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Transient Voltage Suppression Manual

GENERAL ELECTRIC

TRANSIENT VOLTAGE SUPPRESSION MANUAL

GENERAL ELECTRIC SEMICONDUCTOR PRODUCTS DEPARTMENT

Contributing Editor: David C. Kay
Application Engineer
Auburn, New York

Contributing Authors: J. Bliven
W. Kram
F. Martzloff
J. May
B. Redfoot
B. Wolff

Layout/Design: D.K. Barney

Production: N.A. Patrick
D.G. Seefeld

SEMICONDUCTOR PRODUCTS DEPARTMENT
GENERAL ELECTRIC
ELECTRONICS PARK, SYRACUSE, NEW YORK 13201

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INTRODUCTION:
FAILURE

Perhaps the reason failure is so disturbing to us is that we often do not understand its causes. When failure strikes a product for which we are responsible, we spend considerable time and money to resolve the problem. In electrical products there are many causes for failure, and they are rarely fully understood. A significant and not always recognized cause is the transient over-voltage. Misunderstanding the "transient," its causes, and the means for eliminating it, costs money through failures, over-design, and the misuse of suppressors.

It is the object of this manual to remove much of the mystery of the transient over-voltage, and give the reader the effective techniques to combat it. For this reason, the three topics of this manual are transients, suppression theory, and the GE-MOV® Varistor, a versatile suppression device. This manual has no pretentions of being a complete treatment of these subjects, but is simply a guide; references are provided for those desiring in-depth information.

CHAPTER I

TRANSIENTS, THEIR EFFECTS AND DETECTION

To treat any problem, the size, nature, and source of the problem must first be established. This chapter is an overview of the sources and nature of transient over-voltages, the problems they cause, and some equipment for detecting them.

1. TRANSIENTS – IDENTIFIABLE SOURCE

Try to change the electrical conditions of any practical circuit, and the energy stored in inductance and capacitances will cause a "transient voltage." More specifically: if you try to cause a rapid decrease in current, any inductance in that circuit will generate a higher-than-normal voltage equal to L, the inductance, multiplied by the rate of change of current (di/dt), and of a polarity that causes current to continue flowing in the same direction, as if the inductor were a power source.

It is this effect which accounts for most transient over-voltages. The effect is brief, since the source is the energy stored in the inductance ($= \frac{1}{2} Li^2$), and it is generally dissipated at a high instantaneous power (Energy = power x time).

Effective transient voltage protection is the science of dissipating this transient energy at a voltage low enough to insure survival of circuit components.

Some common sources of transient voltages are illustrated below:[1]

a. Energizing The Transformer Primary

When a transformer is energized at the peak of the supply voltage, the coupling of this voltage step function to the stray capacitance and inductance of the secondary will generate an oscillatory transient up to twice the normal peak secondary voltage.

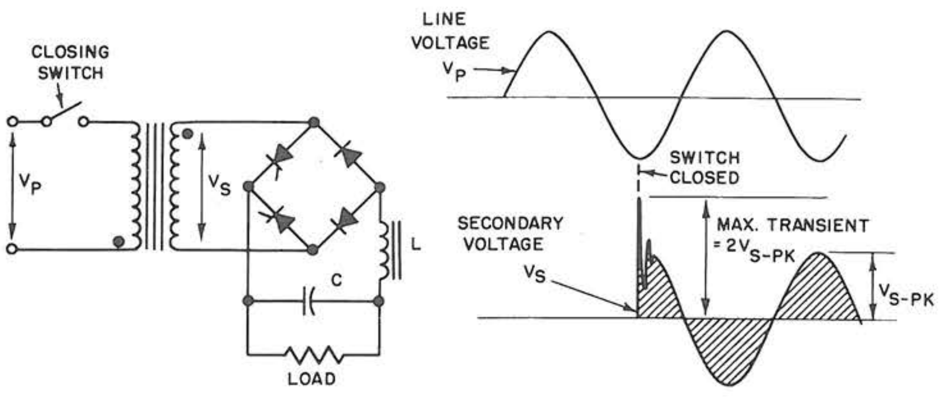

FIGURE 1.1: VOLTAGE TRANSIENT DUE TO ENERGIZING TRANSFORMER PRIMARY

b. De-Energizing The Transformer Primary

The opening of the primary circuit of a transformer generates extreme voltage transients, especially if the transformer drives a high impedance load. Transients in excess of ten times normal have been observed across power semiconductors when this type of switching occurs.

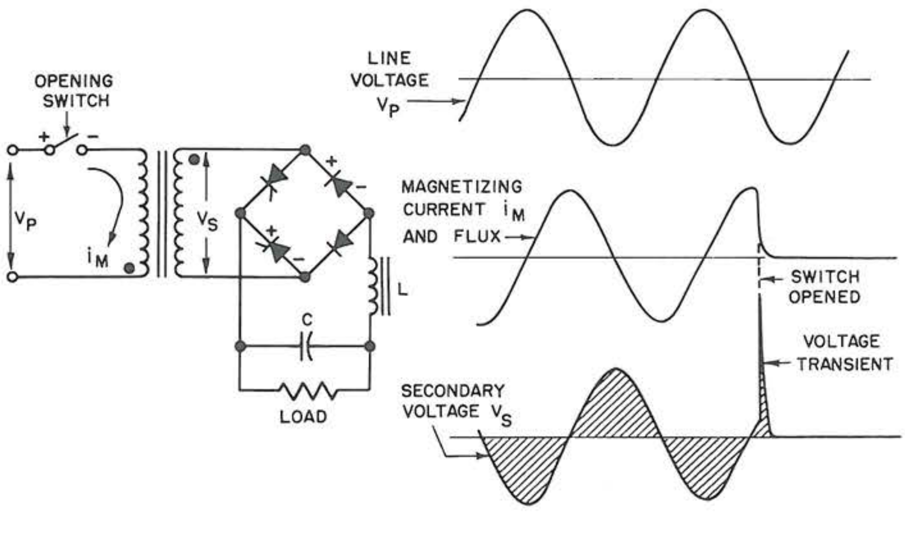

FIGURE 1.2: VOLTAGE TRANSIENT DUE TO INTERRUPTION OF TRANSFORMER MAGNETIZING CURRENT

Interrupting the transformer magnetizing current, and the resulting collapse of this current, couples a high voltage transient into the transformer secondary as is shown in Figure 1.2. Unless a low impedance discharge path is provided, this burst of transient energy appears across the load. If, by chance, this load happens to be a semiconductor of insufficient voltage capabilities, the device will be put in jeopardy. The transients produced from interrupting the magnetizing current are usually of a severe magnitude; for example, a 150 kVA transformer may create a 9 joule (watt-second) transient.

c. Fault With Inductive Power Source

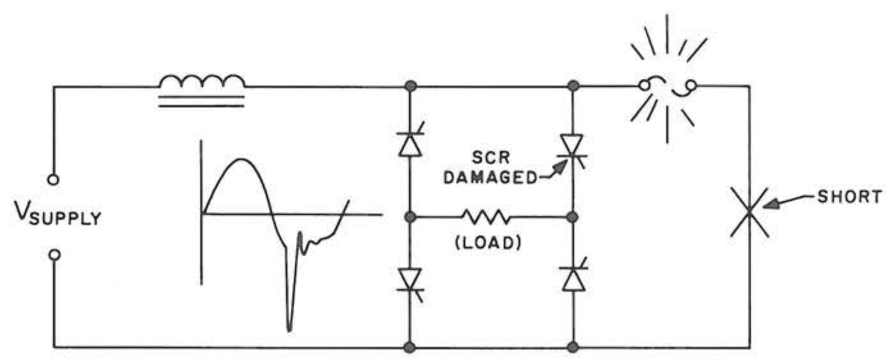

FIGURE 1.3

If a short develops on any power system, parallel devices may be destroyed when a fuse clears, as above. When the fuse or circuit breaker "blows," it interrupts a very high current, causing the slightly inductive power source to generate a very high voltage (= L di/dt), high energy ($= \frac{1}{2}$ Li^2) transient across any parallel devices. Dropping a high current load will have a similar effect on smaller parallel loads.

d. Switch Arcing

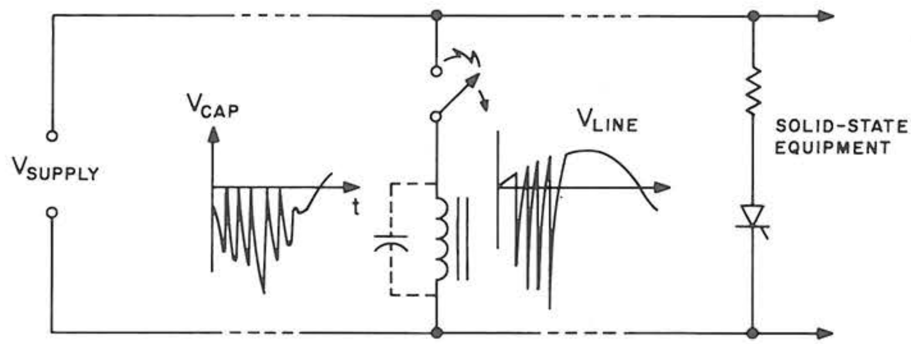

FIGURE 1.4

When the contacts controlling an inductor open, the coil maintains its current and charges up its stray capacitance. Coil voltage increases until the air gap of the contacts breaks down, discharging the high voltage into the power line. Many of these pulses are generated until the inductance is de-energized.

e. Switching Transients

High voltages are to be expected at any switch element controlling an inductive load, when current is stopped.

For example, a set of switch contacts opening while conducting 100 mA to an auxilliary relay coil having 1 Henry of inductance and about .001 microfarads of stray winding capacitance can produce the arc voltage shown below, with a 3000 volt peak.

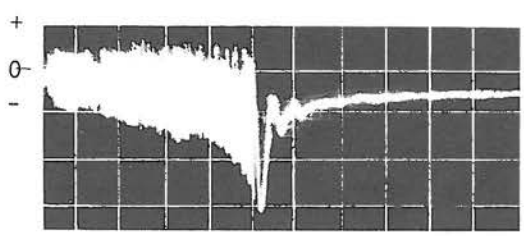

FIGURE 1.5: HORIZONTAL – t, 500μsec/cm
VERTICAL – V, 1.0kV/cm

A transistor switch can also develop high voltages at its terminals. The transistor below controls a 400 mA current through a 70 mH solenoid. When switched off, the transistor sees over 400 volts at the collector.

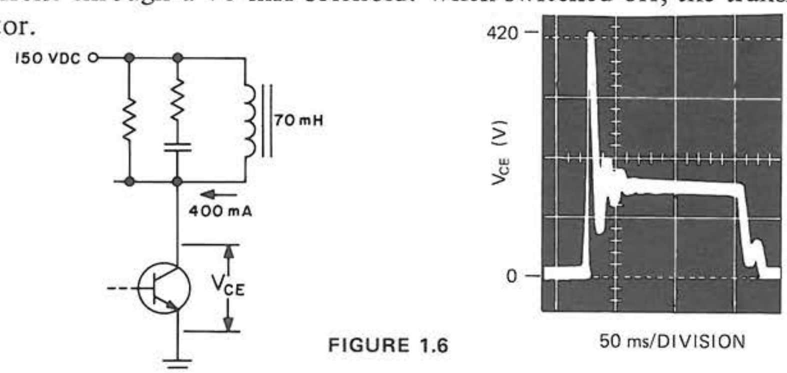

FIGURE 1.6

Whenever possible, it is recommended that a system be examined for potential sources, and the problem eliminated at the source rather than at the places affected, since usually one source can affect many components. If the sources are many (or unidentifiable) and the susceptible components few, then it may be more practical to apply suppression of the components.

2. TRANSIENTS – UNIDENTIFIABLE SOURCE

Frequently, transient problems arise not from within the system, but from the source of power (or load). It is these transients which create the most consternation, as it is nearly impossible to predict the amplitude of these transients. These transients are generally caused by parallel loads on the same branch of the distribution system, but may also be caused by lightning, especially on communication lines, such as alarm and telephone systems.

To deal with random transients, a statistical approach is the only practical method. Considerable research has been done in this area, but rarely on a large enough basis to state that on such-and-such a distribution system, there is an "X" probability of encountering a transient voltage of "Y" amplitude.

There is, however, sufficient evidence to say the following about transients on power lines:

Amplitude and Frequency of Occurrence:

Residential 120V AC lines are found to experience peak voltages up to 6000 volts. Switching of internal loads is generally responsible for repetitive transients up to about 2500 volts. The higher transients are more frequently lightning-associated. One can be 90% confident that between 1% and 4.7% of residences will experience peaks of over 1200 volts repetitively at 120V AC outlets.[2]

Similar data on higher voltage systems is not known to be available. Nevertheless, research on 240 volt systems has shown that one may expect daily excursions to 500 volts peak (including line voltage), and 1kV on a yearly basis, on low-current systems.[4] Note that this statement is not made in the same manner as for 120V AC systems, and that one may expect a small percentage of systems will differ greatly from these voltages. Some indication may perhaps be taken from the industrial practice of choosing semiconductor ratings. Most industrial users of power semiconductors choose voltage ratings of from 2.0 to 2.5 times the peak steady-state voltage used, in order to insure good reliability over many years. Whether this is related to voltage transients has not been established; the safety factor is simply chosen by experience.

In general, transients are lower in voltage and in rate of occurrence nearer the distribution transformer. Furthermore, a rough rule of thumb is that for a given system, transient voltages occur from 2 to 10 times less frequently for each doubling in peak voltage.[4]

Duration and Waveforms:

Most residential 120V AC power system transients will have an underdamped oscillatory waveform, ranging from a few tens of kilohertz to several megahertz in fundamental frequency. Components may range into hundreds of megahertz, however. Generally, they will last from 0.1 to 100 microseconds, being damped out in a few cycles.

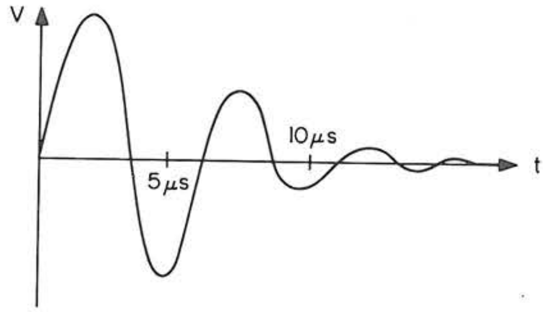

FIGURE 1.7: "TYPICAL" TRANSIENT VOLTAGE

This waveform is characteristic more of lumped-parameter systems than of distributed-parameter (transmission line) systems, which tend to experience a higher percentage of single-polarity transients.

Impedance:

Effective impedance to the surge is an extremely important characteristic, and, yet, is frequently neglected or deliberately assumed to be zero, an over-conservative assumption. Impedance determines the energy and current-handling requirements of the suppression circuit.

As a rule of thumb, one may expect a typical (U.S.) residential branch circuit to exhibit an effective impedance of up to three hundred ohms to a surge, due to the high frequency nature of the transient, compared to the 50-60 Hz power frequency.[2] Closer to the source of power or to the transient source, this may drop to five or ten ohms. Lower frequency-content transients will most likely experience lower impedance. This impedance is not completely attributable to the wiring but, also, to the effective impedance of the source.

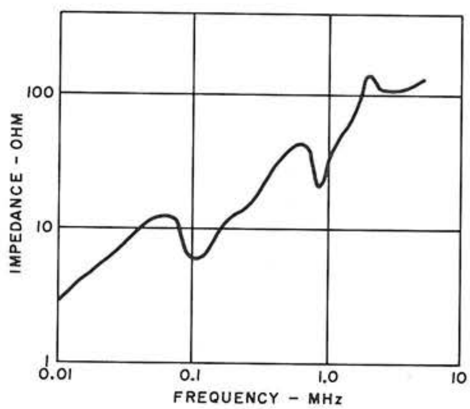

FIGURE 1.8

The figure above shows the typical impedance between live and ground terminals near the service entrance of a residence.[4] This is not necessarily the impedance of the home wiring to a transient voltage observed on a branch circuit, but is indicative of the high impedance (and wide variations) to high frequency-content surges.

"Industrial" electrical environments vary widely, depending upon the loads and distribution system. High-power electromagnetic machinery is capable of generating high energy (tens of joules), high current transients when switched on or off, when loads are suddenly removed, or when power-factor correction capacitors are switched. Solid-state controls generate repetitive spikes during phase control operation. Faults cause very high current, high energy transients when fuses and circuit breakers open.

Use of high current ("stiff") power supplies and resistive loads tend to reduce the voltage amplitude of those transients reflected into the common distribution system. In any case, industrial suppressors generally need to be quite rugged in transient-handling capability.

Equivalent Circuits

Given a sufficient statistical base, one can then develop a Thevenin equivalent circuit to represent the worst expected transient.

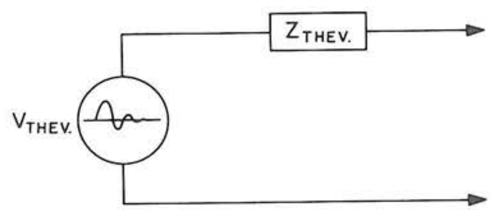

FIGURE 1.9

The suppressor requirements can then either be determined theoretically, or by tests using an actual transient generator with the same equivalent circuit.

Such tests are often suggested by various authorities such as Underwriter's Laboratories, the Institute of Electrical and Electronic Engineers, and the Rural Electrification Administration. These tests may have widely varying parameters, depending upon the application and the data used to substantiate the tests. An IEEE committee investigating the effect of transients in switching stations on solid-state equipment suggested the characteristics below as a representative waveform.[13]

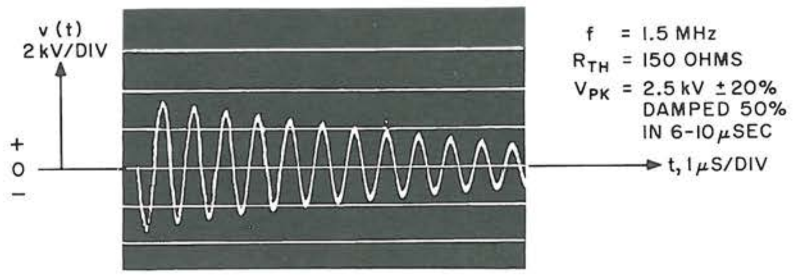

FIGURE 1.10

(A circuit to generate this transient may be found in G.E. Semiconductor Products Department's Application Note 200.73, *"Testing of GE-MOV® Varistors."*)

Underwriter's Laboratories, which is involved with safety electronics such as the ground-fault circuit interrupter, is considering the use of an oscillatory transient voltage waveform to test the susceptibility of such GFCI's to residential 120V AC power line transients.[7] A waveform under consideration is that shown below. (See also Appendix B.)

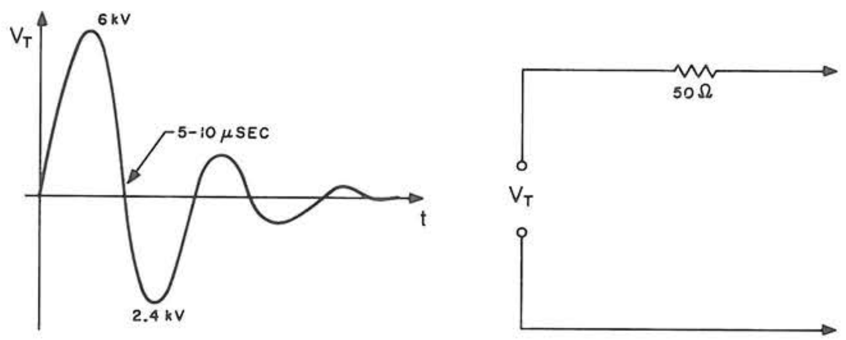

FIGURE 1.11: PROPOSED U.L./NEMA GFCI TRANSIENT TEST

Automobile Transients[18]

The automobile suffers from three fundamental transients, those of "load dump," inductive switching, and alternator field decay.

The "load dump" transient is the most severe, having considerable energy (tens of joules), voltage (≤ 125V), and duration (.1 to 4.5 seconds). This transient originates when a load is removed from the alternator output; most particularly, the disconnecting of a discharged battery (due to poor connections, for example) will create a severe load dump transient.

Switching of inductive loads (see example D, Section I), such as motors and solenoids, will also create essentially negative transient voltages with a smaller positive excursion. The voltage waveform has been observed to rise to as much as -210V and +80V, lasting as long as 320 microseconds. The impedance to the transient is unknown, however, causing most designers to test with zero impedance (with the unfortunate side effect of forcing the use of more expensive, rugged components).

The alternator field decay transient is essentially an inductive load switching transient, having negative peaks on the order of -40 to -100 volts, decaying to zero in about 200 milliseconds, and occurring when the ignition is switched off.

Other unexplained transients have been recorded with peaks of 600 volts upon engine shutdown. Furthermore, removal of regulation devices, particularly the battery, will raise normally innocuous effects to dangerous levels. (For example, ignition pulses up to 75 volts and 90 microseconds in duration have been observed with the battery disconnected.)

Telecommunication Line Transients

Telephone lines present special transient problems. First, there are many thousands of lines; second, they are exposed to frequent thunderstorm activity. This means that much sensitive (and, frequently, expensive to repair) equipment must be reliably and inexpensively protected against the effects of lightning strokes.

Statistics provide the most accurate picture of the nature of these surges. Such analyses, however, require volumes of data, especially in such a reliability-sensitive industry where considerable confidence is necessary. For this reason, it has taken many years to accumulate the present data, which unfortunately, is still largely incomplete in the areas of peak current and energy at the suppressor.

For this reason, the current and energy delivered to protectors under existing tests is specified according to the capabilities of the existing suppressor which has been found to be suitable by experience. The energy delivered may, therefore, be well in excess of the actual field conditions.

The most recent published voltage waveform data was taken by Bennison, Ghazi and Ferland[15] on the Canadian telephone system (and was determined to be essentially the same for U.S. systems). Paired wire and coaxial cables were found to exhibit similar surge waveforms (i.e., unipolar with decay times considerably longer than rise times); open wire experiences a more underdamped, oscillatory waveform. In general, paired wire and coaxial cables will have lower peak voltages and longer surge durations than open wire, with the coaxial cable having nearly twice the rise and decay times as the paired cable, with somewhat lower voltage peaks.

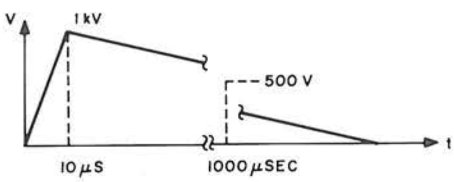

FIGURE 1.12: TELEPHONE SURGE TEST WAVEFORM FOR PAIRED AND COAXIAL LINES

Peak current data is considerably more scarce, but a recent theoretical analysis[19] shows that 99.8% of the surges encountered at a typical central office will deliver under 1000 amps to a short-circuit. Typically, one may expect a few tens of amperes. Actual suppressor current will be partially dependent upon the suppressor characteristics. Currents will tend to be higher during transients occurring at the user (station) end due to the increased exposure to lightning of an individual line.

3. EFFECTS OF TRANSIENTS

Effects on Semiconductors

Semiconductor devices can be destroyed or damaged by voltage transients in several ways. Commonly, damage occurs when a high reverse voltage is applied to a non-conducting PN junction. Avalanche currents heat the junction irregularly; this heating, in turn, releases more carriers, which conduct more current in that spot. This regenerative action eventually causes melting at the "hot spot," and the junction is damaged. High leakage results, and the ensuing heat generation by steady-state currents may ultimately destroy the device.

If the junction between emitter and base of a transistor is "zenered" or "avalanched," the effect may not be catastrophic, but will reduce the transistor's gain through creation of "trapping centers" which restrict the free flow of carriers. The cathode-gate junction of a thyristor will respond similarly, reducing the triggering sensitivity of the device.

Other types of failures can also occur. If a transistor is operating in its active region, a transient voltage may bring it out of its Safe-Operating-Area (S.O.A.). This causes thermal runaway due to the sudden increase in gain – a result of the heating effect of the transient.

Thyristors can also be damaged when turned on by a high voltage spike (forward breakover), under conditions that allow a rapid rate of current increase (di/dt). This can occur with capacitive, incandescent lamp, or saturated-inductor loads.

If a rectifier or SCR is conducting when a reverse-bias transient is applied, severe damage may occur as high recovery currents are generated. This damage may occur without the PRV rating of the device ever being exceeded.

Effects on Electromechanical Contacts[5]

The high voltage generated by breaking current to an inductor with a mechanical switch will ultimately cause pitting, welding, material transfer, or corrosion of the contacts. The time and nature of ultimate failure of the contacts depends upon numerous factors, including type of metal used, rate of opening, contact bounce, atmosphere, temperature, steady-state and in-rush currents, AC or DC operation, and others. Additionally, and perhaps most important, is the amount of energy dissipated in each operation of the contacts.

The actual breaking of current by a set of contacts is a complex operation. The ultimate break occurs at a microscopic bridge of metal which, due to the inductive load, is forced to carry nearly all the original steady-state current. Ohmic heating of this bridge causes it to form a plasma, which will conduct current between the contacts when supplied with a current and voltage above a certain threshold. The inductor, of course, is more than happy to supply adequate voltage ($= L\, di/dt$). As the contacts separate and the current decreases, a threshold is reached, and the current stops abruptly ("chopping"). Inductor current then charges stray capacitances up to the breakdown voltage of the atmosphere between the contacts. (For air, this occurs at about 300 volts). The capacitance discharges and recharges repeatedly until all the energy is dissipated. This arc causes sufficient contact heating to melt or "burn" the metal, and when the contacts close again, the contacts may form a poorer connection. (If they "bounce," or are closed soon after arcing, the contacts may be sufficiently molten to weld or stick shut. Welding can also occur as a result of high in-rush currents passing through the initially formed bridges upon closing).

Good suppression techniques can significantly reduce the amount of energy dissipated at the contacts, with a proportional increase in operating life. Suppression can also reduce the noise generated by this arcing. Voltage-limiting devices are particularly suited to preventing the noisy high-voltage "showering" arc described above.

Effects on Insulation[17]

The effect of high transient voltages on insulation can be significant, but it is not always as obvious as the familiar carbonized puncture. An electric clock manufacturer dramatically illustrated this by reducing his failure rate to *one one-hundredth* of its initial value, when he increased his insulation level from 2kV to 6kV.[2]

The breakdown of a gaseous or liquid dielectric, of course, is generally not significant since the damaged material is dispersed and replaced. With a finite volume of material, however, frequent breakdown will cause an increased concentration of damaged dielectric; this "pollution" ultimately degrades the dielectric qualities of the device.

Breakdown of a solid insulator generally results in localized carbonization. This damage may not be catastrophic, but may result instead in substantially decreased dielectric strength. Subsequent transients will produce breakdown at the same place, until the insulation can no longer withstand steady-state voltage.

Breakdown, along a surface, such as on a printed circuit board, will result in a path of slightly conductive carbonized insulation. Vaporized metal from the circuit will also contribute to this path. In fact, the most significant damage from such an event may be the degradation of the metal from which arcing is originated. Another effect is the increased exposure to transients of other circuit elements through this new "connection."

Arcing between windings of a coil, such as in a transformer or motor winding, is frequently the result of self-induced voltages with steep wavefronts, which are unevenly distributed across the turns. The enamel commonly used to insulate the turns can break down at voltages as low as 500 volts.

With any insulation breakdown problem, the ultimate catastrophic damage generally occurs, not during the transient, but when current from the steady-state power source follows. This may not occur for a considerable period of time after the occurrence of the transient, often misleading the observer to suspect other causes.

Noise Generation

With sensitive logic gates gaining popularity, especially in environments with electromechanical devices, noise problems are frequent. Noise can upset automatic manufacturing equipment, medical equipment, computers, alarms and thyristor-controlled machinery; such disruption can cause loss of product, time, money and even human life.

Noise enters a system either directly on wires or grounds connected to the source, or through coupling to adjacent wires. Noise problems are dealt with by suppression at the source or at the receiver, or by isolation. Volumes can be written on the science of noise reduction, so this brief discussion is limited to noise due to transients, and its suppression at the source.

The source of transient noise is almost always an inductor, and most frequently, a relay coil. When the coil is de-energized, a high voltage appears at the switching element. This voltage can be fed back to the controlling logic through the reverse gain of the transistor or electromagnetic coupling. This voltage can be controlled by suppression at the switch or coil, at the expense of coil drop-out time.

Noise is induced when stray capacitance or mutual inductance links the susceptible system to the noise generating system. The amplitude of the induced noise is then related to the rate-of-change of either current or voltage of the noise source. The low-frequency components of the induced noise (which are hardest to filter out) are a result of the amplitude of the original transient impulses.

Good suppression at the source will, therefore, consist of both voltage rate-of-rise limiting ("snubbing") elements and voltage limiting components. These components (which may be as simple as a capacitor) are then placed to allow the longest decay of current possible through the transmitting wires. Some experimentation must usually be made to determine the most effective components and their optimal placement.

Frequently, the source of noise is the arcing of contacts breaking current through an inductor, such as a relay coil. A low-current, high-voltage arc (known as a "showering" arc and described in Chapter 4, Section 2) creates a series of brief discharges of a damped oscillatory nature, occurring at a rate of about 10^6 per second and having an amplitude of 300 to several thousand volts. These pulses (and their reflections from loads and line discontinuities) travel along the power wires, easily inducing noise in adjacent wiring by their high-frequency nature. These pulses are best eliminated by preventing them at the source (the inductance) with voltage limiting devices.

4. TRANSIENT DETECTION

Transients, by definition, are brief and frequently random in time; they are, therefore, hard to detect. If the source is known, they can be generated at will and observed on a high-frequency recording oscilloscope. A wide variety of both digital and analog instruments are available, each having distinct advantages (resolution, speed, expanding capability). Such an instrument can also be left connected to a line where transients are suspected, and set to trigger at a certain threshold, thereby recording a number of transient waveforms.

Often, it will suffice to simply find the frequency of occurrence of a transient exceeding a certain threshold. Instruments can be bought or constructed which will either count, record, or indicate the existence of one or more high-voltage events. A list of some such instruments follows.* (This list is by no means a complete compilation of available equipment).

MANUFACTURER	MODEL	FEATURES	APPROX. PRICE
Recording Oscilloscopes:			
Tektronix[20]	400 Series	350 MHz, 130 cm/μs speed, portable	$3,000
Tektronix	Telequipment	50 MHz, 0.25 dv/μs, portable	$1,000
Tektronix	7000 Series	Multimode storage, 100 MHz, 1000 cm/μs, digital processing add-ons	$4,000
Micro-Instrument[21]	Memory Voltmeter	500 MHz, records, displays voltage waveforms, levels up to 2kV	$1,700
Peak Recording Instruments:			
Pioneer[22]	Peaklok 800	Records peak voltages > .5 μs duration	$ 850
"Home-Brew" Information:			
G.E. SCR Manual, 5th Edition		Records single event	$ 25
IEEE Trans. Power Apparatus & Systems, PAS-84, pp. 417-422, 5/65		Six-channel solid-state counter with 20 μs response time	
Radio & Electronics Engineering, Vol. 28, pp. 191-197, 9/64		Surge counter	

*Inclusion of any manufacturer or product in this listing does not constitute an endorsement, nor does exclusion imply any judgment upon the same.

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22 Pioneer Instrumentation Division, Pioneer-Standard Electronics, Inc., 4800 E. 131st Street, Cleveland, Ohio 44105.

CHAPTER II

SUPPRESSION – THEORY AND DEVICES

This chapter will discuss briefly the operation of various types of suppressors, how they reduce transient over-voltages, and their effects on circuit design and operation.

1. SUPPRESSION THEORY

"Random" Transients

Random transients, or transients with an unidentified source, can be viewed as a voltage source with some finite impedance appearing at the terminals of your equipment. The voltage amplitude and waveform can be measured, or taken from transient voltage studies. The impedance can be calculated from line inductance or transmission line characteristics, or actually measured.

A suppression circuit or element applied to the terminals is then designed to by-pass transient current around your equipment at a low voltage, dropping the remaining voltage across the transient's impedance, or across some impedance built into the suppression circuit.

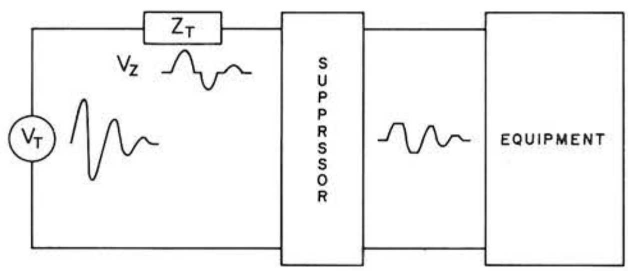


FIGURE 2.1: PROTECTION BLOCK DIAGRAM

Inductive Transients

The current in an inductor cannot change instantaneously. For this reason, a suppressor placed on an inductor will have to conduct a peak current equal to the inductor's current at the time switching "off" occurs, and conduct it at a low voltage.

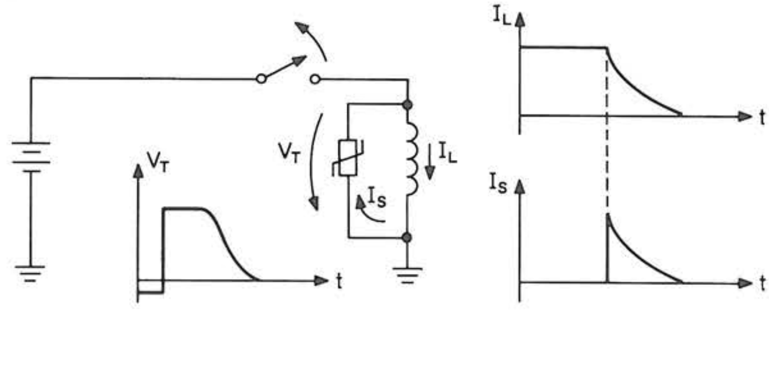


FIGURE 2.2: INDUCTIVE TRANSIENT

This peak current will never be higher than the steady-state current and will be lower only if there is a parallel path for inductor current to flow.

2. SUPPRESSORS

Filters

The frequency components of a transient are usually several orders of magnitude above the steady-state voltage frequency, so an obvious solution is to install a low-pass filter.

The simplest form of filter is a capacitor placed across the terminals. Hopefully, the capacitor will present an impedance to the transient much lower than the transient source impedance, forming a voltage divider. This works well as long as the capacitor does not load down the desired voltage, and does not create in-rush current problems in thyristors or other switches. Large capacitors may have the added problem of parasitic inductance, which will spoil the high-frequency admittance of the device. A resistor added in series with the capacitor will reduce current in-rush problems, but will reduce the effectiveness of the network, as well. Using a capacitor network is also ineffective if the transient has a high energy content in either polarity (a high DC current component). Inductance associated with a filter resistor or large capacitor will also reduce filter effectiveness.

Filters may also be constructed using inductors or even active devices. These, however, become expensive and can lead to other problems if not carefully designed.

Suppression Devices

Special suppression devices are of two basic types: "constant voltage" and "crowbar." Constant voltage devices conduct very little at steady-state voltage, but above a certain voltage level conduct very heavily. When the voltage returns to normal, however, they do not continue conducting heavily. A "crowbar" device can be envisioned as something which senses a high voltage and throws a short circuit (or low resistance) across the line. The short is not removed until the current through the device (from any source) is brought to a low level. A constant voltage device will never reduce the line voltage below its peak steady-state voltage; a crowbar often will.

Zeners, avalanche diodes, and varistors are "constant voltage" types; spark gaps, gas-discharge tubes and thyristors are crowbars.

Operation and Performance of Suppressors — Zeners, Avalanche Diodes

These diodes are designed to tolerate breakdown in the reverse direction. They are presently the most "constant voltage" devices available; that is, voltage is only very slightly dependent on current. When put across a line to suppress transients, they will "clip" at a level largely independent of the transient's impedance.

Because their operation takes place within a very small volume of silicon, however, the energy (or heat) generated by a transient can easily heat the junction area to the point of failure. The high-energy transients found in industrial power could easily destroy all but the most expensive, high energy zener or avalanche diode.

Gas Breakdown Devices

On the opposite end of the ruggedness spectrum are the spark gaps and gas-discharge tubes (GDT's). These depend on the formation of an ionized gas between metal electrodes. The gap length, gas pressure, and several other factors determine the breakdown voltage. When an arc is formed, the suppressor is capable of conducting high currents (X1000A) at a low voltage ($\lesssim$ 100V).

Unfortunately, the steady-state power source is frequently capable of keeping the arc conducting until current and voltage are reduced, temporarily disabling the supply. Many such suppressors also have a noticeable response time, such that a fast-rising transient reaches a high voltage before the arc can form. Construction techniques make the GDT a relatively expensive device, and they are not generally feasible below 90 volts.

Selenium Cells and Silicon Carbide

Durable, high energy solid-state suppressors were created using two separate technologies. Selenium suppressors used the polycrystalline selenium diode, specially designed to tolerate reverse breakdown currents. These diodes have considerable dissipating area and thermal mass, being intimately connected to metal plates. Silicon carbide is a ceramic material which has a bidirectional breakdown. Energy is dissipated throughout the entire volume of material, making an even more rugged suppressor.

Both these devices suffer from a "soft" breakdown (relative to a zener diode) which causes them to dissipate noticeable power while "standing by" and to have a "clipping" voltage which is quite dependent upon the transient current (although the selenium is better in this respect than the silicon carbide).

Metal-Oxide Varistors

A new breed of ceramic suppressors has been developed which, unlike the silicon carbide, has a very nonlinear (zener-like) bidirectional breakdown. One of these, General Electric's GE-MOV® Varistor is a versatile, zinc-oxide/bismuth oxide ceramic device having many of the silicon carbide's qualities of energy-handling and high current density capability. Its breakdown characteristic is the closest of any other type suppressor to the avalanche-rectifier suppressor characteristic. These qualities allow for effective and reliable suppression in a small package.

There are only a few limitations to the metal-oxide varistor technology. Varistors with very low breakdown voltages are not feasible with the existing technology; however, recent advances have allowed breakdown voltages (at 1 milliampere) of 22 volts. A slight capacitance is also inherent, depending on the thickness and diameter of the varistor disc; the effects of this capacitance are generally not significant, except at radio frequencies.

3. SUPPRESSOR SIDE EFFECTS

Loading (Power Consumption)

Most devices used for transient suppression also tend to draw current from the steady-state supply. In an industrial environment this may be quite acceptable. In low current or portable equipment, such consumption is uneconomical and generates heat. "Crowbar" devices are often the best in this respect, except for drawing follow-on current.

In high-frequency circuits, suppressor capacitance may unduly reduce signal levels, as well.

Coil Drop-Out Time

Any attempt to limit the voltage generated by an inductor will increase the time required to reduce the current through it. Since the inductance is a current source with finite energy, the time required to de-energize the coil is less if the rate of energy dissipation (= power dissipation) is high. Power dissipation during the transient period is dependent upon the voltage at which inductor-generated current is dissipated in the suppressor. Therefore, the more complete the suppression, the longer the de-energizing time.

De-energizing time changes affect the timing of control systems, the frequency of electro-mechanical oscillators, and even the contact life of relays whose coils experience suppression! (Slow coil drop-out can substantially increase arcing damage; early relay contact failures due to the use of rectifier diodes as suppressors on D.C. coils have been observed.)

Ringing

The use of capacitor networks or suppressors with considerable capacitance will result in transient oscillations due to stray inductance. This effect is not necessarily troublesome as a noise source, since it occurs where otherwise a multi-frequency pulse would be found.

A capacitance can, however, have the effect of increasing a transient voltage if the transient's source impedance is largely inductive. (Of course, if the capacitance is associated with a voltage clipping device, the voltage will still be limited.)

Surge Currents

Capacitor suppression circuits also have the effect of creating current transients – that is, surge currents resulting from their charging or discharging. Both the magnitude and rate-of-rise of these transients can damage solid-state or mechanical switches.

If, for example, an SCR is paralleled by a capacitor, the SCR will discharge the capacitor through a very low resistance loop.

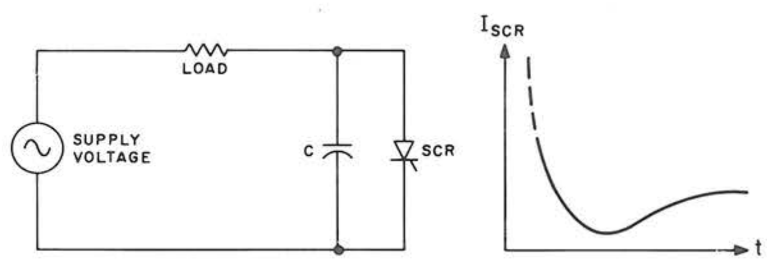


FIGURE 2.3: SCR SURGE CURRENT DUE TO CAPACITOR

Even if the SCR can handle the surge current amplitude, the rate-of-rise of current may exceed the rate at which the SCR can turn on across its area, thereby causing current crowding and damage. Similarly, mechanical switches can be burned or welded by high in-rush currents. Frequently, a compromise is achieved between good suppression and surge current limiting by adding either resistance or inductance in series with the capacitor.

System Reliability

The intent of adding suppression elements is to improve reliability; but the opposite effect can occur if the suppressor is ill-chosen. For example, if ordinary 200-volt "zeners" are used to protect a 200 volt rated SCR on a 110 volt A.C. line, there is a good chance the zeners will fail more frequently than the SCR would otherwise, due to low voltage, moderate energy transients.

The SCR has a 200 volt *minimum* rating, while the zeners will surely break down between 180 and 220 volts, and will eventually get more energy than they can handle.

Adding a suppressor only marginally capable of handling the transient current and energy is, therefore, worse than no suppressor at all.

CHAPTER III

GE-MOV® VARISTOR BASICS

INTRODUCTION

The first GE-MOV® Varistors were introduced in 1972 and several product lines now have been developed. Although these offer a wide range of characteristics and ratings, they all have a zinc-oxide based material in common. Because of the metal oxide composition the device is referred to also as a metal oxide varistor.

The GE-MOV® Varistor is a voltage dependent, non-linear resistor with symmetrical conductive properties. An oscillograph of the V-I characteristic is shown in Figure 3.2. The response is very similar to back-to-back zener diodes.

The voltage across a varistor and the current through it are related by a power law $I = kV^{\alpha}$. The exponent α will typically have values 25 to 50 or more. Over a wide current range, the voltage remains within a very narrow band for a specific device, and can be referred to as the "varistor voltage" for that device. The non-linear electrical characteristic makes the device useful in voltage regulation applications, and in particular for limiting surges and transient voltages that may appear on power lines.

1. CONSTRUCTION AND MICROSTRUCTURE

Structure[1]

A schematic representation of the varistor structure is shown in Figure 3.1. The device consists of a polycrystalline ceramic body between electrodes that direct current flow. Zinc oxide and bismuth oxide, desirable ingredients for a high exponent varistor, are mixed with other metal oxide additives in powder form, pressed into disks and sintered above 1200°C. The bismuth oxide is molten above 825°C, assisting in the initial densification of the polycrystalline ceramic. At higher temperatures grain growth occurs forming a structure with controlled grain size. In the final ceramic, each grain is separated from its neighbor by an intergranular electrical barrier.

The ceramic body acts as a bulk effect device having many grain boundaries with each grain boundary acting as a low voltage breakdown "junction." It is the accumulation of these grain boundaries that yield the overall varistor characteristic. For a given ceramic powder composition electrical properties are controlled by pressing to a given dimension; i.e., thickness and area.

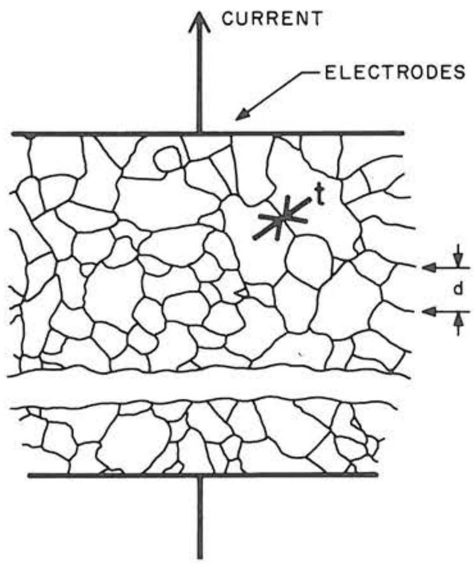


FIGURE 3.1: SCHEMATIC DEPICTION OF THE MICROSTRUCTURE OF A METAL-OXIDE VARISTOR. GRAINS OF CONDUCTING ZnO (AVERAGE SIZE) ARE ARRAYED IN A MATRIX OF INTERGRANULAR MATERIAL OF THICKNESS t. ELECTRODES ARE ATTACHED AND CURRENT FLOWS AS INDICATED.

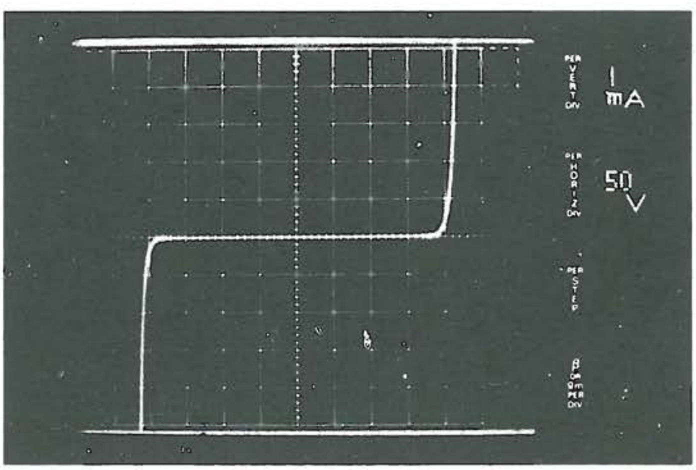


FIGURE 3.2: I-V OSCILLOGRAPH (ACTUAL PHOTO)

Construction

The process of fabricating a GE-MOV® Varistor is diagrammed in the flow chart of Figure 3.3. There are two versions of the starting material which differ in the composition of the additive oxides. One material is used for all low voltage products and the other is used for the higher end of the voltage range. The dividing line is at approximately 100 volts D.C.

Device electrical targets are determined at the pressing operation. The powder is pressed in the form of round discs of predetermined thickness and diameter. To obtain a desired value of nominal voltage, the disc body is varied in thickness. To obtain the desired ratings of peak current and energy capability, the area is varied. The range of diameters obtainable in product offerings are listed here:

Nominal Disc Diameter – mm	3	6	14	20

Of course, other shapes, such as rectangles, are also possible by simply changing the press dies.

Electroding is accomplished by means of thick film silver fired onto the ceramic surface. Wire leads or strap terminals then can be soldered in place. A recently introduced method of connecting contacts to the 3 mm disc is based on a conductive silver epoxy.

Encapsulation is of two forms – an epoxy fluid bed coating or a transfer molded alkyd package. Different package styles allow variation in energy and power ratings, as well as in mechanical mounting. Figure 3.4 illustrates a sampling of three basic package forms – the leaded radial (LA, ZA Series), the axial (MA Series) and the power configuration (PA Series).

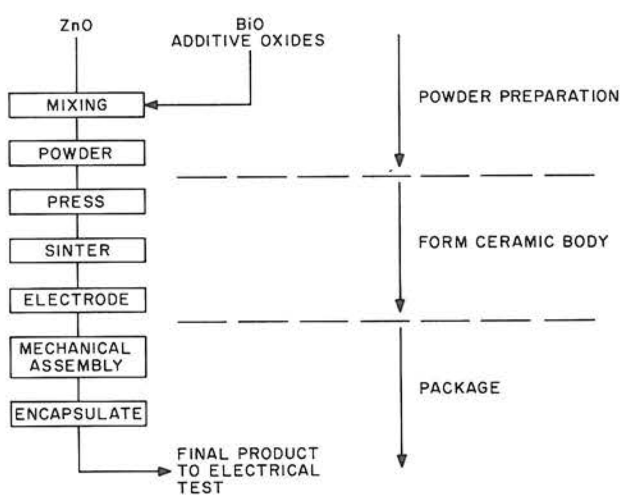


FIGURE 3.3: SCHEMATIC FLOW DIAGRAM OF GE-MOV® VARISTOR FABRICATION

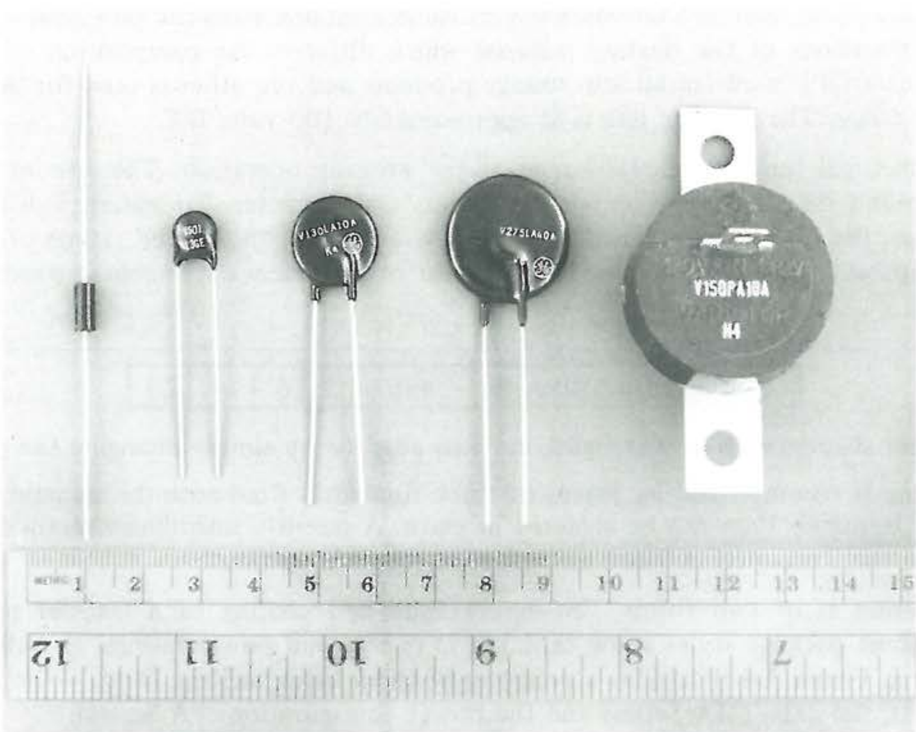
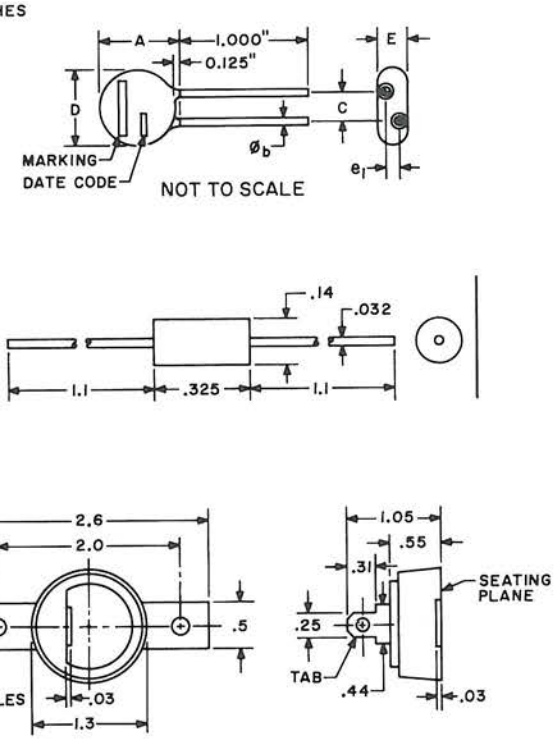


FIGURE 3.4: GE-MOV ® VARISTOR PACKAGES PRESENTLY AVAILABLE

DIMENSIONS IN INCHES

SEE SPEC SHEET FOR SPECIFIC DIMENSIONS



RADIAL PACKAGE
LA, ZA SERIES

AXIAL PACKAGE
MA SERIES

POWER
PA SERIES

FIGURE 3.4b: MECHANICAL OUTLINES OF VARISTOR PACKAGES

Microstructure Properties

An attractive property of the GE-MOV® Varistor is that the electrical characteristics are related to the bulk of the device. Each ZnO grain of the ceramic acts as if it has a "junction" at the surface of the grain boundary. A cross-section of the material is shown in Figure 3.5, which illustrates the ceramic microstructure. The individual ZnO grain boundaries can be clearly observed. The non-linear electrical behavior occurs at the boundary of each conducting ZnO grain. The varistor can be considered a "multi-junction" device composed of many series and parallel connections of grain surfaces. Device behavior must be analyzed with respect to the details of the ceramic microstructure. Mean grain size and grain size distribution play a major role in electrical behavior.

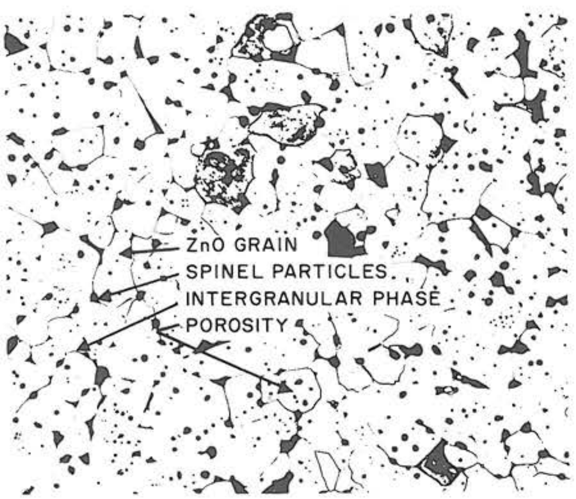


FIGURE 3.5: PHOTOMICROGRAPH OF A POLISHED AND ETCHED SECTION OF A GE-MOV® VARISTOR. INDIVIDUAL ZnO GRAINS ARE CLEARLY DELINEATED. PORES AND INSULATING PARTICLES ARE NOT SIGNIFICANT IN AFFECTING DEVICE ELECTRICAL PROPERTIES.

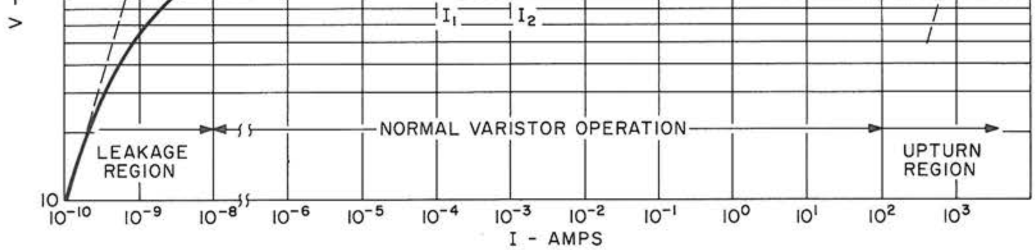


FIGURE 3.6: IDEALIZED VARISTOR V-I CURVE PLOTTED ON LOG-LOG SCALE.

Properties of ZnO Grains

The rather low resistivity, about 1 ohm-cm at 25°C, of semiconducting zinc oxide is attributed to conduction electrons from ionized zinc interstitial atoms. The addition of trivalent ions such as Co^{3+} contribute additional electrons with a further reduction in resistivity. Bismuth doping of the zinc oxide grains is less than 100 ppm as determined by electron microprobe analysis. Trivalent bismuth ions would be expected to decrease the resistivity of zinc oxide, but in this concentration, they probably have a negligible effect. In addition to altering grain resistivity, small amounts of metal oxide additives perform a critical function, acting as grain growth controllers. In this manner, the size of the ZnO grains in the sintered ceramic can be predetermined.

Electrical Effects of Microstructure

A fundamental property of the ZnO varistor is that the voltage drop across a single interface "junction" between grains is constant. Observations over a wide range of compositional variations and processing conditions show a constant drop of approximately 2 volts per grain boundary junction. Also, the drop does not vary for grains of different sizes.

It follows, then, that the varistor voltage will be determined by the thickness of the material and the size of the ZnO grains. The relationship can be stated very simply as follows:

Varistor Voltage, $V = (2 \text{ volts})\, n$

where, n = average number of grain boundaries between electrodes

Varistor Thickness, $W = (n + I)\, d$

$$\simeq \frac{V_I}{2} d$$

where, d = average grain size (see Figure 3.1)

Some typical values of dimensions for GE-MOV® Varistors are given in the table below:

VARISTOR VOLTAGE	AVERAGE GRAIN SIZE	n	GRADIENT	DEVICE THICKNESS
VOLTS	MICRONS		v/mm AT 1mA	mm
200 volts DC	16	110	125	1.8
33 volts DC	60*	17	33	1.0

*Low voltage formulation.

Capacitance of the varistor occurs at the intergranular boundary between the conducting grains. As expected from the microstructure model, the small signal capacitance between electrodes is inversely proportional to the number of grain boundaries. The approximate capacitance of a varistor can be determined by this relation:

Device Capacitance, $C \approx A\, kc/n$

where, n = average number of grain boundaries between electrodes

$kc = .02\ \text{uf/cm}^2$ at 1 MHz

A = Area of electrode

Also, $C \approx 2\, kc\, A/\text{Varistor Voltage}$

which indicates capacitance is a function of varistor voltage rating.

2. THEORY OF OPERATION

Several theoretical models have been suggested to explain the non-linear conduction mechanism of the ZnO metal oxide varistor. The difficulty faced by researchers is to determine the exact location, structure and dimension of the region responsible for varistor action. Some investigators presume that the intergranular barrier is composed of an insulating, thin film oxide phase which completely surrounds the conducting ZnO grains. By analogy with non-linear conduction mechanisms proposed for thin film insulators, conduction mechanisms of varistor action are suggested. Another approach to a theoretical model is based on interface barriers such as exist in PN junctions and materials of differing work functions and band gaps. A summary of current theories can be grouped into three differing viewpoints.

1) The first explanation proposed for varistor action in zinc oxide varistors was that of space charge limited currents (SCLC). This theory was originally developed to explain injection current phenomena in insulators. According to this model, the initial injected carrier density is less than the thermally generated free carrier density and the I-V characteristic is ohmic. When the injected carrier density exceeds the thermally generated carrier density, departure from Ohm's Law occurs, the current becomes space charge limited and takes the form of the Mott-Gurney square law. This region ($I = kV^2$) is strongly affected by the trap density. As the traps become filled, the current rises rapidly until it reaches the trap-free space charge limited value. The SCLC model was chosen because the investigator took the film thickness to be about 10,000 Å and, therefore, had to reject tunneling. Avalanche multiplication was rejected, because it did not follow the observed temperature dependence.

2) An alternate theory presumes a thin film oxide phase completely surrounding and insulating the conducting ZnO grains. This intergranular barrier is estimated to be on the order of 100 Å and the field at breakdown to be about 10^6V/cm. These values are consistent with a model of quantum mechanical tunneling (Fowler-Nordheim tunneling). The V-I relation of the model takes the form $J = J_o \exp(-\gamma/F)$. Where J is the current density, F is the field, and J_o and γ are constants. With appropriate approximations and expansions, this equation can be made compatible with the varistor power law equation.

   At low fields a second process takes effect which is similar to Schottky emission. The process is the Poule-Frenkel effect which describes localized electron emission over a coulombic barrier.

3) This theory views the intergranular barrier to be more of a surface effect on the ZnO grains which are sufficiently close as to be considered touching. A model is derived by assuming interface states and Schottky barriers on each individual grain. Instead of the ZnO playing a passive role as a conductor, the active region is located at the ZnO interface. A Schottky depletion width is computed to be about 500 to 1,000 Å. The varistor power law equation is then formulated on the model of a reversed-biased Schottky junction assuming the presence of surface states.

3. ELECTRICAL CHARACTERIZATION

Idealized V-I Characteristic

Most circuit engineers are accustomed to viewing V-I traces on a linear scale, such as the oscillograph of Figure 3.2. This presentation is not convenient for the highly non-linear varistor for two reasons:

1) The "knee" of the characteristic depends upon the linear scale factors and its location can be deceiving.
2) The current range is limited to one order of magnitude.

1) *Leakage Region*

At low current levels the V-I curve approaches a linear (ohmic) relationship and shows a significant temperature dependence. The varistor is in a high resistance mode, approaching 10^{12} ohms, and appears as an open circuit.

2) *Normal Varistor Region*

The varistor characteristic follows the equation, $I = kV^{\alpha}$, where k is a constant and α is the non-linear exponent. Alpha is a figure of merit and can be determined from the slope of the V-I curve or calculated from the formula:

$$\alpha = \frac{\log (I_2/I_1)}{\log (V_2/V_1)}$$

$$= \frac{1}{\log (V_2/V_1)} \quad \text{for } I_2/I_1 = 10$$

3) *Upturn Region*

At high currents, approaching the maximum rating, the varistor becomes nearly a short circuit. The curve departs from the non-linear relation and approaches the value of the material bulk resistance, about 1-10 ohms.

Temperature Dependence

The effect of temperature on the characteristic curve is shown in Figure 3.7. A distinct tem-

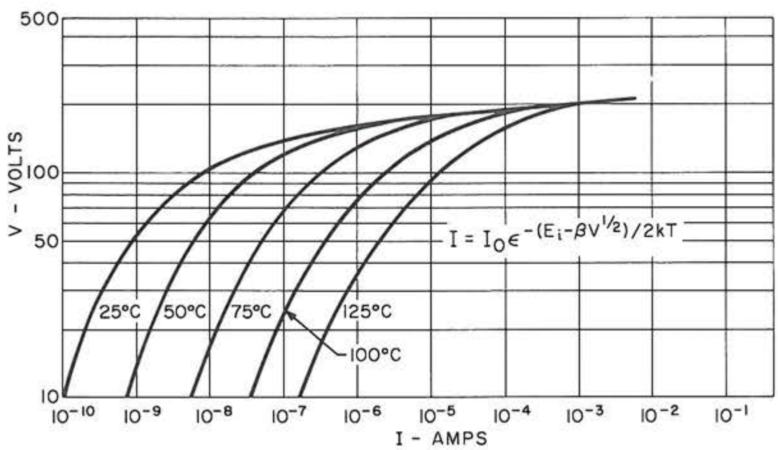


FIGURE 3.7: TEMPERATURE DEPENDENCE OF THE CHARACTERISTIC CURVE

perature dependence is noted in the leakage region. However, at higher currents, at and above the milliamp range, temperature variation becomes minimal. The relation between the leakage current, I, temperature, T, and applied voltage V, is

$$I = I_o \exp - (E_i - \beta V^{1/2})/2\, kT$$

where: I_o, β are constants
k = Boltzmann's constant
$E_i = 1.6$ eV

The plot of the temperature coefficient, dv/dT, is given in Figure 3.8. It should be noted that the temperature coefficient is negative and decreases as current rises.

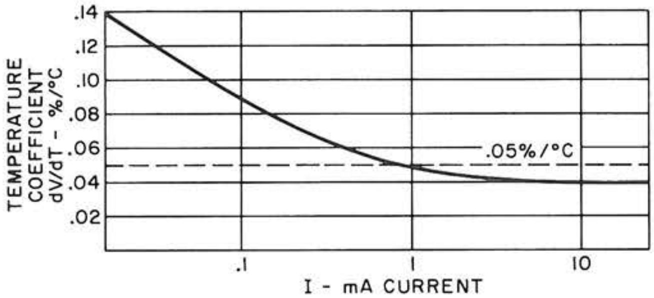


FIGURE 3.8: RELATION OF TEMPERATURE COEFFICIENT, dv/dt TO VARISTOR CURRENT

Device Resistance

The static resistance of the varistor is defined by $R_v = \frac{V}{I}$; and the dynamic resistance by $Z_v = dv/dI = V/\alpha I = R_v/\alpha$.

Plots of typical resistance values vs. current, I, are given in Figure 3.9 and Figure 3.10.

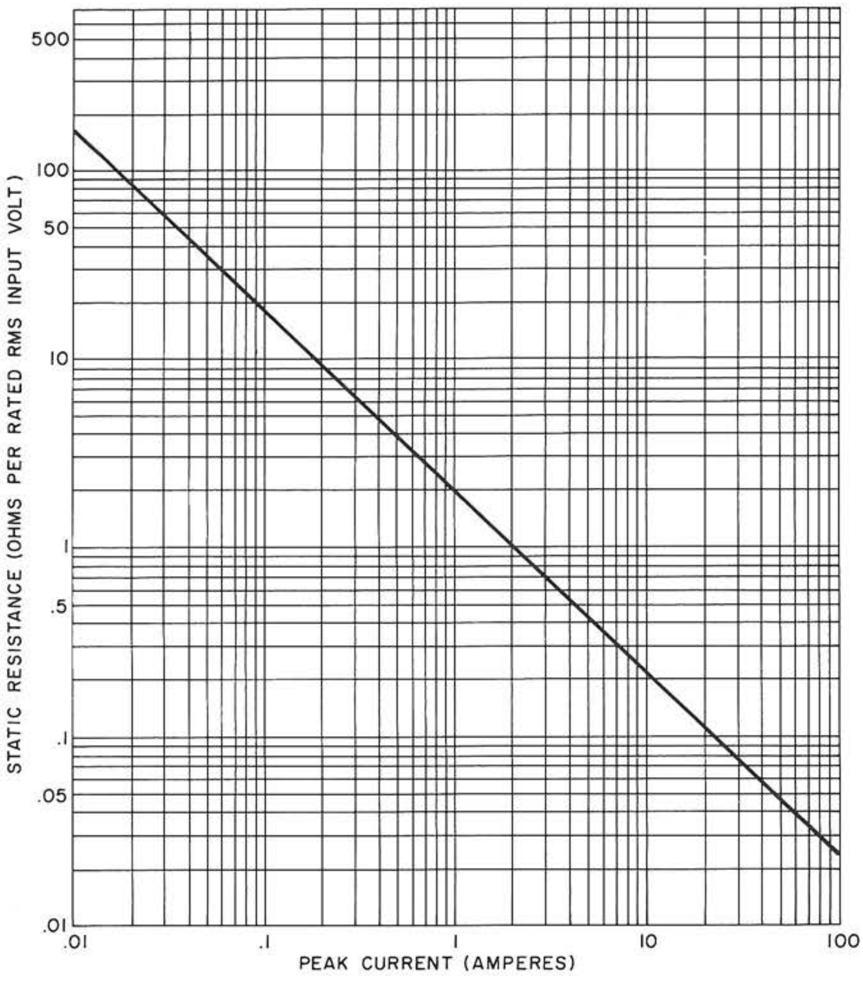


FIGURE 3.9: R_V, STATIC VARISTOR RESISTANCE

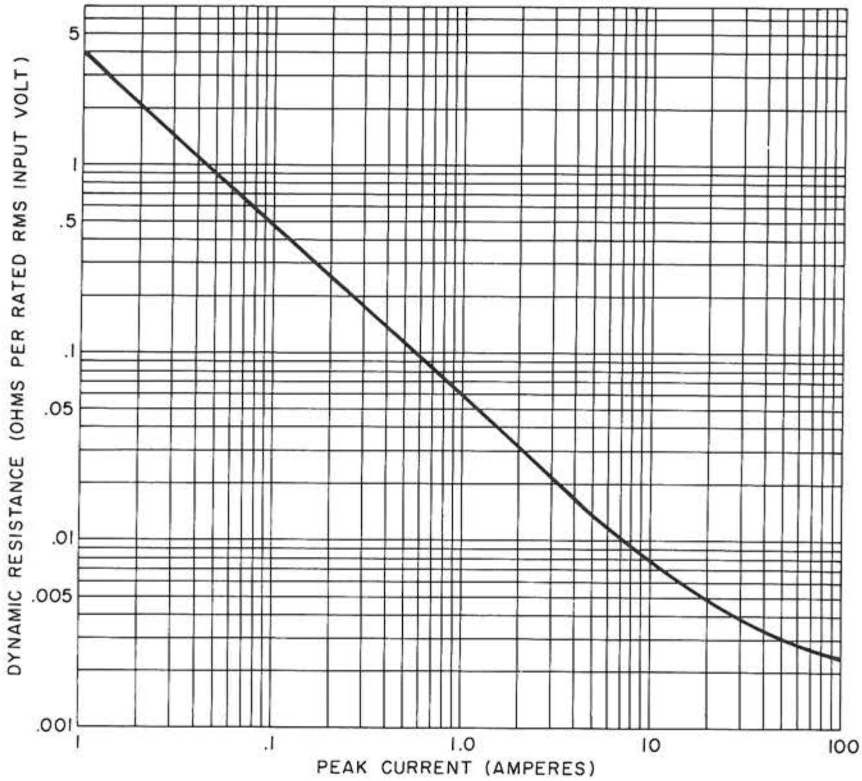


FIGURE 3.10: Z_V, DYNAMIC VARISTOR RESISTANCE

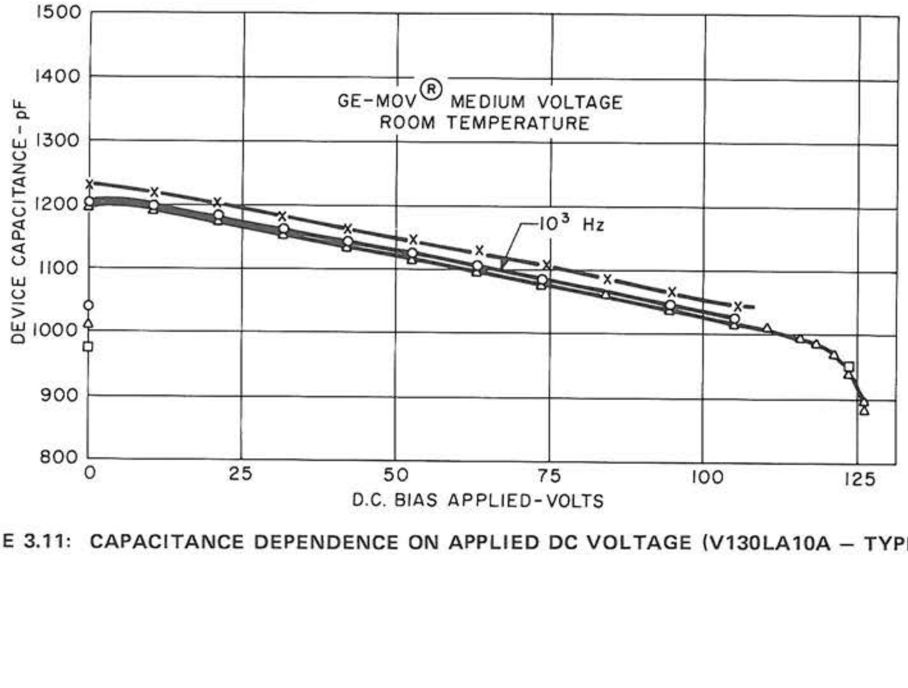


FIGURE 3.11: CAPACITANCE DEPENDENCE ON APPLIED DC VOLTAGE (V130LA10A – TYPICAL)

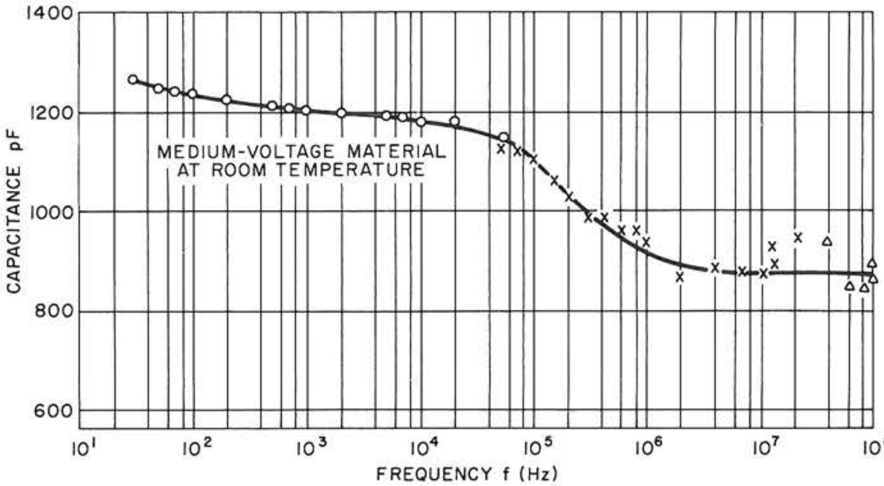


FIGURE 3.12: CAPACITANCE VARIATION WITH FREQUENCY (V130LA10A – TYPICAL)

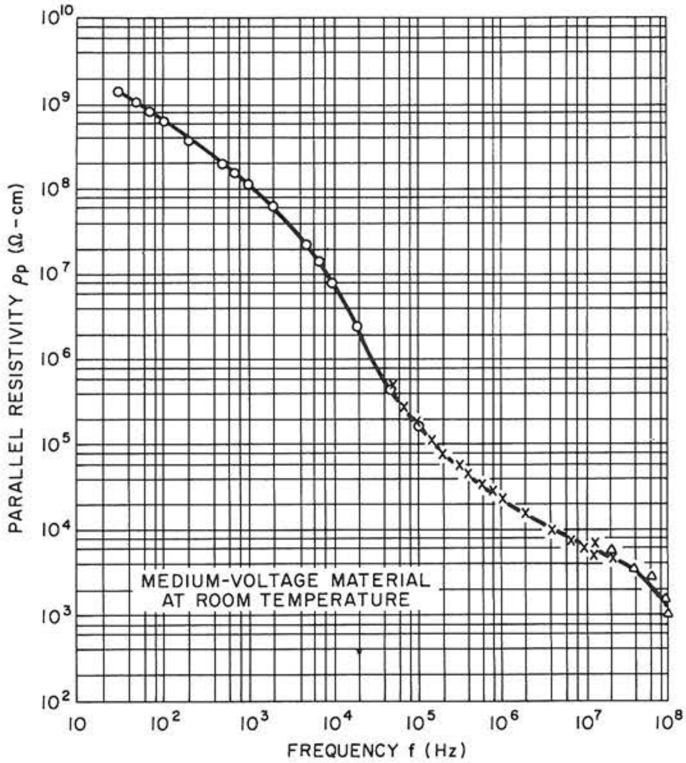


FIGURE 3.13: PARALLEL RESISTANCE VARIATION WITH FREQUENCY

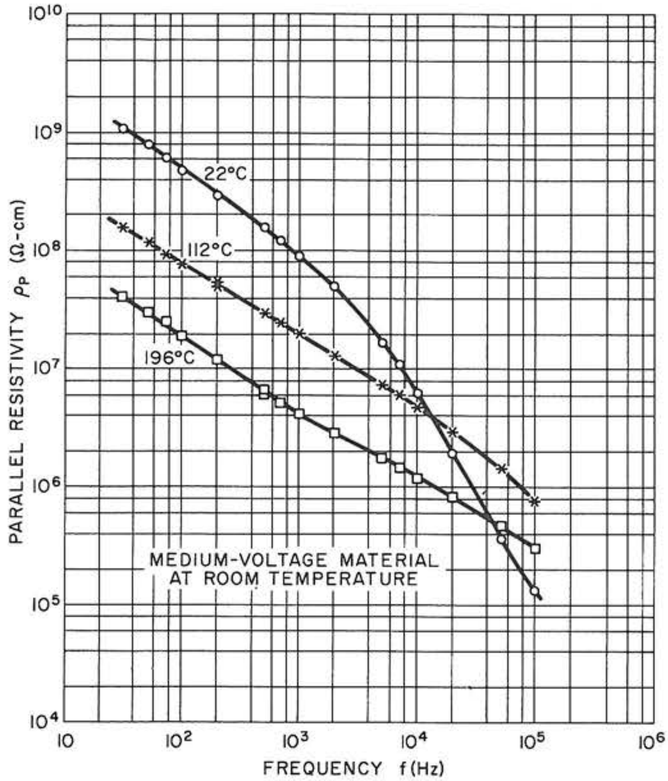


FIGURE 3.14: PARALLEL RESISTANCE VARIATION WITH TEMPERATURE

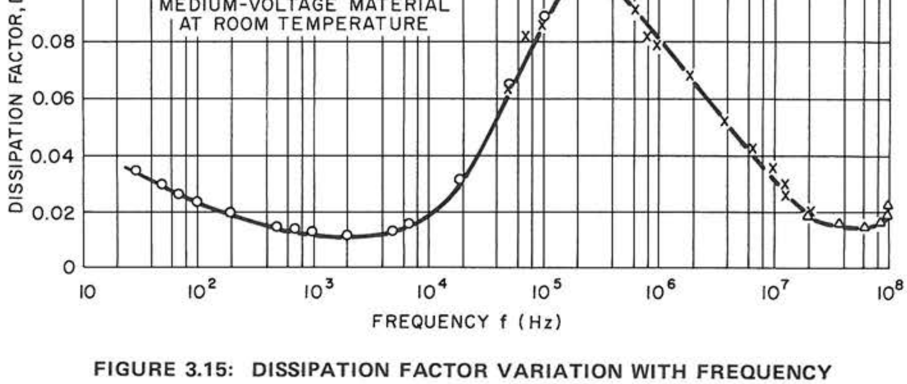


FIGURE 3.15: DISSIPATION FACTOR VARIATION WITH FREQUENCY

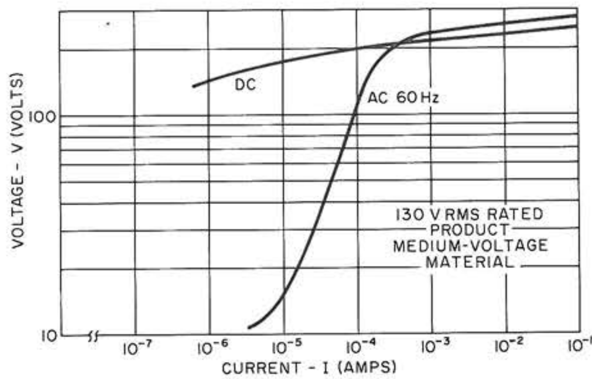


FIGURE 3.16: AC AND DC CHARACTERISTIC CURVES

Equivalent Circuit

An electrical model for the varistor can be represented by the simplified equivalent circuit below.

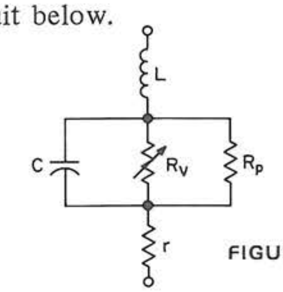


FIGURE 3.17

Appropriations:

R_p = parallel resistance
R_v = non-linear varistor resistance
C = capacity between electrodes
L = lead inductance
r = bulk resistance ~ 1-10 ohms

Varistor Electrical Model

At low currents, in the range of the leakage region, the equivalent circuit can be further simplified. R_v can be ignored because the effect of R_p in parallel will predominate. Also, r, being only a few ohms, will be insignificant compared to R_p.

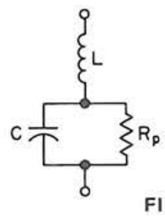


FIGURE 3.18

Equivalent Circuit at low Currents

It is of interest to examine the elements of the varistor model and determine their behavior with frequency, voltage and temperature.

Capacitance

For a given varistor device, capacitance remains approximately constant over a wide range of voltage and frequency. Figure 3.11 shows the capacitance vs. voltage relation. The value of capacitance drops only slightly as voltage is applied to the varistor. As the voltage approaches the nominal varistor voltage, the capacitance abruptly decreases.

Capacitance variation with frequency is plotted in Figure 3.12. Up to 100 KHz capacitance is nearly constant. Above 1 MHz the capacitance curve again flattens to a level value.

Temperature variation is not plotted. Sensitivity to temperature is low, the 25°C value of capacitance being well within ± 10% from -40°C to +125°C.

Parallel Resistance

The varistor appears as an open circuit when the applied voltage is in the leakage region. The value of R_p is very high, but it varies with frequency as shown in Figure 3.13. The relationship is approximately linear with inverse frequency

$$R_p \sim \frac{I}{f}$$

Variation with temperature is plotted in Figure 3.14. R_p drops at higher temperatures, but its resistance is still extremely high and in the range of the room temperature values.

Response of R_p to applied voltage (below nominal varistor voltage) is minimal and, for that reason, is not shown.

Dissipation Factor

In Figure 3.15 the dissipation factor is plotted. The parallel combination R_p and C is predominantly capacitive at any frequency of interest. This is because R_p and capacitive reactance vary approximately linearly with I/f.

Lead Inductance

This can be obtained from the total length of cut lead wire used in the circuit. Lead inductance effects are the same as encountered with disc capacitors. A series resonance will be obtained with the varistor capacitance. With no wire leads the varistor disc will have a small value of self inductance. This has been observed as a resonance above 10^8 Hz.

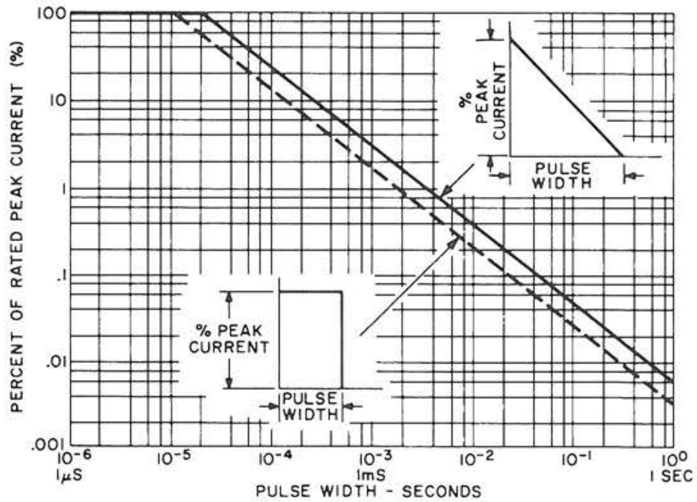


FIGURE 3.19: NON-RECURRENT PEAK CURRENT VS. PULSE WIDTH FOR "L" SERIES VARISTORS

Speed of Response

The varistor depends upon a conduction mechanism similar to solid state, semiconductor devices. For this reason, conduction occurs very rapidly, in the order of 1 nanosecond or less. Measurements in this time interval are difficult. Device capacitance and lead inductance will predominate, so the varistor needs to be examined in disc form. At this time, response below 1 nanosecond has not been evaluated. In any event, it is of academic interest only with respect to a packaged varistor with electrode leads.

It should be noted that the V-I characteristics of the varistor will differ depending on whether DC, AC, or pulses are applied. Partly, this is caused by device C and L, and partly because of inherent device behavior. Figure 3.16 is a plot of the AC V-I response compared with the DC curve. The effect of device capacitance is observed in the lowered voltage at the low current leakage region. At 1 mA and higher, the V-I curve is shifted upward by about 3-6% and is accounted for on varistor specifications. This effect is unexplained and is an inherent characteristic on AC operation.

Overshoot

When the varistor is subjected to a rapidly increasing voltage, the maximum voltage for a given current will exceed the DC value for that current by 3-10% typically. The "worse-case" or maximum voltage V-I characteristic curves published for GE-MOV® Varistors contain an additional allowance for overshoot which is sufficient to include most applications with voltage rates-of-rise of the order of $\leqslant$ 100V/μsec and peak current densities of $\leqslant$ 10A/cm^2. In applications where the

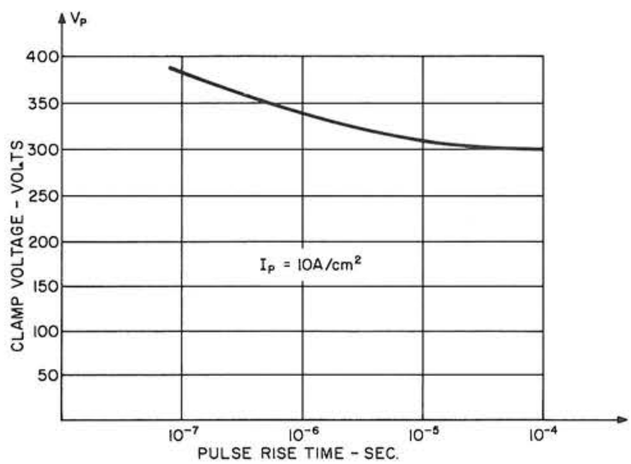


FIGURE 3.20: PULSE RESPONSE CHARACTERISTICS OF CLAMPING VOLTAGE

current density and rates-of-rise exceed these values, the clamping voltage may be as high as 25% above the DC clamping value. Varistor capacitance and the higher impedance of power lines at high frequencies (high dv/dt) tends to reduce the occurrence of this effect, as do voltage snubber circuits and stray capacitances frequently associated with semiconductors and loads. The overshoot effect is illustrated in Figure 3.21 which shows typical clamping voltage variation with rise time for a fixed current level. In general, overshoot is less for longer pulse rise times and lower currents.

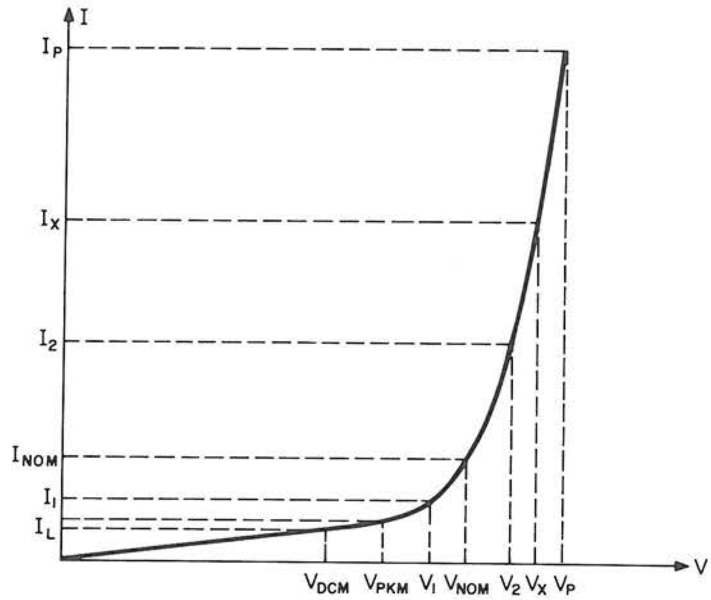


FIGURE 3.21: I-V GRAPH ILLUSTRATING SYMBOLS AND DEFINITIONS

V_X	Varistor voltage at current, I_X.
V_{NOM}	Nominal varistor voltage at specified current, I_{NOM}.
Alpha	Varistor non-linear exponent given by $$\alpha = \frac{\log I_2/I_1}{\log V_2/V_1}$$
V_p	Peak voltage of varistor at peak current, I_p.
R_c	Voltage ratio given by $R_c = V_p/V_X$.
V_{PKM}	Maximum rating of peak applied voltage for a 50-60 Hz sinusoidal waveform.
V_{DCM}	Maximum rating of DC applied voltage.

4. TERMINOLOGY AND RATINGS

A variety of different terms have grown into use through industry practice for non-linear resistance or varistor devices. These terms often reflect the specific interest of the application or the conventional conception of the physics of the device behavior. Although the terminology often may be different, there is, nonetheless, a similarity in the electrical characteristics exhibited by different devices. This section defines a basic set of terms that are generic in their nature, and that are similar to those which commonly appear in manufacturer and user specifications.

Definition of Terms

The defined terms are of two groups. The first group of terms describes the device characteristics. The second group defines those terms which are the maximum allowable ratings of electrical stress which may be applied to the device without the possibility of causing premature degradation or failure of the device.

The relation of these terms on a varistor I-V graph is illustrated in Figure 3.19.

TERMS DESCRIBING VARISTOR CHARACTERISTICS

TERMS	SYMBOL	DESCRIPTION
Varistor Voltage	V_X	Voltage of the varistor measured at a given current value, I_X, denoted by subscript, x.
Nominal Varistor Voltage	V_{NOM}	Voltage which is characteristic of the varistor in the low current non-linear resistance region as measured at a specified DC current pulse, I_{NOM}. This voltage normally is expressed with a tolerance or as a range of values.
Peak Nominal Varistor Voltage	V_{nom}	Like above, except measured at a specified peak AC current, I_{nom}.
Peak Voltage	V_p	Voltage of the varistor measured under conditions of a specified peak pulse current, I_p, and specified waveform. This may be expressed as a maximum for the product model.
Voltage Ratio	R_c	A measure of the varistor large signal non-linearity as defined by: $R_c = \frac{V_P}{V_X}$
Non-linear Exponent	α	A measure of varistor non-linearity between two given operating points, I_1 and I_2, as described by: $I = kV^{\alpha}$ where k is a device constant, $I_1 \leqslant I \leqslant I_2$, and $\alpha = \frac{\log I_2/V_1}{\log V_2/V_1}$
Dynamic Impedance	Z_v	A measure of small-signal non-linearity at a given operating point as defined by: $Z_v = \frac{d\,V_x}{d\,I_x}$
Resistance	R_v	Static resistance of the varistor at a given operating point as defined by: $R_v = \frac{V_x}{I_x}$
AC Idle Power	P_d	Varistor power dissipation measured at maximum rated RMS applied voltage, V_{ACM}, 50-60 Hz.
Leakage Current	I_L	Varistor current measured at 25°C under condition of a DC applied voltage which is equal to the maximum rated value, V_{DCM}, for that product model.

TERMS	SYMBOL	DESCRIPTION
Voltage Overshoot	V_O	Difference between peak voltage of the varistor as observed on a rising transient and varistor voltage, V_x, as observed in steady-state or decay of transient. (**Note**: the maximum peak voltage values shown on GE-MOV® specifications include the voltage overshoot of typical application transients such as 8 x 20 μsec waveforms.)
Percent Voltage Overshoot	$\%V_O$	Difference between V_p and V_x in percent as defined by: $$\%V_O = \frac{(V_p - V_x)}{V_x} 100$$ (**Note**: for typical applications of GE-MOV® Varistors the value of $\%V_O$ is in the range of 3 to 10%.)
Failure		A change greater than ± 10% in V_{NOM} of a GE-MOV® Varistor.
Life		Events required under given ambient and electrical conditions to cause a given statistical level of failure.
Maximum DC Applied Voltage	V_{ACM}	Maximum steady-state DC voltage which may be applied to the varistor by a power source.
Maximum RMS Applied Voltage	V_{ACM}	Maximum steady-state RMS voltage which may be applied to the varistor by a 50-60 Hz sinusoidal AC power source.
Maximum Transient Peak Current	I_{TM}	Maximum non-recurrent peak current from a random transient source which may be passed through the varistor. This current is a function of pulse width and must not exceed the derating curve for the GE-MOV® Varistor model. See Figure 3.20 for an example. For pulse widths greater than shown, the pulse current should be such that the maximum energy rating is not exceeded.
Maximum Transient Energy	W_{TM}	Maximum non-recurrent electrical energy from a random transient source which may be dissipated in the varistor from one or more pulses. If the rating of peak current versus pulse width is observed, the energy rating is satisfied for one pulse.
Maximum Transient Average Power Dissipation	P_{TAM}	Maximum average power which may be dissipated in the varistor by a group of transient pulses.

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CHAPTER IV

DESIGNING WITH GE-MOV® VARISTORS

1. SELECTING THE VARISTOR

The varistor must operate under both a steady-state and transient condition. Ratings are given to ensure the varistor's reliability under both conditions. Characteristics are given to allow proper matching to the rest of the circuit.

Selection is, for most applications, a five-step process:

- Determine the necessary steady-state voltage rating.
- Establish the transient energy absorbed by the varistor.
- Calculate the peak transient current through the varistor.
- Determine any power dissipation requirements.
- Select a model to provide the required voltage-limiting characteristic.

A. Steady-State Voltage Rating:

Consider the maximum steady-state voltage the varistor should ever see; include any high line conditions (i.e., 110% or more of nominal voltage). Ratings are given for sinusoidal AC, pure DC, and non-sinusoidal voltage waveforms.

MAXIMUM RATINGS:

MODEL NUMBER	RMS APPLIED VOLTAGE	RECURRENT PEAK IDLE VOLTAGE	DC APPLIED VOLTAGE	ENERGY*	AVERAGE POWER DISSIPATION	PEAK CURRENT FOR $t_p < 6\ \mu s$

FIGURE 4.1

B. Energy:

This step is not as easy. You need to know or assume the characteristics of your transient source. The energy dissipated in the varistor is calculated as the integral of the instantaneous power dissipation. This can be done graphically. It is rarely worth the effort to do mathematically.[1] Usually a conservative estimate will suffice. Below is an example of such an approximation.

MAXIMUM RATINGS:

MODEL NUMBER	RMS APPLIED VOLTAGE	RECURRENT PEAK IDLE VOLTAGE	DC APPLIED VOLTAGE	ENERGY*	AVERAGE POWER DISSIPATION	PEAK CURRENT FOR $t_p < 6\ \mu s$
	Volts	Volts	Volts	Joules	Watts	Amperes
V130LA10A	130	184	175	10	0.5	1000
V130LA20A				20	0.85	2000
V130LA20B				20	0.85	2000

*Energy capability is slightly dependent upon pulse duration. "Energy" is more accurately given by published maximum current vs. pulse-width curves.

FIGURE 4.2

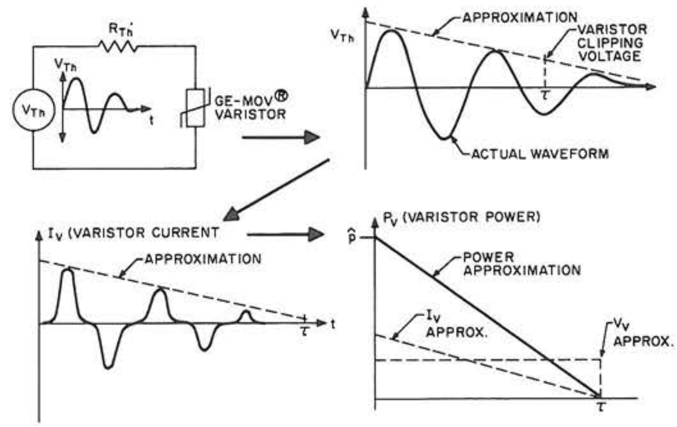


FIGURE 4.3

Energy would then be conservatively given as ½ $\hat{P}T$.

If the source is an inductor alone (that is, the transient current does not circulate through the steady-state power source), varistor energy dissipation can be conservatively assumed to be ½ Li^2, the inductor's stored magnetic energy. This estimate can be refined by calculating coil resistance losses. If the coil, suppressor, and power source form a loop, the power source contributes energy equal to $V_{SS} \int i \, dt$. For this case, an accurate figure is better arrived at by oscillograph and graphical integration of the varistor's instantaneous power.

C. *Peak Current:*

The peak transient current is quickly determined. If the transient is inductor-generated, the peak current will be no more than the inductor's current at the time of switching, and will usually be slightly less (due to parallel loads, stray capacitance, etc.). If the transient is random, a Thevenin equivalent will quickly yield the peak current. (See below.)

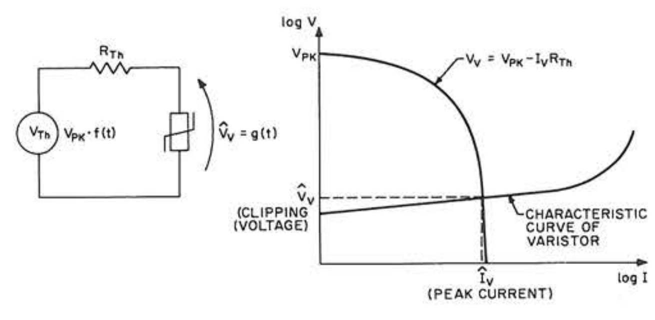


FIGURE 4.4

D. *Power Dissipation Requirements:*

Power dissipation is a measure of how easily heat is transferred from the point of generation to the environment. Since a transient generates heat in a suppressor too quickly to be transferred, power dissipation capability is not necessary for a suppressor unless transients will be occurring in rapid succession. Under this condition, the power dissipation required is simply the energy (watt-seconds) per pulse times the number of pulses per second ($sec.^{-1}$).

E. Clipping ("Clamping") Characteristic Section:

Most models of GE-MOV® Varistors are available with two or three clamping selections, "A" being the standard with "B" and "C" being progressively lower in clamping voltage (that is, the voltage to which the transient is reduced). For example the V130LA___ "Maximum Volt-Ampere Characteristic" reproduced below has two possible selections.

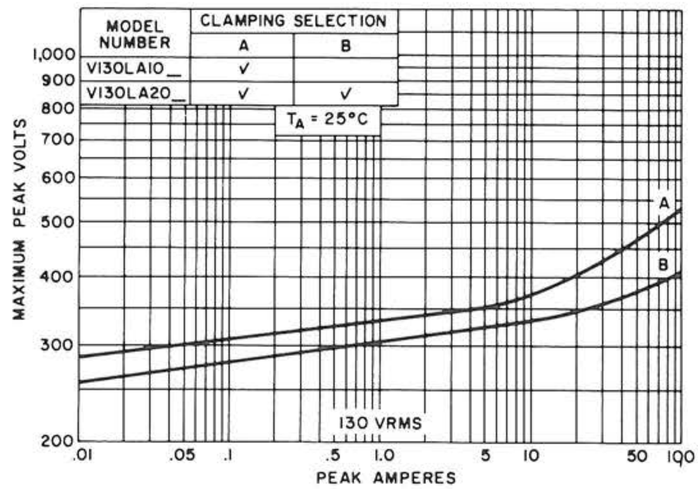


FIGURE 4.5

These characteristics show the *maximum* voltage across that varistor model for a given transient current; that is, the highest voltage characteristic any varistor shipped under that model number will exhibit. The slight dependency of voltage upon current puts us in a quandary: voltage depends on current; but current may well depend on voltage, so just how low will this varistor clip?

If the transient source is an inductor, the current is already established, so there is no problem. If we are using a Thevenin equivalent, however . . .

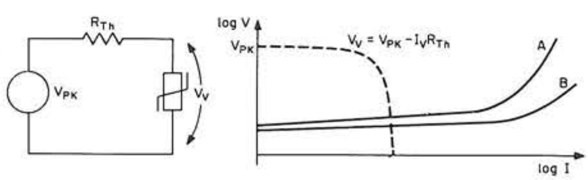


FIGURE 4.6

. . . a curve is drawn according to the loading equation $\hat{V}_v = V_{pk} - I_v R_{th}$, where $\hat{V}_v$ is the peak varistor voltage, V_{pk} is the peak Thevenin transient voltage, I_v is varistor current, and R_{th} is the Thevenin resistance. The intersection of this curve and the varistor characteristic curve gives the peak suppressed transient voltage and the varistor transient current.

This same result can be arrived at by successive approximations. Estimate a clipping voltage, calculate the resulting current; then check the V-I characteristic at that current and revise your estimate of voltage, re-calculate current, etc. Selection of an "A", "B", or "C" type varistor then depends on the transient voltage withstanding capability of your system.

Ratings of energy, power dissipation capability, and occasionally voltage and peak current are dependent upon the ambient temperature. De-rating curves are provided for this purpose. These curves, however, are conservative in that they allow for the varistor to be placed across a "stiff" power source while experiencing rated power, voltage, energy, and current. If the applied steady-state voltage is low or not "stiff," the varistor is capable of somewhat more rugged use. The factory should be consulted for such applications, if the ratings appear inadequate.

2. APPLICATION EXAMPLES

EXAMPLE (A) – Power Supply Protection Against Line Transient Damage

PROBLEM: It is desired to prevent failure of the below power supply, to be used on residential 117 VAC lines. A representative transient generator is to be used for testing, as shown.

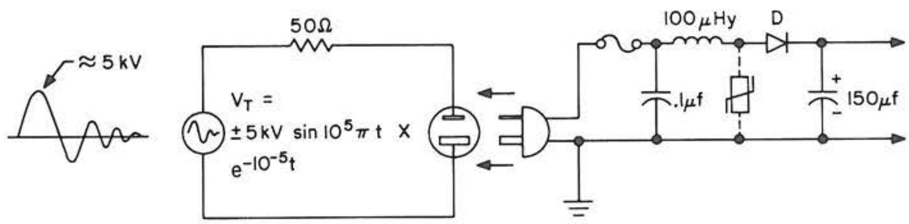


FIGURE 4.7

If the transient is applied to the existing circuit, the rectifier will receive high negative voltages, transmitted through the filter capacitor. The LC network is there to prevent RFI from being transmitted out into the power line (as in a TV set), but also serves to reduce the transient voltage. An approximate analysis shows that the transient will be reduced approximately by half, resulting in about 2.5 kV instead of 5 kV at the plug.

This is still obviously too high for any practical rectifier, so some suppression must be added. It is desirable to use the built-in impedance of the coil to drop the remaining voltage, so the suppressor would best be applied as shown. The selection process for a GE-MOV® Varistor would go as follows:

1) *Steady-State Voltage:* 117 VAC, 110% high line condition is 129 VRMS. The closest higher voltage rating available is 130 V.

2) *Energy & Current:* The 100 μH inductor will look like about 30 ohms to the transient. Taking a first estimate of peak varistor current, 2500 V/30 ohms = 83 A. (This first estimate is high since it assumes varistor clamping voltage is zero.) If we make a tentative selection of a standard-size 130 Volt GE-MOV® Varistor, we find that a current of 83 A yields a voltage of from 400 to 500 Volts, depending on the model (A or B).

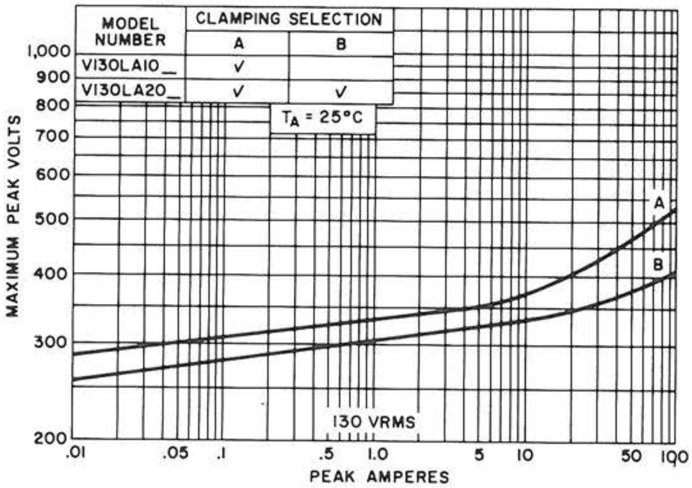


FIGURE 4.8: V130LA__ V-I CURVE

Revising our current estimate, I ≈ (2500V − 400V)/30 Ω = 70 A. For model B, 70 A coincides closely with a 400 Volt clipping level, so there is no need to further refine our estimate of peak current, if model B remains the final selection.

To very conservatively arrive at an energy figure, assume a sawtooth current waveform of 70 A peak, dropping to zero in two time constants, or 20 microseconds.

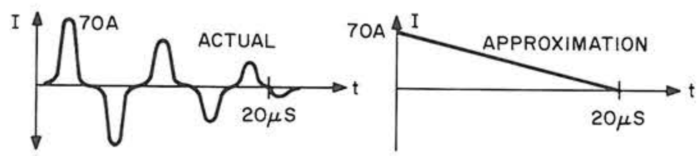


FIGURE 4.9

Energy is then roughly equal to (70 A x 400 V x 20 μsec)/2, the area under the power waveform. Our result is 0.56 Joules, well within the capability of a varistor even smaller than the "B" type (a 20 J varistor). Peak current is also within the 2000 Amp. capability of the "B" type GE-MOV® Varistor, and the 150 Amp. rating of a miniature varistor.

The transient is not repetitive, so we need not be concerned with power dissipation ability.

3) Clamping Selection: If a standard-size varistor is chosen, there are both A and B selections. The miniature varistors are somewhat higher in voltage than the "A" selection. The choice is now economic: is it worth the cost of higher rectifier voltage ratings to choose a less expensive, smaller varistor?

One must also consider the "odds" or probability of rectifier damage. Semiconductors are supplied with a *minimum* voltage rating; devices received may actually be capable of supporting many times the rated steady-state voltage. Additionally, the *transient* voltage withstanding capability of a semiconductor may be well in excess of the steady-state rating. (Occasionally this capability is specified – more often, it is not.) A conservative design, however, will be based upon whatever rating is given.

EXAMPLE (B) – SCR Motor Control

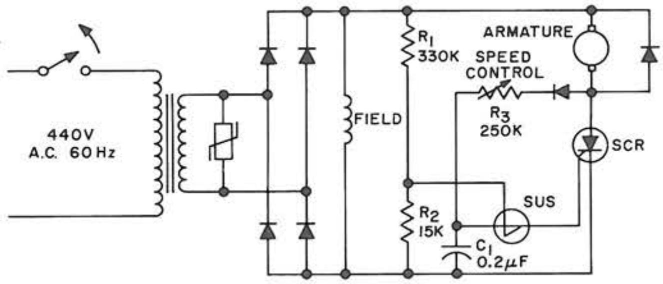


FIGURE 4.10

PROBLEM: The circuit above experiences failures of the rectifiers and SCR when the transformer primary is switched off. The manufacturer has tried 600 volt components with little improvement.

SOLUTION:

(1) Select GE-MOV® Varistor voltage rating: select the lowest voltage GE-MOV® Varistor that is equal to or greater than the maximum high line secondary RMS voltage. The V130LA series fulfills this requirement.

(2) Determine peak suppressed transient voltage due to transient energy source. This in effect means one must determine instantaneous peak transient current of the suppressor, assuming the worst case condition of zero load current. Zero load current is generally a valid assumption, since the dynamic transient impedance of the GE-MOV® Varistor is generally low enough such that the parallel higher impedance load path can be neglected.

Determination of Peak Transient Current

Since transient current is due to the stored energy in the core of the transformer, a brief look at the transformer equivalent circuit as shown in Figure 4.11 will assist in clarifying the transient source. The stored inductive energy is:

$$E_{L_m} = 1/2 L_m \hat{i}_m^{\,2}$$

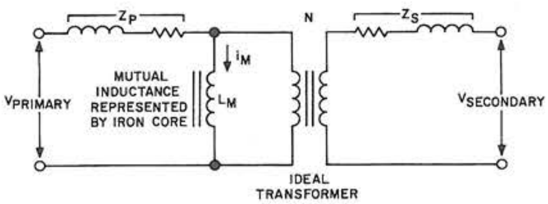


FIGURE 4.11: SIMPLIFIED EQUIVALENT CIRCUIT OF A TRANSFORMER

The designer needs to know both the total energy stored and the peak current transformed in the secondary circuit due to the mutual inductance L_m. At no load the magnetizing or no load current (I_{NL}) is essentially reactive and is equal to i_m. This assumes that the primary copper resistance, leakage reactance and equivalent core resistive loss components are all small compared to L_m. This is generally a valid assumption for all but the smallest control transformers. Since I_{NL} is assumed purely reactive, then:

$$X_{LM} = \frac{V_{pri}}{I_{NL}}$$

$$\text{and } i_m = I_{NL}$$

I_{NL} can often be determined from name plate data. Where name plate data is not available, Figures 4.12 and 4.13 can act as a guide to the designer.

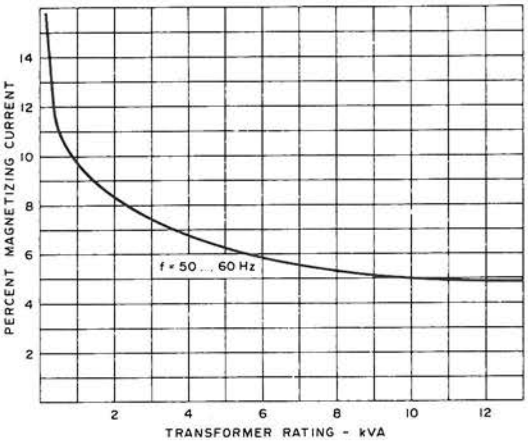


FIGURE 4.12: MAGNETIZING CURRENT OF TRANSFORMERS HAVING SOFT, LOW SILICON STEEL CORE LAMINATIONS.

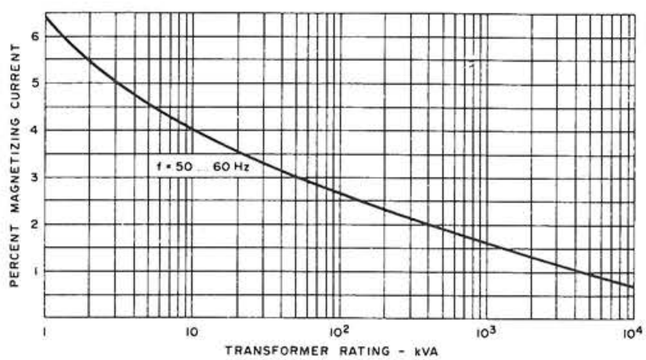


FIGURE 4.13: MAGNETIZING CURRENT OF TRANSFORMERS HAVING COLD ROLLED, HIGH SILICON STEEL & HIGH PERMEABILITY SQUARE LOOP CORE LAMINATIONS.

Assuming an 8% value of magnetizing current, taken from name plate data, the example numerical values follow.

$$i_m = (0.08)\ \frac{20\ \text{KVA}}{480\text{V}}$$

$$= 3.33 \text{ amperes}$$

$$i_m = \sqrt{2}\ i_m$$

$$= 4.7 \text{ amperes}$$

$$X_{L_m} = 480\ \text{V}/3.33 \text{ amperes}$$

$$= 144 \text{ ohms}$$

$$L_m = X_{L_m}/\omega$$

$$= 0.38 \text{ henry}$$

$$E_{L_m} = \frac{0.38\ (4.7)^2}{2}$$

$$= 4.2 \text{ Joules}$$

From this one can select the needed semiconductor voltage ratings and the required varistor energy rating.

Semiconductor Blocking Voltage Ratings Required

Peak varistor current is equal to transformed secondary magnetizing current, i.e., i_m (I/N) or 18.8 amperes. From Figure 4.8, peak suppressed transient voltage is 350 volts with the A selection, 320 volts with the B selection. This allows the use of 300 volt repetitive rated semiconductors with a non-repetitive rating of 400 volts.

Safety margins exist in the above approach due to the following assumptions made.

(1) All of the energy available in the mutual inductance is transferred to the varistor. Actually due to core hysteresis and secondary winding capacitance only a fraction, generally less than two-thirds, is available.

(2) The exciting current is not purely reactive and thus there is a 10% to 20% safety margin in the peak current assumption.

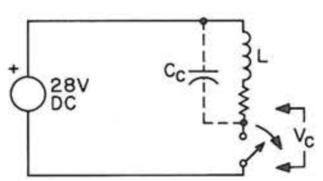
Note that for large transformers the choice of no-load current is particularly important. Since a five to one difference makes a proportionally large difference in energy stored. When the transformer size is in question, estimates have to be made based on type of equipment and common practice used in the field of use.

After determining voltage and peak current, energy and power dissipation requirements must be checked. For the given example, the single pulse energy is well below the V130LA10A varistor rating of 10 Joules at 85°C maximum ambient temperature. Average power dissipation requirements over and above idling power is not needed due to the non-repetitive nature of the expected transient. Should the transient be repetitive in nature, then the average power is calculated from the product of the repetition rate of the transient times the energy of the transient. Should this value exceed the V130LA10A capability of 0.5 watts, the next larger size varistor, the V130LA20A with a 0.85 watt rating would be indicated. For still higher power ratings, power varistors are available with ratings up to 15 watts. Paralleling requires specially matched units and is generally not recommended.

Should the ambient temperature exceed 85°C or the surface temperature exceed 85°C due to high ambient temperature and/or power dissipation, both the single pulse energy ratings and the average power ratings must be derated from data sheet values by the appropriate derating factors supplied on Page 94, Figure 18.

EXAMPLE (C) – Contact Arcing Due to Inductive Load

When relays or mechanical switches are used to control inductive loads, it is necessary to use the contacts at only about 50% of their resistive load current rating to reduce the wear caused by arcing of the contacts. The energy in the arcing is proportional to the inductance and to the square of the current, but inversely proportional to the resistive component of the inductive load.



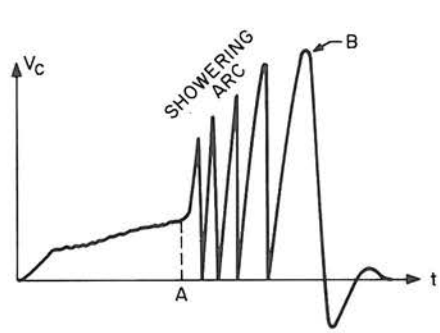


FIGURE 4.14

PROBLEM:

In the preceding circuit example (Figure 4.14), the switch contacts are conducting about 1A of current before opening. The contacts are silver, which will draw an arc upon opening with more than approximately 0.4A and 12 volts. The arc continues until current falls below 0.4A. The inductor, of course, pumps current until completely de-energized.

When the arc extinguishes (point A), the inductor charges up the stray capacitance of its windings and associated wiring until the contact atmosphere (a combination of air and silver ions) breaks down. If the gas is mostly air, this will occur near 300 volts. The capacitance then discharges through the arc. The inductor keeps re-charging the capacitance, which discharges at successively higher voltages as the electrodes separate.

Eventually (point B), the inductor has insufficient energy to charge the capacitance to a voltage high enough to arc across the contacts, and the inductor oscillates with its capacitance until the remaining energy has been dissipated in the coil resistance.

SOLUTION:

To prevent initiation of the arc, it is necessary to reduce the current and voltage of the contacts below the arc threshold levels at the time of opening, and then keep them below the ever-increasing breakdown threshold of the contacts as they open. The obvious approach is to parallel the contacts with a capacitor sufficiently large to conduct the inductor current with a voltage rate-of-rise tracking the breakdown voltage of the contacts. The drawbacks of this approach are the size and cost of the capacitor (especially for high $\frac{1}{2}Li^2$), the passing of AC current, and the creation of substantial in-rush current through the contacts when closed again. This in-rush can be reduced with a resistor in series with the capacitor, but at the expense of network effectiveness during suppression.

A second approach is to put a voltage limiting device across the contacts, such that current is bypassed at a voltage less than breakdown. This is feasible only if the contact breakdown voltage is higher than the supply voltage, since the suppressor should not conduct at steady-state voltages. Otherwise, some low-voltage arcing will occur.

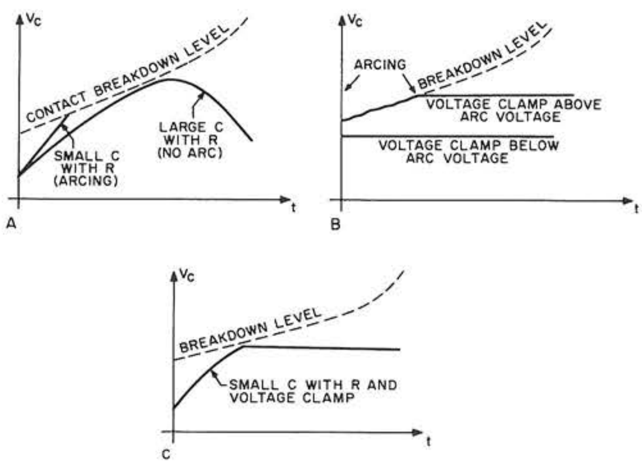


FIGURE 4.15

The third, or combinational approach, is to parallel a voltage clamp and RC network, allowing the RC network to prevent low voltage arcing, and the clamp to prevent high voltage arcs. This allows for a smaller capacitor.

Of course, as ever, any coil suppression will affect dropout time of the coil.

In this example, it's found that a 0.22 μF capacitor and 10 ohm resistor will suppress arcing completely, but by reducing C to 0.047 μF, arcing will start at 65 volts.

Placing only a GE-MOV® Varistor rated for 31 VDC across the contacts results in arcing up to the 65 volt level. By combining the two, the capacitor size and voltage rating are reduced and suppression is complete. The varistor, alone, could be used if the remaining arc is sufficiently brief.

Varistor energy is best determined by observation, but can be estimated by an AC measurement of the coil to determine inductance, and $\frac{1}{2}Li^2$ calculated. Peak current, of course, is under 1 ampere. Power dissipation is negligible unless the coil is switched often (several times per minute).

EXAMPLE (D) – **Noise Suppression**

Noise in an electromechanical system is most frequently a result of the high-voltage discharge of an arcing switch. While the low-voltage continuous arc creates considerable RFI (radio-frequency interference), this disturbance has a moderate rate-of-rise and amplitude. When the high-voltage "showering" discharge occurs, the effect is not unlike repeatedly discharging a capacitor into the power line. This creates high-voltage pulses with rise times into the nanoseconds which travel in both directions down the line. These pulses are practically undetectable, except that they cause noise problems on adjacent lines, trigger SCR's and triacs by dV/dt and breakover, and may damage semiconductors.

Placing a voltage limiting device across the coil or contacts will either prevent such noise by preventing arcing, as previously described, or will at least limit the amplitude of the pulses. One might attempt to suppress the transient with a suppressor on the power line; unfortunately, the inductance associated with such a technique often limits its effectiveness. If the power wires are physically close (a few inches or less) a small capacitor may be effective in reducing these pulses.

EXAMPLE (E) – **Protection of Transistors Switching Inductive Loads**

PROBLEM:

The transistor in the circuit below is to operate a solenoid. It could be called upon to operate as fast as once per second. The circuit (without any suppression) consistently damages the transistor.

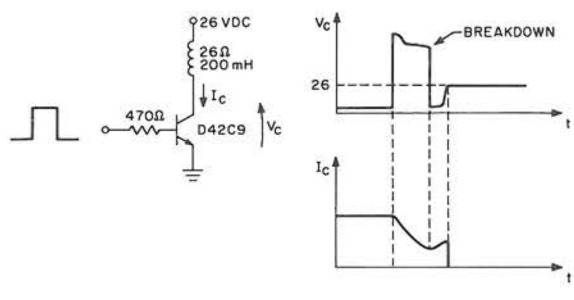


FIGURE 4.16

The inductor drives the collector voltage up until breakdown occurs when the transistor base is grounded (turning "off"). The inductor forces current to flow until the energy stored in its field is dissipated. This energy is dissipated in the reverse bias condition of the transistor and is sufficient to cause breakdown (indicated by the sudden collapse of collector voltage during the pulse).

SOLUTION:

This condition can be eliminated in two ways: either by shunting the transistor with a suppressor or by turning it on with a varistor connected collector-to-base. The first method will considerably reduce the demands upon the safe-operating area (SOA) of the transistor, if the voltage is kept below its breakdown level. All energy will be dissipated in the suppressor. The latter method will cause the transistor to once again dissipate the stored energy, but in the forward-bias or active state in which the transistor can safely dissipate limited amounts of energy. The choice is determined by economics and reliability. A suppressor connected collector-emitter (C-E) will be more expensive than one connected C-B, but will allow the use of a transistor with a smaller SOA, or will produce higher reliability of the larger transistor.

If a collector-emitter GE-MOV® Varistor is used in the above example, the varistor is required to withstand 26 volts DC. The stored energy is $\frac{1}{2}Li^2$, or $\frac{1}{2}(0.200)(1)^2 = 0.1J$. The energy contributed by the power supply is roughly equal to this (coil voltage ≈ supply voltage, since varistor clipping voltage ≈ 2 x supply voltage), so ignoring coil resistance losses for a conservative estimate, varistor energy dissipation is 0.2 J per pulse. The peak current will be one ampere, the same as the coil current when the transistor is switched off.

If the transistor operates once per second, the average power dissipation in the varistor will be 0.2 J x 1 sec^{-1}, or 0.2 W. This is greater than the 0.19 W rating of a small 26 VDC GE-MOV® Varistor (V33ZA1), so the larger, 0.4 W version (V33ZA5) should be used. According to the derating tables, the ambient temperature should not exceed 70°C under these conditions. (The nonrecurrent energy rating of this device is 5J, 25 times the recurrent energy requirement.)

The clipping characteristic of the selected model will provide a 55 volt maximum peak. The transistor should have a 55 volt or greater V_{CER} for this application.

If the collector-base connection is preferred, current, energy and power requirements can be found by simply dividing the collector-emitter device requirements by the minimum gain of the output with the 470 ohm resistor from base to ground.

EXAMPLE (F) – Threshold Detection for High-Voltage Shutdown

Occasionally it is possible for a power supply to generate excessively high voltage, perhaps if a load is removed accidentally, which can damage the rest of the circuit. A simple safeguard is to crowbar or short out the supply with an SCR. To provide the triggering to the SCR, a high-voltage detector is needed; high voltage avalanche diodes are effective, but expensive. An axial leaded GE-MOV® Varistor provides an effective, inexpensive replacement.

In the circuit below, it is found that without protection, the voltage can exceed twice the normal 240 volt peaks, damaging components downstream. A simple circuit to crowbar the supply is shown below.

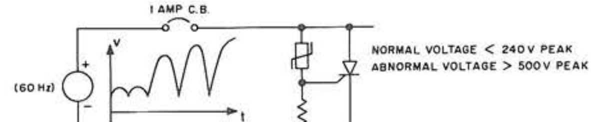


FIGURE 4.17

The supply shown can provide 2A RMS of short-circuit current and has a 1-ampere circuit-breaker. The SCR has a 4-ampere capability; to trigger it will require at least 0.2 volts gate-to-cathode, and no more than 2.0 volts and 25 mA at 25°C ambient.

Checking the MA Series GE-MOV® Varistor specifications (the least expensive) for a device capable of supporting 240 volts peak, one finds that the V270MA4B can handle 242 volts.

Since, according to its spec. of 1mA at 270 volts ± 10%, the V270MA4B will conduct 1mA DC at no less than 243 volts, the gate-cathode resistor can be chosen to provide 0.2 volts (the minimum trigger voltage) at 1mA, and the SCR will not trigger below 243 volts. Therefore, R_{GK} should be 220 ohms, ± 10%.

The maximum voltage to trigger the circuit is dependent upon the maximum current the varistor is required to pass to trigger the SCR. This condition occurs with an SCR requiring 2.0 volts and 25mA. At 2.0 volts, R_{GK} draws 10mA or less; the varistor must, therefore, pass 35mA of peak current. According to the spec. sheet, the varistor voltage will not exceed 380 volts with this current. The circuit will, therefore, trigger at between 243 and 382 volts peak, and a 400 volt rated SCR can be used.

Application Note 201.28 can then be used to determine that the maximum energy per pulse with this waveform will not exceed approximately $\frac{I}{2}$ x 0.15 x V_{pk} x V_{pk} x T (duration of $\frac{I}{2}$wave pulse), or 8.2 mJ for this example. Since the voltage does not drop to zero in this case, the SCR remains on, and the varistor sees only one pulse; there is, therefore, no steady-state power consideration.

3. SUPPRESSION TECHNIQUES

A. *Using Available Impedance*

When protecting against random transients appearing on a power line, it is desirable to have as much impedance as possible between the transient source and the affected component. Frequently, the load can be used when protecting a switching element by placing the suppressor around the element. Loads such as motors and solenoids are especially effective due to their inductance. Capacitive or incandescent loads rarely exhibit enough impedance to be useful.

Care should be taken, however, to insure that the load will not, itself, be damaged by the voltage dropped across it, and that an apparently inductive load does not have a large stray capacitance which will pass the transient.

B. *"Staging" and Combination*

Suppressors can be combined with themselves or other devices to gain advantages or ruggedness, speed and clipping level. For example, two identical suppressors can be applied across a line with impedance between them to decrease clipping voltage. The first suppressor takes the brunt of the transient, using the inherent impedance of the transient to drop the voltage. The second then

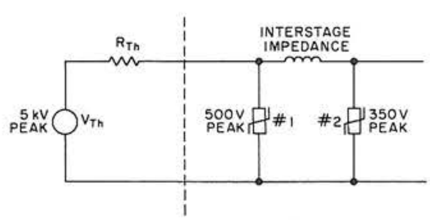


FIGURE 4.18

needs only to drop a small voltage across a small added impedance. Because the first, or primary suppressor does most of the work, the secondary device can be smaller and less rugged. (For example, a gas-discharge tube could be used for the primary and a small GE-MOV® Varistor for the secondary suppressor.)

Care must be taken when secondary devices have an inherently lower clipping characteristic than the primary, or else the secondary will be destroyed before the primary sees enough voltage to conduct. Good characterization of the transient waveform and conservative selection of the interstage impedance will insure proper performance.

For example, consider the GE-MOV® Varistor, Resistor and Zener Diode network of Figure 4.18. This simple circuit is capable of reducing a 100 ampere surge to 50 volts on a 40 volt DC line with an inexpensive varistor and zener diode. To use a zener diode alone might cost several times as much.

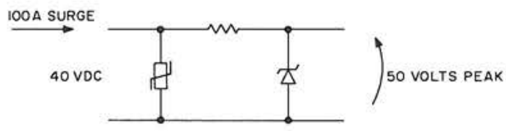


FIGURE 4.19

The V56ZA8 can withstand 100 amperes for 100 microseconds, clamping the surge to 120 volts or less. The 50 volt "5 watt" zener is found to withstand a surge of about 5 amperes for the same time period; therefore, to limit the zener current to 5 amperes, a resistor of (120V – 50V)/5A, or about 15 ohms must be used.

Similar techniques can be used with other components, such as GDT's and varistors, in combination.

It is tempting to consider using suppressors in parallel to achieve more ruggedness, but since "identical" suppressors have a specified tolerance in their characteristics, they should not be paralleled without some interstage impedance lest one of them do all the work.

Seriesing of GE-MOV® Varistors and other constant voltage devices is useful to achieve nonstandard voltage ratings and increase energy-handling ability. There is no problem with this, since the applied voltage shares well. Energy shares according to the breakdown voltage of each.

CHAPTER V

GE-MOV® VARISTOR RELIABILITY AND TESTING

1. RELIABILITY

The GE-MOV® Varistor is a rugged suppressor capable of improving system reliability without causing reliability problems of its own. To insure this, considerable device hours have been accumulated with accelerating stress applied. (Due to the increasing interest in highly recurrent pulse applications, pulse life data is presently being acquired.)

Test Conditions:

GE-MOV® Varistor reliability prediction tests consist of AC 60 Hz bias for mid-volt (95-1000V RMS); LA, LB and PA Series) and, currently, DC bias for low-volt product (20-105V DC).

130V RMS rated devices (10 and 20 Joule) are selected from mid-volt production lots and placed on test at 130V AC (50-60 Hz) at an ambient temperature of 100°C. (This constitutes an accelerated stress in that 130V RMS rated devices are typically used on 117 volt nominal line 10% below the varistor rating. Furthermore, the ambient temperature is 15°C above the maximum rated ambient temperature without derating.)

Low voltage product is evaluated using the V68ZA2 or V68ZA10 devices at the rated 56V DC and 85°C ambient. (These devices are typically operated at 48V DC nominal voltage.) Samples are also occasionally selected from V33ZA1 and V33ZA5 product and tested at the rated 26V DC and 85°C conditions. V68ZA2 devices have also been tested at 40V AC and 85°C (maximum rated AC conditions).

The results of the above tests are included in this section. The time span covered was from May, 1973 to June, 1975 and includes products made at both domestic and offshore plants.

Test Results:

(A summary of reliability test results is shown in Figure 5.1.)

Failures are classified into two categories – *degradation* and *catastrophic.* A *degradation failure* is defined as a device exhibiting a shift in the varistor voltage at 1 milliampere (V_1) in excess of ± 10% of the initial varistor V_1 value. The failure is normally a result of a decreasing V_1 value, and the minimum limit (90% V_1 initial) is slightly over the V_1 that might cause the device to draw excessive current and go into thermal runaway under normal operating voltage. A *catastrophic failure* is a device that develops an open or a short while on load life test. In the time frame specified (5/73 to 6/75) there have been no catastrophic failures. (No effort has been made to isolate the device from random line transients, but devices are fused for reasons explained later.)

From Figure 5.1, on the following page, the best estimate mean life for the mid-volt product is 450,000 hours (the reciprocal of .22%/K hours at 100°C. Using an Arrhenius relationship, it may be projected that at an operating ambient of about 40°C the best estimate mean life would be 40 x 10^6 hours.

Likewise, using the best estimate mean life for the low-volt product, or 220,000 hours at 85°C, the Arrhenius relationship for that product predicts a mean life of 7 x 10^6 hours at a 40°C ambient.

DEVICE TYPE AND STRESS LEVEL	DEVICE HOURS	DEGRADATION $V_1 > \pm 10\%$	OBSERVED FAILURE RATE	BEST EST. (λ .5)	90% CONF. (λ .9)
V130LA10A and LA20A: 130V AC, 100°C	1,660,000	3	.18%/khrs	.22%/khrs	.40%/khrs
V68ZA2/10A: 40V AC, 85°C	150,000	0	0%	.47%	1.53%
V68ZA2/10A and V33ZA1/5A: 56V DC, 85°C 26V DC, 85°C	450,000	2	:44	.59%	1.17%
Total Low Volt (V33 & V68ZA)	600,000	2	.33%	.45%	.88%
Total	2,260,000	5	.22%	.25%	.41%
V220MA2A[1]: 130V, 100°C	389,000	1	.26	.43%	1.0%
Total GE-MOV®	2,649,000	6	.23	.25%	.40%

[1]M.A. = Molded Body with Axial Leads.

FIGURE 5.1: GE-MOV® ACCELERATED LIFE TEST SUMMARY

Stability, Failure Modes and Causes:

The stability of leakage current and varistor V_1 voltage throughout the accelerated stress period is shown in Figures 5.2 and 5.3, respectively, for mid-volt product and Figures 5.4 and 5.5 for low-volt product.

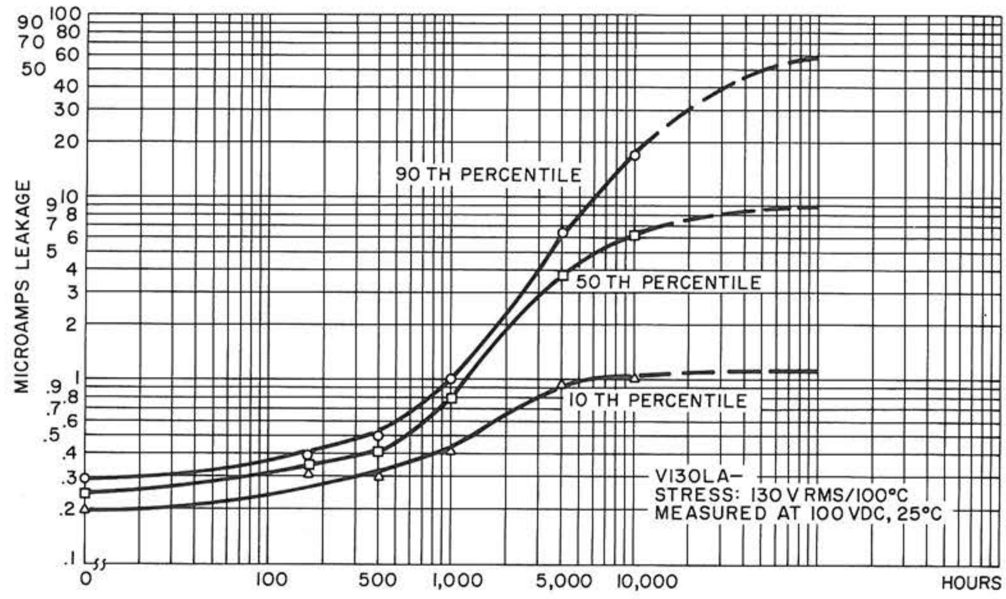


FIGURE 5.2: LEAKAGE CURRENT

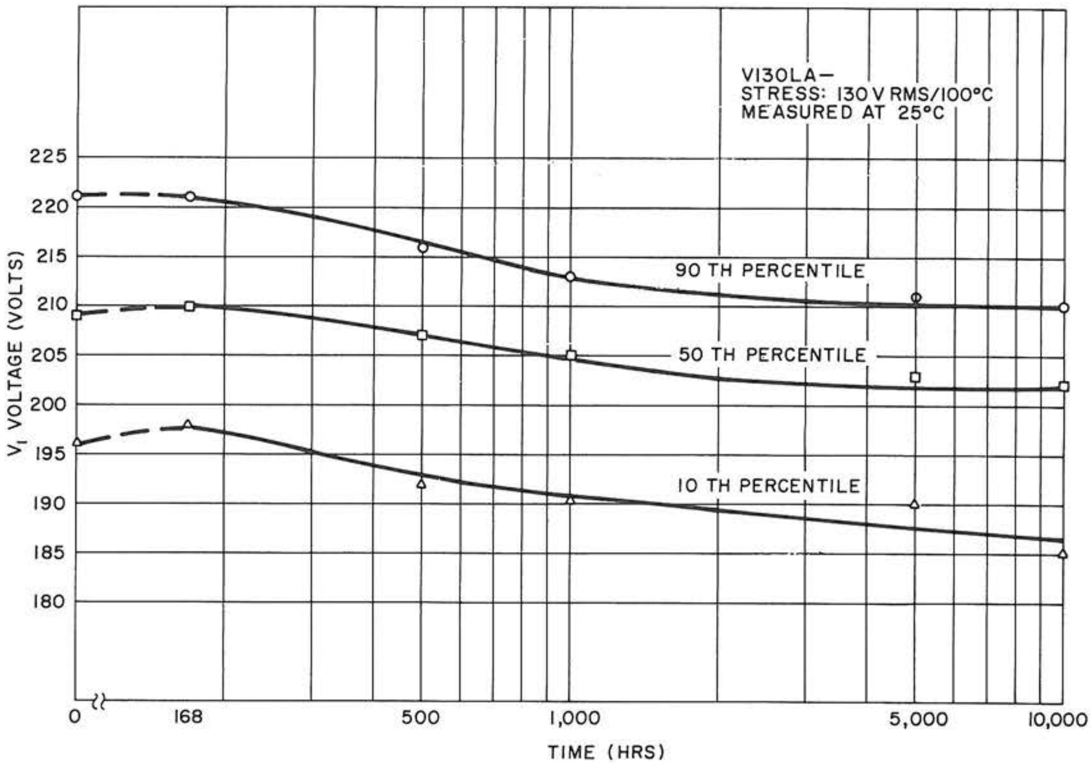


FIGURE 5.3: VOLTAGE STABILITY

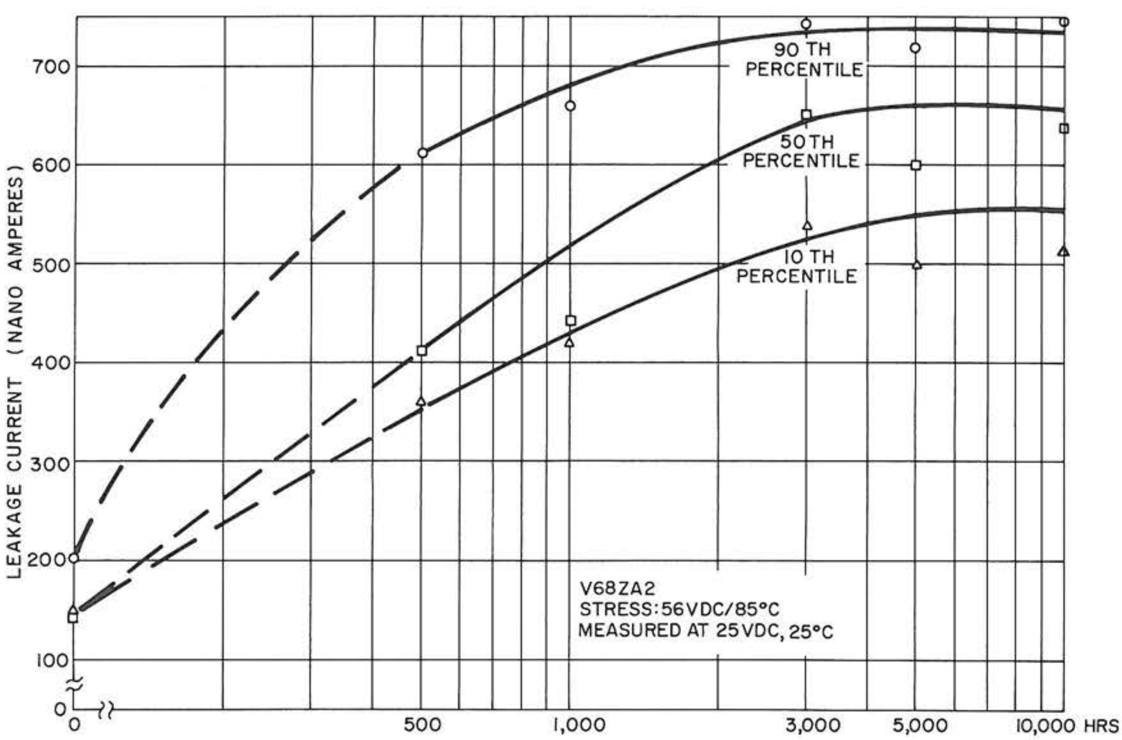


FIGURE 5.4: LEAKAGE CURRENT

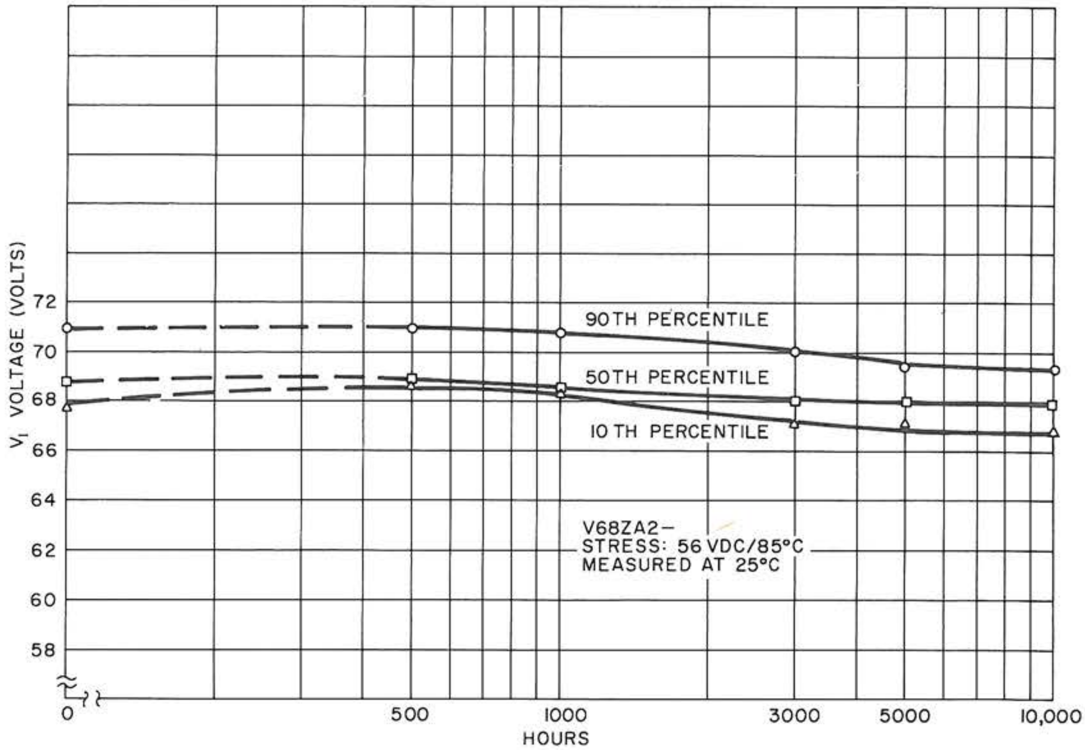


FIGURE 5.5: VOLTAGE STABILITY

Typical leakage currents for mid-volt product prior to accelerated life testing are less than 500 x 10^{-9} amperes. Typically, a varistor will then exhibit minor V_1 instability between 0 and 100 life hours with the V_1 voltage increasing perhaps 2%. By 200 hours of life the V_1 has returned to or below its original value and will remain stable to less than a 5% downshift to 10,000 hours.

The low voltage product behaves in a very similar manner; however, this product has not been in existence long enough to accumulate 10,000 hours of life test results. It is expected that the leakage current will level off at something less than 1 microampere and V_1 voltage will stabilize at 95% to 98% of initial V_1. The curves of Figures 5.4 and 5.5 are actual device performance plots representative of the sample.

2. FAILURE CHARACTERISTICS AND SAFETY

Failure may be defined as being of a degradation or catastrophic nature, as previously described. That is, the occurrence of a gradual shift in breakdown voltage approaching the point of thermal runaway, or a sudden transition to a low resistance (<20 Ohms) or short (<1 Ohm) condition.

There are two possible sequences of events leading to a failure; overstress near ratings or overstress greatly exceeding ratings. These sequences are described, as follows:

(1) Overstress Near Ratings:

When the transient (peak current or energy) or steady-state (voltage or power) ratings are marginally exceeded, leakage current will increase and not stabilize; breakdown voltage will decrease in a similar manner. If the varistor is connected to a low impedance power line of a voltage near the varistor rating, the varistor will ultimately go into thermal runaway. "Catastrophic" damage occurs as the device draws high current and experiences high localized heating from supply line power. The metal oxide ceramic may melt and puncture as a result; concurrently, the heat may decompose, crack and possibly char the epoxy coating. The coating is made from a self-extinguishing material as defined by UL490. Accordingly, and in keeping with good safety practices, the varistor should be placed following the equipment fuse, as should all other components of the system to minimize the effects of heating resulting from failure of an overstressed component. In the event of a marginally overstressed varistor, as described above, the fuse may even clear before the varistor reaches a low resistance or shorted condition, depending on the ratings of the fuse (or circuit breaker).

(2) Extreme Overstress:

Applying conditions well in excess of either transient or steady-state ratings will cause the varistor to fail catastrophically and immediately. The ceramic varistor material will short with a subsequent puncture or shattering. Fusing will minimize this damage, but will not prevent varistor destruction, unless the fuse ampere-time clearing characteristic is coordinated with the peak current versus pulse width curve of the varistor.

GE-MOV® Varistors have received listing under an Underwriters' Laboratories, Inc. standard for across-the-line components, UL E56529, *"Component-Radio and TV Receiving Appliances, Accessories."*

3. TESTING PROCEDURES AND EQUIPMENT

Methods of testing the various characteristics of a GE-MOV® Varistor are often of interest to the user who wishes to insure that received devices are within specifications, or to check for degradation.

A device characteristic is an inherent and measureable property that can be expressed as a value for stated or recognized conditions. It may also be a set of related values, usually shown in graphical form. A device rating, on the other hand, is a value that establishes either a limiting capability or condition for the device. It is determined for specified values of environment and operation, and may be stated in any suitable terms.

Tests on varistors may check against specification such characteristics as nominal varistor voltage, peak voltage, alpha, capacitance and transient suppression, as well as acceptability on the basis of voltage, current and energy ratings. Since the GE-MOV® Varistor has a temperature coefficient, this must be considered when tests and measurements are made.

Nominal Varistor Voltage (V_{NOM}):

The nominal voltage is the DC or AC peak voltage for a specified current from a DC or 50-60 Hz source. This voltage may be readily measured using: 1) current-voltage curve tracer, such as the Tektronix[1] Model 576 or 577; 2) a programmable DC current source, such as the HP6186B (Hewlett-Packard)[2] with a digital voltmeter, such as the Fluke 8000. To insure consistent measurement, it should be noted that the voltage for a particular current decreases with current duration.

Figure 5.6 shows plots of varistor current i(t) and voltage v(t) immediately following connecting a GE-MOV® Varistor to an essentially constant-current DC supply. The voltage is seen to decrease with time for constant current, mostly occurring during the time interval of tens of milliseconds. Figure 5.7 shows constant-current DC varistor voltage versus time characteristics of the varistor of Figure 5.6 for an expanded voltage scale and for each of several time scales. From these characteristics, a voltage decrease of several percent is seen to occur over a time interval on the order of seconds, with the major change taking place within 10 milliseconds. Consequently, DC varistor voltages should be measured after 20 milliseconds. With AC applied, the current-time waveform now will show a series of nearly sinusoidal pulses superimposed on a capacitative sinusoidal current slightly out of phase. The peak varistor voltage will be observed to increase during the first few cycles. It is, therefore, essential to measure AC peak voltage in steady-state.

Leakage Current, Power Dissipation, and Applied Voltage Ratings:

GE-MOV® Varistor voltage specifications include the maximum RMS applied voltage rating, the maximum recurrent peak applied voltage rating, and the maximum DC applied voltage rating. These steady-state ratings should not be exceeded in operation under high line voltage conditions or during device life tests.

RMS And Recurrent Peak Applied Voltage Ratings (V_{ACM}, V_{PKM}):

A sinusoidal input voltage being presumed, the recurrent peak applied voltage rating is larger by $\sqrt{2}$ than the RMS rating. The peak voltage rating is also used for non-sinusoidal voltage waveforms. Voltage ratings are determined by the steady-state power input, referred to as the AC idle power, P_d. The P_d characteristic is appropriately measured at the rated voltage, V_{ACM}.

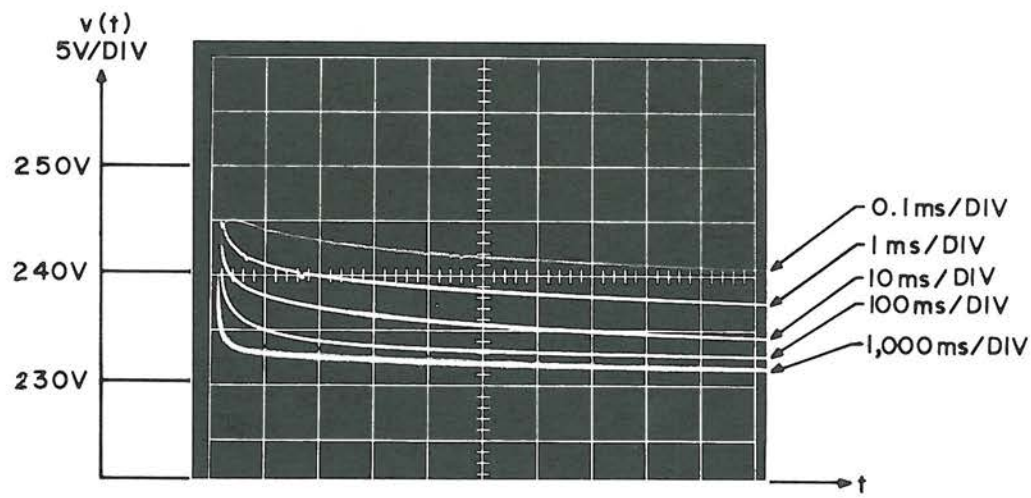


FIGURE 5.6: VOLTAGE-TIME v(t) CHARACTERISTICS OF A GE-MOV® VARISTOR (V130LA10) OPERATING AT A CONSTANT DC CURRENT OF 1.0 mA.

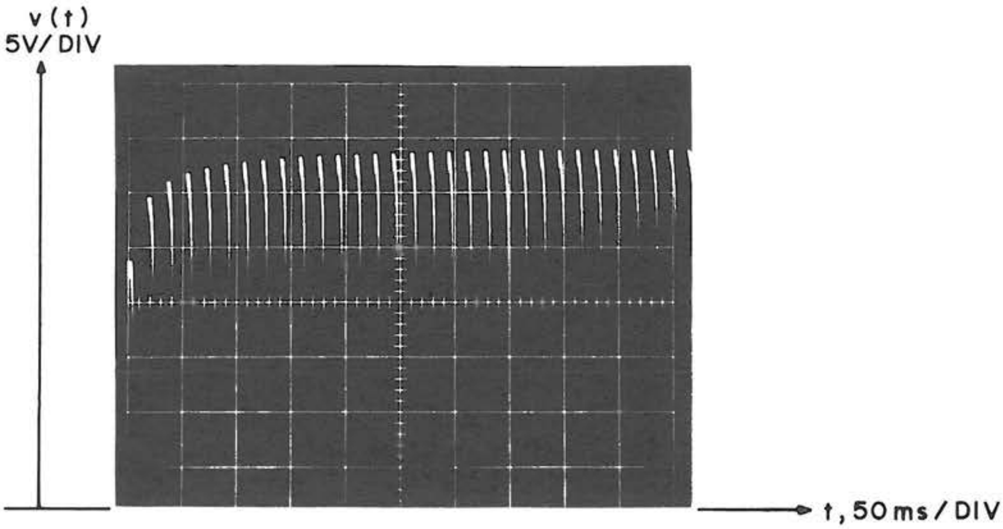


FIGURE 5.7: (V130LA10) VARISTOR VOLTAGE FOR THE INITIAL CYCLES OF 60 Hz OPERATION AT A PEAK CURRENT OF 1.0 mA.

DC Applied Voltage Rating (V_{DCM}):

Like other voltage ratings, the DC voltage rating is determined by its idle power, which is much less than the average power rating. However, the DC voltage ratings are usually lower than the recurrent peak-voltage ratings, because the idle power for a constant applied voltage is larger than that for a sinusoidal voltage of the same amplitude. Leakage current, I_L, is usually measured with the maximum rated voltage, V_{DCM}, applied to the varistor.

Peak Voltage and Alpha Determination:

The determination of the maximum peak voltage for a given high current, and of alpha (see Chapter III), requires measurement of voltages and currents under conditions such that neither the energy capability nor the average power rating of the device is exceeded. Therefore, pulse techniques are required whereby the specified peak current versus pulse width curve is not exceeded and the duty cycle is such that the power rating is not exceeded.

The pulse source may be a commercial pulse generator such as the Velonex[3] Model 350 or the Cober Electronics[4] 604-A. The peak current may be measured through use of either a clip-on current probe (in conjunction with a current transformer as required for range extension), such as the Tektronix Model 6021, or a non-inductive shunt, such as the T&M Research Products, Inc.[5] Model F500-2. The varistor voltage may be observed on an oscilloscope or peak-responding voltmeter. Varistor current should be observed on an oscilloscope to distinguish capacitative current from varistor current which will appear as current "overshoot" and stabilization, respectively. (All these pulse functions may be served for laboratory, automated incoming inspection, and outgoing product test purposes, by Keytek Instrument Corp.[6] Model 424 surge generator/monitor, which will also afford variation in pulse waveshape. Care should, however, be exercised in the measurement of true varistor current). Alpha, of course, is done by testing at two current levels within the logarithmic range of the varistor.

Capacitance:

Since the bulk region of a GE-MOV® Varistor acts as a dielectric, the device has a capacitance that depends directly on its area and varies inversely with its thickness. Therefore, the capacitance of a GE-MOV® Varistor is a function of its voltage and energy ratings, since the voltage rating is determined by device thickness and the energy rating is directly proportional to volume.

GE-MOV® Varistor capacitance can be measured through use of a conventional capacitance bridge and is found to be somewhat frequency dependent, decreasing with an increase in frequency. Typically, capacitance and dissipation-factor measurements are made at 1 kHz with dissipation factor D being of the order of one percent for zero DC bias.

When measured in the presence of a DC bias voltage, the capacitance of a GE-MOV® Varistor is found to decrease significantly (and D is observed to increase) as the voltage is increased to values approaching the varistor peak voltage. Furthermore, the capacitance change caused by an applied voltage (either DC or AC) may persist when the voltage is removed, with the capacitance gradually increasing toward the pre-bias value. Because of this phenomenon, it is important that the electrical history of a GE-MOV® Varistor be known when measuring capacitance.

Maximum Transient Current, Energy and Average Power:

To test the current or energy capability of the varistor may require a high-energy pulse generator, depending on the size of varistor being tested. (A generator for this purpose may be found in G.E. SPD Application Note #200.73.) Failure may be based on either a degradation (shift in V_{NOM} more than ± 10% of the initial value) or catastrophic (short to < 20 ohms) failure. However, a few caveats are in order before proceeding.

As the applied transient current or pulse width is increased, the energy dissipation and internal heating of the varistor increases rapidly. Therefore, whether for testing or application of a varistor, it is essential not to exceed the derating curve of peak current versus pulse width as in the example of Figure 3.20. Providing this is observed, then the maximum transient energy rating will not be exceeded by a single transient pulse.

For multiple pulses within one second or for pulses of greater width than shown on the derating curve, the maximum transient energy rating is applicable to limit excessive heating of the varistor. For calculation purposes, it is useful to remember that the energy, W, of a constant-current constant-voltage pulse is the product of the current, I, the voltage, V, and the pulse duration, T; that is, $W = VIT$. For pulses of other than rectangular waveform, convenient conversion factors can be found in G.E. SPD Application Note #201.28.

A third limitation to prevent excessive build-up of heat in the varistor is the rating of maximum transient average power dissipation. It may be possible to apply repeated transients to the varistor at a faster rate than the resulting heat is able to flow out of the varistor to the mountings and surrounding air. Under repeated transients a net accumulation of heat then could raise the internal varistor temperature toward a very high steady-state level. Therefore, the transient repetition rate must be kept sufficiently low so that the transient average power dissipation is below maximum rating, P_{TAM}. If the pulse energy, W, is known, the time period, γ, in seconds between the start of each pulse must satisfy the inequality, $\gamma \leqslant W/P_{TAM}$.

Transient Testing:

For a given application, it may be desirable to test the performance of the varistor with an actual representative transient waveform. Various waveforms have been considered by the Rural Electrification Administration, Underwriters Labs and IEEE Committees, to name a few, for various transients. Nearly all can supply circuit diagrams for generators for these transients. A circuit for simulating residential power line transient conditions is also given in the Appendix. (Data supporting this waveform is found in Appendix A.)

REFERENCES

[1] Tektronix, Inc., Box 500, Beaverton, Oregon 97005.

[2] Hewlett-Packard Corporation, 195 Page Mill Rd., Palo Alto, California 94306.

[3] Velonex, Varian Div., 560 Robert Ave., Santa Clara, California 95050.

[4] Cober Electronics, Inc., 7 Gleason Ave., Stamford, Connecticut 06902.

[5] T&M Research Products, Inc., 129 Rhodes Island, N.E., Albuquerque, New Mexico 87108.

[6] Keytek Instrument Corp., 40 Guinan St., P.O. Box 109, Waltham, Massachusetts 02154.

Surge Voltages in Residential and Industrial Power Circuits

FRANÇOIS D. MARTZLOFF, MEMBER, IEEE, AND GERALD J. HAHN

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***Abstract*—Special instrumentation was developed for monitoring the magnitude and frequency of occurrence of surge voltages in residential and industrial circuits. Over a period of 2 years, more than 400 locations in 20 cities were surveyed. Monitoring was accomplished by automatic recording cathode-ray oscilloscopes and simple surge counters. In residential circuits, two significant sources of surge voltages were identified: load switching within the house, and external surges, most likely associated with lightning, coming through the service drop. In industrial circuits, the levels of surges are lower than in residential circuits. However, switching surges on the load side of the switch can be severe. Internally generated surges as high as 2500 volts were recorded during this test program, and surges due to lightning reaching 5600 volts have been recorded on a 120-volt overhead distribution line.**

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The authors are with the Research and Development Center, General Electric Company, Schenectady, N. Y. 12305.

Introduction

THE successful operation of semiconductors and new insulation systems in appliances and consumer electronic devices may be adversely affected by transient overvoltages occurring on the 120-volt power supply. Detection and measurement of these transient surges permits a designer to provide suitable built-in tolerance, or at least to recognize that there is a need for appropriate suppression or protection.

Special instrumentation has been developed for detection and measurement of surge voltages. In the first phase of testing, automatic recording cathode-ray oscilloscopes (CRO) provided complete information on waveshape, and on magnitude and frequency of occurrence at a small number of arbitrarily chosen locations. These data, although statistically restricted, were adequate to demonstrate the existence of the problem, define some sources, and indicate typical waveshapes. It also became clear that there was a need for a larger sample that would be more statistically valid. In the second phase of testing, 100 surge counters, simple in design and easy to install, were developed especially for this program. These counters were installed in several hundred homes in various cities located in the East and Midwest of the United States.

The purpose of this paper is to discuss recordings obtained during the two phases of this program and the statistical aspects of the results. It is hoped that publication of this paper will encourage other investigators to publish their findings. This would provide a broader statistical base for verification of the frequency and magnitude of surge voltages.

In regard to industrial circuits, less data have been accumulated, but a number of significant case histories are presented to illustrate the problems likely to be encountered in that field.

Instrumentation

Recording surge voltages in the field poses special problems. For example, the instruments cannot be continually attended, and the signals to be recorded are unpredictable in magnitude, polarity, and frequency of occurrence.

In cooperation with Tektronix, Inc., a type 515 CRO was modified to record transients on film, with automatic advance of the film after a recording.

The modifications involved a change in the trigger and sweep circuits, as well as removal of all knobs (an important detail for an instrument to be left in all types of locations).

Most oscilloscope trigger circuits are polarized. This often causes a loss of recording when the polarity of the initial signal is not known. For surge recording, the trigger circuit was modified by feeding to the time base trigger through two OR logic diodes the push–pull signal that is applied to the input of the oscilloscope delay line. With this modification, the sweep is started for either polarity, while the signal is delayed before reaching the deflection plate of the cathode-ray tube (CRT). In addition, the conventional blanking circuit holds the beam in low intensity before the sweep starts.

A second modification changed the sweep from a constant speed to a logarithmic speed, fast at the start and slow toward the end. This allows the recording of an impulse front with good resolution, while providing sufficient duration of the sweep to record a long tail.

Finally, a relay was added with its coil energized whenever the beam sweep is triggered. Through a set of contacts on this relay, the film advance sequence in the camera is activated.

The camera, attached to the scope bezel is a Beattie–Coleman system, accommodating 100 feet of 35-mm film, with no shutter, and recording on a 24- by 36-mm frame the trace displayed on the CRT. Following the sweep, the contact mentioned above closes the motor circuit, advancing the film to the next frame in a few seconds. This film transport duration is matched in the oscilloscope trigger circuit by a hold off so that no sweep will occur during film advance.

In order to prevent the film from being fogged by extended exposure to the faint glow on the phosphor (caused by imperfect blanking of the beam, cathode glow, or light leaks) a built-in timer in the oscilloscope advances the film by one frame every hour. This provides an approximate method for timing the occurrence of surges. Since the surge-voltage survey was conducted, an automatic time recording feature has been added to give a more precise recording of time at each event.

Fig. 1 shows this oscilloscope camera system. The relatively high cost of this system, its conspicuous presence (e.g., size, camera noise, etc.) in a home, and the amount of film to be scrutinized frame by frame limit the number of locations at which recordings can be made. However, for conclusions to rest on a sound statistical basis, it is necessary to investigate a large number of locations. To be acceptable to cooperative home owners, a transient detector should therefore lend itself to inconspicuous installation and simple data handling. Thus a device which can merely be plugged into a wall receptacle, and that has a digital counter indicating the number of surges occurring above a specified threshold is satisfactory for widespread recording.

Fig. 1. Oscilloscope and camera.

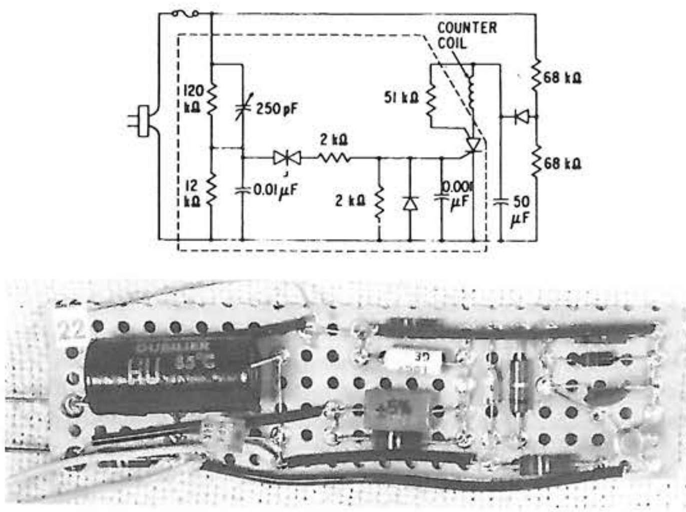

Fig. 2. Surge-counter circuit.

The circuit shown in Fig. 2 was developed for this purpose. This device is connected to a wall receptacle by a conventional appliance cord, not a special probe. This connection is simple, establishes a typical final path for a surge impinging upon any appliance connected to this particular wall receptacle, and provides power for the high-impedance rectifier circuit and a signal input to the trigger-sensor circuit.

A crudely compensated divider attenuates the incoming surge before application to the silicon symmetrical switch (SSS). This device has the characteristic of turning on abruptly whenever the voltage across it reaches a threshold, such as 250 volts. This threshold remains constant for durations as short as 0.1 μs. When the SSS turns on, the attenuated surge is applied to the gate of the very-sensitive fast-switching silicon controlled switch (SCS). If the polarity of this surge is positive, the SCS turns on, allowing the 50-μF capacitor to discharge through the coil of the solenoid-actuated counter. A high-impedance divider and

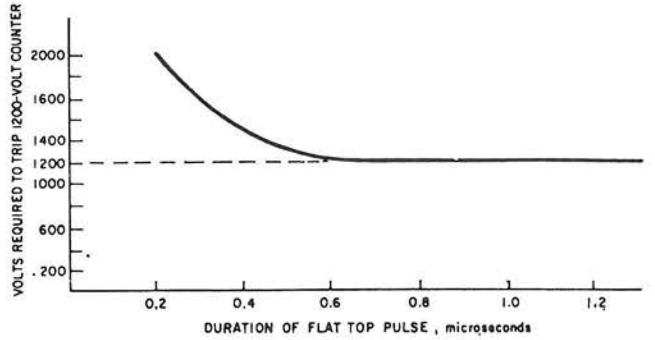

Fig. 3. Response characteristic of counter.

half-wave rectifier provide a trickle charge 15-volt supply for the 50-μF capacitor. The resistance of this divider represents a negligible load for the house wiring system, yet is sufficiently low to allow some leakage in the electrolytic capacitor. The long charging time (several seconds) of the capacitor is not objectionable since the transients to be detected do not have a high repetition rate.

Calibration of the circuit is obtained by adjusting the value of the divider elements. In these tests, the threshold level was set at 1200 volts for one group of counters and at 2000 volts for another group. A bench circuit was set up, whereby a surge with adjustable level and duration could be superimposed on a 60-Hz 120-volt power supply. Some consideration was given to the need to segregate, or filter out, the surge from the 60-Hz power voltage; in this case, however, with the minimum level at 1200 volts, the base 170-volt crest represented a small contribution and was included in the signal detected by the circuit. Surges with approximately flat top and durations from several to 0.2 μs were applied to determine the variation of the threshold voltage as a function of surge duration. A typical response curve is shown in Fig. 3. The response of this crest-indicating counter can be considered satisfactory since the oscilloscope recordings in homes, as will be discussed later, have indicated that the shortest half-period of oscillatory surges is in the order of 2 μs.

Recording Procedure

In the first phase, oscilloscopes were installed at the basement service entrance of homes in the Schenectady, N. Y., area. These locations do not represent a statistician's ideal sampling, but during the initial phase of the program, the nature of transients, rather than statistical accuracy, was the major subject of interest. Later in the program, the range of locations was broadened to include homes in other urban and rural areas, particularly in Florida and South Carolina.

In the second phase, surge counters were installed at unspecified outlets in the homes of engineers in 20 cities in the Northeast and Midwest. Two distinct recording periods were scheduled: winter, because there is usually a minimum of lightning activity at that time of year; and summer, which ordinarily includes a maximum of lightning activity.

Since the oscilloscope input circuit operates at a level of a few volts, it is somewhat sensitive to direct radiation of electromagnetic noise in the preamplifier, even if there is no signal from the probe. In order to discriminate against this type of spurious indication, the recording procedure included a period during which the oscilloscope probe was shorted with the ground terminal remaining connected so that spurious signals due to ground loops would be detected. In this manner, any noise entering the system could be recorded and later recognized for what it was in the analysis of the recordings made with the short circuit removed from the probe.

The surge counters record only one polarity; in order to minimize record keeping by the homeowner, the connection of the cord was not polarized. In the event of an oscillatory surge (which is always quickly damped in these systems), two cases of counting can occur. For instance, the high side of the divider can be connected to the "hot" terminal of the receptacle (Fig. 5). If the first half-cycle is positive and exceeds 1200 volts, a count is registered. If the first half-cycle is negative, and the second, positive half is highly damped, no count is registered. If the first half-cycle is well above 1200 volts causing the second half, in spite of some damping, to exceed 1200 volts, a count is registered. For the reverse connection, the same would occur for reverse polarity. Thus the actual number of surge occurrences of both polarities in excess of 1200 volts is between 1 and 2 times the number indicated by the counter. The objective of the recording in this test series was only to determine whether or not surges occurred rather than their exact number. Consequently, the value of the multiplying factor is not very significant.

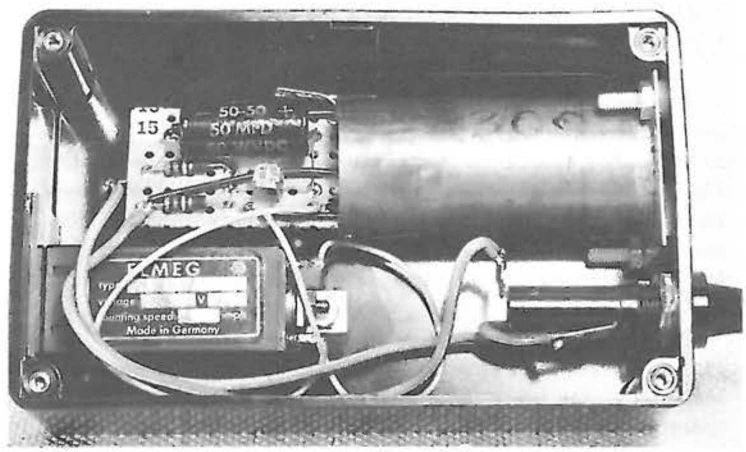

Fig. 4. Surge-counter package.

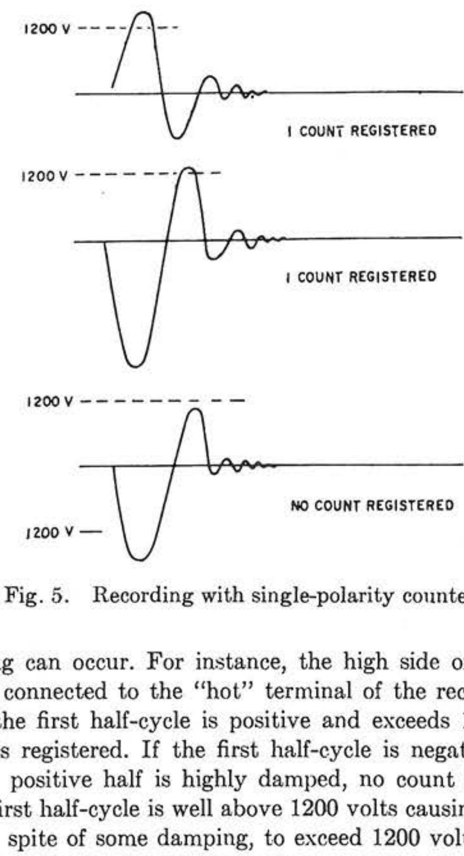

Fig. 5. Recording with single-polarity counter.

TABLE I

Detailed Analysis of Recorded Surges

House	Most Severe Surge: Type*	Most Severe Surge: Crest (volts)	Most Severe Surge: Duration (μs or cycles)	Most Frequent Surge: Type*	Most Frequent Surge: Crest (volts)	Most Frequent Surge: Duration (μs or cycles)	Average Surges per Hour	Remarks
1	*A*-1.5	700	10 μs	*A*-1.5	300	10 μs	0.07	
2	*A*-2.0	750	20 μs	*A*-2.0	500	20 μs	0.14	fluorescent light switch-
3	*B*-0.5	600	1 cycle	*B*-0.5	300	1 cycle	0.05	ing
4	*B*-0.5	400	2 cycles	*B*-0.5	300	2 cycles	0.2	
5	*C*	640	5 μs	too few to show typical			10 total	
6	*B*-0.3	400	1 cycle	*B*-0.3	250	1 cycle	0.01	
7	*B*-1	1800	1 cycle	*B*-1.0	800	1 cycle	0.03	lightning storm
8	*C*	1200	10 μs	*B*-0.5	300	4 cycles	0.1	
9	*B*-0.25	1500	1 cycle	same as most severe			0.2	oil burner
10	*B*-0.25	2500	1 cycle	*B*-0.25	2000	1 cycle	0.4	oil burner
11	*B*-0.2	1500	1 cycle	same as most severe			0.15	water pump
12	*B*-0.2	1700	1 cycle	*B*-0.2	1400	1 cycle	0·06	oil burner
13	*B*-0.1	350	1 cycle	too few to show typical			4 total	house next to 12
14	*C*	800	15 μs	—	—	—	1 total	lightning
15	*B*-0.25	800	3 cycles	*B*-0.25	600	3 cycles	0.05	rural area
16	*B*-0.15	400	15 μs	*B*-0.13	200	30 μs	0.4	surges
Street pole	*B*-0.5	5600	4 cycles	*B*-0.3	1000	1 cycle	0.1	lightning stroke nearby
Hospital	*C*	2700	9 μs	*C*	900	5 μs	0.1	lightning storm
Hospital	*B*-0.3	1100	1 cycle	too few to show typical			4 total	
Department store	*B*-0.5	300	1 cycle	*B*-0.5	300	1 cycle	0.5	
Street pole	*B*-0.2	1400	4 cycles	*B*-0.2	600	4 cycles	0.07	lightning storm

* *A*—long oscillation; *B*—damped oscillation; *C*—unidirectional. Number shows frequency in megahertz.

Results of the Recordings

Oscilloscopes

The first recording analysis revealed that some homes were subject to frequent surge voltages, some experienced only a few isolated surges, and others did not experience any surges in excess of the trigger level (300 to 400 volts). Furthermore, among those installations where surge voltages frequently occurred, the surges at some houses were relatively low (rarely in excess of 800 volts), while other houses had surges in the range of 1200 to 2500 volts. Rates of surge occurrence ranged from 0 (no surge in 1 to 2 weeks) to 0.5 per hour, with peak values from 300 volts (trigger threshold) to 5600 volts.

At the conclusion of the recording program, a total of 30 locations, including two overhead distribution poles had been monitored for a total of about 10 000 hours. Table I shows a detailed analysis of the recordings at 21 locations. Three homes and six industrial locations did not produce any triggering with the threshold as low as 400 volts.

Further analysis of some recordings was made by deliberate switching of loads in the houses where frequent surges had been observed. In some cases, the operation of a specific device (e.g., oil burner, fluorescent lamp, pump motor, refrigerator, food mixer, etc.) was found to be the cause of the surges. In other cases, no amount of deliberate load switching could reproduce surges such as those recorded during unattended monitoring. The home owner was occasionally able to correlate surge recordings with lightning or power system disturbances.

A pattern emerged from all this information, showing two definite causes of surge voltages in the homes: load switching within the house and lightning storms.

Load Switching: Load switching in the house occasionally produced transient surges; these affected only that particular house. For any particular house, these transient surges had a waveshape which was consistently repeated with variations in amplitude along the entire film recording. This probably resulted from a combination of the switch characteristics and the impedance of the house wiring system; the variations in amplitude were probably caused by variations of the switching angle and/or connected loads. In an industrial circuit, the same repetition of a particular pattern was also noted [1]. Typical waveshapes of the recorded surges are shown in Figs. 6–8.

In one case, it was possible to install an oscilloscope in a house adjacent to that where repetitive surges up to 1700 volts were being recorded. The service drops were connected to the same pole, yet no surges occurring simultaneously were recorded in the second house.

Lightning: Surge voltages not associated with load switching within the house were associated with lightning storms. In some cases, the home owner was able to correlate the film advance counts with the storm. Although recorded during lightning storms at two different locations, the surges shown in Figs. 9 and 10 present the interesting characteristic of being oscillatory at a frequency in the range of 300 kHz. The surge shown in Fig. 9 was recorded at the overhead distribution line (oscilloscope mounted on the pole), while the surge of Fig. 10 was recorded at the service entrance in a home. The first exhibits far less damping than the second; this might be explained by the lower damping due to lower resistance of the system at the pole than at the end of a service drop. Both of these surges, as well as most of the other surges recorded during lightning storms, exhibit this oscillatory characteristic at a frequency which is nearly constant for a particular locality. This constancy suggests that the oscillation of the system followed an excitation caused by the lightning stroke. A number of surges in the range of 800 to 1200 volts were observed during several storms. The maximum

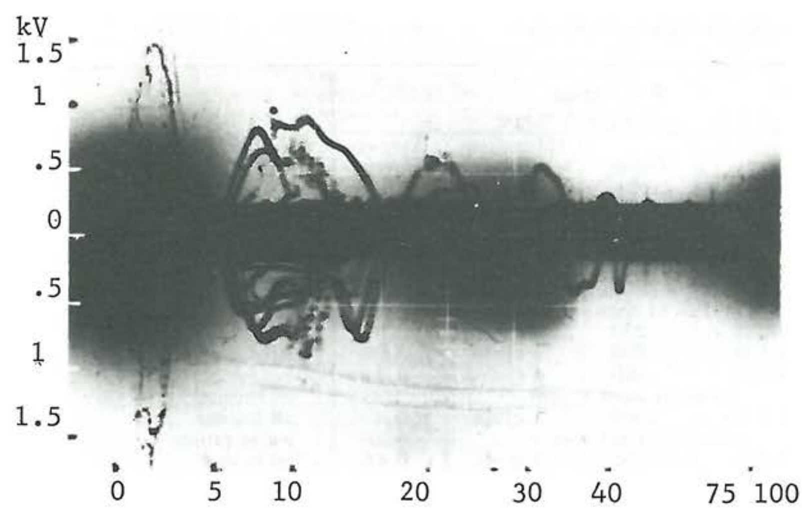

Fig. 6. Residential surges, 24-hour composite. Black band is ±170-volt sweeps at hourly intervals.

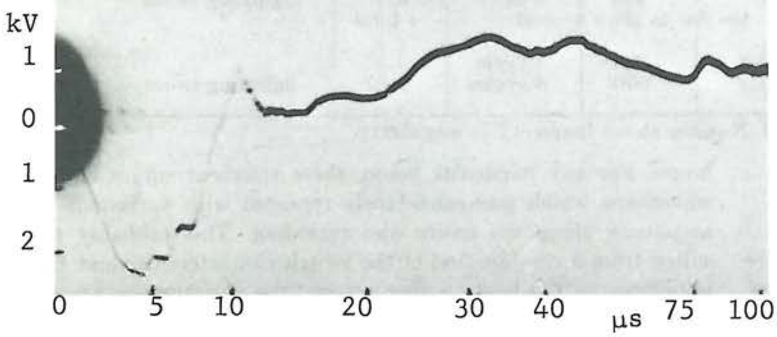

Fig. 7. Residential surge, oil burner ignition.

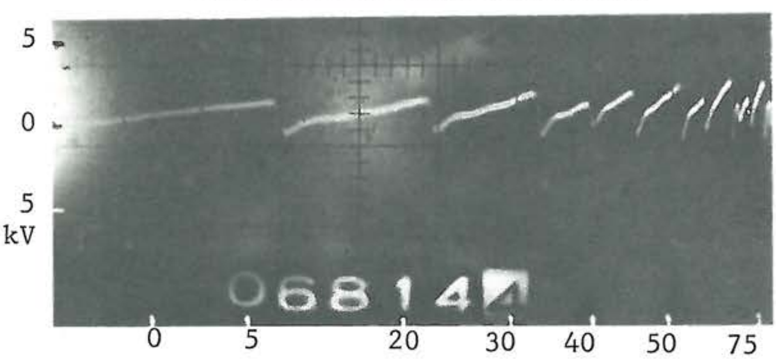

Fig. 8. Industrial circuit. Surge due to equipment maintenance; note digital timer record.

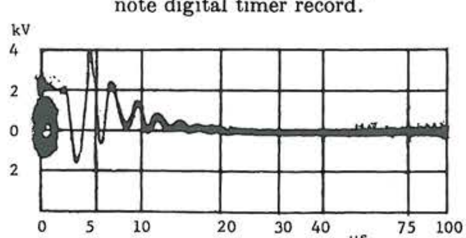

Fig. 9. Surge recorded on street pole in Charleston, N. C.

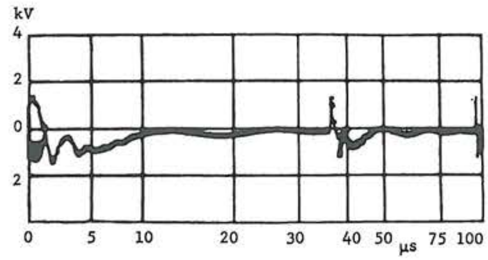

Fig. 10. Surge recorded at service entrance of Florida home.

TABLE II

NUMBER OF HOUSES WITH REPETITIVE SURGE ACTIVITY ABOVE 1200 VOLTS

Location	Number of Homes Surveyed	Recording Period (weeks)	Houses with Repetitive Surges
Providence, R. I.	4	2–6	none
Cleveland, Ohio	28	2–4	none
Auburn, N. Y.	12	2–3	none
Lynchburg, Va.	3	2–3	none
Syracuse, N. Y.	8	1–2	1
Chicago, Ill.	23	1–6	none
Ashland, Mass.	24	1–2	1
Holland, Mich.	6	2–10	none
Louisville, Ky.	10	2–6	none
Somersworth, N. H.	50	1–2	1
Plainville, Conn.	5	10	none
Asheboro, N. C.	24	1–2	none
Fort Wayne, Ind.	38	1–4	3
DeKalb, Ill.	14	3–12	none

TABLE III

SURGE COUNTER RECORDINGS ABOVE 1200 VOLTS (SPRING, SUMMER, AND FALL)

Location	Number of Homes	Total Homes × Weeks	Number of Surges
Providence, R. I.	6	60	1
Ashboro, N. C.	13	85	none
DeKalb, Ill.	11	60	2
Somersworth, N. H.	3	48	1
Chicago, Ill.	12	58	none
Cleveland, Ohio	8	106	1
Decatur, Ill.	12	72	2
Holland, Mich.	7	56	none
Auburn, N. Y.	3	70	none
Springfield, Pa.	1	24	none
Ashland, Mass.	6	72	none
Pittsfield, Mass.	3	60	1
Plainville, Conn.	3	60	none
Lynchburg, Va.	3	15	none
Total	91	846	8 in 8 homes

surge voltage recorded was 5600 volts; several other surges recorded during the same period were in excess of 4000 volts [2].

Counters

With the two causes of transients identified by the oscilloscope measurements, the surge counters were applied in two separate programs. First, during the winter months, the counters were installed in a large number of houses for periods of 1 or 2 weeks; the objective was to determine how many houses sustained repetitive surges. Second, during spring, summer, and fall, each counter was left at one or two locations for periods of 9 to 48 weeks; it was known from the first test that these homes were not subject to load switching surges. The objective was to determine the frequency and characteristics of externally generated surges, presumably caused by lightning.

The first period produced the data shown in Table II, and the results obtained during the second period are shown in Table III.

Statistical Analysis of the Recordings

Internally Generated Surges

The data in Table II show that 6 houses, or 2.4 percent, were subject to repetitive surges from among a total of 250 homes sampled. The true percentage doubtless differs somewhat from 2.4 percent due to statistical variations.

However, one may be 90-percent confident that the true percentage is between 1.0 and 4.7 percent.[1] This band could be narrowed by taking additional samples. However, it should be noted that the precision is proportional to the square root of the sample size. Thus four times the number sampled, or 1000 homes, would be necessary to cut the size of the statistical error band by approximately one half. Since the preceding results refer to statistical variations only, they do not take into account possible biases due to such factors as restrictions in selecting members of the sample (principally engineers in a number of designated locations) or the time of year (winter months).

The probability of internally generated surges undoubtedly varies among economic groupings (i.e., the devices in use in homes probably vary with the economic status of the resident); however, devices found to generate surges (i.e., furnaces, refrigerators, etc.) exist in most homes.

Externally Generated Surges

Results from the second testing period that was concerned with externally generated surges are shown in Table III. From 39 counters installed in a total of 91 homes in 14 localities, a total of 8 occurrences in 6 separate localities were observed during an equivalent exposure time of 846 weeks. A ninth occurrence was disregarded in this analysis because it occurred in the same home during the same storm. Of the two pairs of occurrences which took place in the same location, one pair occurred during the same storm and the second involved two occurrences at different times.

Analyses could be conducted based on the following alternative assumptions.

1) Voltage surges above 1200 volts occur only during the period of the year that the counters were installed in the homes. Thus although the counters were in homes for only part of the year, the time involved (i.e., the summer months) was so chosen that no further surges would have been noted even if each counter had been run for 52 consecutive weeks. The average number of surges per year would then be estimated as 8/39, or 0.205, with a 90-percent confidence band of 0.102 to 0.370.

2) Voltage surges occur randomly at a constant rate throughout the year. Thus a counter which was in use 9 weeks, on the average, would be subject to a third as many surges as a counter in use for a period of 27 weeks. Under this assumption, a total of 8 surges observed in a total time equivalent to 16 years (846 weeks) yield an estimated average of 0.5 surges per year, with a 90-percent confidence band of 0.25 to 0.90.

Using these two extreme assumptions, a range could be established for the estimated number of surges per year. The preceding calculations refer only to single-polarity surges. If all surges are being considered, the given value must be multiplied by a value corresponding to the additional proportion of opposite polarity surges above 1200 volts which do not also result in positive surges above 1200 volts. This multiplying factor is probably about 1.6.

Lightning-induced surges are likely to affect more than one house when they occur. Local geographical and meteorological conditions are critical influences on these surges; however, these factors could not be considered in this preliminary investigation.

To relate the preceding data to risk of appliance failure, the given values must be modified by the probability that a surge above 1200 volts would cause failure of operating appliances. Failure effects would vary with different appliances.

Possible Further Analysis

A more refined analysis to estimate the probability of voltage surges per lightning storm is possible if the geographical location of the homes, the occurrence rate of lightning storms during the testing period, and exact dates at which voltage surges occur is considered. The resulting values can then be used in conjunction with information given in [8], [9] to calculate the probability of a voltage surge in any specified geographic area and season. Such an analysis would remove the need for making one of the two alternative assumptions stated previously and lead to a single set of estimates. However, this would require more detailed data than could be collected in this program.

Finally, it is noted that if one has knowledge of the actual voltage surges, rather than merely the information concerning whether or not a surge above 1200 volts occurred, a more sensitive analysis is possible. In this case, for example, probability plotting and other techniques based upon the statistical theory of extreme values [5], [7] might well be applicable.

[1] This result is obtained by the well-known method of setting confidence intervals for a percentage from a sample. Further details may be found in statistical texts [3]–[5].

Effects of Surge Voltages on Connected Electrical Devices

The surges which have been recorded in this program occurred during normal operation of the household, with no knowledge of the connected load situation at the time of occurrence.

The question of energy involved in the surge is related to the impedance of the system since these recordings provide voltage data only. Surge impedance measurements of a house wiring cable indicate a value of 100 to 300 ohms for a typical branch circuit so that the surge impedance at the service entrance could be in the order of 5 to 10 ohms. However, this low value exists only for the travel time (i.e., a fraction of a microsecond). Connected loads will have a lower impedance than that of the branch circuit. This value will be dependent upon frequency whenever inductive components are present. These loads will absorb part of the energy of the surges and thus lower their peak.

Devices such as motors and transformers have solid insulation and such a long history of successful application that their performance is not in question. Perhaps unusual failures can be explained by extreme values of surges as indicated by the data.

Defective wiring practices (e.g., pinched insulation, reduced air clearances in wall boxes, etc.) will cause air flashover with or without 60-Hz power follow. In fact, one house was brought to our attention because of complaints of sparking in a light fixture. With the switch in the ground wire and the frame attached to a grounded pipe, flashover at 1700 volts was observed in correlation with the start of an oil burner in the house. This defective light fixture was acting as a voltage limiting gap for the house.

Appliances containing semiconductors and directly exposed to the line transients may be more vulnerable. Actually, the 1200-volt threshold level was selected as the result of this consideration. It is interesting to note that, although a number of surges above 2000 volts were recorded by the oscilloscopes, the few surge counters calibrated for 2000 rather than 1200 volts did not produce any recording above 2000 volts.

An independent study of clock motor failures produced information on failure rates versus withstand levels. This study was very pertinent to the surge counter program since thousands of clocks are connected at all times to the power system. Over a period of 3 years, failure rates were correlated with the insulation level of the coils. A very significant 100 to 1 drop in failure rate resulted from an increase in withstand voltage from approximately 2000 to approximately 6000 volts. This shows that, even though no surges over 2000 volts were recorded by the 2000-volt counters, surges in excess of 2000 volts do indeed occur.

Industrial Circuit Case Histories

The authors have been associated with a number of investigations where surges were suspected to be the cause of equipment problems. In the industrial environment, isolated cases tend to attract more attention than in residential circuits. The few case histories briefly summarized in this paper illustrate the types of problems likely to be encountered, where often surges are not in fact the cause of the problem, but where the presence of the test crew at the site precipitates a more thorough evaluation of the problem and sometimes reveals an unsuspected new fact.

On the occasion of these investigations, the surge counters were installed at the same time on the system and left for several weeks or months at the site whenever possible. So far, in over 15 locations, no surge over 1200 volts has been recorded on 240- or 480-volt buses ("mains"). On the other hand, severe surges have sometimes been recorded on the load side of the switch. However, these load side surges are associated with the subsystem operation and can be controlled (if recognized) by the subsystem designer or operator, in contrast with the surges on the mains that affect all users in the house, building, or plant, and on which they have little control.

Problem

Occasional flashover in a 480-volt distribution system at a steel welding shop.

Suspect: Switching surges associated with arc welding.

Investigation: Install surge recording oscilloscopes on the bus.

Result: No surges recorded.

Second Investigation: Power factor capacitors had been installed on the bus, but this fact had not been revealed by the initial discussions; their presence on the bus practically eliminated the possibility of surges on the bus. (Switching the whole bus system was tested and produced no surges in this case.) Final conclusion was contamination of the insulation in the polluted atmosphere.

Problem

Failures of a 480-volt saturable reactor in a motor control system.

Suspect: Switching surges associated with contactor operation.

Investigation: Record surges on site during deliberate, controlled switching of the contactor.

Result: Contactor bouncing and restrike produce a number of steep front (0.1 μs) surges on the winding, causing excessive turn-to-turn stress.

Problem

Failures of rotor windings in 440-volt induction motors in a crane system.

Suspect: Switching surges associated with contactor operation.

Investigation: Record surges with monitoring oscilloscope during deliberate, controlled switching of the contactor.

Result: No excessive surges found; however the test crew notices during the on-site test that the overspeed protection of the motor control had been bypassed by the user.

Problem

Frequent blowing of fuses in a power factor correction capacitor bank.

Suspect: Switching surges.

Investigation: Record current in the fuse and system voltage during switching operation.

Result: Contactor bouncing produces a number of inrush current surges exceeding the rms capability of the fuse.

Problem

Failures of lamp ballasts in an industrial plant.

Suspect: Switching surges.

Investigation: Install monitoring oscilloscopes.

Results: No surges found in several weeks of monitoring, no further problem.

Conclusion: The best surge suppressor is a surge monitor.

Conclusions

1) Residential power circuits are subjected to surge voltages due to two distinct causes: load switching within the house, and externally generated surges that are most likely associated with lightning.

2) Internally generated surges caused by load switching are likely to be repetitive. They can generally be associated with a specific device, probably operating erratically or exciting some natural frequency of the wiring system. They are not related to lightning or disturbances from the utility. Peaks as high as 2500 volts have been observed. The best single statistical estimate is that 2.4 percent of households of the type sampled experience these internally generated repetitive surges in excess of 1200 volts. However, because of the statistical variability in the sample, this value may be as low as 1 percent or as high as 4.7 percent. Surges may be repeated several times a day.

3) The frequency of surges caused by lightning is not affected by household electrical devices but rather by local geographical and meteorological conditions. The limited data in this program reveal several lightning-caused surge occurrences above 3000 volts with one reaching 5600 volts.

4) Independent evidence shows that a significant number of surges above 2000 volts do occur periodically in residential power lines.

5) Industrial power circuits appear less likely to be subjected to surges on the mains. However, switching surges in subsystems can originate at the switch and affect the loads.

Acknowledgment

The authors wish to thank the hundreds of individuals involved in the data collection and J. E. Lenz and D. W. Spencer for the data on overhead distribution lines and industrial circuits.

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APPENDIX **B**

HIGH-VOLTAGE IMPULSE TESTERS

by

E. K. Howell* and F. D. Martzloff
Physics and Electronics Engineering Laboratory

Report No. 75CRD039 March 1975

GENERAL ELECTRIC COMPANY
CORPORATE RESEARCH AND DEVELOPMENT
Schenectady, N.Y.

TECHNICAL INFORMATION SERIES

*General Electric Circuit Protective Devices Products Department, Plainville, CT.

CLASS 1

I. INTRODUCTION

The high-voltage impulse generators described in this report have been developed by several individuals for the purpose of simulating transient overvoltages as they occur on residential or industrial low-voltage a-c power circuits (120 or 220 volts).

Each circuit was developed on the basis of certain objectives, and consequently the designs are quite different. An evaluation and comparison has been made, from the point of view of producing a simple and economical system limited to generating the proposed "typical" surge wave shape on a 120 volt single-phase circuit. (1-3)

The objective of this test circuit is to superimpose on a 120-volt, 60 Hz power line a wave shape having a rise time to first peak of a 500 kHz wave, followed by a damped ringing at 100 kHz in which each successive peak should be about 60% of the preceding peak amplitude, the amplitude of the first peak being adjustable from 0 to 8000 volts. The source impedance for the high-voltage wave should be 50 ohms.

The three circuits are the following:

1. General-purpose ignitron switch generator, suitable for 20 kV, 20 kA pulses.

2. Specialized generator with low-voltage SCR switch and step-up pulse transformer.

3. Relay-type switch and resonant circuit (recommended circuit).

II. GENERAL-PURPOSE CIRCUIT

This circuit is assembled from available laboratory components, with an ignitron switch built especially for the purpose. (4) The circuit schematic is shown in Fig. 1. The switch is SW; the energy storage element Z_0 can be a line (cable) or capacitor bank, charged by the high-voltage supply HVDC. The surge is produced across the matching impedance R by discharging the cable when the switch is fired.

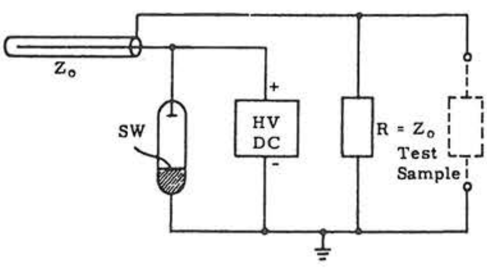


Fig. 1 Schematic diagram of surge generator.

The surges developed by this circuit can be coupled into an a-c power supply, with a suitable filter inserted between the bench supply and the receptacle where the device under test will be connected, and where the surge is injected, in a shunt mode; that is, directly across the a-c terminals (Fig. 2). This shunt mode allows very fast rise time for the pulse, typically 50 to 100 nsec in the absence of deliberate sloping network. Furthermore, the source impedance of the surge can be readily adjusted as desired by controlling the parameters (cable characteristic impedance, or surge impedance of a capacitor bank).

In fact, the very flexibility of the circuit becomes a handicap in this case (too complicated for routine testing to a specific wave shape), and together with the relatively high cost and inability (as designed) to produce repetitive pulses, this makes this approach less attractive than the two others. On the other hand, when experimentation is the object, the flexibility of this circuit is a great asset.

III. THYRISTOR SWITCH AND STEP-UP PULSE TRANSFORMER

This circuit was designed with the specific objective of producing spikes on the a-c line, with the further aim of avoiding a high-voltage switch and the need for a filter. The surge is to be injected in series with the a-c line by a coupling transformer acting as a step-up pulse transformer. Figure 3 shows the schematic diagram of the circuit. Energy is stored in capacitor C, at about 500 volts. The thyristor discharges the capacitor through the primary of T_1 and the pulse is coupled across inductance L by the coupling capacitor C_2. C_4 and C_3 serve, respectively, to bypass the a-c line and to control the ringing frequency. 60 Hz power is supplied through the isolating transformer T_2.

The difficulty in this circuit, when fast rise times are desired, is to control the inductance of the T_1 primary loop, which must be in the order of 0.2 μH or less for the rise time desired in this case. While the components for this circuit are of special design, a supplier was identified who could produce them for interested users. However, the relative complication of the circuit, the cost of the high current SCR required, made this approach less attractive than the third circuit, which will now be described in detail.

IV. RELAY-TYPE SWITCH WITH RESONANT CIRCUIT

The basic schematic diagram of the tester is shown in Fig. 4, and the relay control circuit is given in Fig. 5. Photographs of the waveforms are shown in Figs. 6 through 10.

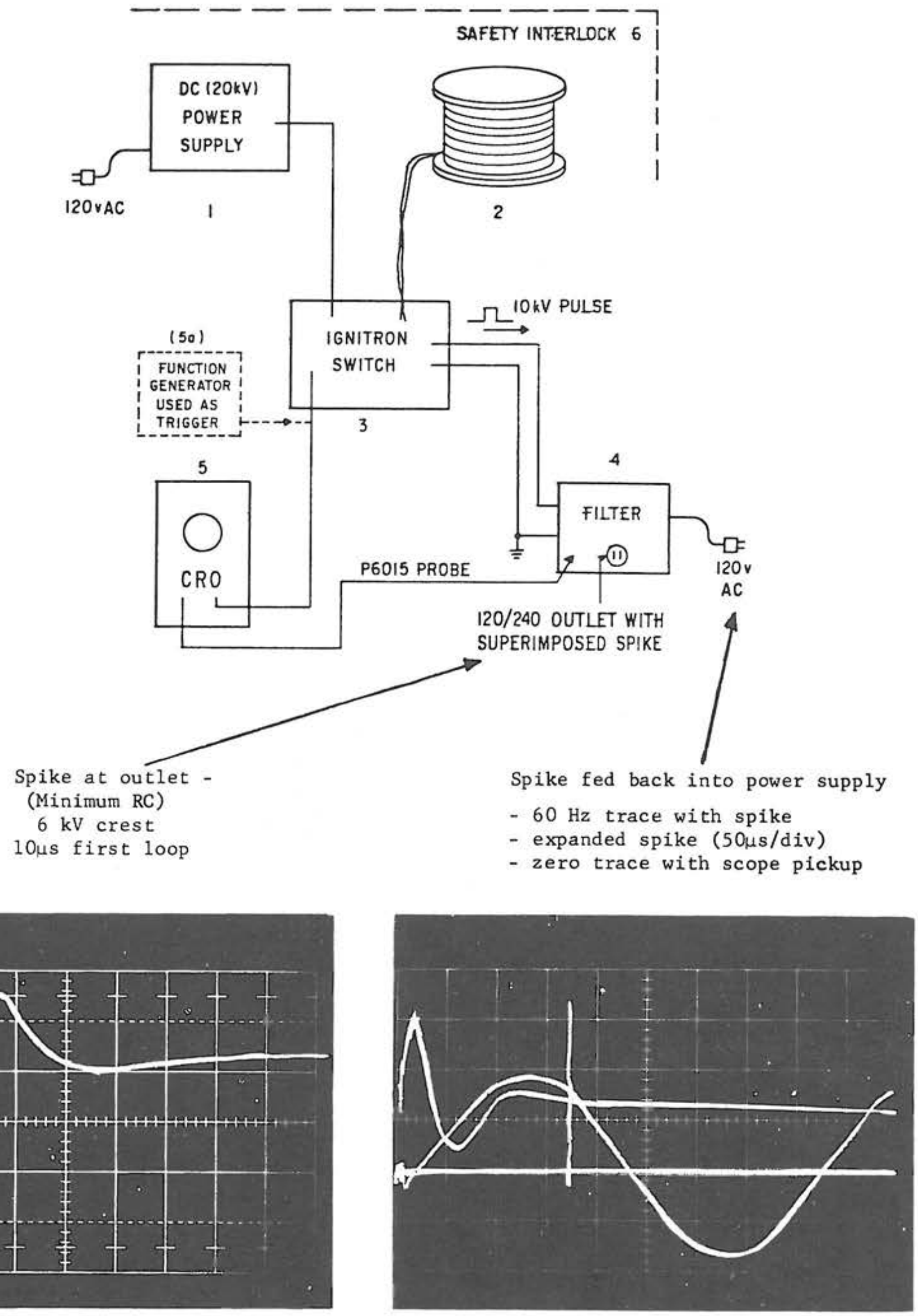


Fig. 2 Surges developed by the general-purpose circuit can be coupled into an a-c power supply.

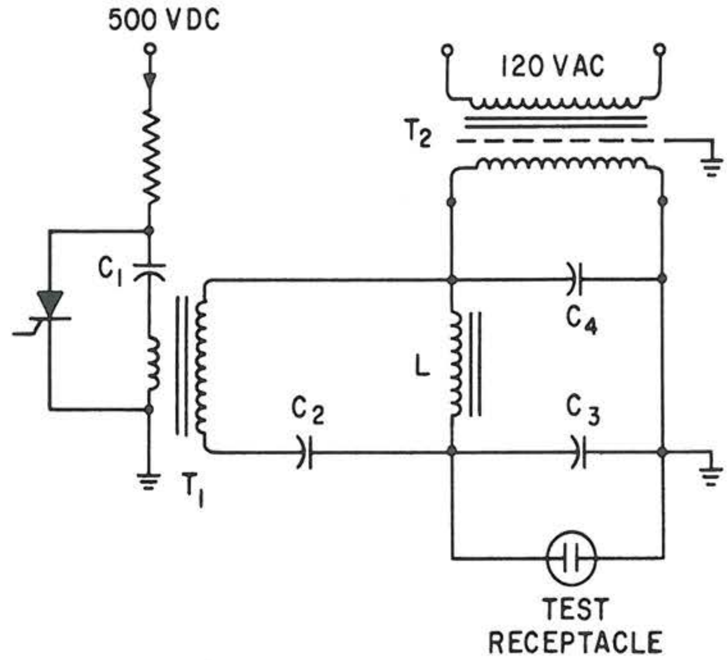
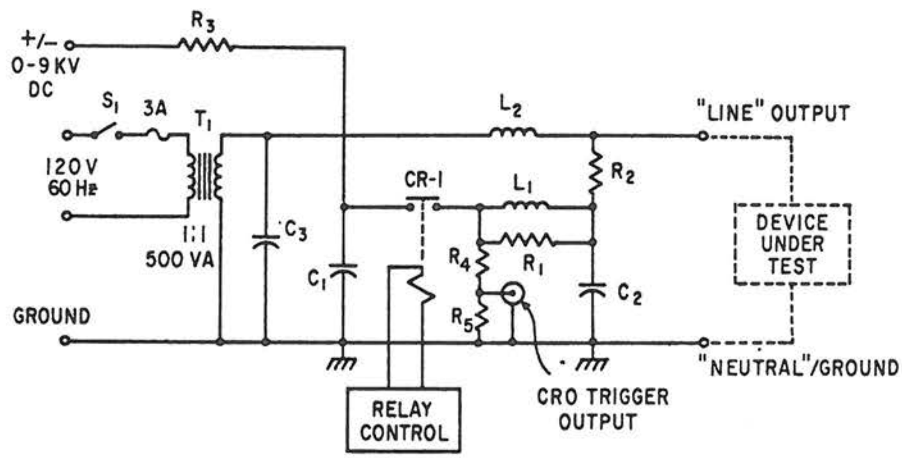


Fig. 3 Schematic circuit of test circuit with series injection by pulse transformer.



* C1 – .025μF, 10kV, (Gudeman, 2 x .01 + .005)

C2 – .002μF, 7.5kV, Ceramic (Sprague or equivalent

C3 – 4μF, 400V

L1 – 15μH (32 turns, # 23 wire, 0.7" dia. Air Core)

L2 – 70μH (28 turns, # 23 wire, 2.6" dia Air Core)

R1 – 22Ω, 1W, Comp.

R2 – 12Ω, 1W, Comp.

R3 – 1.3MΩ (12 x 110KΩ, 1/2W)

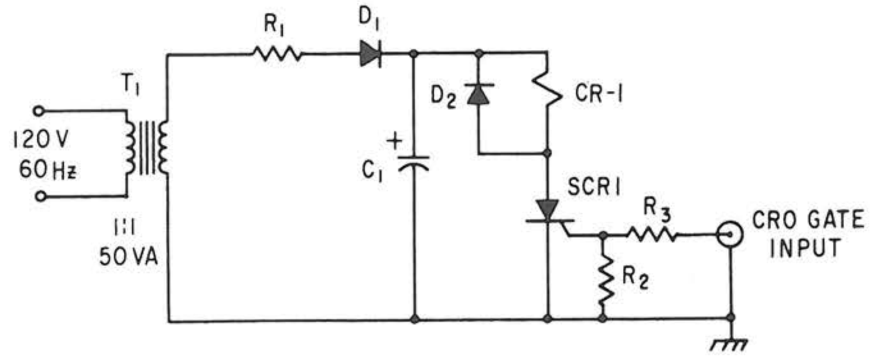
R4 – 47KΩ (10 x 4.7KΩ, 1/2W)

R5 – 200Ω, 1/2W

CR-1 – Relay, 2 N.O. poles in series GE CR2790 E 100 A2

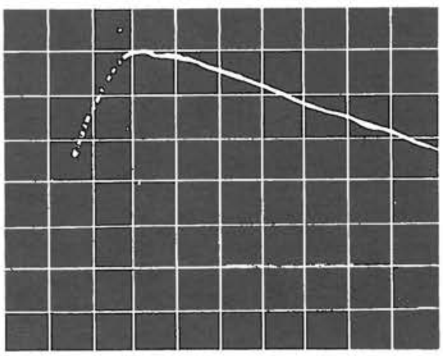
* Gudeman GC 245S103M37 – 01μF
Gudeman GC 245S502M37 – .005μF
Plastic Cap. Inc. 0F100-103F – .01μF

Fig. 4 Basic impulse generator circuit.



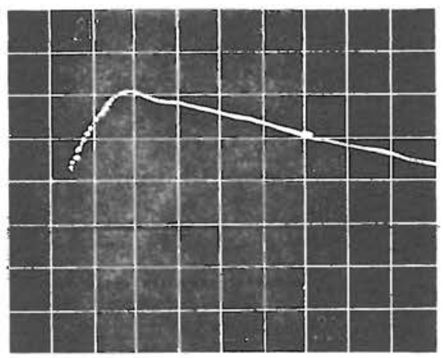
R1 - 10KΩ, 1W	*D1,D2* - IN5060
R2 - 1KΩ, 1/2W	*SCR1* - GE C122B
R3 - 1KΩ, 1/2W	*CR-1* - Relay GE CR 2790 E 100 A2
C1 - 32μF, 250V	*T1* - Triad N4S X

Fig. 5 Relay control circuit for impulse generator.



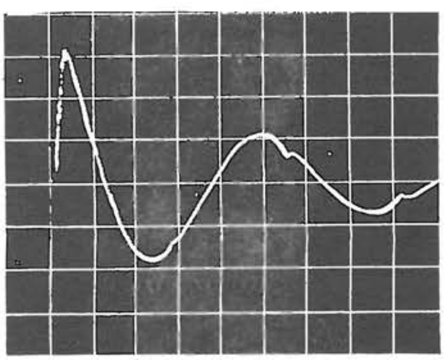
Vert: 2 kV/div Hor: 0.2μs/div

Fig. 6 Impulse rise - no load.



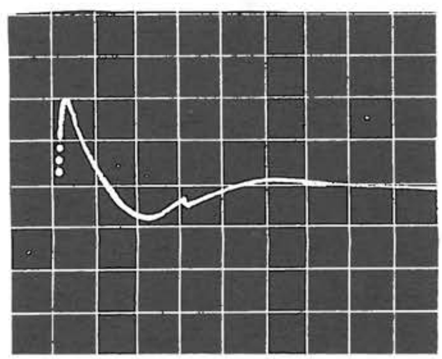
Vert: 2 kV/div Hor: 0.2μs/div

Fig. 7 Impulse rise - 50 ohm load.



Vert: 2 kV/div Hor: 2μs/div

Fig. 8 Ringing wave - no load.



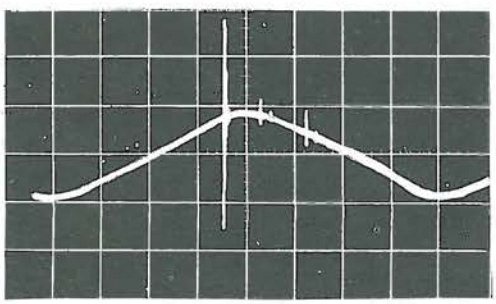
Vert: 2 kV/div Hor: 2μs/div

Fig. 9 Ringing wave - 50 ohm load.

In principle, a d-c voltage is stored on capacitor C1. At about the 70 degree point on the 60 Hz supply wave, a pair of relay contacts are closed to connect C1 to the Line Output terminal by way of a wave-shaping network L1, R1, C2, R2, and L2. A large capacitor, C3, prevents transmission of the wave back into the power system. Figure 10 shows the pulse superimposed on the 60 Hz, 120 volt line (contact bounce produced two subordinate trailing pulses).

The 500 kHz rise characteristic is obtained by the series resonance of L1 and the capacitance of C1 and C2 in series. Component values are selected to make $\sqrt{L/C}$ approximately 50 ohms, and R1 was selected to provide heavy damping for a smooth transition to the following wave. Figure 6 shows the rise time, open-circuit, and Fig. 7 with 50 ohm load.

The 100 kHz damped ring results from the parallel resonance of L2 with the parallel capacitance of C1 plus C2. Again, $\sqrt{L/C}$ is about 50 ohms. The series damping resistor R2 was selected to produce the decay to 60% amplitude between successive peaks. Figure 8 shows the ringing wave on open circuit, and Fig. 9 shows the same wave when loaded by 50 ohms. A comparison of first-peak amplitudes shows that the source impedance is approximately the desired 50 ohms. Approximately 8 kV d-c charge on C1 is required to produce an open-circuit peak of 6 kV on the output terminal because of the charge transferred to C2.



Vert: 200V/div Hor: 2ms/div

Fig. 10 Impulse superimposed on 120 volt line voltage - output of impulse tester.

At low voltages, the relay contacts behave normally, but at high voltages they can no longer be considered as contacts but rather as a moving spark gap. In Figs. 8 and 9 disturbances in the sinusoidal shape occur as current in the plasma reverses in each half-cycle. The introduction of heavy metal ions into the plasma, such as by use of a mercury relay, can reduce the extent of such waveform distortions; however, it is considered that these distortions do not materially affect the validity of this waveform for the proposed tests.

Laboratory tests with this circuit used a storage CRO with delayed sweep and single sweep capabilities. The main sweep gate output was used to trigger the relay control circuit, and the main sweep was triggered from the 60 Hz line such as to produce the high-voltage surge at the desired point of line voltage. Main sweep duration was about 20 msec. The delayed sweep was first delayed 1 msec, then triggered by the output from divider R4, R5 at the start of the high-voltage rise time. Since the charging time constant on C1 is 0.033 second, the test can be repeated within 0.5 second.

It should be emphasized that this is an experimental design to illustrate a concept, not a product design. There are no operator-safety provisions shown, and only "qualified persons" must be allowed to operate the apparatus. The component values are approximations taken for ready availability and ease of construction. The performance does show, however, that the proposed test waveform can be produced by a relatively simple, inexpensive method.

ACKNOWLEDGMENTS

The general-purpose ignition switch and its control circuits were developed by R.N. Bushman as part of the laboratory equipment used in transients investigations at Corporate R&D.

The SCR/pulse transformer circuit and magnetic components was designed by H.W. Lord, especially for the purpose of producing the spikes on the a-c line voltage.

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GE-MOV®

Metal Oxide Varistors

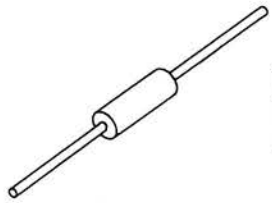
33-430 VOLTS D.C. NOMINAL VARISTOR VOLTAGE
RATINGS OF 23-365 VOLTS D.C., 18-264 VOLTS RMS,.1-.7 JOULES

APPENDIX **C**

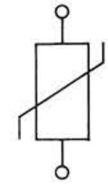
SERIES MA

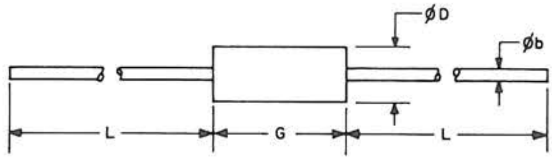
Description:

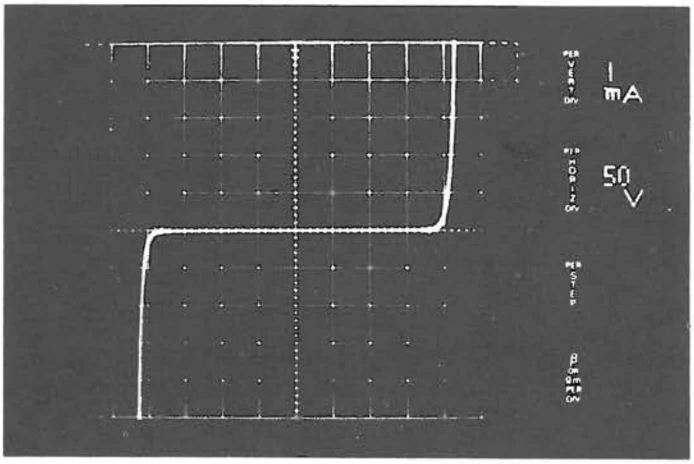
GE-MOV® zinc oxide varistors are voltage dependent, symmetrical resistors which perform in a manner similar to back-to-back zener diodes in circuit protective functions and offer advantages in performance and economics. The MA (molded axial) series is characterized at the 1mADC varistor voltage following ±10% EIA values as are zener diodes and other varistors used as transient suppressors. When exposed to high energy voltage transients, the varistor impedance changes from a very high standby value to a very low conducting value thus clamping the transient voltage to a safe level. The dangerous energy of the incoming high voltage pulse is absorbed by the GE-MOV® varistor, thus protecting your voltage sensitive circuit components.



SYMBOL	MILLIMETERS MIN.	MILLIMETERS MAX.	INCHES MIN	INCHES MAX.
Øb	.79	.83	.031	.033
ØD	3.43	3.68	.135	.145
G	8.01	8.50	.315	.335
L	26.0	29.0	1.03	1.14







I-V Oscillograph
(Actual Photo)

Features:

- Excellent Clamping
- Peak Transient Current Capability Up To 20 Amps
- Wide Operating Temperature Range (-40°C to 125°C)
- Low Temperature Coefficient (-.03%/°C)
- Low Capacitance
- Low Standby Drain
- Compact and Lightweight
- Compatible With Automatic Insertion

Benefits:

- Improves Circuit, Component and System Reliability
- Extends Contact Life
- Reduction of Secondary Lightning Effects
- Promotes System Cost Reduction
- Reduces System Size and Weight Requirements
- Increases Product Safety
- No Follow-On Current
- Reduces Electrical "Spike" Noise

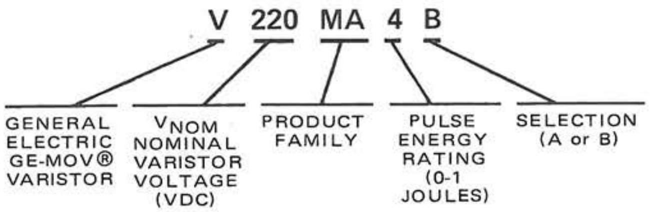
Replacement For The Following When Used As Transient Suppressors:

- Zener Diodes
- Silicon Carbide
- Selenium Thyrectors
- R-C Networks (non dv/dt)
- Neon Bulbs
- Miniature Electronic Crowbars

Applications:

- Telephone Relays
- Telephone Solid State Circuits
- Communication Equipment
- Relay Coils
- Traffic Controllers
- Computer Equipment
- Railroad Circuitry
- Numerical Control
- Test Equipment
- Instrumentation
- Solid State Motor Control
- Television
- Copier Machines
- Calculators
- Contact Arc Suppression
- Solid State Relays/Timers
- Automobiles
- Solid State Security Systems
- Medical Equipment
- Fire Alarms

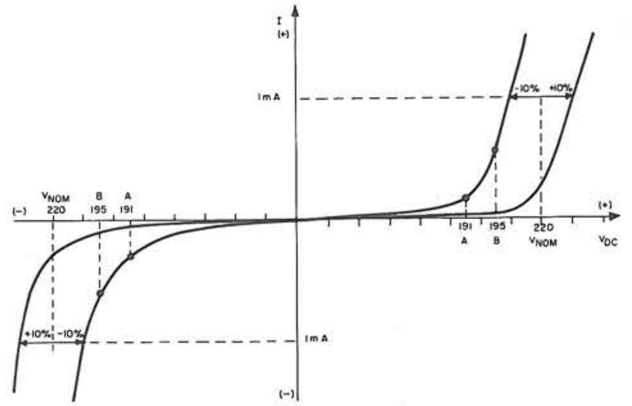
Model Number Nomenclature:



The MA series GE-MOV® varistors are characterized at the 1mADC varistor voltage according to EIA values.

For example – V220MA4B; the nominal varistor voltage is 220VDC, ±10%, at 1mADC. The maximum allowable steady state applied voltages, 191 VDC and 195 VAC (peak) fall below the low side nominal varistor voltage of 198 VDC (220 – 10%) to insure the maximum idle power dissipation characteristics (See V-I curve to the right).

Example:
V220MA4B V-1 Characteristics:



A – Maximum allowable steady state DC applied voltage.
See Ratings Table.
B – Maximum allowable steady state recurrent peak applied voltage.
See Ratings Table.
V_{NOM} – Nominal Varistor voltage at 1mADC.
See Characteristics Table.

ABSOLUTE MAXIMUM RATINGS

Maximum Electrical Ratings:

Maximum Energy, Power and Peak Current . . . . See Rating Table
Storage Temperature, T_{STG} . . . . -55°C to +125°C
Operating Ambient Temperature (Without Derating) . . . . 75°C
Maximum Voltage Temperature Coefficient . . . . -.03%/°C

Mechanical Ratings:

Insulation Resistance – Megohms . . . . > 1000
Hipot Encapsulation – Volts D.C. for 1 Minute 1000
Solderability . . . . Per Mil Std 202D Method 208B

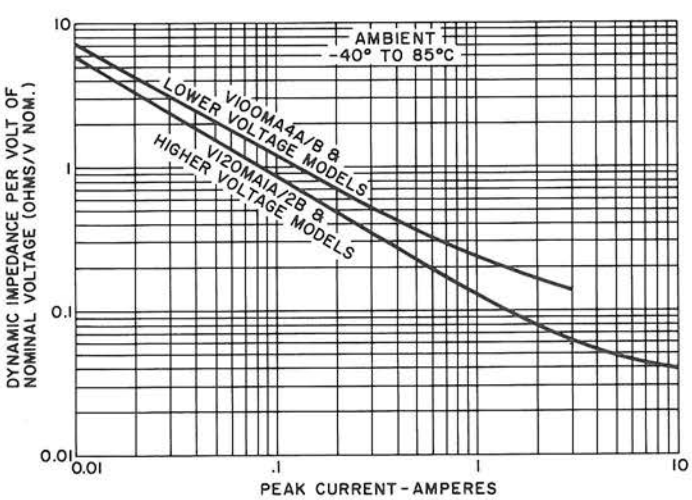


FIGURE 1 TYPICAL CHARACTERISTIC OF DYNAMIC IMPEDANCE VS. PEAK CURRENT

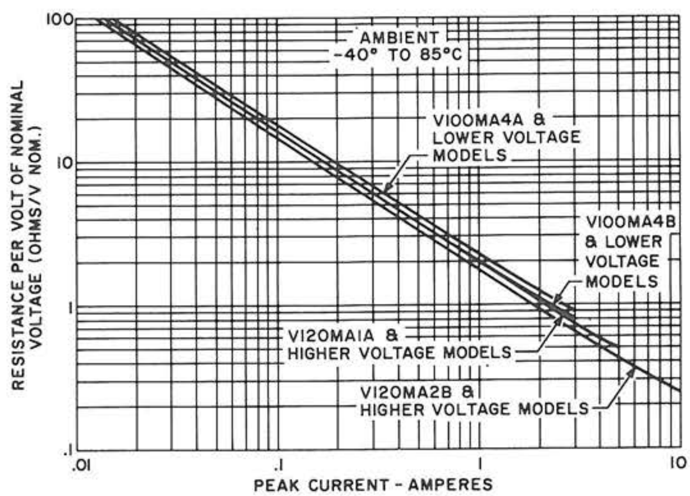


FIGURE 2 MAXIMUM STATIC RESISTANCE VS. PEAK CURRENT

MAXIMUM RATINGS TABLE

MODEL NUMBER	STEADY STATE (1) DC APPLIED VOLTAGE (2,4)	RMS (2,3,4) APPLIED VOLTAGE 50-60 Hz AC	RECURRENT PEAK APPLIED VOLTAGE (2,3,4)	TRANSIENT ENERGY (4)	AVERAGE POWER DISSIPATION (4)	NON-RECURRENT PEAK PULSE CURRENT (4, 5)
	VOLTS	VOLTS	VOLTS	JOULES (WATT-SECS)	MILLIWATTS (FREE AIR)	AMPERES
V33MA1A V33MA1B	23 26	18 20	26 28	.13 .15	200	10
V39MA2A V39MA2B	28 31	22 25	31 35	.16 .18	200	10
V47MA2A V47MA2B	34 38	27 30	38 42	.19 .21	200	10
V56MA2A V56MA2B	40 45	32 35	45 49	.23 .25	200	10
V68MA3A V68MA3B	48 56	38 40	54 57	.26 .30	200	10
V82MA3A V82MA3B	60 66	45 50	65 71	.33 .37	200	10
V100MA4A V100MA4B	72 81	57 60	80 85	.40 .45	200	10
V120MA1A V120MA2B	97 101	72 75	102 106	.10 .20	200	10 20
V150MA1A V150MA2B	121 127	88 92	124 130	.10 .20	200	10 20
V180MA1A V180MA3B	144 152	105 110	148 156	.15 .30	200	10 20
V220MA2A V220MA4B	181 191	132 138	187 195	.20 .40	200	10 20
V270MA2A V270MA4B	224 235	163 171	230 242	.20 .40	200	10 20
V330MA2A V330MA5B	257 274	188 200	266 283	.25 .50	200	10 20
V390MA3A V390MA6B	322 334	234 242	331 342	.30 .60	200	10 20
V430MA3A V430MA7B	349 365	253 264	358 373	.35 .70	200	10 20

(1) Steady State defined as the normal input conditions existing when no transients are present.

(2) Applied Voltage is that voltage which appears across the varistor terminals when no transient is present. High line voltage conditions should be included in the value for Applied Voltage used to select the correct model. (i.e., applications for 117 V_{RMS} should use ratings of 129 V_{RMS} or more.)

(3) For AC applications a sinusoidal Applied Voltage is assumed to be the normal input condition. If Applied Voltage is non-sinusoidal, Recurrent Peak Applied Voltage values should be used to select correct model.

(4) See Figure 3.

(5) See Figure 8.

CHARACTERISTICS TABLE

MODEL NUMBER	V_{NOM} VARISTOR VOLTAGE @ 1.0mA DC CURRENT (6)		LEAKAGE CURRENT @ MAX. RATED DC VOLTAGE		ALPHA (7) I_2 = 1mA, I_1 = 0.1mA			MAXIMUM AC IDLE POWER	MAXIMUM THERMAL RESISTANCE BODY TO AIR	TYPICAL CAPACITANCE
			TYP.	MAX.	MIN.	TYP.	MAX.			
	VOLTS	± TOL. %	MICROAMPERES					MILLIWATTS	°C/W	PICOFARADS
V33MA1A V33MA1B	33	20 10	10	250	12	20	55	8	250	300
V39MA2A V39MA2B	39	20 10						9		250
V47MA2A V47MA2B	47	20 10			↓	↓		11		210
V56MA2A V56MA2B	56	20 10			16	25		13		180
V68MA3A V68MA3B	68	20 10						15		150
V82MA3A V82MA3B	82	20 10						18		120
V100MA4A V100MA4B	100	20 10			↓	↓		20		100
V120MA1A V120MA2B	120	15 10			25	32		22		40
V150MA1A V150MA2B	150	15 10						25		32
V180MA1A V180MA3B	180	15 10						30		27
V220MA2A V220MA4B	220	15 10						40		21
V270MA2A V270MA4B	270	15 10						45		17
V330MA2A V330MA5B	330	15 10						55		14
V390MA3A V390MA6B	390	15 10						65		12
V430MA3A V430MA7B	430	15 10	↓	↓	↓	↓	↓	70	↓	11

(6) 1mA DC current pulse, 10-50 msec.

(7) $1 = KV^{\alpha}$, Where $\alpha = \frac{\text{Log } I_2/I_1}{\text{Log } V_2/V_2}$

NOTE:

The GE-MOV® varistor may be operated at maximum energy, power, peak pulse current, and applied voltage (AC or DC) ratings up to 75°C ambient. Above 75°C ambient these values must be derated in order to remain below a limit of 125°C average surface temperature. The magnitude of total average power dissipation is determined by averaging the energy of repetitive transients over their time base (0.1 Watt = 0.1 Joules/Sec) and then adding the idle power dissipation of the varistor.

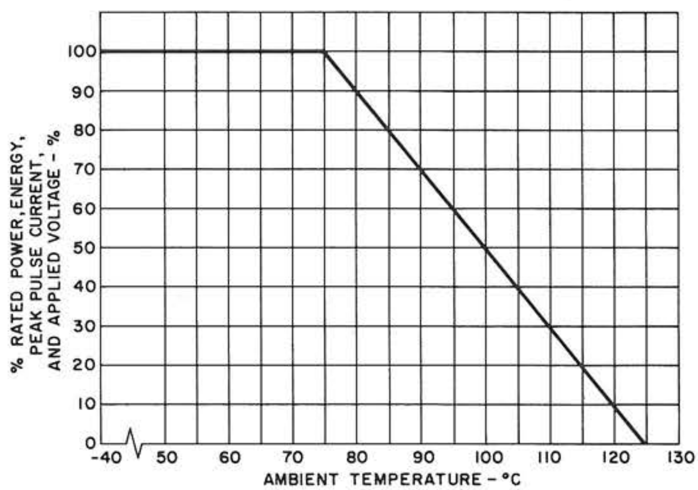


FIGURE 3 % RATED POWER, ENERGY, PEAK PULSE CURRENT AND APPLIED VOLTAGE (AC OR DC) VS T_A

MAXIMUM VOLT – AMPERE CHARACTERISTICS (T_A = 25°C)

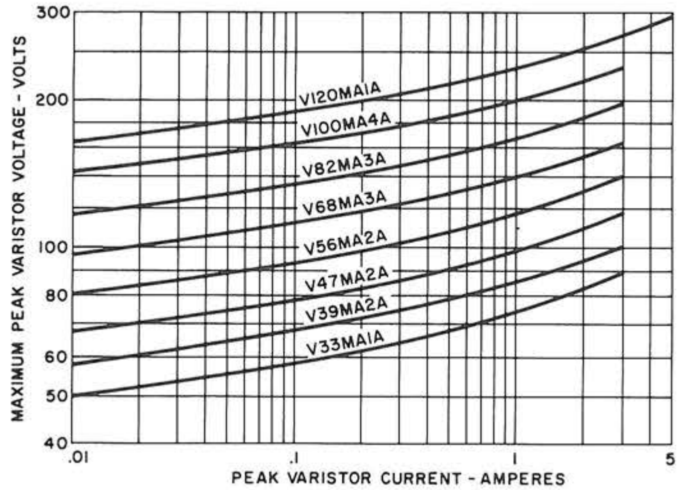


FIGURE 4 PEAK VARISTOR CURRENT – AMPERES

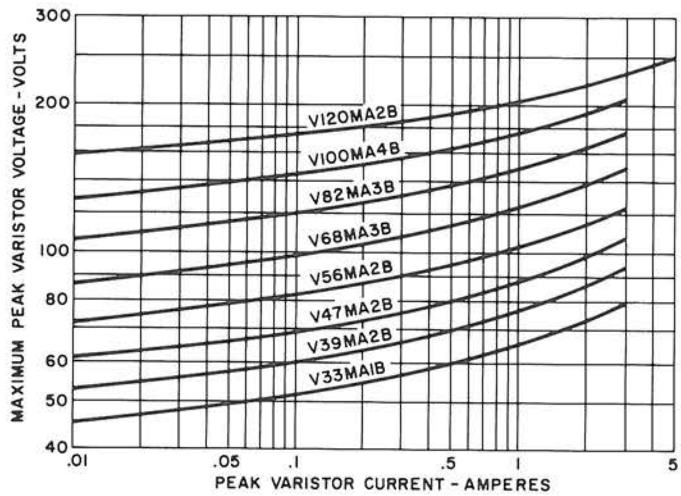


FIGURE 5 PEAK VARISTOR CURRENT – AMPERES

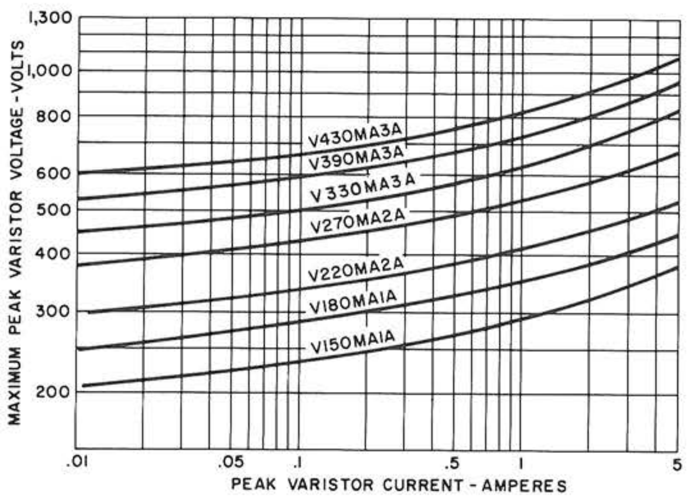


FIGURE 6 PEAK VARISTOR CURRENT – AMPERES

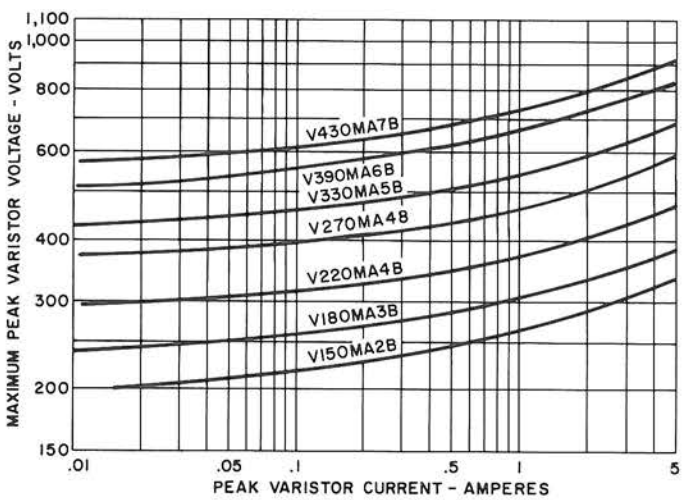


FIGURE 7 PEAK VARISTOR CURRENT – AMPERES

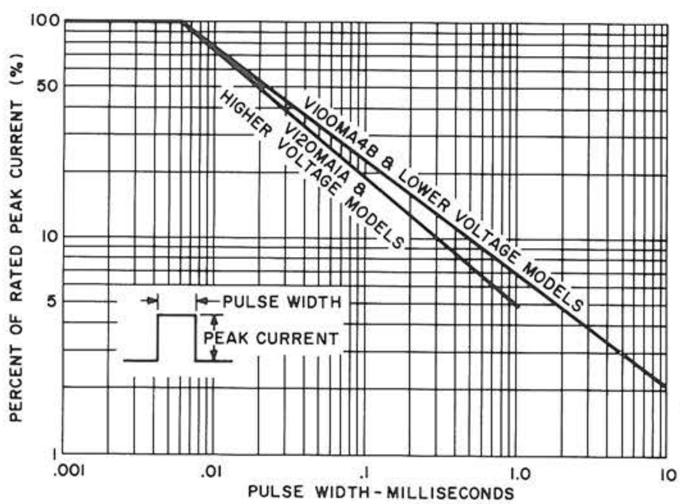
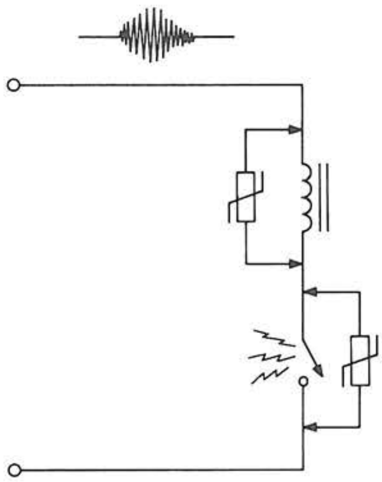


FIGURE 8 % RATED NON-RECURRENT PEAK PULSE CURRENT VS. PULSE WIDTH (T_A = 25°C)

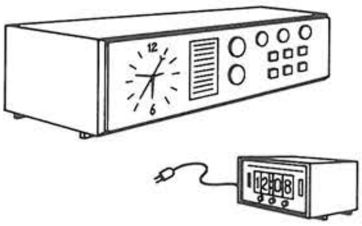
GE-MOV® VARISTOR APPLICATIONS



CONTACT ARCING / NOISE

Switch contacts interrupting an inductive load current will arc causing deterioration of the contacts and noise-generating "spikes" on the power line.

Placing an MA Series GE-MOV® varistor across the load or contacts is a low-cost method to suppress high voltage spikes, and (particularly at lower currents or voltages) to reduce contact damage due to arcing. Their bi-directional characteristic makes them useful for AC or DC applications without affecting load operation or suffering voltage damage themselves, as diodes or capacitors may do.



RESIDENTIAL POWER LINE TRANSIENT VOLTAGES

About 2% of all homes experience repeated transient voltages (over 1200 volts) of a level potentially damaging to home appliances. GE-MOV® axial-leaded varistors provide a reliable, cost-effective way to reduce these voltages to acceptable levels.

GE-MOV® VARISTOR APPLICATION NOTES AND SPECIFICATION SHEETS

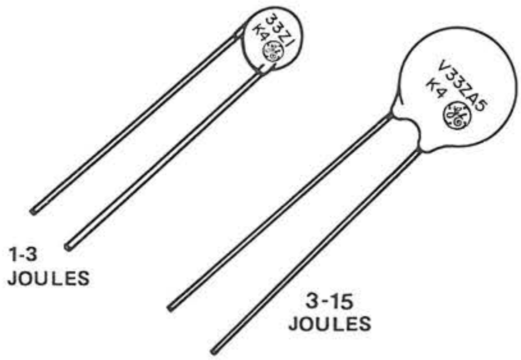
PUB. NO.	TITLE
200.60	GE-MOV® Varistors Voltage Transient Suppressors
200.72	Using GE-MOV® Varistors To Extend Contact Life
200.73	Testing GE-MOV® Varistors
200.77	Detecting And Suppressing Nanosecond Wide Spikes With GE-MOV® Varistors
201.28	Energy Dissipation In GE-MOV® Varistors For Various Pulse Shapes
95.44	GE-MOV® Varistor Reliability Report
660.30	Six Ways To Control Voltage Transients, Reprint From *Electronic Design*
660.32	Transient Suppression . . . Don't Make The Cure Worse Than The Disease, Reprint From *Machine Design*
180.75	GE-MOV® Varistor "PA" Series (Up to 15 Watt Power Dissipation)
180.59	GE-MOV® Varistor "L" Series (Up to 1000 Volts RMS)
180.73	GE-MOV® Varistor "ZA" Series (As Low As 16 Volts DC)

GE-MOV®

Metal Oxide Varistors

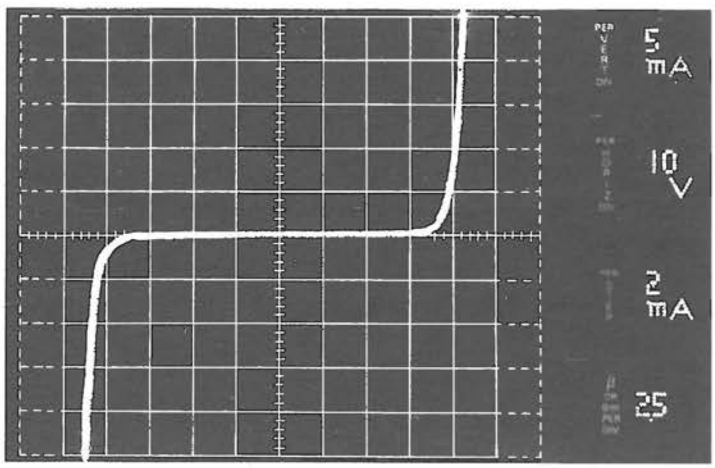
SERIES ZA

22-180 VOLTS D.C. NOMINAL VARISTOR VOLTAGE
RATINGS OF 16-153 VOLTS D.C., 20-115 VOLTS RMS, 1-15 JOULES



Description:
GE-MOV® zinc oxide varistors are voltage dependent, symmetrical resistors which perform in a manner similar to back-to-back zener diodes in circuit protective functions and offer advantages in performance and economics. The ZA series is characterized at the 1mADC varistor voltage following ±10% RETMA values as are zener diodes and other varistors used as transient suppressors. When exposed to high energy voltage transients, the varistor impedance changes from a very high standby value to a very low conducting value thus clamping the transient voltage to a safe level. The dangerous energy of the incoming high voltage pulse is absorbed by the GE-MOV® varistor, thus protecting your voltage sensitive circuit components.

Replacement For:
- Zener Diodes
- Silicon Carbide
- Selenium Thyrectors
- R-C Networks (non dv/dt)



I-V Oscillograph
(Actual Photo)

Features:
- Low Voltage Design
- Excellent Clamping
- High Transient Current Capability (250 Amps)
- Fast Response (< 1.0 Nanosecond)
- Compact and Lightweight High Energy Capability
- Wide Operating Temperature Range
- Low Temperature Coefficient
- Low Standby Drain

Benefits:
- Improves Circuit, Component and System Reliability
- Extends Contact Life
- Reduction of Lightning Effects
- Promotes System Cost Reduction
- Reduces System Size and Weight Requirements
- Increases Product Safety
- No Follow-On Current

Applications:
- Telephone Relays
- Telephone Solid State Circuits
- Communication Equipment
- Relay Coils
- Traffic Controllers
- Computer Equipment
- Railroad Circuitry
- Numerical Control
- Test Equipment
- Instrumentation
- Solid State Motor Control
- Television
- Copier Machines
- Calculators
- Contact Arc Suppression
- Solid State Relays/Timers
- Power Supplies
- Solid State Security Systems
- Medical Equipment
- Fire Alarms

Maximum Electrical Ratings:

Maximum Energy, Power and Peak Current	See Rating Table
Storage Temperature, T_{STG}	-40°C to +125°C
Operating Surface Temperature, T_S	115°C
Operating Ambient Temperature (without derating)	85°C
Maximum Voltage Temperature Coefficient	-0.05%/°C

Mechanical Ratings:

Insulation Resistance–Megohms	> 1000
Hipot Encapsulation–Volts D.C. for 1 Minute	2500
Solderability	Per Mil Std 202D Method 208B

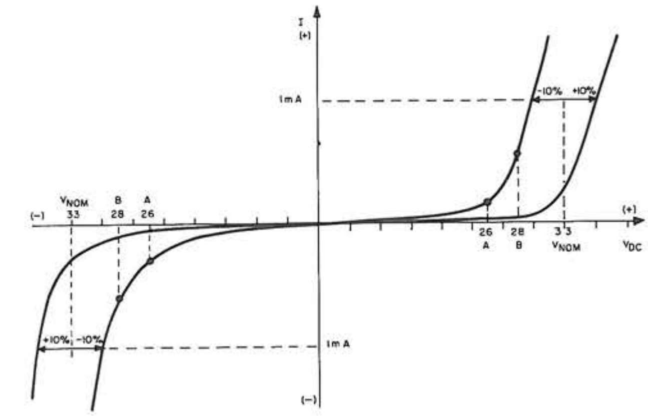
Model Number Nomenclature:

V 33 ZA 5

- V — GENERAL ELECTRIC GE-MOV® VARISTOR
- 33 — V_{NOM} NOMINAL VARISTOR VOLTAGE (VDC)
- ZA — PRODUCT FAMILY
- 5 — PULSE ENERGY RATING (JOULES)

The ZA series GE-MOV® varistors are characterized at the 1mADC varistor voltage according to RETMA values. For example–V33ZA5: The nominal varistor voltage is 33VDC, ±10%, at 1mADC. The maximum allowable steady state applied voltages, 26VDC and 28VAC (peak) fall below the low side nominal varistor voltage of 29.7VDC (33VDC–10%) to insure the maximum idle power dissipation characteristics are not exceeded.

V33ZA5 Typical V-I Characteristics:



A–Maximum allowable steady state DC applied voltage. *See Ratings Table.*
B–Maximum allowable steady state recurrent peak applied voltage. *See Ratings Table.*
V_{NOM}–Nominal Varistor voltage at 1mADC. *See Characteristics Table.*

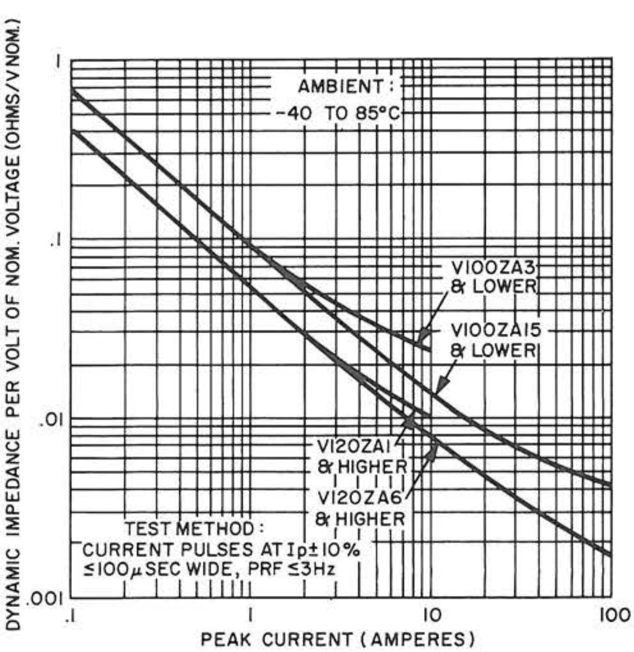


Figure 1. TYPICAL CHARACTERISTIC OF DYNAMIC IMPEDENCE VS. PEAK CURRENT

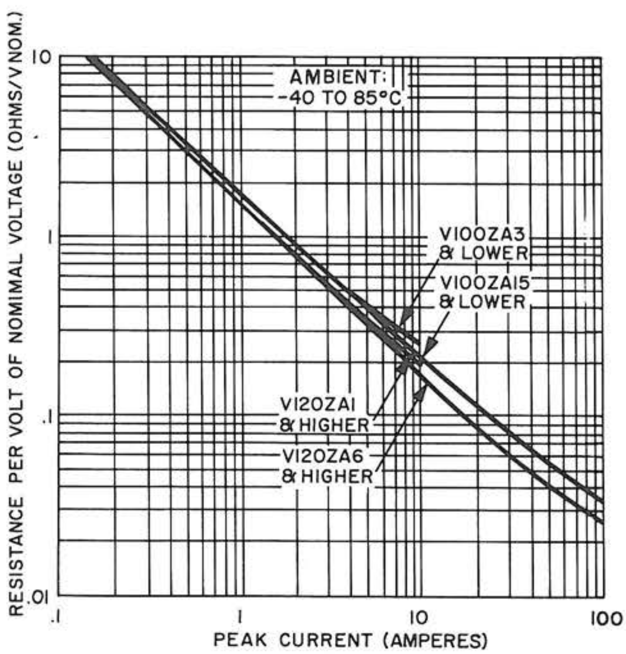


Figure 2. MAXIMUM RESISTANCE VS. PEAK CURRENT

MAXIMUM RATINGS

MODEL NUMBER	STEADY STATE (1)			TRANSIENT		
	DC APPLIED VOLTAGE (2,4)	RMS (2,3,4) APPLIED VOLTAGE 50-60 Hz AC	RECURRENT PEAK APPLIED VOLTAGE (2,3,4)	ENERGY (4)	AVERAGE POWER DISSIPATION (4)	PEAK CURRENT (5)
	VOLTS	VOLTS	VOLTS	JOULES (WATT-SECS)	WATTS	AMPERES
V22ZA1	16	12	17	0.6	.18	50
V22ZA3	16	12	17	3	.40	250
V24ZA1	19	15	21	0.8	.18	50
V24ZA4	19	15	21	4	.40	250
V27ZA1	20	15	21	0.8	.18	50
V27ZA4	20	15	21	4	.40	250
V33ZA1	26	20	28	1.0	.19	50
V33ZA5	26	20	28	5	.40	250
V39ZA1	31	25	35	1.2	.20	50
V39ZA6	31	25	35	6	.45	250
V47ZA1	38	30	42	1.4	.21	50
V47ZA7	38	30	42	7	.45	250
V56ZA2	45	35	49	1.7	.22	50
V56ZA8	45	35	49	8	.45	250
V68ZA2	56	40	57	2.0	.24	50
V68ZA10	56	40	57	10	.50	250
V82ZA2	66	50	71	2.5	.25	50
V82ZA12	66	50	71	12	.50	250
V100ZA3	81	60	85	3.0	.26	50
V100ZA15	81	60	85	15	.55	250
V120ZA1	97	70	99	1.0	.2	150
V120ZA6	102	75	106	6	.45	1000
V150ZA1	119	85	120	1.2	.2	150
V150ZA8	127	95	134	8	.45	1000
V180ZA1	146	105	149	1.5	.2	150
V180ZA10	153	115	163	10	.45	1000

1. Steady state defined as the normal input conditions existing when no transients are present.
2. Applied Voltage is that voltage which appears across the varistor terminals when no transient is present. High line voltage conditions should be included in the value for Applied Voltage used to select the correct model.
3. For AC applications a sinusoidal Applied Voltage is assumed to be the normal input condition. If Applied Voltage is non-sinusoidal, Recurrent Peak Applied Voltage values should be used to select correct model.
4. See Figure 5.
5. See Figure 3.

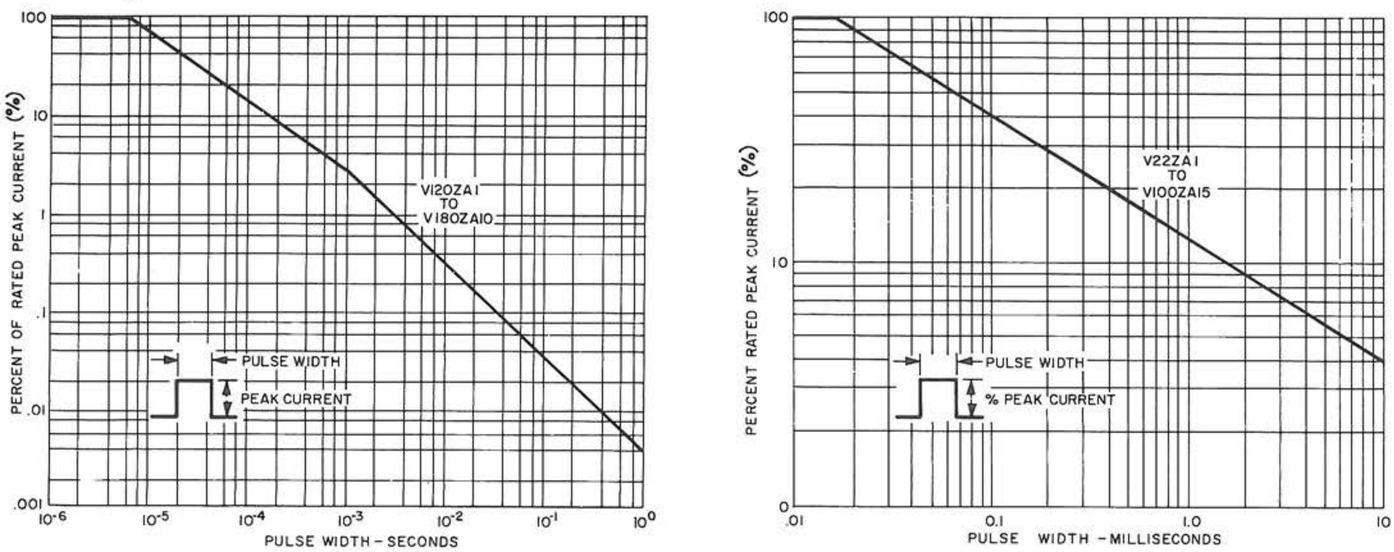


Figure 3. % NON-RECURRENT PEAK PULSE CURRENT VS. PULSE WIDTH ($T_A = 25^\circ C$)

CHARACTERISTICS AT 25°C

MODEL NUMBER	V_{NOM} VARISTOR VOLTAGE @ 1.0mA DC CURRENT (6)		LEAKAGE CURRENT @ MAX. RATED DC VOLTAGE		ALPHA (7) $I_2 = 1mA, I_1 = 0.1mA$			MAXIMUM AC IDLE POWER	MAXIMUM THERMAL RESISTANCE BODY TO AIR	TYPICAL CAPACITANCE
			TYPICAL	MAX.	MIN.	TYP.	MAX.			
	VOLTS	TOL.	MICROAMPERES					WATTS	°C/W	PICOFARADS
V22ZA1	22	±15%	20	200	15	20	60	.005	170	2000
V22ZA3	22	±15%	20	200	15	20	60	.005	75	10000
V24ZA1	24	±10%	20	200	15	20	60	.006	170	1700
V24ZA4	24	±10%	20	200	15	20	60	.006	75	8500
V27ZA1	27	±15%	20	200	15	20	60	.006	170	1700
V27ZA4	27	±15%	20	200	15	20	60	.006	75	8500
V33ZA1	33	±10%	20	200	17	25	60	.008	160	1400
V33ZA5	33	±10%	20	200	17	25	60	.008	75	7000
V39ZA1	39	±10%	20	200	17	25	60	.009	150	1200
V39ZA6	39	±10%	20	200	17	25	60	.009	70	6000
V47ZA1	47	±10%	20	200	17	25	60	.011	140	1000
V47ZA7	47	±10%	20	200	17	25	60	.011	70	5000
V56ZA2	56	±10%	20	200	20	30	60	.013	135	800
V56ZA8	56	±10%	20	200	20	30	60	.013	70	4000
V68ZA2	68	±10%	20	200	20	30	60	.015	125	700
V68ZA10	68	±10%	20	200	20	30	60	.015	65	3500
V82ZA2	82	±10%	20	200	20	30	60	.018	120	600
V82ZA12	82	±10%	20	200	20	30	60	.018	60	3000
V100ZA3	100	±10%	20	200	20	30	60	.022	115	500
V100ZA15	100	±10%	20	200	20	30	60	.022	55	2500
V120ZA1	120	±10%	5	100	25	45	70	.010	150	200
V120ZA6	120	±10%	10	200	25	45	70	.020	67	1200
V150ZA1	150	±10%	5	100	25	45	70	.012	150	170
V150ZA8	150	±10%	10	200	25	45	70	.025	67	1000
V180ZA1	180	±10%	5	100	25	45	70	.015	150	140
V180ZA10	180	±10%	10	200	25	45	70	.030	67	800

NOTES: Maximum Temperature Coefficient of Varistor Peak Voltage @ 1mA DC = - 0.05%/°C (All Types).

(6) 1mA DC current pulse, 20 msec Min. (7) $I = KV^{\alpha}$, Where $\alpha = \frac{\text{Log } I_2 / I_1}{\text{Log } V_2 / V_1}$

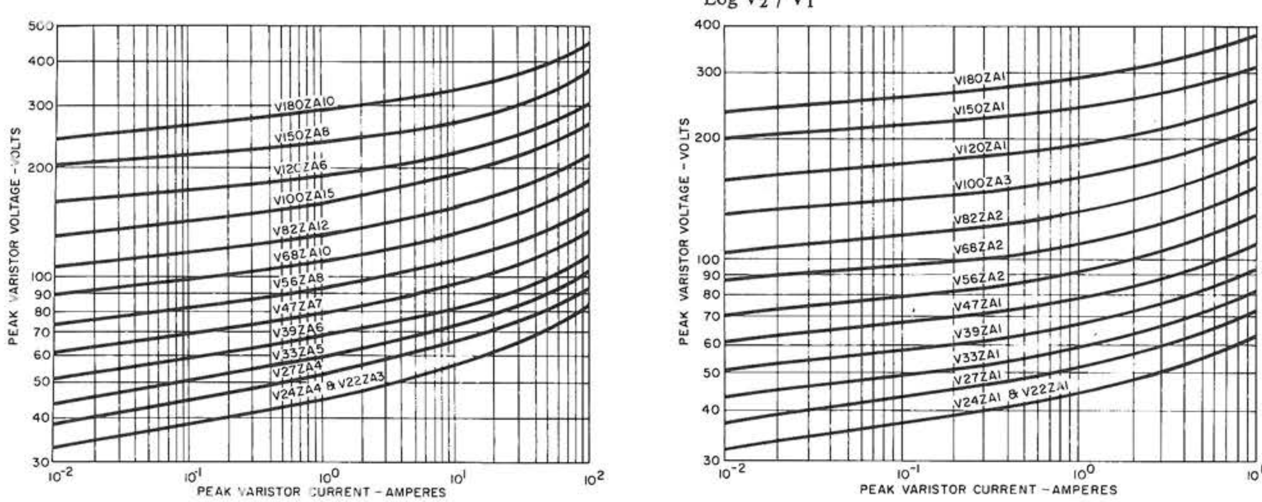
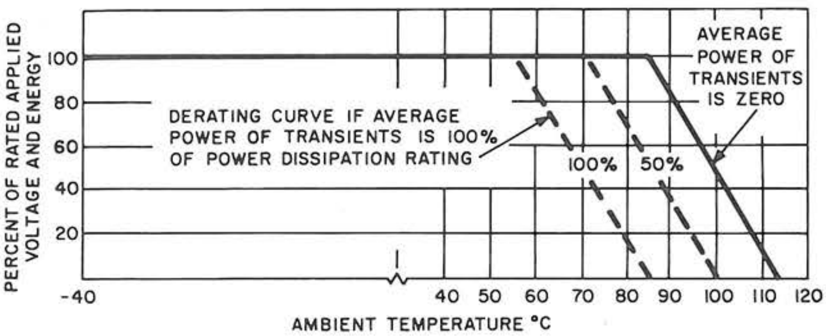


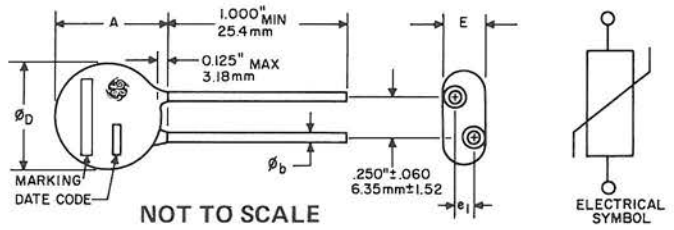
Figure 4. MAXIMUM VOLT-AMPERE CHARACTERISTICS (T_A = 25°C)



The maximum allowable operating ambient temperature without derating is 85°C if the average power of the input transients is zero. This condition is satisfied if the voltage transients are random and non repetitive. Above 85°C the applied voltage and energy ratings both are reduced.

If the voltage transients are repetitive the allowable ambient is reduced according to the level of the average power input. For example, if the average power of the transients is 50% of the dissipation rating the maximum allowable ambient temperature without derating is 70°C. Then, for operation above 70°C the applied voltage and energy ratings are linearly reduced to zero at 100°C.

Figure 5. VOLTAGE AND ENERGY RATINGS VS. AMBIENT TEMPERATURE AND AVERAGE POWER OF INPUT TRANSIENTS

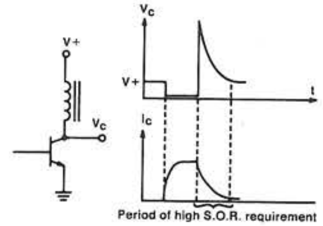


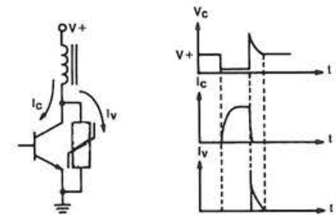
MODEL NUMBER	MARKING	A		ØD		E		e1				Øb			
		MAX.		MAX.		MAX.		MIN.		MAX.		MIN.		MAX.	
		IN	MM	IN	MM	IN	MM	IN	MM	IN	MM	IN	MM	IN	MM
V22ZA1	22Z1	.461	11.7	.335	8.51	.158	4.0	.038	0.98	.079	2.0	.023	.59	.027	.68
V22ZA3	V22A3	.745	16.9	.636	16.15	.173	4.4	.043	1.09	.079	2.0	.030	.77	.034	.86
V24ZA1	24Z1	.461	11.7	.315	8.51	.158	4.0	.038	0.98	.079	2.0	.023	.59	.027	.68
V24ZA4	V24ZA4	.745	18.9	.636	16.15	.173	4.4	.043	1.09	.079	2.0	.030	.77	.034	.86
V27ZA1	27Z1	.461	11.7	.335	8.51	.158	4.0	.038	0.98	.079	2.0	.023	.59	.027	.68
V27ZA4	V27ZA4	.745	18.9	.636	16.15	.197	5.0	.054	1.36	.099	2.5	.030	.77	.034	.86
V33ZA1	33Z1	.461	11.7	.335	8.51	.158	4.0	.038	0.98	.079	2.0	.023	.59	.027	.68
V33ZA5	V33ZA5	.745	18.9	.636	16.15	.197	5.0	.054	1.36	.099	2.5	.030	.77	.034	.86
V39ZA1	39Z1	.461	11.7	.335	8.51	.178	4.5	.048	1.24	.099	2.5	.023	.59	.027	.68
V39ZA6	V39ZA6	.745	18.9	.636	16.15	.197	5.0	.054	1.36	.099	2.5	.030	.77	.034	.86
V47ZA1	47Z1	.461	11.7	.335	8.51	.197	5.0	.059	1.50	.119	3.0	.023	.59	.027	.68
V47ZA7	V47ZA7	.745	18.9	.636	16.15	.212	5.4	.065	1.63	.119	3.0	.030	.77	.034	.86
V56ZA2	56Z2	.461	11.7	.335	8.51	.197	5.0	.059	1.50	.119	3.0	.023	.59	.027	.68
V56ZA8	V56ZA8	.745	18.9	.636	16.15	.237	6.0	.075	1.90	.138	3.5	.030	.77	.024	.68
V68ZA2	68Z2	.461	11.7	.335	8.51	.217	5.5	.068	1.75	.138	3.5	.023	.59	.027	.68
V68ZA10	V68ZA10	.745	18.9	.636	16.15	.251	6.4	.086	2.17	.158	4.0	.030	.77	.034	.86
V82ZA2	82Z2	.461	11.7	.335	8.51	.237	6.0	.079	2.01	.158	4.0	.023	.59	.027	.68
V82ZA12	V82ZA12	.745	18.9	.636	16.15	.275	7.0	.097	2.44	.178	4.5	.030	.77	.034	.86
V100ZA3	100Z	.461	11.7	.335	8.51	.256	6.5	.089	2.27	.178	4.5	.023	.59	.027	.68
V100ZA15	V100ZA15	.745	18.9	.636	16.15	.291	7.4	.107	2.71	.197	5.0	.030	.77	.034	.86
V120ZA1	120Z	.461	11.7	.335	8.51	.158	4.0	.038	0.98	.079	2.0	.023	.59	.027	.68
V120ZA6	V120ZA6	.745	18.9	.636	16.15	.197	5.0	.059	1.36	.099	2.5	.030	.77	.034	.86
V150ZA1	150Z	.461	11.7	.335	8.51	.178	4.5	.048	1.24	.099	2.5	.023	.59	.027	.68
V150ZA8	V150ZA8	.745	18.9	.636	16.15	.197	5.0	.054	1.36	.099	2.5	.030	.77	.034	.86
V180ZA1	180Z	.461	11.7	.335	8.51	.178	4.5	.048	1.24	.099	2.5	.023	.59	.027	.68
V180ZA10	V180ZA10	.745	18.9	.636	16.15	.212	5.4	.065	1.63	.119	3.0	.030	.77	.034	.86

GE-MOV® VARISTOR APPLICATIONS

ELECTRONIC SWITCHING OF INDUCTIVE LOADS

When an inductive load is switched off by a transistor, a high S.O.R. (Safe Operation Region) is required of the transistor to prevent reverse-biased second breakdown. If a GE-MOV® Varistor is connected from collector to emitter, the energy stored in the inductor is no longer forced through the transistor but instead is transferred to the Varistor. This results in a significant decrease in transistor stress and a much more reliable circuit operation.

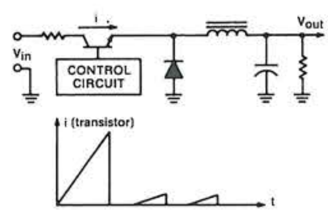


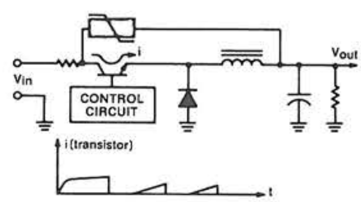


ELECTRONIC SWITCHING FOR REGULATION

Sudden application of supply voltage (or initial turn-on) can damage a switch mode regulator switching device by subjecting it to the heavy current surge required to charge the uncharged filter capacitor.

A GE-MOV® Varistor can be used to shunt the initial surge around the switching device, precharging the capacitor to a safe value. The Varistor will not affect circuit operation at times other than at initial turn-on because it draws extremely little current at a voltage of $V_{IN} - V_{OUT}$. Applied in this manner, the GE-MOV® Varistor can offer important protection for a line operated power supply.





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180.59	GE-MOV® Varistor "L" Series (Up to 1000 volts RMS)

GE-MOV®

Metal Oxide Varistors

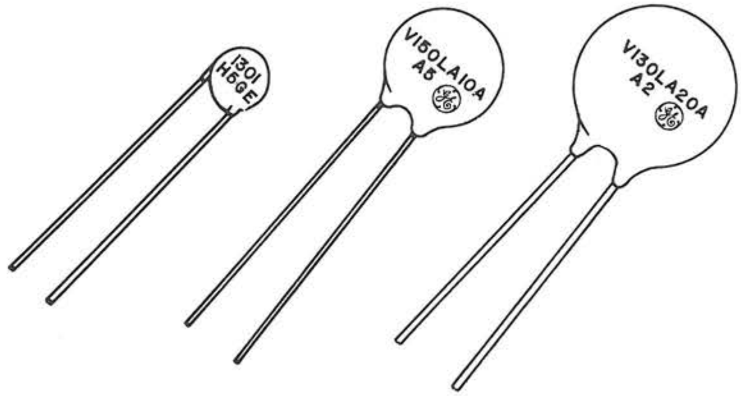
RATINGS OF 130-1200 VOLTS D.C., 95-1000 VOLTS RMS, 1-160 JOULES

SERIES L

Description:

GE-MOV® zinc oxide varistors are voltage dependent, symmetrical resistors which perform in a manner similar to back-to-back zener diodes in circuit protective functions and offer advantages in performance and economics.

When exposed to high energy voltage transients, the varistor impedance changes from a very high standby value to a very low conducting value thus clamping the transient voltage to a safe level. The dangerous energy of the incoming high voltage pulse is absorbed by the GE-MOV® varistor, thus protecting your voltage sensitive circuit components.

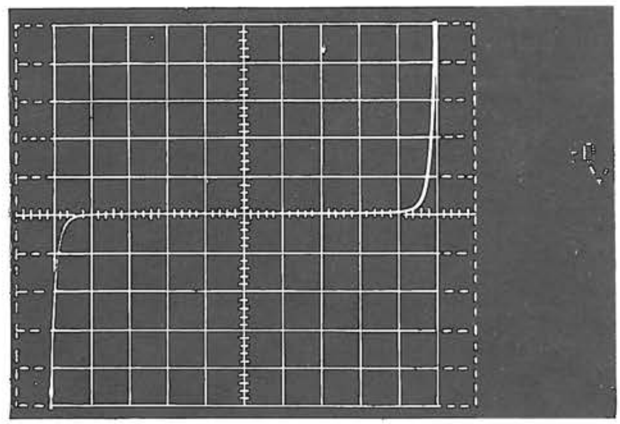


Replacement For:

- Zener Diodes
- Silicon Carbide
- Selenium Thyrectors
- R-C Networks (non dv/dt)

Features:

- Excellent Clamping
- High Transient Current Capability (2750 Amperes)
- Fast Response (Nanosecond Switching)
- Compact and Lightweight High Energy Capability
- Wide Operating Temperature Range
- Low Temperature Coefficient
- Low Standby Drain



I-V Oscillograph
(Actual Photo)

Benefits:

- Improves Circuit, Component and System Reliability
- Extends Contact Life
- Reduction of Lightning Effects
- Promotes System Cost Reduction
- Reduces System Size and Weight Requirements
- Increases Product Safety
- No Follow-On Current

Maximum Electrical Ratings:

Maximum Energy, Power and Peak Current . . . . See Rating Table
Storage Temperature, T_{STG} . . . . -40°C to +125°C
Operating Surface Temperature, T_S . . . . 115°C
Operating Ambient Temperature (Without Derating) . . . . 85°C
Maximum Voltage Temperature Coefficient . . . . -0.05%/°C

Mechanical Ratings:

Insulation Resistance — Megohms . . . . >1000
Hipot Encapsulation — Volts D.C. for 1 Minute 2500
Solderability . . . . Per Mil Std 202D Method 208B

MAXIMUM RATINGS TABLE

MODEL NUMBER	STEADY STATE (1)				TRANSIENT		
	MODEL SIZE (2)	RMS (3) APPLIED VOLTAGE	RECURRENT (3) PEAK IDLE VOLTAGE	DC APPLIED VOLTAGE	ENERGY (4)	AVERAGE (4) POWER DISSIPATION	PEAK (5) CURRENT FOR $t_p < 20\ \mu s$
		VOLTS	VOLTS	VOLTS	JOULES	WATTS	AMPERES
V95LA7A V95LA7B	2	95	134	130	7	0.45	1000 1200
V130LA1 V130LA2	1	130	184	175	1 2	0.24	100 200
V130LA10A V130LA20A V130LA20B	2 3 3	130	184	175	10 20 20	0.5 0.85 0.85	1000 2000 2500
V150LA1 V150LA2	1	150	212	200	1 2	0.24 0.24	100 200
V150LA10A V150LA20A V150LA20B	2 3 3	150	212	200	10 20 20	0.5 0.85 0.85	1000 2000 2500
V250LA2 V250LA4	1	250	354	330	2 4	0.28 0.28	100 200
V250LA15A V250LA20A V250LA40A V250LA40B	2 2 3 3	250	354	330	15 20 40 40	0.6 0.6 0.9 0.9	1000 1200 2000 2500
V275LA2 V275LA4	1	275	389	375	2 4	0.28	100 200
V275LA15A V275LA20A V275LA40A V275LA40B	2 2 3 3	275	389	369	15 20 40 40	0.6 0.6 0.9 0.9	1000 1200 2000 2500
V300LA2 V300LA4	1	300	424	405	2 4	0.28	100 200
V320LA15A V320LA20A V320LA40A V320LA40B	2 2 3 3	320	452	420	15 20 40 40	0.6 0.6 0.9 0.9	1000 1200 2000 2500
V420LB20A V420LB40A V420LB40B	2 3 3	420	595	560	20 40 40	0.55 0.9 0.9	1200 2200 2750
V460LB20A V460LB40A V460LB40B	2 3 3	460	650	615	20 40 40	0.55 0.9 0.9	1200 2200 2750
V480LB20A V480LB40A V480LB80A V480LB80B	2 2 3 3	480	679	640	20 40 80 80	0.55 0.7 1.0 1.0	800 1200 2200 2750
V510LB20A V510LB40A V510LB80A V510LB80B	2 2 3 3	510	721	675	20 40 80 80	0.55 0.7 1.0 1.0	800 1200 2200 2750
V550LB20A V550LB40A V550LB80A V550LB80B	2 2 3 3	550	778	700	20 40 80 80	0.6 0.7 1.0 1.0	800 1200 2200 2750
V575LB20A V575LB40A V575LB80A V575LB80B	2 2 3 3	575	813	730	20 40 80 80	0.65 0.8 1.1 1.1	800 1200 2200 2750
V1000LB80A V1000LB160A V1000LB160B	2 3 3	1000	1414	1200	80 160 160	0.9 1.3 1.3	1200 2200 2750

(1) Steady State defined as the normal input conditions existing when no transients are present.
(2) Relative size only (See Pages 95, 96 "Dimensions Table").
(3) Sinusoidal voltage assumed as normal input conditions. If nonsinusoidal wave input is present, peak voltage input values should be used to select model.
(4) See Figure 18.
(5) Peak current ratings specified with full bias applied. See Figure 17. For additional pulse shapes see Application Note 201.28 Energy Dissipation in GE-MOV ® Varistors for Various Pulse Shapes.

CHARACTERISTICS TABLE

MODEL NUMBER	CHARACTERISTICS AT 25°C				
	MODEL SIZE (2)	VARISTOR (6) PEAK VOLTAGE @ 1mA AC PEAK		MAXIMUM THERMAL RESISTANCE BODY TO AIR	TYPICAL CAPACITANCE f = .1 – 1MHz
		MINIMUM	MAXIMUM		
		VOLTS	VOLTS	°C/W	PICOFARADS
V95LA7A V95LA7B	2	134	207 170	67	1050
V130LA1 V130LA2	1	202	273	125	105
V130LA10A V130LA20A V130LA20B	2 3 3	184	254 254 238	60 37 37	700 1500 1500
V150LA1 V150LA2	1	227	301	125	105
V150LA10A V150LA20A V150LA20B	2 3 3	212	282 282 255	60 37 37	640 1400 1400
V250LA2 V250LA4	1	386	509	110	58
V250LA15A V250LA20A V250LA40A V250LA40B	2 2 3 3	354	472 472 472 428	50 50 35 35	375 375 820 820
V275LA2 V275LA4	1	423	579	110	53
V275LA15A V275LA20A V275LA40A V275LA40B	2 2 3 3	389	522 522 522 495	50 50 35 35	360 360 780 780
V300LA2 V300LA4	1	462	607	110	50
V320LA15A V320LA20A V320LA40A V320LA40B	2 2 3 3	462	635 635 635 580	50 50 35 35	300 300 650 650
V420LB20A V420LB40A V420LB40B	2 3 3	595	800 800 752	55 35 35	225 490 490
V460LB20A V460LB40A V460LB40B	2 3 3	650	878 878 800	55 35 35	210 460 460
V480LB20A V480LB40A V480LB80A V480LB80B	2 2 3 3	679	914 914 914 878	55 45 30 30	195 195 430 430
V510LB20A V510LB40A V510LB80A V510LB80B	2 2 3 3	721	970 970 970 914	55 45 30 30	185 185 405 405
V550LB20A V550LB40A V550LB80A V550LB80B	2 2 3 3	778	1060 1060 1060 963	50 45 30 30	175 175 390 390
V575LB20A V575LB40A V575LB80A V575LB80B	2 2 3 3	813	1115 1115 1115 970	47 36 27 27	165 165 365 365
V1000LB80A V1000LB160A V1000LB160B	2 3 3	1414	1900 1900 1750	35 24 24	90 210 210

(2) Relative size only (See Pages 95, 96 "Dimensions Table").
(6) 1 mA standby current based upon 60 Hz sinusoidal input.

MAXIMUM VOLT-AMPERE CHARACTERISTICS

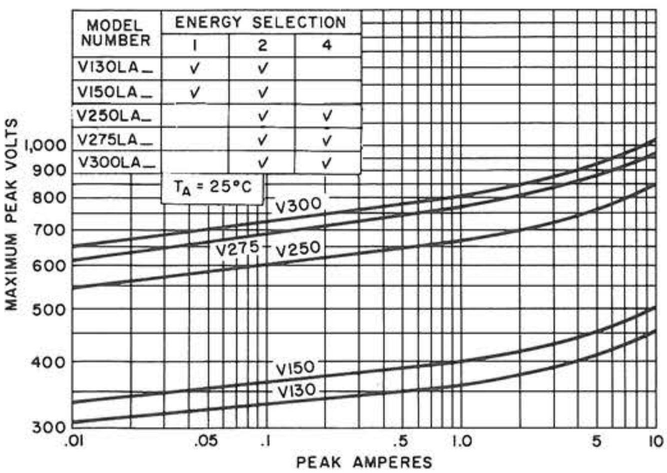


FIGURE 1

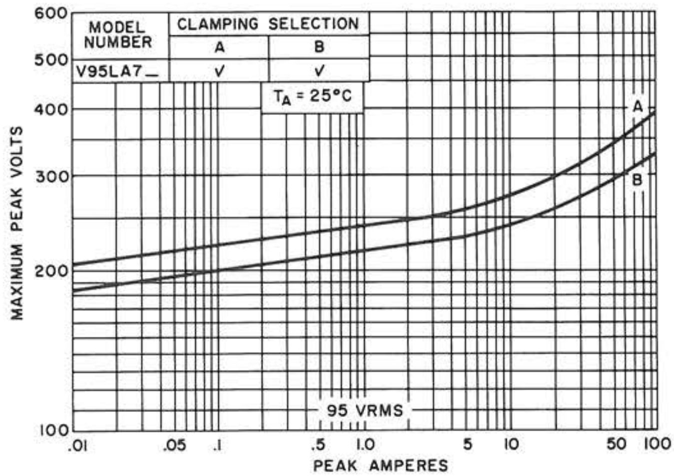


FIGURE 2

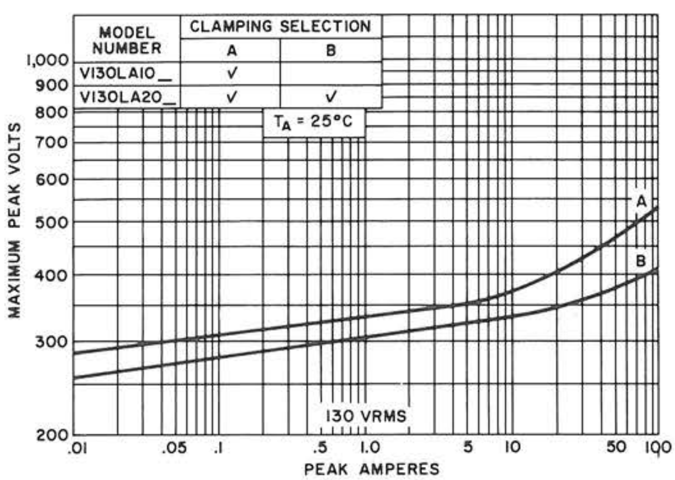


FIGURE 3

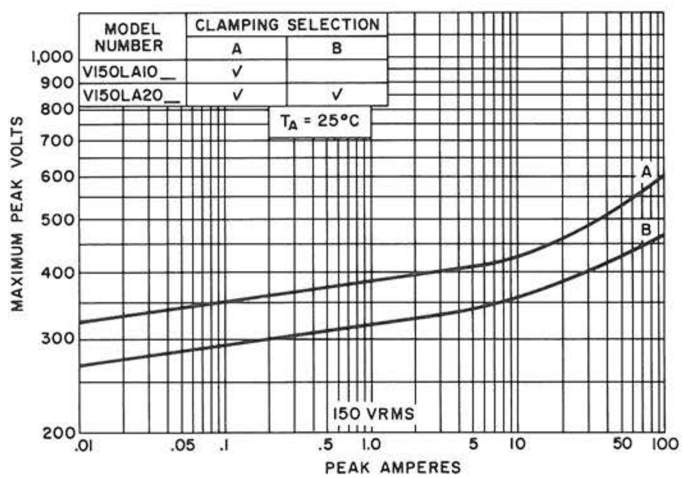


FIGURE 4

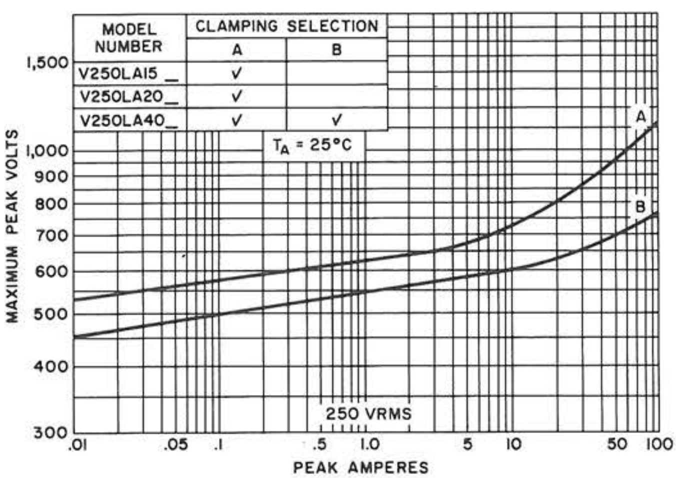


FIGURE 5

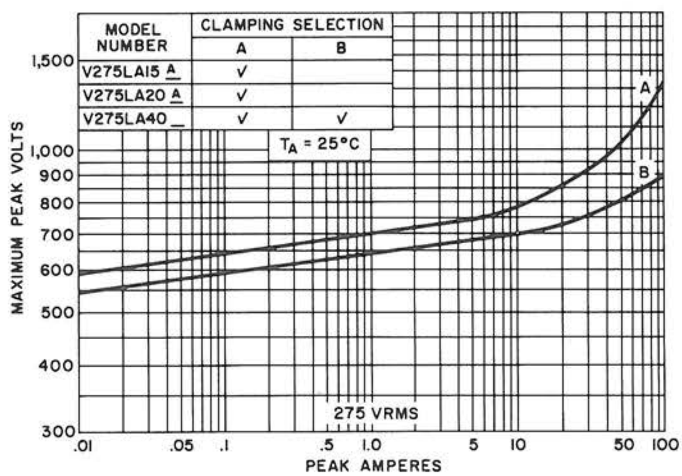


FIGURE 6

MAXIMUM VOLT-AMPERE CHARACTERISTICS

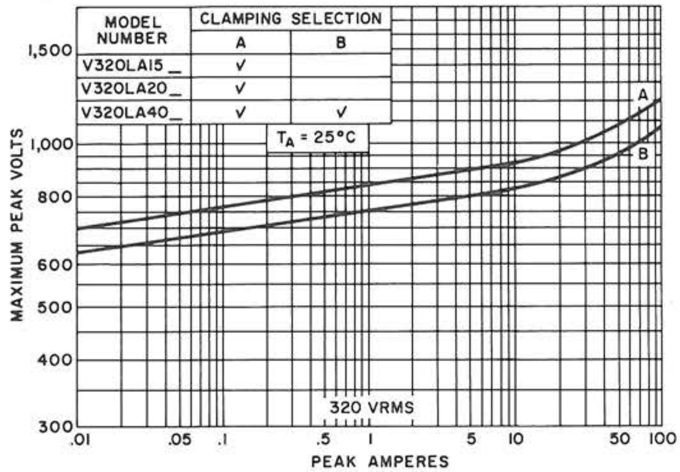


FIGURE 7

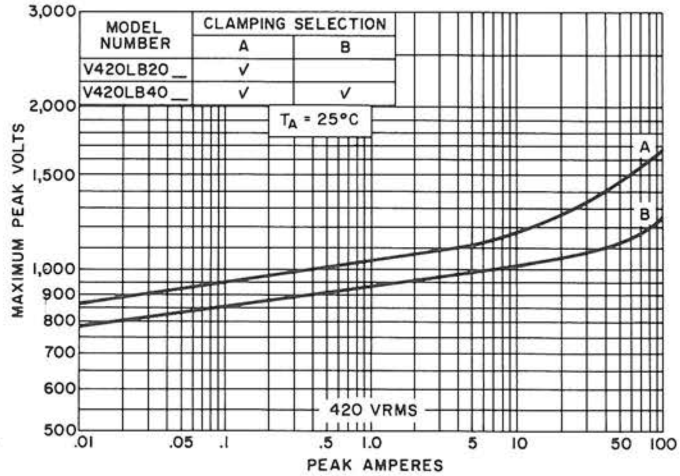


FIGURE 8

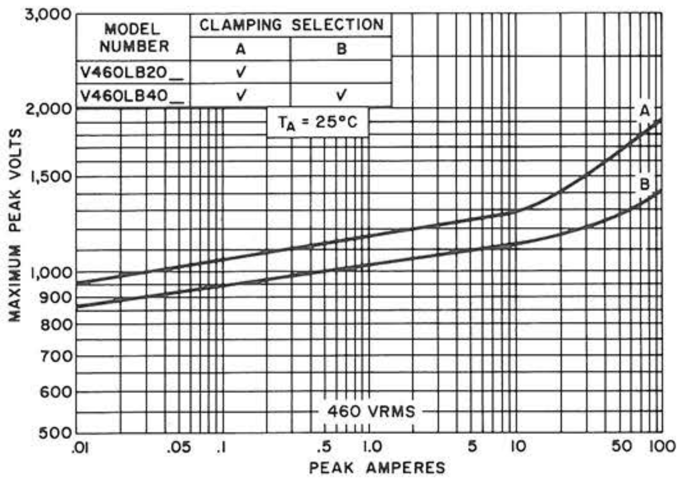


FIGURE 9

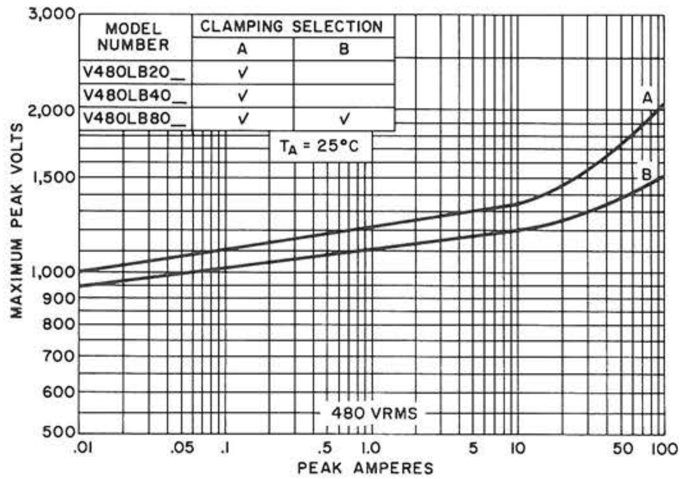


FIGURE 10

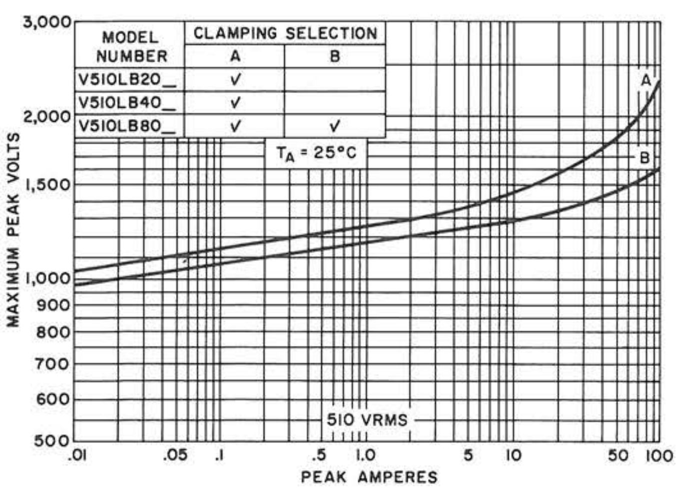


FIGURE 11

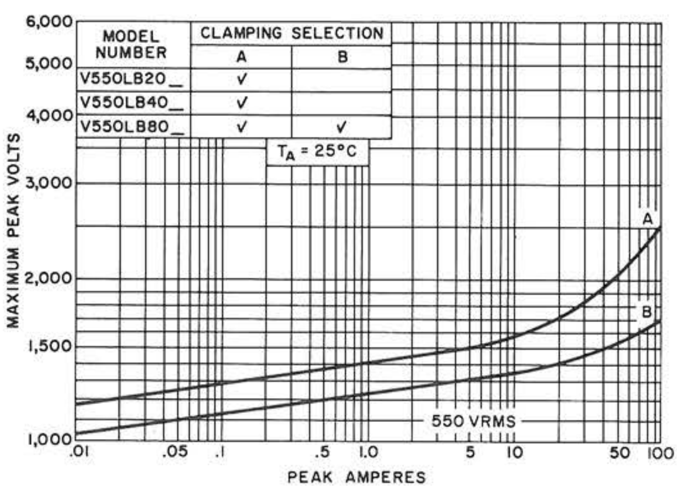


FIGURE 12

MAXIMUM VOLT-AMPERE CHARACTERISTICS

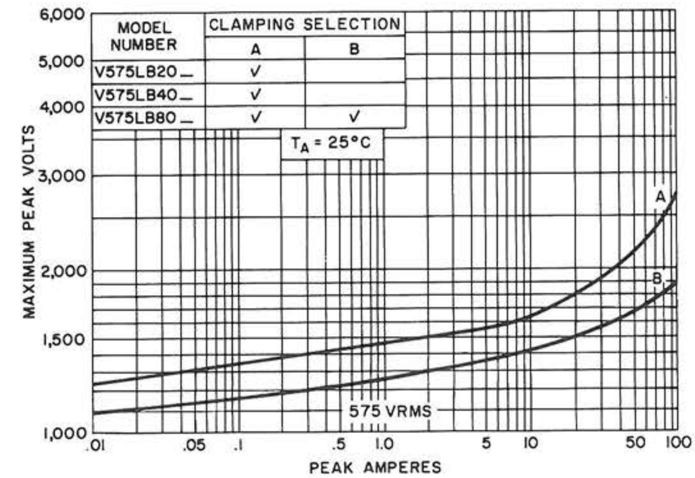


FIGURE 13

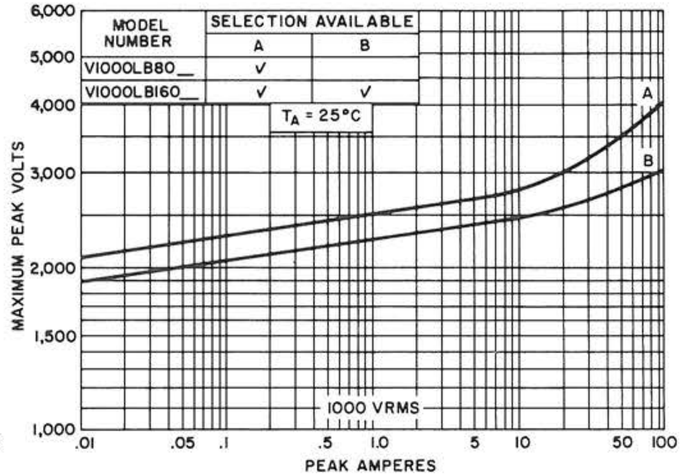


FIGURE 14

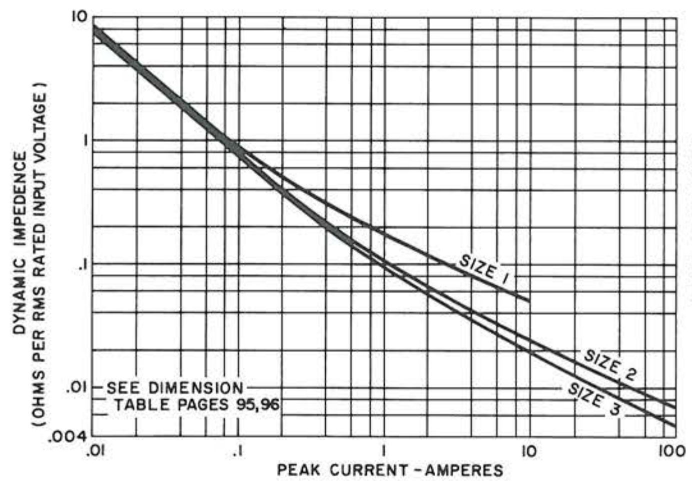


FIGURE 15 TYPICAL DYNAMIC IMPEDANCE VS. PEAK CURRENT

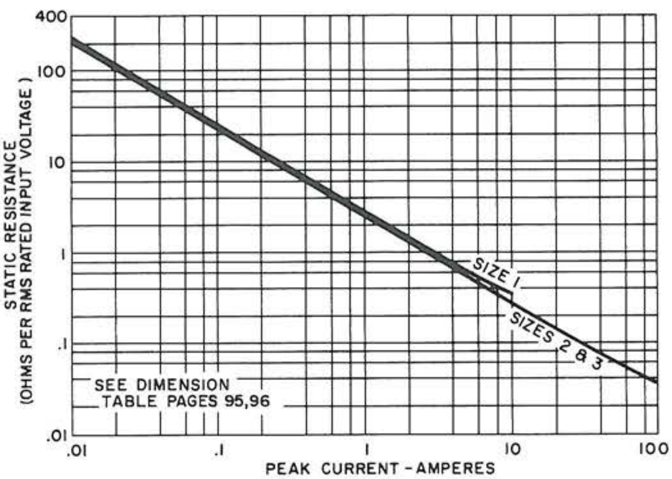


FIGURE 16 TYPICAL STATIC RESISTANCE VS. PEAK CURRENT

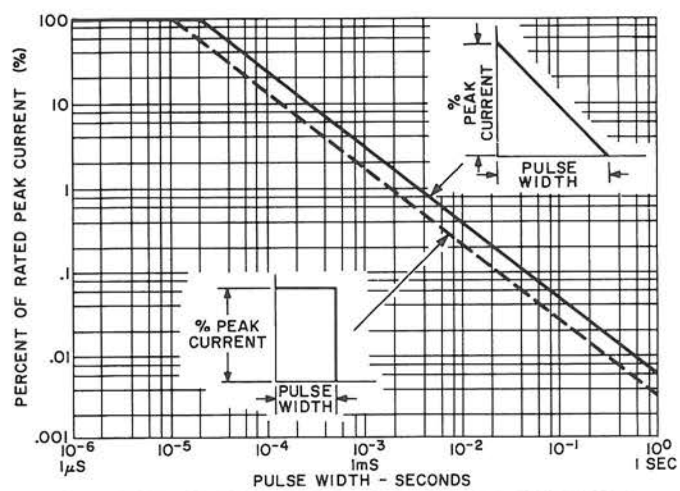


FIGURE 17 % NON-RECURRENT PEAK CURRENT VS. PULSE WIDTH (T_A = 25°)

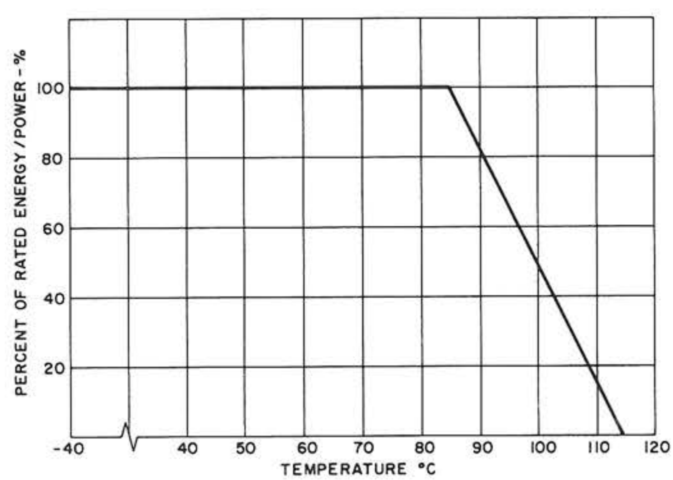
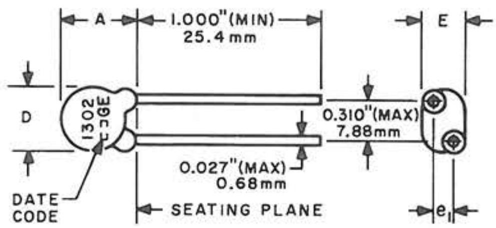


FIGURE 18 POWER AND ENERGY RATING VS. TEMPERATURE

DIMENSIONS TABLE

MODEL NUMBER	MARKING (1, 2)	A MAXIMUM		D MAXIMUM		E MAXIMUM		e_1 MINIMUM		e_1 MAXIMUM	
		INCHES	MM	INCHES	MM	INCHES	MM	INCHES	MM	INCHES	MM
V130LA1 V130LA2	1301 1302	.46	11.7	.34	8.7	.20	5.0	.07	1.9	.12	3.1
V150LA1 V150LA2	1501 1502					.21	5.3	.08	2.1	.13	3.3
V250LA2 V250LA4	2502 2504					.27	6.9	.12	3.2	.19	4.9
V275LA2 V275LA4	2752 2754					.29	7.4	.14	3.5	.22	5.5
V300LA2 V300LA4	3002 3004					.30	7.7	.15	3.8	.23	5.7

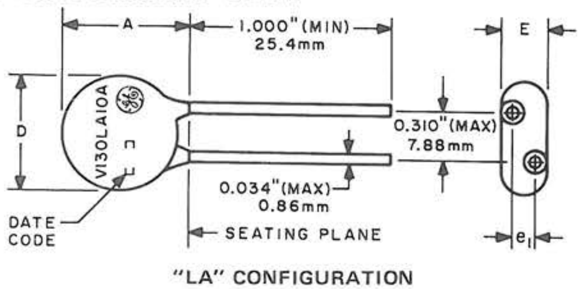
OUTLINE DRAWING SIZE 1



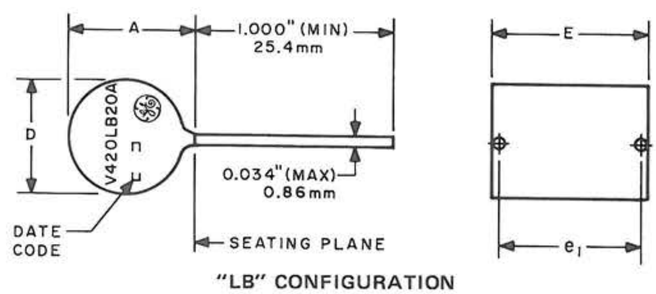
DIMENSIONS TABLE

MODEL NUMBER	MARKING (1, 2)	A MAXIMUM		D MAXIMUM		E MAXIMUM		e_1 MINIMUM		e_1 MAXIMUM	
		INCHES	MM	INCHES	MM	INCHES	MM	INCHES	MM	INCHES	MM
V95LA7	V95LA7 _	.74	18.9	.65	16.4	.17	4.4	.07	1.7	.11	2.7
V130LA10 V150LA10	V130LA10 _ V150LA10 _					.21	5.3	.08	2.1	.14	3.5
V250LA15 V250LA20	V250LA15 _ V250LA20 _					.26	6.7	.13	3.4	.20	5.0
V275LA15 V275LA20	V275LA15 _ V275LA20 _					.29	7.3	.14	3.7	.22	5.5
V320LA15 V320LA20	V320LA15 _ V320LA20 _					.32	8.2	.16	4.2	.25	6.4
V420LB20 V460LB20	V420LB20 _ V460LB20 _					.41	10.3	.21	5.4	.33	8.5
V480LB20 V480LB40	V480LB20 _ V480LB40 _					.42	10.7	.23	5.9	.35	8.8
V510LB20 V510LB40	V510LB20 _ V510LB40 _					.44	11.1	.25	6.4	.36	9.2
V550LB20 V550LB40	V550LB20 _ V550LB40 _					.46	11.6	.26	6.7	.38	9.6
V575LB20 V575LB40	V575LB20 _ V575LB40 _					.49	12.4	.27	6.9	.41	10.5
V1000LB80	V1000LB80 _					.72	18.4	.46	11.7	.65	16.5

OUTLINE DRAWING SIZE 2



"LA" CONFIGURATION



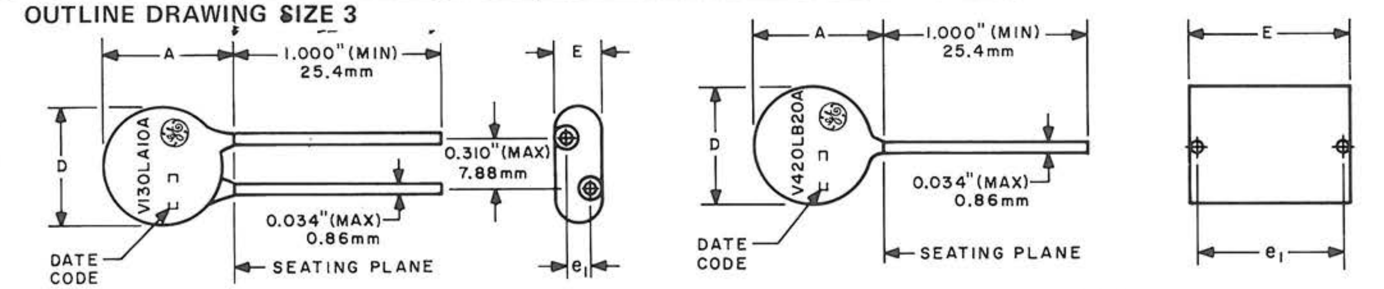
"LB" CONFIGURATION

(1) (–) A, B or C selection.
(2) All devices to be marked with part designation as indicated plus 2, digit date code and either the General Electric monogram or the initials GE.
(3) Drawings are not to scale.
(4) Lead dimensions as measured within 0.05 inches (1.3mm) of seating plane.

DIMENSIONS TABLE

MODEL NUMBER	MARKING (1, 2)	A MAXIMUM INCHES	A MAXIMUM MM	D MAXIMUM INCHES	D MAXIMUM MM	E MAXIMUM INCHES	E MAXIMUM MM	e_1 MINIMUM INCHES	e_1 MINIMUM MM	e_1 MAXIMUM INCHES	e_1 MAXIMUM MM
V130LA20 V150LA20	V130LA20 _ V150LA20 _	1.00	25.5	.89	22.5	.21	5.3	.08	2.1	.14	3.5
V250LA40 V275LA40	V250LA40 _ V275LA40 _					.29	7.3	.14	3.5	.22	5.6
V320LA40	V320LA40 _					.32	8.2	.17	4.4	.26	6.5
V420LB40 V460LB40	V420LB40 _ V460LB40 _	1.10	27.9	0.95	24.1	.41	10.4	.22	5.5	.34	8.7
V480LB80 V510LB80	V480LB80 _ V510LB80_					.44	11.1	.24	6.0	.37	9.4
V550LB80 V575LB80	V550LB80 _ V575LB80 _					.49	12.4	.27	6.8	.42	10.7
V1000LB160	V1000LB160 _					.73	18.6	.47	12.0	.67	16.9

OUTLINE DRAWING SIZE 3



"LA" CONFIGURATION

"LB" CONFIGURATION

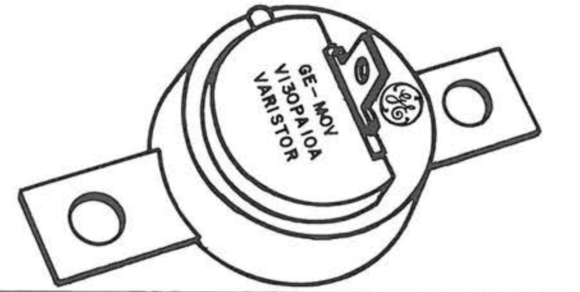
(1) (–) indicates A, B or C selection.
(2) All devices are to be marked with part designation as indicated, plus a 2-digit date code and either the General Electric Monogram or the initials GE.
(3) Drawings are not to scale.
(4) Lead dimensions as measured within 0.05 inches (1.3mm) of seating plane.

GE-MOV®

Metal Oxide Varistors

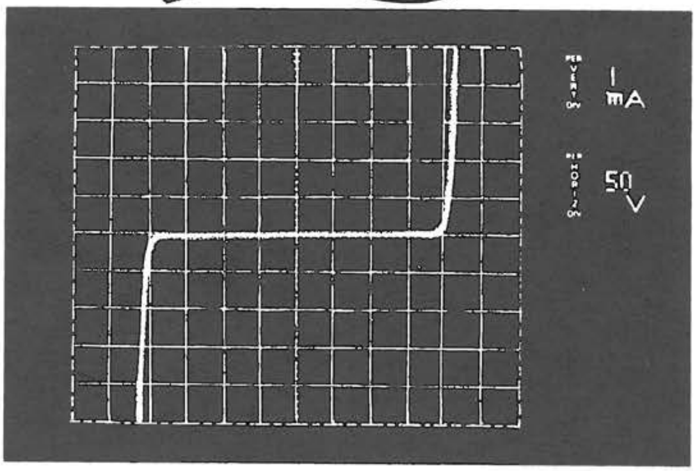
SERIES PA

RATINGS OF 170-750 VOLTS D.C., 130-575 VOLTS RMS.



Description:

GE-MOV® zinc oxide varistors are voltage dependent, symmetrical resistors which perform in a manner similar to back-to-back zener diodes in circuit protective functions and offers advantages in performance and economics. When exposed to high energy voltage transients, the varistor impedence changes from a very high standby valve to a very low conducting valve thus clamping the transient voltage to a safe level. The energy of the incoming high voltage pulse is absorbed by the GE-MOV® varistor, thus protecting sensitive circuit components.



I-V Oscillograph (Actual Photo)

Replacement For:

- Zener Diodes
- Silicon Carbide
- Selenium Thyrectors
- R-C Networks (non dv/dt)

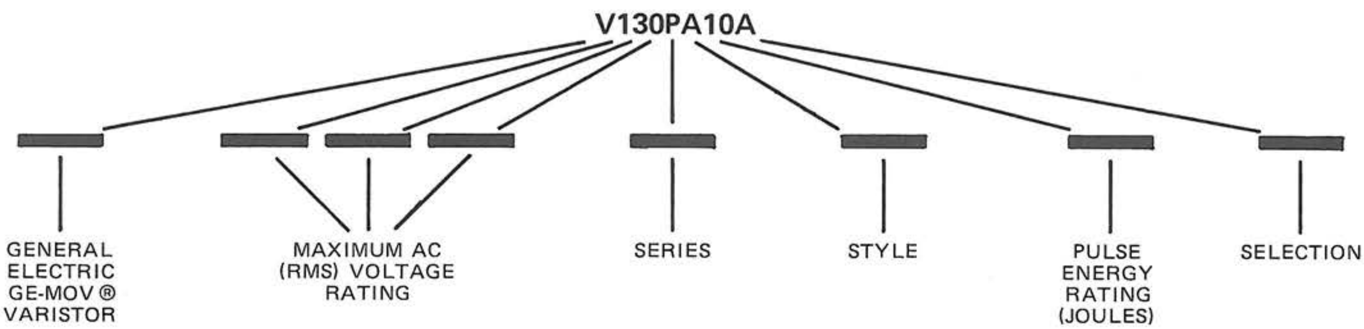
Features:

- Up to 15 Watt Average Power Dissipation
- NEMA Creep and Strike Distances
- Excellent Clamping (as low as 1.7 @ 10 amps.)
- Discharge Current Capability as high as 2750 amps.
- Energy Dissipation up to 80 watt-seconds
- Fast Response (<50 nanoseconds)
- Low Standby Power Dissipation
- Quick Connect Terminal

Benefits:

- Improves Circuit, Component and System Reliability
- Extends Contact Life
- Reduction of Lightning Effects
- Promotes System Cost Reduction
- Reduces System Size and Weight Requirements
- Increases Product Safety
- No Follow-On Current

Model Number Nomenclature:



Ratings:

Maximum Energy, Power and Peak Current . . . . See Rating Table
Storage Temperature, T_{STG} . . . . -40°C to +125°C
Maximum Hot Spot Temperature, T_{HS} . . . . 125°C
Operating Case Temperature (without derating). . . . . 70°C
Maximum Thermal Impedance Case to Ambient for Maximum Recurrent Peak AC Voltage . . . . ≤ 8°C/Watt
Maximum Thermal Impedance Case to Ambient for Maximum DC Input. . . . . ≤ 5°C/Watt
Maximum Voltage Temperature Coefficient . . . . -0.05%/°C

Mechanical:

Insulating Resistance – Megohms . . . . > 1000
Hipot Encapsulation – Volts DC for 1 Minute 2500
Maximum Weight . . . . 45 Grams

MAXIMUM RATINGS AND CHARACTERISTICS

MODEL NUMBER	RATINGS						CHARACTERISTICS		
	RMS [1,2] APPLIED VOLTAGE 50-60 HZ	RECURRENT PEAK APPLIED VOLTAGE	DC [1] APPLIED VOLTAGE	ENERGY [3]	AVERAGE [3] POWER DISSIPATION	PEAK [4] CURRENT	VARISTOR PEAK VOLTAGE @ 1MA AC MIN.	MAX.	THERMAL RESISTANCE HOT SPOT TO CASE
	VOLTS	VOLTS	VOLTS	JOULES	WATTS	AMPERES	VOLTS	VOLTS	°C/WATT
V130PA10 (*) 20 (*)	130	184	170	10 20	8 15	1200 2750	185	255	6.8 3.6
V150PA10 (*) 20 (*)	150	212	195	10 20	8 15	1200 2750	214	298	6.8 3.6
V250PA10 (*) 20 (*) 40 (*)	250	354	330	10 20 40	4 7 13	600 1200 2750	358	480	13.7 7.8 4.2
V275PA10 (*) 20 (*) 40 (*)	275	389	360	10 20 40	4 7 13	600 1200 2750	390	523	13.7 7.8 4.2
V320PA40 (*)	320	452	415	40	12	2750	448	601	4.5
V420PA20 (*) 40 (*)	420	595	540	20 40	5 10	1200 2750	585	802	11.0 5.5
V460PA20 (*) 40 (*)	460	650	600	20 40	5 10	1200 2750	648	880	11.0 5.5
V480PA20 (*) 40 (*) 80 (*)	480	679	625	20 40 80	3 5 10	600 1200 2750	680	918	18.3 11.0 5.5
V510PA20 (*) 40 (*) 80 (*)	510	721	655	20 40 80	3 5 10	600 1200 2750	713	962	18.3 11.0 5.5
V550PA20 (*) 40 (*) 80 (*)	550	778	720	20 40 80	3 5 9	600 1200 2750	782	1072	18.3 11.0 6.1
V575PA20 (*) 40 (*) 80 (*)	575	813	750	20 40 80	3 5 9	600 1200 2750	816	1119	18.3 11.0 6.1

1. Applied voltage is that voltage which appears across the varistor terminals when no transient is present. High line voltage conditions must be included in the value for applied voltage used to select the correct model.
2. For AC applications, a sinusoidal applied voltage is assumed to be the normal input condition. If applied voltage is non-sinusoidal, recurrent peak applied voltage values should be used to select correct model.
3. See Figure 12.
4. See Figure 13. Peak currents apply for full rated bias.

PEAK VOLT – AMPERE CHARACTERISTIC CURVES:

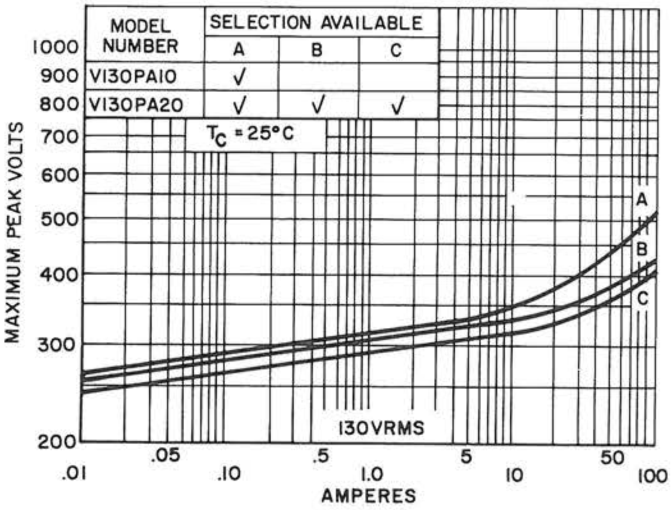


FIGURE 1

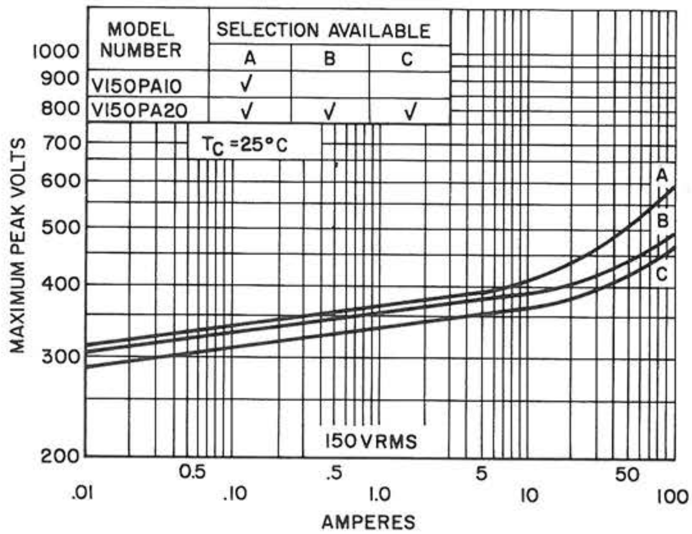


FIGURE 2

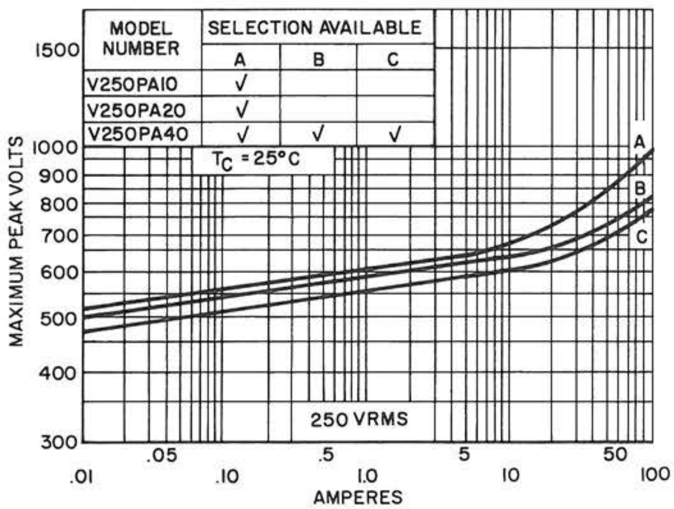


FIGURE 3

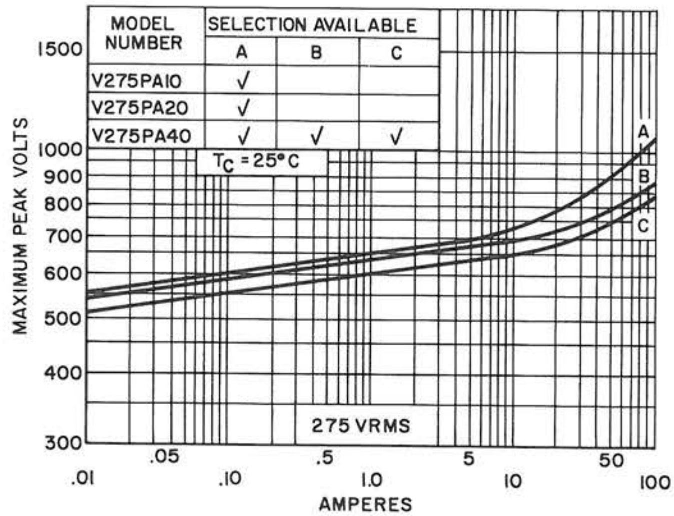


FIGURE 4

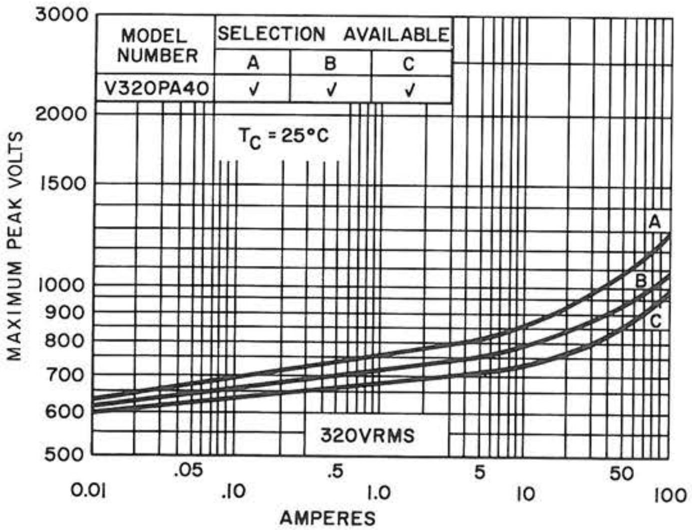


FIGURE 5

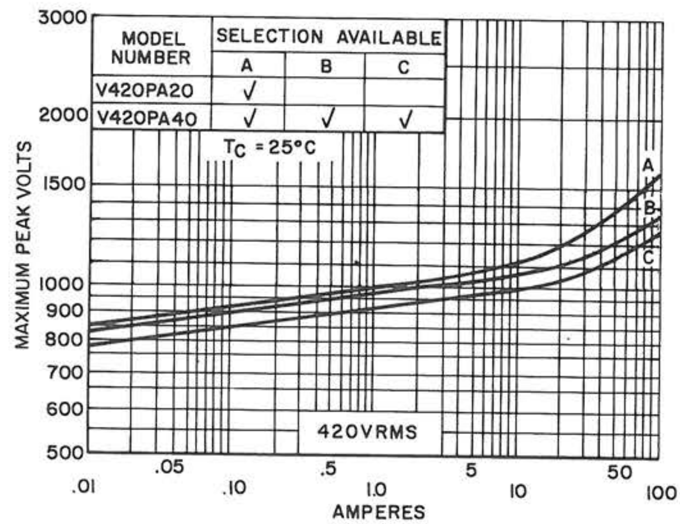


FIGURE 6

PEAK VOLT — AMPERE CHARACTERISTIC CURVES:

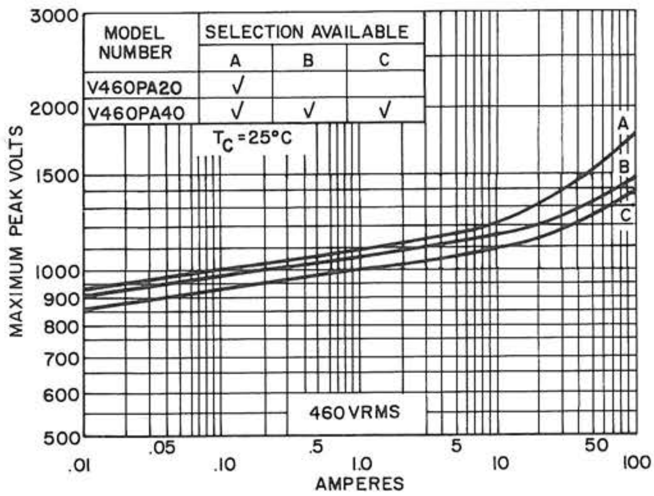


FIGURE 7

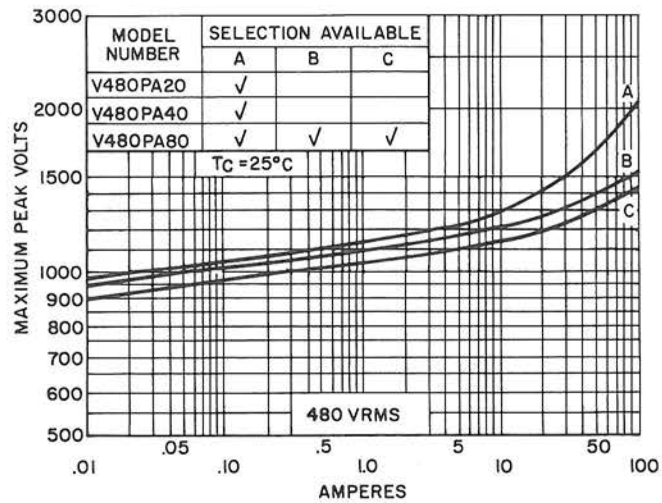


FIGURE 8

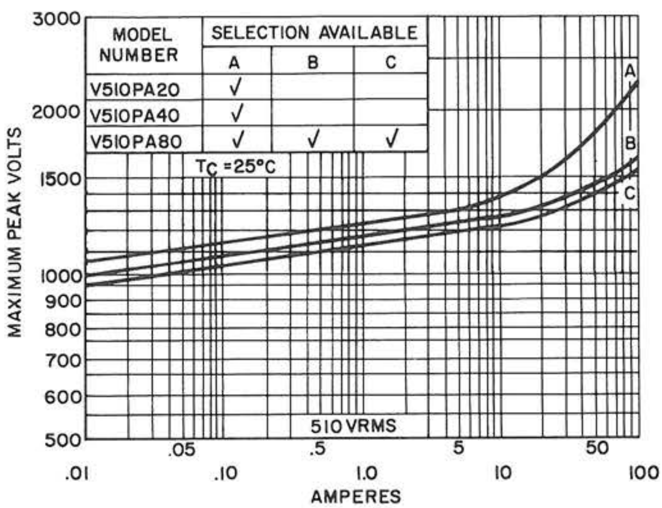


FIGURE 9

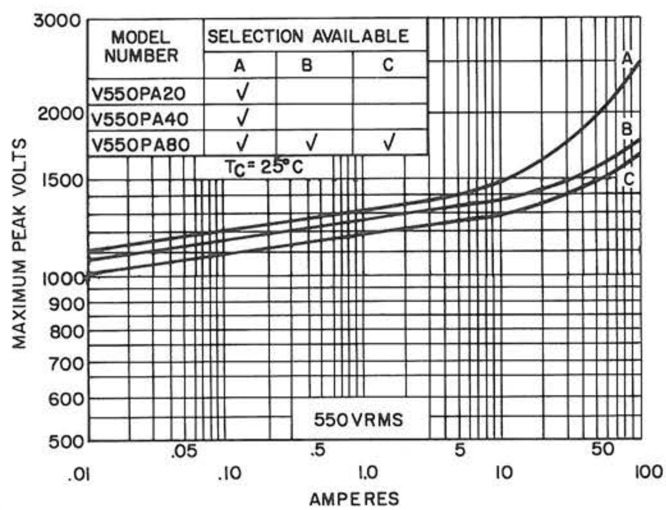


FIGURE 10

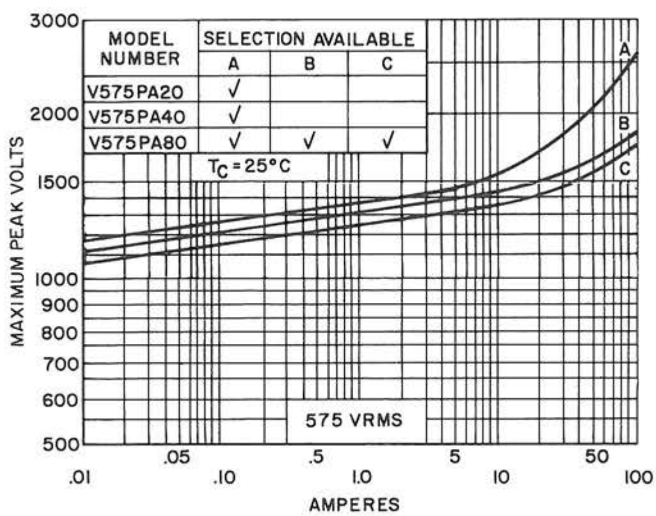


FIGURE 11

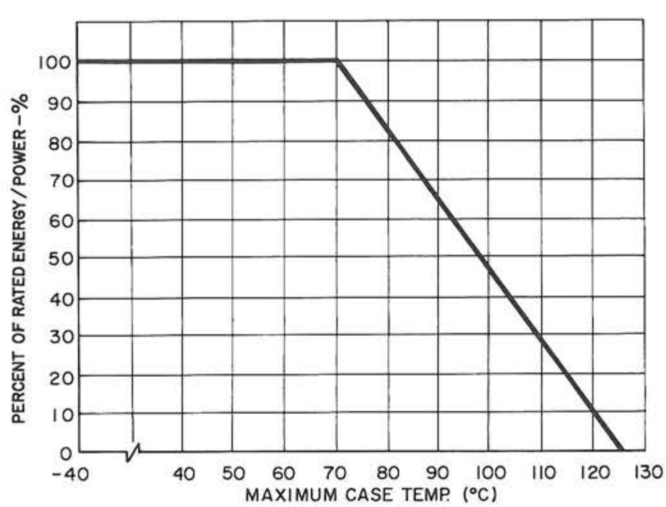


FIGURE 12

ENERGY AND POWER RATING VS. CASE TEMPERATURE

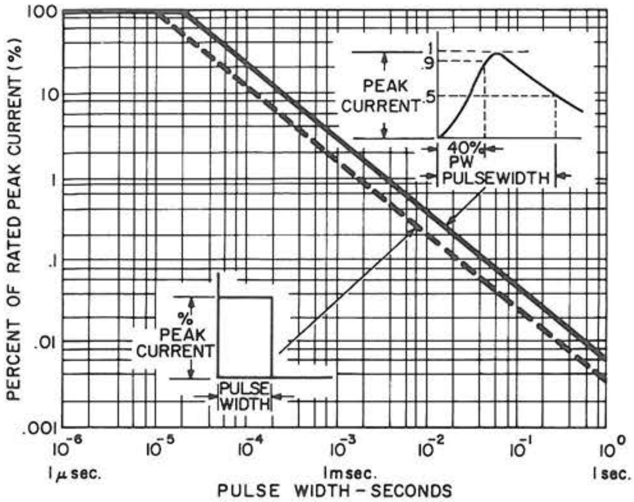


FIGURE 13

% NON-RECURRENT PEAK PULSE CURRENT VS PULSE WIDTH (T_A = 25°C)

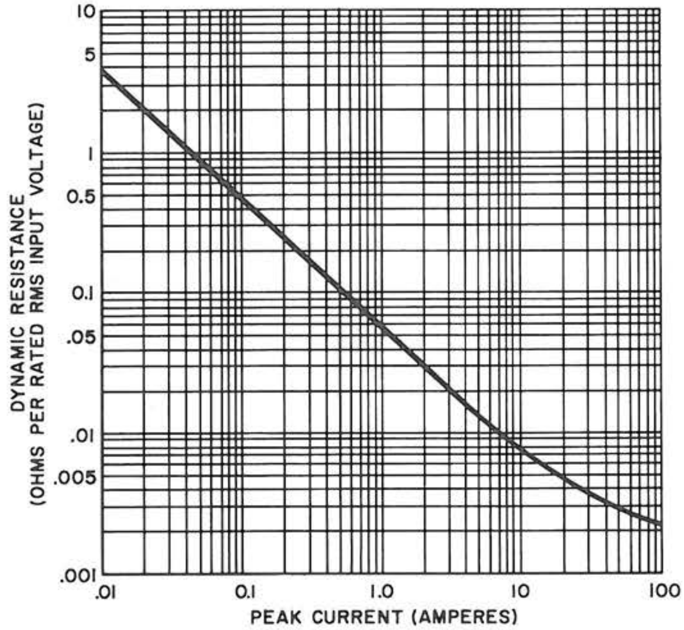


FIGURE 14

DYNAMIC RESISTANCE VS. PEAK CURRENT

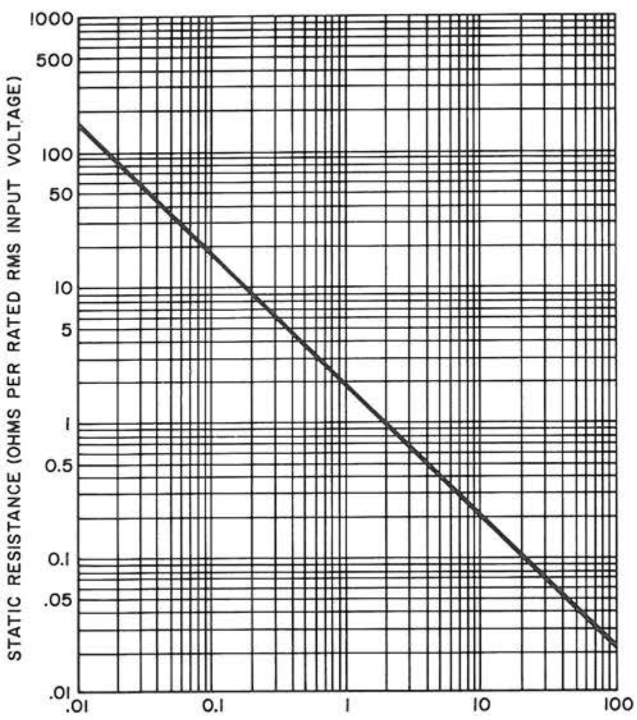
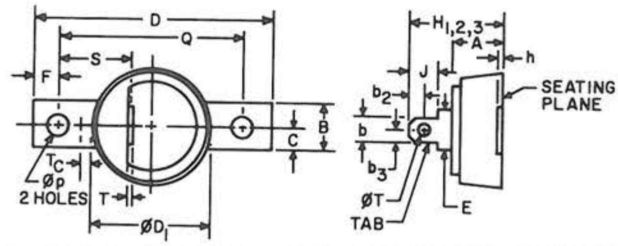


FIGURE 15

TYPICAL RESISTANCE VS. PEAK CURRENT



SYMBOL	INCHES			MILLIMETERS			NOTES
	MIN.	NOM.	MAX.	MIN.	NOM.	MAX.	
A			.57			14.3	
b			.26			6.6	1
b_2		.16			4.1		
b_3		.13			3.2		
B			.51			12.9	
C			.26			6.5	
D			2.61			66.2	
ϕD_1			1.32			33.5	
E		.44			11.2		
F		.30			7.7		
h		.03	.04		.8	.9	
H_1	.91		1.01	23.2		25.5	3
H_2	.96		1.12	24.6		28.3	3
H_3	1.03		1.29	26.3		32.6	3
J			.32			8.1	
ϕp	.22		.24	5.8		6.0	
Q	1.99	2.00	2.01	50.6	50.8	51.0	
S		.76			19.2		
T			.04			1.0	1
ϕT	.11			2.8			
T_c		.13			3.2		2

NOTES:

1. Tab is designed to fit 1/4″ quick connect terminal.
2. Case temperature is measured at T_C on top surface of base plate.
3. H_1 (130-150 V_{RMS} devices)
   H_2 (250-320 V_{RMS} devices)
   H_3 (420-575 V_{RMS} devices)
4. Electrical connection: top terminal and base plate.

FIGURE 16

DIMENSION TABLE

PROPER MOUNTING OF THE "PA" SERIES VARISTOR

When applying the varistor in a manner which requires high power dissipation capability, the possibility of necessary heat sinking should be taken into consideration. Figure 12 allows one to determine the maximum power dissipation for a given case temperature. To determine if a varistor has been properly heat sinked, a measurement of strap temperature, T_C, (see outline drawing) should be made under required worst case power and thermal conditions.

To describe the proper heat sink for any application, a fundamental knowledge of heat transference is required. Heat generated by power dissipated in the varistor, will flow through the mounting junction, to the heat sink, and finally to the surrounding ambient. The varistor case temperature (T_C) is a function of both the heat sink temperature (T_S) and the ambient temperature (T_A) which are directly proportional to the amount of heat flow (P) from the junction and the thermal resistances of the mounting ($R_{\theta CS}$) and the heat sink ($R_{\theta SA}$). Figure 17 shows a thermal schematic of a mounted varistor.

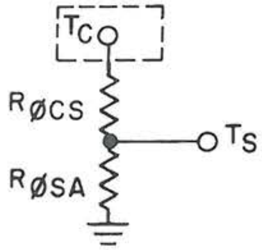


FIGURE 17
EQUIVALENT THERMAL RESISTANCE NETWORK FOR A POWER VARISTOR

The relationship between power dissipated (P), or heat flow, and temperature may be expressed as:

$$\frac{T_C - T_A}{P} = R_{\theta CS} + R_{\theta SA}$$

Table I lists some typical values for $R_{\theta CS}$ for various mounting methods.[1]

TABLE I

EXPECTED $R_{\theta CS}$ FOR
FOR GE-MOV® VARISTOR POWER PACKAGE

MOUNTING DESCRIPTION	TYPICAL $R_{\theta CS}$*
Screws (a)	0.9 °C/Watt
Screws (a) With Thermal Grease	0.3 °C/Watt
Screws (b) With Insulation Kit	2.0 °C/Watt
Screws (b) With Insulation Kit and Thermal Grease Both Faces	1.0 °C/Watt

(a) 10-32 Screw Torqued to 12-15 in lbs.
(b) 6-32 Screw Torqued to 405 in lbs.

*Values given in the table are for devices mounted on a clean, flat heatsink. The surface under the varistor contact surface should be flat to within .001 in. per inch with a surface finish of 63 micro-inches or smoother. Surfaces must be free of burrs, holes, paint or other foreign material and should be cleaned just prior to varistor mounting. Rough, curved or bent heatsink surfaces will cause increased thermal resistance and may result in premature device failure.

[1] For further information on heatsinking and values of $R_{\theta SA}$, refer to Application Note #200.55 *Handling and Thermal Considerations for General Electric Power Devices.*

TYPICAL NON-ISOLATED MOUNTING

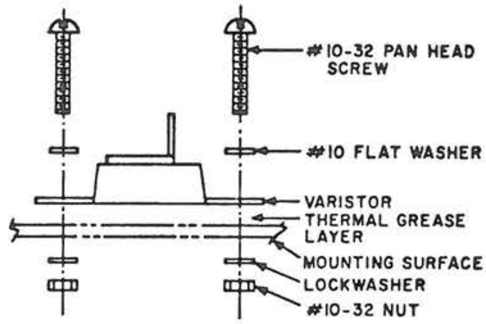


FIGURE 18

TYPICAL ISOLATED MOUNTING

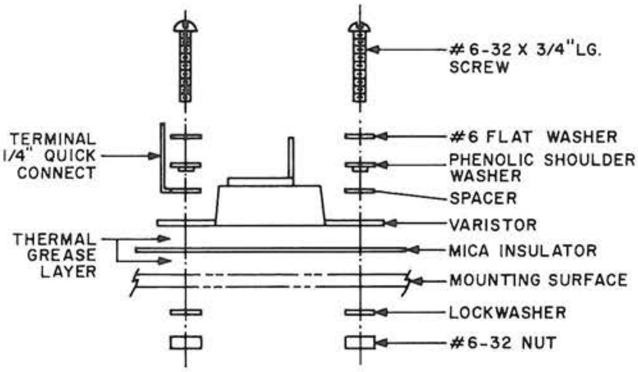


FIGURE 19

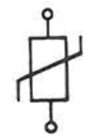
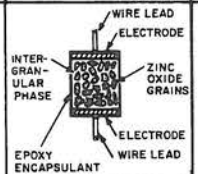
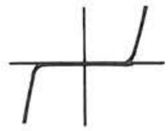
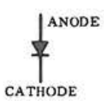
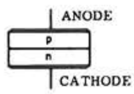
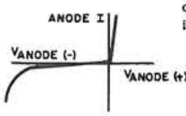
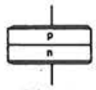
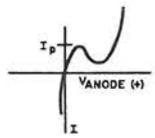
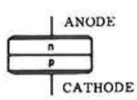
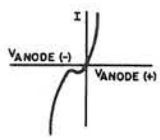
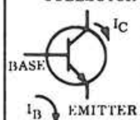
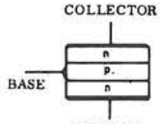
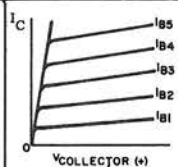
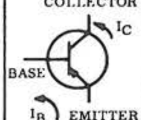
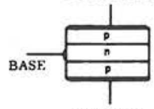
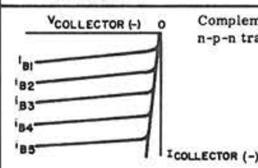
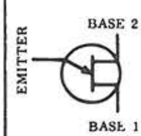
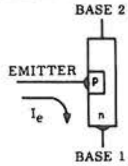
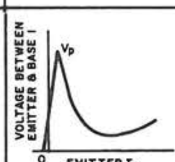
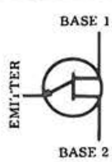
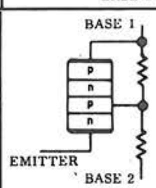
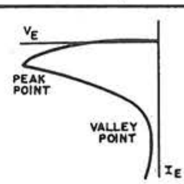
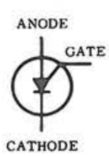
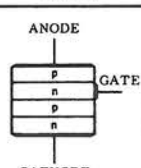
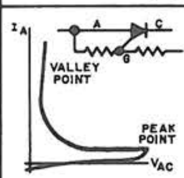
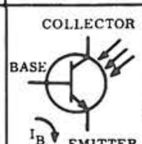
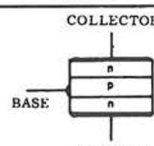
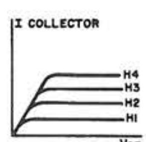
NOTE:

1 GE G623, Dow Corning, DC3, 4, 340, or 640 Thermal Grease is recommended.

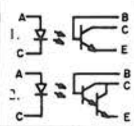
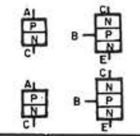
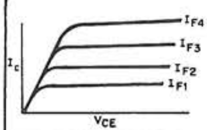
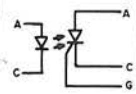
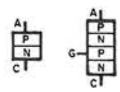
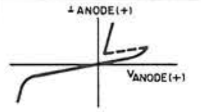
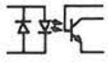
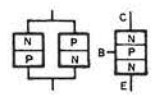
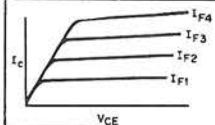
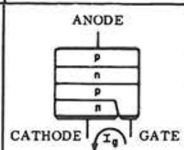
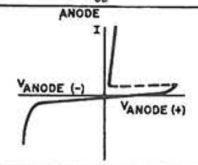
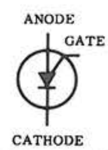
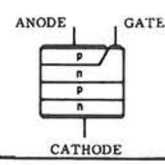
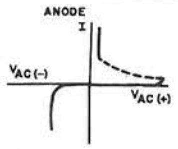
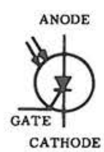
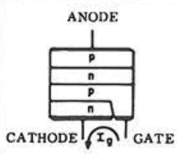
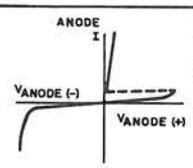
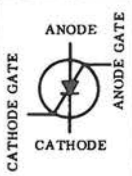
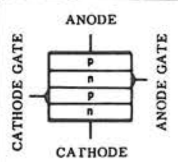
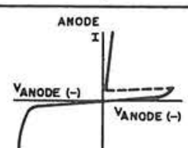
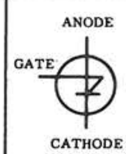
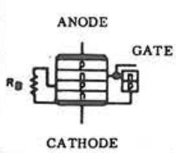
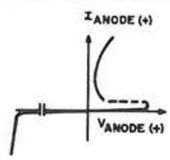
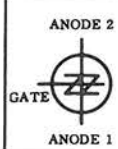
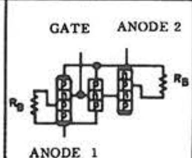
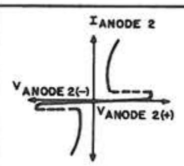
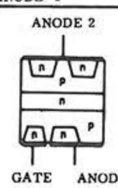
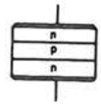
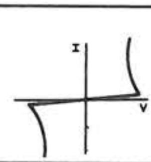
2 Isolation kits containing the following parts can be ordered by part #A7811055.

(1) MICA insulation 1" x 3.1" x .005" thick.
(2) #6-32 x 3/4" screw.
(2) #6 flat washer.
(2) Phenolic shoulder washer.
(2) #6 internal tooth lock washer.
(2) #6-32 nut.
(1) 1/4" quick connect terminal.
(1) Spacer

MAJOR GENERAL ELECTRIC SEMICONDUCTOR COMPONENTS

NAME OF DEVICE	CIRCUIT SYMBOL	COMMONLY USED JUNCTION SCHEMATIC	ELECTRICAL CHARACTERISTICS	MAJOR APPLICATIONS
GE-MOV® Varistor			 When exposed to high energy transients, the varistor impedance changes from a high standby value to a very low conducting value, thus clamping the transient voltage to a safe level.	Voltage transient protection High voltage sensing Regulation
Diode or Rectifier			 Conducts easily in one direction, blocks in the other	Rectification Blocking Detecting Steering
Tunnel Diode			 Displays negative resistance when current exceeds peak point current I_p	UHF converter Logic circuits Microwave circuits Level sensing
Back Diode			 Similar characteristics to conventional diode except very low forward voltage drop	Microwave mixers and low power oscillators
n-p-n Transistor			 Constant collector current for given base drive	Amplification Switching Oscillation
p-n-p Transistor			 Complement to n-p-n transistor	Amplification Switching Oscillation
Unijunction Transistor (UJT)			 Unijunction emitter blocks until its voltage reaches V_p; then conducts	Interval timing Oscillation Level Detector SCR Trigger
Complementary Unijunction Transistor (CUJT)			 Functional complement to UJT	High stability timers Oscillators and level detectors
Programmable Unijunction Transistor (PUT)			 Programmed by two resistors for V_p, I_p, I_v. Function equivalent to normal UJT.	Low cost timers and oscillators Long period timers SCR trigger Level detector
Photo Transistor			 Incident light acts as base current of the photo transistor	Tape readers Card readers Position sensor Tachometers

MAJOR GENERAL ELECTRIC SEMICONDUCTOR COMPONENTS

NAME OF DEVICE	CIRCUIT SYMBOL	COMMONLY USED JUNCTION SCHEMATIC	ELECTRICAL CHARACTERISTICS	MAJOR APPLICATIONS
Opto Coupler 1) Transistor (H11A, H15A) 2) Darlington (H11B, H15B) Outputs			 Output characteristics are identical to a normal transistor/Darlington except that the LED current (I_F) replaces the base drive (I_B).	Isolated interfacing of logic systems with other logic systems, power semiconductors and electro-mechanical devices. Solid state relays.
Opto Coupler SCR Output (H11C)			 With Anode voltage (+) the SCR can be triggered with a forward LED current. (Characteristics identical to a normal SCR except that LED current (I_F) replaces gate trigger current – I_{GT}).	Isolated interfacing of logic systems with AC power switching functions. Replacement of relays; microswitches.
AC Input Opto Coupler (H11AA)			 Identical to a "standard" transistor coupler except that LED current can be of either polarity.	Telecommunications – ring signal detection, monitoring line usage. Polarity insensitive solid state relay. Zero voltage detector.
Silicon Controlled Rectifier (SCR)			 With anode voltage (+), SCR can be triggered by I_g, remaining in conduction until anode I is reduced to zero	Power switching Phase control Inverters Choppers
Complementary Silicon Controlled Rectifier (CSCR)			 Polarity complement to SCR	Ring counters Low speed logic Lamp driver
Light Activated SCR* L8, L9			 Operates similar to SCR, except can also be triggered into conduction by light falling on junctions	Relay Replacement Position controls Photoelectric applications Slave flashes
Silicon Controlled Switch* (SCS)			 Operates similar to SCR except can also be triggered on by a negative signal on anode-gate. Also several other specialized modes of operation	Logic applications Counters Nixie drivers Lamp drivers
Silicon Unilateral Switch (SUS)			 Similar to SCS but zener added to anode gate to trigger device into conduction at ~ 8 volts. Can also be triggered by negative pulse at gate lead.	Switching Circuits Counters SCR Trigger Oscillator
Silicon Bilateral Switch (SBS)			 Symmetrical bilateral version of the SUS. Breaks down in both directions as SUS does in forward.	Switching Circuits Counters TRIAC Phase Control
Triac			 Operates similar to SCR except can be triggered into conduction in either direction by (+) or (–) gate signal	AC switching Phase control Relay replacement
Diac Trigger			 When voltage reaches trigger level (about 35 volts), abruptly switches down about 10 volts.	Triac and SCR trigger Oscillator

NOTES

NOTES

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