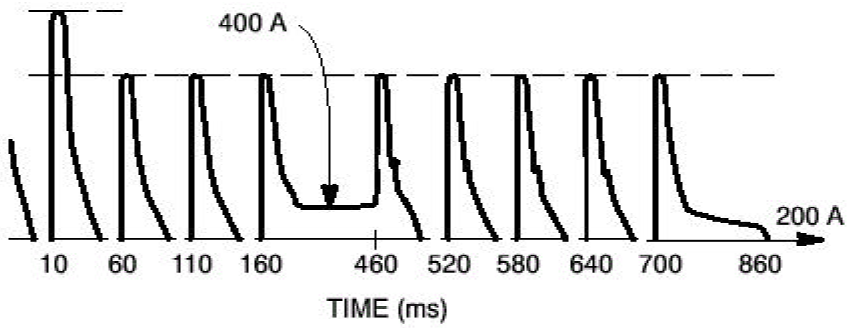
V_{RMW} - The maximum reverse working voltage where leakage current is measured, usually a few microamperes
$V_{(BR)}$ – The avalanche voltage where a specified amount of reverse current is flowing, usually 1 to 100milliamperes
V_{RSM} – The maximum reverse voltage, aka clamping voltage at the maximum rated current, usually 1 to 1000 amperes

“Transient voltage waveforms are commonly described in terms of a dual exponential wave ………… The standard chosen for power lines is a 1.2/50 ms voltage wave which **causes an 8/20 ms current wave**. Although the source of the most severe transients on telecom lines is the same as for power lines and lightning, the higher impedance per unit length of the telephone line stretches the waves as they propagate through the lines.”

“The 10/1000 ms wave approximates the worst case waveform observed on data and telecom lines. **TVS devices intended for this service are usually rated and characterized using a 10/1000 waveform**. The Bell South study revealed that the worst transient energy handled by primary protectors on lines entering a central office was equivalent to only 27 A peak of a 10/1000 wave. This level is considerably less than that required by secondary protectors in most of the standards in use today. This finding is particularly significant because the Bell South service area includes Central Florida, the region experiencing the highest lightning activity in the U.S.”[3] (emphasis added)

Finally by combining the standard current waveforms, worst case scenarios can be constructed consisting of a plurality of transient events. These current waveforms can then be accurately reproduced so that their effect on TVS devices can be studied.

Consider the following Severe Lightning Model:[4]



Depending on various conditions, continuing current may or may not be present in a lightning strike. A severe lightning model has also been created, which gives an indication of the strength which can be expected during worst case conditions at a point very near the strike location. The figure above shows this model. Note that continuing current is present at more than one interval, greatly exacerbating the damage which can be expected. A severe strike can be expected to ignite combustible materials.

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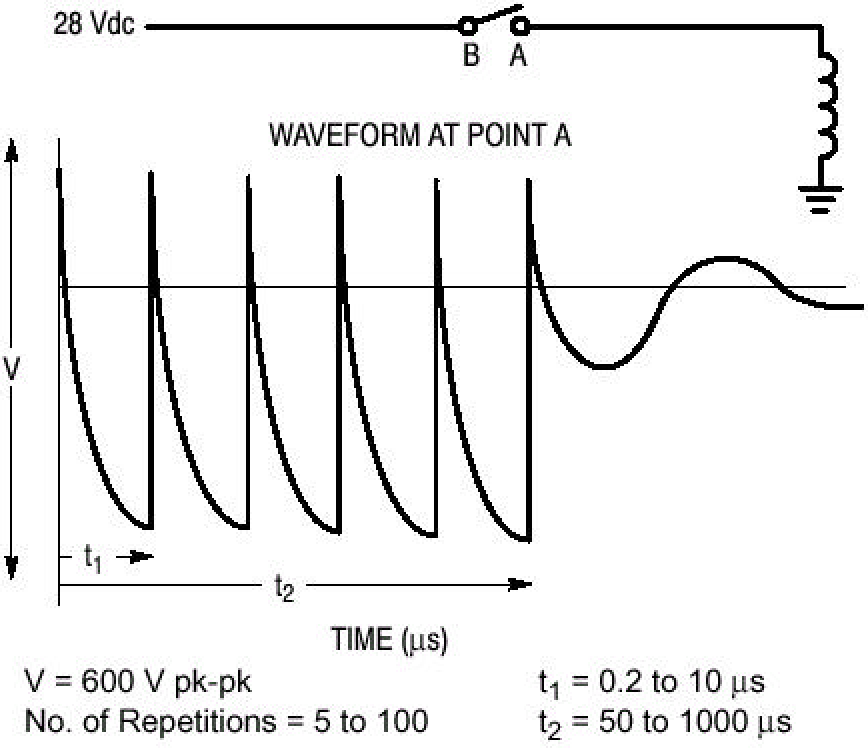
[3] ON Semiconductor, “TVS/Zener Device” Databook, Rev2 2001, page 387.
[4] ON Semiconductor, “TVS/Zener Device” Databook, Rev2 2001, page 384.

Another example of multiple transient events is as follows:



"After characterizing electrical overstress on aircraft power buses, Boeing published **Document D6-16050** as shown.

The military has developed switching transient definitions within several specifications including:

> **DOD-STD-1399** for shipboard
> **MIL-STD-704** for aircraft
> **MIL-STD-1275** for ground vehicles

The International Electrotechnical Commission (IEC) is now promoting their specification **IEC 801-4** throughout the European community. This describes an inductive switching transient voltage threat having 50 ns wide spikes with amplitudes from 2 kV to 4 kV occurring in 300 ms wide bursts.[5]

Besides these particular military specifications, many are application specific and functional tests exist. A supplier of transient voltage suppressor components will be expected to perform to a wide variety of them."[6]

The initial focus of this study will be the variation and shifting of reverse breakdown and clamping voltages due to absorbing transient energy. The availability of using a digital arbitrary waveform allows for measurements when one or more standard waveform transients are generated.

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[5] O. M. Clark, "Transient Voltage Suppression (TVS)," 1989, page 7.

[6] ON Semiconductor, "TVS/Zener Device" Databook, Rev2 2001, page 386.

The first order effects and observations of this energy dissipation would involve:

- Increase in die temperature
- Stressing/Evaluation of die bonds
- Current sharing and/or channeling
- Thermal gradients across the die
- Thermal gradients from die to ambient via packaging
- Overall power dissipation capabilities

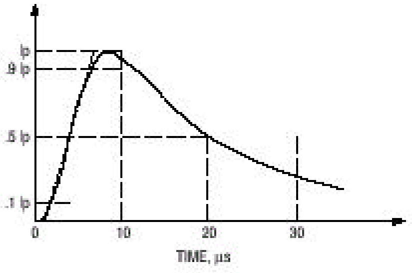
In general terms, as a result of these and subsequent studies, the following benefits could be expected:

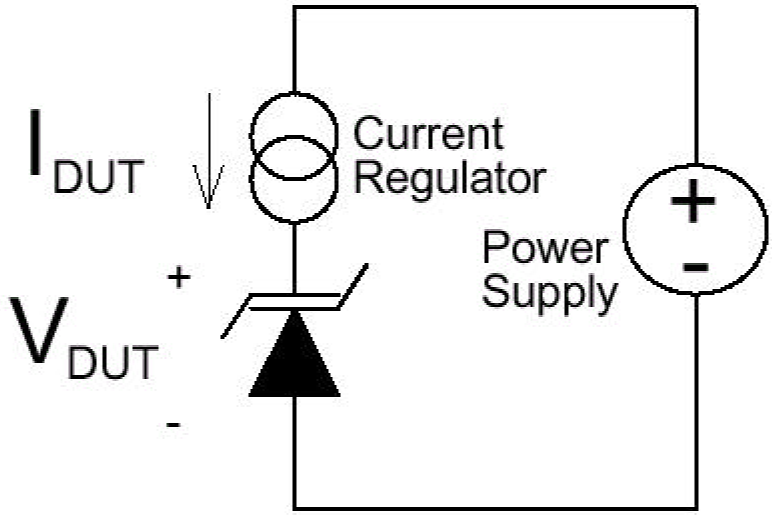
- Improvements to silicon TVS device designs
- Advancement in packaging
- Qualifying silicon TVS devices to match particular applications
- Integrating TVS protection into ICs

C. The Method

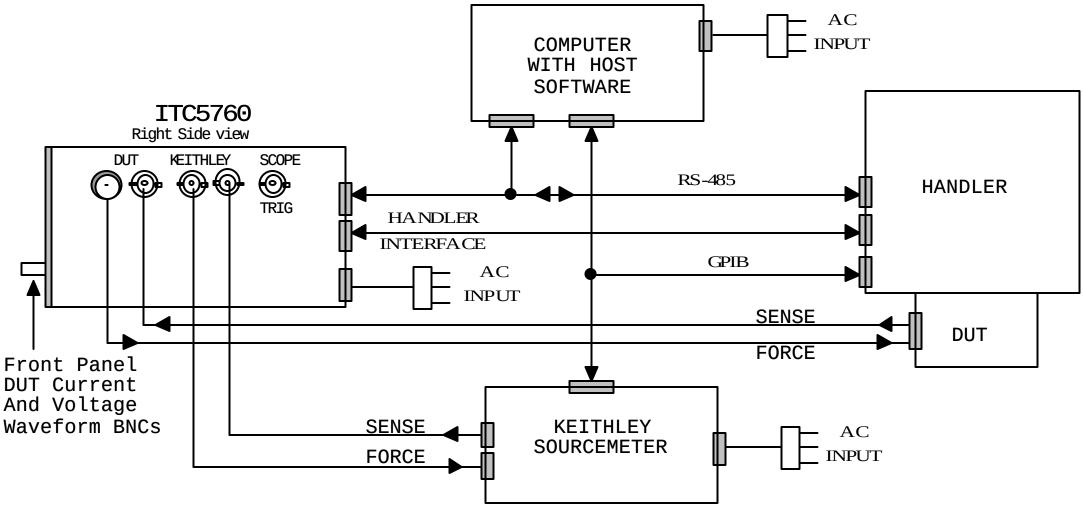
A TVS test system, the ITC 5760, was developed by Integrated Technology Corporation to digitally generate the current waveforms, store the resulting TVS voltage data, and analyze test results. Conventional transient test systems have often used traditional RLC networks to generate the standard current waveforms. The ITC 5760 was designed with a programmable active current regulator to provide a wide range of accurate current waveforms up to 320 amperes and could be easily customized to generate almost any waveform. Waveforms can also be downloaded from Excel spreadsheet files.

The basic block diagram of the current loop used generate almost any current surge waveform is show below:





The main system Host software runs on a PC computer and provides a user interface to setup, run, and record all the tests. This software was written and compiled using the LabView Development Software Suite of tools provided by National Instruments. Once the operator has selected a particular test, this information is downloaded via a high speed RS-485 network to the ITC 5760 test station. The operator can then initiate testing. The resulting DUT voltage and current waveforms are digitized, returned to the PC via the RS-485 network, and displayed on the PC's user screen. In addition, a digital oscilloscope connects to the front panel BNCs and captures DUT voltage and current waveforms for correlation or other use. The Handler and Keithley Sourcemeter are not utilized with these transient tests but are used for DC testing such as leakage. The DUT is placed in the DUT test fixture as shown with force and sense connections.



The current waveforms used for testing were initially generated in Excel spreadsheets and then imported using one of the utility programs the ITC 5760 software provides. Each waveform can contain up to 1000 datapoints that can source from 10 milliamperes to 320 amperes of DUT current at a rate of 1uS to 100 uSec per datapoint. DUT voltages can be digitized and measured up to 400 Vdc.

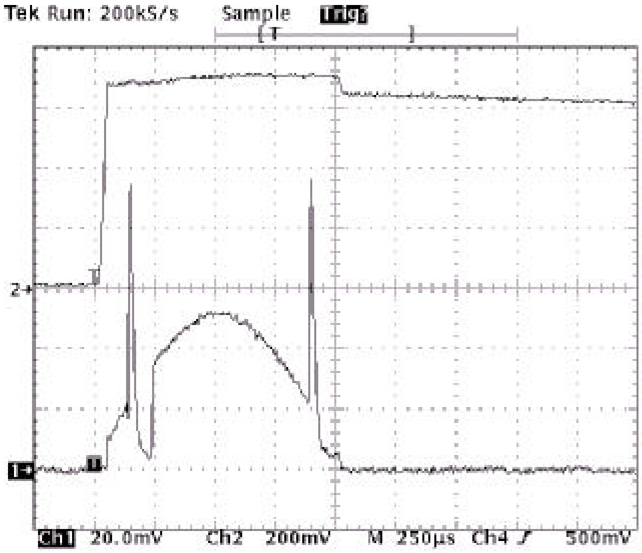
D. Test Results

Two different ON Semiconductor TVS devices were selected for testing in this study:

1SMB75CAT3 Bidirectional 600 Watt Peak Power Zener TVS. SMT Plastic SMB
V_{RMW}: 75 Volts at I_R = 5 uA
$V_{(BR)}$: 83.3 to 92.07 Volts at I_Z = 1 mA
$V_{(BR)}$: 121 Volts MAX at I_Z = 4.9 A, 10x1000 uSec Pulse Width at T_C = 30 deg C

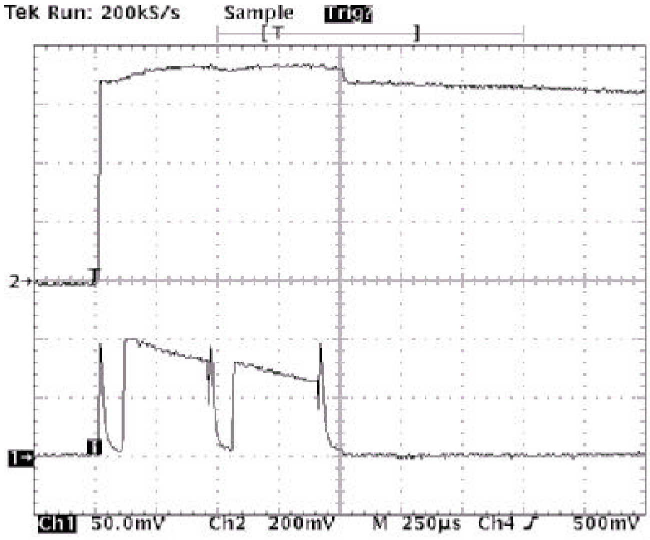
MR2835S Overvoltage Transient Suppressor, SMT Automotive System TVS
V_{RMW}: 23 Volts at I_R = 5 uA
$V_{(BR)}$: 24 to 32 Volts at I_Z = 100 mA
$V_{(BR)}$: 40 Volts MAX at I_Z = 80 A, 80 uSec Pulse Width at T_C = 85 deg C

The first DUT Current Waveform used is shown below is basically a combination of 2, 8x20 waveforms at the beginning and end of a 1 mSec Half Sine wave. In addition there are 1% current pedestals during the first and last 50 uSec of the waveform. Obviously many other current waveforms and test protocols could be utilized.



Waveform #1-2x8x20+1mSec Half Sine
1SMB75CAT3 Waveforms
Channel 1: DUT Current, 0.20A/div
I = 0.96A-peak
Channel 2: DUT Voltage, 20V/div
Delta V = 71 – 68 = 3V

Note how the voltage waveform rises during the testing due to the heating effects of the transients. The 8x20 transients contain far less total energy than the 1mSec half sine envelope. At these current levels the 8x20 transient effect on the DUT voltage is negligible.

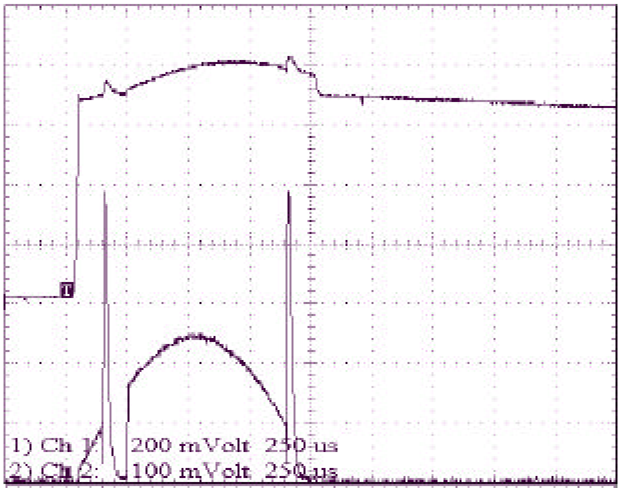


Waveform #2 – 3x8x20+10x1000
1SMB75CAT3 Waveforms
Channel 1: DUT Current, 0.50A/div
I = 1.0A-peak
Channel 2: DUT Voltage, 20V/div
Delta V = 74 – 68 = 4V

Note how the voltage waveform rises during the testing mainly due to the heating effects of the 10x1000 transient. Once again the 8x20 transients contain far less total energy than the 10x1000 envelope. At these current levels the 8x20 transient effect on the DUT voltage is negligible.

Now the current will be increased from 1 amp to 5 amps which is slightly beyond its maximum specified current limit of 4.9 amps. There should now be some visible effects of this higher current as follows:

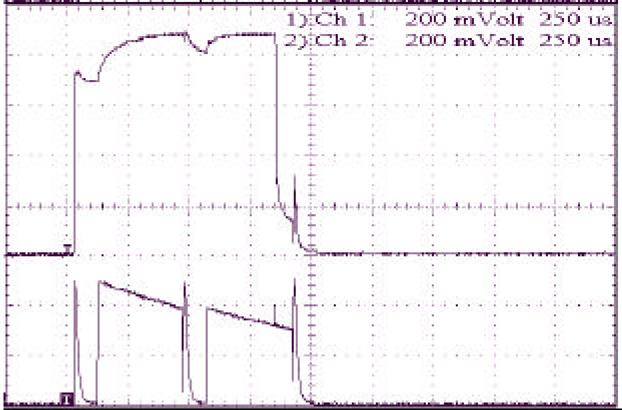
- Shifting of Clamping Voltage during the 8x20 transients
- Thermal time constant will be visible
- Variation of Clamping Voltage due to current variation
- Maximum current limits with multiple transients



Waveform #3-2x8x20+1mSec Half Sine 1SMB75CAT3 Waveforms

Channel 1: DUT Voltage, 20V/div
Delta V = 84 – 70 = 14V
Channel 2: DUT Current, 1.0A/div
I = 5.0A-peak

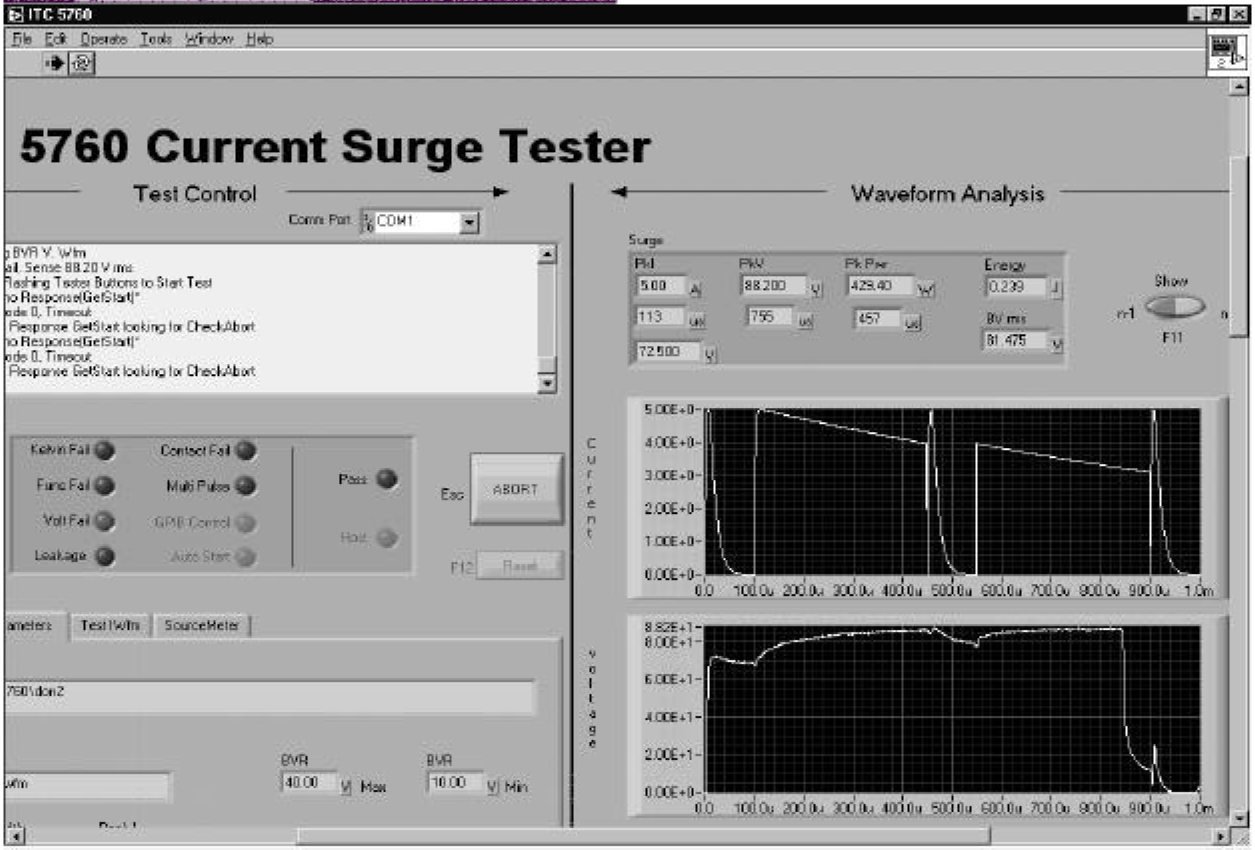
Note how the voltage waveform rises significantly during the 8x20 transient and how the second 8x20 has a higher clamping voltage. The voltage also shows a thermal phase shift with regard to the peak current.



Waveform #4 – 3x8x20+10x1000 1SMB75CAT3 Waveforms

Channel 1: DUT Voltage, 20V/div
Delta V = 88 – 73 = 15V,
then **FAILURE**
Channel 2: DUT Current, 2.0A/div

Failure at 880uSec. Note how the DUT voltage drops suddenly while the current waveform remains unchanged. The PC screen is also shown below.



Comm Port: COM1

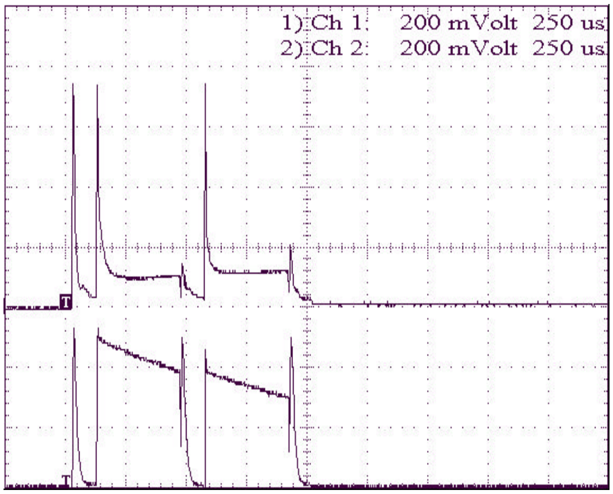
```
g BVR V. Wfm
ail. Sense 88.20 V ms
Flashing Tester Buttons to Start Test
no Response(GetStart)"
ode 0, Timeout
 Response GetStart looking for CheckAbort
no Response(GetStart)"
ode 0, Timeout
 Response GetStart looking for CheckAbort
```

Surge
Pk I: 5.00 A; 113 us; 72.500 V
Pk V: 88.200 V; 755 us
Pk Pwr: 429.40 W; 457 us
Energy: 0.239 J
BV rms: 81.475 V

760\don2

wfm

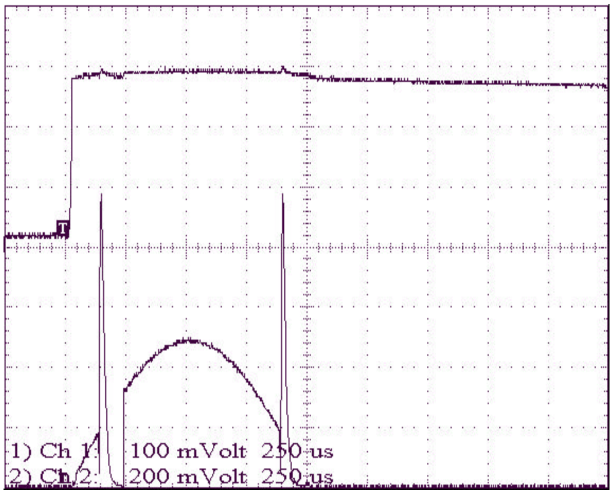
BVR 40.00 V Max
BVR 10.00 V Min



Waveform #5 – 3x8x20+10x1000
1SMB75CAT3 Waveforms
Channel 1: DUT Voltage, 20V/div
FAILURE
Channel 2: DUT Current, 2.0A/div
I = 5.0A-peak

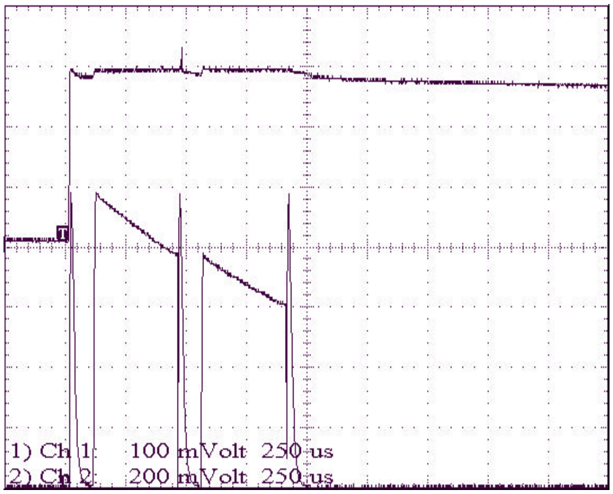
This is another surge with the part that just failed as shown in Waveform #4. At this point the DUT is low impedance as shown by this waveform. Note the voltage rises and then collapses at the point where the transient occurs.

The next phase of testing will use the MR3525S parts, higher current and lower voltage:



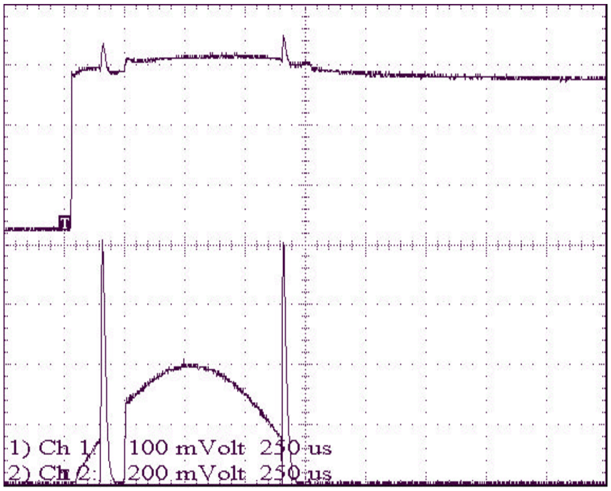
Waveform #6-2x8x20+1mSec Half Sine
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 30 – 28 = 2V
Channel 2: DUT Current, 2.0A/div
I = 10A-peak

Note how the voltage waveform rises during the testing due to the heating effects of the transients. At these current levels the 8x20 transient is barely visible.



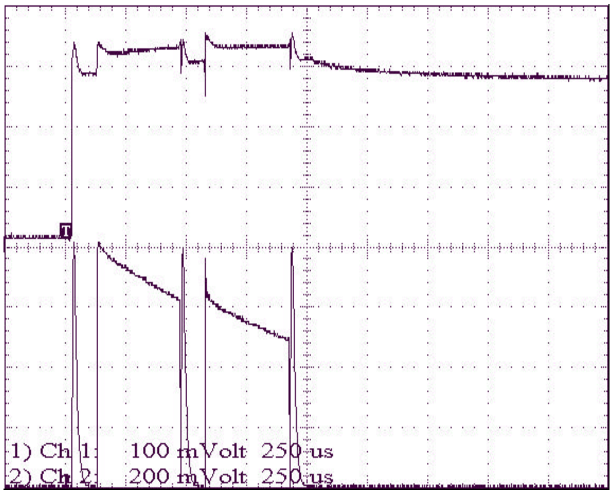
Waveform #7 – 3x8x20+10x1000
MR2835S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 30 – 29 = 1V
Channel 2: DUT Current, 2.0A/div
I = 10A-peak

Again the voltage waveform rises very little during the testing. At these current levels the 8x20 transient effect on the DUT voltage is also negligible.



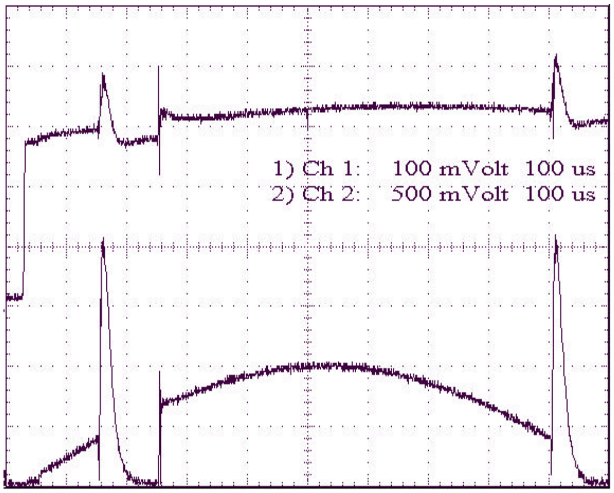
Waveform #8 - 2x8x20+1mSec Half Sine
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 35 – 33 = 2V
Channel 2: DUT Current, 20A/div
I = 80A-peak

At this point the 8x20 transients are visible although the voltage differential between the 2 transients is about the same as the 10A pulse.



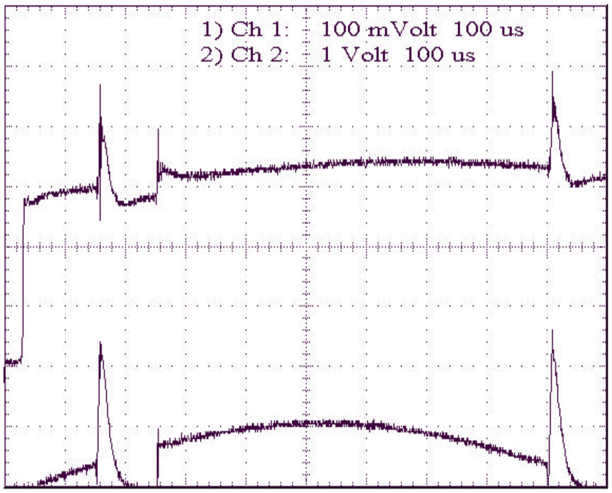
Waveform #9 – 3x8x20+10x1000
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 36 – 34 = 2V
Channel 2: DUT Current, 20A/div
I = 80A-peak

Again the 8x20 transients are visible although the voltage differential between the 2 transients is about the same as the 10A pulse.



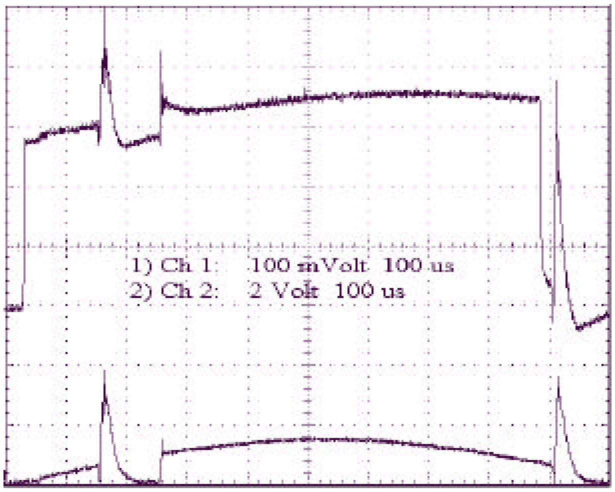
Waveform #10 - 2x8x20+1mSec Half Sine
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 42 – 38 = 4V
Channel 2: DUT Current, 50A/div
I = 200A-peak

The 8x20 transients are clearly visible and the voltage differential between the 2 transients has doubled to 4 volts indicative of higher die temperature and greater overall stress.



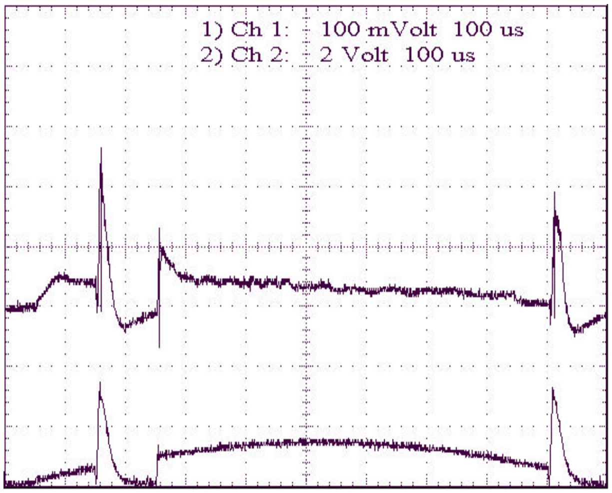
Waveform #11 – 3x8x20+10x1000
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
Delta V = 45 – 39 = 6V
Channel 2: DUT Current, 100A/div
I = 250A-peak

The 8x20 transients continue to push the clamping voltage higher with increased current. The voltage differential between the 2 transients has increased another 50% while the current has increased only 25%. It would appear that die temperature and overall stress is rising even higher.



Waveform #12 - 2x8x20+1mSec Half Sine
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
FAILURE
Channel 2: DUT Current, 200A/div
I = 300A-peak

Failure at 880uSec. Note how the DUT voltage drops suddenly while the current transient waveform remain unchanged.



Waveform #13 -2x8x20+1mSec Half Sine
MR3528S Waveforms
Channel 1: DUT Voltage, 10V/div
FAILURE
Channel 2: DUT Current, 2.0A/div
I = 5.0A-peak

This is another current surge with the part that just failed as shown in Waveform #4. At this point the DUT is low impedance as shown by this waveform. Note the voltage rises and then collapses at the point where the current transient occurs.

E. Conclusions

This study was admittedly a first step. Many other application-specific uses of these basic methods are envisioned. Although many issues were only briefly presented, some general conclusions should be of interest to all personnel involved in phases of TVS design and application.

Namely,

1. A flexible, programmable current surge tester can reveal and record a wide variety of important TVS device characteristics.

2. Both standard and customized current surges are useful. The ability to load and accurately reproduce standardized current pulses and import waveforms affords new opportunities in device evaluation.

3. The effects of multiple transients can be used to insure transient protection is adequate and relates well to real-world events.

4. One particular characteristic studied was the shifting of clamping voltage during multiple current transients. This shifting is an indication of die temperature and overall TVS stresses during transient conditions.

5. Measuring TVS operating voltages and surge currents plus the stresses they create can also be used to improve TVS device design, packaging, die attachment, reliability, life expectancy, and many other related TVS properties.