Improved Metal Oxide Varistor Packaging Technology For Transient Voltage Surge Suppressers (TVSS)

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Introduction

With the ever-increasing population of sensitive electronic equipment, today's workplace is undoubtedly much more vulnerable than ever before to damage and increasingly susceptible to disturbances such as electrical overstress. Overstress in this context is a voltage/current surge resulting from natural or manmade influences, which has a potentially damaging magnitude. In many cases, the damaging effect of overstress can be additive, in that each successive overstress, though individually nonfatal to the attached load, can compound the damage caused by previous occurrences.

The sources of electrical overstress are typically lightning, an electromagnetic pulse (EMP) from a high power microwave or from the detonation of a nuclear weapon (nuclear EMP), an electrostatic discharge (ESD, commonly known as *static electricity*), or switching of a reactive load such as a large motor or capacitor bank. Another source of overstress can be due to equipment design. For example, the design of today's electronic equipment more and more uses silicon-based circuits with microscopic spacing and very thin conductors. These circuits are thus designed to use highly dense packaging, and unfortunately, this high-density packaging can cause the circuitry to be extremely vulnerable to damage from over voltages. Given the industry trend in circuit design toward an ever-greater degree of high-density packaging, with more and more solid-state components packed into smaller and smaller packages, the protection of these high-density circuits from the damage of transients and over voltages thus becomes a major priority.

When unprotected or improperly protected from transients and over voltages, the circuit's performance and reliability will be highly jeopardized. For example, transients and over voltages can contribute to failures, permanent degradation, or temporary malfunction of the electrical and electronic devices and equipment. Moreover, when these overstress problems occur, they may in turn, cause the electrical/electronic circuits within complete systems to fail and thus cause even more serious damage to property and possibly even damage to personnel.

To help alleviate and even to prevent these overstress problems, Transient Voltage Surge Suppression (TVSS) devices are becoming a standard solution. These devices which protect against transient overvoltages can be divided into three classes:

1. shielding and grounding
2. filtering

3. application of nonlinear devices

Shielding and grounding can help in reducing the damaging secondary effects of lightning related overstresses. But shielding and grounding are effective primarily in the area of induced phenomena. Every circuit, whether power, process, communications or data circuit entering a facility must be protected to provide comprehensive protection.

Filtering is effective in reducing noise induced on power, process, communications or data lines, but really does not adequately protect a facility from elevated currents and voltages associated with electrical overstress.

Of these three classes, the application of nonlinear devices for protection against transient overvoltages composes the overwhelming majority of protection. Nonlinear devices can block or limit the surge currents with a large series impedance or divert surges with a small shunt impedance. These two methods can be used together in so called hybrid protective schemes. Currently, there are no known nonlinear series elements, except for positive thermal coefficient (PTC) resistors, which will present a small impedance during normal voltages, but will become a large impedance during overvoltages. Inductors and resistors are commonly used for limiting the surge current in circuits where the attenuation of the input signal caused by an addition of the series impedance is acceptable.

Other nonlinear devices, which can protect against surges, are spark gaps and gas discharge tubes, avalanche diodes, thyristors and triacs, silicon carbide and metal oxide varistors. Of these, more than 95% of the TVSS devices that are designed to protect AC power and AC control/signal circuitry utilize metal oxide varistor (MOV) technology. For protection from transient overvoltages that propagate on the mains of electronic systems, most design engineers would agree that varistors are currently the best of the available nonlinear devices.

Conventional metal oxide varistors (MOV)

The MOV was invented in Japan by the employees at Matsushita Electric Company, and licensed to other companies.

The primary component of the MOV is a powder of metal oxides, the most common being zinc oxide (ZnO). The metal oxide powder is placed in a fixture, typically cylindrical, in which the powder is subjected to elevated temperatures and pressures. The resulting MOV billet is the sliced to the thickness that has been determined to operate at the desired voltage threshold. The characteristics of the MOV with respect to current density, or the current that can pass through a unit area of the MOV surface, is determined by the size and uniformity of the oxide flake composing the powder.

The conventional type MOVs most widely used for power protection consist of a disk with a diameter of 14mm to 20mm and two leads soldered to the opposite surfaces of the disk (Figure 1). The disk is coated with a thin insulating film. The IEEE Standard C62.33-1982 describes the MOV characteristics as follows:

Clamping Voltage, V_c. Peak voltage across the varistor is measured under conditions of a specified peak pulse current and specified waveform. The peak voltage and peak current are not necessarily coincidental in time.

A typical V-I curve for a metal oxide varistor is shown in Figure 2. The MOV is a symmetrical bipolar device that clamps either positive or negative voltages.

There are three characteristic regions for MOV operation. At very small currents, less than 0.1mA, the varistor behaves like a simple resistor, called R_{leak}. At very large currents, the bulk resistance of the device, R_{bulk}, dominates the varistor response. Between these currents, the varistor performs according to Equation 1:

$$I = kV^{\alpha} \tag{1}$$

The circuit diagram that corresponds to this model of a varistor is shown in Figure 3. The inductance, L, is due to packaging and the lead length in a particular application. The voltage, V, in Equation 1 is across R_x and does not include the voltage drop across R_{bulk}. The current in Equation 1 is through R_x and does not include the current through R_{leak} and current through capacitor C.

The value of α characterizes the nonlinear V-I characteristic. A V-I characteristic for an ordinary resistor is linear and has $\alpha = 1$. Generally, the greater the value of α, the closer the V-I approaches the ideal characteristic—when the current is constant and independent of the voltage variation in a wide range. Modern metal oxide varistors have values for α between 25 and 60.

Rated Peak Single Pulse Transient Current, I_{tm}. This is the maximum peak current that may be applied for a single 8/20μs impulse, with rated voltage also applied, without causing the device to fail.

The MOV fails when exposed to an excessive surge current and its package may rupture or cause an expulsion of material, which results in an open circuit.

Lifetime Rated Pulse Currents

These currents are de-rated values of I_{tm} for impulse durations exceeding that of 8/20µs waveshape, and for multiple pulses, which may be applied over device rated time.

Typical curves for lifetime-rated pulse currents are shown in Figure 4. MOVs degrade when subjected to surge current. The "end" of life is usually specified when MOV voltage, V_n, has changed by ±10%. However, the varistor is still functional after the "end" of life. Normally the value of V_n decreases with exposure to surge currents. This degradation can be detected by measuring the leakage current at the maximum normal operating voltage in the system. Excessive leakage current during normal steady-state operation will cause heating in the varistor. Because the MOV has a negative temperature coefficient, the resistance will decrease as the MOV becomes hotter and this will cause a further increase in current. Thermal runaway may occur, with consequent failure of the MOV. This mode of the MOV failure is a short circuit.

Rated RMS Voltage, $V_{M(AC)}$ This value is the maximum continuous sinusoidal RMS voltage that may be applied.

Rated DC Voltage, $V_{M(DC)}$ This value is the maximum continuous DC voltage that may be applied.

DC Standby Current, I_D This value is the varistor current measured at rated voltage, $V_{M(DC)}$.

Nominal Varistor Voltage, $V_{N(DC)}$ This value is the Voltage across the varistor measured at a specified pulsed DC current, $I_{n(dc)}$, of specific duration as specified by the varistor manufacturer.

Peak nominal Varistor Voltage, $V_{N(AC)}$ This value is the voltage across the varistor measured at a specified peak AC current, $I_{n(ac)}$, of specific duration. $I_{n(ac)}$ as specified by the varistor manufacturer.

Rated Single Pulse Transient Energy, W_{tm}. This value is the energy that may be dissipated for a single impulse of maximum-rated current for a specific waveshape, with rated rms voltage or rated dc voltage also applied, without causing device failure.

The electrical energy of a surge applied to the MOV is transformed into heat and has to be absorbed in a short time duration: nanoseconds or microseconds. Heat should be instantly and evenly distributed throughout the device. Varistors meet these requirements much better than other clamping devices like zeners, transzorbs, etc.

Response Time. The response time is the time between the point at which the wave exceeds the clamping voltage level V_c and the peak of the voltage overshoot. For the purpose of this definition, clamping voltage is defined with an 8/20µs current waveform of the same peak current amplitude as the waveform used for this response time.

In the conventional lead-mounted devices, the inductance of the leads will completely mask the fast action of the varistor. Tests made on lead-mounted devices show that the voltage induced in the loop formed by the leads contribute to a substantial part of the voltage appearing across the terminal of a varistor at high currents and fast current rise. The voltage overshoot is dependent on current rise, therefore, for measuring response time, pulse current with rise time of 0.5µs or 1µs is used.

A fundamental property of the ZnO MOV is that the voltage drop across the single interface junction between the grains is nearly constant and does not vary for grains of different sizes. Therefore, the thickness of the material and the size of the ZnO grains will determine the MOV voltage. The MOV voltage, V_n, is the voltage across a varistor at the point on its V-I characteristic (Figure 2) where the transition is complete from the low-level linear region to the highly nonlinear region. For standard measurement purposes, it is arbitrarily defined as the voltage at a current of 1mA or 5 mA.

If the thickness of the disk determines the MOV voltage, the diameter of the disk determines the maximum value of the peak surge current that the MOV is able to withstand without being damaged. The volume of a MOV disk, which is the product of the thickness of the disk and the disk surface's area, determines the maximum transient power and energy that the device can be exposed to without being damaged. If the source of the surge has the peak surge current or amount of transient energy exceeding the MOV rating, a MOV of larger diameter will be required to satisfy the protection requirements.

Another solution for this problem is the utilization of several MOVs of the same diameter connected in parallel. When connecting MOVs in parallel, it is important to assure that the V-I characteristic of the parallel-connected devices are as identical as possible. A modest 5% mismatch in V_n (which is better than the typical manufacturer's tolerance of ±10%) between two connected in parallel MOVs can result in a disproportionate share of surge current passing throughout. Fortunately, this uneven distribution of surge current has a tendency to decrease as the resistance of the MOV approaches the value of R_{bulk}—a value that is essentially the same for both devices.

LEC's Sandwich Block Modules (SBMs).

Construction

Lightning Eliminators & Consultants, Inc. (LEC) has patented the Sandwich Block Module (SBM) and introduced a new MOV packaging technology. This new technology has solved many shortcomings and problems typically associated with single MOV disks that have conventional radial leads and are connected in parallel. With the SBM, LEC has enhanced the performance characteristics of these devices.

Traditional MOV construction is based on the use of traditional electronic component construction techniques. Leads are soldered to the surfaces of the MOV disk. The current capabilities of the MOV rely on the sizes of the metal oxide particles of which the disks are composed, as well as the area of the lead connection to the surface of the disk. Since the lead connection comprises a small portion of the total disk area, the usable area of the disk is limited to the area covered by the connection. The leads in this type of design offer little benefit for the thermal capacity of the lead-connected MOV and remain too fragile for many severe industrial applications, due to the high temperatures and high level of mechanical vibration found in many industrial environments.

Evolutionary development of MOVs has resulted in lead designs which were initially designed to improve the structural integrity of the MOV component when installed in an industrial environment. The inadvertent secondary benefit of this design is an increase in the MOV disk to lead area, resulting in improved transient current capacity. Also, the rigid terminals found this design have resulted in increased thermal sinking capacity.

All form factors of traditional commercially available MOVs impose limitations to performance with respect to maximum surge current capability. The restricted effective area of the MOV surface presented to the circuit limits the maximum surge current capability. Thermal limitations are imposed due to the limited thermal transfer mechanism offered to the MOV disk.

LEC has found the limitations of conventional MOVs too restrictive to the development of a truly effective surge suppression product. The solution to the limitations of current MOV technologies lies in the solution to the circuit-MOV interface deficiencies. It was assumed during this investigation that improvements in the crucial circuit-MOV interface would benefit all of the MOV component electrical, mechanical and thermal characteristics.

The results of LEC's investigation into the critical component interface have led to the development of the SBM component technology. The SBM is a full-face MOV, in that the entire surface of the MOV disk is included in the circuit-disk interface, resulting in the complete utilization of the MOV disk.

The construction of the SBM is shown in Figure 5. The opposite surfaces of a MOV disk are coated with a thin conductive film of copper, silver or aluminum. The disk is sandwiched between two metal plates that serve as terminals for the device. The module is encapsulated to provide electrical insulation of the disk(s), electrical separation of the MOV electrodes, and to ensure isolation of the disk(s) from environmental contaminants. Should higher values of maximum peak surge current be desired, two or more disks (up to eight in present design) can be placed between aluminum plates.

The benefits associated with the SBM component are enhanced thermal transfer from the MOV disk to the electrodes, uniform heat transfer, increased component life, increased physical strength, and improved margin before the onset of MOV thermal runaway.

The enhanced thermal transfer mechanism is attributable to the electrodes acting as heatsinks, offering simultaneous cooling to both of the flat surfaces of each MOV disk. The electrode/heatsink is in contact with the entire face of each MOV disk, resulting in the maximum thermal transfer possible. The end result of this construction form is increased component life due to the improved thermal mechanism inherent in the design of the SBM.

Mechanically, there is no stronger MOV construction available. The metal plates used for the electrodes of the MOV component, the fastening hardware used to form the basic module mechanical connection, and the additional support added by encapsulation make the SBM the most rigid and mechanically stable MOV on the market.

The electrical characteristic benefiting from the SB technology is the ability of each MOV disk to handle higher surge current than a conventional MOV disk of the same diameter. Additionally, it delays the onset of thermal runaway, which is an inherent characteristic of every form of basic MOV material.

Thermal runaway is a phenomenon that occurs whenever the metal oxide comprising the MOV disk is exposed to elevated temperatures during operation. The MOV, when exposed to temperatures in excess of the critical temperature (T_c), begins to conduct at a voltage below the rated clamping or switching voltage of the disk. Conduction evolves into runaway at this point because thermally induced conduction current causes additional heat to be generated inside the disk. This heat supplements the external heat mechanism, in turn lowering further the internal resistance of the MOV disk, and through a positive feedback-style mechanism continues the runaway. The eventual result of the thermal runaway phenomenon is the physical destruction of the MOV component. It should be noted that the normal failure mode of an MOV is a short circuit.

The final step in the construction of the SB MOV is to insulate all external surfaces of the module with a nonconductive coating, which allows compact positioning of the module in an assembly designed to protect one or more electrical phases or modes.

Advantages of LEC's SBM Design:

1. The magnitude of the rated maximum peak surge current is increased at least 2.5 times compared with the current for a disk of the same diameter but with radial leads. This increased capacity has become possible because of a remarkable improvement in the way that the current is distributed along the surface of the disk. Radial leads soldered to the central limited region of the disk surface cause a concentration of the surge current around the lead connections, and this leaves the current density at the locations close to the edge of the disk much lower than in the central region of the disk. The uneven distribution of the current density along the disk surface is corrected by replacing radial leads with plates. With plates connected to all parts of the disk, the central region and regions close to the edge are equally engaged in conducting the surge current.

2. The ability to absorb a transient energy is increased several times because of two factors: (1) the increase of the maximum peak surge current, and (2) the excellent heat sinking characteristic of the thick aluminum plates used as the terminals of the device.

3. The SBM can withstand a temporary overvoltage without thermal runaway much longer than a conventional device that has the same dimensions and material. That means, that the SBM can tolerate a smaller margin between a maximum continuous operating voltage (MCOV) and rated rms voltage of the device, and that lowers the degree of overvoltage stress on the protected equipment.

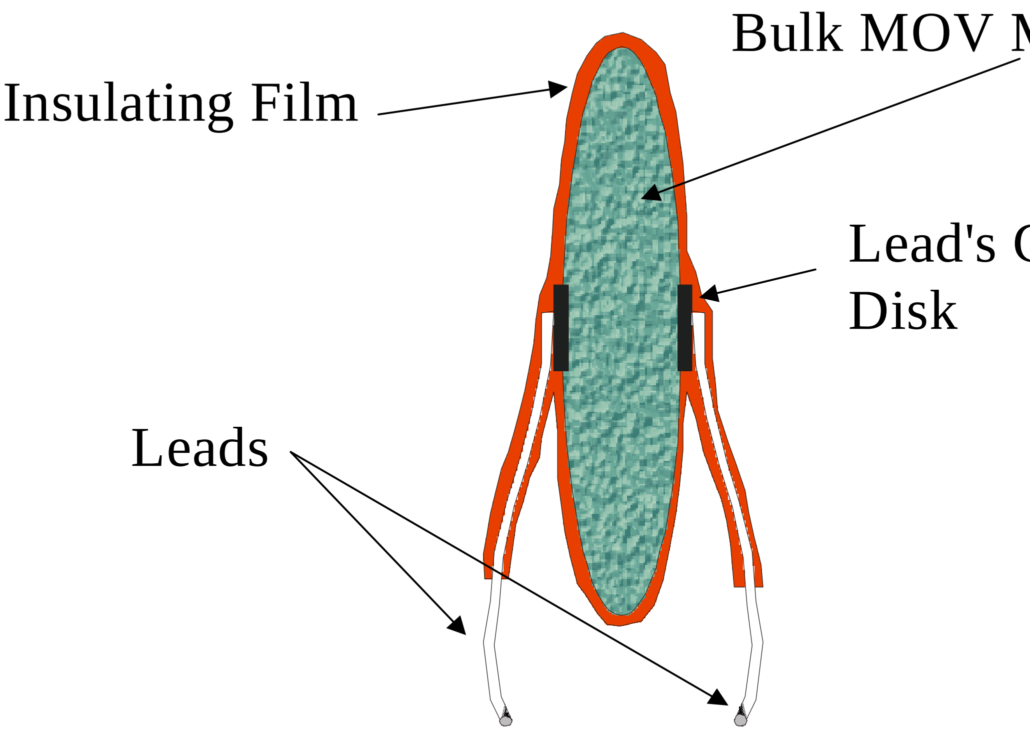
4. The V-I characteristic of the SBM device has a significant extension of the nonlinear region B (see Figure 2) to the direction of higher currents, which provides relatively low values for the clamping voltages at higher magnitudes of the surge currents.

5. The even distribution of the current through the total surface area of the disk decreases significantly the difference between the V-I characteristics of the devices with the same specified parameters. This much closer match of the V-I characteristics allows it to have more even distribution of the total surge current between two or more devices connected in parallel.

6. Because the SBM has a much higher lifetime-rated pulsed current, the time for the device to degrade is much slower, and that results in increased time in service.

7. The replacement of the radial leads by aluminum plates makes the response time of the device much shorter because the part of the voltage overshoot measured across the device and caused by voltage drop along the leads is eliminated.

Typical MOV for Power Applications



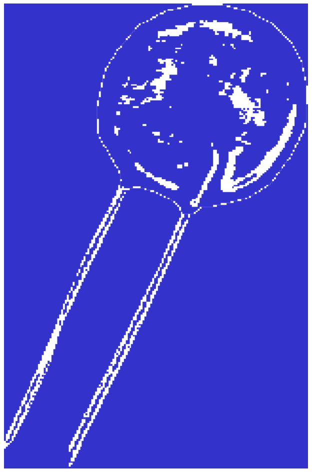


Figure 1.

V-I characteristic of an MOV

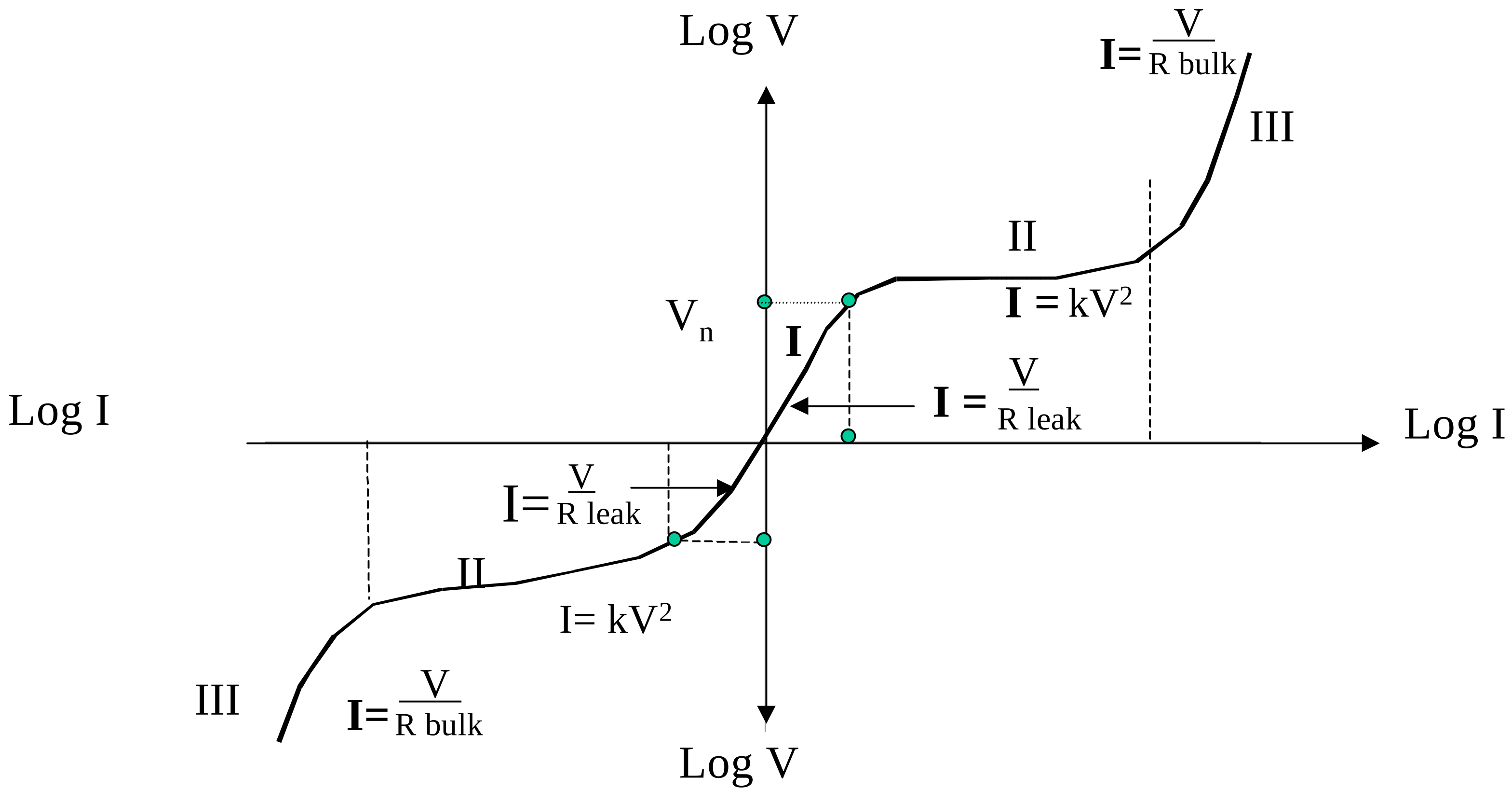


Figure 2.

MOV Equivalent Circuit Model

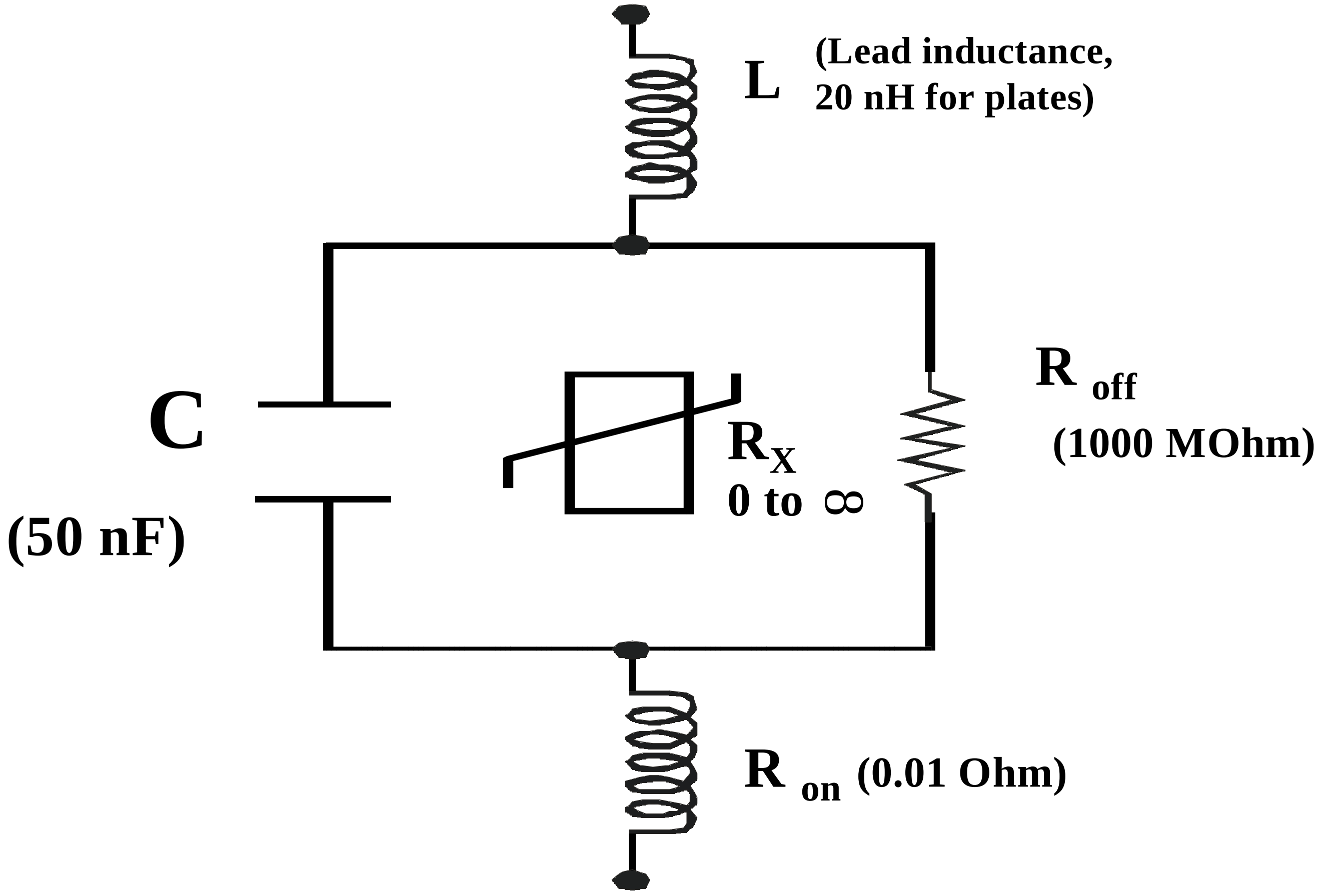


Figure 3.

Lifetime Rated Pulse Current

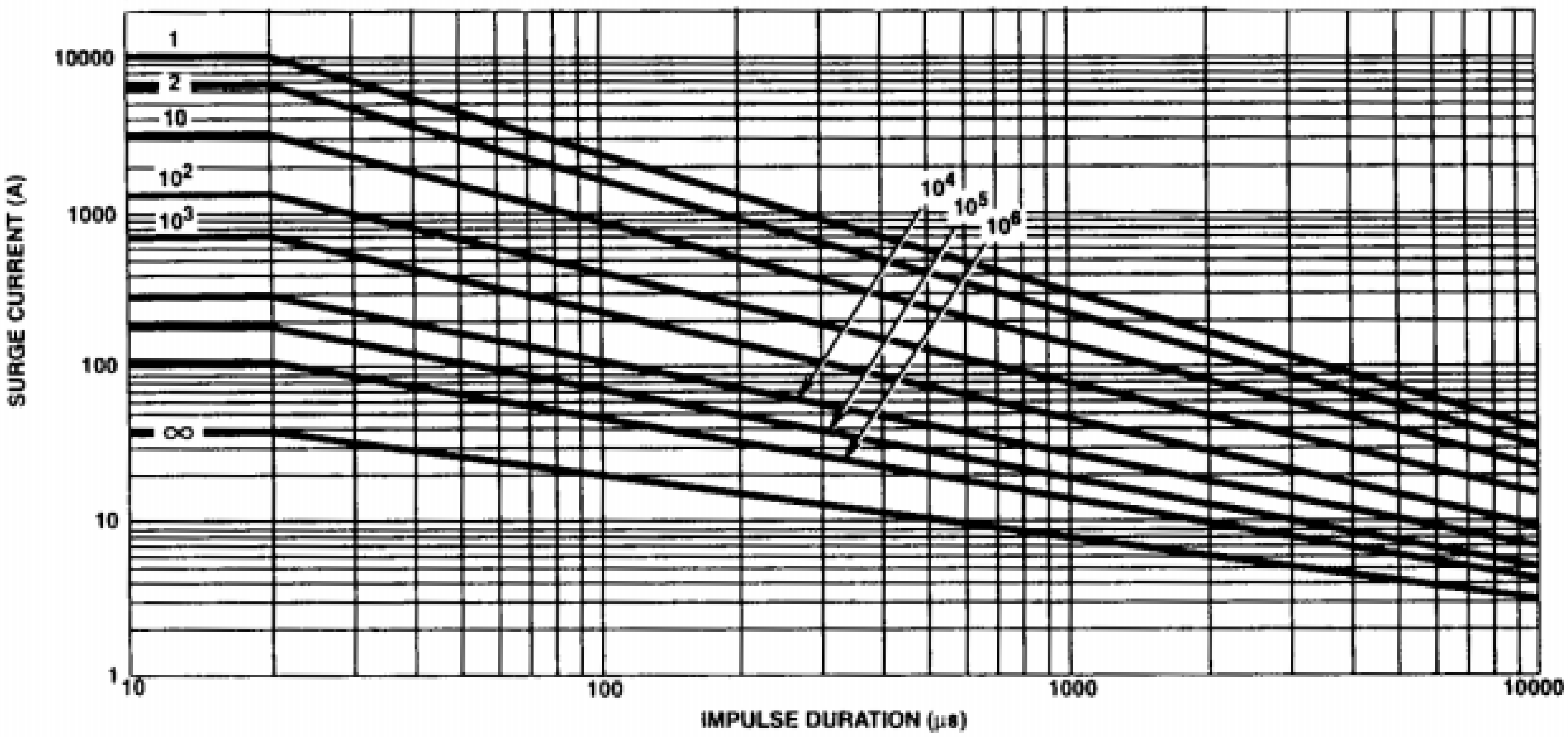


Figure 4

Sandwich Block ^{TM} Construction

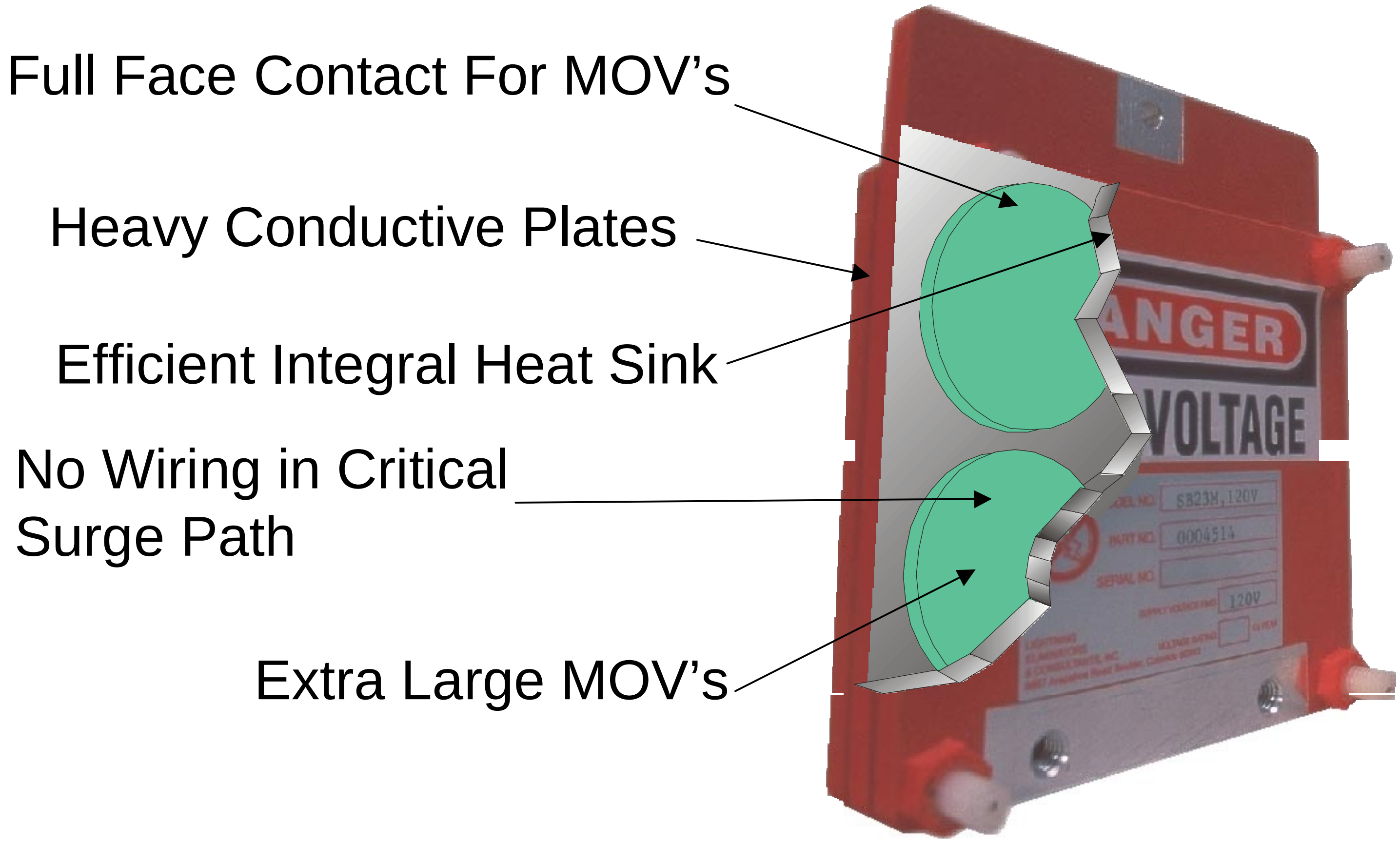


Figure 5.