THE CONNECTOR PIN VARISTOR FOR TRANSIENT VOLTAGE PROTECTION IN CONNECTORS

Connector pin varistors provide a unique means of surge protection in electronic systems. Advantages include size, conductive and dissipation features, ruggedness, fast response time and radiation hardness.

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INTRODUCTION

Nonlinear devices have long been used for transient voltage protection and have been available in conventional package configurations -- axial, radial, and power packages (Figure 1). The connector pin varistor represents a new approach to transient suppression by forming the active material into a shape which requires no leads or package (Figure 2). The idea was developed many years ago, but only recently have breakthroughs in the manufacturing process allowed cost-effective production of such devices.

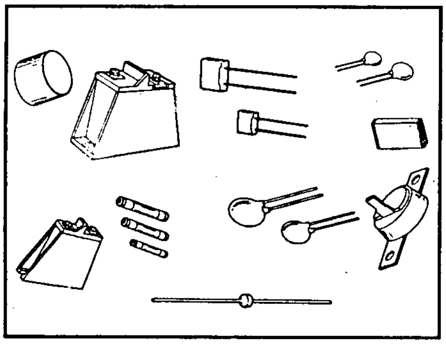

Figure 1. Conventional Package Configurations.

Connector pin varistors are voltage dependent nonlinear semiconducting devices having electrical behavior similar to back-to-back zener diodes. The symmetrical sharp breakdown characteristic enables the varistor to provide excellent transient suppression. As the voltage of a transient rises, the impedance of the varistor changes from a very high value to an extremely low value, limiting the voltage rise across the varistor (Figure 3). The destructive energy is absorbed by circuit impedance and varistor impedance. Energy is converted into heat and, if the varistor is properly rated, no components are harmed.

To obtain the lowest clamping voltage, the impedance of the varistor (Z_S) and the impedance of the varistor leads (Z_C), should be as low as possible, but the impedance of the line (Z_L) and the transient source (Z_T) should be as high as possible (Figure 4). The part of Z_L which is contributed by the ground return also reduces Z_L, but at the same time lifts the ground above true ground and therefore should be small. Unfortunately, the impedance of the transient source (Z_T) cannot be controlled and is unknown in most instances.[1]

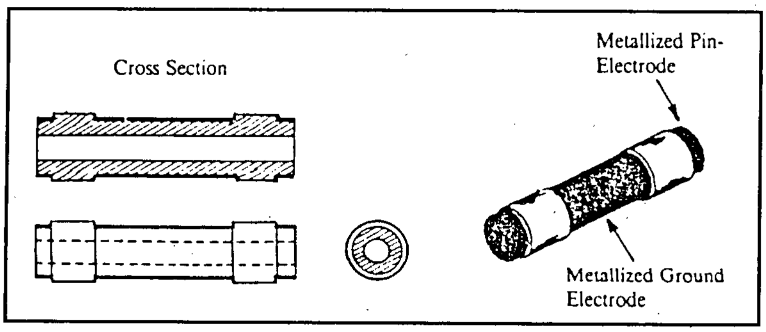

Figure 2. Tubular Varistor (Connector Pin Varistor).

Varistors contain zinc oxide, bismuth, cobalt, manganese and other metal oxides. The structure of the body consists of conductive zinc oxide grains surrounded by a glassy layer (the grain boundary) which provides the 2.5 V PN-junction semiconductor characteristics. Figure 5 shows a simplified cross section of the varistor material.

The varistor is a multi-junction device with many junctions in parallel and series. Each junction is heat sunk by zinc oxide grains resulting in low junction temperatures and large overload capabilities.

As shown in Figure 5, the more junctions that are connected in series, the higher the voltage rating and as more junctions are connected in parallel, the higher the current rating. Energy rating, on the other hand, is related to both voltage and current and is proportional to the volume of the varistor. In summary:

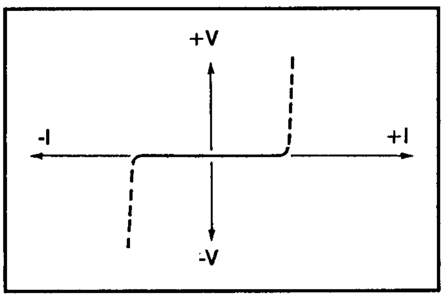

Figure 3. Voltage Impedance Characteristics of a Typical Varistor.

- Thickness is proportional to voltage.
- Area is proportional to current (a x b) or $[(d^2 \cdot \pi)/4]$ or $(d \cdot \pi \cdot \text{length})$.
- Volume is proportional to energy (area x thickness).

ELECTRICAL CHARACTERISTICS

An electrical model for a varistor is represented by the equivalent circuit shown in Figure 6.

PULSE RESPONSE

The pulse response of a varistor is best understood by using the equivalent circuit representation consisting of a pure capacitor (C_p), two batteries, the grain resistance (R_{zno}) and the intergrain capacitance (C_{int}). The off-resistance (R_{OFF}) is not applicable in this discussion.

Due to the varistor capacitance (C_p), the varistor is initially a short circuit to any applied pulse. Varistor breakdown conduction through (V_{B1}) and (V_{B2}), as illustrated in Figure 6 does not occur until this capacitor is charged to the varistor breakdown voltage (V_B). The time is calculated by:

$$t_c = C_p \cdot (V_{B1} / \bar{I}) \text{ or } (2)$$

Where $\bar{I}$ is the average pulse current (capacitor charging current) for $0 \leq t \leq t_c$. The value of the peak current is controlled by $\hat{I} = (di/dt) \cdot C_p$, the source impedance voltage of the transient, and the varistor's dimensions (area proportional to C).

For longer duration pulses $t > t_c$, V_{B1} and V_{B2} will participate on the current conduction process, as the voltage on C_p rises above the breakover voltage (V_B).

SPEED OF RESPONSE

The conduction mechanism is that of a II-VI polycrystalline semiconductor. Conduction occurs rapidly, with no apparent time lag even in the picosecond range.

Figure 7 shows a composite photograph of two voltage traces with and without a varistor connected to a low-inductance high speed pulse generator having a rise time of 500 picoseconds. The second trace is not synchronized with the first, but merely superimposed on the oscilloscope screen, showing the instantaneous voltage clamping effect of the varistor. There is no delay or any indication which would justify concern about response time.

Using conventional lead-mounted varistors, the inductance of the leads completely masks the fast action of the varistor; therefore, the test results as shown in Figure 7 required the insertion of a small piece of varistor material in a coaxial line to demonstrate the intrinsic varistor response.

Tests made on lead-mounted devices, even with careful attention to minimize lead length, show that the voltage induced through lead induc-

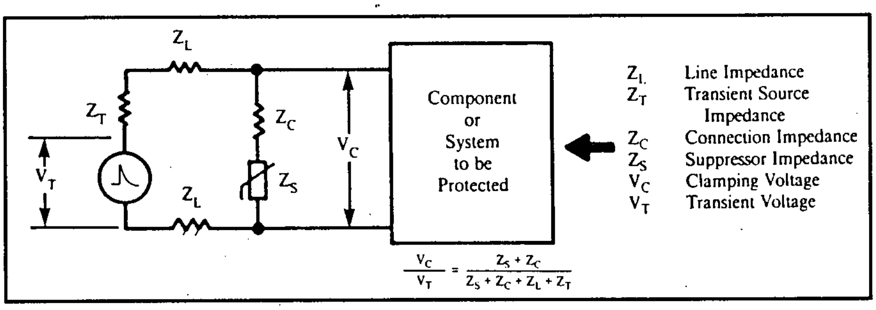

Figure 4. Impedance Relationship in a Transient Suppressor Circuit.

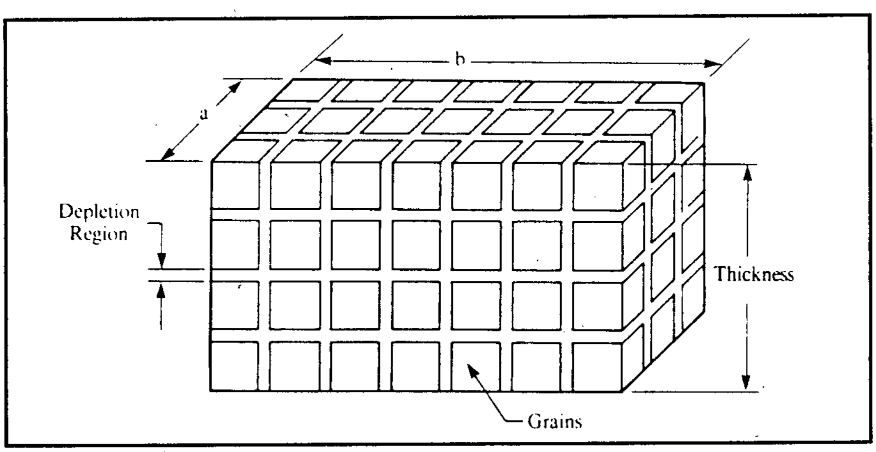

Figure 5. Simplified Microstructure of a Varistor Material.

tance contributes substantially to the voltage appearing across the varistor terminals (Figure 8). These undesirable induced voltages are proportional to lead inductance and di/dt and can be positive or negative.

Figure 9 shows the positive and negative part of the induced voltage, resulting from a pulse with a rise time of 4 ns to a peak current of 2.5 A. When the measurement is repeated with a leadless varistor, such as the connector pin varistor, its unique coaxial mounting allows it to become part of the transmission line. This completely eliminates inductive lead effect (Figure 10).

Calculations of the induced voltage as a direct result of lead effect for different current rise times provides a better understanding of the di/dt value at which the lead effects become significant. Table 1 is based on an assumption of a current pulse of 10 A, 1 inch of lead wire (which translates into approximately 15 nH) and rise times ranging from seconds to femtoseconds.

Figure 11 illustrates the lead effect even more dramatically for fast rising pulses ranging in rise time from milliseconds to femtoseconds.

TEMPERATURE COEFFICIENT (ELECTRICAL)

The temperature coefficient is usually of little importance. It is most pronounced at low voltage and current levels and decreases to practically zero at the upper end of the V-I characteristics (Figure 12).

CONNECTOR PINS VS. CIRCUIT BOARD SUPPRESSORS

Circuit designers may ask, "Why use connector pin varistors when suppressors could be located on the printed circuit board of the electronic control module (ECM)?" Reasons include saving space and avoiding side effects of circuit board suppressor action.

A simplified schematic of an ECM is illustrated in Figure 13. Suppressors usually would be installed across the power analog and digital signal lines entering the ECM. These would divert surges to ground to avoid upset or damage of the ICs fed by those lines. However, side effects could occur if the suppressors are located internally. The paths of circulating current for diverting surges to ground could be of significant length and impedance. If the suppressor current paths share some impedance, then a surge current in one suppressor could cause a surge voltage on the ground line of another circuit. Also, surges can be coupled from one line to another within the ECM by radiation or by capaci-

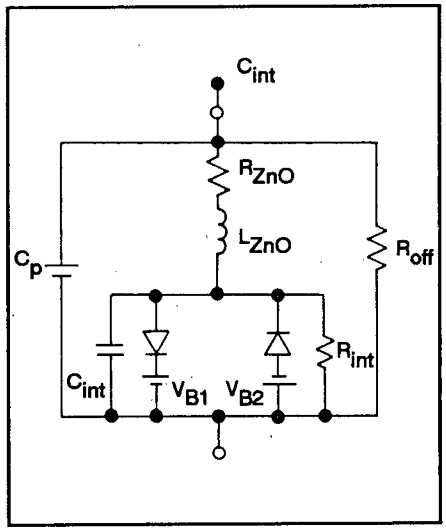

Figure 6. Varistor Equivalent Circuit.

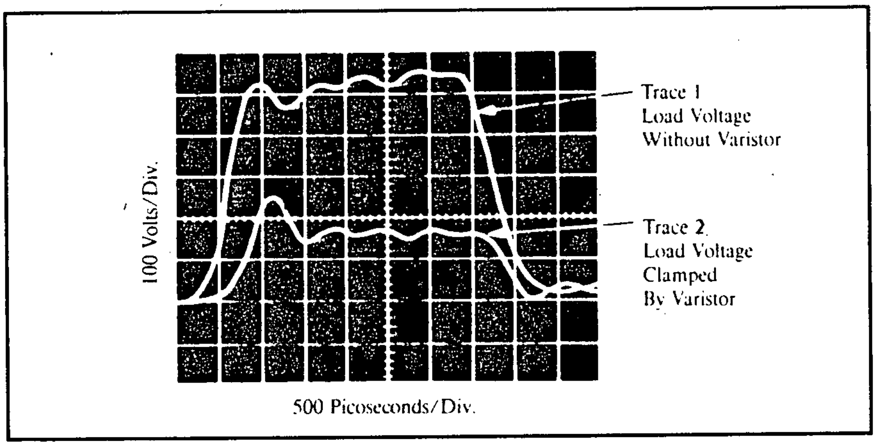

Figure 7. Response of a Varistor to a Fast Rising Pulse ($dv/dt = 1$ million volts/μs).

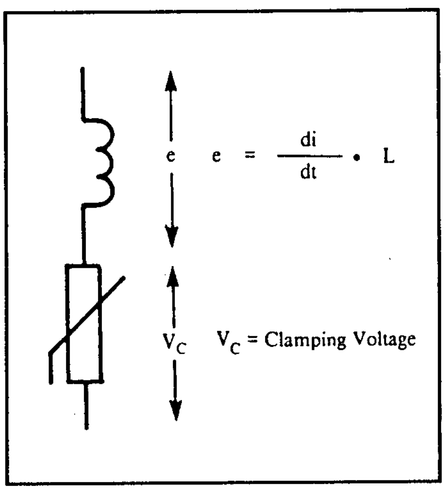

Figure 8. The Electrical Equivalent of a Lead-mounted Varistor.

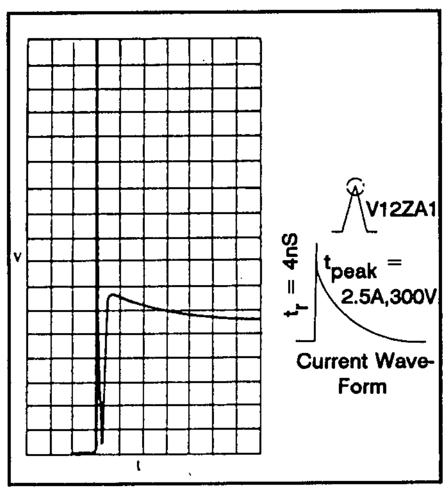

Figure 9. Exponential Pulse Applied to a Radial Device (5v/div., 50S/div.).

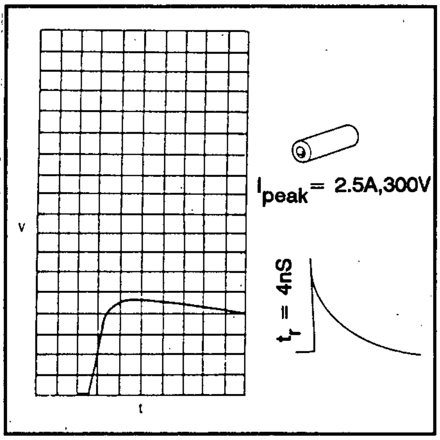

Figure 10. Exponential Pulse Applied to a Pin-varistor (5V/div., 50nS/div.).

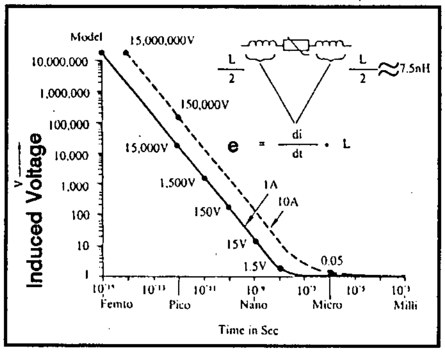

Figure 11. Lead Effect of 1-inch Connection L ≈15nH.

Time		I	L	e
$1 \cdot 10^{0}$	1sec	10A	15nH	$150 \cdot 10^{-9}$
$1 \cdot 10^{-3}$	1ms	10A	15nH	$150 \cdot 10^{-5}$
$1 \cdot 10^{-5}$	1μs	10A	15nH	$150 \cdot 10^{-3}$
$1 \cdot 10^{-9}$	1ns	10A	15nH	150
$1 \cdot 10^{-12}$	1ps	10A	15nH	$150 \cdot 10^{-3}$
$1 \cdot 10^{-18}$	1fs	10A	15nH	$150 \cdot 10^{-6}$

Table 1. Induced Voltage in 1-inch Leads. Peak Current 10A, at Different Current Rise Times.

tive means. These problems are even more likely with surges that have fast fronts causing high V = LdI/dt voltages, such as when gas tubes are activated.

The above concerns are avoided when connector pin varistors are used as shown in Figure 14. Currents then can be diverted directly to a grounding plate within the connector which, in turn, terminates to the exterior of the ECM shielded housing. Surge currents stay outside of the "black box," and sensitive circuits are not exposed to the side effects of suppressor operation. Even if the ICs have on-chip suppressors for ESD protection, or the PC board has local suppressors, the connector pin varistors are desirable because they can divert some of the surge. This permits the local devices, in combination with line impedances and filter chokes, if present, to become secondary protectors. The local surge currents will be less, surge coupling side effects will be reduced, and lower clamping voltages can be attained.

CONNECTOR PINS VS. ZENER DIODES

CLAMPING VOLTAGE

Clamping voltage is an important feature of a transient suppressor. Zener diode type devices have lower clamping voltages than varistors (Figure 15). Because all protective devices are connected in parallel with the device or system to be protected, a lower clamping voltage will apply less stress to the device protected.

SPEEDS COMPARED

Response times of less than 1 picosecond are claimed for zener diodes. For varistors, measurements were made down to 500 picoseconds with a voltage rise time (dv/dt) of 1 million volts per microsecond. Another consideration is the lead effect, previously discussed. Both devices are fast enough to respond to any practical requirements, including NEMP type transients.

LEAKAGE CURRENTS

Leakage current and sharpness of the knee are two areas of misconception about the varistor and zener diode devices. Figure 16 shows a zener diode and a varistor, both recommended by their manufacturers for protection of integrated circuits having 5 V supply voltages.

The zener diode leakage is about 100 times higher at 5 V than the varistor, 200 micro amps versus less than 2 micro amps.

For a leakage current comparison, 25 zener diode devices were measured at 25°C. Only 1 device measured 30 μA. The rest were 150 μA and more. At elevated temperatures, the comparison is even more favorable to the varistor. The zener diode is specified at 1000 μA at 5.5 V.

The leakage current of a zener can be reduced by specifying a higher voltage device which would have a lower leakage current, but the price is a higher clamping voltage and the advantage of the zener disappears.

PEAK PULSE POWER

Transient suppressors have to be optimized to absorb large amounts of power or energy in a short time duration: nanoseconds, microseconds or, in some rare instances, milliseconds.

Electrical energy is transformed into heat and has to be distributed instantaneously throughout the device. Transient thermal impedance is much

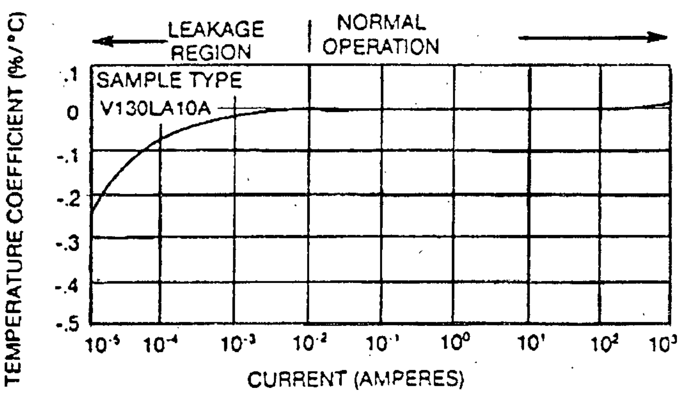

Figure 12. Typical Temperature Coefficient of Voltage vs. Current, -55 to 125°C.

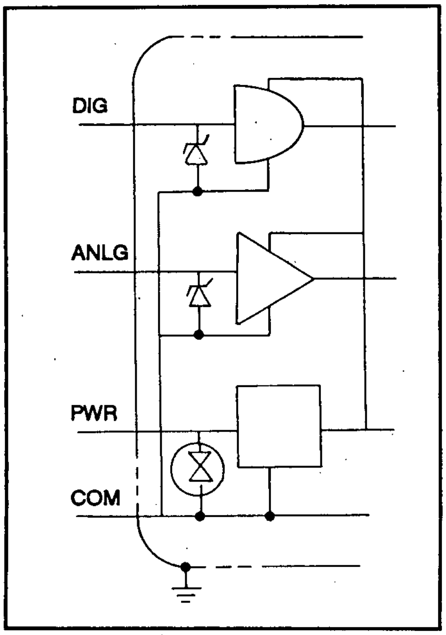

Figure 13. Circuit Board Suppressor Installation.

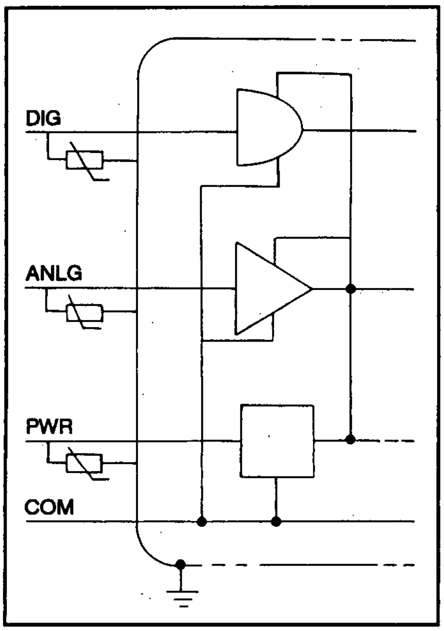

Figure 14. Connector Pin Varistor Installation.

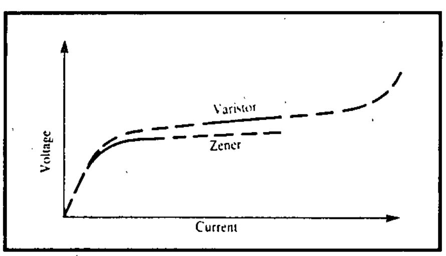

Figure 15. Characteristics of Zener and Varistor.

more important than steady-state thermal impedance, as it keeps peak junction temperature to a minimum. In other words, heat should be instantly and evenly distributed throughout the device.

The varistor meets these requirements: an extremely reliable device with large overload capability. Zener diodes on the other hand, transform electrical energy into heat in the depletion region, an extremely small area, resulting in high peak temperature. From there the heat will flow through the silicon and solder joint to the copper. Thermal coefficient mismatch and large temperature differentials can result in an unreliable device for transient suppression.

Figure 17 shows peak pulse power versus pulse width for the varistor and the zener diode, the same devices compared for leakage current.

At 1 ms, the two devices are almost the same. At 2 μs the varistor is almost 10 times better, 7 kW for the zener versus 60 kW for the varistor.

AGING

A common misconception is that a varistor's V-I characteristic changes every time energy is absorbed. As illustrated in Figure 18, the V-I characteristic changed on some of the devices, but returned to its original value after applying a second or third pulse. Is this an inversion of the aging process? Time and temperature have very similar effects.

To be conservative, peak pulse limits have been established which, in many cases, have been exceeded manyfold without harm to the device. This does not mean that established limits should be ignored, but rather, viewed in perspective of the definition of a failed device. A failed device shows a ± 10 percent change of the V-I characteristic at the 1 mA point. Zener diodes, on the other hand, fail suddenly at predictable power and energy levels.

FAILURE MODE

Varistors fail short, but can also explode when energy is excessive, resulting in an open circuit. Because of the large peak pulse capabilities of varistors, these types of failure are quite rare for properly selected devices.

Zeners, on the other hand, can fail either short or open. If the pellet is connected by a wire, it can act as a fuse, disconnecting the device and resulting in an open circuit. Designers must analyze which failure mode, open or short, is preferred for their circuits.

When a device fails during a transient, a short is preferred, since it will provide a current path bypass and continue to protect the sensitive components. On the other hand, if a device fails open during a transient, the remaining energy ends up in the sensitive components that were supposed to be protected. If the energy is already dissipated, the circuit will now operate without a suppressor and the next transient, or the next few transients, will denigrate the equipment.

Another consideration is a hybrid approach, making use of the best features of both types of transient suppressors (Figure 19).

CAPACITANCE

Depending on the application, transient suppressor capacitance can be a very desirable or undesirable feature compared to zener diodes. Varistors have a higher capacitance. In DC-circuits, capacitance is desirable: the larger the better. Decoupling capacitors are used on IC supply voltage pins and can in many cases be replaced by varistors, providing both the decoupling and transient voltage clamping functions.

The same is true for filter connectors where the varistor can perform the dual functions of providing both filtering and transient suppression.

There are circuits, however, where capacitance is less desirable, such as high frequency digital or some analog circuits.

As a rule, the source impedance of the signal and the frequency as well as the capacitance of the transient suppressor should be considered (Figure 20).

The current through C_p is a function of dv/dt and the distortion is a function of the signal's source impedance. Each case must be evaluated individually to determine the maximum allowable capacitance.

RESPONSE TO RADIATION

For space applications, an extremely important property of a protection device is its response to imposed radiation effects.

ELECTRON IRRADIATION

Figure 21 represents MOV and zener devices exposed to electron irradiation. The V-I curves, before and after test, are shown. The MOV is virtually unaffected, even at the extremely high dose of 10^8 rads, while the zener shows a dramatic increase in leakage current.

NEUTRON EFFECTS

A second MOV-zener comparison was made with respect to neutron fluence. The selected devices were equal in area.

Figure 22 shows the clamping voltage response of the MOV and the zener to neutron irradiation as high as 10^{15} N/cm^2. In contrast to the large change in the zener, the MOV is unaltered. At higher currents where the MOV's clamping voltage is again unchanged, the zener device clamping voltage increases by as much as 36 percent.

Counterclockwise rotation of the V-I characteristics is observed in silicon devices at high neutron irradiation levels. In other words, leakage increases at low current levels and clamping voltage increases at higher current levels.

The solid and open circles for a given fluence represent the high and low breakdown currents for the sample of devices tested. A marked decrease in current (or energy) handling capability with increased neutron fluence should be noted.

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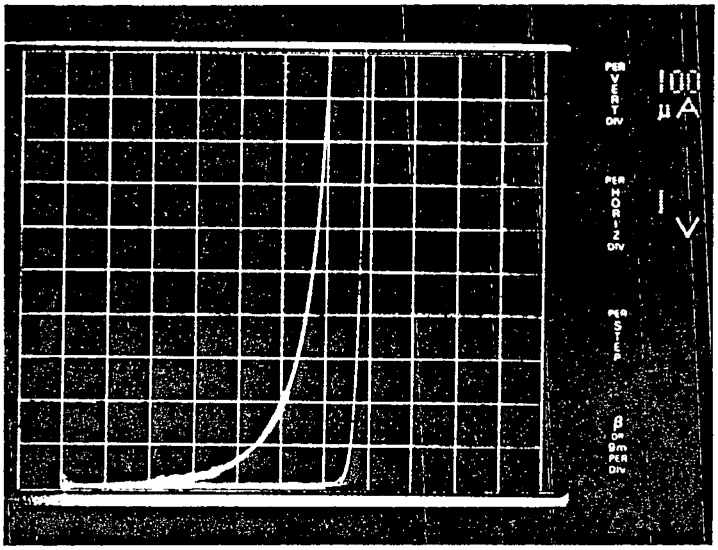

Figure 16. Characteristics of a Zener Diode (on left) vs. a Varistor (on right).

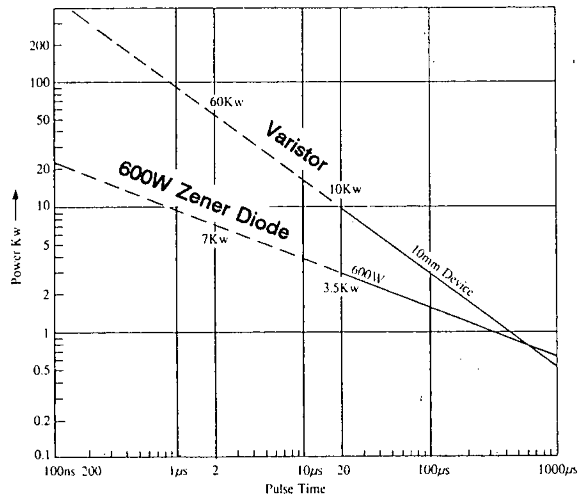

Figure 17. Peak Pulse Power vs. Pulse Time.

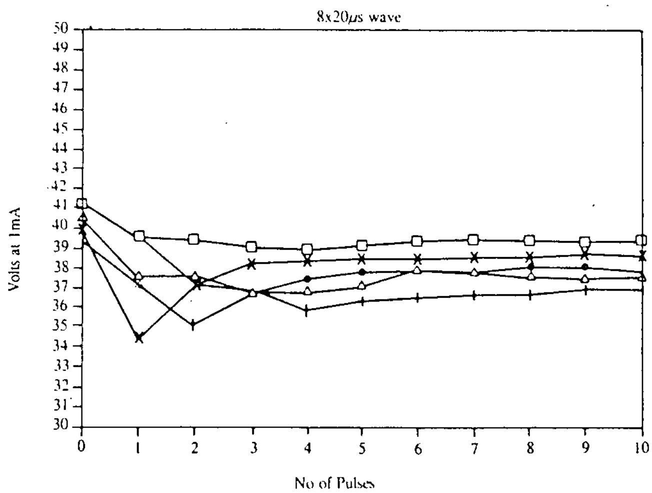

Figure 18. 250A Pulse-withstand Capabilities.

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The failure threshold level of silicon semiconductor junctions is further reduced when high or rapidly increasing currents are applied. Junctions develop hot spots, which enlarge until a short occurs if current is not limited or quickly removed.

The characteristic voltage current relationship of a PN-Junction is shown in Figure 23.

At low reverse voltage, the device will conduct very little current (the saturation current). At higher reverse voltage V_{BO} (breakdown voltage), the current increases rapidly as the electrons are either pulled by the electric field (zener effect) or knocked out by other electrons (avalanching). A further increase in voltage causes the device to exhibit a negative resistance characteristic leading to a secondary breakdown. This manifests itself through the formation of hotspots, and irreversible damage occurs. This failure threshold decreases under neutron irradiation for zeners, but not for zinc oxide varistors.

GAMMA RADIATION[7]

Radiation damage studies were performed on specified varistors. Emission spectra and V-I characteristics were collected before and after irradiation with 10^6 rads Co^{60} gamma radiation.

Both show no change, within experimental error, after irradiation.

MECHANICAL STRENGTH

After sintering, the varistor becomes a strong, rugged ceramic material. As with all ceramic materials, it has high compressive strength and lower tensile or shear strength. An experiment was performed to demonstrate the strength of the varistor material when used in the tubular form. Results are shown in Table 2. P1 and P2 represent maximum pressures applied before fracture. Directions of applied stresses are shown in Figure 24.

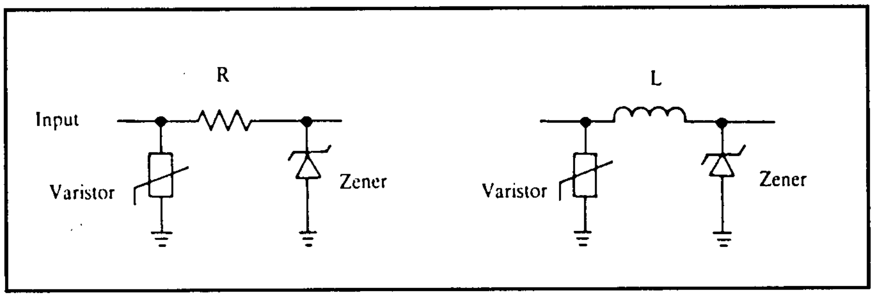

Figure 19. Hybrid Protection Using Varistors, Zeners, R and L.

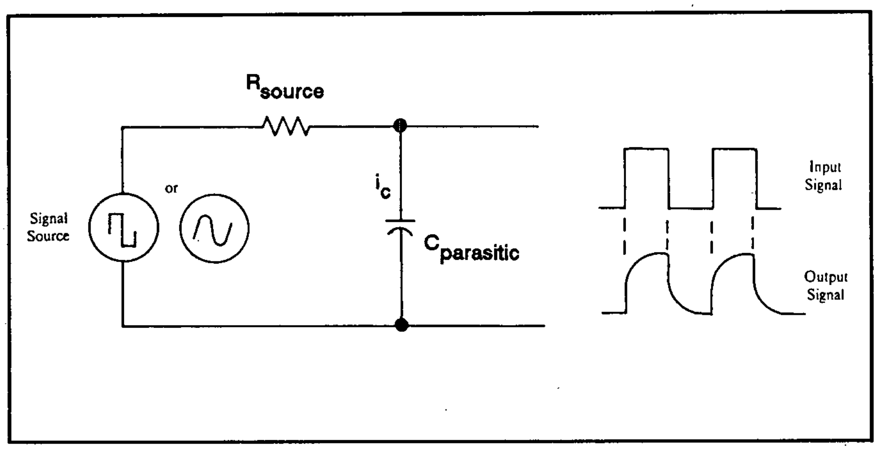

Figure 20. Source Impedance (R_s) and Parasitic Capacitance (C_p).

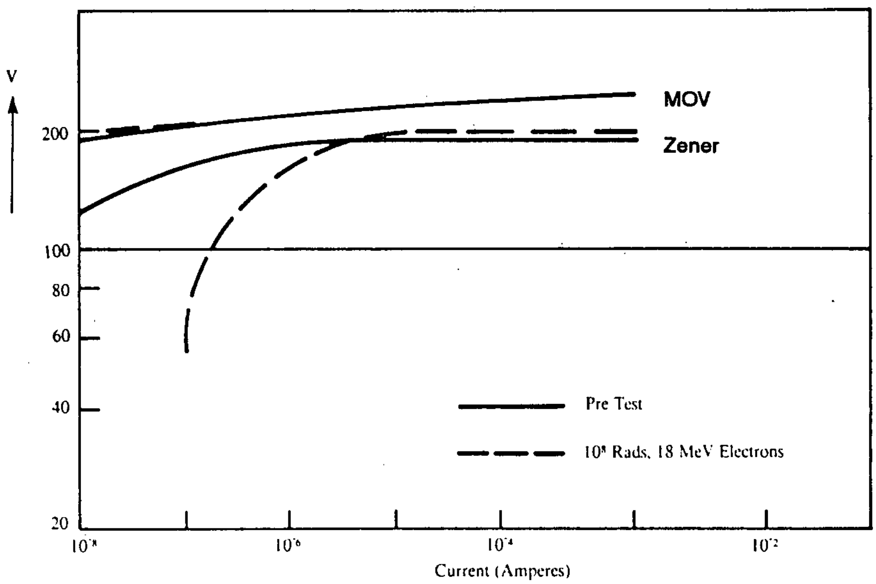

Figure 21. Radiation Sensitivity of MOV and Zener Devices.

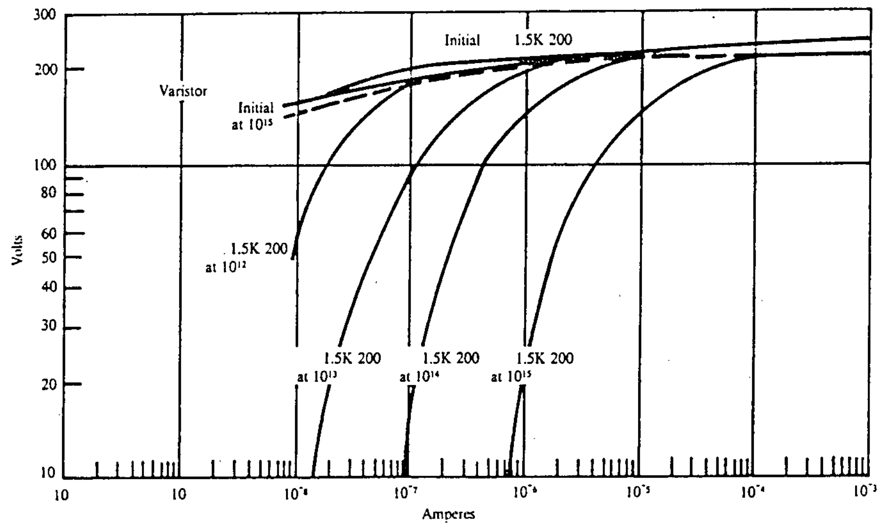

Figure 22. Voltage Currents Characteristic Response to Neutron Irradiation for MOV and Zener Diode Devices.

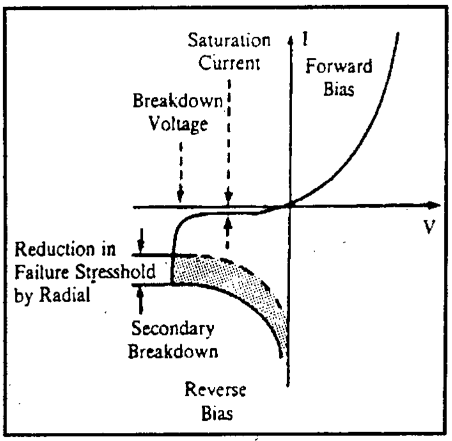

Figure 23. Voltage Currents Characteristic of PN-junction.

Part Size	P1	P2
20A	100 lbs.	30 lbs.
20B	100 lbs.	14 lbs.
22B	100 lbs.	14 lbs.

Table 2. Varistor Material Strength.

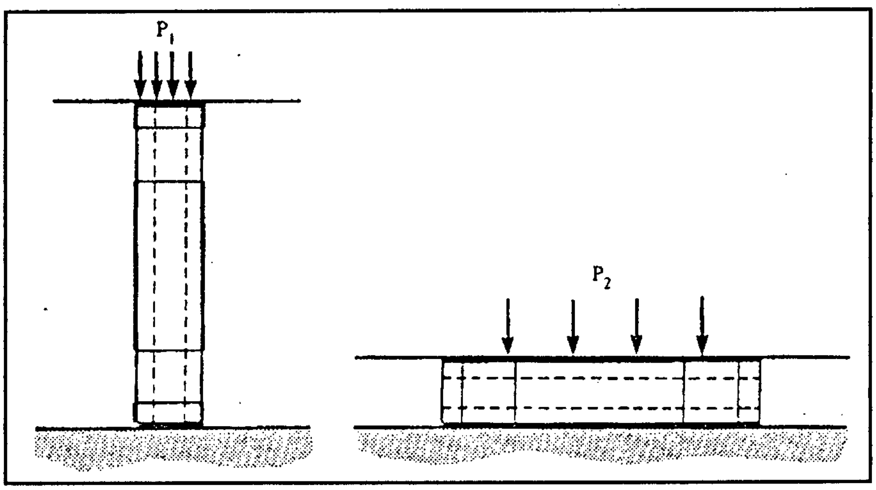

Figure 24. Applied Stresses.

CONCLUSIONS

Connector pin varistors provide a unique way to install surge protection in electronic systems without the bulkiness of some approaches. The tubular form of this varistor gives a relatively large area for conducting surge currents, with an inherent mass for dissipating electrical heat energy. The rugged body physically resembles passive components; but, because it is a semiconductor device, response time is very fast. The leadless form reduces the voltage overshoot that can be caused by lead inductance. Also, the device has a high degree of inherent radiation hardness. Connector pin varistors divert surge currents to the outside surface of the "black box" housing, not to printed board runs feeding sensitive circuits, thereby helping to avoid or reduce surge coupling side effects. ■

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