

TVS

DESIGN GUIDE

WHITE PAPER



CARLISLE
INTERCONNECT TECHNOLOGIES

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ECS



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INTRODUCTION

Lightning strikes Aircraft, Helicopters, UAV's, and Ships with a higher frequency than most people would believe. There also exists the potential of a nuclear event that would propagate an Electro Magnetic Pulse (EMP) to consider. The performance and signal integrity necessary for the continued functionality of the systems used on these platforms is critical.

The aerospace industry and the military have developed standards to address this issue, system designers have a criteria guideline to insure the safety and integrity of the systems (RTCA/DO-160-Section 22, Airbus ABD0100, Boeing D6-16050-4 & D6-16050-5).

For the purpose of this handbook, we will use RTCA/DO-160 as our reference. This specification defines a number of waveforms in section 22 with peak pulse currents ranging from 4 amps up to 5,000 amps and voltages from 100 volts through 3,200 volts. (See tables 22-2 and 22-3) The pulse durations of these waveforms range from $6.4\mu s$ to $500\mu s$. The specifications alone have many variables, and this does not take into account the differences between pin injection and cable bundle testing.

By using Transient Voltage Suppression (TVS) devices, we can guard against the destructive energy spikes generated by lightning. Although there are other devices available, Silicon TVS devices are the most reliable for repeated surges because they do not degrade with each surge, and they afford lower clamping voltages than can be achieved with other methods.

This guide will explain many of the considerations needed to select the proper device for each line. It will give examples of device selections to guide you through the process. Our goal is to give you the understanding needed to make these selections properly and with confidence.

Level	Waveforms		
	3/3	4/1	5A
	Voc/Isc	Voc/Isc	Voc/Isc
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	600/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600

Table 22-2

Level	Waveforms				
	2/1	2/1	3/3	4/1	4/5A
	VL/IT	VL/IT	VL/IT	VL/IT	VL/IT
1	50/100	50/100	100/20	50/100	50/150
2	125/250	125/250	250/50	125/250	125/400
3	300/600	300/600	600/120	300/600	300/1000
4	750/1500	750/1500	1500/300	750/1500	750/2000
5	1600/3200	1600/3200	3200/640	1600/3200	1600/5000

Table 22-3



HIGH LINE VOLTAGE SURGES

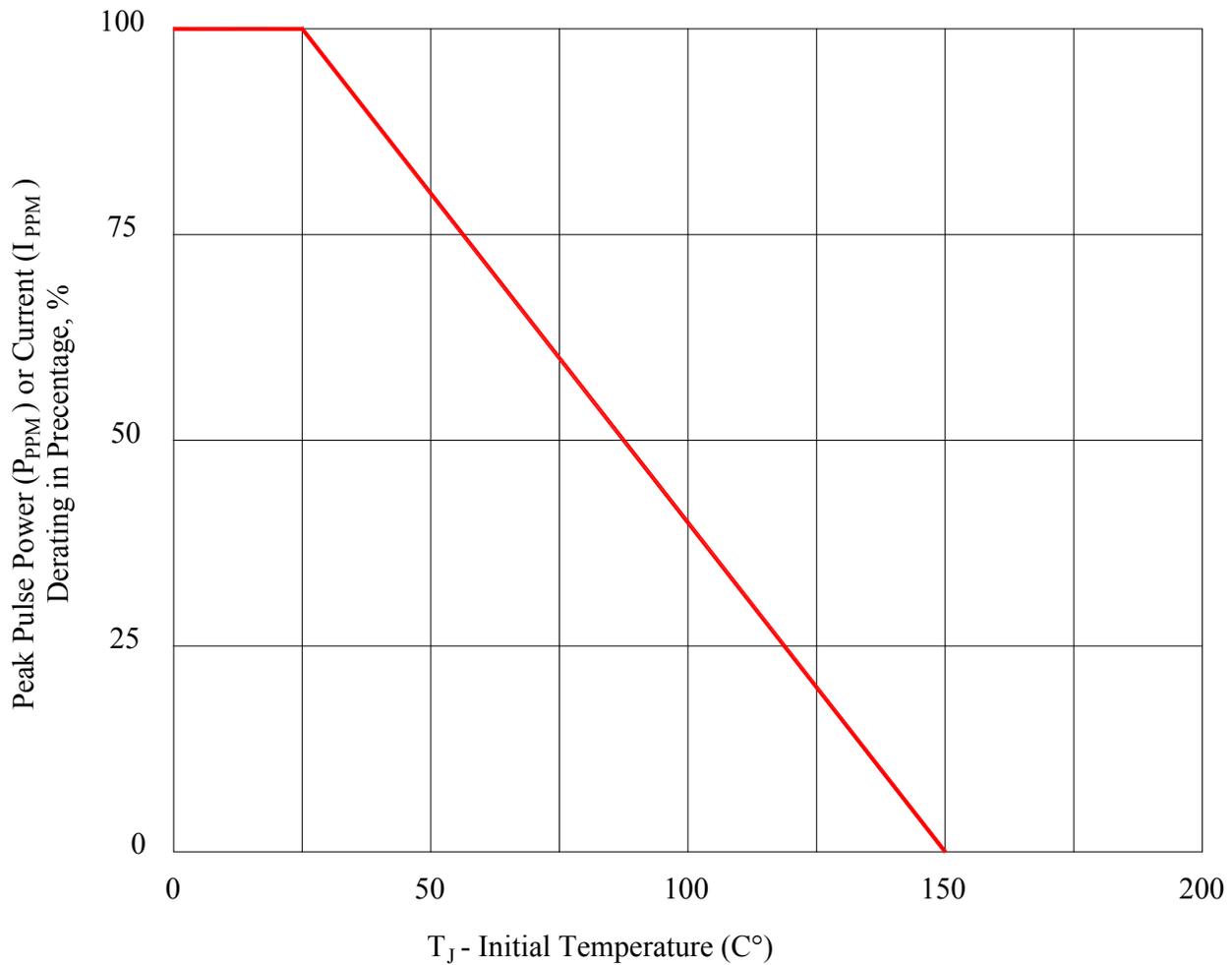
Referring to Section 16 of RTCA/DO-160, power lines are shown with long duration voltage surges (often exceeding 100ms), and typically have very low source impedance (often in the milliohms). These surges contain high levels of energy and are impossible to clamp at levels below their peak voltage using TVS diodes alone. It is possible to voltage limit lines using built-in circuitry, please contact the factory to discuss your specific needs.

Most equipment designs tolerate these over-voltage conditions, do not try to clamp power lines to levels below these surge levels, otherwise you will have failure during normal operation. Devices that must work directly off the power distribution lines should be rated to tolerate the abnormal voltage conditions that occur.

Keep in mind that TVS devices are rated for DC voltage; AC voltage is measured in RMS and its peak voltage is 1.414 times higher. It may also be necessary to use high power TVS devices with-in your design to prevent switching transients from damaging components.

TEMPERATURE DERATING

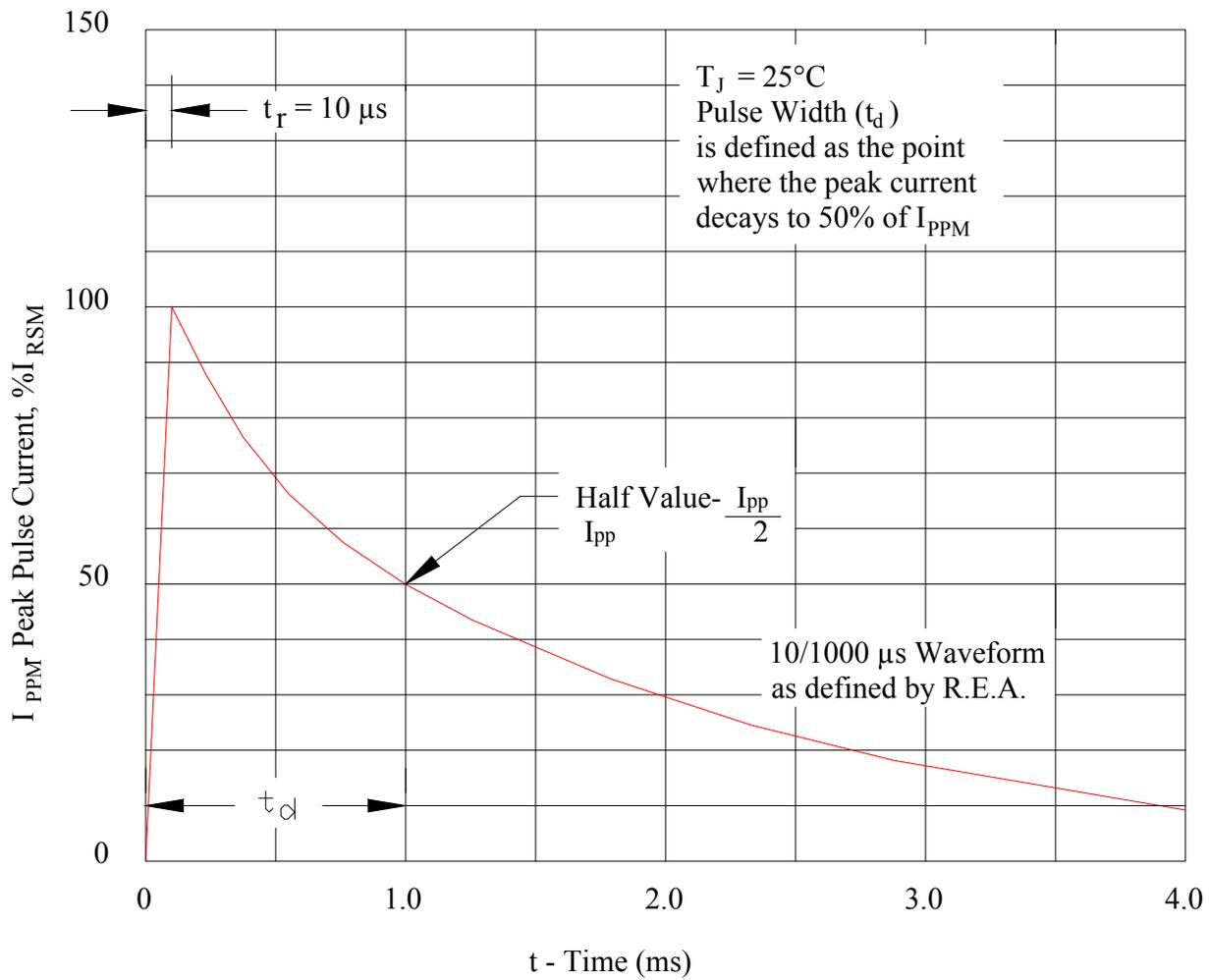
Most TVS device specifications are rated @ 25°C, and since most equipment operates at higher temperatures, we need to reduce the current capability of the TVS accordingly. The following chart is a typical derating curve for TVS devices.



As an example, a TVS that can clamp 40A @ 25°C operating @ 125°C needs derating by 80% and will only handle 8A.

THE 10/1000 μ S WAVEFORM

Typical silicon TVS devices use the 10/1000 μ S waveform to specify the peak pulse power handling capability, as shown below.



The table on page 7 will help determine the true power handling capability of both 600W, 1500W, 3000W, 5000W, & 15KW rated devices. This will allow calculation of the current handling capability in terms of pulse width equivalency.

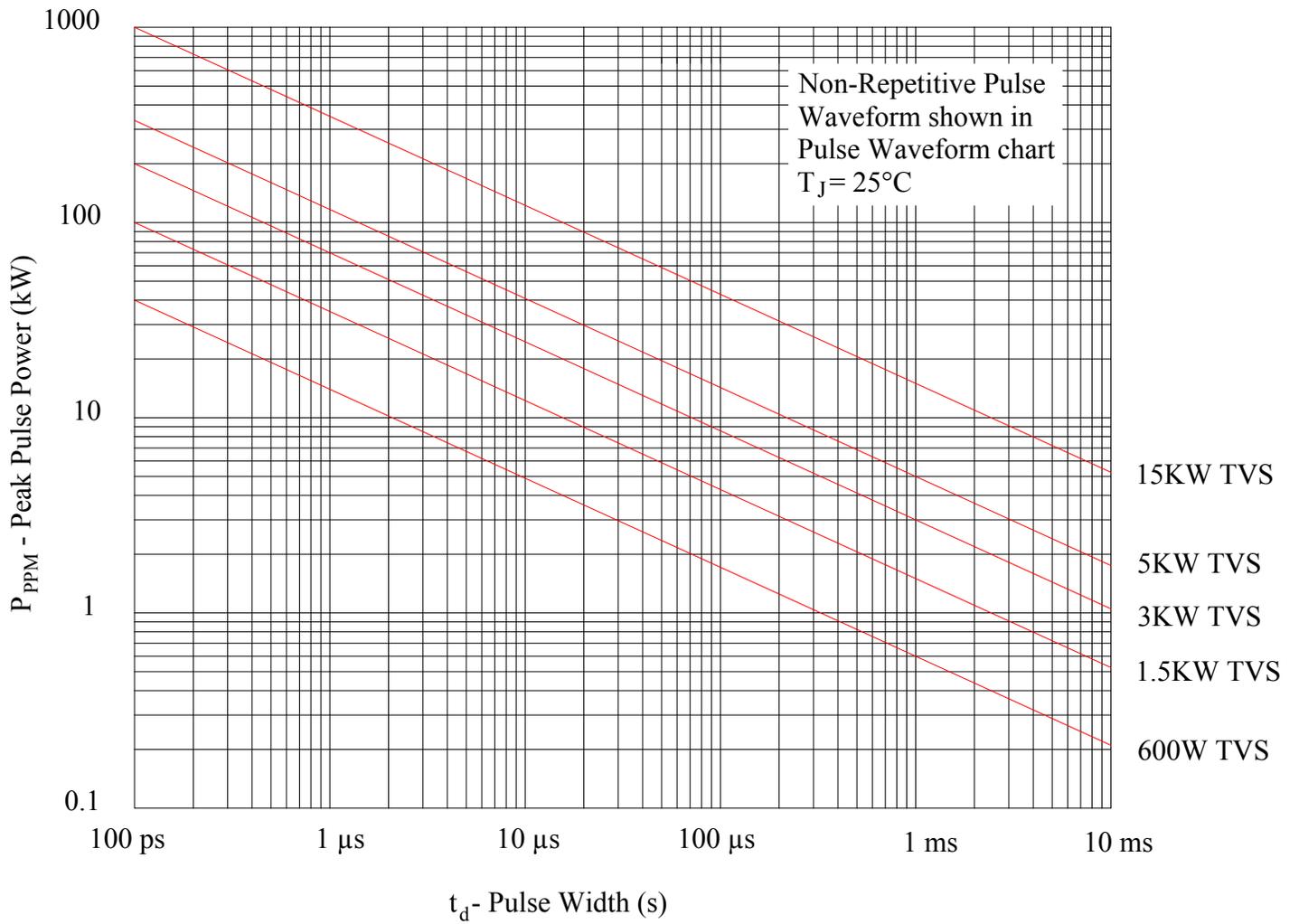
THE 10/1000 μ s WAVEFORM (cont.)

Note: The power slopes shown in the graph to the right are a slightly derated version of the Wunsch-Bell relation using a square wave.

The power of the device is the same as where it crosses the 1ms line; this is because the 10/1000 μ s pulse has a pulse equivalency of 1ms (See the 10/1000 μ s Waveform). To use this chart take the pulse equivalency of the waveform you are using, for example Waveform 5A (144 μ s) and follow that pulse width up to the device power rating (For the 1500W device it \sim 3700W peak power). If the device in question is a 12V/1500W TVS diode then it has a clamping voltage of 19.9Vdc and a peak current of 75.4A, multiplying voltage and current yield power (19.9V x 75.4A = 1500W). The same holds true with the shorter pulse of 144 μ s (3700W / 19.9V = 185.9A).

Since TVS diodes have a zener curve, as current goes up the clamping voltage also goes up, therefore in real terms we need to look at the device clamping curve. Although the curve is typically very sharp, once clamping has occurred some rise in voltage should be expected. This slope is typically about 2% (i.e. Δ Voltage/ Δ Current \sim .02) or in our example, the actual voltage is \sim 21.8Vdc and the current is \sim 169.7A when clamping a 144 μ s pulse. This 1500W device works when protecting a pin injection Level 2, Waveform 5A running @ 60°C, for a Level 3 Waveform 5A running @ 60°C, one would need a 5000W device for the pin injection test.

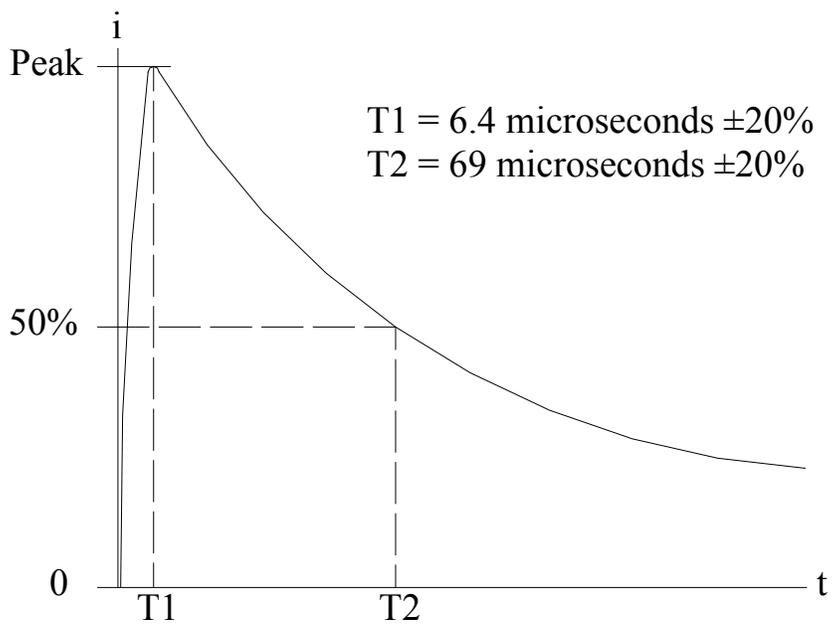
We should specify cable bundle with shield wherever possible, as this is far less severe since the grounded shield is a low impedance and carries most of the current. The current coupled into each wire is a function of impedance and coupling; this makes each wire carry various amounts of the total current in the bundle, so even though the total current is greater, the individual wires carry less current.



DO-160 WAVEFORM EQUIVALENT'S

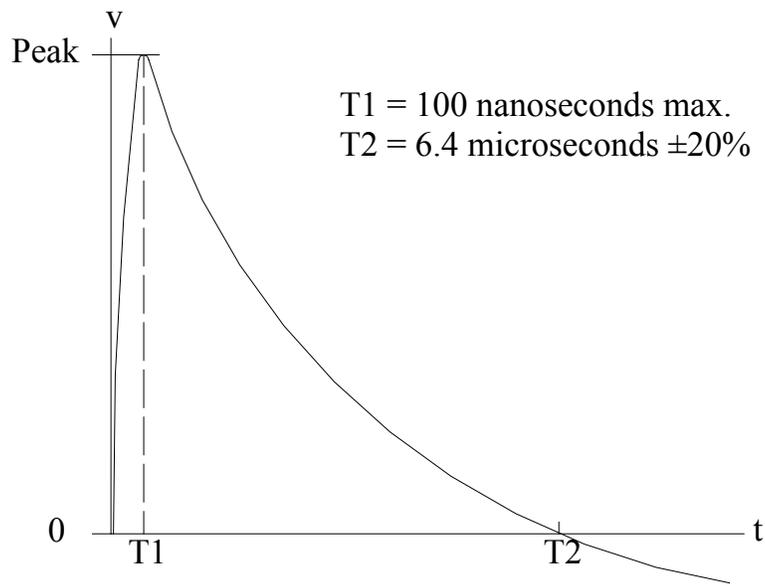
There are five basic waveforms shown in RTCA/DO-160, some are current waveforms and some are voltage waveforms, although all of them specify both voltage and current values for the different levels of threat. Waveforms 3, 4, & 5A are pin injection test waveforms from Table 22-2 and waveforms 1, 2, 3, 4, & 5A are cable bundle test waveforms from Table 22-3.

For simplicity, we will convert each of these to their pulse equivalents so comparing them to the TVS 10/1000 μ s specification is easy.



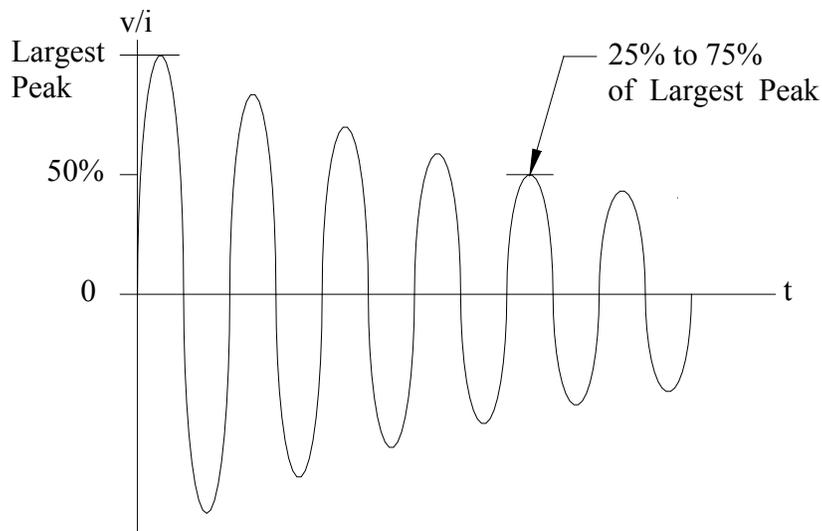
Current Waveform 1

Current Waveform 1 (Figure 22-2) is a 6.4/69 μ s pulse but it has a $\pm 20\%$ tolerance so we shall take the higher pulse of 84 μ s as its equivalent.



Voltage Waveform 2

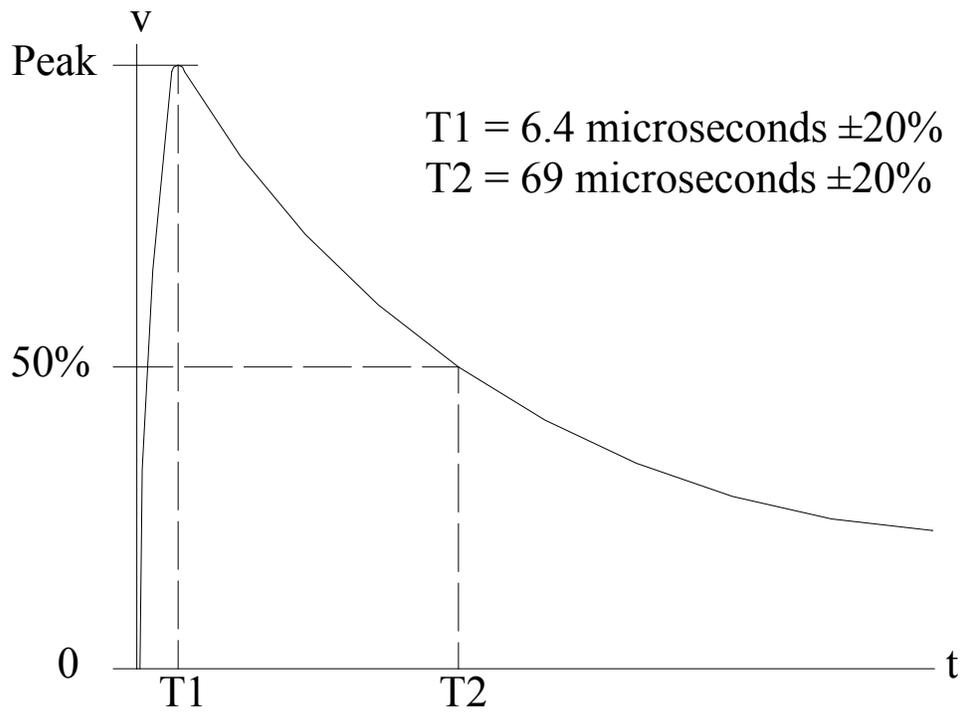
Voltage Waveform 2 (Figure 22-3) is a 100nS/6.4 μ s pulse it also is $\pm 20\%$ tolerance so its pulse equivalent is 7.8 μ s



Voltage/Current Waveform 3

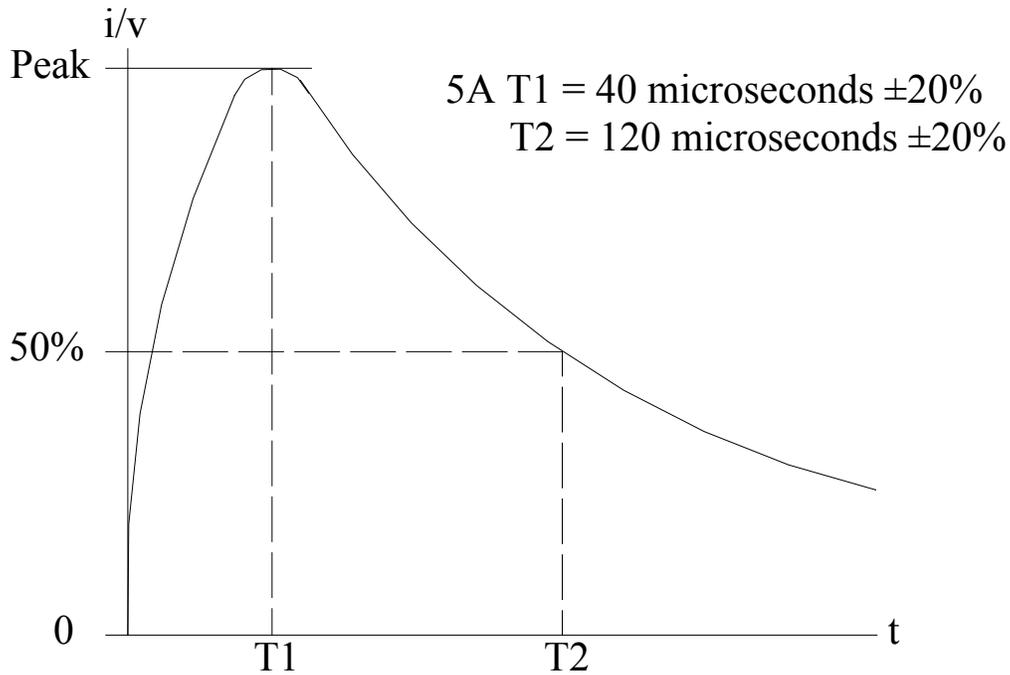
Voltage/Current Waveform 3 (Figure 22-4) is a dampened sine wave with either 1MHz or 10MHz frequency. Since the 1MHz waveform is the greatest energy of the two, we will take that and it equates to 5.7 μ s with correction to equivalent double exponential waveform

DO-160 WAVEFORM EQUIVALENT'S (cont.)



Voltage Waveform 4

Voltage Waveform 4 (Figure 22-5) is the voltage version of Current Waveform 1 and is an 84 μ s pulse.



Current/Voltage Waveform 5

Current/Voltage Waveform 5A (Figure 22-6) is a 40/120 μ S pulse with a $\pm 20\%$ tolerance; again taking the larger pulse, we have a 144 μ s equivalent.

The table below is provided to make selection of devices easier. The wattage represents the waveform amperage times the clamping voltage without consideration for increased clamping voltage due to increases in current.

Mathematically Derived Equivalent Wattage				
Device	Waveforms 1 & 4	Waveform 2	Waveform 3 (1MHz)	Waveform 5A
600W	1,875 W	5,595W	6,463W	1,463W
1,500W	4,687W	13,987W	16,158W	3,658W
3,000W	9,375W	27,974W	32,316W	7,316W
5,000W	15,624W	46,624W	53,860W	12,193W

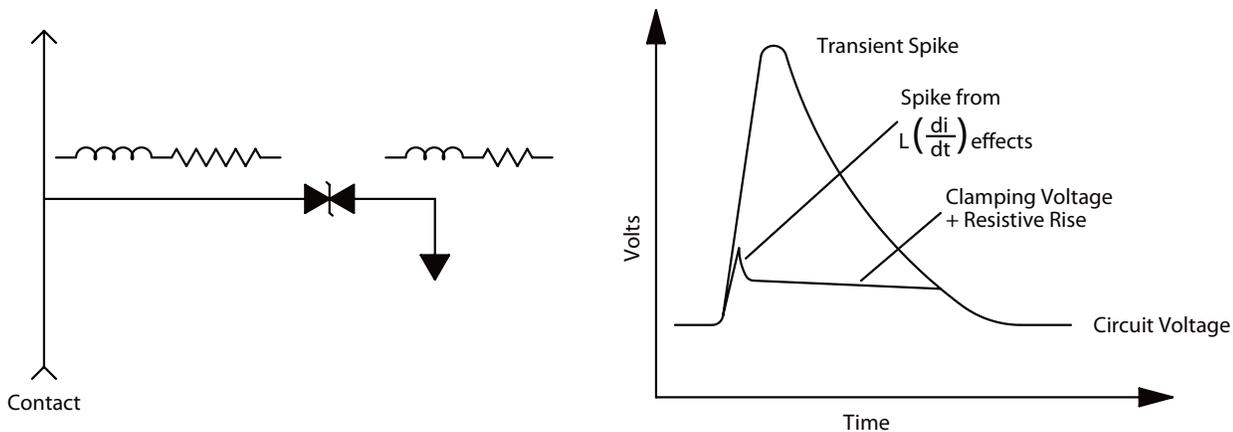
Note: Values may differ slightly dependant on actual TVS device.

THE EMBEDDED DESIGN

The CarlisleIT/Jerrik Embedded design for packaging semiconductors has some real advantages over those of our competitors. Some of our competitors use a leaded diode construction, in this construction it is necessary to run PCB traces from the connector pins to the leaded diodes mounted around the perimeter of the connector arrangement.

These traces and the leads of the packaged diodes create inductances and resistances between the pin and the TVS diode and ground. Note: This also applies to surface mount devices placed radially around the perimeter of the contact arrangement.

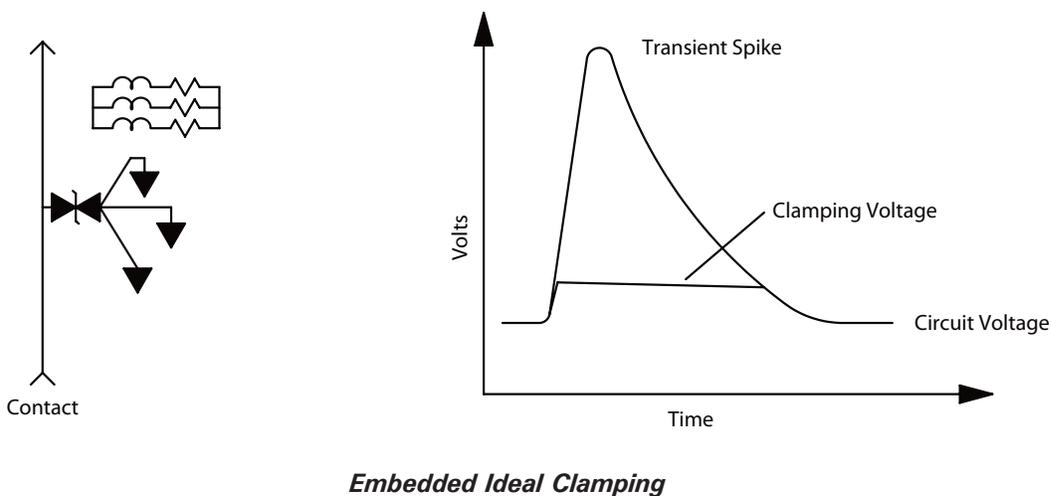
Using Faraday's law of induction we know that changes in current across an inductor creates a voltage difference; this can be significant when dealing with very fast rise times, ($V(t) = L(\Delta I/\Delta t)$). This can cause a voltage spike to pass through the connector prior to settling at the clamping voltage of the TVS diode. In addition, there is inherent resistance in this circuit, although small, when large current spikes shunt across them the resistance can be significantly large. Even a few milliohms resistance times a current spike of 50 to 100 ampere can create voltages of .25 to 1 volt and this voltage adds to the clamping voltage making it appear higher.



Cord Wood Voltage Overshoot

The CarlisleIT/Jerrick patented approach places the TVS diode die adjacent to the pin, within .025" and creates multiple current paths through multiple ground planes to the shell ground. Inductance and resistance in parallel lower the values.

Thusly, we have minimized both inductance and resistance in our circuits, virtually eliminating the associated problems with both. In addition, since we embedded TVS die directly in the circuit board the heat generated by the diode during these transients directly couples to both the board and contact lowering the thermal impedance below what one would see with an individually packaged device.



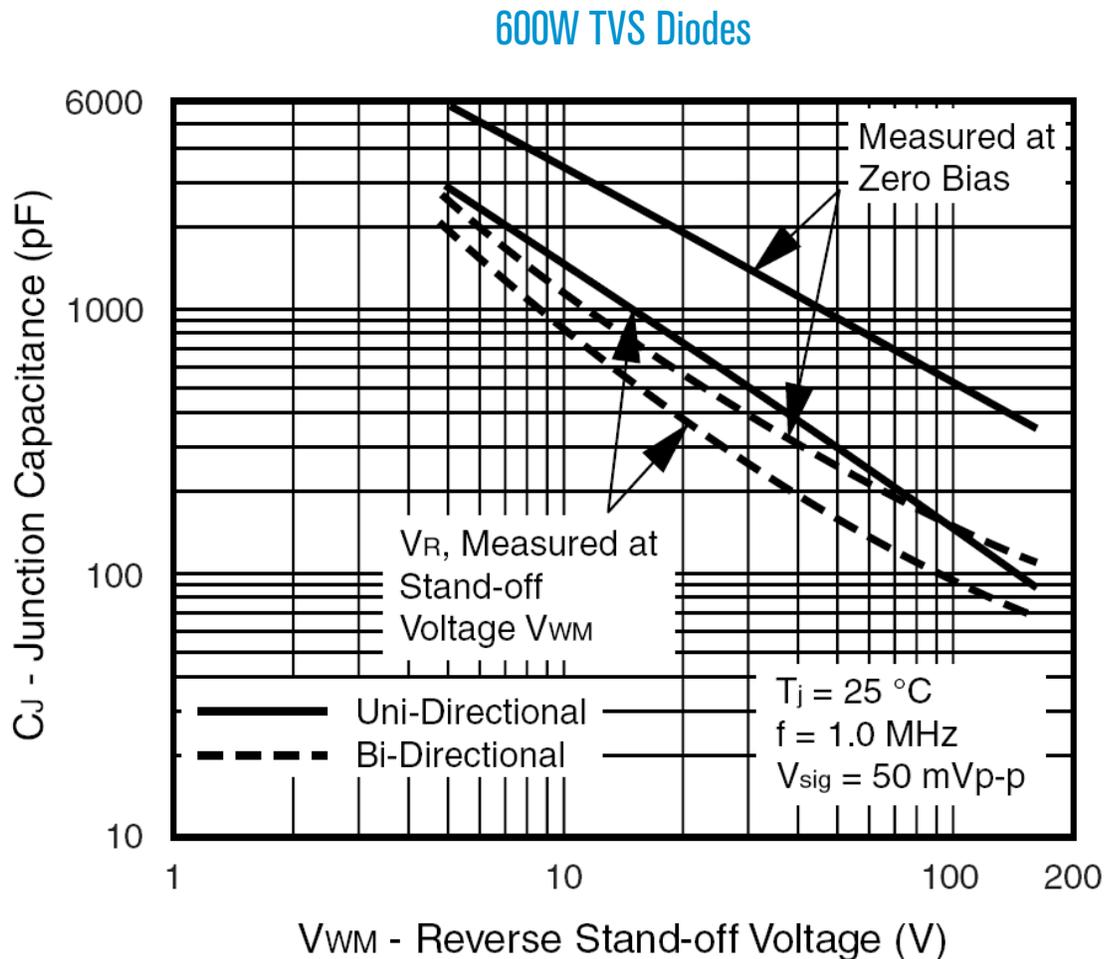
Embedded Ideal Clamping

Now let us take a quick look at the method that places TVS diodes directly on the contact. In this method, they also have eliminated the inductance and resistance problems. But this approach has limitations in the size of TVS diode and the contact becomes the only heat sink, limiting heat dissipation.

In Jerrick's Embedded approach, the usable die size is larger because the space between the contacts is fully used. On high density, size 22 contact arrangements we can employ 600W TVS diodes on every pin, on lower density arrangements even 1500W TVS diodes are usable. With size 20 contacts, every pin of these can have 1500W TVS diodes. Contact the factory if you need higher power TVS diodes for your requirements.

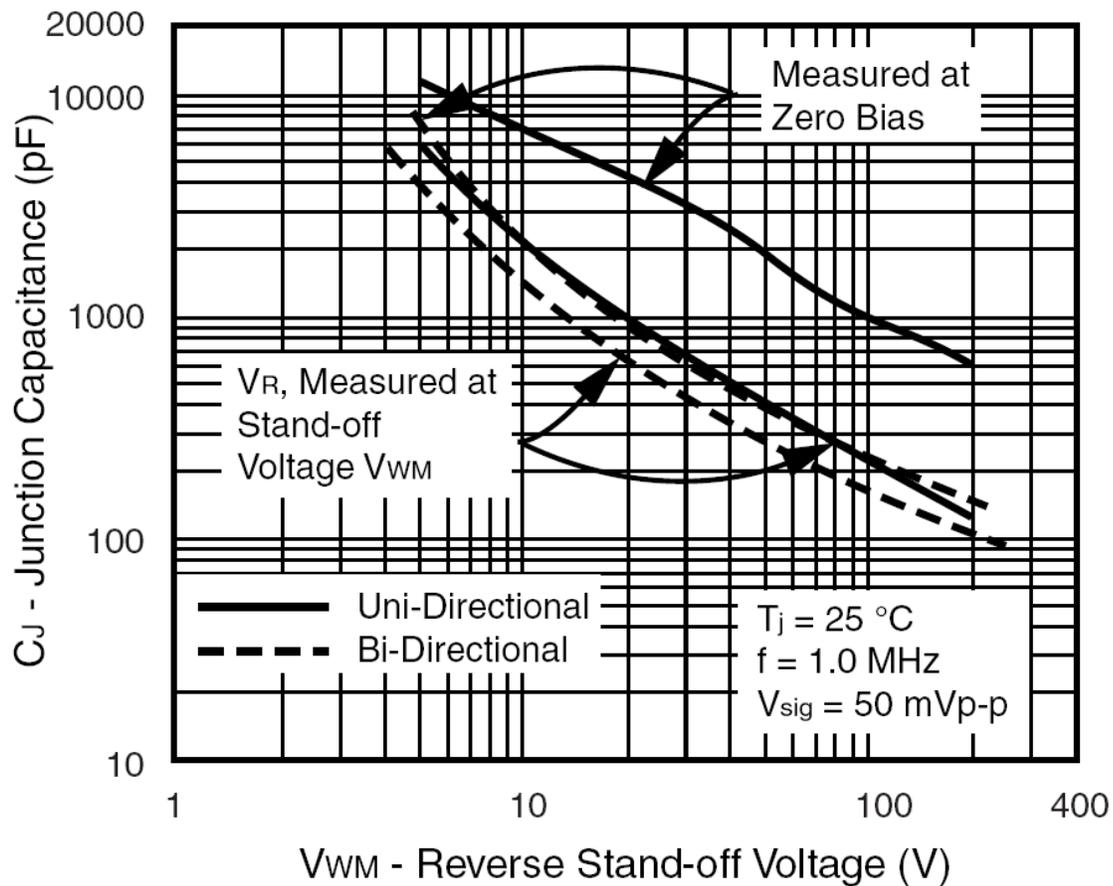
CAPACITANCE OF TVS DIODES

The capacitance of TVS diodes depend on many factors; stand-off voltage (V_{wm}), Wattage (W), uni-directional or bi-directional and bias voltage. The idea that there is a TVS diode with low capacitance is misleading, the low capacitance diode employs a fast power rectifier in series with the TVS diode to create a low capacitance combination. Fast power rectifiers typically have capacitances in the 50pF to 100pF range depending on the power handling capability. The graphs on page 13 show that the capacitance for TVS diodes can range from 70pF to well over 10,000pF all dependent on the factors noted previously.



We can also see that bi-directional diodes have significantly less capacitance than uni-directional diodes; this is due to their construction. If a need for lower capacitance uni-directional TVS diodes are required our supplier does make a device with lower capacitance, but is limited to values below 45VDC. Otherwise, we can build low capacitance stacks as described with some limitations. Please consult the factory about your needs.

1500W TVS Diodes



LEAKAGE CURRENT OF TVS DIODES

Leakage current at working voltage in low voltage TVS diodes can be as high as 2mA, although this does not present a problem in many circuits; it can affect sensory circuits and some low current driver circuits.

In sensory circuits, many times the maximum voltage the sensor can tolerate is higher than the amplifier used in the circuit, keep this in mind when protecting them. Also, consider using a TVS diode with a higher working voltage than those used in the circuit, the further below the clamping voltage the TVS sees the less leakage current it will have.

This also applies to driver circuits that can handle 12 to 15V peak voltages for durations many times longer than a lightning strike induced pulse. So clamping a driver at a voltage of 14V allows the use of a uni-directional TVS diode with an 8V working voltage that has a maximum of $50\mu\text{A}$ and still clamps surge currents of 44.1 Amps. Moreover, when you consider that the signal level will only be 5V or lower this device will have leakage currents far lower than $50\mu\text{A}$.

Also, consider the effects of temperature to leakage current since at higher temperatures the leakage increases, in some cases doubling.

SERIES STACKING TVS DIODES FOR HIGHER SURGE CURRENT

Often we see a need to protect high voltage lines from lightning surges, but as can be seen in specification sheets the higher the voltage the lower the current handling capacity of the TVS diode. We can overcome this with higher power level TVS diodes or by series stacking lower voltage devices. At first, many people think of parallel stacking the diodes, but this requires carefully matching the clamping voltages of the individual devices to prevent all the current going to the lowest clamping device. In series stacking this problem does not exist since all the devices will have to reach their respective clamping voltages to turn on the others.

The proper method of series stacking is to place plates between each TVS diode in order to increase the mass of the stack and prevent heat buildup in the stack from derating the individual components. This method also has the lowest inductance between each diode in the chain.

Various voltages are possible using this approach, but as with any chain, the weakest link defines the strength of the chain. As an example, we can build a stack with a working voltage of 150 Volts, a breakdown voltage of 188 Volts maximum, and a maximum clamping voltage of 247.2 Volts by stacking three TVS diodes with 51 Volts working voltage. Building this stack with 600W diodes allows for a maximum clamping current of 7.3 Amps, this compares to a single 1500W device with a 150 Volts working voltage. This 1500W device would have a breakdown voltage of 185 Volts maximum, with a maximum clamping voltage of 243 Volts, and maximum clamping current of 6.2 Amps.

As we can see, this method can extend both the power and voltage of TVS diodes to meet almost any requirement.

QUALITY ASSURANCE AND SCREENING

Our TVS diode screening process starts with our suppliers, the manufacturer of the TVS diodes is one of the best in the world. They do 100% die mapping, and dicing of the bare die then they send the bare die to our stocking supplier where they are 100% inspected and packaged in wafer packages for us. Once the TVS Die arrives at Jerrik, all the paperwork is checked and certifications are verified before stocking them.

During every stage of construction, trained operators inspect the assembly prior to starting the next stage of building the embedded diode board. Once the board is constructed, technicians test each diode for proper function. The boards are then subjected to a full visual inspection before building the sub assembly used in the connector.

During the processing of the sub assembly several inspection and testing steps occur to insure full functionality of the product. Before encapsulation, each device is subjected to a High Temperature Reverse Bias burn-in for 48 hours, in each direction, for bi-directional devices. A 96 hour High Temperature Reverse Bias burn-in is conducted for uni-directional devices. All devices are tested both before and after burn-in. The sub-assembly is then encapsulated using high quality semiconductor grade encapsulant and again tested prior to shell insertion.

At this point, the build of an embedded TVS diode connector is the same as our filter connector and follows similar processes, including final testing and any additional testing that is customer specified. All sub-assembly and final assembly testing is conducted using automatic testers with the data being stored for future reference. Testing performed on automatic testers includes leakage current at standoff voltage, breakdown voltage at either 1mA or 10mA, capacitance at 1MHz 50mV pp with or without offset voltage of 2V.

SUMMARY

At CarlisleIT/Jerrik we have been a leader in filter connectors for over 15 years and now can say we are a technology leader in lightning protection with our patented Embedded Design for semiconductors. This new technology has placed us clearly in the forefront of the industry and allows us to better service our customers in an ever-evolving Mil/Aerospace environment. We know that the challenges faced by our customers can be great, with rapid changes in both electronics and the environment we use them in, composite aircraft, high-tech ground forces, sea borne platforms, and space applications to name a few.

This design guide is one of the many ways we are helping you meet your design challenges. Making the highest quality, best constructed product at a reasonable price is our goal and service to our customer is our requirement. It is our belief that we can be the filter TVS connector house of choice for your company as it is for many others.

Our sales and engineering staff are available to our customers for any questions that they may have, so feel free to call on us for answers.

WRITER'S NOTE

Writing this handbook has been both an educational and informative endeavor. We can hope that it is as informative to the reader as it has proven enlightening to us, in that putting all this information together and into some semblance of order made us review all that we have learned about this subject. This handbook is only a move in the direction companies, as ours need to make in service to our customers. We are sure this will not be the last, as our commitment to our customers is first and our efforts to stand out as the best in the field will continue.

Sincerely,

Bruce Lane
Design Engineer

Pulse Power Calculation

$$P := 1500$$

$$PW := 144 \cdot 10^{-6}$$

$$P_d := \frac{P}{(.001)^{-.46}} \cdot PW^{-.46}$$

$$P_d = 3.658 \times 10^3$$

P = TVS Device Power @ 10/1000 waveform

PW = Pulse Width equivalency

Pd = Wattage at Pulse Width

Note: Pulse Power Calculation has some derating built-in.

Energy in a 10/1000 waveform clamped with a TVS diode

$$t_r \equiv 10 \cdot 10^{-6} \cdot s$$

$$t_{50pct} \equiv 1000 \cdot 10^{-6} \cdot s$$

$$t := \frac{-(t_{50pct} - t_r)}{\ln(.5)}$$

$$CV \equiv 21.2 \cdot V$$

CV = Clamping Voltage

$$CI \equiv 71 \cdot A$$

CI = Clamping Current

$$t = 1.428 \times 10^{-3} \cdot s$$

$$I_{wvfrm}(I_{max}, t_r, t_{50pct}, t) := \begin{cases} \tau \leftarrow \frac{-(t_{50pct} - t_r)}{\ln(.5)} \\ I \leftarrow \frac{I_{max}}{t_r} \cdot t \text{ if } (t \geq 0 \cdot s) \wedge (t < t_r) \\ I \leftarrow I_{max} \cdot e^{\frac{-(t-t_r)}{\tau}} \\ I \end{cases}$$

$$p(t) := CV \cdot I_{wvfrm}(CI, t_r, t_{50pct}, t)$$

$$\text{energy} := \int_{0 \cdot s}^{\infty \cdot s} p(t) dt$$

$$\text{energy} = 2.165J$$

$$\text{Watts} := CV \cdot CI$$

$$\text{Watts} = 1.505 \times 10^3 \cdot W$$

Dampened Sine Wave per DO160 Section 22

Voltage peak (Vp) = 1500 V	Vp:= 1500
Frequency Hz (f) = 1M or 10M +/-20%	f:= 10·10 ⁶
Quality Factor (Q) = 6 to 15 (Damping Factor)	Q:= 10
Source Impedance (Z) = 25	Z:= 25

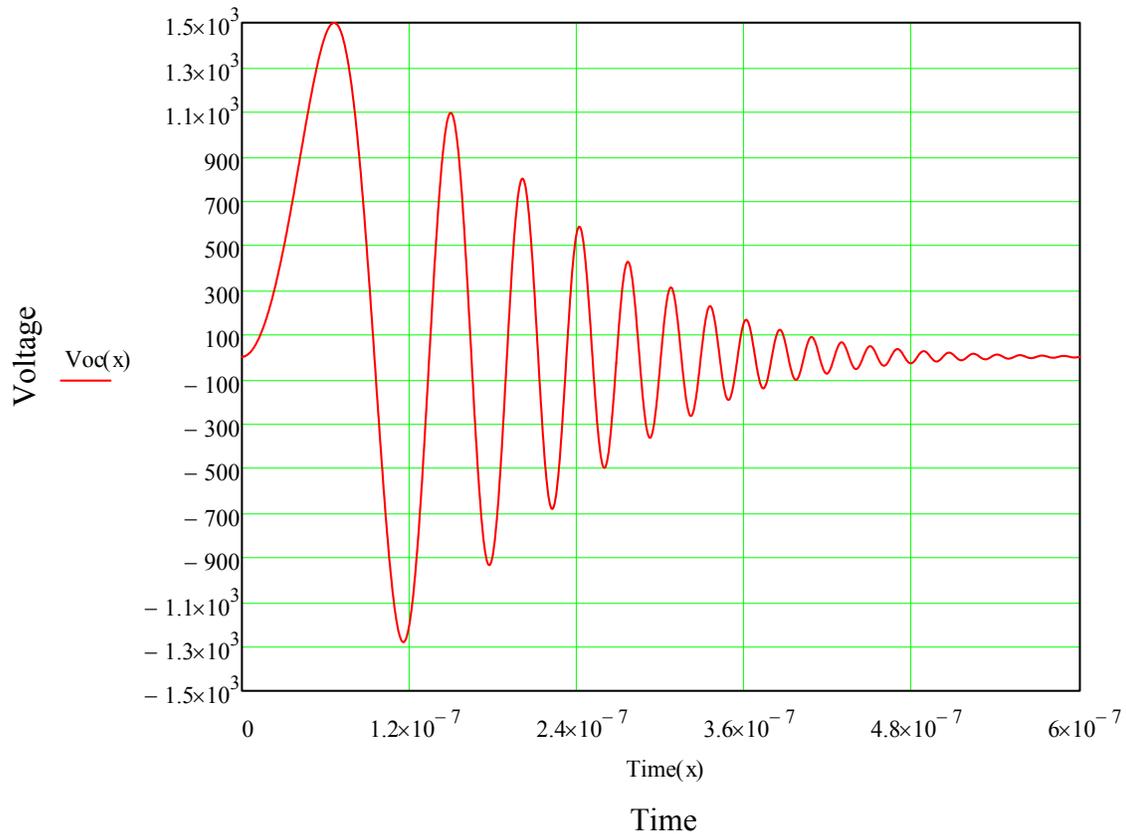
x:= 0, 1.. 1200

$$\text{Time}(x) := x \cdot \left[\left(\frac{1}{f} \right) \cdot Q \right]$$

Rad(x) := x·deg

$$\text{Voc}(x) := \left[V_p \cdot \left[1 + \left[.8 \cdot \left(\frac{1}{Q} \right) \right] \right] \right] \cdot \exp \left[\frac{-[(\text{Rad}(x)) \cdot f \cdot \text{Time}(x)]}{(2 \cdot Q)} \right] \cdot \sin[(\text{Rad}(x)) \cdot f \cdot \text{Time}(x)]$$

$$\text{Isc}(x) := \frac{\text{Voc}(x)}{Z}$$



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