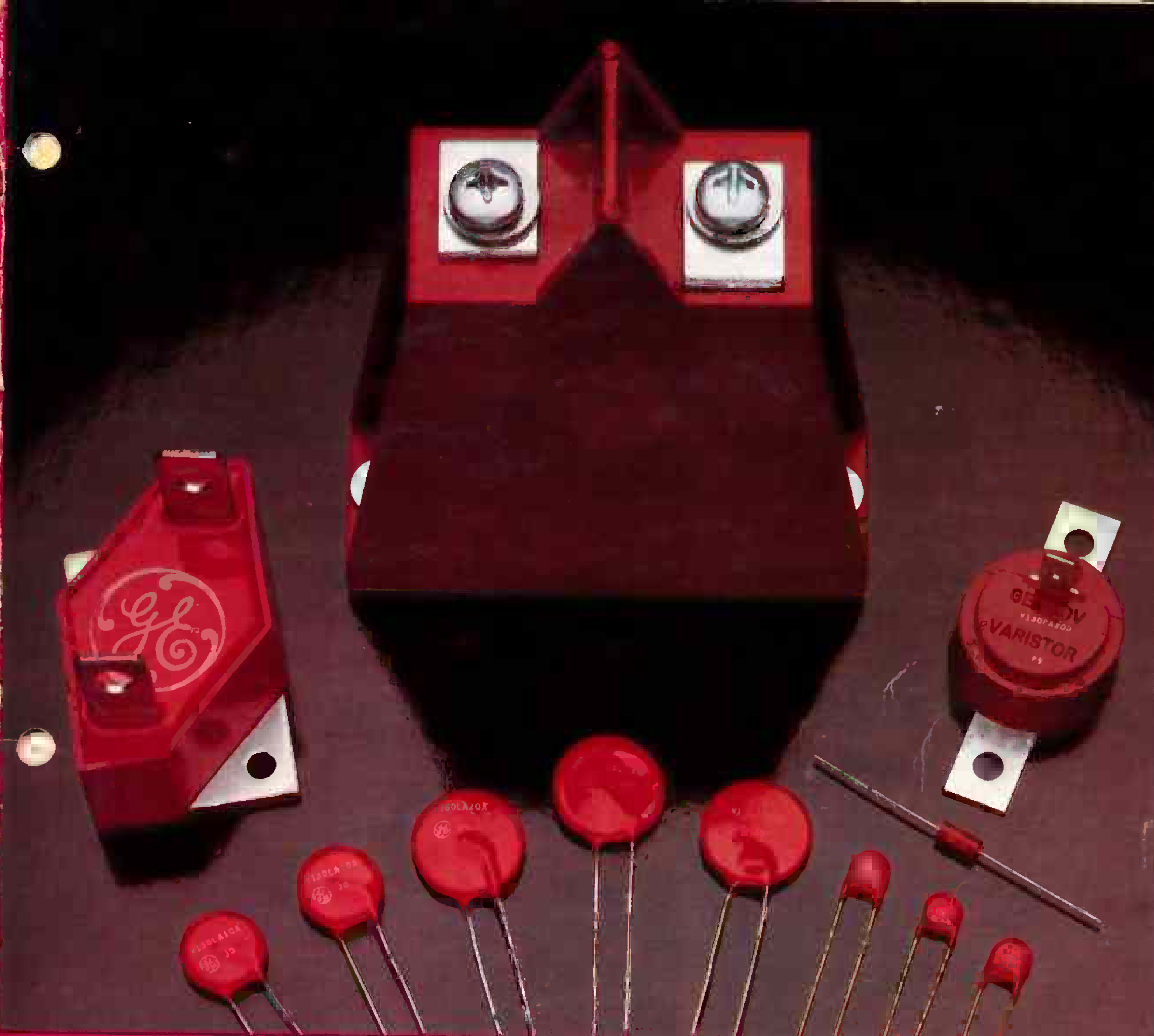


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# TRANSIENT VOLTAGE SUPPRESSION

GENERAL ELECTRIC

# TRANSIENT VOLTAGE SUPPRESSION

## Third Edition

Semiconductor Products Department
General Electric Company
Auburn, NY 13021

GENERAL ELECTRIC

# **Transient Voltage Suppression** manual, **Third Edition:**

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The Semiconductor Products Department of General Electric Company acknowledges the efforts of all the contributing authors and editors of the **First** and **Second Editions** of the General Electric **Transient Voltage Suppression** manual.

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# TABLE OF CONTENTS

## TABLE OF CONTENTS (Continued)

# INTRODUCTION

General Electric, a major U.S. manufacturer of electrical equipment, has for many years researched the causes, effects and frequency of transitory voltage variations resulting from atmospheric and other disturbances. Several members of General Electric's Research and Development Center are recognized worldwide as experts in this field. The need for expertise in this area has become even more critical as solid-state controls have achieved widespread incorporation into industrial, as well as consumer products.

Electromechanical and vacuum tube circuits were less susceptible to damage by high voltage transients, so there was little requirement for superior surge-voltage protection devices. With increased usage of solid-state controls, surge suppression requirements have become much more stringent. Traditional methods of suppression were in many instances no longer adequate—a new way had to be found. One solution was a new, ceramic, nonlinear semiconductor, generically known as a ZnO metal oxide varistor. General Electric's Semiconductor Products Department introduced the GE-MOV® metal oxide varistor in 1972, and its acceptance was instantaneous. Here was the solution to many of the new transient voltage suppression problems. It was fast (nanosecond response time), compact (typically 7-20mm. diameter, 1-3mm. thick), had high energy capability (up to 200J, 6000A surge) and was more economical than equivalent devices that had been used to suppress transients.

Since 1972, General Electric has refined suppression technology via improved varistor performance and has continued extensive research into causes and effects of transient voltages. Product improvements have evolved through better ceramic material and the introduction of new GE-MOV® Varistor package configurations to accommodate industry requirements. The latest of product developments from the Semiconductor Products Department is the introduction of the GE-MOV® II Varistor. The GE-MOV® II Varistor is an improved metal oxide varistor with energy capacity rated significantly above the original product. Now, for the same price and in the same size package, you are guaranteed more protection than ever before.

To complement the introduction of GE-MOV®II Varistors, General Electric has produced this completely revised *Third Edition Transient Voltage Suppression* manual. This is a demonstration that General Electric will continue to be a world leader in understanding the cause of equipment malfunction and failure and in devising preventative methods.

We trust you will find this manual useful in determining the suppression requirements of your products. General Electric offers a wide range of protection devices, from the small Molded Axial product rated below 2J and 100A, up to the High Energy product capable of 6500J and 50,000A. With this broad product offering, a solution to most transient voltage problems can be realized. GE-MOV®II Varistors are available to you from authorized electronic products distributors throughout the U.S. and the world. You may also obtain devices or further information from any one of our Electronic Components Sales offices listed on pages 162 and 163.

chapter 1

# VOLTAGE TRANSIENTS - AN OVERVIEW

To treat any problem, the scope of the problem must first be established. This chapter is an overview of the sources and nature of transient overvoltages, the problems they can cause and the equipment for testing and monitoring them.

Transients in electrical circuits result from the sudden release of previously stored energy. This energy can be stored within the circuit and released by a voluntary or controlled switching action or it can be stored outside the circuit and be injected or coupled into the circuit of interest by some action beyond the control of the circuit designer.

Transients may occur either in repeatable fashion or as random impulses. Repeatable transients, such as commutation voltage spikes, inductive load switching, etc., are more easily observed, defined and suppressed. Random transients are more elusive. They occur at unpredictable times, at remote locations, and require installation of monitoring instruments to detect their occurrence. In fact, a direct corollary of Murphy's law states that the best transient suppressor is a transient monitor! However, enough experience has been accumulated to provide reasonable guidelines for the transient environments in low voltage ac power circuits,[1,2] telecommunications equipment,[3] and automotive electrical systems.[4]

Effective transient overvoltage protection requires that the impulse energy be dissipated in the added suppressor at a voltage low enough to ensure the survival of circuit components. The following sections will discuss in detail the two categories of transients, how they occur, their effects and their detection.

## 1.1 REPEATABLE TRANSIENTS

A sudden change in the electrical conditions of any circuit will cause a transient voltage to be generated from the energy stored in circuit inductance and capacitance. The rate of change in current (di/dt) in an inductor (L) will generate a voltage equal to $-L\,di/dt$, and it will be of a polarity that causes current to continue flowing in the same direction.

It is this effect that accounts for most switching-induced transient overvoltages. It occurs as commutating spikes in power conversion circuits, when switching loads and under fault conditions. The effect is brief, since the source is limited to the energy stored in the inductance ($1/2\ Li^2$), and it is generally dissipated at a high instantaneous power (Energy = power x time). But the simple effect of one switching operation can be repeated several times during a switching sequence (consider arcing in the contact gap of a switch), so that cumulative effects can be significant.

### *1.1.1 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 winding can generate an oscillatory transient voltage with a peak amplitude up to twice the normal peak secondary voltage.

Subsequent oscillations depend on the L and C parameters of the circuit. Another important point to remember is that the secondary side will be part of a capacitive divider network in series with the transformer interwinding capacitance ($C_s$). This capacitively coupled voltage spike has no direct relationship to the turns ratio of the transformer, so that it is conceivable that the secondary circuit can see the peak applied primary voltage.

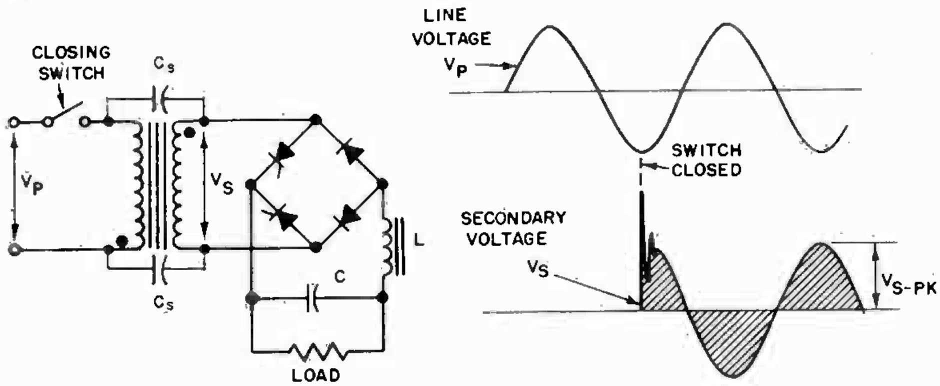


FIGURE 1.1: VOLTAGE TRANSIENT CAUSED BY ENERGIZING TRANSFORMER PRIMARY

### *1.1.2 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 voltage have been observed across power semiconductors when this type of switching occurs.

Interrupting the transformer magnetizing current, and the resulting collapse of the magnetic flux in the core, couples a high voltage transient into the transformer secondary winding, as shown in Figure 1.2.

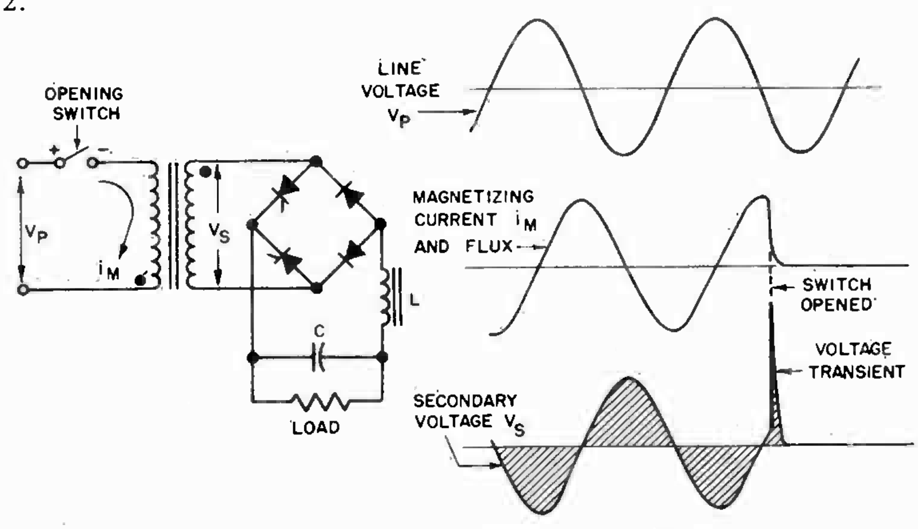


FIGURE 1.2: VOLTAGE TRANSIENT CAUSED BY INTERRUPTION OF TRANSFORMER MAGNETIZING CURRENT

Unless a low-impedance discharge path is provided, this burst of transient energy appears across the load. If this load is a semiconductor device or capacitor with limited voltage capabilities, that component may fail. The transients produced by interrupting the magnetizing current are usually quite severe. For example, the stored energy in the magnetizing field of a 150kVA transformer can be 9J.

*1.1.3 Fault with Inductive Power Source*

If a short develops on any power system, devices parallel to the load may be destroyed as the fuse clears.

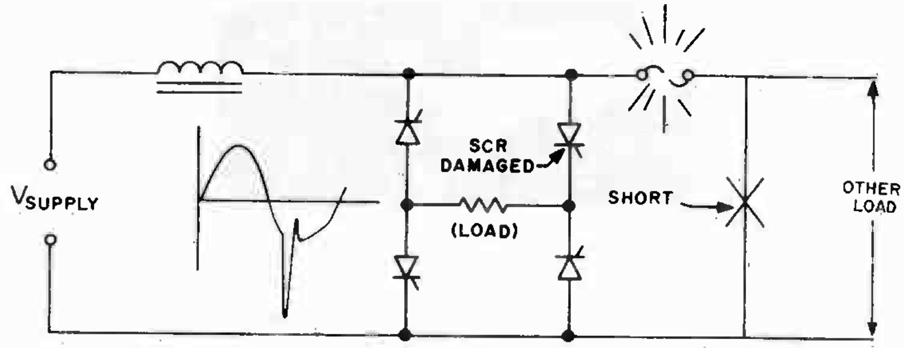


**FIGURE 1.3: VOLTAGE TRANSIENT CAUSED BY FUSE BLOWING DURING POWER FAULT**

When the fuse or circuit breaker of Figure 1.3 opens, it interrupts the fault current, causing the slightly inductive power source to generate a high voltage ($-L\,di/dt$), high energy ($1/2\,Li^2$) transient across any parallel devices. Suddenly interrupting a high current load will have a similar effect.

*1.1.4 Switch Arcing*

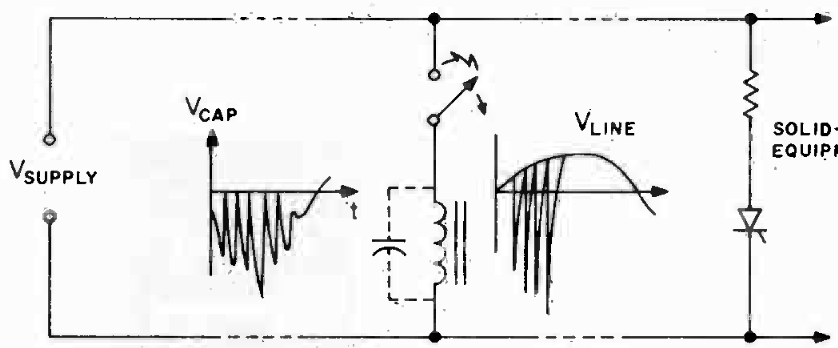


**FIGURE 1.4: VOLTAGE TRANSIENTS CAUSED BY SWITCH ARCING**

When current in an inductive circuit, such as a relay coil or a filter reactor, is interrupted by a contactor, the inductance tries to maintain its current by charging the stray capacitance. Similar action can take place during a closing sequence if the contacts bounce open after the initial closing. The high initial charging current will oscillate in the inductance and capacitance at a high frequency. When the voltage at the contact rises, breakdown of the gap is possible since the distance is still very small during the opening motion of the contact. The contact arc will clear at the current zero of the oscillation but it will restrike as the contact voltage rises again. As the contacts are moving farther apart, each restrike must occur at a higher and higher voltage until the contact succeeds in interrupting the current.

This restrike and escalation effect is particularly apparent in Figure 1.5, where a switch opens a relay coil of 1 H, having about 0.001 $\mu$F of distributed (stray) capacitance in the winding. Starting with an initial dc current of 100 mA, the circuit produces hundreds of restrikes (hence, the "white" band on the oscillogram) at high repetition rate, until the circuit clears, but not before having reached a peak of 3 kV in contrast to the initial 125 V in the circuit.

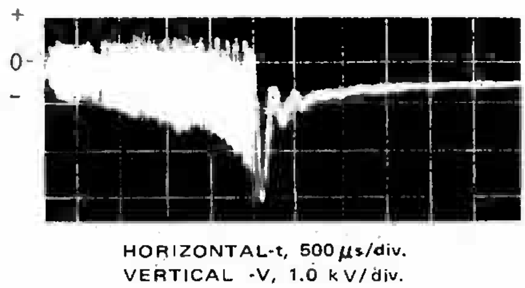


**FIGURE 1.5: VOLTAGE ESCALATION DURING RESTRIKES**

Electromechanical contacts generate transients which they generally can survive. However, in the example just discussed, the 2.5 ms long sequence of restrikes and attendant high current may be damaging to the contacts. Also, the transients injected into the power system during the restrike can be damaging to other loads.

In an attempt to eliminate electromechanical switches and their arcing problem, solid-state switches are recommended with good reason! However, if these switches are applied without discrimination in inductive circuits, the very effectiveness of the interruption can lead the solid-state switch to "commit suicide" by generating high transients,

In the example of Figure 1.6, the transistor used for switching 400mA in a 70mH solenoid is exposed to 420V spikes, although the circuit voltage is only 150V.

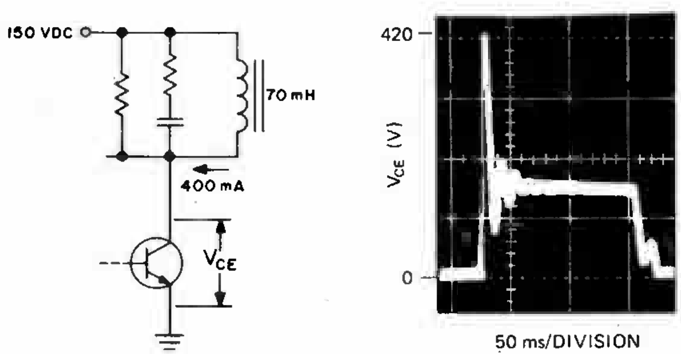


**FIGURE 1.6: TRANSISTOR SWITCHING TRANSIENT**

Whenever possible, a system should be examined for potential sources of transient overvoltage so they can be eliminated at the source, for one source can affect many components. If the sources are many (or unidentifiable) and the susceptible components few, it may be more practical then to apply suppression at the components.

## 1.2 RANDOM TRANSIENTS

Frequently, transient problems arise from the power source feeding the circuit. These transients create the most consternation because it is difficult to define their amplitude, duration and energy content. The transients are generally caused by switching parallel loads on the same branch of a distribution system, although they also can be caused by lightning. Communication lines, such as alarm and telephone systems, are also affected by lightning and power system faults.

To deal with random transients, a statistical approach has been taken to identify the nature of line overvoltages. While recordings of transients have been made, one cannot state that on a specific system there is an "X" probability of encountering a transient voltage of "Y" amplitude. Therefore, one is limited to quoting an "average" situation, while being well aware that large deviations from this average can occur, depending on the characteristics of the specific system.

In the following sections, the recorded experiences of three types of systems will be described. These are: 1) ac power lines (less than 600V); 2) telecommunication systems; and 3) automotive systems. The more exotic environmental conditions such as NEMP (nuclear electromagnetic pulse) are intentionally omitted from this discussion because they are the subject of specialized study by a limited community.

### 1.3 TRANSIENTS ON AC POWER LINES

Data collected from various sources has provided the basis for this guide to transient overvoltages.[1,5,6,7,8] (Reference 1, "The Development of a Guide on Surge Voltage in Low-Voltage AC Power Circuits," is reprinted in full at the end of this chapter, with the permission of the IEEE.)

#### *1.3.1 Amplitude and Frequency of Occurrence*

The amplitude of transient recordings covers the range from harmless values just above normal voltage to several kilovolts. For 120V ac lines, flashover of the typical wiring spacing produces an upper limit between 6 and 8kV. Ironically, the better the wiring practices, the higher the flashover, allowing higher transients to exist in the wiring system. Studies of the frequency of occurrence and amplitude agree on an upper limit and a *relative* frequency of occurrence. Figure 1.7 shows frequency as a function of amplitude. Experience indicates that devices with less than 2kV withstand capability will have poor service life in the unprotected residential environment. Prudent design will aim for 3kV capability, although, where safety is of the utmost concern, designing for 6kV can cope with these rare but possible occurrences.

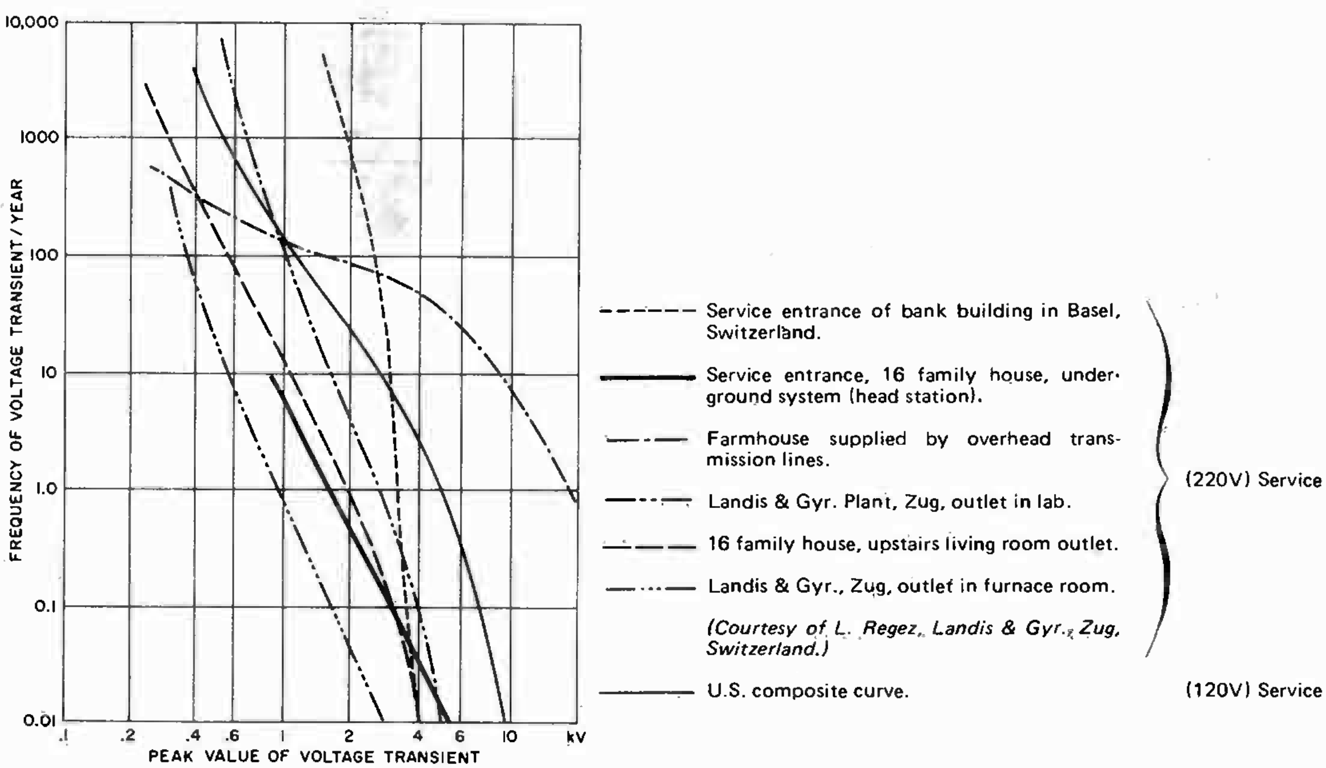


**FIGURE 1.7: FREQUENCY OF OCCURRENCE OF TRANSIENT OVERVOLTAGES IN 220V AND 120V SYSTEMS**

For systems of higher voltages (220/240V, 480V), limited data is available for U.S. systems. However, the curves of Figure 1.8 indicate the difference between the two classes, 120V and 220V systems, is smaller than the differences within each class.[8] One can conclude that the amplitude of the transient depends more upon the amount of externally coupled energy and the system impedance than upon the system voltage.

For internal switching transients in the power system, Figure 1.8 shows the relationship (computed and measured) between system voltage and transient peaks.[8] Clearly, there is no direct linear increase of the transient amplitude as the system voltage is increased.

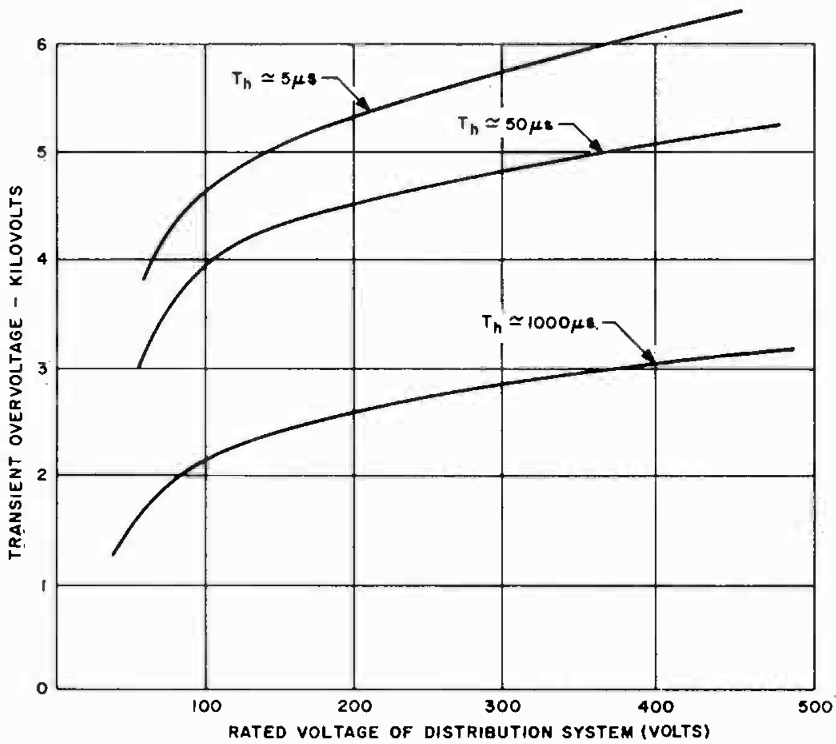


FIGURE 1.8: SWITCHING VOLTAGE TRANSIENTS AS A FUNCTION OF THE SYSTEM VOLTAGE FOR THREE VALUES OF THE TRANSIENT TAIL (TIME TO HALF-VALUE)
*(Data Courtesy of L. Regez, Landis & Gyr., Zug, Switzerland)*

Some indication of the uncertainty concerning the expected transient level can be found in the industrial practice of choosing semiconductor ratings. Most industrial users of power semiconductors choose semiconductor voltage ratings from 2.0 to 2.5 times the applied peak steady-state voltage, in conjunction with rudimentary transient suppression, in order to ensure long-term reliability. Whether or not this ratio is realistically related to actual transient levels has not been established; the safety factor is simply chosen by experience. While it is dangerous to argue against successful experience, there are enough cases where this rule of thumb is insufficient and thus a more exact approach is justified. Another objection to the indiscriminate rule of thumb is economic. Specifying 2.5 times the peak system voltage results in a high price penalty for these components. It is normally unrealistic and uneconomical to specify semiconductors that should withstand transients without protection. The optimum situation is a combination of low cost transient protection combined with lower cost semiconductors having lower voltage ratings.

### *1.3.2 Duration, Waveform and Source Impedance*

There is a lack of definitive data on the duration, waveform and source impedance of transient overvoltages in ac power circuits. These three parameters are important for estimating the energy that a transient can deliver to a suppressor. It is desirable to have a means of simulating the environment through a model of the transient overvoltage pulse. Suggestions have been made to use standard impulses initially developed for other applications. For instance, the classical 1.2 x 50$\mu$s unidirectional voltage impulse specified in high voltage systems has been proposed.[9] Also, the repetitive burst of 1.5 MHz oscillations ("SWC") specified for low-voltage and control systems exposed to transients induced by high-voltage disconnect switches in utility switch yards is another suggestion.[10]

Working Groups of the IEEE and the International Electrotechnical Commission have developed standard test waves and source impedance definitions. These efforts are aiming at moving away from a concept whereby one should *duplicate* environmental conditions and towards a concept of one standard wave or a few standard waves *arbitrarily* specified. The justifications are that equipments built to meet such standards have had satisfactory field experience and provide a relative standard against which different levels of protection can be compared. A condition for acceptance of these standard waves is that they be easy to produce in the laboratory.[11] This is the central idea of the TCL (Transient Control Level) concept which is currently being proposed to users and manufacturers in the electronics industry. Acceptance of this concept will increase the ability to test and evaluate the reliability of devices and systems at acceptable cost.

## 1.4 TELECOMMUNICATION LINE TRANSIENTS

Transient overvoltages occurring in telephone lines can usually be traced to two main sources: lightning and 50/60 Hz power lines. Lightning overvoltage is caused by a strike to the conductor of an open wire system or to the shield of a telephone cable. Most modern telephone lines are contained in shielded cables. When lightning or other currents flow on the shield of a cable, voltages are induced between the internal conductors and the shield.[12] The magnitudes of the induced voltages depend on the resistance of the shield material, openings in its construction, and on the dielectric characteristics and surge impedance of the cable.

Limited data has been collected on lightning voltages in telephone cables because of the difficulty of obtaining such data without interfering with the system operation.[13] Also, the carbon-block or spark gap protectors presently used have provided adequate protection for most installations using electromechanical components.

The close proximity of telephone cables and power distribution systems, often sharing right-of-way-poles and even ground wires, is a source of transient overvoltages for the telephone system. Overvoltages can arise from physical contact of falling wires, electromagnetic induction, and ground potential rise. Chapter 5 of this manual presents a detailed discussion of lightning-induced and power system-induced transients.

## 1.5 AUTOMOBILE TRANSIENTS

Four principal types of voltage transients are encountered in an automobile. These are "load dump," alternator field decay, inductive switching and mutual coupling.[4] In addition, cold morning "jump starts" with 24V batteries occur in some areas.

The load dump transient is the most severe and occurs when the alternator current loading is abruptly reduced. The most demanding case is often initiated by the disconnection of a partially discharged battery due to defective terminal connections. Transient voltages have been reported over 100V lasting up to 500ms with energy levels in the range of tens to hundreds of Joules.

Switching of inductive loads, such as motors and solenoids, will create negative polarity transient voltages with a smaller positive excursion. The voltage waveform has been observed to rise to a level of -210V and +80V and last as long as 320μs. The impedance to the transient is unknown, leading some designers to test with very low impedance, resulting in the use of more expensive components than necessary.

The alternator field decay transient is essentially an inductive load switching transient. When the ignition switch is turned off, the decay of the alternator field produces a negative voltage spike, whose amplitude is dependent on the voltage regulator cycle and load. It varies between -40V to -100V and can last 200ms.

Other unexplained transients have been recorded with peaks of 600V 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 75V and 90μs in duration have been observed with the battery disconnected.

Chapter 6 provides a comprehensive review of automotive transients and practical suppression techniques to protect automotive electronics.

## 1.6 EFFECTS OF VOLTAGE TRANSIENTS

### *1.6.1 Effects on Semiconductors*

Most semiconductor devices are intolerant of voltage transients in excess of their voltage ratings. Even such a short-lived transient as a few microseconds can cause the semiconductor to fail catastrophically or may degrade it so as to shorten its useful life.

Frequently, damage occurs when a high reverse voltage is applied to a non-conducting PN junction. The junction may avalanche at a small point due to the non-uniformity of the electric field. Also, excess leakage current can occur across the passivated junction between the terminations on the pellet surface. The current can create a low resistance channel that degrades the junction blocking voltage capability below the applied steady-state voltage. In the avalanche case, thermal runaway can occur because of localized heating building up to cause a melt-through which destroys the junction.

If the base-emitter junction of a transistor is repetitively "avalanched" or "zenered" by a reverse pulse, the forward current gain may be degraded. The triggering sensitivity of a thyristor will be reduced in the same manner by "zenering" the gate-cathode junction. Thyristors can also be damaged if turned on by a high voltage spike (forward breakover) under bias conditions that allow a rate of current increase (di/dt) beyond device capability. This will occur in virtually all practical circuits because the discharge of the RC dv/dt protection circuits will exceed device capability for di/dt and destroy the thyristor.

### *1.6.2 Effects on Electromechanical Contacts*

The high voltage generated by breaking current to an inductor with a mechanical switch will ultimately cause pitting, welding, material transfer, or erosion of the contacts. The nature of ultimate failure of the contacts depends upon such factors as the type of metal used, rate of opening, contact bounce, atmosphere, temperature, steady-state and in-rush currents, and ac or dc operation. 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 ($E_L = -L\,di/dt$).

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 30kV/in.) The capacitance discharges and recharges repeatedly until all the energy is dissipated. This arc causes sufficient contact heating to melt, oxidize, 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 closed. Welding can also occur as a result of high in-rush currents passing through the intially 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 and illustrated in Section 1.1.4.

### *1.6.3 Effects on Insulation*

Transient overvoltages can cause breakdown of insulation, resulting in either a temporary disturbance of device operation or instantaneous failure. The insulating level in the former case will be weakened leading to premature failure.

The severity of the breakdown varies with the type of insulation – air, liquid, or solid. The first two tend to be self-healing, while breakdown of solid insulation (generally organic materials) is generally a permanent condition.

Air clearances between metal parts in electrical devices and power wiring constitute air gaps, which behave according to the usual physics of gap breakdown (pressure, humidity, shape of electrodes, spacing). The International Electrotechnical Commission Working Group on Low Voltage Insulation Coordination has developed a table listing the minimum clearances in air for optimum and worst case electric field conditions existing between electrodes.[14] Breakdown of the clearance between metal parts can be viewed as a form of protection, limiting the overvoltage on the rest of the circuit. However, this protection is dependent upon the likelihood of ac line current that may follow during the arc breakdown. Normally, follow-on current should cause the system fuse or breaker to function. If the follow-on current heat is limited by circuit impedance, then the system fusing may not operate. In that case, sufficient heat could be generated to cause a fire. Experience with power wiring has shown that metal clearances flash-over regularly and harmlessly under transient voltage conditions, and power follow-on problems are rare, but can occur.

In liquid dielectrics, an impulse breakdown not followed by a high current is normally harmless. However, this type of breakdown is of limited interest in low-voltage systems, where liquid insulation systems are seldom used, except in combination with some degree of solid insulation.

Breakdown of solid insulation generally results in local carbonization of an organic material. Inorganic insulation materials are generally mechanically and permanently damaged. When no power follow-on current takes place, the system can recover and continue operating. However, the degraded insulating characteristic of the material leads to breakdown at progressively lower levels until a mild overvoltage, even within ac line overvoltage tolerances, brings about the ultimate permanent short circuit. Since the final failure can occur when no transients are present, the real cause of the problem may be concealed.

Breakdown along surfaces of insulation is the concern of "creepage" specifications. The working group of IEC cited above is also generating recommendations on creepage distances. The behavior of the system where creepage is concerned is less predictable than is breakdown of insulation in the bulk because the environment (dust, humidity) will determine the withstand capability of the creepage surface.

When considering the withstand capabilities of any insulation system, two fundamental facts must be remembered. The first is that breakdown of insulation is not instantaneous but is governed by the statistics of avalanche ionization. Hence there is a "volt-time" characteristic, which challenges the designer to coordinate protection systems as a function of the impinging waveshape. The second is that the distribution of voltage across insulation is rarely linear. For example, a steep wave front produces a piling up of voltage in the first few turns of a motor winding, often with reflections inside the winding. Also, the breakdown in the gap between the electrodes, initiating at the surface, is considerably dependent upon the overall field geometry, as well as on macroscopic surface conditions.

### *1.6.4 Effects on Power Consumption*

As a result of the increasing emphasis on energy conservation, a number of transient voltage suppression devices have been offered for sale as energy savers. The premise seems to be that transient overvoltages would cause degradation of electrical equipment leading to increased losses and thus to a waste of energy. No convincing proof has been offered to support this claim, and injunctions against making such claims have been obtained in several states.[15]

### *1.6.5 Noise Generation*

With sensitive logic gates gaining popularity, noise problems are frequent, especially in environments with electromechanical devices. 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, at the receiver, or by isolation. 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 the current or the 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.

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 creates a series of brief discharges of a damped oscillatory nature, occurring at kHz to MHz frequencies with amplitudes of from 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. This interference is best eliminated by preventing it at the source (the inductance) with voltage-limiting devices such as varistors.

## 1.7 TRANSIENT DETECTION

Voltage transients are brief and unpredictable. These two characteristics make it difficult to detect and measure them. Even transients described earlier in this chapter as "repeatable" are subject to variations resulting from the timing of the switching operation, the erratic bouncing of contacts, and other random combinations.

The transient detector *par excellence* is the high-frequency storage oscilloscope, but its cost limits its availability. Custom systems have been built to monitor transients on location,[16,17] but cost has been a limiting factor in this method of detection as well. A conventional oscilloscope with high-frequency response can be used as a monitor if it is provided with single-sweep controls for monitoring transients occurring at random times but at relatively low frequent rates. The operator sets the trigger controls at some threshold level in single-sweep mode and watches the "ready" light on the oscilloscope panel while a camera with open shutter records the screen display. The film is pulled after the operator notices that sweep occurred and, thus, a record is obtained. While not very efficient for efficient for extensive monitoring, this method is very effective for short-term panics — the most frequent situation when transients are suspected. Digital storage oscilloscopes with automatic data transfer to a magnetic disc are now available for unattended monitoring.

In recent years, leading oscilloscope manufacturers have developed improved versions of storage oscilloscopes and high-frequency oscilloscopes, and most laboratories now are equipped with one or another. The experienced engineer can put them to work and obtain satisfactory recordings by the technique described above, using normal safeguards against erroneous recordings (check on noise background, stray ground currents, radiation of noise into preamplifier circuits, etc.).

A wide variety of suitable analog or digital test instruments is commercially available, as indicated in Chapter 7. These allow economical monitoring of a remote location by providing various degrees of storage (single-event recording, counting above a threshold, digital memory for playback, etc.).

Trade magazines and engineering papers have also described a number of homemade detectors. While these are undoubtedly performing to the satisfaction of their creators, one can question the economic wisdom of investing time and engineering resources to duplicate, debug, and calibrate a homemade device when so many commercial units offering guaranteed and instant performance are available.

## 1.8 TRANSIENT TESTING AND STANDARDS

It is desirable to have test criteria and definitions that provide a common engineering language beneficial to both the user and manufacturer of surge protective devices. Regretfully, different terms have come into use through industry practice over the years. Testing standards have tended to proliferate as the measurement objective defines either the characteristics of the protective device or the environment of the application.

The characteristics of each device will vary according to its basic construction. Protective devices are diverse, being based on ionized gas breakdown, semiconductor junction breakdown, and "charge hopping" conduction. For this reason, it seems sensible to group devices by physical category and set up pertinent standards that are suitable for characterizing their behavior. The standards would use appropriate stress levels and measure those parameters that are critical to ensuring proper performance.

The application environment has demanded different conditions of transient levels. Standards vary depending on system usage, whether protection is intended for power lines, telecommunications, automotive, or aircraft, to name a few. Each environment also has been defined with less than full precision leading to additional diversity on choice of waveshape, amplitude and duration.

Several organizations such as IEEE, IEC, UL, NEMA are currently developing guidelines and standards to describe what the environment is likely to be, on the basis of accumulated recording and field experience. From this, test specifications are being prepared[17,18,19,20] that will allow objectives and realistic evaluation of suppressor applications. A brief review of these will be found in Chapter 7.

# REFERENCES


1. Martzloff, F.D., "The Development of a Guide on Surge Voltages in Low-Voltage AC Power Circuits," Report 81CRD047, General Electric, Schenectady, New York 1981.
2. Greenwood, Allan, Electrical Transients in Power Systems, Wiley-Interscience, New York, 1971.
3. Bodle, D.W., A.J. Ghaze, M. Syed and R.L. Woodside, Characterization of the Electrical Environment, Toronto: University of Toronto Press, 1970.
4. Recommended Environmental Practices for Electronic Equipment Design, Publication SAE J1211, Society of Automotive Engineers, Warrendale, Pennsylvania.
5. Hahn, G.J. and F.D. Martzloff, "Surge Voltages in Residential and Industrial Power Circuits," IEEE Trans. PAS-89, No. 6, July-Aug. 1970, pp. 1049-1056.
6. Bull, J.H., "Voltage Spikes in L.V. Distribution Systems and Their Effects on the Use of Electronic Control Equipment," Report No. 5254, Electrical Research Assn., Cleeve Rd., Leatherhead, Surrey, Great Britain, 1968.
7. IEEE Surge Protective Devices Committee, "Bibliography on Surge Voltages in AC Power Circuits Rated 600 Volts or Less," IEEE Trans. PAS-89, No. 6, July-Aug. 1970, pp. 1056-1061.
8. Data contributed by L. Regez (Landis & Gyr. Co., Zug, Switzerland), Swiss representative to IEC Working Group 28A on Low Voltage Insulation Coordination.
9. Surge Arresters for Alternating Current Power Circuits, ANSI Standard C62.1, IEEE Standard 28, 1974.
10. Guide for Surge Withstand Capability (SWC) Test, ANSI Standard C37.90a, 1974, IEEE Standard 472, 1974.
11. Martzloff, F.D. and F.A. Fisher, "Transient Control Level Philosophy and Implementation — The Reasoning Behind the Philosophy," 77CH1224-SEMC, Proceedings of the 2nd Symposium on EMC, Montreux, June 1977.
12. Fisher, F.A., "A Way to Evaluate the Effects of Changing Magnetic Fields on Shielded Conductors," Report 77CRD158, General Electric, Schenectady, New York, July 1977.
13. Bennison, E., A. Ghazi and P. Ferland, "Lightning Surges in Open Wire, Coaxial and Paired Cables," IEEE Trans., COM-21, Oct. 1973, pp. 1136-1143.
14. "Insulation Co-ordination Within Low-Voltage Systems, including Clearances and Creepage Distances for Equipment" IEC Report 664, 1980.
15. "Evaluation of Transient Voltage Suppressors for Saving Electric Energy," EPRI EM-1722, February 1981.
16. Allen, George W., "Design of Power-Line Monitoring Equipment," IEEE Trans. PAS-90, No. 6, Nov.-Dec. 1971, pp.2604-2609.
17. Herzog, R., "How to Catch a Transient," Machine Design Magazine, March 1973, pp. 170-175.
18. Test Specification for Gas Tube Surge Protective Devices, IEEE Std. C62.31, 1981.
19. Test Specifications for Low Voltage Air Gap Surge Protective Devices, Excluding Valve and Expulsion Type Devices, IEEE Std. C62.32, 1981.
20. Test Specifications for Varistor Surge Protective Devices, IEEE Std. C62.33, 1982.

# The Development of a Guide on Surge Voltages in Low-Voltage AC Power Circuits

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Surge voltages in ac power circuits become more significant with the increased application of miniaturized electronics in consumer and industrial products. A Working Group of IEEE has prepared a Guide describing the nature of these surges in ac power circuits up to 600V, and is currently developing an Application Guide for using the environmental data defined in the Guide to improve protection.

The Guide proposes two waveforms, one oscillatory, the other unidirectional, depending on the location within the power system. It also includes recommendations for source impedance or short-circuit current. This paper describes the data base and approach used by the Working Group and the recommendations proposed to represent typical surges, in order to obtain feedback for writing the Application Guide.

## INTRODUCTION

Surge voltages occurring in ac power circuits can be the cause of misoperation or product failure for residential as well as industrial systems. The problem has received increased attention in recent years because miniaturized solid state devices are more sensitive to voltage surges (spikes and transients) than were their predecessors.

Although surge voltage amplitudes and their frequency of occurrence on unprotected circuits are well known, their waveshapes and energy content are less well known. On the basis of measurements, statistics, and theoretical considerations, a practical guide for outlining the environment for use in predicting extreme waveshapes and energy content can nevertheless be established. A Working Group of the Surge Protective Devices Committee has completed such a descriptive Guide,[1] and is now developing an Application Guide. This paper presents a brief overview of the Guide and of the approach taken in the Application Guide. Discussion and comments on the objectives and approach of the Application Guide are welcome.

## SCOPE

Both guides primarily address ac power circuits with rated voltages up to 277V line to ground, although some of the conclusions offered could apply to higher voltages and also to some dc power systems. Other standards have been established,[2] such as IEEE Standard 472, *Guide for Surge Withstand Capability (SWC) Tests,* intended for the special case of high-voltage substation environments, and IEEE Standard 28, *Standard for Surge Arrestors for ac Power Circuits,*[3] covering primarily the utilities environment. The Guides are intended to complement, not conflict with, existing standards.

The surge voltages considered in the Guides are those exceeding two per unit (or twice the peak operating voltage) and having durations ranging from a fraction of a microsecond to a millisecond. Overvoltages of less than two per unit are not covered, nor are transients of longer duration resulting from power equipment operation and failure modes. Because these low-amplitude and long-duration surges are generally not amenable to supression by conventional surge protective devices, they require different protection techniques.

While the major purpose of the existing Guide is to *describe the environment*, a secondary purpose is to lead toward standard tests that will appear eventually in the Application Guide.

## THE ORIGINS OF SURGE VOLTAGES

Surge voltages occurring in low-voltage ac power circuits originate from two major sources: system switching transients and direct or indirect lightning effects on the power system. System switching transients can be divided into transients associated with (1) major power system switching disturbances, such as capacitor bank switching; (2) minor switching near the point of interest, such as an appliance turnoff in a household or the turnoff of other loads in an individual system; (3) resonating circuits associated with switching devices, such as thyristors; and (4) various system faults, such as short circuits and arcing faults.

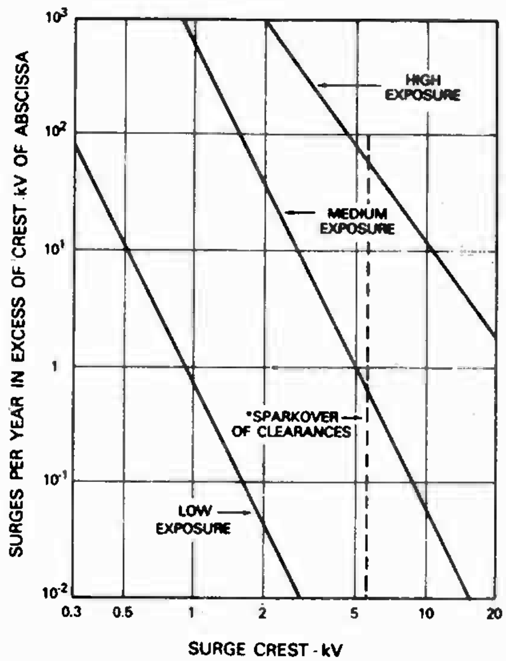



FIGURE 1. RATE OF SURGE OCCURRENCE VERSUS VOLTAGE LEVEL AT UNPROTECTED LOCATIONS
* IN SOME LOCATIONS, SPARKOVER OF CLEARANCES MAY LIMIT THE OVERVOLTAGES.

Measurements and calculations of lightning effects have been made to yield data on what levels can be produced, even if the exact mechanism of any particular surge is unknown. While the data have been recorded primarily on 120, 220/380, or 277/480V systems, the general conclusions should be valid for 600V systems. To the extent that surge voltages are produced by a discrete amount of energy being dumped into a power system, low-impedance, heavy industrial systems can be expected to experience lower peaks from surge voltages than 120V residential systems, but comparable, or greater, amounts of energy potentially available for deposition in a surge suppressor.

## RATE OF OCCURRENCE AND VOLTAGE LEVELS IN UNPROTECTED CIRCUITS

The rate of occurrence of surges varies over wide limits, depending on the particular power system. Prediction of the rate for a particular system is always difficult and frequently impossible. Rate is related to the level of the surges; low-level surges are more prevalent than high-level surges.

It is essential to recognize that a surge voltage observed in a power system can be either the driving voltage or the voltage limited by the sparkover of some clearance in the system. Hence, the term *unprotected circuit* must be understood to be a circuit in which no low-voltage protective device has been installed but in which clearance sparkover will eventually limit the maximum voltage. The distribution of surge levels, therefore, is influenced by the surge-producing mechanisms as well as by the sparkover level of clearances in the system. This distinction between actual driving voltgage and voltage limited by sparkover is particularly important at the interface between outdoor equipment and indoor equipment. Outdoor equipment has generally higher clearances, hence higher sparkover levels: 10kV may be typical, but 20kV is possible. In contrast, most indoor wiring devices used in 120-240V systems have sparkover levels of about 6kV; this 6kV level, therefore, can be selected as a typical cutoff for the occurrence of surges in indoor power systems.

Data collected from many sources have led to the plot shown in Figure 1. This prediction shows with certainty only a *relative* frequency of occurrence, while the *absolute* number of occurrences can be described only in terms of "low exposure," "medium exposure," or "high exposure." These exposure levels can be defined in general terms as follows:

**Low Exposure** Systems in geographical areas known for low lightning activity, with little load switching activity.

**Medium Exposure** Systems in geographical areas known for high lightning activity, with frequent and severe switching transients.

**High Exposure** Rare but real systems supplied by long overhead lines and subject to reflections at line ends, where the characteristics is the installation produce high sparkover levels of the clearances.

The two lower lines of Figure 1 have been drawn at the same slope, since the data base shows reasonable agreement among several sources on that slope. All lines may be truncated by sparkover of the clearances at levels depending on the withstand voltage of these clearances. The "high-exposure" line needs to be recognized, but it should not be applied indiscriminately to all systems. Such application would penalize the majority of installations, where the exposure is lower.

From the relative values of Figure 1, two typical levels can be cited for practical applications. First, the expectation of 3kV transient occurrence on a 120V circuit ranges from 0.01 to 10 per year at a given location—a number sufficiently high to justify the recommendation of a minimum 3kV withstand capability. Second, the sparkover of wiring devices indicates that a 6kV withstand capability may be sufficient to ensure device survival indoors, but a withstand capability of 10kV, or greater, may be required outdoors.

The voltage and current amplitudes presented in the Guide attempt to provide for the vast majority of lightning strikes but should not be considered as "worst case," since this concept cannot be determined realistically. One should think in terms of the statistical distribution of strikes, accepting a reasonable upper limit for most cases. Where the consequences of a failure are not catastrophic but merely represent an annoying economic loss, it is appropriate to make a tradeoff of the cost of protection against the likelihood of failure caused by a high but rare surge. For instance, a manufacturer may be concerned with nation-wide failure rates, those at the upper limits of the distribution curve, while the user of a specific system may be concerned with a single failure occurring at a specific location under "worst-case conditions." Rates can be estimated for average systems, however, and even if imprecise, they provide manufacturers and users with guidance. Of equal importance is the observation that surges in the range of 1 to 2kV are fairly common in residential circuits.

Surges occur at random times with respect to the power frequency, and the failure mode of equipment may be affected by the power frequency follow current. Furthermore, the timing of the surge with respect to the power frequency may affect the level at which failure occurs. Consequently, when the failure mode is likely to be affected, surge testing should be done with the line voltage applied to the test piece.

Lightning surges are completely random in their timing with respect to the power frequency. Switching surges are likely to occur near or after current zero, but variable load power factors will produce a quasi-random distribution. Some semiconductors exhibit failure levels that depend on the timing of the surge with respect to the conduction of power frequency current. Gaps or other devices involving a power-follow current may withstand this power follow with success, depending upon the fraction of the half-cycle remaining after the surge before current zero. Therefore, it is important to consider the timing of the surge with respect to the power frequency. In performing tests, either complete randomization of the timing or controlled timing should be specified, with a sufficient number of timing conditions to reveal the most critical timing.

## WAVESHAPE OF REPRESENTATIVE SURGE VOLTAGES

### *Waveshapes in Actual Occurrences*

**Indoor** Measurements in the field, measurements in the laboratory, and theoretical calculations indicate that most surge voltages in indoor low-voltage systems have oscillatory waveshapes, unlike the well-known and generally accepted unidirectional waves specified in high-voltage insulation standards. A surge impinging on the system excites the natural resonant frequencies of the conductor system. As a result, not only are the surges typically oscillatory, but surges may have different amplitudes and waveshapes at different places in the system. These oscillatory frequencies of surges range from 5kHz to more than 500kHz. A 30 to 100kHz frequency is a realistic measure of a "typical" surge for most residential and light industrial ac line networks.

**Outdoor and Service Entrance** Surges encountered in outdoor locations have also been recorded, some oscillatory, other unidirectional. The "classical lightning surge" has been established as 1.2 / 50μs for a voltage wave and 8 / 20μs for a current wave, but these waveshapes should not be construed as typical waves for low-voltage circuits. Lightning discharges induce oscillations, reflections, and disturbances that ultimately appear as decaying oscillations in low-voltage systems. Lenz[4] reports 50 lightning surges recorded in two locations, the highest at 5.6kV, with frequencies ranging from 100 to 500kHz. Martzloff[5] reports oscillatory lightning surges in a house during a multiple-stroke flash.

Because the prime concern here is the energy associated with these surges, the waveshape to be selected must involve greater energy than that associated with the indoor environment. Secondary surge arresters have a long history of successful performance, meeting the ANSI C62.1 specification, as detailed below; consequently, these specifications can be adopted as a realistic representation of outdoor waveshapes.

### *Selection of Representative Waveshapes*

The definition of a waveshape to be used as representative of the environment is important for the design of candidate protective devices, since unrealistic requirements, such as excessive duration of the voltage or very low source impedance, place a high energy requirement on the suppressor, with a resulting cost penalty to the end user. The two requirements defined below reflect this tradeoff.

**Indoor** Based on measurements conducted by several independent organizations in 120 and 240V systems, the waveshape shown in Figure 2 is reasonably representative of surge voltages in these power circuits. Under the proposed description of a "0.5μs - 100kHz ring wave," this waveshape rises in 0.5μs, then decays while oscillating at 100kHz, each peak being about 60% of the preceding peak.

The fast rise can produce the effects associated with nonlinear voltage distribution in windings and the dv/dt effects on semiconductors. Shorter rise times are found in many transients, but, as those transients propagate into the wiring or are reflected from discontinuities in the wiring, the rise time becomes longer.

The oscillating and decaying tail produces the effects of voltage polarity reversals in surge suppressors or other devices that may be sensitive to polarity changes. Some semiconductors are particularly sensitive to damage when being forced into or out of a conducting state, or when the transient is applied during a particular portion of the 60Hz supply cycle.

**Outdoor** In the outdoor and service entrance environment, as well as in locations close to the service entrance, substantial energy, or current, is still available, in contrast to the indoor environment, where attenuation has taken place. For these locations, the unidirectional impulses long established for secondary arresters are more appropriate than the oscillatory wave.

Accordingly, the recommended waveshape is 1.2 / 50$\mu$s for the open-circuit voltage or voltage applied to a high-impedance device, and 8 / 20$\mu$s for the discharge current or current in a low-impedance device. The numbers used to describe the impulse, 1.2 / 50 and 8 / 20, are those defined in IEEE Standard 28 - ANSI Standard C62.1; Figure 3 presents the waveshape and a graphic description of the numbers.

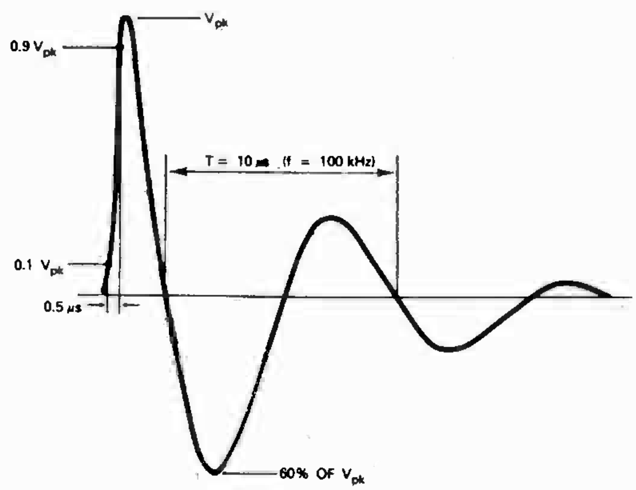



FIGURE 2. THE PROPOSED 0.5 $\mu$s - 100 kHz RING WAVE (OPEN-CIRCUIT VOLTAGE)

## ENERGY AND SOURCE IMPEDANCE

### *General*

The energy involved in the interaction of a power system with a surge source and a surge suppressor will divide between the source and the suppressor in accordance with the characteristics of the two impedances. In a gap-type suppressor, the low impedance of the arc after sparkover forces most of the energy to be dissipated elsewhere: for instance, in a resistor added in series with the gap for limiting the power-follow current. In an energy-absorber suppressor, by its very nature, a substantial share of the surge energy is dissipated in the suppressor, but its clamping action does not involve the power-follow energy resulting from the short-circuit action of a gap. It is therefore essential to the effective use of suppression devices that a realistic assumption be made about the source impedance of the surge whose effects are to be duplicated.

The voltage wave shown in Figure 2 is intended to represent the waveshape a surge source would produce across an open circuit. The waveshape will be different when the source is connected to a load having a lower impedance, and the degree to which it is lower is a function of the impedance of the source.

To prevent misunderstanding, a distinction between *source impedance* and *surge impedance* needs to be made. Surge impedance, also called *characteristic impedance*, is a concept relating the parameters of a line to the propogation of traveling waves. For the wiring practices of the ac power circuits discussed here, this characteristic impedance would be in the range of 150 to 300Ω, but because the durations of the waves being discussed (50 to 20µs) are much longer than the travel times in the wiring systems being considered, traveling wave analyses are not useful here.

Souce impedance, defined as "the impedance presented by a source of energy to the input terminals of a device, or network" (IEEE Standard 100), is a more useful concept here. In the conventional Thevenin's description, the open-circuit voltage (at the terminals of the network or test generator) and the source impedance (of the surge source or test generator) are sufficient to calculate the short-circuit current, as well as any current for a specified suppressor impedance.

The measurements from which Figure 1 was derived were of voltage only. Little was known about the impedance of the circuits upon which the measurements were made. Since then, measurements have been reported on the impedance of power systems. Bull[6] reports that the impedance of a power system, seen from the outlets, exhibits the characteristics of a 50Ω resistor with 50µH in parallel. Attempts were made to combine the observed 6kV open-circuit voltage with the assumption of a 50Ω/50µH

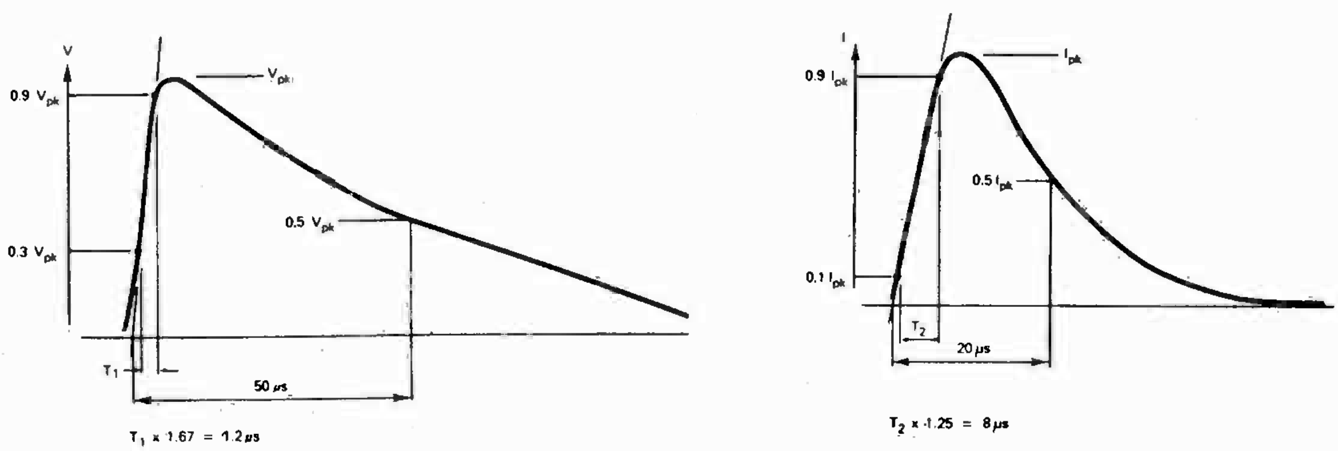



**FIGURE 3. UNIDIRECTIONAL (ANSI STANDARD C62.1) WAVESHAPES (A) OPEN-CIRCUIT VOLTAGE WAVEFORM (B) DISCHARGE CURRENT WAVEFORM**

impedance.[7] This combination resulted in low energy deposition capability, which was contradicted by field experience of suppressor performance. The problem led to the proposed definition of oscillatory waves as well as high-energy unidirectional waves, in order to produce both the effects of an oscillatory wave and the high-energy deposition capability.

The degree to which source impedance is important depends largely on the type of surge suppressors that are used. The surge suppressors must be able to withstand the current passed through them by the surge source. A test generator of too high an impedance may not subject the device under test to sufficient stresses, while a generator of too low an impedance may subject protective devices to unrealistically severe stresses. A test voltage wave specified without reference to source impedance could imply zero source impedance—one capable of producing that voltage across any impedance, even a short circuit. That would imply an infinite surge current, clearly an unrealistic situation.

Because of the wide range of possible source impedances and the difficulty of selecting a specific value, three broad categories of building locations are proposed to represent the vast majority of locations, from those near the service entrance to those remote from it. The source impedance of the surge increases from the outside to locations well within the building. Open-circuit voltages, on the other hand, show little variation within a building because the wiring provides little attenuation. Figure 4 illustrates the application of the three categories to the wiring of a building.

For the two most common location categories, Table 1 shows the recommended surge voltages and currents, with the waveforms and amplitudes of the surges, and high- or low-impedance specimen. For the discharge current shown, the last two columns show the energy that would be deposited in a

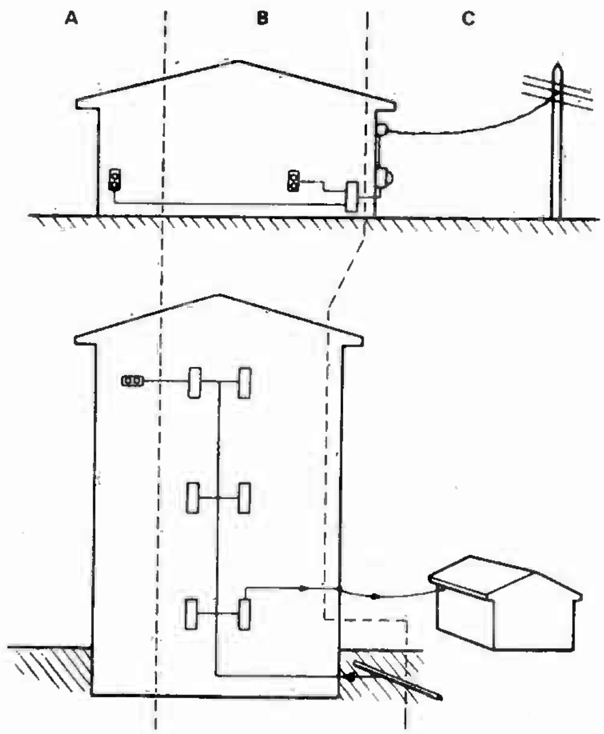



**FIGURE 4. LOCATION CATEGORIES**

**A. Outlets and Long Branch Circuits**
- All outlets at more than 10m (30 ft) from Category B with wires #14-10
- All outlets at more than 20m (60 ft) from Category C with wires #14-10

**B. Major Feeders and Short Branch Circuits**
- Distribution panel devices
- Bus and feeder systems in industrial plants
- Heavy appliance outlets with "short" connections to the service entrance
- Lighting systems in commercial buildings

**C. Outside and Service Entrance**
- Service drop from pole to building entrance
- Run between meter and distribution panel
- Overhead line to detached buildings
- Underground lines to well pumps

suppressor clamping at 500V and 1000V, typical of 120V or 240V applications, respectively. For higher system voltages (assuming the same current values), the energy would increase in proportion to the clamping voltage of a suppressor suitable for that system voltage.

The values shown in Table 1 represent the maximum range and correspond to the "medium exposure" situation of Figure 1. For less exposed systems, or when the prospect of a failure is not highly objectionable, one could specify lower values of open-circuit voltages with corresponding reductions in the discharge currents.

The 6kV open-circuit voltage derives from two facts: the limiting action of wiring device sparkover and the unattenuated propagation of voltages in unloaded systems. The 3kA discharge current in Category B derives from experimental results: field experience in suppressor performance and

## TABLE 1. SURGE VOLTAGES AND CURRENTS DEEMED TO REPRESENT THE INDOOR ENVIRONMENT AND RECOMMENDED FOR USE IN DESIGNING PROTECTIVE SYSTEMS

| LOCATION CATEGORY | COMPARABLE TO IEC 664 CATEGORY | IMPULSE | | TYPE OF SPECIMEN OR LOAD CIRCUIT | ENERGY(JOULES) DEPOSITED IN A SUPPRESSOR(3) WITH CLAMPING VOLTAGE OF | |
|---|---|---|---|---|---|---|
| | | WAVEFORM | MEDIUM EXPOSURE AMPLITUDE | | 500V | 1000V |
| | | | | | (120V System) | (240V System) |
| A. Long branch circuits and outlets | II | 0.5μs - 100kHz | 6kV<br>200A | High impedance(1)<br>Low impedance(2) | —<br>0.8 | —<br>1.6 |
| B. Major feeders short branch circuits, and load center | III | 1.2/50μs<br>8/20μs | 6kV<br>3kA | High impedance(1)<br>Low impedance(2) | —<br>40 | —<br>80 |
| | | 0.5μs - 100kHz | 6 kV<br>500A | High impedance(1)<br>Low impedance | —<br>2 | —<br>4 |

Notes: (1) For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.
(2) For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.
(3) Other suppressors which have different clamping voltages would receive different energy levels.

simulated lightning tests. The two levels of discharge currents from the 0.5μs - 100kHz wave derive from the increasing impedance expected in moving from Category B to Category A.

Location Category C is likely to be exposed to substantially higher voltages than location Category B because the limiting effect of sparkover is not available. The "medium exposure" rates of Figure 1 could apply, with voltage in excess of 10kV and discharge currents of 10kA, or more. Installing unprotected load equipment in location Category C is not recommended; the installation of secondary arresters, however, can provide the necessary protection. Secondary arresters having 10kA ratings have been applied successfully for many years in location Category C (ANSI Standards C62.1 and C62.2).

Subcommittee 28A of the International Electrotechnical Commission has also prepared a report[8] in which installation categories are defined. These installation categories divide the power systems according to the location in the building, in a manner similar to the location categories defined in the Guide. The three categories presented here are comparable to three of the four categories defined by Subcommittee 28A, with the added specification of a source impedance or discharge current. Equipment connected to the outlets of Category A corresponds to equipment located in IEC Category I; Category C corresponds to IEC Category IV.

There are, however, some significant differences between the two concepts. First, the IEC categories are defined for a "Controlled Voltage Situation," a phrase that implies the presence of some surge suppression device or surge attenuation mechanism to reduce the voltage levels from one category to the next. Second, the IEC report is more concerned with insulation coordination than with the application of surge protective devices; therefore it does not address the question of the coordination of the protectors, but rather the coordination of insulation levels—that is, voltages. Source impedances, in contrast to the Guide, have not been defined. Further discussion and work toward the Application Guide and the IEC Report should eventually produce a consistent set of recommendations.

### APPLICATION GUIDE

The broad range of surge voltages occurring in low-voltage ac power circuits can be simulated by a limited set of test waves, for the purpose of evaluating their effects on equipment. Field measurements, laboratory experiments, and calculations indicate that two basic waves, at various open-circuit voltages and short-circuit current values, can represent the majority of surges occurring in residential, commercial, and light industrial power systems rated up to 600V RMS.

Exceptions will be found to a single, broad guide; however, such exceptions should not detract from the benefits that can be expected from a reasonably valid uniformity in defining the environment. Test waves of different shapes may be appropriate for other purposes, and the Guide should not be imposed where it is not applicable. The forthcoming Application Guide will detail waves and shapes for specific applications.

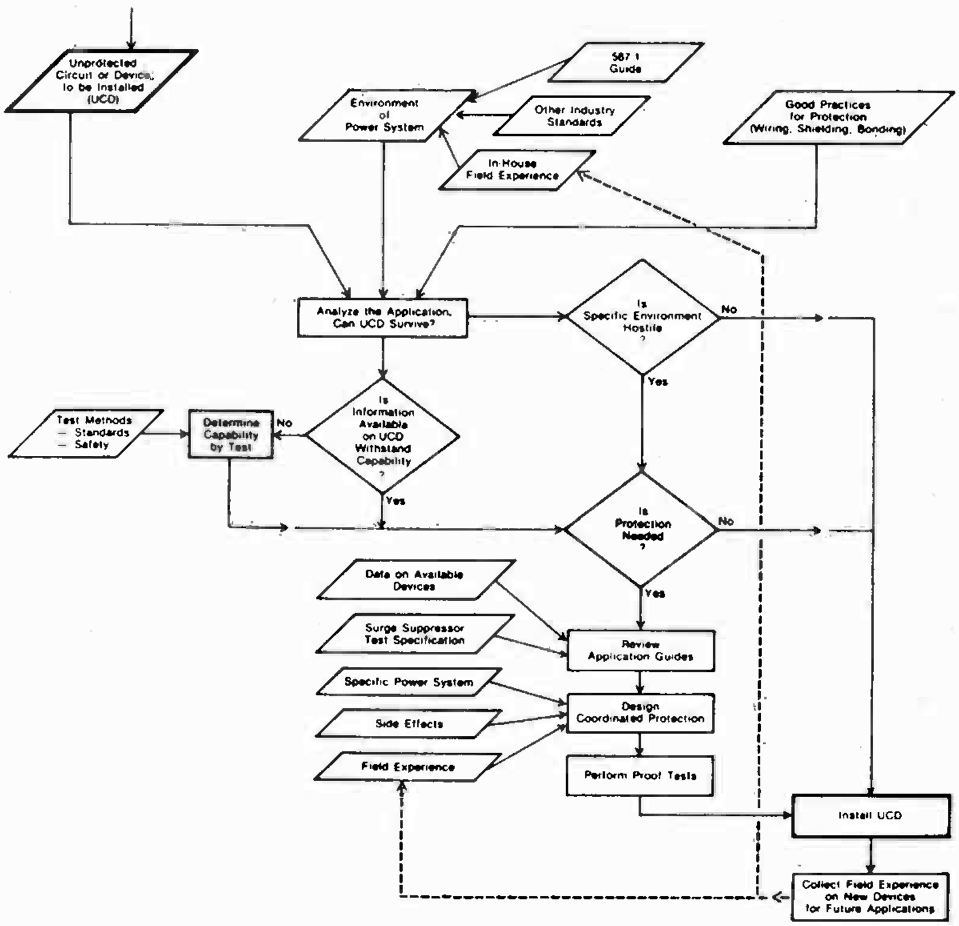



FIGURE 5. COORDINATION OF PROTECTION SCHEMES

The Application Guide approach will be to compare the known characteristics of the environment, as defined by the Guide on Surge Voltages, and the known (or to be determined) withstand capability of the unprotected load circuit to be installed in that environment. Through a systematic process of analysis and/or test, using the Transient Control Level concept[9] for instance, the user will be able to determine whether or not protection is required, what coordination is necessary, and what economic/performance tradeoffs can be made. Figure 5 shows a flow chart proposed to guide this evaluation process.

The Working Group, in coordination with other interested organizations, will proceed toward the preparation of this Application Guide; the Working Group invites comments and suggestions.

## REFERENCES


1. Guide on Surge Voltages in AC Power Circuits Rates Up to 600V, Final Draft, May 1979. Document prepared by Working Group 3.4.4 of the Surge Protective Device Committee of the Power Engineering Society, Institute of Electrical and Electronics Engineers (Now IEEE Standard 587-1980).
2. Guide for Surge Withstand Capability (SWC) Tests, ANSI Standard C37.90a, 1974; IEEE Standard 472-1974.
3. Surge Arrestors for Alternating-Current Power Circuits, IEEE Standard 28-1974; ANSI Standard C62.1-1975; IEC Standard 99-2.
4. Lenz, J.E., "Basic Impulse Insulation Levels of Mercury Lamp Ballast for Outdoor Applications," Illuminating Engrg., February 1964, pp. 133-140.
5. Martzloff, F.D. and G.J. Hahn, "Surge Voltage in Residential and Industrial Power Circuits," IEEE PAS-89, 6, July/August 1970, 1049-1056.
6. Bull, J.H., "Impedance on the Supply Mains at Radio Frequencies," Proceedings of 1st Symposium on EMC, 75CH1012-4 Mont., Montreux, May 1975.
7. Martzloff, F.D. and F.A. Fisher, "Transient Control Level Philosophy and Implementation: The Reasoning Behind the Philosophy," Proceedings 2nd Symposium on EMC, 77CH1224-5EMC, Montreux, June 1977.
8. Insulation Coordination Within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment, International Electrotechnical Commission Report 664.
9. Fisher, F.A. and F.D. Martzloff, "Transient Control Levels, a Proposal for Insulation Coordination in Low-Voltage Systems," IEEE PAS-95, 1, January/February 1976, pp. 120-129.


## ACKNOWLEDGMENTS


The concepts presented in this paper have greatly benefited from the informed questions and discussions by members of the Working Group on Surge Voltage in AC Power Circuits Rated 600V or Less, and from interested reviewers; particular appreciation for effective critiques from Catharine Fisher and Peter Richman is acknowledged. The data base used in developing the Guide was broadened by the contributions of the Bell Telephone Laboratories and Landis & Gyr, Inc. The flow chart approach to the Application Guide was suggested by Paul Speranza.

# chapter 2

# TRANSIENT SUPPRESSION — DEVICES AND PRINCIPLES

This chapter presents a brief description of available transient suppressors and their operation, and discusses how these devices can be applied.

## 2.1 TRANSIENT SUPPRESSION DEVICES.

There are two major categories of transient suppressors: a) those that attenuate transients, thus preventing their propagation into the sensitive circuit; and b) those that divert transients away from sensitive loads and so limit the residual voltages.

Attenuating a transient—that is, keeping it from propagating away from its source or keeping it from impinging on a sensitive load—is accomplished with filters inserted in series within a circuit. The filter, generally of the low-pass type, attenuates the transient (high frequency) and allows the signal or power flow (low-frequency) to continue undisturbed.

Diverting a transient can be accomplished with a voltage-clamping type device or with a "crowbar" type device. The designs of these two types, as well as their operation and application, are different enough to warrant a brief discussion of each in general terms. A more detailed description will follow later in this chapter.

A voltage-clamping device is a component having a variable impedance depending on the current flowing through the device or on the voltage across its terminal. These devices exhibit a non-linear impedance characteristic—that is, Ohm's law is applicable but the equation has a variable R. The variation of the impedance is monotonic; in other words, it does not contain discontinuities in contrast to the crowbar device, which exhibits a turn-on action. The volt-ampere characteristic of these clamping devices is somewhat time-dependent, but they do not involve a time delay as do the sparkover of a gap or the triggering of a thyristor.

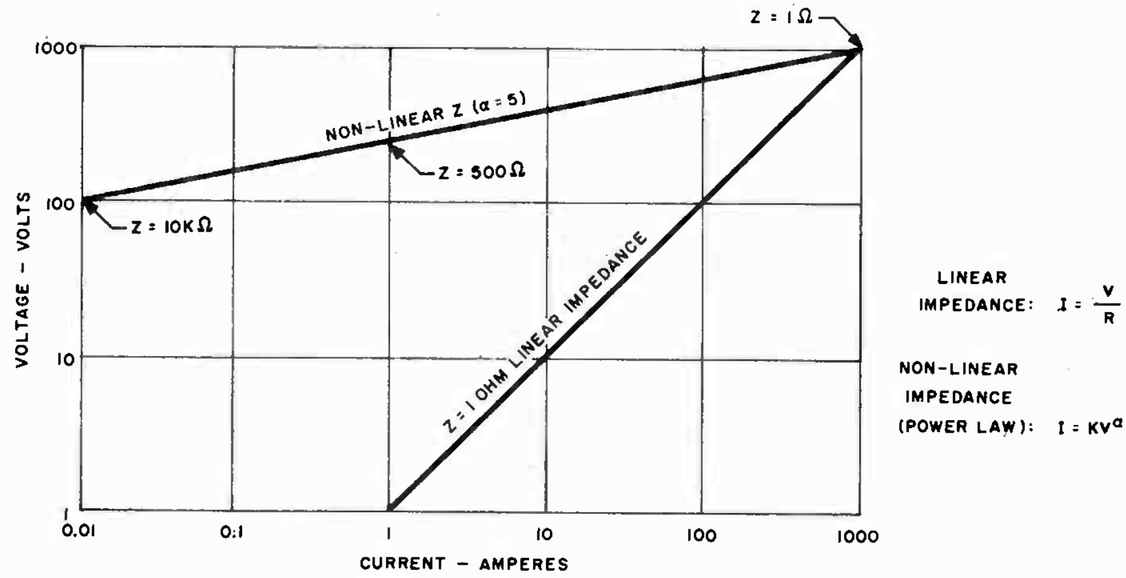



FIGURE 2.1: VOLTAGE/CURRENT CHARACTERISTIC FOR A LINEAR 1 OHM RESISTOR AND NON-LINEAR VARISTOR

With a voltage-clamping device, the circuit is unaffected by the presence of the device before and after the transient for any steady-state voltage below the clamping level. The voltage clamping action results from the increased current drawn through the device as the voltage tends to rise. If this current increase is faster than the voltage rise, the impedance of the device is nonlinear (Figure 2.1). The apparent "clamping" of the voltage results from the increased voltage drop (IR) in the source impedance due to the increased current. It should be clearly understood that the device depends on the source impedance to produce the clamping. One is seeing a voltage divider action at work, where the ratio of the divider is not constant but changes. However, if the source impedance is very low, then the ratio is low. The suppressor cannot be effective with zero source impedance (Figure 2.2) and works best when the voltage divider action can be implemented.

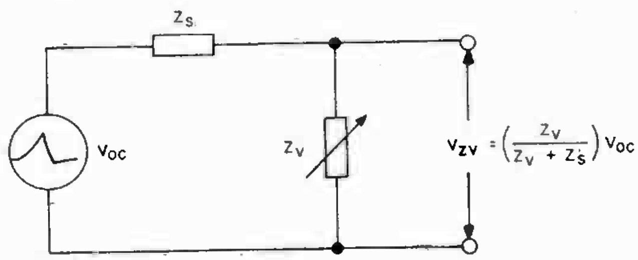



**FIGURE 2.2: DIVISION OF VOLTAGE WITH VARIABLE IMPEDANCE SUPPRESSOR**

Crowbar-type devices involve a switching action, either the breakdown of a gas between electrodes or the turn-on of a thyristor. After switching on, they offer a very low impedance path which diverts the transient away from the parallel-connected load.

These crowbar devices have two limitations. The first is their delay time, typically microseconds, which leaves the load unprotected during the initial rise. The second limitation is that a power current from the steady-state voltage source will follow the surge discharge (called "follow-current" or "power-follow"). In ac circuits, this power-follow current may or may not be cleared at a natural current zero; in dc circuits the clearing is even more uncertain. Therefore, if the crowbar device is not designed to provide self-clearing action within specified limits of surge energy and system voltage and power-follow current, additional means must be provided to open the power circuit.

### *2.1.1 Filters*

The frequency components of a transient are several orders of magnitude above the power frequency of an ac circuit and, of course, a dc circuit. Therefore, an obvious solution is to install a low-pass filter between the source of transients and the sensitive load.

The simplest form of filter is a capacitor placed across the line. The impedance of the capacitor forms a voltage divider with the source impedance, resulting in attenuation of the transient at high frequencies. This simple approach may have undesirable side effects, such as a) unwanted resonances with inductive components located elsewhere in the circuit leading to high peak voltages; b) high in-rush currents during switching, or, c) excessive reactive load on the power system voltage. These undesirable effects can be reduced by adding a series resistor—hence, the very popular use of RC snubbers and suppression networks. However, the price of the added resistance is less effective clamping.

Beyond the simple RC network, conventional filters comprising inductances and capacitors are widely used for interference protection. As a bonus, they also offer an effective transient protection, provided that the filter's front-end components can withstand the high voltage associated with the transient.

There is a fundamental limitation in the use of capacitors and filters for transient protection when the source of transients in unknown. The capacitor response is indeed nonlinear with frequency, but it is still a linear function of current.

In Chapter 1, it was explained that to design a protection scheme against random transients, it is often necessary to make an assumption about the characteristics of the impinging transient. If an error in the source impedance or in the open-circuit voltage is made in that assumption, the consequences for a linear suppressor and a nonlinear suppressor are dramatically different as demonstrated by the following comparison.

**A SIMPLIFIED COMPARISON BETWEEN PROTECTION WITH LINEAR and NONLINEAR SUPPRESSOR DEVICES**

*Assume* an open-circuit voltage of 3000V (see Figure 2.2):

1. If the source impedance is $Z_s = 50\Omega$
   with a suppressor impedance of $Z_v = 8\Omega$
   the expected current is:

$$I = \frac{3000}{50 + 8} = 51.7\text{A and } V_R = 8 \times 51.7 = 414\text{V}$$

The maximum voltage appearing across the terminals of a typical nonlinear V130LA20A varistor at 51.7A is 330V.

Note that:

$$\begin{aligned} Z_s \times I &= 50 \times 51.7 = 2586\text{V} \\ V_R \times I &= 8 \times 51.7 = \underline{\ \ 414\text{V}} \\ &= 3000\text{V} \end{aligned}$$

2. If the source impedance is only $5\Omega$ (a 10:1 error in the assumption), the voltage across the same linear $8\Omega$ suppressor is:

$$V_R = 3000 \frac{8}{5 + 8} = 1850\text{V}$$

However, the nonlinear varistor has a much lower impedance; again, by iteration from the characteristic curve, try 400V at 500A, which is correct for the V130LA20A; to prove the correctness of our "educated guess" we calculate I.

$$I = \frac{3000 - 400\text{V}}{5} = 520\text{A}.$$

$$\begin{aligned} Z_s \times I &= 5 \times 520 = 2600\text{V} \\ V_C &= \underline{\ \ 400\text{V}} \\ &= 3000\text{V} \end{aligned}$$

which justifies the "educated guess" of 500A in the circuit.*

**Summary**

3000V "OPEN-CIRCUIT" TRANSIENT VOLTAGE

| Protective Level Achieved | Assumed Source Impedance | |
|---|---|---|
| | $50\Omega$ | $5\Omega$ |
| Linear $8\Omega$ | 414V | 1850V |
| Nonlinear Varistor | 330V | 400V |

Similar calculations can be made, with similar conclusions, for an assumed error in open-circuit voltage at a fixed source impedance. In that case, the linear device is even more sensitive to an error in the assumption. The calculations are left for the interested reader to work out.

*An educated guess, or the result of an iteration — see further in the manual, "Designing with GE-MOV®II Varistor," Chapter 4.

The example calculated in the box shows that a source impedance change from an assumed 50Ω to 5Ω can produce a change of about 414V to 1850V for the protective voltage of a typical linear suppressor. With a typical nonlinear suppressor, the corresponding change is only 330V to 400V. In other words, a variation of only 21% in the protective level achieved with a nonlinear suppressor occurs for a 10 to 1 error in the assumption made on the transient parameters, in contrast to a 447% variation in the protective level with a linear suppressor for the same error in assumption. Nonlinear voltage-clamping devices give the lowest clamping voltage, resulting in the best protection against transients.

### *2.1.2 Crowbar Devices*

This category of suppressors, primarily gas tubes (also called "spark gaps") or carbon-block protectors, is widely used in the communication field where power-follow current is less of a problem than in power circuits. Another form of these suppressors is the hybrid circuit which uses solid-state or ionic devices where a control circuit causes turn-on of an active component.

In effect, a crowbar device short-circuits a high voltage to ground. This short will continue until the current is brought to a low level. A voltage clamping device will never reduce the line voltage below its steady-state value but the crowbar device often will. Because the voltage (arc or forward-drop) during the discharge is held very low, substantial currents can be carried by the suppressor without dissipating a considerable amount of energy within the suppressor. This capability is the major advantage of these suppressors. However, two limitations must be considered.

**Volt-Time Response.** When the voltage rises across a spark-gap, no significant conduction can take place until transition to the arc mode has occurred by avalanche breakdown of the gas between the electrodes. The delay time, typically microseconds, leaves the load unprotected during the initial rise.

Since the process is statistical in nature, there is a considerable variation in the sparkover voltage obtained in successive operations. For some devices, this sparkover voltage also can be substantially higher after a long period of rest than after a succession of discharges. From the physical nature of the process, it is difficult to produce consistent sparkover voltage for low voltage ratings. The difficulty is compounded by the effect of manufacturing tolerances on very small gap distances. One way to alleviate the difficulty is to fill the tube with a gas having a lower breakdown voltgage than that of air. However, this substitution creates a reliability problem if the enclosure seal is lost and the gas is replaced by air. Some applications require providing a second gap in parallel with the first, with slightly higher sparkover voltage for backup against failure of the gas tube.

**Power-Follow.** The second limitation is that a power current from the steady-state voltage source will follow the surge discharge (called "follow-current" or "power-follow"). In ac circuits, this power-follow current may or may not be cleared at a natural current zero; in dc circuits the clearing is even more uncertain. Therefore, if the crowbar device is not designed to provide self-clearing action within specified limits of surge energy and system voltage and power-follow current, additional means must be provided to open the power circuit.

### *2.1.3 Voltage-Clamping Devices*

To perform the voltage limiting function, voltage-clamping devices discussed at the beginning of the chapter depend on their nonlinear impedance in conjunction with the transient source impedance. Three types of devices have been used: reverse selenium rectifiers, avalanche (zener) diodes and varistors made of different materials, i.e., silicon carbide, zinc oxide, etc.[1]

**Selenium Cells.** Selenium transient suppressors apply the technology of selenium rectifiers in conjunction with a special process allowing reverse breakdown current at high-energy levels without damage to the polycrystalline structure. These cells are built by developing the rectifier elements on the surface of a metal plate substrate which gives them good thermal mass and energy dissipation performance. Some of these have self-healing charcteristics which allows the device to survive energy discharges in excess of the rated values for a limited number of operations — characteristics that are useful, if not "legal" in the unsure world of voltage transients.

The selenium cells, however, do not have the clamping ability of the more modern metal-oxide varistors or avalanche diodes. Consequently, their field of application has been considerably diminished.

**Zener Diodes.** Silicon rectifier technology has improved the performance of regulator-type zener diodes in the direction of the design of surge-suppression type avalanche diodes. The major advantage of these diodes is their very effective clamping, which comes closest to an ideal constant voltage clamp. They are also available in low-voltage ratings.

Since the diode maintains the avalanche voltage across a thin junction area during surge discharge, substantial heat is generated in a small volume. The major limitation of this type of device is its energy dissipation capability.

**Varistors.** A *varistor* functions as a nonlinear variable impedance. The relationship between the current in the device, I, and the voltage across the terminals, V, is typically described by a power law: $I = kV^{\alpha}$. While more accurate and more complete equations can be derived to reflect the physics of the device,[2,3] this definition will suffice here. A more detailed discussion will be found in Chapter 3.

The term $\alpha$ (alpha) in the equation represents the degree of nonlinearity of the conduction. A linear resistance has an $\alpha = 1$. The higher the value of $\alpha$, the better the clamp, which explains why $\alpha$ is sometimes used as a figure of merit. Quite naturally, varistor manufacturers are constantly striving for higher alphas.

**Silicon Carbide.** Until recently, the most common type of varistor was made from specially processed silicon carbide. This material has been and is still very successfully applied in high-power, high-voltage surge arresters. However, the relatively low $\alpha$ values of this material produce one of two results. Either the protective level is too high for a device capable of withstanding line voltage or, for a device producing an acceptable protective level, excessive stand-by current would be drawn at normal voltage if directly connected across the line. Therefore, a series gap is required to block the normal voltage.

A detailed discussion of series gap/silicon carbide block combinations is beyond the scope of this manual, but many references and standards on the design, testing and application of surge arresters are available.[4,5]

In lower voltage electronic circuits, silicon carbide varistors have not been widely used because of the need for using a series gap, which increases the total cost and reproduces some of the undesirable characteristics of gaps described earlier. However, this varistor has been used as a current-limiting resistor to assist some gaps in clearing power-follow current.

**Metal-Oxide Varistors.** A number of recent developments[6,7] have produced a new family of varistors made of sintered metal oxides, primarily zinc oxide with suitable additives. These new varistors have $\alpha$ values considerably greater than those of silicon carbide varistors, typically in the range of an effective value of 15 to 30 measured over several decades of surge current. One type of varistor, the General Electric GE-MOV®II Varistor, will be described in greater detail in Chapter 3. For the moment, the description will be limited to what is necessary for understanding the discussion of suppression and application in this chapter.

The high exponent values ($\alpha$) of the metal-oxide varistors have opened completely new fields of applications by providing a sufficiently low protective level and a low standby current. The opportunities for applications extend from low-power electronics to the largest utility-type surge arresters. However, for this manual, the emphasis is primarily on circuit voltages below 1000V rms and surge energies of less than 1000J. Higher voltages can be readily obtained by connecting several devices in series. However, increased current values by parallel connection cannot be obtained without careful matching of device characteristics. On the low end of the voltage scale, the metal-oxide varistors, as they exist today, are limited to 10 V rms.

The structural characteristics of metal-oxide varistors unavoidably result in an appreciable capacitance between the device terminals, depending on area, thickness and material processing. For the majority of power applications, this capacitance is not significant. In high-frequency applications, however, the effect must be taken into consideration in the overall system design.

## 2.2 TRANSIENT SUPPRESSORS COMPARED

Because of diversity of characteristics and nonstandardized manufacturer specifications, transient suppressors are not easy to compare. A graph (Figure 2.3) shows the relative volt-ampere characteristics of the four common devices that are used in 120V ac circuits. A curve for a simple ohmic resistor is included for comparison. It can be seen that as the alpha factor increases, the curve's voltage-current slope becomes less steep and approaches an almost constant voltage. High alphas are desirable for clamping applications that require operation over a wide range of currents.

It also is necessary to know the device energy-absorption and peak-current capabilities when comparisons are made. The table below includes other important parameters of commonly used suppressors.

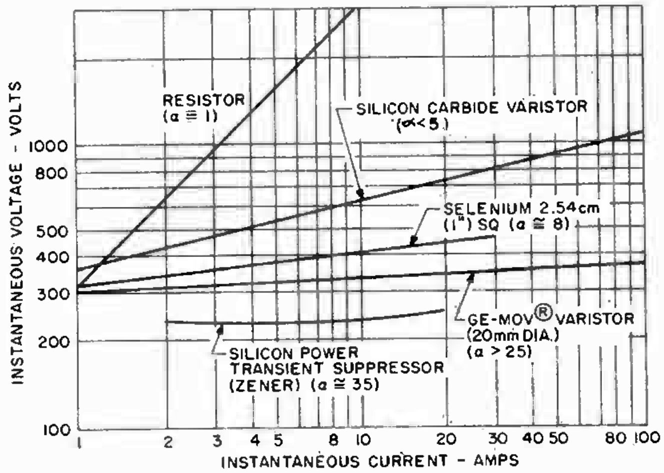



FIGURE 2.3: V-I CHARACTERISTICS OF FOUR TRANSIENT SUPPRESSOR DEVICES

### TABLE 2.1: SUPPRESSOR CHARACTERISTICS

| SUPPRESSOR TYPE | STANDBY CURRENT mA | PEAK CURRENT @ 1 ms A | PEAK POWER @ 1 ms kW | PEAK ENERGY JOULES | VOLTAGE CLAMPING RATIO @ 10 A | VOLTAGE RANGE DC |
|---|---|---|---|---|---|---|
| GE-MOV®II Varistor (20mm diameter) | 1 | 120 | 40 | 70 | 1.7 | 14-1200 |
| Zener Diode (1W) | .005 | 5.5 | 1.5 | 2 | 1.65 | 5-200 |
| Selenium (1" Sq.) | 12 | 30 | 9 | 9 | 2.3 | 35-700 |
| Spark Gap | – | >500 | – | – | 2.4-8.8* | 90-1400 |
| Silicon Carbide Varistor (0.75" diameter) | 5 | – | – | 50 | 4.6 | 15-300 |

*Range of impulse spark-over voltage at 1 kV/μs, then drops to <1.

**Standby power** —the power consumed by the suppressor unit at normal line voltage—is an important selection criterion. Peak standby current is one factor that determines the standby power of a suppressor. The standby power dissipation depends also on the alpha characteristic of the device.

As an example, the selenium suppressor in Table 2.1 has a 12mA peak standby current and an alpha of 8 (Figure 2.3). Therefore, it has a standby power dissipation of about 0.5W on a 120V rms line (170V peak). A zener-diode suppressor has standby power dissipation of less than a milliwatt. And a silicon-carbide varistor, in a 0.75" diameter disc, has standby power in the 200mW range. High standby power in the lower alpha devices is necessary to achieve a reasonable clamping voltage at higher currents.

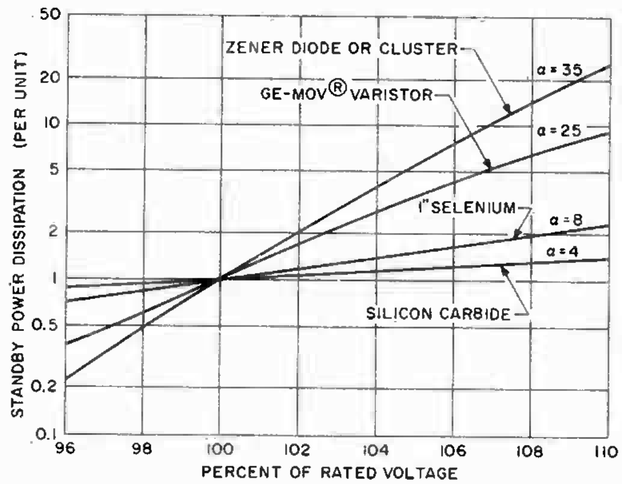



FIGURE 2.4: CHANGES IN STANDBY POWER ARE CONSIDERABLY GREATER WHEN THE SUPPRESSOR'S ALPHA IS HIGH

The amount of standby power that a circuit can tolerate may be the deciding factor in the choice of a suppressor. Though high-alpha devices have low standby power at the nominal design voltage, a small line-voltage rise would cause a dramatic increase in the standby power. Figure 2.4 shows that for a zener-diode suppressor, a 10% increase above rated voltage increases the standby power dissipation above its rating by a factor of 30. But for a low-alpha device, such as silicon carbide, the standby power increases by only 1.5 times.

Typical volt-time curves of a gas discharge device are shown in Figure 2.5 indicating an initial high clamping voltage. The gas-discharge suppressor does not turn on unless the transient pulse exceeds the impulse sparkover voltage. Two representative surge rates—1kV/$\mu$s and 20kV/$\mu$s—are shown in Figure 2.5. When a surge voltage is applied, the device turns on at some point within the indicated limits. At 20kV/$\mu$s, the discharge unit will sparkover between 600 and 2500V. At 1kV/$\mu$s, it will sparkover between 390 and 1500V.

In use for the protection of ac line surges, the gas discharge device may experience follow current. As the voltage passes through zero at the end of every half cycle the arc will extinguish, but if the electrodes are hot and the gas is ionized, it may re-ignite on the next cycle. Depending on the power source, this current may be sufficient to cause damage to the electrodes. The follow current can be reduced by placing a limiting resistor in series with the device, reducing its current, but at a penalty of increased clamping voltage.

The gas discharge device is useful for high current surges but it is not effective in protecting low voltage, low impedance circuits. It is often advantageous to provide another suppression device in a combination that allows the added suppressor to protect against the high initial impulse. Several hybrid combinations with a varistor or avalanche diode are possible. Care in design is required to direct the initial portion of the impulse to the solid state device and to divert the high current of the later portion of the pulse to the gas discharge element. Precautions must also be taken against voltages induced in adjacent wiring by the sharp current rise associated with the gap sparkover.

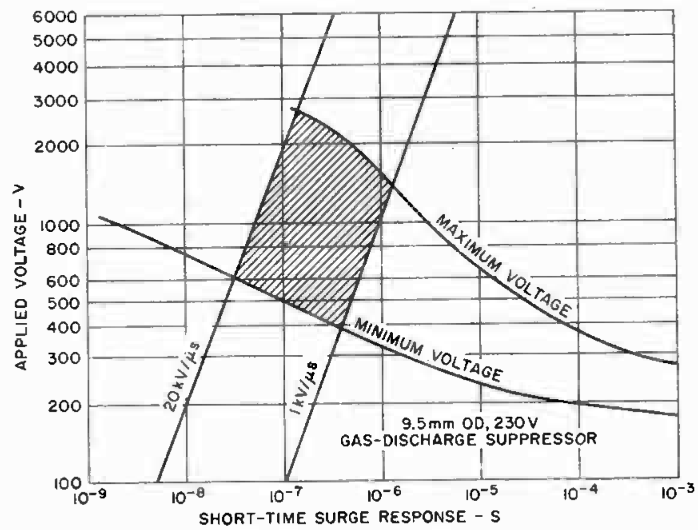



FIGURE 2.5: IMPULSE BREAKOVER OF A GAS-DISCHARGE DEVICE DEPENDS UPON THE RATE OF VOLTAGE RISE AS WELL AS THE ABSOLUTE VOLTAGE LEVEL

## 2.3 PROOF TESTS

To consider protective devices while a system is being designed and to follow with proof tests should be axiomatic, but historical evidence makes it apparent that this is not so. Thus, retrofit of transient suppressors is common practice. Actually, one can view this retrofit as part of the tradeoff process, with iterative corrections in a calculated risk approach. It may be justifiable to attempt applying some device with minimal protection in the harsh outside world, and later, when found necessary, to take corrective action. Hence, retrofit should then be the result of informed choice, not an unforeseen need for correction. Even here some form of proof testing will be required to ascertain that the retrofit will do the job.

The nature of the transient environment comes under examination when a retrofit must be applied. There is some factual knowledge on the subject, discussed in Chapter 1, but there are also many tentative "generalizations" that require confirmation. Test standards and specifications, then, become useful guides to the extent that they are not applied or enforced blindly.[8]

Some test specifications emphasize *voltage* tests. This is natural because historically, electrical equipment had dielectric failures as the major consequence of overvoltages. One can, therefore, specify some voltage test wave that the equipment must withstand without breakdown. However, with the inclusion of a protective device within the boundaries of an eletronic black box, a simple voltage test is no longer meaningful. What is needed is the two-step approach discussed below, where the voltage allowed by the protector is determined first, then the effects on the downstream components determined. *Coordination* is the key concept.

One point to remember when specifying or performing a test is the difference between a *voltage* and a *current* test.

In testing a device for voltage withstand capability, proper recognition must be given to the impedance of the device being tested and to whether or not it already contains a transient suppressor. It would seem obvious that one does not specify a voltage test and then crank up the generator until that specified steady-state voltage is achieved at the terminals of the black box containing a suppressor. Yet this has been attempted!

Conversely, applying a voltage test to a black box containing a suppressor will be meaningless if the source impedance of the test generator is too high or too low. It is more appropriate, at least in the design stage, to separate the test from the design steps. First, one specifies the test circuit which will exercise the suppressor: open circuit voltage, (amplitude and duration) and source impedance. This determines the clamp voltage that will be developed across the shunt-connected suppressor (Figure 2.6). Second, one designs the protected circuit for this clamp voltage allowing adequate margins. After the design, this two-step approach can also be applied for demonstrating that withstand capability has been achieved.

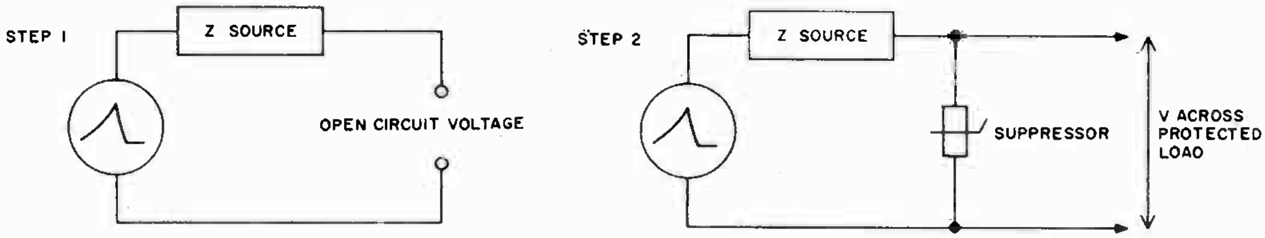



FIGURE 2.6: TWO STEPS FOR EVALUATING PROTECTION REQUIREMENTS

Chapter 7 provides detailed information on varistor testing, both for evaluating varistor characteristics and for conducting realistic proof tests.

## REFERENCES

1. Sakshaug, E.C., J.S. Kresge and S.A. Miske, "A New Concept in Station Arrester Design," IEEE Trans. PAS-96, No. 2, March-April 1977, pp. 647-656.
2. Philipp, H.R. and L.M. Levinson, "Low Temperature Electrical Studies in Metal Oxide Varistors—A Clue to Conduction Mechanisms," Journal of Applied Physics, Vol. 48, April 1977, pp. 1621-1627.
3. Philipp, H.R. and L.M. Levinson, "Zinc Oxide for Transient Suppression," IEEE Trans. PHP, December 1977.
4. Surge Arresters for Alternating Current Power Circuits, ANSI Standard C62.1, IEEE Standard 28.
5. Lightning Arresters. Part I: Nonlinear Resistor Type Arresters for AC Systems, IEC Recommendation 99-1, 1970.
6. Matsuoka, M., T. Masuyama and Y. Iida, Supplementary Journal of Japanese Society of Applied Physics, Vol. 39, 1970, pp. 94-101.
7. Harnden, J.D., F.D. Martzloff, W.G. Morris and F.B. Golden, "Metal-Oxide Varistor: A New Way to Suppress Transients," Electronics, October 2, 1972.
8. Martzloff, F.D., "The Development of a Guide on Surge Voltages in Low-Voltage AC Power Circuits," Report 81CRD047, General Electric, Schenectady, New York, 1981.

Notes

chapter 3

# GE-MOV®II VARISTORS BASIC PROPERTIES, TERMINOLOGY AND THEORY

## 3.1 WHAT IS A GE-MOV®II VARISTOR?

GE-MOV® II Varistors are voltage dependent, nonlinear devices which have an electrical behavior similar to back-to-back zener diodes. The symmetrical, sharp breakdown characteristics shown in Figure 3.1 enable the varistor to provide excellent transient suppression performance. When exposed to high voltage transients the varistor impedance changes many orders of magnitude from a near open circuit to a highly conductive level, thus clamping the transient voltage to a safe level. The potentially destructive energy of the incoming transient pulse is absorbed by the varistor, thereby protecting vulnerable circuit components.

The varistor is composed primarily of zinc oxide with small additions of bismuth, cobalt, manganese and other metal oxides. The structure of the body consists of a matrix of conductive zinc oxide grains separated by grain boundaries providing P-N junction semiconductor characteristics. These boundaries are responsible for blocking conduction at low voltages and are the source of the nonlinear electrical conduction at higher voltages.

Since electrical conduction occurs, in effect, between zinc oxide grains distributed throughout the bulk of the device, the GE-MOV®II Varistor is inherently more rugged than its single P-N junction counterparts, such as zener diodes. In the varistor, energy is absorbed uniformly throughout the body of the device with the resultant heating spread evenly through its volume. Electrical properties are controlled mainly by the physical dimensions of the varistor body which generally is sintered in the shape of a disc. The energy rating is determined by volume, voltage rating by thickness or current flow path length, and current capability by area measured normal to the direction of current flow.

GE-MOV®II Varistors are available with ac operating voltages from 6V to 2800V. Higher voltages are limited only by packaging ability. Peak current handling exceeds 50,000A and energy capability extends beyond 6500J for the larger units. Package styles include the axial device series for automatic insertion and progress in size up to the rugged high energy device line.

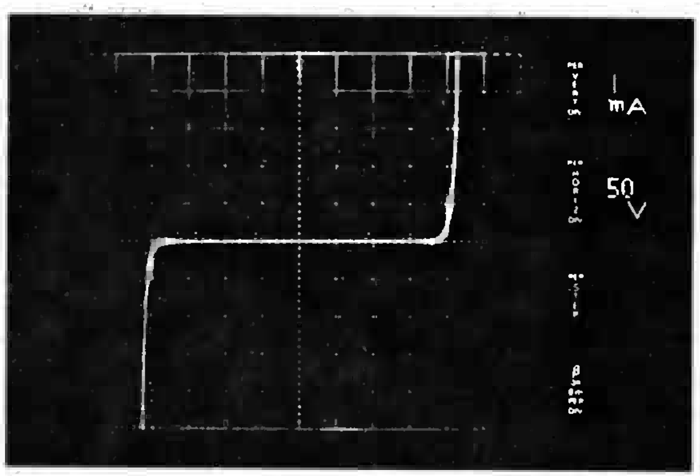
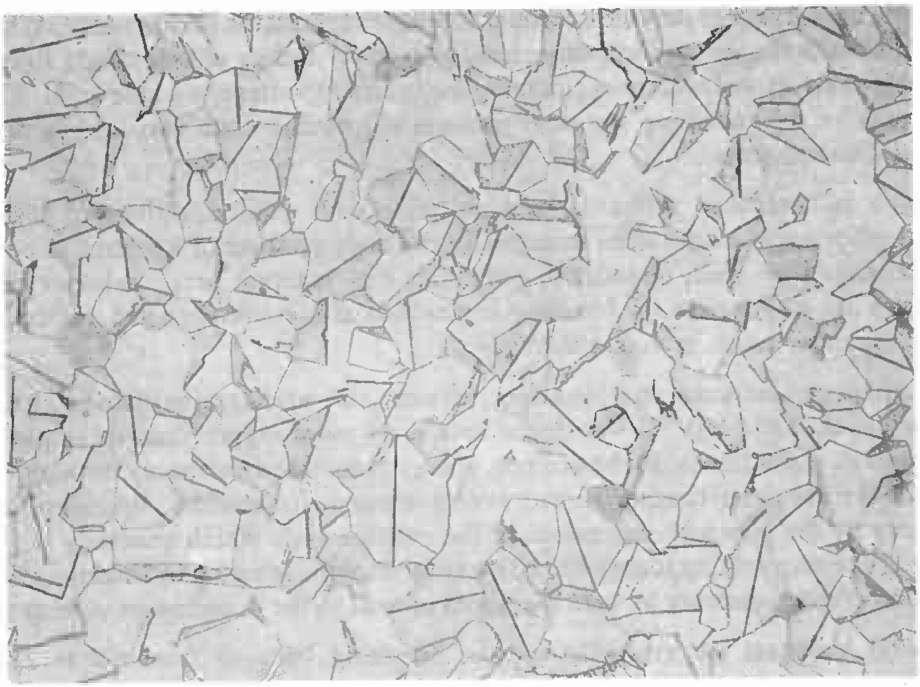



FIGURE 3.1: TYPICAL VARISTOR I-V CHARACTERISTIC

## 3.2 PHYSICAL PROPERTIES

### *3.2.1 Introduction*

An attractive property of the metal oxide varistor, fabricated from zinc oxide (ZnO), 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 semiconductor junction at the grain boundry. A cross-section of the material is shown in Figure 3.2, which illustrates the ceramic microstructure. The ZnO grain boundaries can be clearly observed. Since the nonlinear electrical behavior occurs at the boundary of each semiconducting ZnO grain, the varistor can be considered a "multi-junction" device composed of many series and parallel connections of grain boundaries. Device behavior may be analyzed with respect to the details of the ceramic microstructue. Mean grain size and grain size distribution play a major role in electrical behavior.



|—— 100μ ——|

FIGURE 3.2: OPTICAL PHOTOMICROGRAPH OF A POLISHED AND ETCHED SECTION OF A GE-MOV® VARISTOR

### *3.2.2 Varistor Microstructure*

GE-MOV®II Varistors are formed by pressing and sintering zinc oxide-based powders into ceramic discs. These discs are then electroded with thick film silver to provide solderable contact areas. The bulk of the varistor between contacts is comprised of ZnO grains of an average size "d" as shown in the schematic model of Figure 3.3. Resistivity of the ZnO is <0.3ohm-cm.

Designing a varistor disc for a given nominal varistor voltage, $V_N$, is basically a matter of selecting a disc thickness such that the appropriate number of grains, n, are in series between electrodes. In practice, the varistor material is characterized by a voltage gradient measured across its thickness by a specific volts/mm value. By controlling composition and manufacturing conditions the gradient remains fixed. Because there are practical limits to the range of disc thickness achievable, more than one voltage gradient value is desired. By altering the composition of the metal oxide additives it is possible to change the grain size "d" and achieve the desired result.

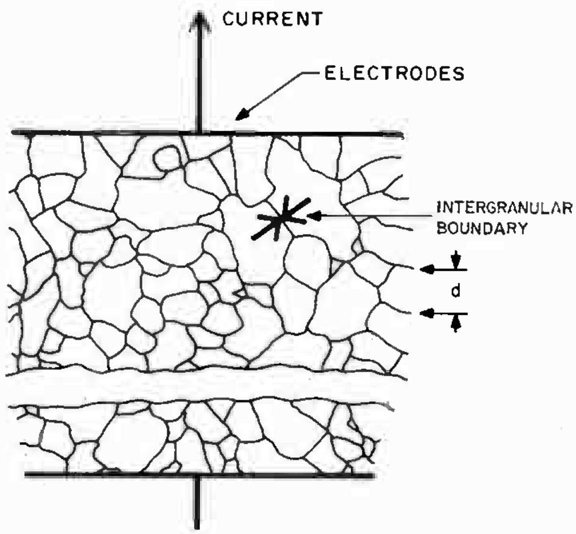



FIGURE 3.3: SCHEMATIC DEPICTION OF THE MICROSTRUCTURE OF A METAL-OXIDE VARISTOR. GRAINS OF CONDUCTING ZnO (AVERAGE SIZE d) ARE SEPARATED BY INTERGRANULAR BOUNDARIES

A fundamental property of the ZnO varistor is that the voltage drop across a single interface "junction" between grains is nearly constant. Observations over a range of compositional variations and processing conditions show a fixed voltage drop of about 2-3V per grain boundary junction. Also, the voltage 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, $V_N$ | $=$ | $(3V)\,n$ |
| where, | $n$ | $=$ | average number of grain boundaries between electrodes |
| and, | varistor thickness, $D$ | $=$ | $(n+1)\,d$ |
| | | $\approx$ | $\dfrac{V_N \times d}{3}$ |
| where, | $d$ | $=$ | average grain size |

The varistor voltage, $V_N$, is defined as the voltage across a varistor at the point on its V-I characteristic where the transition is complete from the low-level linear region to the highly non-linear region. For standard measurement purposes, it is arbitrarily defined as the voltage at a current of 1 mA.

Some typical values of dimensions for GE-MOV®II varistors are given in the table below.

| VARISTOR VOLTAGE | AVERAGE GRAIN SIZE | n | GRADIENT | DEVICE THICKNESS |
|---|---|---|---|---|
| VOLTS | MICRONS | | V/mm AT 1 mA | mm |
| 150V RMS | 20 | 75 | 150 | 1.5 |
| 25V RMS | 80* | 12 | 33 | 1.0 |

*Low voltage formulation.

*3.2.3 Theory of Operation*

Because of the polycrystalline nature of metal oxide semiconductor varistors, the physical operation of the device is more complex than that of conventional semiconductors. Intensive measurement has determined many of the device's electrical characteristics, and much effort continues to better define the varistor's operation. In this section we will discuss some theories of operation, but from the user's viewpoint this is not nearly as important as understanding the basic electrical properties as they relate to device construction.

The key to explaining metal oxide varistor operation lies in understanding the electronic phenomena occurring near the grain boundaries, or junctions between the zinc oxide grains. While some of the early theory supposed that electronic tunneling occurred through an insulating second phase layer at the grain boundaries, varistor operation is probably better described by a series-parallel arrangement of semiconducting diodes. In this model, the grain boundaries contain defect states which trap free electrons from the n type semiconducting zinc oxide grains, thus forming a space charge depletion layer in the ZnO grains in the region adjacent to the grain boundaries.[6]

Evidence for depletion layers in the varistor is shown in Figure 3.4 where the inverse of the capacitance per boundary squared is plotted against the applied voltage per boundary.[7] This is the same type of behavior observed for semiconductor abrupt p-n junction diodes. The relationship is:

$$\frac{1}{C^2} = \frac{2(V_b + V)}{q\epsilon s N}$$

Where $V_b$ is the barrier voltage, V the applied voltage, q the electron charge, $\epsilon s$ the semiconductor permittivity and N is the carrier concentration. From this relationship the ZnO carrier concentration, N, was determined to be about $2 \times 10^{17}$ per $cm^3$.[7] In addition, the width of the depletion layer was calculated to be about 1000 Angstrom units. Single junction studies also support the diode model.[9]

It is these depletion layers that block the free flow of carriers and are responsible for the low voltage insulating behavior in the leakage region as depicted in Figure 3.7. The leakage current is due to the free flow of carriers across the field lowered barrier, and is thermally activated, at least above about 25°C.

Figure 3.5 shows an energy band diagram for a ZnO-grain boundary-ZnO junction.[11] The left-hand grain is forward biased, $V_L$, and the right side is reverse biased to $V_R$. The depletion layer widths are $X_L$ and $X_R$, and the respective barrier heights are $\phi_L$ and $\phi_R$. The zero biased barrier height is $\phi_O$. As the voltage bias is increased, $\phi_L$ is decreased and $\phi_R$ is increased, leading to a lowering of the barrier and an increase in conduction.

The barrier height $\phi_L$ of a low voltage varistor was measured as a function of applied voltage (see Reference 11) and is presented in Figure 3.6. The rapid decrease in the barrier at high voltage represents the onset of nonlinear conduction.[12]

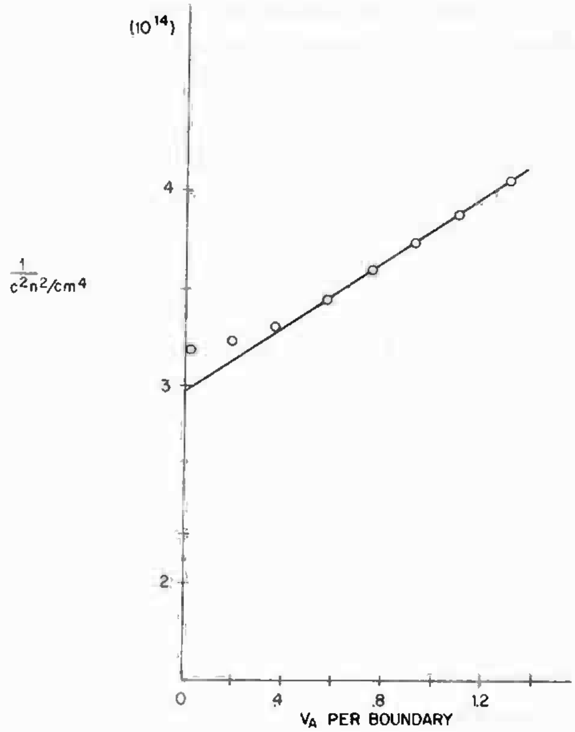



**FIGURE 3.4: CAPACITANCE-VOLTAGE BEHAVIOR OF GE-MOV® VARISTOR RESEMBLES A SEMICONDUCTOR ABRUPT-JUNCTION REVERSED BIASED DIODE. $N_d \sim 2 \times 10^{17}/cm^3$**

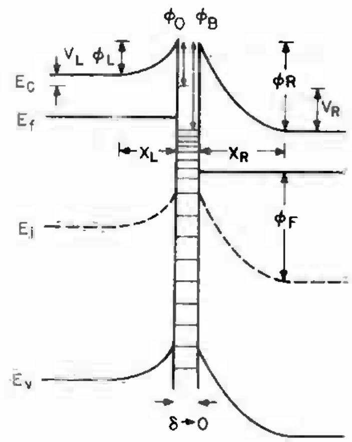



**FIGURE 3.5: ENERGY BAND DIAGRAM OF A ZnO-GRAIN BOUNDARY-ZnO JUNCTION**

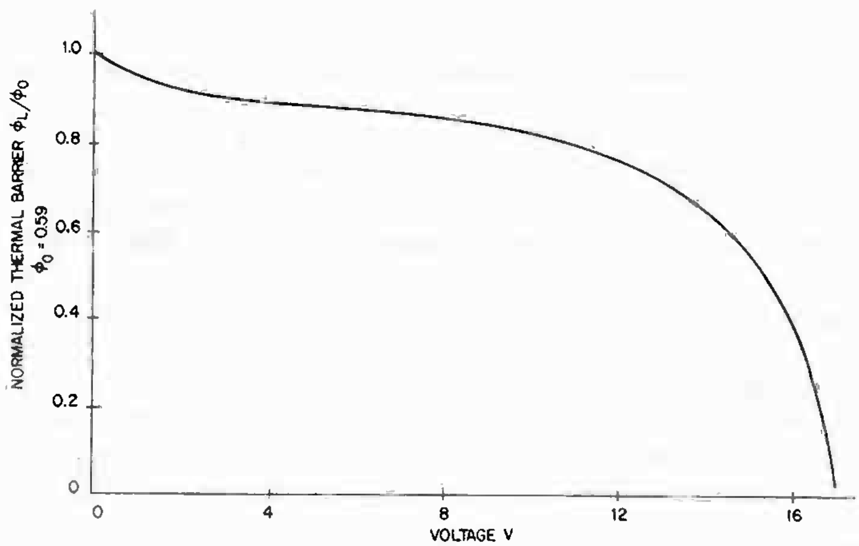



**FIGURE 3.6: THERMAL BARRIER AS A FUNCTION OF APPLIED VOLTAGE**

Transport mechanisms in the nonlinear region are very complicated and are still the subject of active research. Most theories draw their inspiration from semiconductor transport theory and the reader is referred to the literature for more information.[3,5,13,14,15]

Turning now to the high current upturn region in Figure 3.10 (see page 48), we see that the I-V behavior approaches an ohmic characteristic. The limiting resistance value depends upon the electrical conductivity of the body of the semiconducting ZnO grains, which have carrier concentrations in the range of $10^{17}$ to $10^{18}$ per $cm^3$. This would put the ZnO resistivity below 0.3 Ωcm.

## 3.3 VARISTOR CONSTRUCTION

The process of fabricating a GE-MOV®II Varistor is illustrated in the flow chart of Figure 3.7. The starting material may differ in the composition of the additive oxides, in order to cover the voltage range of product.

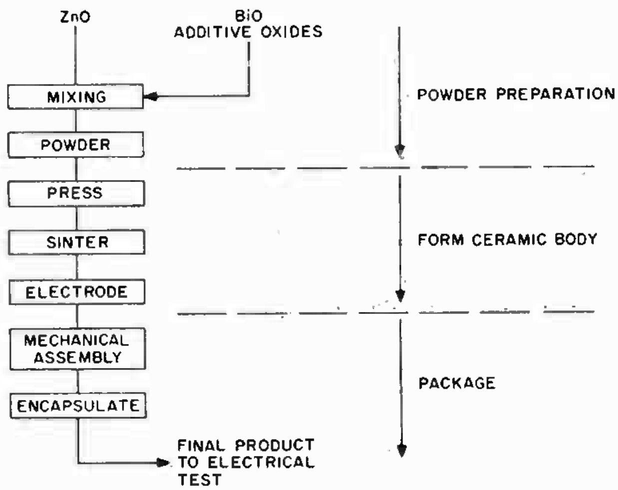



FIGURE 3.7: SCHEMATIC FLOW DIAGRAM OF GE-MOV® II VARISTOR FABRICATION

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, disc diameter is varied. The range of diameters obtainable in product offerings is listed here:

| | | | | | |
|---|---|---|---|---|---|
| Nominal Disc Diameter – mm | 3 | 7 | 14 | 20 | 32 |

Of course, other shapes, such as rectangles, are also possible by simply changing the press dies. After pressing, the discs are placed in a kiln 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.

Electroding is accomplished by means of thick film silver fired onto the ceramic surface. Wire leads or strap terminals are then soldered in place. A conductive epoxy is used for connecting contacts to the molded axial 3mm discs.

Encapsulation is of three forms: an epoxy fluid bed coating for radial lead packages; a molded plastic for the molded axial and power packages, and a cast epoxy in a molded plastic shell for the high energy series package. Different package styles allow variation in energy ratings, as well as in mechanical mounting. Figure 3.8 illustrates a sampling of four basic package forms—the axial (MA Series), the leaded radial (L, Z Series), the power configuration (P Series), and the High Energy (HE Series).

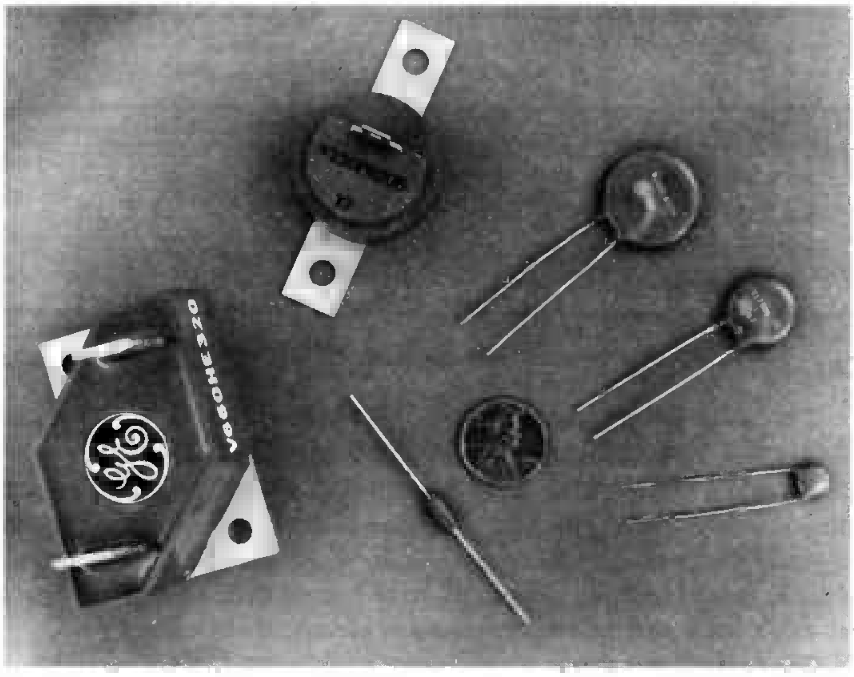


FIGURE 3.8: GE-MOV® VARISTOR PACKAGES PRESENTLY AVAILABLE

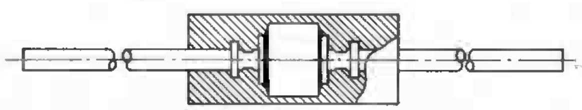


FIGURE 3.9A: CROSS-SECTION OF MOLDED AXIAL PACKAGE

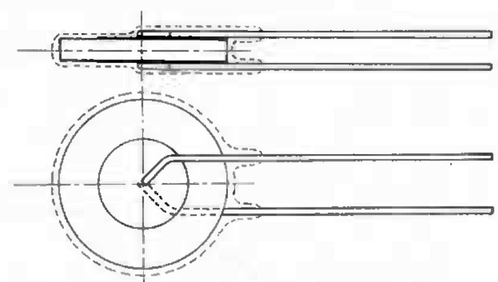


FIGURE 3.9B: CROSS-SECTION OF RADIAL LEAD PACKAGE

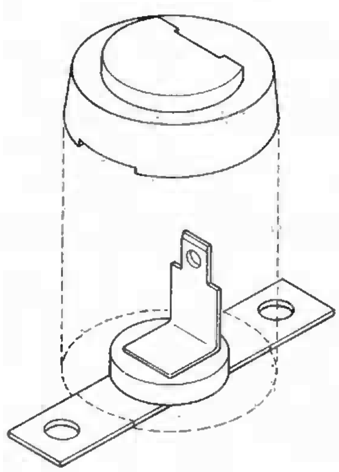


FIGURE 3.9C: PICTORIAL VIEW OF POWER MOV PACKAGE

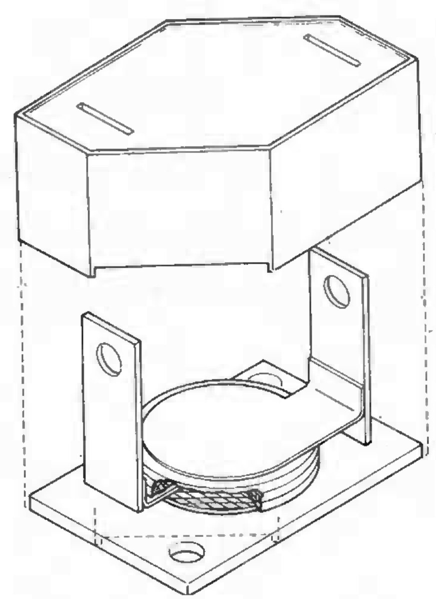


FIGURE 3.9D: PICTORIAL VIEW OF HIGH ENERGY PACKAGE

Figure 3.9 shows detailed construction details of the four basic packages. Disc diameters by package type are given below:

| PACKAGE TYPE | DISC DIAMETER – mm |
|---|---|
| Molded Axial (MA Series) | 3 |
| Radial Lead (LA & ZA Series) | 7, 10, 14 & 20 |
| Power (PA Series) | 20 |
| High Energy (HE Series) | 32 |

## 3.4 ELECTRICAL CHARACTERIZATION

### *3.4.1 Varistor V-I Characteristics*

Varistor electrical characteristics are conveniently displayed using log-log format in order to show the wide range of the V-I curve. The log format also is clearer than a linear representation which tends to exaggerate the nonlinearity in proportion to the current scale chosen. A typical V-I characteristic curve is shown in Figure 3.10. This plot shows a wider range of current than is normally provided on varistor data sheets in order to illustrate three distinct regions of electrical operation.

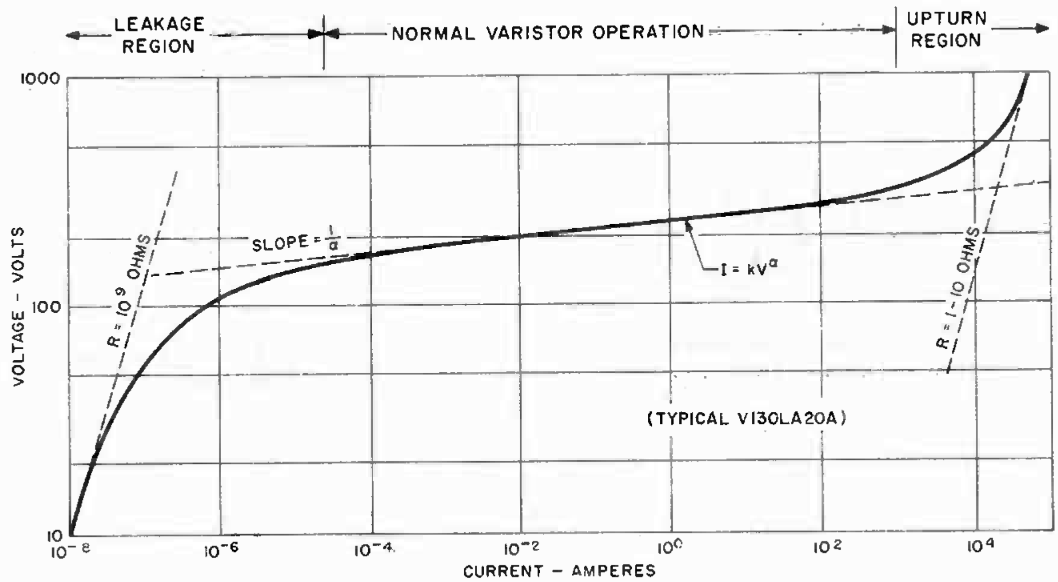



FIGURE 3.10: TYPICAL VARISTOR V-I CURVE PLOTTED ON LOG-LOG SCALE

### *3.4.2 Equivalent Circuit Model*

An electrical model for the varistor can be represented by the simplified equivalent circuit of Figure 3.11.

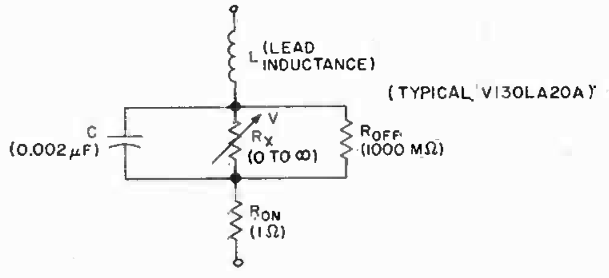



FIGURE 3.11: VARISTOR EQUIVALENT CIRCUIT MODEL

### *3.4.3 Leakage Region of Operation*

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 $10^9$ ohms) and appears as an open circuit. The nonlinear resistance component, $R_X$, can be ignored because $R_{OFF}$ in parallel will predominate. Also, $R_{ON}$ will be insignificant compared to $R_{OFF}$.

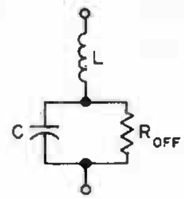



**FIGURE 3.12: EQUIVALENT CIRCUIT AT LOW CURRENTS**

For a given varistor device, capacitance remains approximately constant over a wide range of voltage and frequency in the leakage region. 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 remains nearly constant with frequency change up to 100 kHz. Similarly, the change with temperature is small, the 25 °C value of capacitance being well within ±10% from −40°C to +125°C.

The temperature effect of the V-I characteristic curve in the leakage region is shown in Figure 3.13. A distinct temperature dependence is noted.

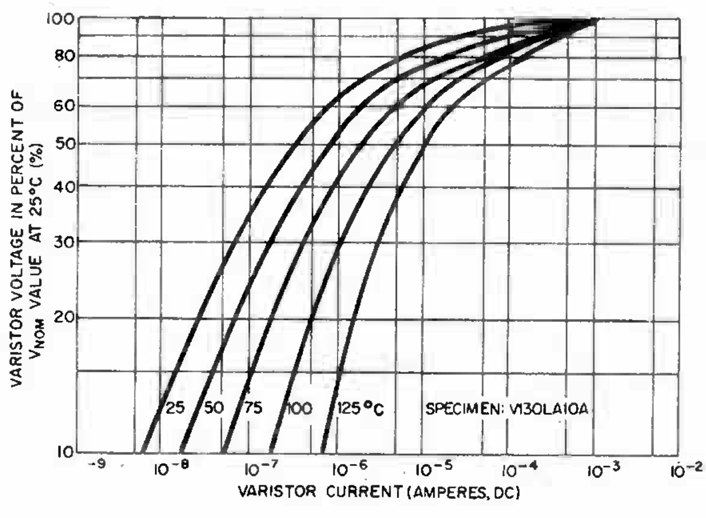



**FIGURE 3.13: TEMPERATURE DEPENDENCE OF THE CHARACTERISTIC CURVE IN THE LEAKAGE REGION**

The relation between the leakage current, I, and temperature, T, is:

$$I = I_o \, \epsilon^{\cdot V_B/kT}$$

where: $I_o$ = constant
$k$ = Boltzmann's Constant
$V_B$ = 0.9 eV

The temperature variation, in effect, corresponds to a change in $R_{OFF}$. However, $R_{OFF}$ remains at a high resistance value even at elevated temperatures. For example, it is still in the range of 10 to 100 megaohms at 125°C.

Although $R_{OFF}$ is a high resistance it varies with frequency. The relationship is approximately linear with inverse frequency.

$$R_{OFF} \sim \frac{1}{f}$$

However, the parallel combination of $R_{OFF}$ and C is predominantly capacitive at any frequency of interest. This is because the capacitive reactance also varies approximately linearly with 1/f.

At higher currents, at and above the milliamp range, temperature variation becomes minimal. The plot of the temperature coefficient (dv/dt) is given in Figure 3.14. It should be noted that the temperature coefficient is negative and decreases as current rises. In the normal operational range of the varistor (I > 1mA), the temperature dependency is less than $-0.05\%/°C$.

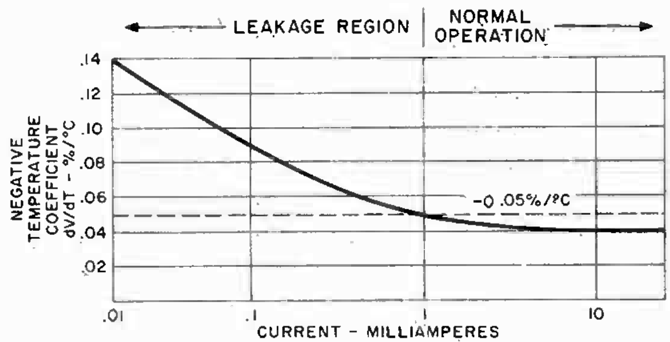



FIGURE 3.14: RELATION OF TEMPERATURE COEFFICIENT, DV/DT TO VARISTOR CURRENT

### *3.4.4 Normal Varistor Region of Operation*

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

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

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

In this region the varistor is conducting and $R_X$ will predominate over C, $R_{ON}$ and $R_{OFF}$. $R_X$ becomes many orders of magnitude less than $R_{OFF}$, but remains larger than $R_{ON}$.


FIGURE 3.15: EQUIVALENT CIRCUIT AT VARISTOR CONDUCTION

During conduction the varistor voltage remains relatively constant for a change in current of several orders of magnitude. In effect, the device resistance, $R_X$, is changing in response to current. This can be observed by examining the static or dynamic resistance as a function of current. The static resistance is defined by:

$$R_x = \frac{V}{I}$$

and the dynamic resistance by:

$$Z_x = \frac{dv}{di} = V/\alpha I = R_x/\alpha$$

Plots of typical resistance values vs. current, I, are given in Figure 3.16.

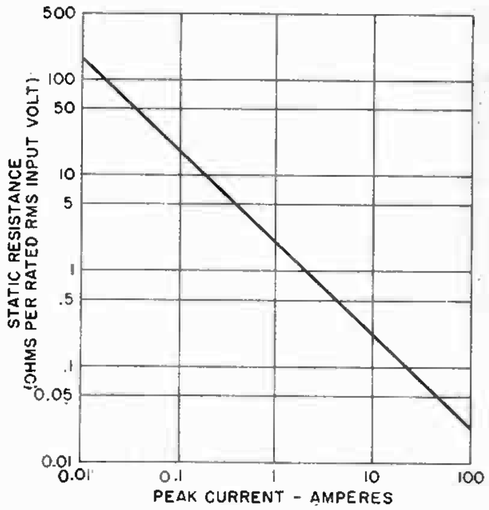



FIGURE 3.16A: $R_x$ STATIC VARISTOR RESISTANCE

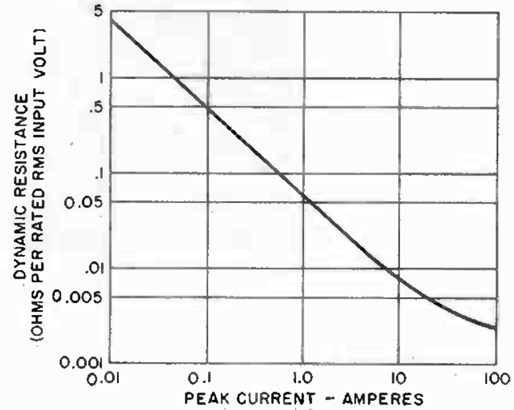



FIGURE 3.16B: $Z_x$ DYNAMIC VARISTOR RESISTANCE

### *3.4.5 Upturn Region of Operation*

At high currents, approaching the maximum rating, the varistor approximates a short-circuit. The curve departs from the nonlinear relation and approaches the value of the material bulk resistance, about 1-10 ohms. This upturn, or saturated region, takes place as $R_X$ approaches the value of $R_{ON}$. Resistor $R_{ON}$ represents the bulk resistance of the zinc oxide grains. This resistance is linear (which appears as a steeper slope on the log plot) and occurs at currents of 50 to 50,000A, depending on the varistor size.

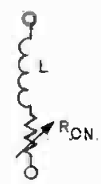



FIGURE 3.17: EQUIVALENT CIRCUIT AT VARISTOR UPTURN

### *3.4.6 Speed of Response and Rate Effects*

The varistor action depends on a conduction mechanism similar to that of other semiconductor devices. For this reason, conduction occurs very rapidly, with no apparent time lag—even into the nanosecond range. Figure 3.18 shows a composite photograph of two voltage traces with and without a varistor inserted in a very low inductance impulse generator. The second trace (which is not synchronized with the first, but merely superimposed on the oscilloscope screen) shows that the voltage clamping effect of the varistor occurs in less than one nanosecond.

In the conventional lead-mounted devices, the inductance of the leads would completely mask the fast action of the varistor; therefore, the test circuit for Figure 3.15 required insertion of a small piece of varistor material in a coaxial line to demonstrate the intrinsic varistor response.

Tests made on lead-mounted devices, even with careful attention to minimizing lead length, show that the voltages induced in the loop formed by the leads contribute a substantial part of the voltage appearing across the terminals of a varistor at high current and fast current rise. Fortunately, the currents which can be delivered by a transient source are invariably slower in rise time than the observed voltage transients. The applications most frequently encountered for GE-MOV®II Varistors involve *current* rise times longer than 0.5 $\mu$s.

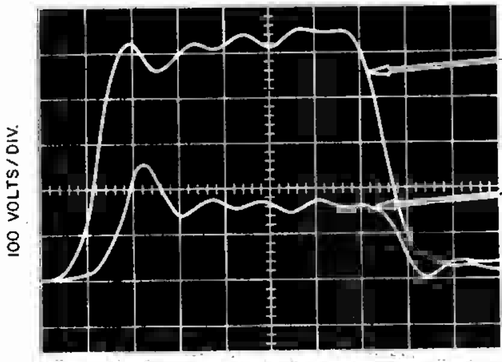
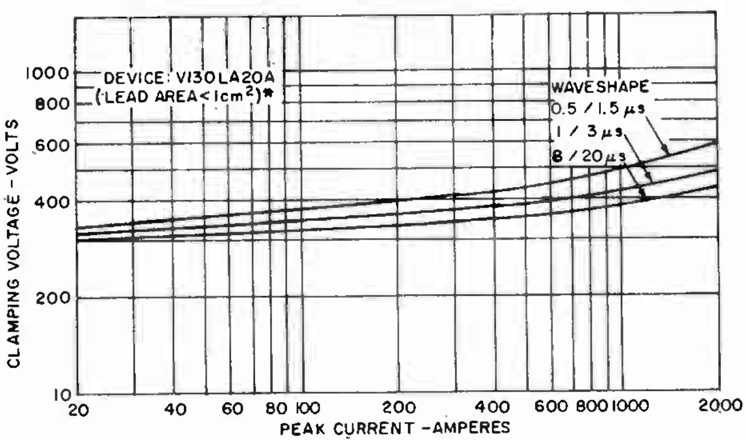
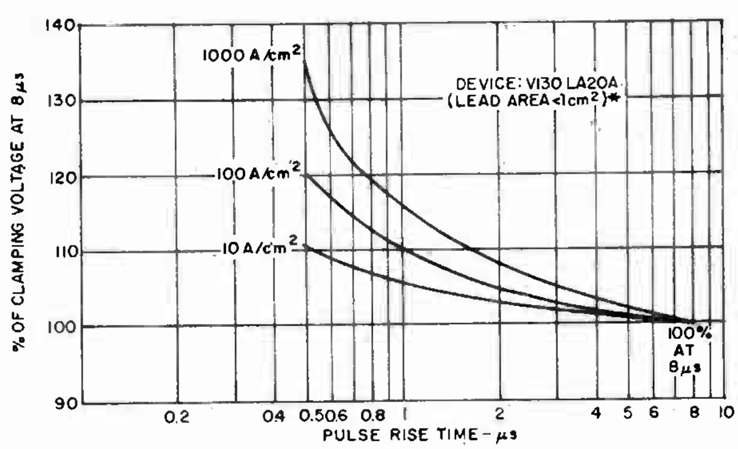



**FIGURE 3.18: RESPONSE OF A ZnO VARISTOR TO A FAST RISE TIME (500 PICOSECOND) PULSE**

Voltage rate-of-rise is not the best term to use when discussing the response of a varistor to a fast impulse (unlike spark gaps where a finite time is involved in switching from non-conducting to conducting state). The response time of the varistor to the transient current that a circuit can deliver is the appropriate characteristic to consider.




a) V-I Characteristics For Various Current Rise Times




b) Overshoot Defined With Reference To The Basic 8 /20μs Current Pulse

*Refer to Section 7.3.2.

**FIGURE 3.19a and b: RESPONSE OF LEAD-MOUNTED VARISTORS TO CURRENT WAVEFORM**

The V-I characteristic of Figure 3.19a shows how the response of the varistor is affected by the current waveform. From such data, an "overshoot" effect can be defined as being the relative increase in the maximum voltage appearing across the varistor during a fast current rise, using the conventional 8 / 20$\mu$s current wave as the reference. Figure 3.19b shows typical clamping voltage variation with rise time for various current levels.

## 3.5 VARISTOR TERMINOLOGY

The following tabulation defines the terminology used in varistor specifications. Existing standards have been followed wherever possible.

### *3.5.1 Definitions (IEEE Standard C62.33, 1982)*

A characteristic is an inherent and measurable property of a device. Such a property may be electrical, mechanical, or thermal, and can be expressed as a value for stated conditions.

A rating is a value which establishes either a limiting capability or a limiting condition (either maximum or minimum) for operation of a device. It is determined for specified values of environment and operation. The ratings indicate a level of stress which may be applied to the device without causing degradation or failure. Varistor symbols are defined on the linear V-I graph illustrated in Figure 3.20.

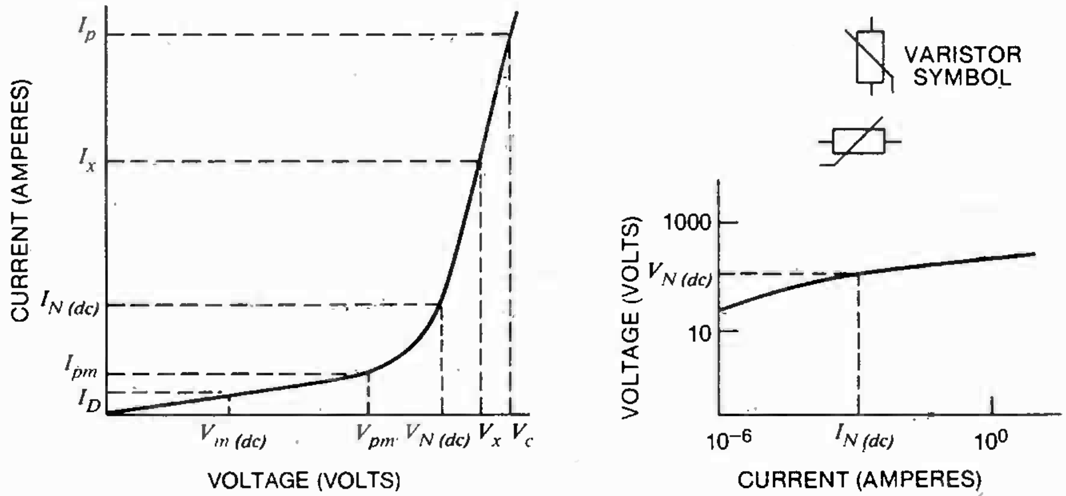



**FIGURE 3.20: I-V GRAPH ILLUSTRATING SYMBOLS AND DEFINITIONS**

### *3.5.2 Varistor Characteristics (IEEE Standard C62.33-1982 Subsection 2.3 and 2.4)*

| Term and Description | Symbol |
|---|---|
| **2.3.1 Clamping Voltage.** Peak voltage across the varistor measured under conditions of a specified peak pulse current and specified waveform. *Note:* Peak voltage and peak currents are not necessarily coincidental in time. | $V_c$ |
| **2.3.2 Rated Peak Single Pulse Transient Currents (Varistor).** Maximum peak current which may be applied for a single 8/20$\mu$s impulse, with rated line voltage also applied, without causing device failure. | $I_{tm}$ |
| **2.3.3 Lifetime Rated Pulse Currents (Varistor).** Derated values of $I_{tm}$ for impulse durations exceeding that of an 8/20$\mu$s waveshape, and for multiple pulses which may be applied over device rated lifetime. | — |
| **2.3.4 Rated RMS Voltage (Varistor).** Maximum continuous sinusoidal rms voltage which may be applied. | $V_{m(ac)}$ |
| **2.3.5 Rated DC Voltage (Varistor).** Maximum continuous dc voltage which may be applied. | $V_{m(dc)}$ |
| **2.3.6 DC Standby Current (Varistor).** Varistor current measured at rated voltage, $V_{m(dc)}$. | $I_D$ |
| **2.4** For certain applications, some of the following terms may be useful. | |
| **2.4.1 Nominal Varistor Voltage.** Voltage across the varistor measured at a specified pulsed dc current, $I_{N(dc)}$, of specific duration. $I_{N(dc)}$ is specified by the varistor manufacturer. | $V_{N(dc)}$ |
| **2.4.2 Peak Nominal Varistor Voltage.** Voltage across the varistor measured at a specified peak ac current, $I_{N(ac)}$, of specific duration. $I_{N(ac)}$ is specified by the varistor manufacturer. | $V_{N(ac)}$ |
| **2.4.3 Rated Recurrent Peak Voltage (Varistor).** Maximum recurrent peak voltage which may be applied for a specified duty cycle and waveform. | $V_{pm}$ |
| **2.4.4 Rated Single Pulse Transient Energy (Varistor).** Energy which may be dissipated for a single impulse of maximum rated current at a specified waveshape, with rated rms voltage or rated dc voltage also applied, without causing device failure. | $W_{tm}$ |
| **2.4.5 Rated Transient Average Power Dissipation (Varistor).** Maximum average power which may be dissipated due to a group of pulses occurring within a specified isolated time period, without causing device failure. | $P_{t(AV)m}$ |
| **2.4.6 Varistor Voltage.** Voltage across the varistor measured at a given current, $I_x$. | $V_x$ |
| **2.4.7 Voltage Clamping Ratio (Varistor).** A figure of merit measure of the varistor clamping effectiveness as defined by the symbols $V_c/V_{m(ac)}$, $V_c/V_{m(dc)}$. | $\frac{V_c}{V_{pm}}$ |
| **2.4.8 Nonlinear Exponent.** A measure of varistor nonlinearity between two given operating currents, $I_1$ and $I_2$, as described by $I = kV^\alpha$ where k is a device constant, $I_1 \leq I \leq I_2$, and $\alpha_{12} = \frac{\log I_2/I_1}{\log V_2/V_2}$ | $\alpha$ |
| **2.4.9 Dynamic Impedance (Varistor).** A measure of small signal impedance at a given operating point as defined by: $Z_x = \frac{dV_x}{dI_x}$ | $Z_x$ |
| **2.4.10 Resistance (Varistor).** Static resistance of the varistor at a given operating point as defined by: $R_x = \frac{dV_x}{dI_x}$ | $R_x$ |

| Term and Description | Symbol |
|---|---|
| **2.4.11 Capacitance (Varistor).** Capacitance between the two terminals of the varistor measured at specified frequency and bias. | C |
| **2.4.12 AC Standby Power (Varistor).** Varistor ac power dissipation measured at rated rms voltage $V_{m(ac)}$. | $P_d$ |
| **2.4.13 Voltage Overshoot (Varistor).** The excess voltage above the clamping voltage of the device for a given current that occurs when current waves of less than 8μs virtual front duration are applied. This value may be expressed as a % of the clamping voltage ($V_c$) for an 8/20 current wave. | $V_{os}$ |
| **2.4.14 Response Time (Varistor).** The time between the point at which the wave exceeds the clamping voltage level ($V_c$) and the peak of the voltage overshoot. For the purpose of this definition, clamping voltage is defined with an 8/20μs current waveform of the same peak current amplitude as the waveform used for this response time. | — |
| **2.4.15 Overshoot Duration (Varistor).** The time between the point at which the wave exceeds the clamping voltage level ($V_c$) and the point at which the voltage overshoot has decayed to 50% of its peak. For the purpose of this definition, clamping voltage is defined with an 8/20μs current waveform of the same peak current amplitude as the waveform used for this overshoot duration. | — |

### *3.5.3 Test Waveform*

At high current and energy levels, varistor characteristics are measured, of necessity, with an impulse waveform. Shown in Figure 3.21 is the ANSI Standard C62.1 waveshape, an exponentially decaying waveform representative of lightning surges and the discharge of stored energy in reactive circuits.

The 8 / 20μs current wave (8μs rise and 20μs to 50% decay of peak value) is used as a standard, based on industry practices, for the characteristics and ratings described. One exception is the energy rating ($W_{tm}$), where a longer waveform of 10 / 1000μs is used. This condition is more representative of the high energy surges usually experienced from inductive discharge of motors and transformers. GE-MOV®II Varistors are rated for a maximum pulse energy surge that results in a varistor voltage ($V_N$) shift of less than ±10% from initial value.

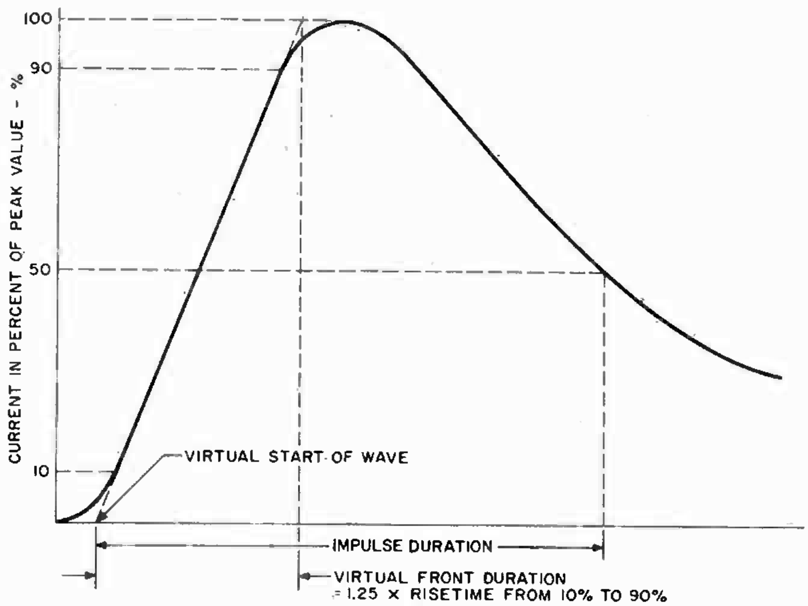



**FIGURE 3.21: DEFINITION OF PULSE CURRENT WAVEFORM**

## REFERENCES


1. Harnden, J.D., F.D. Martzloff, W.G. Morris and F.B. Golden, "The GE-MOV® Varistor—The Super Alpha Varistor," Electronics, Vol. 45, No. 21, 1972, p. 91.
2. Morris, W.G., "Electrical Properties of ZnO-$Bi_2O_3$ Ceramics," Journal of the Am. Ceram. Soc., Vol. 56, 1973.
3. Matsuoka, M., "Non-Ohmic Properties of Zinc Oxide Ceramics," Japanese Jnl. Appl. Phys., Vol. 10, 1971, p. 736.
4. Mahan, G., L. Levinson and H. Philipp, "Single Grain Junction Studies at ZnO Varistors—Theory & Experiment," Report #78CRF160, General Electric, Schenectady, N.Y., 1978. Forthcoming in Applied Physics Letters.
5. Mahan, G., L. Levinson and H. Philipp, "Theory of Conduction in ZnO Varistors," Journal of Applied Physics (in press).
6. Levine, J.D., "Theory of Varistor Electronic Properties," Critical Review of Solid State Science, 5, 1975, pp. 597-608.
7. May, J.E., "Carrier Concentration and Depletion Layer Model of Zinc Oxide Varistors," Bulletin of the American Ceramic Society, Vol. 57, No. 3, 1978, p.335.
8. Sze, S.M., "Physics of Semiconductor Devices," John Wiley & Sons, New York, N.Y., 1969.
9. Einzinger, R., "Microcontact Measurement of ZnO Varistors," Ber. Dt. Keram, Vol. 52, 1975, pp. 244-245.
10. Lou, L.F., "Current-Voltage Characteristics of ZnO-$Bi_2O_3$ Heterojunction," Journal of Applied Physics, Vol. 50, 1979, p. 555.
11. Lou, L.F., "Semiconducting Properties of ZnO-Grain Boundary-ZnO Junctions in Ceramic Varistors," Appl. Phys. Letters, Vol. 36, 1980, pp. 570-572.
12. Lou, L.F. and J.E. May, Unpublished Research, General Electric, Syracuse, N.Y., 1981.
13. Morris, W., "Physical Properties of the Electrical Barriers in Varistors," J. Vac. Sci. Technol., 13, 1976, pp. 926-931.
14. Bernasconi, J., S. Strassler, B. Knecht, H. Klein and A. Menth, Solid State Communication, Vol. 21, 1977, pp. 867-869.
15. Pike, G. and C. Seager, "The DC Voltage Dependence of Semiconductor Grain-Boundary Resistance," Journal of Appl. Phys., Vol. 50, 1979, pp. 3414-3422.

chapter 4

# DESIGNING WITH GE-MOV®II VARISTORS

## 4.1 SELECTING THE VARISTOR

The varistor must operate under steady-state and transient conditions. Device ratings allow a selection of the proper size device to insure reliable operation. The selection process requires a knowledge of the electrical environment. When the environment is not fully defined, some approximations can be made.

For most applications, selection is a five-step process:

1) Determine the necessary steady-state voltage rating
2) Establish the transient energy absorbed by the varistor
3) Calculate the peak transient current through the varistor
4) Determine power dissipation requirements
5) Select a model to provide the required voltage-clamping characteristic

### *4.1.1 Steady-State Voltage Rating*

Consider the maximum steady-state voltage applied to the varistor including any high line conditions (i.e., 110% or more of nominal voltage). Ratings are given for sinusoidal ac and constant dc. If a nonsinusoidal waveform is applied, the recurrent peak voltage should be limited to $\sqrt{2} \times V_{m(ac)}$.

Specifications for the L Series varistor are shown in Figure 4.1 for 130V ac rated devices to illustrate the use of the ratings and characteristics table.

| MODEL NUMBER | MAXIMUM RATINGS (25°C) | | | | CHARACTERISTICS | | | | | | MODEL SIZE (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CONTINUOUS | | TRANSIENT | | VARISTOR VOLTAGE @ 1mA DC TEST CURRENT | | | MAX. CLAMPING VOLTAGE $V_c$ @ TEST CURRENT (8 / 20μs) | | TYPICAL CAPACITANCE | |
| | RMS VOLTAGE | DC VOLTAGE | ENERGY (10 / 1000μs) | PEAK CURRENT (8 / 20μs) | | | | | | | |
| | $V_{m(ac)}$ | $V_{m(dc)}$ | $W_{tm}$ | $I_{tm}$ | MIN. | $V_N$ | MAX. | $V_C$ | $I_P$ | f = 0.1-1 MHz | |
| | VOLTS | VOLTS | JOULES | AMPERES | VOLTS | VOLTS | VOLTS | VOLTS | AMPS | PICOFARADS | |
| V130LA1 | 130 | 175 | 7 | 800 | 184 | 200 | 255 | 390 | 10 | 180 | 7 |
| V130LA2 | | | 11 | 1200 | | | 228 | 340 | 10 | 180 | 7 |
| V130LA10A | | | 38 | 4500 | | | 228 | 340 | 50 | 1000 | 14 |
| V130LA20A | | | 70 | 6500 | | | 228 | 340 | 100 | 1900 | 20 |
| V130LA20B | | | 70 | 6500 | | | 220 | 325 | 100 | 1900 | 20 |

FIGURE 4.1: RATINGS AND CHARACTERISTICS TABLE

**Model Number** – Indicates an ac voltage rating of 130V ac RMS.

**$V_{m(ac)}$** – These models can be operated continuously with up to 130V ac RMS at 50-60 Hz applied. They would be suitable for 117 V ac nominal line operation and would allow for a 110% high line condition.

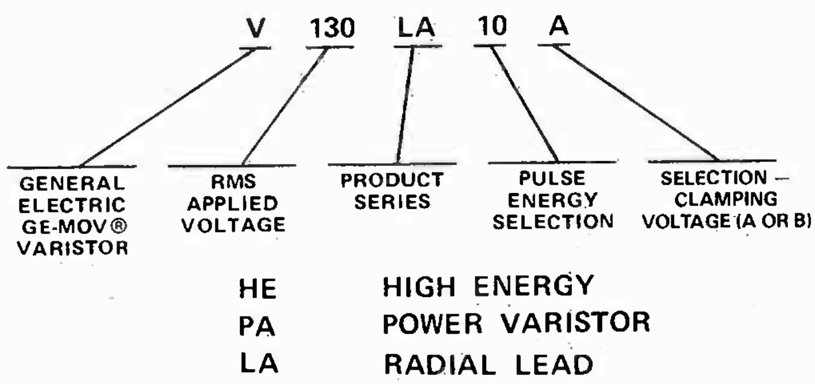
**$V_{m(dc)}$** – Operation is allowable with up to 175V dc constant voltage applied continuously.

**$V_{N(dc)}$ Min.** – Indicates the minimum varistor terminal voltage that will be measured with 1 mA dc applied. This is a characteristic of the device and is a useful parameter for design or for incoming inspection.

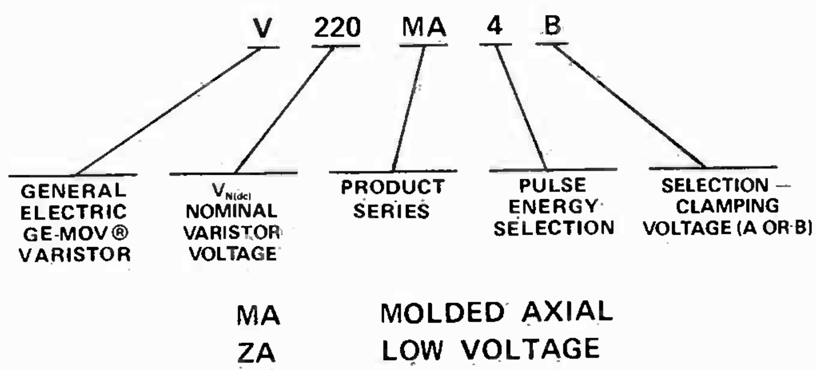
**$V_{N(dc)}$ Max. @ 1mA dc** – Indicates the maximum limit of varistor terminal voltage measured at 1 mA dc.

**$V_{N(ac)}$ Max. @ 1mA ac Peak** – Indicates the maximum limit of varistor terminal voltage measured at 1mA ac, 50-60 Hz. Note: this voltage is about 7% higher than the dc measurement. This is an inherent characteristic of the varistor.

The format for the model number designation is shown below. Note, the model series are grouped in two forms. One group is based on the ac voltage rating for applications primarily across the power line. The second group is based on $V_{N(dc)}$ characteristic voltage where dc applications are of more interest.




a) Models intended primarily for ac power line applications.




b) Models intended primarily for dc and circuit applications.

FIGURE 4.2: MODEL NUMBER NOMENCLATURE

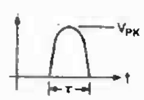
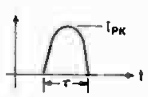
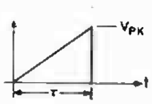
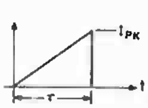
### *4.1.2 Energy*

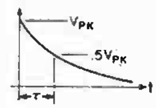
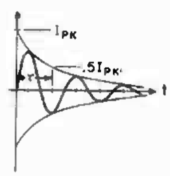
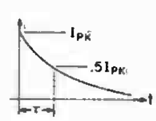
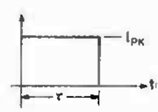
Transient energy ratings are given in the $W_{tm}$ column of the specifications in joules (watt-second). The rating is the maximum allowable energy for a single impulse of 10 / 1000$\mu$s current waveform with continuous voltage applied. Energy ratings are based on a shift of $V_N$ of less than $\pm$ 10% of intial value.

When the transient is generated from the discharge of an inductance (i.e., motor, transformer) or a capacitor, the energy content can be calculated readily. In many cases the transient is from a source external to the equipment and is of unknown magnitude. For this situation an approximation technique can be used to estimate the energy of the transient *absorbed* by the varistor. The method requires a measurement of the transient current and voltage at the varistor. To determine the energy *absorbed* the following equation applies:

$$E = \int_0^{\tau} V_c(t)I(t)\Delta t = KV_cI\tau$$

where I is the peak current applied, $V_C$ is the clamp voltage which results, $\tau$ is the impulse duration and K is a constant. K values are given in Figure 4.3 for a variety of waveshapes frequently encountered. The K value and pulse width should correspond to either a current waveform or a voltage waveform. For complex waveforms, this approach also can be used by dividing the shape into segments that can be treated separately.

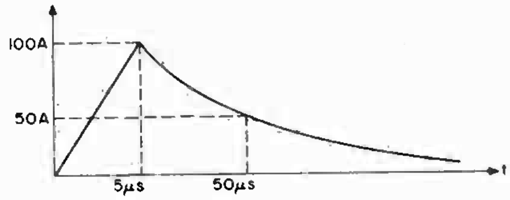
| WAVESHAPE | EQUATION | K* |
|---|---|---|
|  | $V_{PK} \sin(\frac{\pi}{\tau} t)$ | 0.15 |
|  | $I_{PK} \sin(\frac{\pi}{\tau} t)$ | 0.637 |
|  | $V_{PK} (\frac{t}{\tau})$ | 0.038 |
|  | $I_{PK} (\frac{t}{\tau})$ | 0.5 |

| WAVESHAPE | EQUATION | K* |
|---|---|---|
|  | $V_{PK}\ e^{-t/1.4\tau}$ | 0.056 |
|  | $I_{PK} \sin(\pi t) e^{-t/\tau}$ | 0.86 |
|  | $I_{PK}\ e^{-t/1.44\tau}$ | 1.4 |
|  | $I_{PK}$ | 1.0 |

*Based upon alpha of 25 to 40.

**FIGURE 4.3: ENERGY FORM FACTOR CONSTANTS**

Consider the condition where the exponential waveform shown below is applied to a V130LA1 GE-MOV®II Varistor.




The waveform is divided into two parts that are treated separately using the factors of Figure 4.3: current waveform section (1) 0 to 5μs to infinity. The maximum voltage across the V130LA1 at 100A is found to be 500V from the V-I characteristics of the specification sheet.

Section (1) $\quad E = KV_C I \tau = (0.5)\ (500)\ (100)\ (5)(10^{-6}) \quad = 0.13J$

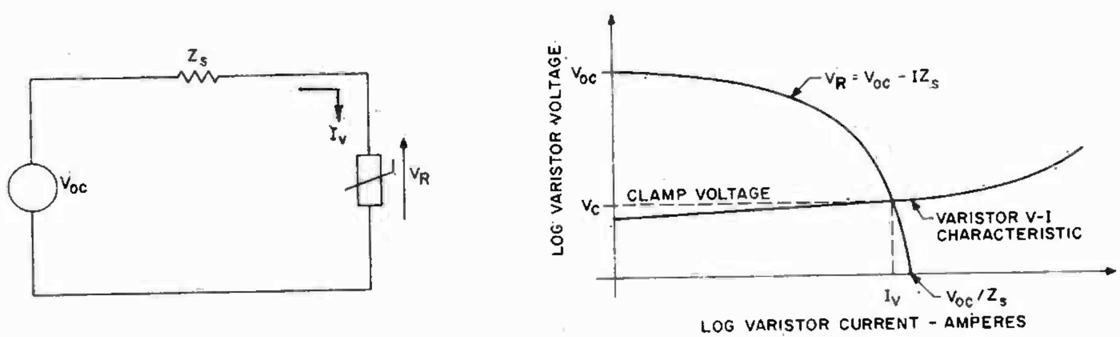
Section (2) $\quad E = KV_C I \tau = (1.4)\ (500)\ (100)\ (50 - 5)\ (10^{-6}) \quad = \underline{3.15J}$

3.28J Total

The specifications of Figure 4.1 indicate a rating of 4J for this device which is just adequate for the application. For more safety factor, a V130LA2 rated at 8J would be a better choice.

### *4.1.3 Peak Current*

The peak current rating can be checked against the transient current measured in the circuit. If the transient is generated by an inductor, the peak current will not be more than the inductor current at the time of switching. Another method for finding the transient current is to use a graphical analysis. When the transient voltage and source impedance is known, a Thevenin equivalent circuit can be modeled. Then, a load line can be drawn on the log — log, V-I characteristic as shown in Figure 4.4. The two curves intersect at the peak current value.




1) Equivalent Circuit

2) Graphical Analysis to Determine Peak I

FIGURE 4.4: DETERMINING VARISTOR PEAK CURRENT FROM A VOLTAGE SOURCE TRANSIENT

The rated single pulse current, $I_{tm}$, is the maximum allowable for a single pulse of 8 / 20μs exponential waveform (illustrated in Figure 3.21). For longer duration pulses, $I_{tm}$ should be derated to the curves in the varistor specifications. Figure 4.5 shows the derating curves for 7mm size, L series devices. This curve also provides a guide for derating current as required with repetitive pulsing. The designer must consider the total number of transient pulses expected during the life of the equipment and select the appropriate curve.

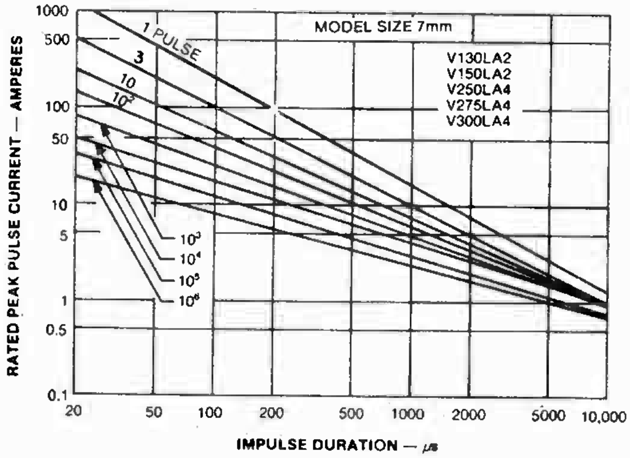



FIGURE 4.5: PULSE LIFETIME RATINGS

Where the current waveshape is different from the exponential waveform of Figure 3.18, the curves of Figure 4.5 can be used by converting the pulse duration on the basis of equivalent energy. This is easily done using the constants given in Figure 4.3. For example, suppose the actual current measured has a triangular waveform with a peak current of 10 A, a peak voltage of 340 V and an impulse duration of 500 $\mu$s.

Then:

$$E = (.5)(10)(340)(500)(10^{-6})$$
$$= 850\ \text{mJ}$$

The equivalent exponential waveform of equal energy is then found from:

$$E_{TRIANGULAR} = E_{EXP}$$
$$850\ \text{mJ} = 1.4\ V_C\ I\ \tau_{EXP}$$

The exponential waveform is taken to have equal $V_C$ and I values. Then,

$$\tau_{EXP} = \frac{850\ \text{mJ}}{1.4\ (340)\ (10)}$$
$$= 179\ \mu s$$

Or:

$$\tau_{EXP} = \frac{K^*\ \tau^*}{1.4}$$

Where: $K^*$ and $\tau^*$ are the values for the triangular waveform and $\tau_{EXP}$ is the impulse duration for the equivalent exponential waveform.

The pulse rise portion of the waveform can be ignored when the impulse duration is five times or more longer. The pulse life for the above example would exceed $10^4$ pulses from the pulse life curves shown in Figure 4.5.

### *4.1.4 Power Dissipation Requirements*

Transients generate heat in a suppressor too quickly to be transferred during the pulse interval. 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. The power so developed must be within the specifications shown on the ratings tables. It is to be noted that varistors can only dissipate a relatively small amount of average power and are, therefore, not suitable for repetitive applications that involve *substantial* amounts of average power dissipation. Futhermore, the operating values need to be derated at high temperatures as shown in Figure 4.6.

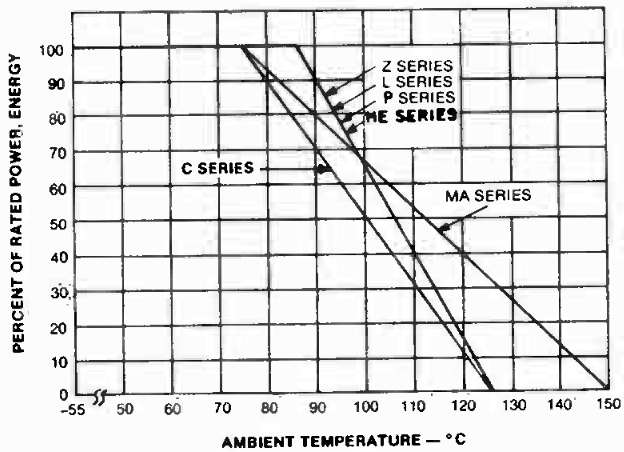



FIGURE 4.6: CURRENT, POWER, ENERGY RATING VS. TEMPERATURE

### *4.1.5 Voltage Clamping Selection*

Transient V-1 characteristics are provided in the specifications for all models of GE-MOV®II Varistors. Shown below in Figure 4.7 are curves for 130V ac rated models of the L series. These curves indicate the peak terminal voltage measured with an applied 8 / 20$\mu$s impulse current. For example, if the peak impulse current applied to a V130LA2 is 10A, that model will limit the transient voltage to no higher than 340V.

If the transient current is unknown, the graphical method of Figure 4.4 can be utilized. From a knowledge of the transient voltage and source impedance a load line is plotted on the V-I characteristic. The intersection of the load line with the varistor model curve gives the varistor transient current and the value of clamped peak transient voltage.

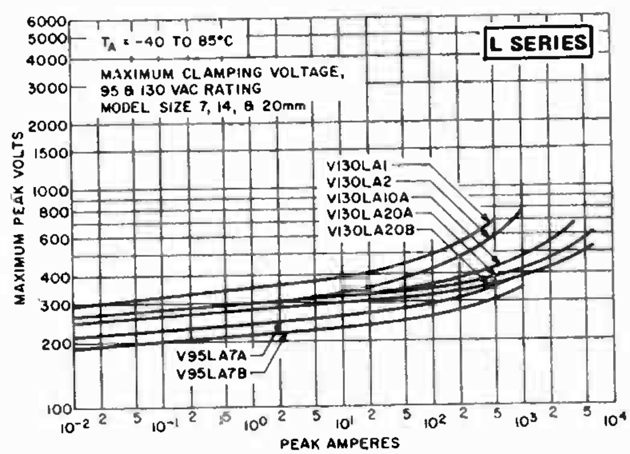



FIGURE 4.7: TRANSIENT V-I CHARACTERISTICS OF TYPICAL L SERIES MODELS

The ability of the varistor to limit the transient voltage is sometimes expressed in terms of a clamp ratio. For example, consider a varistor applied to protecting the power terminals of electrical equipment. If high line conditions will allow a rise to 130V ac, then 184V peak would be applied. The device selected would require a voltage rating of 130V ac or higher. Assume selection of a V130LA2 model varistor. The V130LA2 will limit transient voltages to 340V at currents of 10A. The clamp ratio is calculated to be,

$$\text{Clamp Ratio} = \frac{V_C \ @\ 10\text{A}}{\text{Peak Voltage Applied}}$$

$$= \frac{340\text{V}}{184\text{V}} = 1.85$$

The clamp ratio can be found for other currents, of course, by reference to the V-I characteristic. In general, clamping ability will be better as the varistor physical size and energy level increases. This is illustrated in Figure 4.8 which compares the clamping performance of the different GE-MOV®II Varistor families. It can be seen that the lowest clamping voltages are obtained from the 20mm (L series) and 32mm (HE series) products. In addition, many varistor models are available with two or three clamping selections, designated by an A, B, or C at the end of the model number. The A selection is the standard model, with B and C selections providing progressively tighter clamping voltage. For example, the V130LA20A voltage clamping limit is 340V at 100A, while the V130LA20B clamps at not more than 325V.

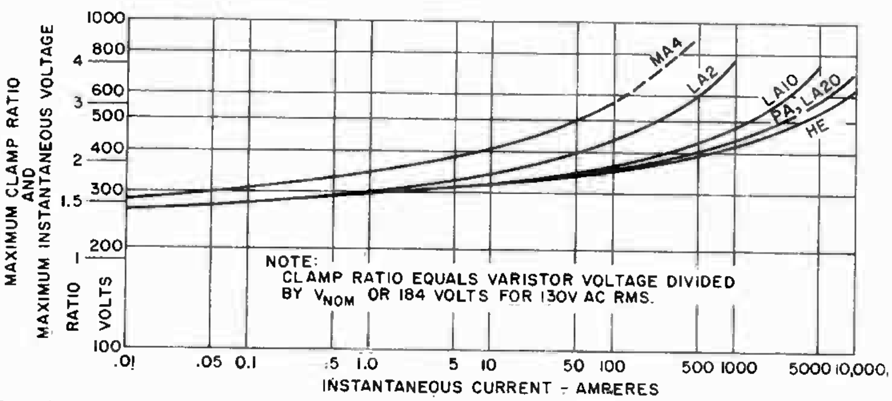



**FIGURE 4.8 VARISTOR V-I CHARACTERISTICS FOR FOUR PRODUCT FAMILIES RATED AT 130V AC**

### *4.1.6 Summary*

The five major considerations for varistor selection have been described. The final choice of model is a balance of these factors with a device cost trade-off. In some applications a priority requirement such as clamp voltage or energy capability may be so important as to force the selection to a particular model. A summary of varistor properties is provided in Figure 4.9 for a quick comparison of operating ranges.

| PEAK PULSE CURRENT (Amps) | ENERGY (Joules) | MAXIMUM STEADY-STATE APPLIED VOLTAGE<br>VOLTS – AC RMS: 15 35 75 95 130 150 275 290 420 480 550 575 1000<br>VOLTS – DC: 20 40 60 80 100 120 140 160 180 200 300 400 500 600 700 800 | PACKAGES |
|---|---|---|---|
| 40-100 | 0.13-1.7 | MA SERIES<br>18-264 VRMS<br>23-365 VDC | |
| 250-4000 | 0.5-25 | Z SERIES<br>6-115 VRMS<br>8-153 VDC | |
| 500-6000 | 4-350 | L SERIES<br>95-1000 VRMS<br>130-1200 VDC | |
| 4000-6000 | 30-250 | P SERIES<br>130-660 VRMS<br>175-850 VDC | |
| 15,000-25,000 | 150-600 | HE SERIES<br>130-660 VRMS<br>175-850 VDC | |

**FIGURE 4.9: VARISTOR PRODUCT FAMILY SELECTION GUIDE**

## 4.2 FAILURE MODES AND VARISTOR PROTECTION

Varistors are inherently rugged and are conservatively rated. Therefore, they exhibit a low failure rate. Nevertheless, the careful designer may wish to plan for potential failure modes and the resultant effects on circuitry being protected.

### *4.2.1 Failure Modes*

Varistors initially fail in a short-circuit mode when subjected to surges beyond their peak current/energy ratings. They also short-circuit when operated at steady-state voltages well beyond their voltage ratings. This latter mode of stress may result in the eventual open-circuiting of the device due to melting of the lead solder joint.

When the device fails in the shorted mode the current through the varistor becomes limited mainly by the source impedance. Consequently, a large amount of energy can be introduced, causing mechanical rupture of the package accompanied by expulsion of package material in both solid and gaseous forms. Steps may be taken to minimize this potential hazard by the following techniques: 1) fusing the varistor to limit high fault currents, and, 2) protecting the surrounding circuitry by physical shielding, or by locating the varistor away from other components.

### *4.2.2 Fusing the Varistor*

Varistor fusing should be coordinated to select a fuse that limits current below the level where varistor package damage could occur. The location of the fuse may be in the distribution line to the circuit or it may be in series with the varistor as shown in Figure 4.10. Generally, fuse rather than breaker protection is preferred. Breaker tripping is too slow to prevent excessive fault energy from being applied.

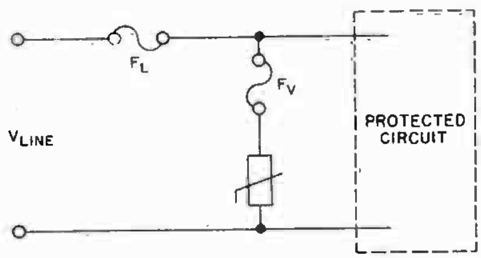



FIGURE 4.10: FUSE PLACEMENT FOR VARISTOR PROTECTION

In high power industrial circuits the line currents are generally so high as to rule out the use of a line fuse for varistor protection. The fuse may not clear under a varistor fault condition and would allow varistor failure. In low power (5-20A) applications it may be feasible to use the line fuse, $F_L$, only.

Use of a line fuse, $F_L$, rather than $F_V$, does not present the problem of having the fuse arc voltage being applied across the circuit. Conversely, with $F_V$ alone, the fuse arc voltage adds to the varistor voltage, increasing the $V_C$, the transient clamp voltage. Since some fuses can have peak arc voltages in excess of twice peak working voltage, fuse clearing can have a significant effect on protection levels.

Another factor in the choice of location is the consequence of system interruption. Fuse location $F_L$ will cause a shutdown of the circuit while location $F_V$ will not. While the circuit can continue to operate when $F_V$ clears, protection no longer is present. For this reason it is desirable to be able to monitor the condition of $F_V$.

### *4.2.3 Fusing Example (Light Industrial Application)*

A process control minicomputer is to be protected from transients on a 115V nominal line. The minicomputer draws 7.5A from the line, which is guaranteed to be regulated to ±10% of nominal line voltage. A V130LA20A varistor is chosen on the basis that the worst-case surge current would be a 10 / 1000$\mu$s pulse of 100A peak amplitude. The rationale for this surge requirement is that the incoming plant distribution system is protected with lightning arrestors having a maximum arrestor voltage of 5kV. Assuming a typical 50$\Omega$ characteristic line impedance, the worst-case transient current through the varistor is 100A. The 1 ms impulse duration is taken as a worst-case composite wave estimate. While lightning stroke discharges are typically less than 100$\mu$s, they can recur in rapid fire order during a 1 s duration. From the pulse lifetime rating curves of the L series size 20 models, it is seen that the V130LA20 single pulse withstand capability at 1 ms impulse duration is slightly in excess of 100A.

This is adequate for application in areas where lightning activity is medium to light. For heavy lightning activity areas, an HE series varistor might be desirable to allow a capability of withstanding over 70 transients. In making the choice between the L series and HE series, the designer must decide on the likelihood of a worst-case lightning stroke and the cost of the fuse replacement should the varistor fail.

Assuming a low lightning activity area, the V130LA20A series is a reasonable choice. To coordinate the fuse with the varistor, the single pulse lifetime curve is redrawn as $I^2t$ vs. impulse duration as shown in Figure 4.11. The $I^2t$ of the composite 10 / 1000$\mu$s impulse is found from:[1]

$$I^2t = \frac{1}{3}\hat{I}^2(10\mu s) + 0.722\,\hat{I}^2(\tau_{(.5)} - 10\mu s)$$

when: $\tau_{(.5)} \geqslant 200\mu s$ (time for impulse current to decay by 0.5)

$$I^2t \approx 0.722\,\hat{I}^2\tau_{(.5)}$$

where: the first term represents the impulse $I^2t$ contributed by the $10\mu s$ rise portion of the waveform and the second term is the $I^2t$ contributed by the exponential decay portion.

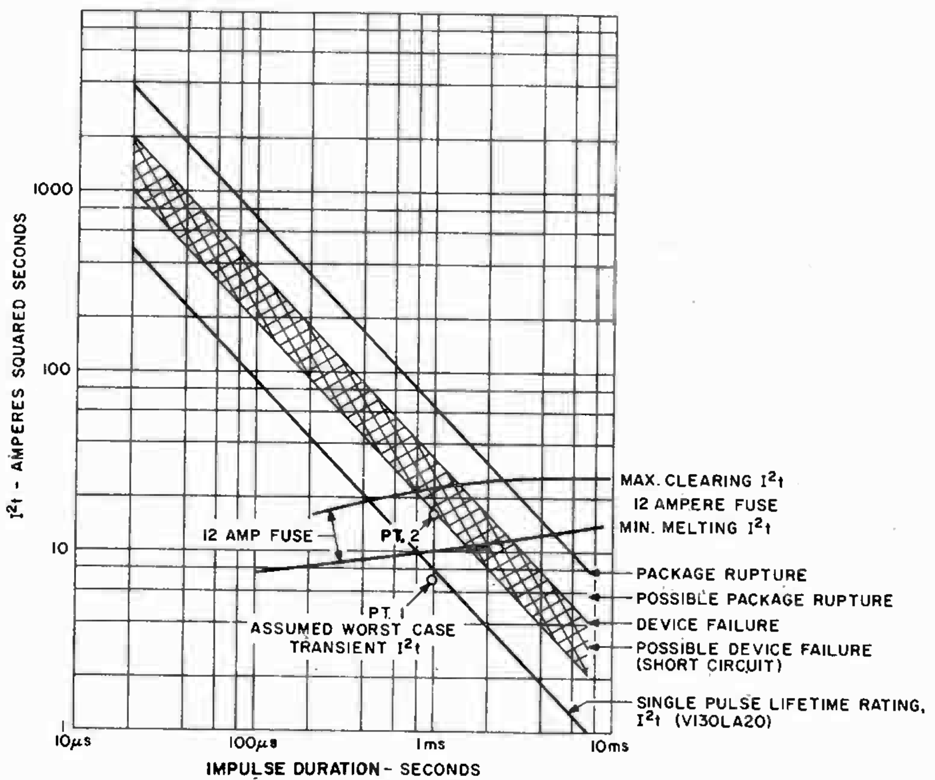



FIGURE 4.11: GE-MOV®II VARISTOR — FUSE COORDINATION CHART

Figure 4.11 shows a cross-hatched area which represents the locus of possible failure of the varistor. This area is equal to an $I^2t$ value of from two to four times that derived from the data sheet peak current pulse life curves. The curve extending beyond the cross-hatched area and parallel to it is where package rupture will take place.

The criteria for fuse selection is given below.

A) Fuse melts; i.e., opens, only if worst-case transient is exceeded and/or varistor fails.

B) If varistor fails, fuse clearing limits $I^2t$ applied to varistor values below that required for package rupture.

C) Fuse is rated at 130V RMS.

D) Fuse provides current limiting for solid-state devices.

Based on the above, a Carbone-Ferraz 12A RMS, 130V RMS, Class FA fuse is tentatively selected. The *minumum* melting $I^2t$ and *maximum* clearing $I^2t$ curves for the 12A fuse are shown superimposed on the varistor characteristics.

This fuse is guaranteed to melt at an $I^2t$ of 40% above the estimated worst-case transient. Upon melting, clearing $I^2t$ and clearing time will depend upon available fault current from the 130V RMS line. Figure 4.12 lists clearing times for the selected fuse versus available prospective circuit current.

| PROSPECTIVE CURRENT AMPS RMS | CLEARING TIME MILLISECONDS |
|---|---|
| 60 | 8.0 |
| 120 | 5.6 |
| 240 | 3.5 |
| 1200 | 1.3 |
| 3600 | 0.57 |

FIGURE 4.12: 12A FUSE – PROSPECTIVE CURRENT VS. CLEARING TIME

As Figure 4.11 shows, a clearing time of less than 1.5ms is desirable. For fault currents in excess of 1.2kA, the fuse will clear at less than $24A^2s$ and 1.3ms. This will prevent varistor package rupturing. However, the distribution line may be "soft," i.e., have a high source impedance at the 60 Hz power frequency that limits the fault current to values below 1.2kA. Then, it is possible that the fuse would not protect the varistor package from rupturing, though it would serve to isolate the varistor in any case.

Upon further examination of this example, it is clear that the varistor will be protected from package rupturing even if the transient pulse current is 50% greater than that of the assumed value, resulting in an $I^2t$ of 16 $A^2s$ (Point 2 on Figure 4.11).

Placement of the fuse for this example application could be in the line or in series with the varistor. If in series with the varistor, the line fuse should be a medium to slow speed, such as a "slow blow" type 15A fuse. That would assure a fault in the varistor would be isolated by the varistor fuse without interrupting the line fuse.

It is desirable to indicate the status of the varistor fuse if one is used in addition to the line fuse. The circuit shown in Figure 4.13 senses the presence of voltage across the varistor by use of a photocoupler. When the fuse interrupts the varistor circuit, the LED of the coupler becomes de-energized, and the coupler output signal can be used to annunciate an unprotected condition. Some fuse manufacturers provide indicating means upon fuse operation that may also be used to trip an alarm.

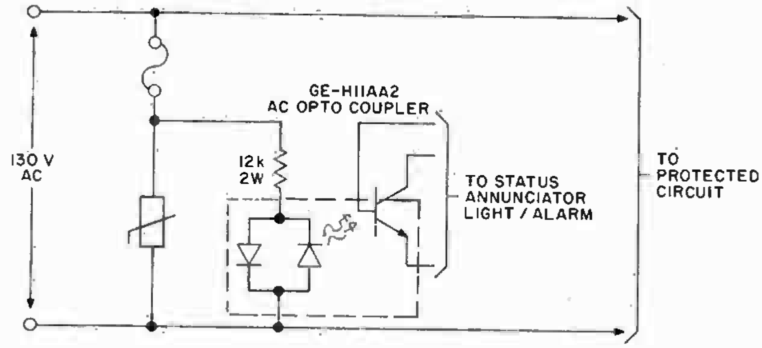



FIGURE 4.13: VARISTOR FUSE STATUS SENSING CIRCUIT

In selecting a fuse, the reader is advised to avoid data based on average values or data taken at operating conditions that are grossly different from the actual application. For example, dc data does not apply when the fuse will be used on an ac circuit. Also, test data taken in a resistive circuit with unity power factor does not hold for low power factor operation.

A list of manufacturers of fast current limiting fuses is given below:

MANUFACTURERS OF CURRENT LIMITING FUSES

Bussmann Manufacturing Division
McGraw-Edison Company
St. Louis, Missouri 63100

Carbone-Ferraz, Inc.
P. O. Box 324
Elm Street
Rockaway, New Jersey 07866

Chase-Shawmut Company
347 Merrimac Street
Newburyport,
Massachusetts 01950

English Electric Corporation
One Park Avenue
New York, New York 10016

General Electric Company
Power Systems Management Dept.
6901 Elmwood Avenue
Philadelphia, Pennsylvania 19142

General Fuse Corporation (GFC)
7954 Cameron Brown Court
Fullerton Industrial Park
Springfield, Virginia 22153

## 4.3 SERIES AND PARALLEL OPERATION OF VARISTORS

In most cases the designer can select a varistor that meets the desired voltage ratings from standard catalog models. Occasionally the standard catalog models do not fit the requirements either due to voltage ratings or energy/current ratings. When this happens, two options are available: varistors can be arranged in series or parallel to make up the desired ratings, or the factory can be asked to produce a "special" to meet the unique application requirement.

### *4.3.1 Series Operation of Varistors*

Varistors are applied in series for one of two reasons: to provide voltage ratings in excess of those available, or to provide a voltage rating between the standard model voltages. As a side benefit, higher energy ratings can be achieved with series connected varistors over an equivalent single device. For instance, assume the application calls for a lead mounted varistor with an rms voltage rating of 375V ac and having a $I_{tm}$ peak current capability of 6000A. The $I_{tm}$ requirement fixes the varistor size. Examining the L series voltage ratings near 375V ac, only 320V and 420V units are available. The 320V is too low and the 420V unit (V420LA40B) results in too high a clamp voltage ($V_C$ of 1060V at 100A). For a V130LA20B and a V250LA40B in series, the maximum rated voltage is now the sum of the voltages, or 380V. The clamping voltage, $V_C$, is now the sum of the individual varistor clamping voltages, or 925V at 1000A. The peak current capability is still 6000A but the energy rating is now the sum of the individual energy ratings, or 140J.

In summary, varistors can be connected in series providing they have identical peak current ratings ($I_{tm}$), i.e., same disc diameter. The composite V-I characteristic, energy rating, and maximum clamp voltages are all determined by summing the respective characteristics and/or ratings of the individual varistors.

### *4.3.2 Parallel Operation of Varistors*

Application requirements may necessitate higher peak currents and energy dissipation than the high energy, HE, series of varistors can supply individually. When this occurs, the logical alternative is to examine the possibility of paralleling varistors. Fortunately, all GE-MOV®II Varistors have a property at high current levels that makes paralleling feasible. This property is the varistor's series-resistance that is prominent during the "up-turn region" of the V-I characteristic. This up-turn is due to the inherent linear resistance component of the varistor characteristic (see Chapter 3). It acts as a series balancing, or ballasting, impedance to force a degree of current sharing that is not possible at lower current levels. This is depicted in Figure 4.14. At a clamp voltage of 600V, the difference in current between a maximum specified sample unit and a hypothetical 20% lower bound sample would be more than 20 to 1. Thus, there is almost no current sharing and only a single varistor carries the current. Of course, at low current levels in the range of 10-100A, this may well be acceptable.

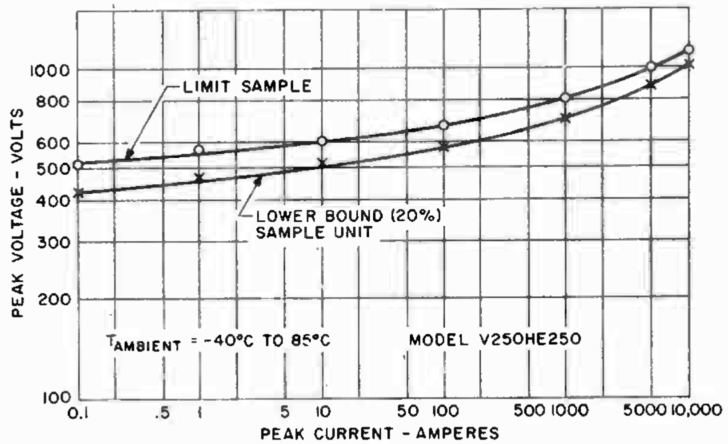



**FIGURE 4.14: PARALLEL OPERATION OF VARISTORS BY GRAPHICAL TECHNIQUE**

At high current levels exceeding 1000A, the up-turn region is reached and current sharing improves markedly. For instance, at a clamp voltage of 900V, the respective varistor currents (Figure 4.14) are 2500A and 6000A, respectively. While far from ideal sharing, this illustration shows the feasibility of paralleling to achieve higher currents and energy than achievable with a single model HE varistor.

Practically, varistors must be matched by means of high current pulse tests to make parallel operation feasible. Pulse testing should be in the range of over 1kA, using an 8 / 20$\mu$s, or similar pulse. Peak voltages must be read and recorded. High current characteristics could then be extrapolated in the range of 100-10,000A. This is done by using the measured data points to plot curves parallel to the data sheet curves. With this technique current sharing can be considerably improved from the near worst-case conditions of the hypothetical example given in Figure 4.14.

Some guidelines for series and parallel operation of varistors are given in Figure 4.15.

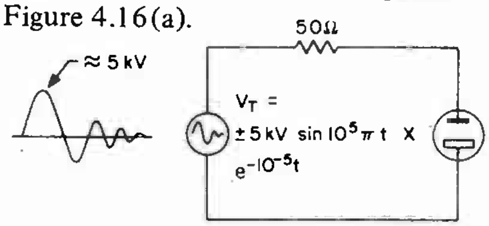
| | SERIES | PARALLEL |
|---|---|---|
| Objective | • Higher Voltage Capability<br>• Higher Energy Capability<br>• Non-standard Voltage Capability | • Higher Current Capability<br>• Higher Energy Capability |
| Selection Required By User | NO | YES |
| Models Applicable | • All, must have same $I_{tm}$ rating. | L, P, Z, HE Series |
| Application Range | • All voltages and currents. | • All voltages – only high currents, i.e., > 100 amperes. |
| Precautions | • $I_{tm}$ ratings must be equal. | • Must use identical voltage rated models.<br>• Must test and select units for similar V-I characteristics. |
| Effect on Ratings | • Clamp voltages additive.<br>• Voltage ratings additive.<br>• Current ratings that of single device.<br>• Energy, $W_{tm}$, ratings additive. | • Current ratings function of current sharing as determined graphically.<br>• Energy ratings as above in proportion to current sharing.<br>• Clamp voltages determined by composite V-I characteristic of matched units.<br>• Voltage ratings that of single unit. |

FIGURE 4.15: CHECKLIST FOR SERIES AND PARALLEL OPERATION OF VARISTORS

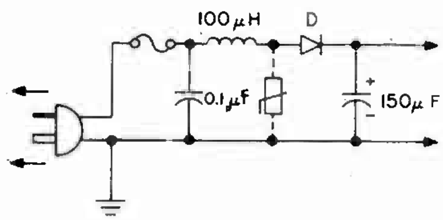
## 4.4 APPLICATIONS

### *4.4.1 Power Supply Protection Against Line Transient Damage*

**PROBLEM**: It is desired to prevent failure of the power supply shown in Figure 4.16(b) to be used on residential 117V ac lines. A representative transient generator is to be used for testing, as shown in Figure 4.16(a).




(a) Transient Generator




(b) Typical Power Supply Circuit

FIGURE 4.16: POWER SUPPLY PROTECTION

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 into the power line (as in a TV set), but also serves to reduce the transient voltage. An analysis shows that the transient will be reduced approximately by half, resulting in about 2.5 kV instead of 5 kV at the rectifier.

This is still 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. A selection process for a GE-MOV®II Varistor is as follows:

## SOLUTION:

### Steady-State Voltage

The 117V ac, 110% high line condition is 129V. The closest voltage rating available is 130V.

### Energy and Current

The $100\mu$H inductor will appear to be about $30\Omega$ to the transient. The $30\Omega$ is derived from the inductive reactance at the transient generator source frequency of $10^5\ \pi$ rad. Taking a first estimate of peak varistor current, $2500\text{V}/80\Omega = 31\text{A}$. (This first estimate is high, since it assumes varistor clamping voltage is zero.) With a tentative selection of a 130V GE-MOV®II Varistor, we find that a current of 31A yields a voltage of from 325V to 430V, depending on the model size, as shown in Figure 4.17

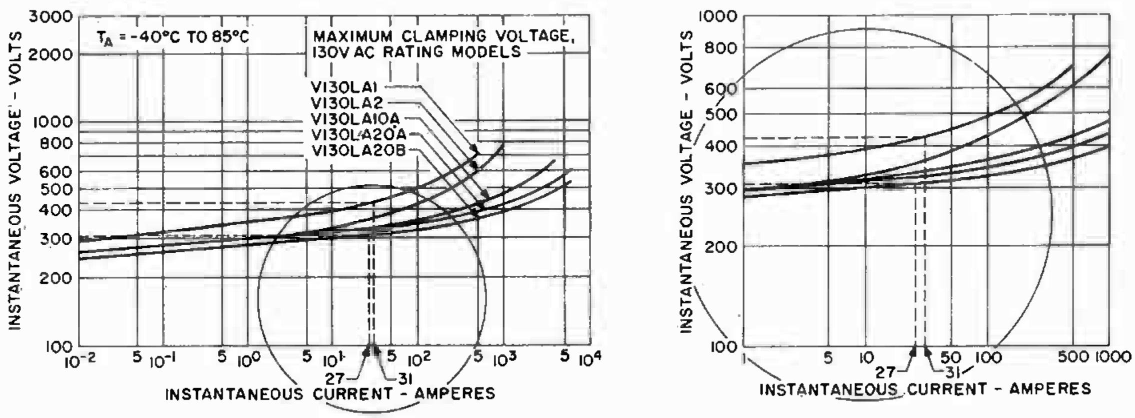



FIGURE 4.17: V130LA VARISTOR V-I CHARACTERISTICS

Revising the estimate, $I \approx (2500\text{V} - 325\text{V})/80\Omega = 27.2\text{A}$. For model V130LA20B, 27.2 A coincides closely with a 320V clamping level. There is no need to further refine the estimate of peak current if model B remains the final selection.

To arrive at an energy figure, assume a sawtooth current waveform of 27 A peak, dropping to zero in two time constants, or $20\,\mu$s.

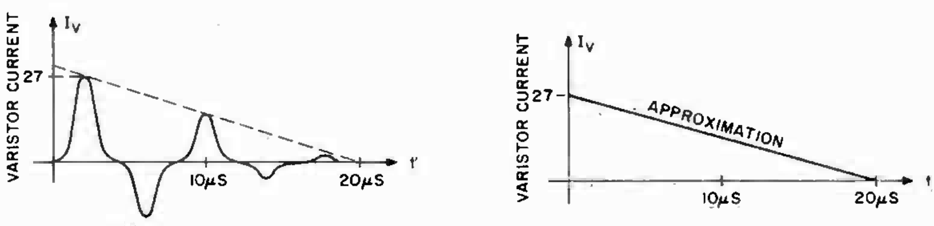



FIGURE 4.18: ENERGY APPROXIMATION

Energy is then roughly equal to $(27A \times 320V \times 20\mu s)/2$, the area under the power waveform. The result is 0.086J, well within the capability of the varistor (50J). Peak current is also within the 6000A rating.

**Model Selection**

The actual varistor selection is a trade off between the clamping voltage desired and the number of transient current pulses expected in the life of the equipment. A 50J rated varistor will clamp at 315V and be capable of handling over $10^5$ such pulses. An 8J unit will clamp to approximately 385V and be capable of handling over 1000 such pulses. Furthermore, the clamping voltage determines the cost of the rectifier by determining the voltage rating required. A smaller, lower cost varistor may result in a more expensive higher voltage rectifier diode.

*4.4.2 SCR Motor Control*

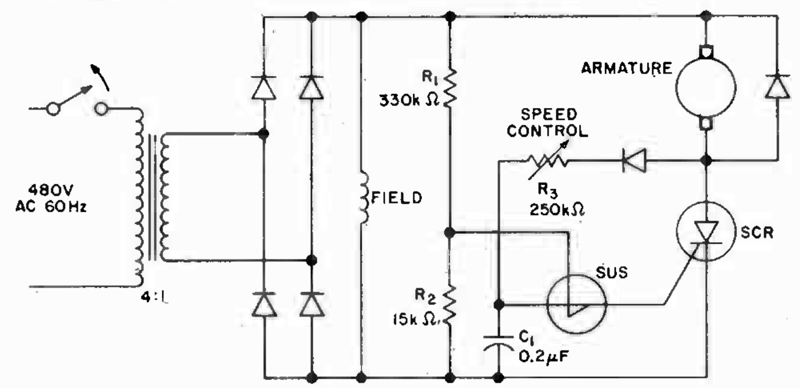



**FIGURE 4.19: SCR MOTOR CONTROL**

PROBLEM: The circuit shown in Figure 4.19 experiences failures of the rectifiers and SCR when the transformer primary is switched off. The manufacturer has tried 600V components with little improvement.

SOLUTION: Add a varistor to the transformer secondary to clamp the transformer inductive transient voltage spike. Select the lowest voltage GE-MOV®II Varistor that is equal to or greater than the maximum high line secondary ac voltage. The V130LA series fulfills this requirement.

Determine the peak suppressed transient voltage produced by the transient energy source. This is based on the peak transient current to the suppressor, assuming the worst-case condition of zero load current. Zero load current is normally a valid assumption. Since the dynamic transient impedance of the GE-MOV®II Varistor is generally quite low, the parallel higher impedance load path can be neglected.

**Determination of Peak Transient Current**

Since transient current is the result of stored energy in the core of the transformer, the transformer equivalent circuit shown in Figure 4.20 will be helpful for analysis. The stored inductive energy is:

$$E_{L_m} = \frac{1}{2} L_m \hat{I}^2_m$$

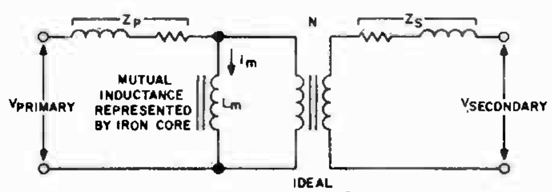



**FIGURE 4.20: SIMPLIFIED EQUIVALENT CIRCUIT OF A TRANSFORMER**

The designer needs to know 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 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 small compared to $L_m$. This is a valid assumption for all but the smallest control transformers. Since $I_{NL}$ is assumed purely reactive, then:

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

and

$$i_m = I_{NL}$$

$I_{NL}$ can be determined from nameplate data. Where nameplate data is not available, Figures 4.21 and 4.22 can guide the designer.

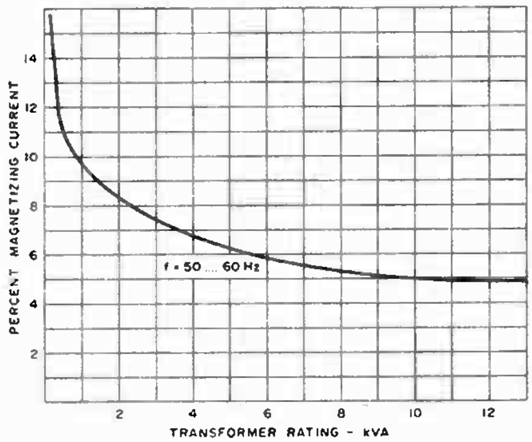



FIGURE 4.21: MAGNETIZING CURRENT OF TRANSFORMERS WITH LOW SILICON STEEL CORE

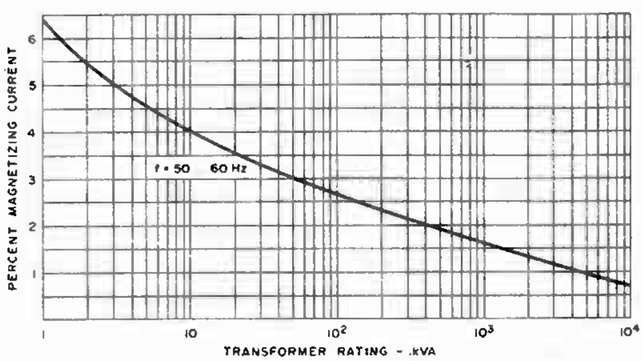



FIGURE 4.22: MAGNETIZING CURRENT OF TRANSFORMERS WITH HIGH SILICON STEEL CORE OR SQUARE LOOP CORE

Assuming a 3.5% value of magnetizing current from Figure 4.22 for a 20kVA transformer with 480V ac primary, and 120V ac secondary:

$$
\begin{aligned}
i_m &= (0.035)\,\frac{20\,\text{kVA}}{480\,\text{V}} \\
&= 1.46\,\text{A} \\
\hat{i}_m &= \sqrt{2}\; i_m \\
X_{L_m} &= 480\text{V}/1.46\text{A} \\
&= 329\,\Omega \\
L_m &= X_{L_m}/\omega \\
&= 0.872\,\text{H} \\
E_{L_m} &= \frac{0.872\,(2.06)^2}{2} \\
&= 1.85\,\text{J}
\end{aligned}
$$

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

**Semiconductor Blocking Voltage Ratings Required**

Peak varistor current is equal to transformed secondary magnetizing current, ie., $\hat{i}_m(N)$, or 8.24A. From Figure 4.17, the peak suppressed transient voltage is 310V with the V130LA10A selection, 295V with the V130LA20B. This allows the use of 300V rated semiconductors. Safety margins exist in the above approach as a result of the following assumptions:

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

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

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 V130LA10 varistor rating of 30J at 85°C maximum ambient temperature. Average power dissipation requirements over idling power are not needed because of the non-repetitive nature of the expected transient. Should the transient be repetitive, then the average power is calculated from the product of the repetition rate times the energy of the transient. If this value exceeds the V130LA20A capability of 0.85W, power varistors (PA series) are available.

Should the ambient temperature exceed 85°C or the surface temperature exceed 85°C, both the single pulse energy ratings and the average power ratings must be derated by the appropriate derating factors supplied on the V130LA20A data sheet.

### *4.4.3 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.

Each time the current in the inductive load is interrupted by the mechanical contacts, the voltage across the contacts builds up as -L di/dt. When the contacts arc, the voltage across the arc decreases and the current in the coil can increase somewhat. The extinguishing of the arc causes an additional voltage transient which can again cause the contacts to arc. It is not unusual for the restriking to occur several times with the total energy in the arc several times that which was originally stored in the inductive load. It is this repetitive arcing that is so destructive to the contacts.

**PROBLEM:** To extend the life of the relay contacts shown in Figure 4.23 and reduce radiated noise, it is desired to eliminate the contact arcing.

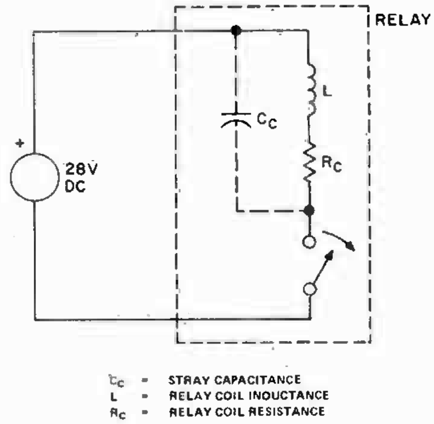



FIGURE 4.23: RELAY CIRCUIT

In the example, $R_C$ is 30Ω and the relay contacts are conducting nearly 1 A. The contacts will draw an arc upon opening with more than approximately 0.4A or 12V. The arc continues until current falls below 0.4A.

**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 breakdown threshold of the contacts as they open. Two obvious techniques come to mind to accomplish this: 1) use of a large capacitor across the contacts, and 2) a voltage clamp (such as a varistor). The clamp technique can be effective only when the minimum arc voltage exceeds the supply voltage.

In this example a clamping device operating above the supply voltage will not prevent arcing. This is shown in Figure 4.24.

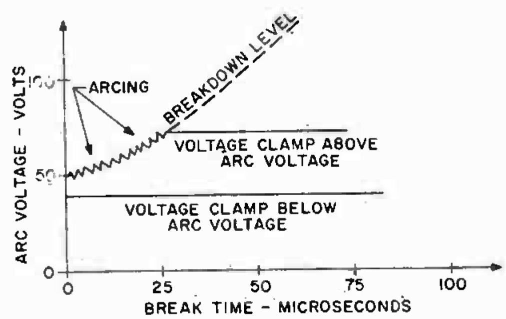
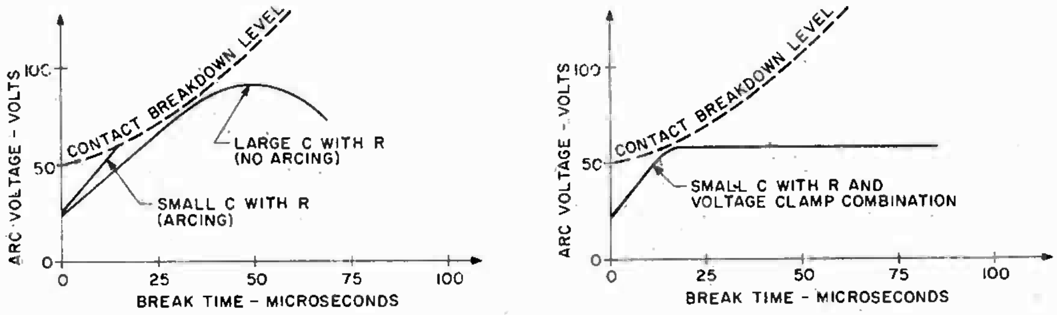



FIGURE 4.24: VOLTAGE CLAMP USED AS ARC SUPPRESSOR

The capacitor technique requires the capacitance to be sufficiently large to conduct the inductor current with a voltage rate-of-rise tracking the breakdown voltage rate-of-rise of the contacts as they mechanically move apart. This is shown in Figure 4.2 (a).




(a) R-C Arc Suppression (b) (R-C) + Clamp Arc Suppression

FIGURE 4.25: RELAY ARC VOLTAGE SUPPRESSION TECHNIQUES

The limitations in using the capacitor approach are size and cost. This is particularly true for those cases involving large amounts of inductive stored energy. Furthermore, the use of a large capacitor alone creates large discharge currents upon contact reclosure during contact bouncing. As a result, the contact material may melt at the point of contact with subsequent welding. To avoid this inrush current, it is customary to add a series resistor to limit the capacitive discharge current. However, this additional component reduces the network effectiveness and adds additional cost to the solution.

A third technique, while not as obvious as the previous two, is to use a combination approach. This technique shown in Figure 4.25(b) parallels a voltage clamp component with an R-C network. This allows the R-C network to prevent the low voltage initial arcing and the clamp to prevent the arcing that would occur later in time as the capacitor voltage builds up. This approach is often more cost effective and reliable than using a large capacitor.

Also, with ac power relays the impedance of a single large R-C suppressor might be so low that it would allow too much current to flow when the contacts are open. The combination technique of a small R-C network in conjunction with a varistor is of advantage here, too.

In this example a $0.22\mu F$ capacitor and $10\Omega$ resistor will suppress arcing completely, but by reducing the capacitance to $0.047\mu F$, arcing will start at 70V.

Thus, to use a varistor as a clamp in conjunction with the R-C network, it must suppress the voltage to below 70V at 1A and be capable of operating at a steady-state maximum dc voltage of 28V + 10%, or 30.8V (assumes a ±10% regulated 28V dc supply).

## Selecting the Varistor

The two candidates that come closest to meeting the above requirement are the molded axial V39MA2B model and the ZA series V39ZA1 model, both of which have maximum steady-state dc voltage ratings of 31V. The V39MA2B V-I characteristic at 1A shows a maximum voltage of 73V, while the V39ZA1 characteristic at 1A shows a maximum voltage of 67V. Thus, the latter varistor is selected. Use of a $0.068\mu F$ capacitor in place of the $0.047\mu F$ previously chosen would allow use of the V39MA2B.

Placing only a GE-MOV®II Varistor rated for 31V dc across the contacts results in arcing up to the 66V level. By combining the two, the capacitor size and voltage rating are reduced and suppression complete.

Besides checking the varistor voltage and arcing elimination, the designer should review energy and peak current requirements. Varistor energy is determined from a measurement of the coil inductance and the calculation $E = ½ Li^2$. Peak current, of course, is under 1A. Power dissipation is negligible unless the coil is switched often (several times per minute).

In those cases where multiple arcs occur, the varistor energy will be a multiple of the above ½ $Li^2$ value. The peak current is well within the rating of either the MA or ZA series of varistors, but the number of contact operations allowable for either varistor is a function of the impulse duration. This can be estimated by assuming a $L/R_C$ time constant at the 1 A or peak current value. Since the voltage across the varistor is 67V at 1A, the varistor static resistance is 67Ω. The coil $R_C$ value is 28V/1 A, or 28Ω. The coil inductance was found to be 20mH. Thus, the approximate time constant is:

$$\tau = L/R_C = \frac{20\,\text{mH}}{95} = 210\,\mu\text{s}$$

From the pulse lifetime curves of the V39ZA1 model, the number of allowable pulses exceeds 100 million.

*4.4.4 Noise Suppression*

Noise in an electromechanical system is a commonly experienced result of interrupting current by mechanical contacts. When the switch contacts open, a hot cathode arc may occur if the current is high enough. On the other hand, low current will permit switch opening without an arc, but with ringing of circuit resonances. As a consequence, voltages can exceed the contact gap breakdown resulting in a replica of the old spark-gap transmitter. It is the low current case that produces the most serious noise disturbances which can result in malfunctions or damage to electrical equipment. These pulses cause noise problems on adjacent lines, trigger SCR's and triacs, and damage semiconductors. In addition, they can raise havoc with microprocessor operation causing memory to be lost and vital instructions to be missed.

**PROBLEM:** Switching of a small timer motor on 120V, 60 Hz, was causing serious malfunctions of an electronic device operating from the same power line. Attempts were made to observe the transient noise on the line with an oscilloscope as the first step in curing the problem. Observed waveforms were "hash," i.e., not readily identifiable.

**SOLUTION:** A test circuit (Figure 4.26) was set up with lumped elements replacing the measured circuit values. The motor impedance was simulated by $R_1$, $L_1$, and $C_1$, and the ac line impedance by $L_2$ and $C_2$. A dc source allowed repeatable observations over the full range of current that could flow through the switch in the normal ac operation. A diode detector was used to observe the RF voltage developed across a 2" length of wire (50nH of inductance).

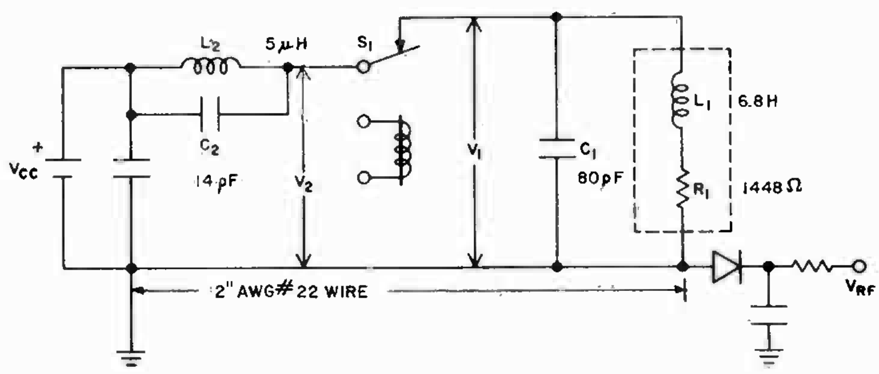
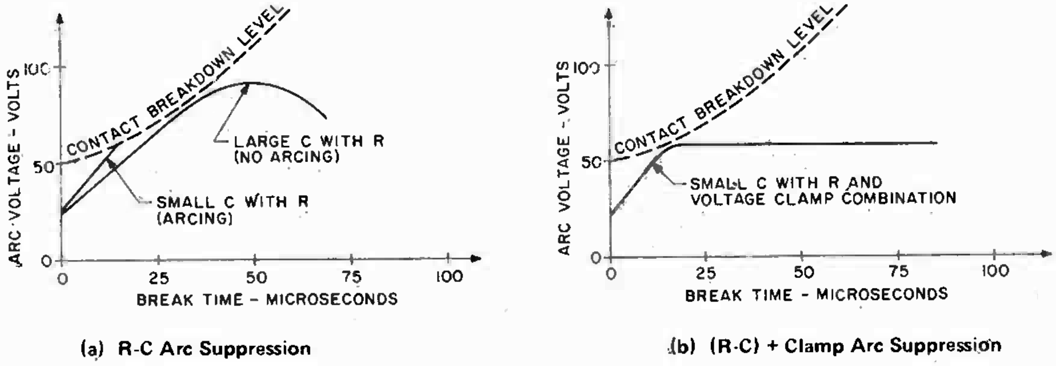



FIGURE 4.26: TEST CIRCUIT

The supply is set at 25mA to represent the peak motor current in normal 120V ac operation. As switch $S_1$ was opened, the waveform in Figure 4.27 was recorded. Note the "showering arc" effect. The highest breakdown voltage recorded here is 1020V, and the highest RF detector output (shown in the lower trace) is 32V.

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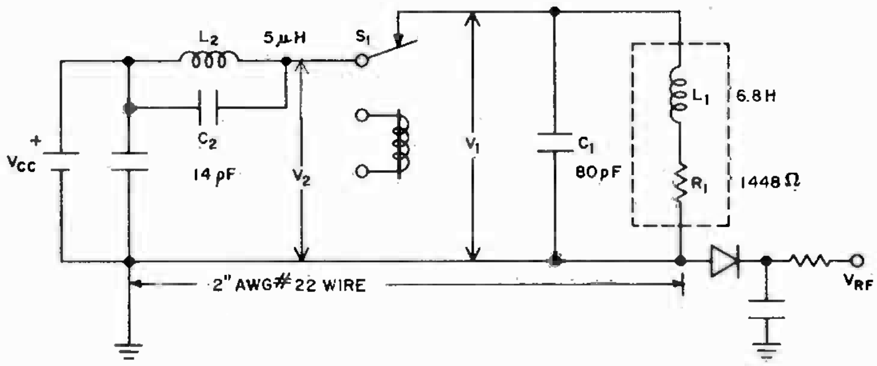
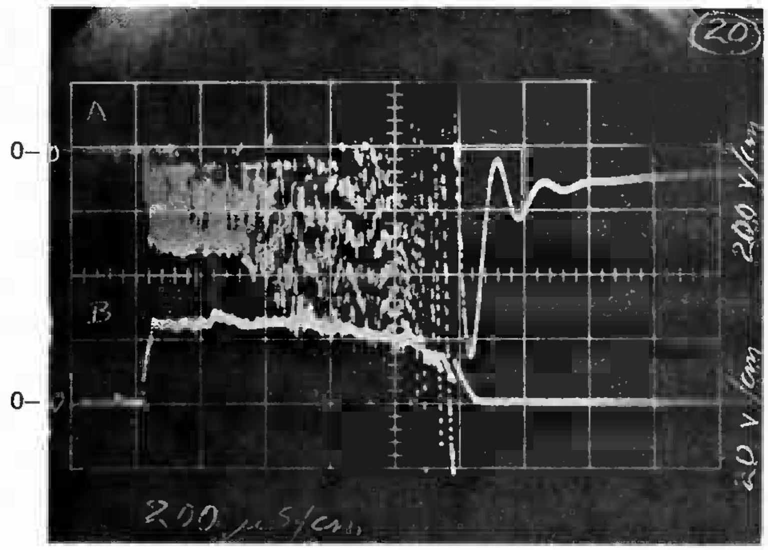



**FIGURE 4.26: TEST CIRCUIT**

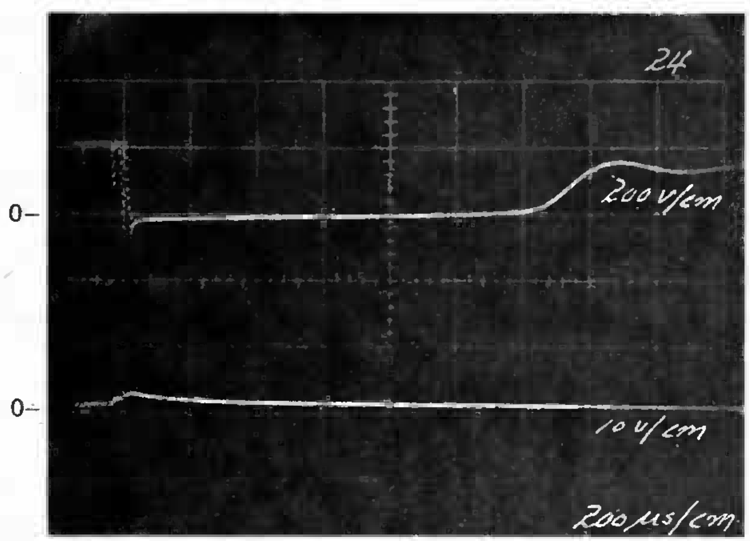
The supply is set at 25 mA to represent the peak motor current in normal 120 V ac operation. As switch $S_1$ was opened, the waveform in Figure 4.27 was recorded. Note the "showering arc" effect. The highest breakdown voltage recorded here is 1020 V, and the highest RF detector output (shown in the lower trace) is 32 V.




Upper $V_1$: 200 V/cm
Lower $V_{RF}$: 20 V/cm
t: 0.2 ms/cm

FIGURE 4.27: UNPROTECTED CONTACTS

Obviously, some corrective action should be taken and the most effective one is that which prevents the repeated breakdown of the gap. Figure 4.28 shows the waveform of $V_1$ (upper trace) and $V_{RF}$ (lower trace) for the same test conditions with a GE-MOV®II Varistor, type V130LA10, connected directly across the switch terminals. The varistor completely eliminates the relaxation oscillations by holding the voltage below the gap breakdown voltage (about 300V) while dissipating the stored energy in the system.

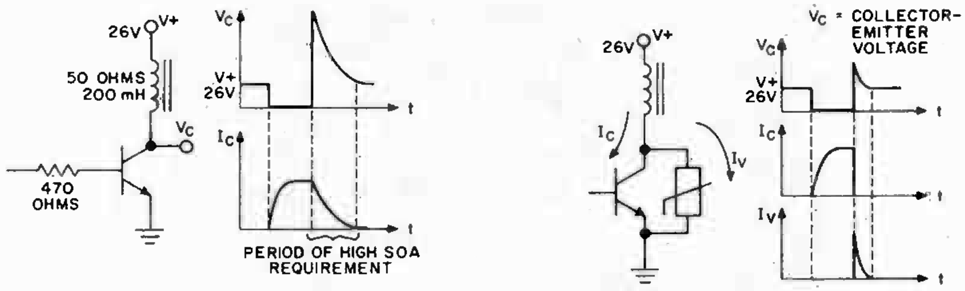



Upper $V_1$: 200 V/cm
Lower $V_{RF}$: 20 V/cm
t: 0.2 ms/cm

FIGURE 4.28: GE-MOV® VARISTOR PROTECTED CONTACTS

*4.4.5 Protection of Transistors Switching Inductive Loads*

**PROBLEM**: The transistor in Figure 4.29 is to operate a solenoid. It may operate as frequently as once per second. The circuit (without any suppression) consistently damages the transistor.




(a) Basic Solenoid Circuit

(b) Solenoid Circuit with Varistor Protection

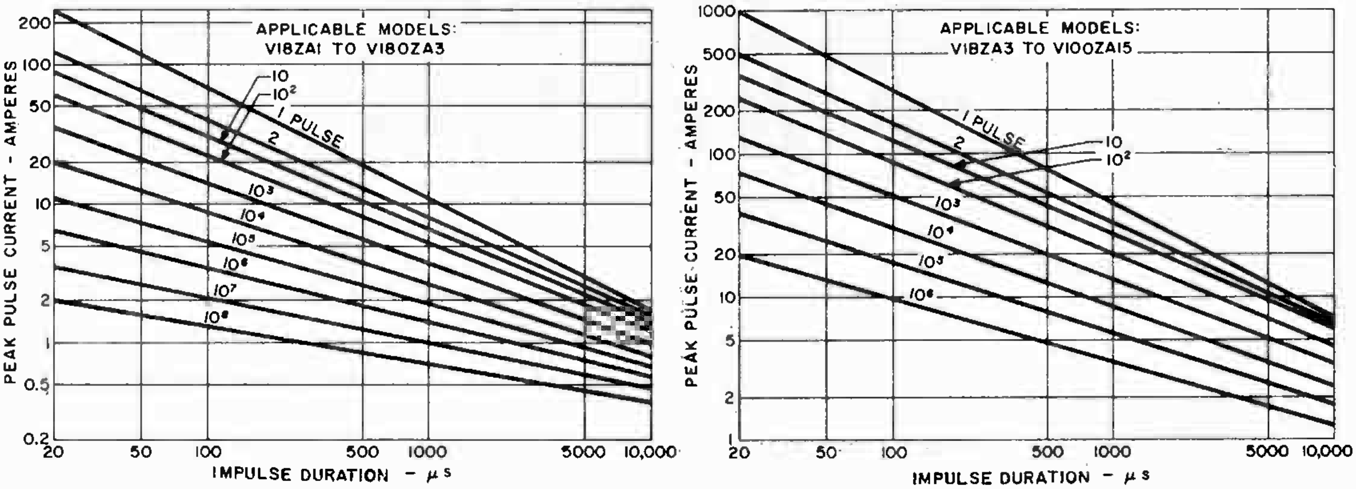
**FIGURE 4.29: TRANSISTOR SWITCHING OF AN INDUCTIVE LOAD**

The inductor drives the collector voltage up 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 a sudden collapse of collector voltage during the pulse).

<u>SOLUTION:</u> This condition can be eliminated 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 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, since it is required to absorb more energy, but will allow the use of a transistor with reduced SOA.

If a collector-emitter varistor is used in the above example, it is required to withstand 28.6V dc worst-case (26 + 10% regulation). The stored energy is $\frac{1}{2}\,Li^2$ or $\frac{1}{2}\,(0.20)\,(0.572)^2 = 0.0327$J. The energy contributed by the power supply is roughly equal to this (coil voltage ≈ supply voltage, since varistor clipping voltage ≈ 2 x supply voltage). Ignoring coil resistance losses for a conservative estimate, varistor energy dissipation is 0.065 J per pulse. The peak current will be 0.572 A, 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 0.065W. This is less than the 0.20W rating of a small 31 V dc varistor (V39ZA1). From the data sheet it can be seen that if the device temperature exceeds 85°C, derating is required. The non-recurrent joule rating is 1.2J, well in excess of the recurrent value. To determine the repetitive joule capability, the current pulse lifetime curves for the ZA series must be consulted. They are shown as Figure 4.30.




(a) V18ZA1 To V180ZA3

(b) V18ZA3 To V100ZA15

**FIGURE 4.30: ZA SERIES PULSE LIFETIME RATINGS**

To use Figure 4.30, the impulse duration (to the 50% point) is estimated from the circuit time constants and is found to be 1240$\mu$s. From Figure 4.30(a), the pulse life is estimated to be slightly over $10^8$ operations. As this may not be adequate, the designer may wish to go to the next larger size varistor (V39ZA6). At 0.572A, the approximate impulse duration is now found to be 1280$\mu$s and using Figure 4.30(b), the designer is faced with the problem of extrapolation below 1 A. This has been done in Figure 4.31 which is a new plot of the data of Figure 4.30(b) at 1280$\mu$s.

We conclude that the life exceeds $10^9$ operations. The reader may question the extrapolation of four orders of magnitude. At low currents the relationship is a straight line extrapolation on log-log paper, as seen from Figure 4.30(a), where the pulse life curves extend to $10^8$ pulses.

The clipping characteristics of the V39ZA6 model will provide a 61V maximum peak. The transistor should have a $V_{CER}$ of 65V or greater for this application.

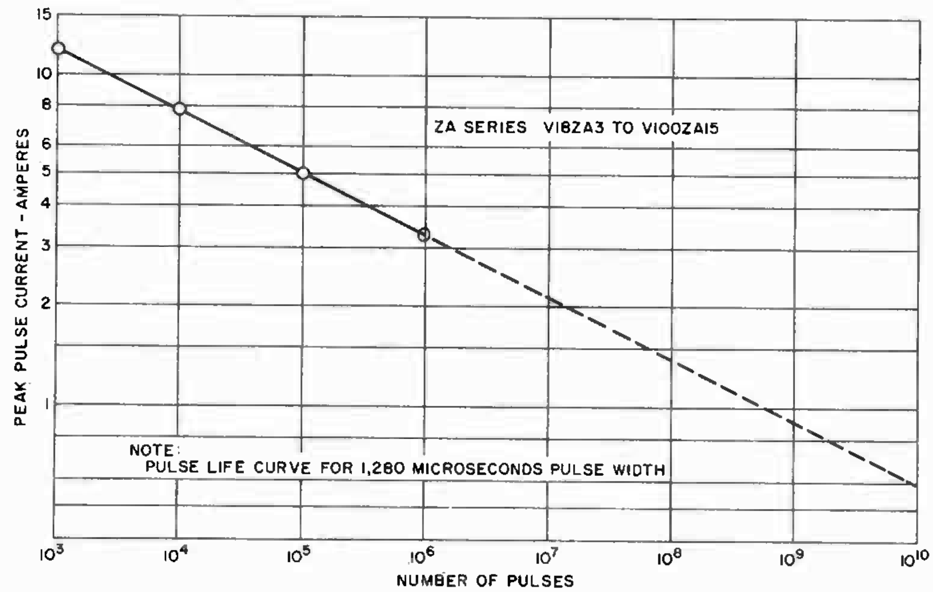



**FIGURE 4.31: EXTRAPOLATED PULSE LIFE CURVES**

### *4.4.6 Motor Protection*

Frequently, the cause of motor failures can be traced to insulation breakdown of the motor windings. The source of the transients causing the breakdown may be from either internal magnetic stored energy or from external sources. This section deals with the self-generated motor transients due to motor starting and circuit breaker operation. Externally-generated transients and their control are covered in Chapter 2.

In the case of dc motors the equivalent circuit consists of a single branch. The magnetic stored energy can be easily calculated in the armature or field circuits using the nameplate motor constants. With ac induction motors the equivalent magnetic motor circuit is more complex and the circuit constants are rarely given on the motor nameplate. To provide a guide for motor protection, Figures 4.32, 4.33 and 4.34 were drawn from typical induction motor data. While the actual stored energy will vary according to motor frame size and construction techniques, these curves provide guidance when specific motor data is lacking. The data is conservative as it assumes maximum motor torque, a condition that is not the typical running condition. Stored energy decreases considerably as the motor loading is reduced. Experience with the suppression of magnetic energy stored in transformers indicates that GE-MOV®II Varistors may be used at their maximum energy ratings, even when multiple operations are required. This is because of the conservatism in the application requirements, as indicated above, and in the varistor ratings. Thus, no attempt is made to derate the varistor for multiple operations because of the random nature of the transient energy experienced.

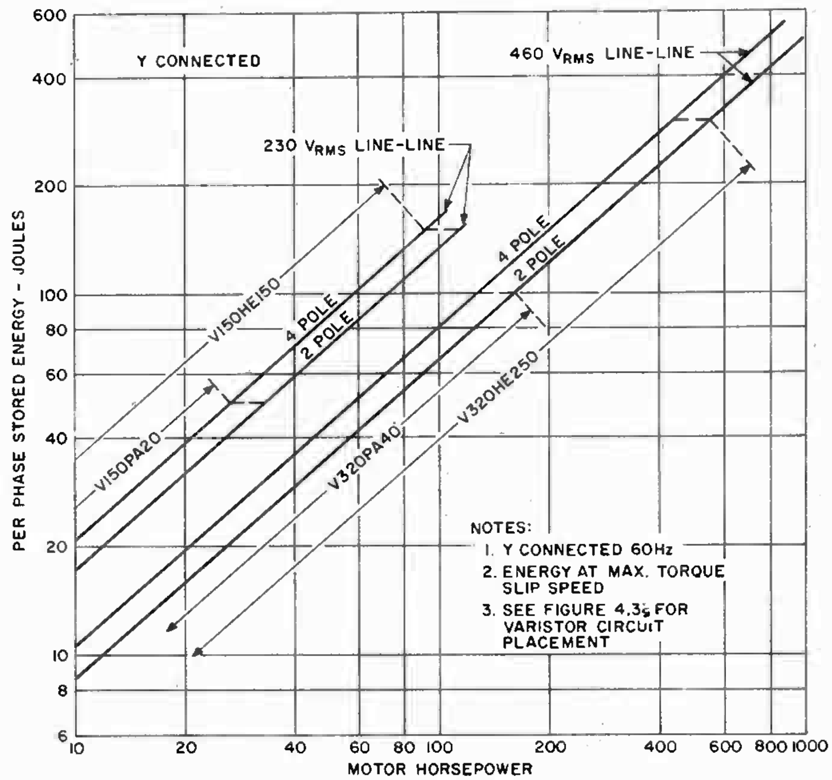



**FIGURE 4.32: STORED ENERGY CURVES FOR TYPICAL WYE-CONNECTED INDUCTION MOTOR**

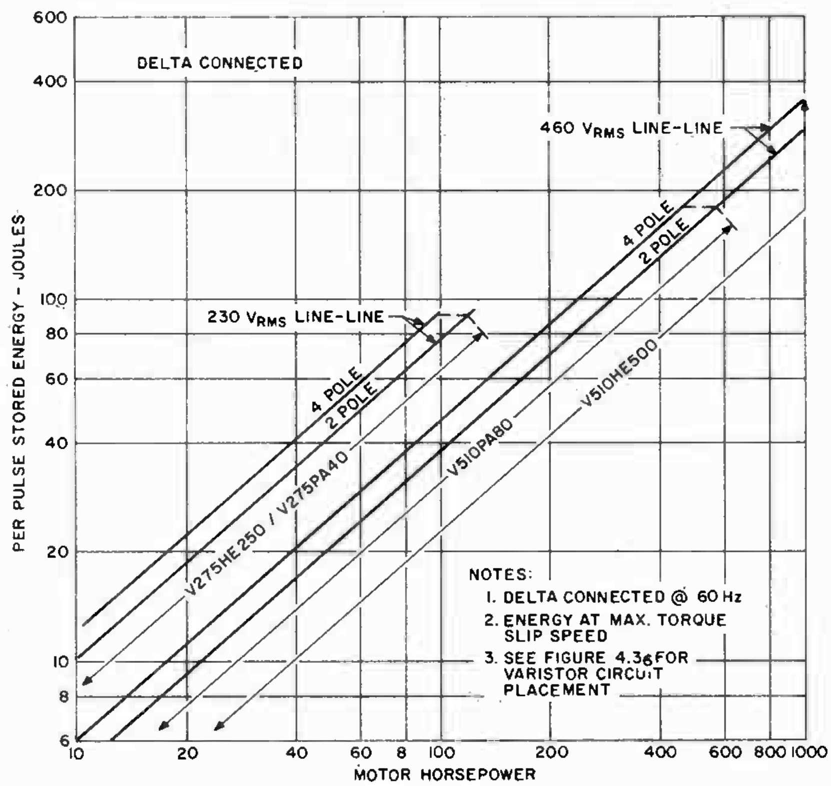



**FIGURE 4.33: STORED ENERGY CURVES FOR TYPICAL DELTA-CONNECTED INDUCTION MOTOR**

To use Figure 4.30, the impulse duration (to the 50% point) is estimated from the circuit time constants and is found to be 1240$\mu$s. From Figure 4.30(a), the pulse life is estimated to be slightly over $10^8$ operations. As this may not be adequate, the designer may wish to go to the next larger size varistor (V39ZA6). At 0.572A, the approximate impulse duration is now found to be 1280$\mu$s and using Figure 4.30(b), the designer is faced with the problem of extrapolation below 1 A. This has been done in Figure 4.31 which is a new plot of the data of Figure 4.30(b) at 1280$\mu$s.

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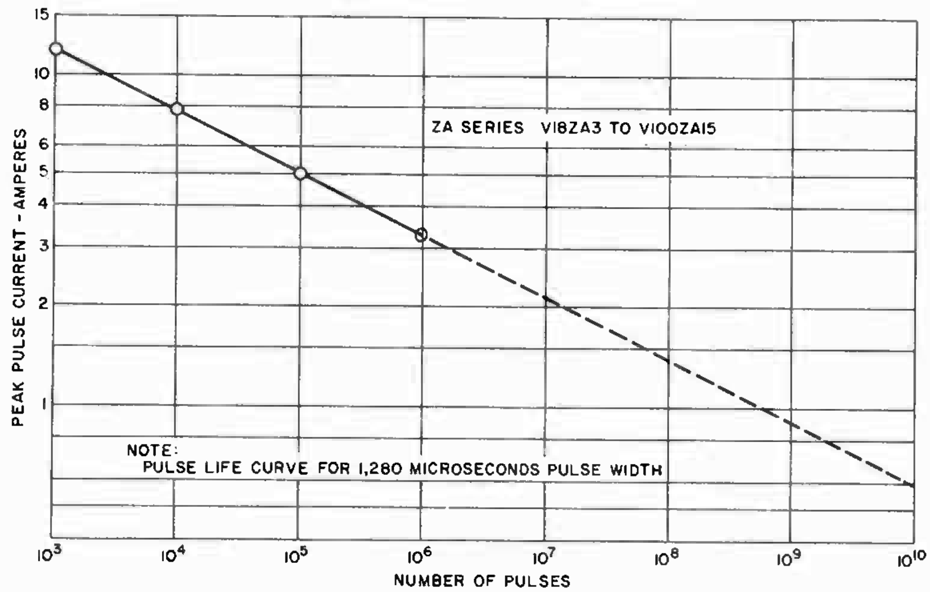


**FIGURE 4.31: EXTRAPOLATED PULSE LIFE CURVES**

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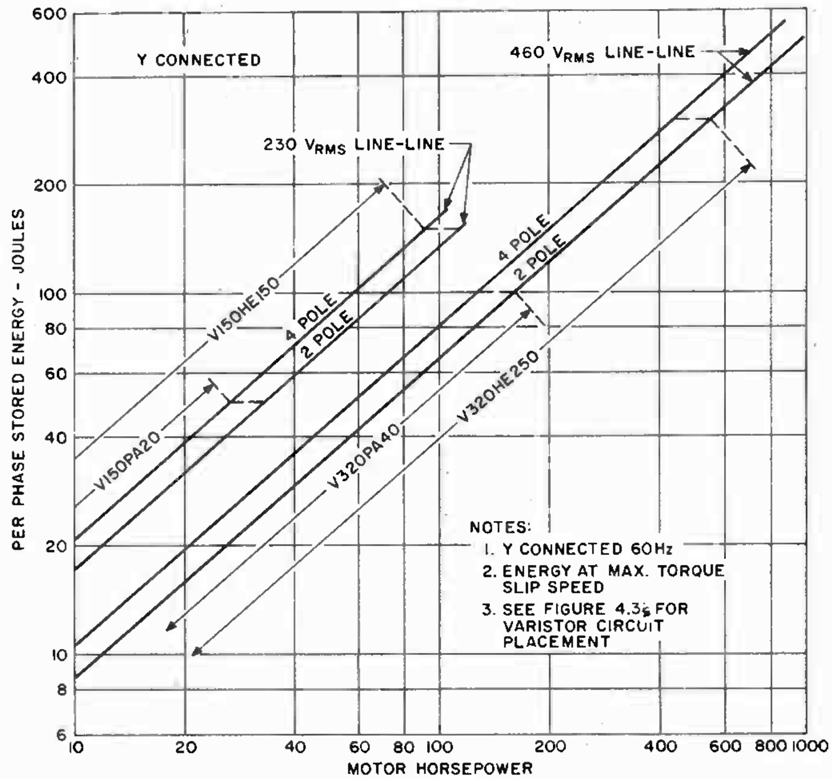



**FIGURE 4.32: STORED ENERGY CURVES FOR TYPICAL WYE-CONNECTED INDUCTION MOTOR**

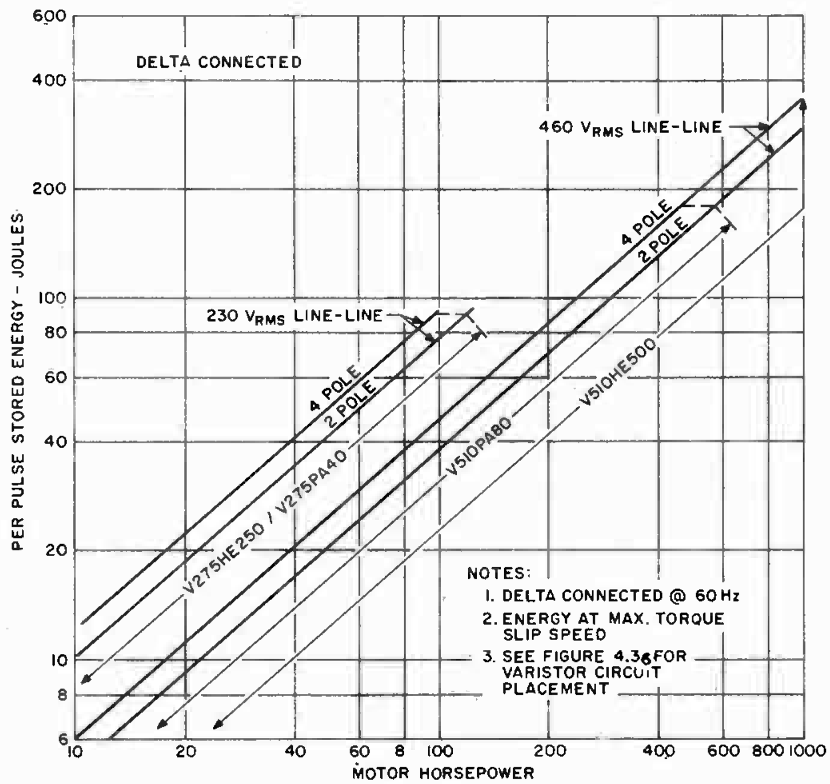



**FIGURE 4.33: STORED ENERGY CURVES FOR TYPICAL DELTA-CONNECTED INDUCTION MOTOR**

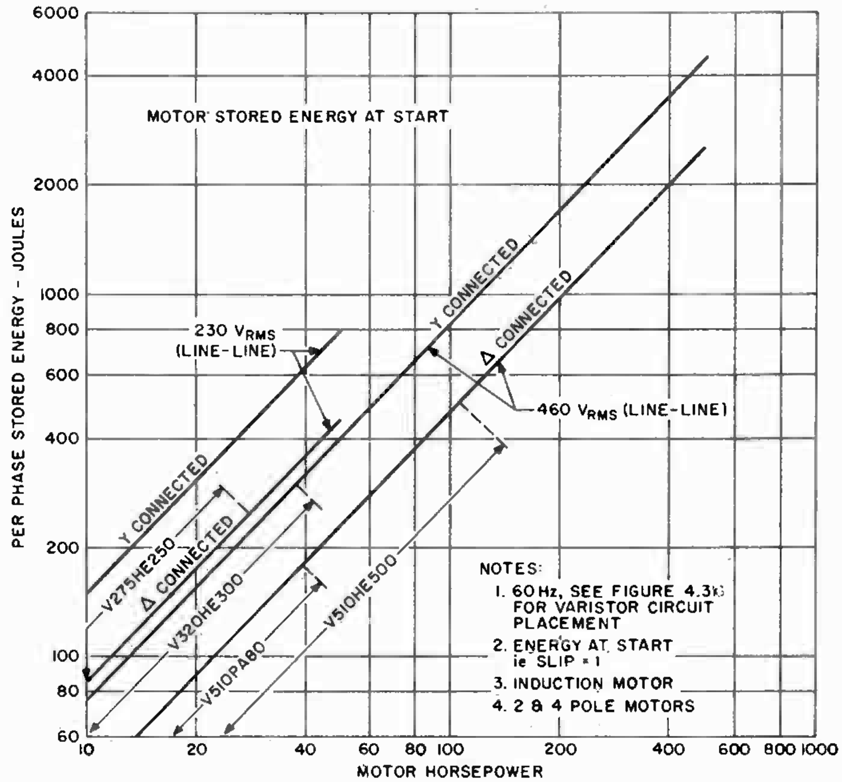


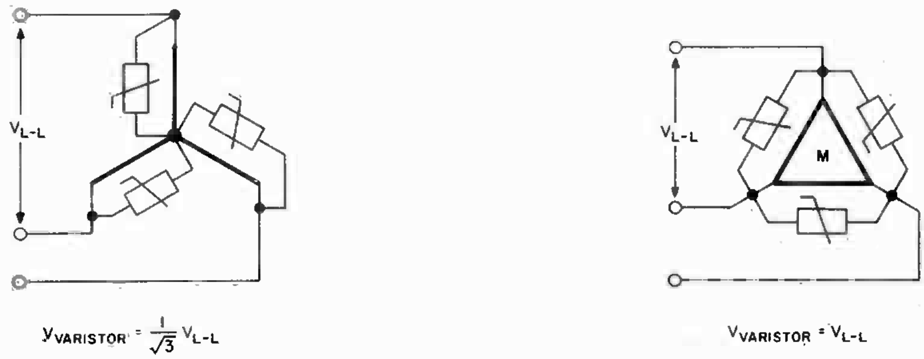

**FIGURE 4.34: STORED ENERGY CURVES FOR A TYPICAL MOTOR WITH STALLED ROTOR**

As an aid in selecting the proper operating voltage for GE-MOV®II Varistors, Figure 4.35 gives guidelines for wye-connected and delta-connected motor circuits at different line-to-line applied voltages. Figure 4.36 provides guidance in proper placement of the varistor.

| RMS LINE VOLTAGE (LINE-LINE) | ⟹ | 230 | 380 | 460 | 550 | 600 |
|---|---|---|---|---|---|---|
| DELTA CONNECTED | APPLIED V. | 230 | 380 | 460 | 550 | 600 |
| | VARISTOR RATINGS | 250/275 | 420/460 | 510/550 | 575/660 | 660 |
| Y CONNECTED | APPLIED V. | 133 | 220 | 266 | 318 | 346 |
| | VARISTOR RATINGS | 150 | 250/275 | 320 | 420 | 420 |

**FIGURE 4.35: PREFERRED VARISTOR VOLTAGE RATINGS FOR DELTA- AND WYE-CONNECTED MOTORS**

Interruption of motor starting currents presents special problems to the user as shown in Figure 4.34. Since the stored magnetic energy values are approximately 10 times the running values, protection is difficult at the higher horsepower levels. Often the motor is started by use of a reduced voltage which will substantially reduce the stored energy. A reduction in starting current of a factor of two results in a four-fold reduction in stored energy. If a reduced voltage starter is not used, then a decision must be made between protection for the run condition only, and the condition of locked rotor motor current. For most applications, the starting condition can be ignored in favor of selecting the varistor for the worst-case run condition.




(a) WYE CONNECTED (b) DELTA CONNECTED

FIGURE 4.36: VARISTOR – 3$\phi$ INDUCTION MOTOR CIRCUIT PLACEMENT

**PROBLEM:** To protect a two-pole, 75 hp, 3$\phi$, 460V RMS line-to-line wye-connected motor from interruption of running transients.

**Specific motor data is not available.**

SOLUTION: Consult Figure 4.32 along with Figure 4.35. Standard varistors having the required voltage ratings are the 320V RMS rated models. This allows a 20% high-line voltage condition on the nominal 460V line-to-line voltage, or 266V line-neutral voltage. Figure 4.32 shows a two-pole 75 hp, wye-connected induction motor, at the running condition, has 52J of stored magnetic energy per phase. Either a V320PA40 series or a V320HE250 series varistor will meet this requirement. The HE series GE-MOV®II Varistor provides a greater margin of safety, although the PA series GE-MOV®II Varistor fully meets the application requirements. Three varistors are required, connected directly across the motor terminals as shown in Figure 4.36(a).

*4.4.7 Power Supply Crowbar*

Occasionally it is possible for a power supply to generate excessively high voltage. An accidental removal of load can cause damage to the rest of the circuit. A simple safeguard is to crowbar or short circuit 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®II Varistor provides an effective, inexpensive substitute.

**PROBLEM:** In the circuit below, the voltage, without protection, can exceed twice the normal 240V peaks, damaging components downstream. A simple arrangement to crowbar the supply is shown.

The supply shown can provide 2A RMS of short-circuit current and has a 1A circuit breaker. A C106 SCR having a 4A RMS capability is chosen. Triggering will require at least 0.4V gate-to-cathode, and no more than 0.8V at 200 $\mu$A at 25°C ambient.

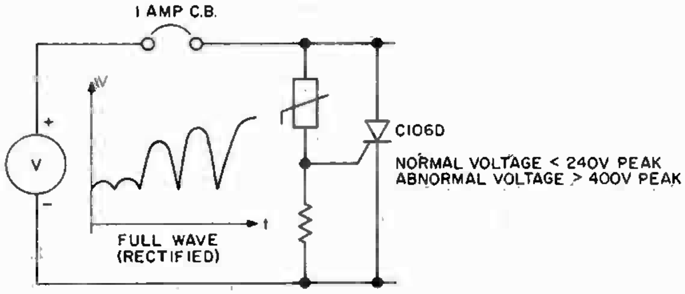



FIGURE 4.37: CROWBAR CIRCUIT

**SOLUTION:** Check the MA series GE-MOV®II Varistor specifications for a device capable of supporting 240 V peak. The V270MA4B can handle $\sqrt{2}$(171 V rms) = 242 V. According to its specification of 270V ±10%, the V270MA4B will conduct 1 mA dc at no less than 243 V. The gate-cathode resistor can be chosen to provide 0.4 V (the minimum trigger voltage) at 1 mA, and the SCR will not trigger below 243 V. Therefore, $R_{GK}$ should be less than 400Ω. The highest value 5% tolerance resistor falling below 400Ω is a 360Ω resistor, which is selected. Thus, $R_{GK}$ is 378Ω maximum and 342Ω minimum. Minimum SCR trigger voltage of 0.4 V requires a varistor of 0.4 V/378Ω, or 1.06 mA for a minimum varistor voltage of ≈ 245 V. The maximum voltage to trigger the circuit is dependent upon the maximum current the varistor is required to pass to trigger the SCR. For the C106 at 25°C, this is determined by calculating the maximum current required to provide 0.8 V across a parallel resistor comprised of the 360Ω $R_{GK}$ selected and the equivalent gate-cathode SCR resistor of 0.8 V/200μA, since the C106 requires a maximum of 200μA trigger current. The SCR gate input resistance is 4KΩ and the minimum equivalent gate-cathode resistance is the parallel combination of 4KΩ and $R_{GK(min)}$, or 360Ω -5%, 342Ω. The parallel combination is 325Ω. Thus, $I_{varistor}$ for maximum voltage-to-trigger the C106 is 0.8 V/315Ω, or 2.54 mA. According to the specification sheet for the V270MA4B, the varistor will not exceed 330V with this current. The circuit will, therefore, trigger at between 245 and 330 V peak, and a 400V rated C106 can be used. The reader is cautioned that SCR gate characteristics are sensitive to junction temperatures, and a value of 25°C for the SCR temperature was merely chosen as a convenient value for demonstrating design procedures.

Figure 4.3 can be used to determine the maximum energy per pulse with this waveform. It will not exceed approximately ½ / 0.15 / $I_{pk}$ / $V_{pk}$ / $\tau$ (duration of ½ wave pulse), or 0.52mJ 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; thus, no steady-state power consideration exists.

### *4.4.8 General Protection of Solid State Circuitry, Against Transients on 117 V ac Lines*

**PROBLEM**: Modern electronic equipment and home appliances contain solid state circuitry that is susceptible to malfunction or damage caused by transient voltage spikes. The equipment is used in residential, commercial, and industrial buildings. Some equipment designs are relatively low cost consumer items while others are for commercial/industrial use where an added measure of reliability is needed. Since solid state circuits and the associated transient sensitivity problem are relatively new, the knowledge of design in the transient environment is still incomplete. Some test standards have been adopted by various agencies (see Chapter 7), and further definition of the environment is underway by the Surge Protective Devices Committee of the IEEE.

The transients which may occur on residential and commercial ac lines are of many waveshapes and of varying severity in terms of peak voltage, current, or energy. For suppressor application purposes, these may be reduced to three categories.

First, the most frequent transient might be the one represented by a 30 or 100 kHz ring wave. This test surge is defined by an oscillatory exponentially decaying voltage wave with a peak open circuit voltage of 6kV. This wave is considered representative of transients observed and reported by studies in Europe and North America. These transients can be caused by distant lightning strikes or distribution line switching. Due to the relatively high impedance and short duration of these transients, peak current and surge energy are lower than the following categories.

The second category is that of surges produced by nearby lightning strokes. The severity of a lightning stroke is characterized in terms of its peak current. The probability of a direct stroke of a given severity can be determined. However, since the lightning current divides in many paths, the peak current available at an ac outlet within a building is much less than the total current of the stroke. The standard impulse used to represent lightning and to test surge protective devices is an 8 / 20 $\mu$s current waveshape as defined by ANSI Standard C68.2, and also described in IEEE Standard 587-1980.

A third category of surges are those produced by the discharge of energy stored in inductive elements such as motors and transformers. A test current of 10 / 1000$\mu$s waveshape is an accepted industry test impulse and can be considered representative of these surges.

Although no hard-and-fast rules can be drawn as to the category and severity of surges which will occur, a helpful guideline can be given to suggest varistors suitable in typical applications.

This guideline recognizes considerations such as equipment cost, equipment duty cycle, effect of equipment downtime, and balances the economics of equipment damage risk against surge protection cost.

**GE-MOV® VARISTOR SELECTION GUIDELINE FOR 117V AC APPLICATION**

| APPLICATION TYPE | DUTY CYCLE | EXAMPLE | SUGGESTED MODEL |
|---|---|---|---|
| Light Consumer | Very Low | Mixer/Blender | V130LA1 |
| Consumer | Low | Portable TV | V130LA10A |
| Consumer | Medium | Console TV | V130LA20A |
| Light Industrial | Medium | Copier | V130LA20A or B |
| Industrial | Medium | Small Computer | V130PA20A, B or C |
| Industrial | High | Large Computer | V130HE150 |
| Industrial | High | Elevator Control | V150HE150 |

## REFERENCE


1. Kaufman, R., "The Magic of $I^2t$," IEEE Trans. IGA-2, No. 5, Sept.-Oct. 1966.

# chapter 5

# SUPPRESSION— TELECOMMUNICATIONS SYSTEMS

## 5.1 INTRODUCTION

Modern telecommunication systems are fast, efficient, and complex. Many improvements have been made in central office equipment and subscriber equipment which involves the use of solid state circuitry. Unfortunately, solid state devices are much more susceptible to malfunction or failure due to transient voltages and noise than are older devices, such as relays, coils, step-switches, and vacuum tubes. To complicate matters further, increased usage of telecommunication lines for data and video transmissions has produced a further intolerance for transient voltages.

Although telecommunications systems have always employed transient protection devices such as the carbon gap, the gas tube, and the heat coil, these are not always adequate to protect solid state circuitry. The GE-MOV®II Varistor shows promise of providing the extra protection necessary for even more reliable telecommunications.

## 5.2 SYSTEM TRANSIENTS

A telecommunication system is made up of subscriber stations linked together through the cable plant and a central office switching network. Included in the system are repeater amplifiers, multiplexers, and other electronic circuits. Supplying the electrical energy to run the system is a main power source.

The cable plant and the power supply provide a path by which damaging transients enter the system, to be transmitted to vulnerable electronic circuitry. The cable plant consists of conductors in shielded cables, which are suspended on poles (shared with power lines) or buried in the earth. A single cable is made up of many conductors, arranged in twisted pairs (tip and ring). Some sections of open-wire transmission lines are still used, but most of these are remote from central offices, and transient protectors are usually provided where the open wire enters the shielded cables. All of these cables (even the ones underground) are capable of picking up transient energy from lightning and conducting them to the central office or subscriber equipment.

The power used by a telecommunication system is usually obtained from commercial power lines. These lines, like the telephone cables, are either suspended on poles or buried. Transient energy is frequently picked up by power lines and transmitted to the central office by direct conduction or by induction into the telephone cable plant. The increased use of off-line power supplies in telephone equipment makes power line transients even more hazardous to the electronic circuitry.

## 5.3 LIGHTNING – INDUCED TRANSIENTS

Lightning is the most common source of over voltage in communication systems. Because of the exposure to lightning strokes, a knowledge of the effects of lightning is important when designing a transient protective system.

Lightning currents may enter the conductive shield of a suspended cable by direct or indirect stroke, or it may enter a cable buried in the ground by ground currents, as shown in Figure 5.1.

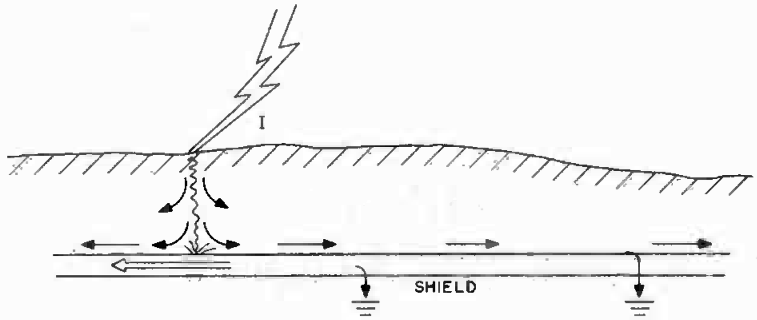



FIGURE 5.1: LIGHTNING CURRENT IN BURIED CABLE

In the case of a suspended cable, the lightning current that enters the cable is seeking a ground and will travel in both directions along the cable. Some of the current will leave the shield at each grounded pole along its path. Studies have shown that all of the lightning current has left the cable shield after passing 10 poles grounded in high-conductivity soils or 20 poles grounded in high resistivity soil.

Stroke currents leave a buried cable in a similar way but with a different mechanism. Since the cable shield has a finite electrical resistance, the current passing through it will produce a potential gradient along its length. This voltage will produce a potential difference between the cable and the soil, as shown in Figure 5.2.

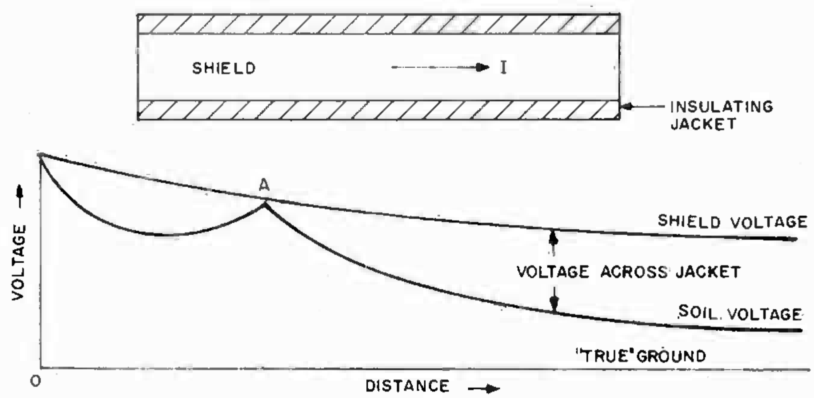



FIGURE 5.2: CONDITION FOR PUNCTURE OF CABLE JACKET

At some point (Point A) the shield-to-earth potential will exceed the dielectric strength of the jacket, causing it to puncture. Some of the lightning current then flows through the puncture into the soil, thus equalizing the potential at that point. The remaining current continues along the shield until another puncture occurs, providing another path to ground.

Lightning currents are usually not harmful to the shield itself, but they do induce surge voltages on the conductors of the cable which are often harmful to central office equipment. The surge voltage that appears at the ends of the cable depends upon the distance to the disturbance, the type of cable, the shield material, and its thickness and insulation, as well as the amplitude and waveshape of the lightning current in the shield. Since the current-derived potential along the cable shield is capacitively coupled to the cabled conductors, the waveshape of the surge voltage on the conductors will closely resemble the waveshape of the lightning current.

Quantitative information on lightning has been accumulated from many sources,[2] with research centers in the United States, Western Europe and South Africa. One of the most comprehensive surveys of available data has been compiled by Cianos and Pierce,[3] describing the amplitude, rate-of-rise, duration, etc., in statistical terms.

# chapter 5

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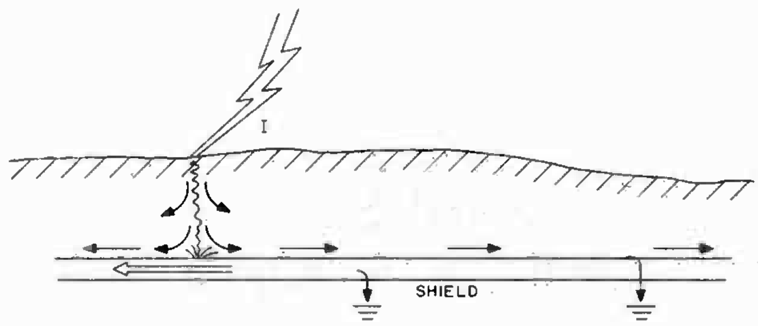


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In the case of a suspended cable, the lightning current that enters the cable is seeking a ground and will travel in both directions along the cable. Some of the current will leave the shield at each grounded pole along its path. Studies have shown that all of the lightning current has left the cable shield after passing 10 poles grounded in high-conductivity soils or 20 poles grounded in high resistivity soil.

Stroke currents leave a buried cable in a similar way but with a different mechanism. Since the cable shield has a finite electrical resistance, the current passing through it will produce a potential gradient along its length. This voltage will produce a potential difference between the cable and the soil, as shown in Figure 5.2.

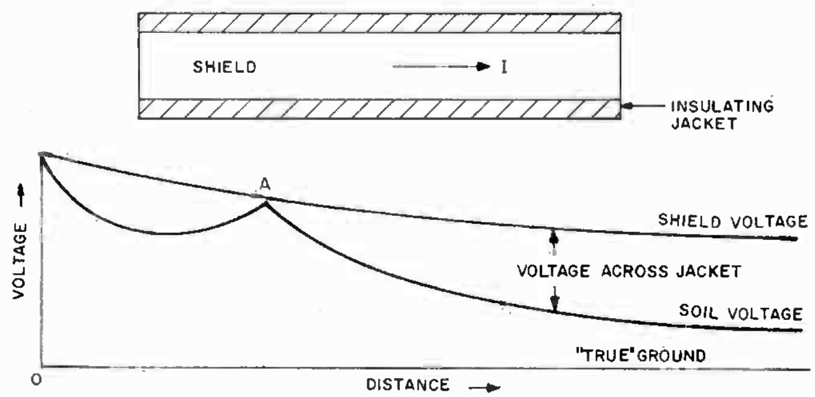



**FIGURE 5.2: CONDITION FOR PUNCTURE OF CABLE JACKET**

At some point (Point A) the shield-to-earth potential will exceed the dielectric strength of the jacket, causing it to puncture. Some of the lightning current then flows through the puncture into the soil, thus equalizing the potential at that point. The remaining current continues along the shield until another puncture occurs, providing another path to ground.

Lightning currents are usually not harmful to the shield itself, but they do induce surge voltages on the conductors of the cable which are often harmful to central office equipment. The surge voltage that appears at the ends of the cable depends upon the distance to the disturbance, the type of cable, the shield material, and its thickness and insulation, as well as the amplitude and waveshape of the lightning current in the shield. Since the current-derived potential along the cable shield is capacitively coupled to the cabled conductors, the waveshape of the surge voltage on the conductors will closely resemble the waveshape of the lightning current.

Quantitative information on lightning has been accumulated from many sources,[2] with research centers in the United States, Western Europe and South Africa. One of the most comprehensive surveys of available data has been compiled by Cianos and Pierce,[3] describing the amplitude, rate-of-rise, duration, etc., in statistical terms.

Using these statistics, one can make numerical calculations of induced voltages in various electrical circuits, such as the cable plant of a communication system. The parameters of interest are the voltages developed as a function of intensity and duration of the lightning impulse. The examples discussed later in this chapter are based on this source of information.

### 5.4 CALCULATIONS OF CABLE TRANSIENTS

The voltage surge induced into the conductors of a cable will propagate as a traveling wave in both directions along the cable from the region of induction. The cable acts as a transmission line. The surge current and voltage are related to each other by Ohm's law where the ratio of voltage to current is the surge impedance ($Z_o$) of the cable. $Z_o$ can also be expressed in terms of the inductance (L) and capacitance (C) per unit length of the cable by the equation,

$$Z_o = \sqrt{L/C}\ (\Omega)$$

The velocity of the surge, as it propagates along the conductors, is also a function of L and C, and can be expressed as

$$\text{Velocity} = \sqrt{1/LC}\ \text{(meters/sec.)}$$

The series resistance of the shield and conductors, as well as losses due to corona and arcing, determine the energy lost as the disturbance propagates along the cable.

Tests conducted on telephone cables[4] have measured surge impedances of 80Ω between any of the conductors and the shield. Shield resistances between 5Ω and 6Ω per mile were found to be typical. These values and the applied lightning current waveform of Figure 5.3 were used to compute the worst case transient which would appear at cable terminals in a central office. The computation assumes the lightning current is introduced into a suspended cable shield at a point 2.75 miles from the central office. An average cable span between poles of 165 feet, with a ground connection on every fourth pole, was assumed. It was also assumed that the cable will support the voltage without arcing over.

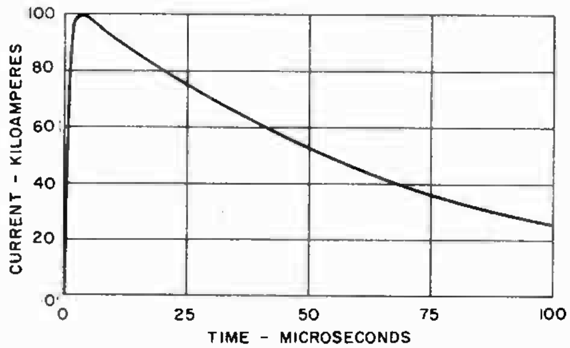



FIGURE 5.3: SEVERE LIGHTNING CURRENT WAVEFORM (2/50 μs)

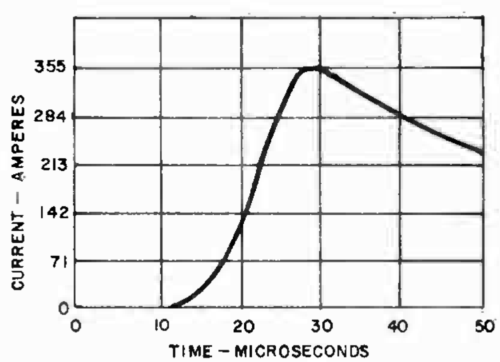



FIGURE 5.4: AVAILABLE CURRENT 2.75 MILES FROM 100kA LIGHTNING STROKE

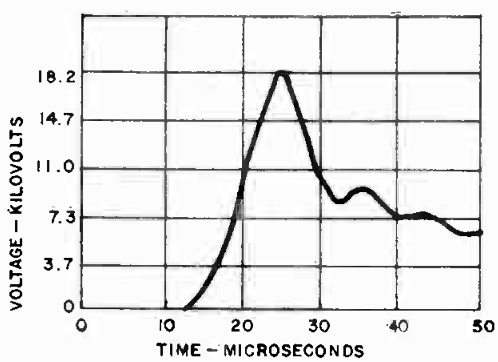



FIGURE 5.5: OPEN CIRCUIT VOLTAGE – 2.75 MILES FROM 100kA LIGHTNING STROKE

The resulting short-circuit current available at the central office is shown in Figure 5.4.

The open-circuit voltage at the cable end is shown in Figure 5.5. This analysis shows that if a severe, 100kA lightning flash strikes a cable at a point 2.75 miles from a central office, a voltage transient reaching a peak of nearly 18kV may appear at the cable end, with about 355A of current available.

Since the cable can be considered to be a linear system, the voltages and currents will bear a linear relation to the lightning stroke amplitude. A tabulation of the open-circuit voltage and available current which would result from stroke currents of various magnitudes is given in Table 5. Included in the table is the probability of occurrence, as given by Cianos and Pierce.[3] It should be realized that voltages in excess of 10kV probably would not be sustained since the cable insulation will break down.

The transient voltage at the central office in any case would be excessive, so that protectors would be required. The protector would conduct up to 213A surge current for most (85%) of the strokes that occur and only up to twice that current on rare occasions.

**TABLE 5.1**

**LIGHTNING TRANSIENTS AT CABLE END 2.75 MILES FROM STROKE POINT**

| LIGHTNING STROKE, PEAK CURRENT (kA) | PROBABILITY OF OCCURRENCE (%) | TERMINAL OPEN-CIRCUIT VOLTAGE (PEAK V) | TERMINAL SHORT-CIRCUIT CURRENT (PEAK A) |
|---|---|---|---|
| 175 | 1 | 32,200 | 621 |
| 100 | 5 | 18,400 | 355 |
| 60 | 15 | 11,040 | 213 |
| 20 | 50 | 3,680 | 71 |

The values shown in Table 5.1 are based on the assumption of a single conductor cable with the stroke point 2.75 miles from the central station. For closer strokes the peak short-circuit current at the cable end will increase as shown in Table 5.2. These calculations were made assuming a breakdown at the stroke point, which gives the worst case result.

Since telephone cables actually have many pairs of wires rather than a single conductor, the peak currents in each wire will be lower. It is assumed that the stroke voltage will be induced equally in all wires if they are equally loaded. Then, the currents in all wires will be equal if all pro-

**TABLE 5.2**

**PEAK LIGHTNING-INDUCED CURRENTS IN VARIOUS LENGTHS OF TELEPHONE CABLE (100kA LIGHTNING STROKE)**

| DISTANCE TO STROKE (Miles) | PEAK CURRENTS (A) | | | |
|---|---|---|---|---|
| | AT STROKE POINT | AT CENTRAL OFFICE | | |
| | | SINGLE CONDUCTOR | 6 PAIR CABLE | 12 PAIR CABLE |
| 2.75 | 630 | 355 | – | – |
| 1.50 | 630 | 637 | – | – |
| 1.00 | 734 | 799 | – | – |
| 0.5 | 1110 | 1120 | 712 | 453 |
| 0.25 | 1480 | 1480 | 852 | 463 |

tectors are identical. To predict the individual wire currents, it is assumed that the wire currents are proportional to sheath current and the ratio of resistances, and are reduced a constant amount by cable inductance. Worst case calculated values for the shortest distances are shown in Table 5.2

An example of the current which a protective device must handle can now be estimated. Assume a cable of six pairs (the smallest available) is struck by lightning, inducing a stroke current of 100kA into the shield, at a distance of 0.25 mile from the protector. The transient current will be divided up among the twelve suppressors at the cable ends. Each protective device must handle up to 852A of peak current in order to clamp the voltage to a protected level.

## 5.5 POWER SYSTEM-INDUCED TRANSIENTS

Since telephone cables very often share a pole and ground wire with the commercial ac utility power system, the high currents that accompany power system faults can induce over-voltages in the telephone cables. These induced over-voltages will be at the power system frequency and can have long duration (compared to the lightning-induced transients) from a few milliseconds to several cycles of power frequency. Three types of over-voltage can occur in conjunction with power system faults:

**Power Contact** – (Sometimes called "power cross") The power lines fall and make contact with the telephone cable.

**Power Induction** – The electromagnetic coupling between the power system experiencing a heavy fault and the telephone cable produces an over-voltage in the cable.

**Ground Potential Rise** – The heavy ground currents of power system faults flow in the common ground connections and cause substantial differences in potential.

There is little definitive data available on the severity of these over-voltages. However, proposals have been made by telephone protection engineers to define the power contact as the most severe condition. The proposed requirement calls for the suppressor to withstand 10A RMS for a duration of power contact ranging from 10 to 60 cycles of the power system frequency.

## 5.6 PROTECTORS – VOLTAGE TRANSIENT SUPPRESSORS

### *5.6.1 Primary Protection*

The oldest and most commonly used primary protector for a telephone system is the carbon block spark gap. The device is made up of two carbon block electrodes separated by a small air gap of between 0.003 and 0.004 inch. One electrode is connected to the telephone cable conductor and the other to the system ground. When an over-voltage transient appears, the gap breaks down diverting the transient and dissipating the energy in the arc and the source impedance of the transient. The carbon gap is a low-cost protector but suffers from a relatively short life and exhibits sparkover voltage variations. Nominal 3-mil carbon gaps statistically sparkover as low as 300V and as high as 1000V – this is a serious problem.

Telephone conductors occur in pairs in a cable so that transient voltages induced into the conductors will be common to both tip and ring conductors, as shown in Figure 5.6. This longitudinal voltage produces no current through the load termination. Normally, there is zero difference in the potential between conductors. If protector, $PR_1$ should break down at 400V, while $PR_2$ requires 700V to break down, then only $PR_1$ would break down on a transient of 600V causing a transient current flow through the load. Even if $PR_2$ does break down but responds later in time than $PR_1$ a transient current will flow.

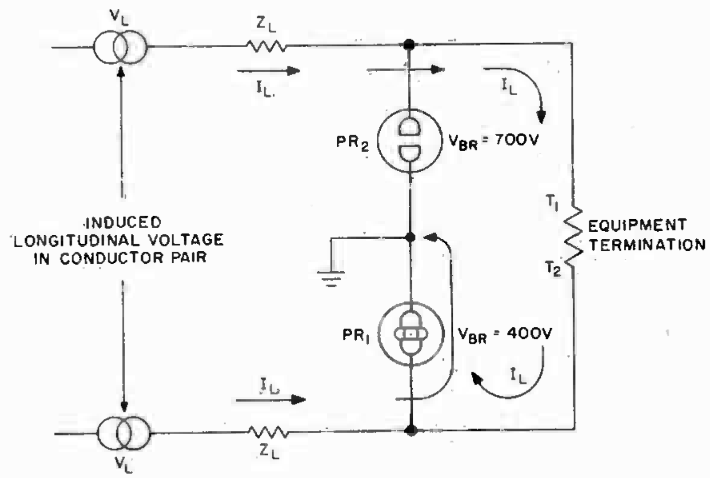



FIGURE 5.6: UNBALANCED LINE PROTECTION

Another common suppressor in telephone systems is the gas tube protector. It consists of two metallic gaps spaced by a distance of 0.010 to 0.015 inch. The electrodes are enclosed in a sealed glass envelope containing a combination of gases at a low pressure. Such gaps offer higher current-carrying capability and longer life than do carbon block devices. However, the possibility of seal leakage and the consequent loss of protection has limited the use of these devices. Dual-gap gas tubes, also called three-electrode gas tubes, have been introduced to alleviate the problem of unbalanced breakdown as described in the preceding paragraph.

GE-MOV®II Varistors have properties that make them excellent candidates for telephone system protectors. These characteristics include tight tolerance, high reliability, high energy capability, and good clamping characteristics. The V130LA20A GE-MOV®II Varistor, for instance, is capable of handling a peak transient current of 6000A (8/20 μs pulse) and dissipating up to 50J of energy. The 6000 A current surge would result in the voltage across the varistor being clamped at a maximum of 600V. A 1000A pulse would be clamped to less than 420V, yet ring voltage peaks of 180V would not be affected by this varistor.

### *5.6.2 Secondary Protection*

Modern solid state communications circuitry can be damaged even if the primary protection is working normally. It is often advisable to provide a secondary protection system to further reduce the voltage transient. As shown in Figure 5.7, the secondary protection removes the over-voltage spike which is passed by the primary protector.

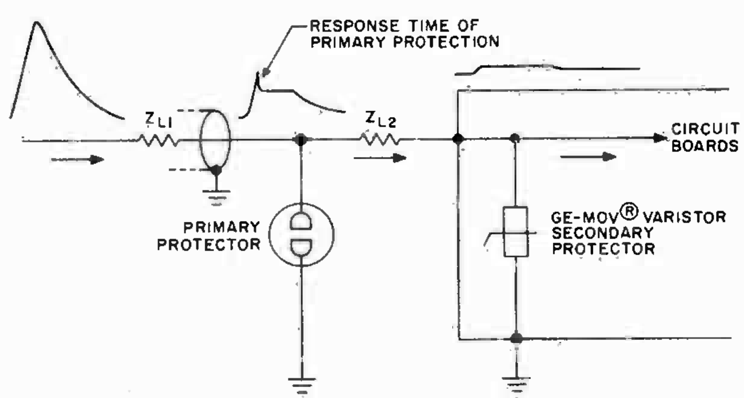



FIGURE 5.7: SECONDARY PROTECTION

In most installations the length of conductor between the primary protector and the telephone circuit boards is greater than 25 feet. The impedance ($Z_{L2}$) presented by this length of wire to most lightning-induced transient voltages will insure that the primary protector will operate first and the secondary protector will not be exposed to the full surge. In the rare cases where a power cross occurs, the varistor may fail, but it will still perform its assigned task of protecting the circuit board. Because its failure mode is a short circuit it will blow the system fuses. Usually the probability of a power cross is so low that the replacement of a damaged varistor is an acceptable alternative to repairing a damaged circuit board.

## 5.7 POWER LINE TRANSIENTS

For transients introduced into a telecommunications system through the power lines, the GE-MOV®II Varistor is a very effective suppressor. Properly selected, the varistor will not effect the normal operation of the line but will clamp heavy transient surges to an acceptable voltage level. Refer to Chapters 2 and 4 for information on the selection of a varistor suppressor.

## 5.8 RELAY CONTACT PROTECTION

Even the most modern telephone equipment requires the use of relays and other electromechanical switching devices. These devices are required to switch currents into inductive loads causing contact arcing, pitting, and noise generation. The GE-MOV®II Varistor is a useful suppressor for increasing contact life, improving reliability, and reducing noise. Chapters 1 and 4 contain selection information for contact protection applications by means of varistors.

## REFERENCES

1. Bennison, E., P. Ferland and A.J. Ghazi, "Lightning Surges in Open-Wire, Coaxial and Paired Cables," IEEE International Conference on Communications, June 1972.
2. Golde, R.H., "Lightning Currents and Related Parameters," Lightning, Vol. 1, Physics of Lightning, Chapter 9, ed. R.H. Golde, Academic Press, 1977.
3. Cianos, N. and E.T. Pierce, "A Ground Lightning Environment for Engineering Usage," Report No. 1, Stanford Research Institute, August 1972.
4. Boyce, C.F., "Protection of Telecommunication Systems," Lightning, Vol. 2, Lightning Protection, Chapter 25, ed. R.H. Golde, Academic Press, 1977.

Notes

chapter 6

# SUPPRESSION— AUTOMOTIVE TRANSIENTS

## 6.1 TRANSIENT ENVIRONMENT

The designer of electronic circuits for automotive applications must ensure reliable circuit operation in a severe transient environment. The transients on the automobile power supply range from the severe, high energy, transients generated by the alternator/regulator system to the low-level "noise" generated by the ignition system and various accessories (motors, radios, transceivers, etc.). Transients are also coupled to the input and output terminals of automotive electronics by magnetic and capacitive coupling in the wiring harness, as well as conductive coupling in common conductor circuits (especially the chassis "ground"). Steady state over-voltages may be applied by the circuit power supply due to the voltage regulator failure or the use of 24 V battery "jump" starts. The circuits must also be designed against the possibility of the battery being connected in reverse polarity. Circuits which drive inductive loads must be protected against the transients resulting from the energy stored in the field of the inductor. These transients can be defined from the load inductance and load current. Figure 6.1 summarizes the automotive power supply transients as documented by the Society of Automotive Engineers (SAE).[1]

| LENGTH OF TRANSIENT | CAUSE | ENERGY CAPABILITY<br>VOLTAGE AMPLITUDE | POSSIBLE FREQUENCY OF APPLICATION |
|---|---|---|---|
| Steady State | Failed Voltage Regulator | $\infty$<br>+ 18 V | Infrequent |
| 5 Minutes | Booster starts with 24V battery | $\infty$<br>$\pm$ 24 V | Infrequent |
| 4.5 ms to 0.1 s | Load Dump – i.e., disconnection of battery while at high charging rates. | $\geqslant$ 10 J<br>$\leqslant$ 125 V | Infrequent |
| $\leqslant$ 0.32 s | Inductive Load Switching Transient | < 1 J<br>-300 V to +80 V | Often |
| $\leqslant$ 0.20 s | Alternator Field Decay | < 1 J<br>-100 V to -40 V | Each Turn-Off |
| 90 ms | Ignition Pulse, Battery Disconnected | < 0.5 J<br>$\leqslant$ 75 V | $\leqslant$ 500 Hz<br>Several times in vehicle life |
| 1 ms | Mutual Coupling in Harness* | < 1 J<br>$\leqslant$ 200 V | Often |
| 15 $\mu$s | Ignition Pulse, Normal | < 0.001 J<br>3 V | $\leqslant$ 500 Hz<br>Continuous |
| | Accessory Noise | $\leqslant$ 1.5 V | 50 Hz to 10 kHz |
| | Transceiver Feedback | $\approx$ 20 mV | R. F. |

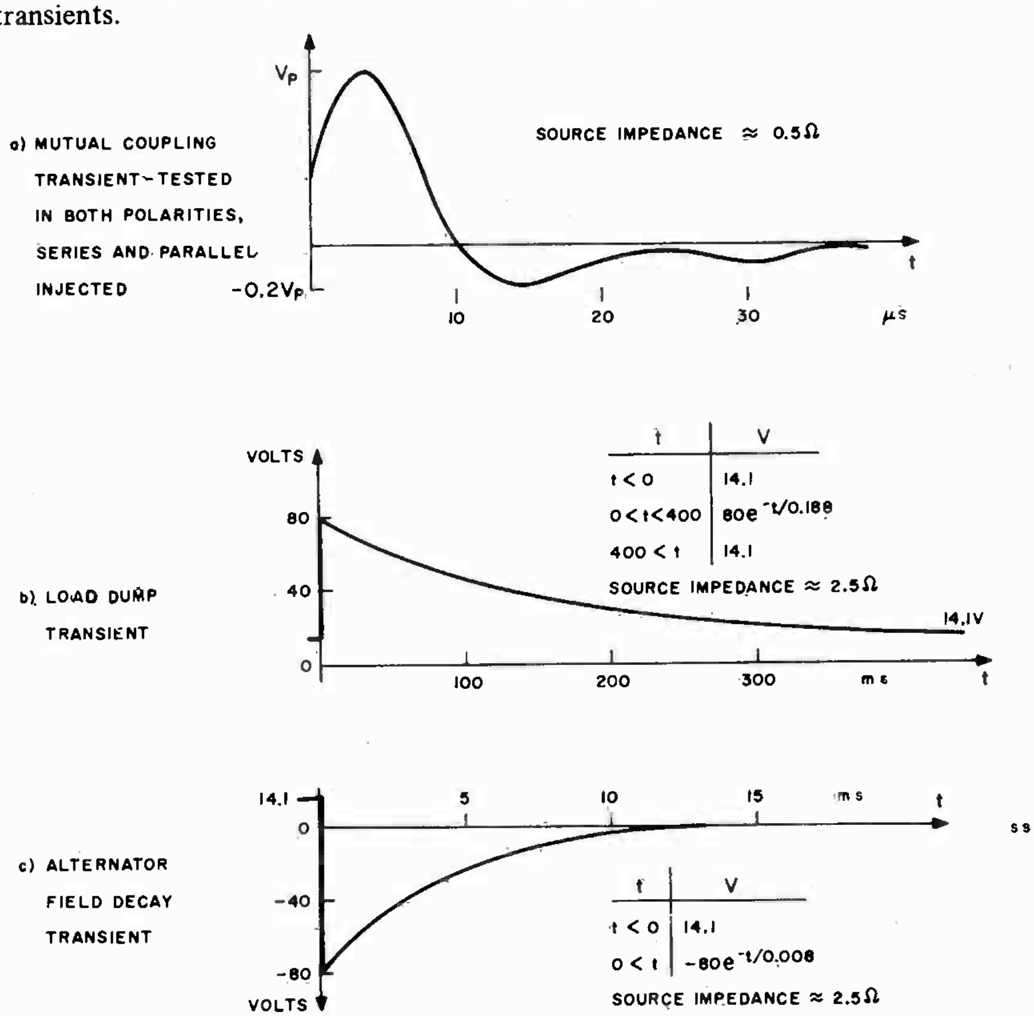
*These transients may be present on any wire in the vehicle.

FIGURE 6.1: TYPICAL AUTOMOTIVE SUPPLY TRANSIENT SUMMARY

Achieving maximum transient protection involves many factors. First, consequences of a failure should be determined. Current limiting impedances and noise immunity requirements need to be considered. The state of the circuit during the transient (on, off, unknown) and the availability of low-cost components capable of withstanding the transient are other factors. Considerable variation has been noted in the data gathered on automotive transients. Further, the interaction of other parts of the automotive electrical system with the circuit under transient conditions may require definition. The empirical evaluation of transient suppression using SAE-recommended test circuits,[2] is invaluable in many cases. Figure 6.2 illustrates the test waveform for the most common, high energy transients.

## 6.2 VARISTOR APPLICATIONS

To illustrate the procedures involved in designing transient protection for automotive electronics, two examples are provided. One example illustrates the protection of a solenoid driver circuit consisting of a logic integrated circuit with power transistor buffer; the second is the protection of an ignition circuit output transistor. These examples also illustrate the difference between protecting against random and repetitive transients. For random transients, energy and clamping vs. standby power dissipation are dominant constraints. For repetitive transients, transient power dissipation places an additional constraint on the choice of the suppression device. The solenoid driver protection circuit also illustrates the conflicting constraints placed on automotive transient suppressors by the low maximum voltage ratings of integrated circuits, the 24V jump start cycle and the load dump transients.




**NOTE:**
Amplitudes, impedances, and time constants vary, depending on the specific electrical system considered and the system loading.

**FIGURE 6.2: SEVERE TRANSIENT TEST WAVEFORMS (FROM SAE PROPOSED TEST PROCEDURES[2])**

### *6.2.1 Protection by a Central Suppressor*

A central suppressor is the principal transient suppression device in a motor vehicle. As such, it is connected directly across the main power supply line without any intervening load resistance. It must absorb the entire available load dump energy, and withstand the full jumpstart voltage. To be cost effective, it usually is best located in the most critical electronic module. Additional suppressors may be placed at other sites for further suppression or to control locally-generated transients.

The load dump energy available to the central suppressor in the worst case depends on variables such as the alternator size, the response of the sampled-data regulator system, and the loads that share the surge current and energy. Each application therefore tends to be somewhat different. However, by combining several applications, it is possible to construct a representative example. The key fact is the alternator surge power available to be dissipated in the suppressor. Figure 6.3 is suggested as a starting point for analysis. Since a peak surge power of 1600W is available, a suppressor with a clamping voltage of 40V would draw a peak current of 40A. The surge energy rating needed for the suppressor can be found by taking the integral of the surge power over time, and is a value of about 85 Joules. A jumpstart rating of 24V is also needed.

Evaluating central suppressor devices can be simplified with the aid of a load dump simulator as shown in Figure 6.4. The inductor L, which simulates the alternator inductance, slows the surge rise time but does not materially affect the analysis. In the absence of a suppressor or load, the output waveform will be similar to that of Figure 6.2b. If a suppressor is inserted, the operating characteristics can be estimated as follows:

$$\text{Assume } V_C = 40V, \text{ then } I_P = (80 - 40V)/R_1 = 40A$$

The energy W dissipated in the varistor may be estimated by: $W = 1.4\, V_C\, I_P \tau$ (see Section 4.1.2). The impulse duration $\tau$ of the surge current (see Figure 3.21) can be estimated from the delay time as:

$$\tau = 0.7\, RC_1$$

where R is the series-parallel combination of the effective resistance of the varistor and simulator components $R_1$ and $R_2$. To facilitate this calculation, assume that the effective resistance is given by $V_C/0.7\, I_P = 1.4$ohm. The delay time constant with the suppressor in the circuit then becomes:

$$RC_1 = \left(\frac{2.4 \times 7}{2.4 + 7}\right)(0.03) = 0.054\text{sec}$$

and the surge impulse duration:

$$\tau = 0.7\, RC_1 = 0.038 \text{ sec}$$

The deposited energy now can be estimated by:

$$W = 1.4\, V_C\, I_P \tau = (1.4)(40)(40)(.038) = 85 \text{ Joules}$$

Hence, the simulator produces unprotected and protected circuit conditions similar to those expected in the vehicle itself.

A suppressor with the needed high energy capability has been developed and already is in use. This improved GE-MOV®II Varistor model V24ZA50 has a load dump rating of 100 Joules. A narrow-tolerance selection can satisfy the clamping requirement of 40V maximum at 40A, with a jumpstart rating of 24V. The protective performance of this suppressor can be measured conveniently using the simulator circuit shown in Figure 6.4.

The suppressor's durability has been demonstrated by subjecting test specimens first to 10 load dumps about 30s apart. After readout, additional stresses were applied consisting of a single dump of 200J and a jumpstart overvoltage of 24V for 5 minutes. Clamping voltage, which is virtually invariant with temperature, was found to remain nearly unchanged by stress up to the single-surge destruction level of about 250J (see Figure 6.5). Standby current, the most sensitive parameter, remained well within limits as shown in Figure 6.6.

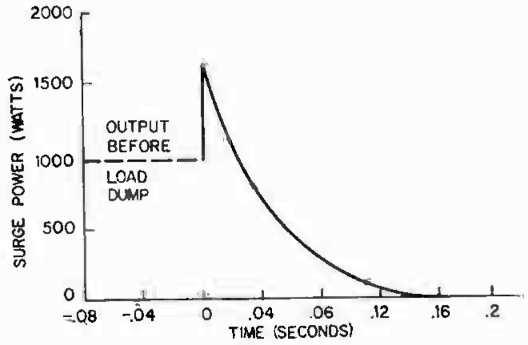



FIGURE 6.3: ALTERNATOR POWER OUTPUT INTO A CENTRAL SUPPRESSOR

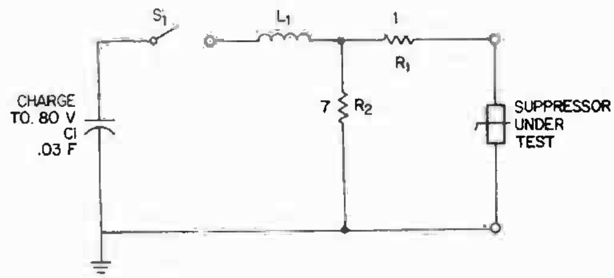



FIGURE 6.4: LOAD DUMP SIMULATOR CIRCUIT

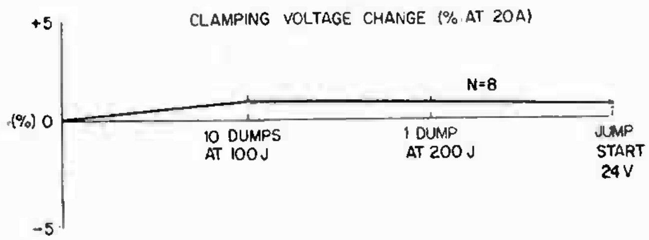



FIGURE 6.5: STABILITY OF CLAMPING VOLTAGE

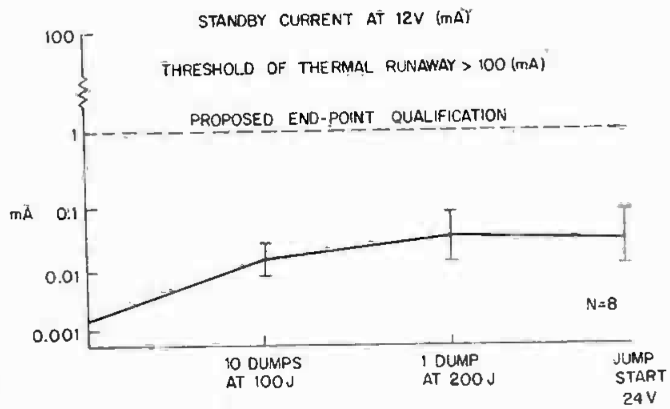
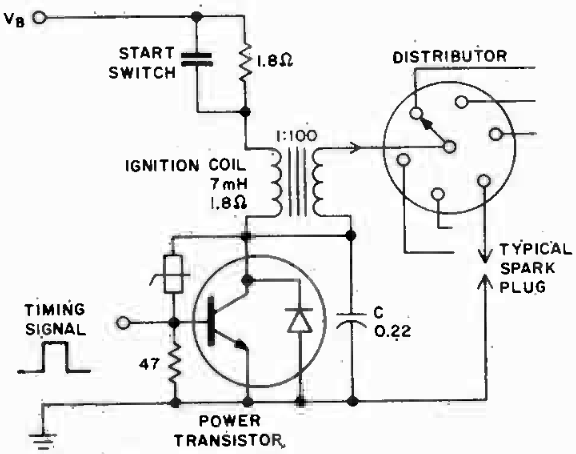



FIGURE 6.6: STABILITY OF STANDBY CURRENT

*6.2.2 Protection Of Electronic Ignition*

In the second example, the protection of the output power transistor in an electronic ignition circuit is analyzed. This power transistor performs the current switching function of mechanical distributor points in the usual Kettering ignition, thus avoiding the pitting, burning, and erosion mechanisms associated with the mechanical points. The ignition circuit is illustrated in Figure 6.7.

In normal operation, the coil primary current builds up when the power transistor is on, storing energy in the coil inductance. The power transistor is then switched off, and the voltage at the collector rises rapidly as the capacitor, C, charges. Transformer action causes the secondary voltage to rise until the spark plug reaches firing voltage, clamping the transistor collector voltage at a safe value. If a spark plug is fouled or disconnected, the collector voltage can rise until either the capacitor contains the stored energy (minus losses), or the transistor breaks down with resulting damage/failure. Since the capacitor is small, transfer of the stored energy of the coil to the capacitor would result in a very high voltage requiring transistor protection. A varistor can be used to turn the transistor on during the period of high voltage, thus dissipating the excess energy safely as heat. The constraints on varistor selection are: clamp voltage must be low enough to protect the transistor; clamp voltage must be high enough to not affect normal spark energy; the power dissipation (with two spark plugs disconnected) must be within varistor ratings for an 8-cylinder, 4-cycle engine at 3300 rpm (misfires at 55 Hz, average). The minimum spark voltage output required is 20,000V, which represents 200V at the transistor collector. The transistor has a breakdown voltage




| SYSTEM CONDITIONS | | |
|---|---|---|
| CONDITION | $V_B$ | START SWITCH |
| RUNNING | 12V TO 16V | OPEN |
| STARTING | 5V TO 12V | CLOSED |

OPERATING TEMPERATURE RANGE
-40°C TO +110°C

FIGURE 6.7: EXAMPLE 2
TYPICAL ELECTRONIC IGNITION CIRCUIT

rating of 400V with the 47Ω base emitter resistor and a current gain over 20. The base emitter on-state voltage, $V_{BE(ON)}$, is between 1.0 and 1.8V, and the collector to emitter saturation voltage is between 0.9 and 1.5V. The varistor clamp voltage range is determined by the 200V needed to supply minimum spark voltage and the 400V rating of the transistor. At 200V the varistor current must be less than:

$$V_{BE(ON)}/47\Omega = \frac{1V}{47\Omega} = 0.02A$$

to prevent unwanted transistor turn-on. The minimum varistor voltage at the 1 mA varistor specification point is found by solving the varistor voltage equation:

$$I = kV^{\alpha},$$

assuming a maximum $\alpha$ of 40. The result is 186V. The peak clamping current (at 400V – $V_{BE(MAX)}$) is found from the energy balance equation for the coil, using the peak coil current, $I_C$. $I_C$ maximum is analyzed under both start and run conditions to determine the worst case:

$$I_{C(start)} \leqslant \frac{12 - 0.9}{1.8\,\Omega} = 6.17A$$

and,

$$I_{C(run)} \leqslant \frac{16 - 0.9}{3.6\,\Omega} = 4.2A$$

The worst case coil current occurs with the start switch closed and will be less than 6.2A. The maximum peak coil current, $I_p$, when clamping is then:

$$\tfrac{1}{2}L\,I_c^{\,2} = \tfrac{1}{2}L\,I_p^{\,2} + \tfrac{1}{2}C\,V_p^{\,2}$$

and with a $V_p$ of 400V:

$$I_{p}{}_2 = I_C^{\,2} - 400^2\,C/L$$

results in 6.0A starting and 3.6A running. The varistor currents corresponding to this are:

$$I_p/h_{FE} + V_{BE}/47\Omega;$$

which gives 0.34A starting and 0.22A running. Peak varistor voltage must be less than:

$$400V - V_{BE} \quad \text{(i.e., 398V at 0.34A)}$$

The varistor power dissipation at 3300 rpm (55 pps), assuming a triangular current waveform with constant voltage and no losses, is found from coil energy balance:

$$\frac{1}{2} L (I_p)^2 = V_{MAX} \frac{I_p}{2} t$$

solving for t:

$$t = \frac{(7)(10^{-3})\ H\ (3.6A)}{400V} = 63\mu s$$

The varistor power dissipation is found to be:

$$V_{MAX.} \frac{I_P}{2} tf = 398V \left(\frac{0.22A}{2}\right)(63)(10^{-6})s\ (55pps) = 0.15W$$

Observations indicate that the losses in the coil and reflected secondary load will reduce this by half to about 75 mW. Using the 110°C ambient temperature derating factor of 0.53, it is found that a varistor of 0.15 W dissipation capability is required. The varistor parameters are now defined as $V_x$ of at least 186 V at 1 mA but less than 398 V at 0.34A and capable of at least 0.15W dissipation. The V220MA2A and V270MA4B both fit these requirements.

As these examples have illustrated, the use of the GE-MOV®II Varistor in automotive circuits for transient protection is both technically and economically sound. Design procedures are identical to the procedures used in the other environments. Experimental verification of the degree of protection can be made using standard waveforms reported by automotive engineering investigators.

## REFERENCES


1. Preliminary Recommended Environmental Practices for Electronic Equipment Design, Society of Automotive Engineers, 2 Pennsylvania Plaza, N.Y., N.Y. 10001.
2. Electromagnetic Susceptibility Test Procedures for Vehicle Components (except Aircraft), Society of Automotive Engineers, 2 Pennsylvania Plaza, N.Y., N.Y. 10001.

Notes

# chapter 7

# VARISTOR TESTING

## 7.1 INTRODUCTION

As with any device, metal oxide varistors possess a number of parameters which can be identified and measured in several ways. However, to minimize testing effort, the test parameters should be reduced to the essential few. Also, tests should be conducted in a standard way to assure correlation of measured values between maker and user. The essential varistor parameters are defined in Chapter 3. This chapter will detail the tests of these varistor parameters, describe suitable test methods using simplified test circuits, and list some available test equipment.

It should be noted that all tests are performed at 25°C, unless otherwise specified. Also, the test circuits and methods given herein are intended as a general guide only, and may not be generally applicable to the test equipment available to the user. Since the tests frequently entail high voltages and currents, the user must exercise appropriate safety precautions.

## 7.2 TEST OBJECTIVES

Varistor testing that would be undertaken by a user will depend considerably on prior knowledge of both the device and the application. Factors are the relative severity of the application (both electrical and environmental), the number of devices to be used, and the possible adverse effect of device misapplication or malfunction. Further considerations are resources available to the user and the economics of alternate uses of those resources versus more extensive varistor testing. Equipment makers designing transient protection into their products will have different objectives in varistor testing than a user simply adding a few varistors to existing equipment as a protective step. Finally, the user may have different test requirements depending on which point in the cycle of system design or component evaluation and procurement the testing is being done.

### *7.2.1 Engineering Evaluation*

For the original equipment maker, the process of evaluating and procuring a new component begins with an initial evaluation of the component itself. Typically, the circuit or systems engineer will obtain a few samples of the candidate component for evaluation in the prototype equipment design. He may seek recommendations from his component engineer in selecting from devices available in the market. It is important to focus on the key characteristics and ratings to determine if the component can perform as expected. Typically, varistor voltage, clamping voltage, standby current, insulation resistance, and capacitance of the samples should be measured according to the methods given in section 7.3. Assuming that a varistor type has been selected according to the design application examples of Chapter 4, the engineer obviously will verify that the component performs as expected when placed in the breadboard circuit. Also, it should be verified that variation of these parameters within their specification values are consistent with the application requirements. The surge current, or energy, and waveshape available in the circuit together with its frequency of occurrence should be measured or computed. These characteristics of the expected transients should then be checked against the pulse lifetime and the power dissipation ratings of the selected varistor type. Where suitable equipment is available, the rating of the varistor may be verified by injections of transients into the varistor alone or into the prototype circuit. See section 7.6 and 7.7 of this chapter for a discussion of transient test equipment and test waves.

### *7.2.2 Product Qualification*

In some user organizations, selection and evaluation of the varistor as a component may pass to a specialized group that evaluates component engineering and reliability. The final output of this evaluation will be a purchase specification detailing the mechanical and electrical requirements and ratings of the component, and possible approved sources for the part. A product qualification plan often will be used to detail the electrical and environmental tests to which a sample of the candidate component may be subjected and which it must pass in order to be approved. Frequently the manufacturer will be asked to supply supporting data for his in-house testing to supplement and minimize the qualification testing. The suggested electrical characteristics tests are (with appropriate conditions and limits): nominal varistor voltage, $V_N$; maximum clamping voltage, $V_C$; dc standby current, $I_D$ (optional, especially for ac applications); insulation resistance; and capacitance. These characteristics will be measured frequently in the component/equipment cycle thereafter, and care should be excercised that they are neither too many and complex nor too few to be meaningful to the application. Reliability requirements of operating conditions and expected life will sometimes be specified and usually tested for early in the qualification phase of the component. These tests may be performed at special conditions of environment or temperature to stress the component as proof of its intended use or design capability. A test to insure surge current withstand capability may be included in the qualification plan. This test must be carefully performed and specified (by using either 8 / 20$\mu$s or 10 / 1000$\mu$s waveshapes) in line with the recommendations of Chapter 3 and consistent with the pulse lifetime rating chart of the varistor selected. Other qualification tests may be used to ensure mechanical integrity, humidity resistance, solderability, and terminal/lead strength. These tests should be of a standard nature wherever possible to assure reproducibility.

### *7.2.3 Incoming Inspection*

Once the component has been qualified, the equipment maker will wish to verify that shipments received consist of correct parts at the expected quality level. Shipments will be sample-tested to assure correct markings, appearance, finish, and major or critical electrical parameters. It is especially desirable to prevent material with incorrect voltage characteristics from entering assembly operations so as to minimize troubleshooting and rework. For incoming inspection of GE-MOV®II Varistors, it is recommended that sample testing include nominal varistor voltage, $V_N$, tested against the minimum and maximum voltages specified on the purchase drawing/specification. Components below specification limits may lead to premature degradation or circuit failure. If above specification, they may not deliver the required protection from transients and may possibly allow other failures. Other electrical sampling tests frequently performed can include insulation resistance and capacitance. Tests such as maximum clamping voltage, $V_C$, and dc standby current, $I_D$, are usually checked only on a periodic audit basis.

### *7.2.4 Field Maintenance*

Field maintenance testing is done to verify that the varistor is still providing the intended protection function or, in the case of sensitive circuit applications, that the varistor has not degraded. Since the usual change of GE-MOV®II Varistor characteristics when over-stressed is toward lower resistance, it is very unlikely that the protection function will deteriorate unless the electrode system is damaged. The varistor should be physically examined for loose leads, charred or broken areas in the encapsulant, solder dribbles on the leads, or other evidence of overheating damage. If physically acceptable, the varistor may be tested electrically.

The nominal varistor voltage should be tested against the minimum limits for the model using the method described in section 7.3.1. If the varistor is open, short, or more than 10% outside either limit, it should be discarded. The dc standby current also should be measured. If more than twice the specification, the varistor is significantly degraded and should be discarded. If the varistor is physically sound and shows no evidence of degradation in these electrical tests, it is fully functional.

## 7.3 MEASUREMENT OF VARISTOR CHARACTERISTICS[1]

### *7.3.1 Nominal Varistor Voltage $V_N$*

This is measured at a dc test current, $I_N$, of 1mA for product models. A simplified circuit for instrumenting this test, shown in Figure 7.1, is suitable for varistors up through a rating of 300V RMS. Above the 300V RMS rating, a higher supply voltage will be needed. Resistor R1 has a dual purpose. In conjunction with the variable voltage supply, E1, it forms a quasi-current source providing up to 6mA when switch S1 is closed. Also, R1 is used as a current sensor to measure current flowing through the varistor-under-test. To use the circuit, the operator places switch S2 in position I and S3 into position

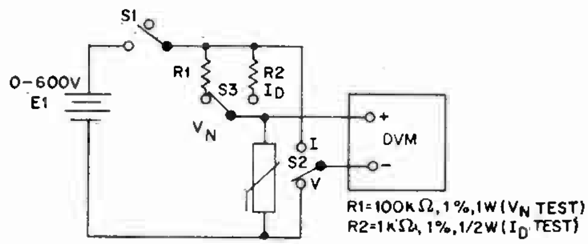



FIGURE 7.1: SIMPLIFIED CIRCUIT FOR VARISTOR VOLTAGE AND DC STANDBY CURRENT TESTS

$V_N$. A test device is then inserted into the socket and S1 is closed. E1 is then adjusted to obtain a reading of 100 ± 5V on the digital voltmeter. Approximately 1mA of current will be flowing in R1. When switch S2 is placed in position V, the varistor voltage will be indicated on the voltmeter. The values of R1 and E1 supply voltage can be scaled appropriately for other voltage-current test points.

If the varistor voltage test is implemented on automatic test equipment, a "soak" time of 20ms minimum should be allowed after application of test current before voltage measurement. This is necessary to allow varistor voltage to settle toward a steady-state value. Figure 7.2 illustrates the time response of a specimen varistor with a constant 1.0mA current applied. As can be seen, the varistor voltage initially may rise to a value up to 6% greater than final. With a 20ms or greater soak time, the measured value will differ by less than 2% from the steady-state value.

For varistor models that are commonly used on 60 Hz power lines, the $V_N$ limits may be specified for a 1.0mA peak ac current applied. If an ac test is preferred by the user, a schematic approach similar to that shown in Figure 7.1 is used, except an ac Variac™ is substituted for the dc power supply, and an oscilloscope is substituted for the voltmeter. This circuit is equivalent to that of a typical curve tracer instrument.

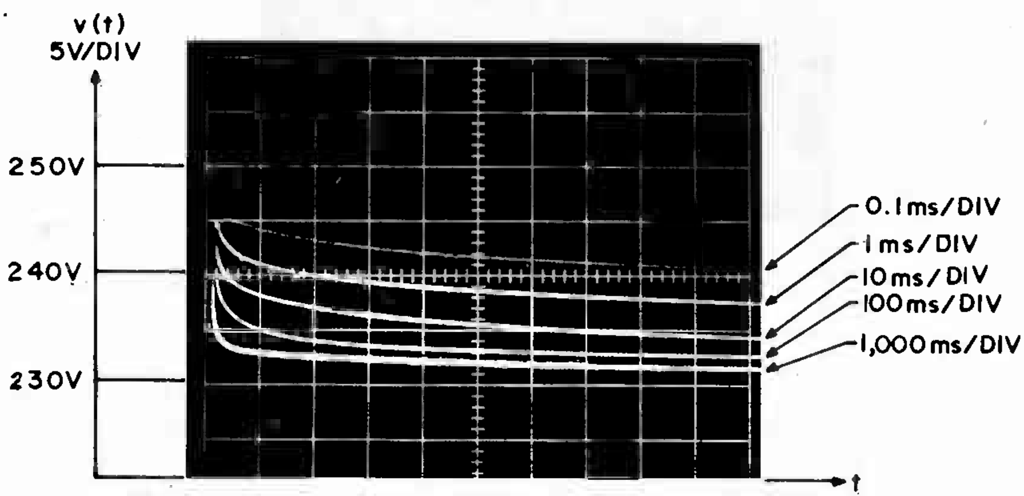



FIGURE 7.2: VOLTAGE-TIME V(T) CHARACTERISTICS OF A GE-MOV®II VARISTOR (V130LA10A) OPERATING AT A CONSTANT DC CURRENT OF 1.0mA

To avoid unnecessary concern over minor measurement anomalies, three behavioral phenomena of metal oxide varistors should be noted. First, it is normal for the peak varistor voltage measured with ac current to be about 2% to 5% higher than the dc value, as illustrated by Figure 7.3. This "ac-dc difference" is to be expected, since the one-quarter cycle period of a 60 Hz wave is much less than the 20ms minimum settling time required for dc readout.

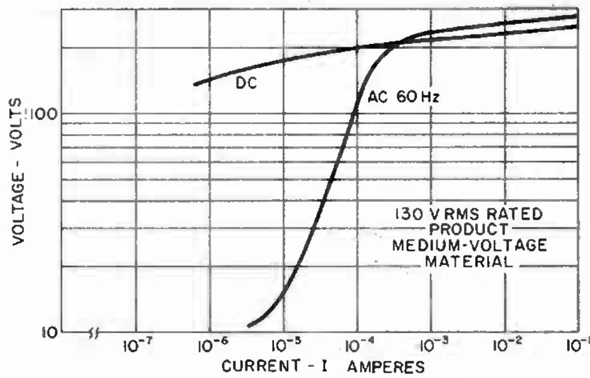



FIGURE 7.3: AC AND DC CHARACTERISTIC CURVES

Second, it is normal for the varistor voltage to increase slightly when first subjected to electrical current, as shown in Figure 7.4 This might be considered a "break-in" stabilization of the varistor characteristics. During normal measurement the voltage shift typically is less than 1%. This voltage shift is of little consequence for most measurement purposes but might be noticeable when viewing a DVM as in the test method of Figure 7.1. The visual DVM observation should be made shortly after power is applied, with measurement to not more than three significant figures.

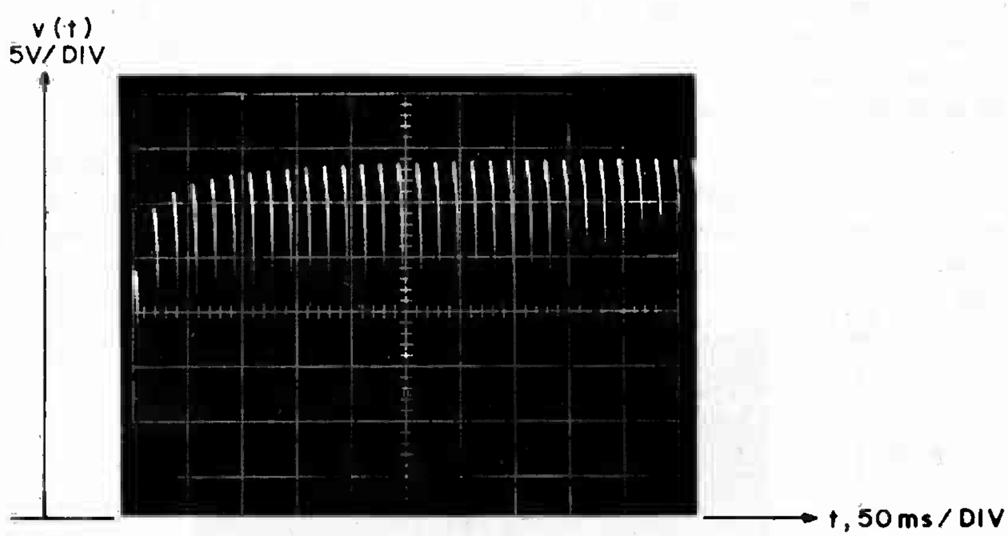


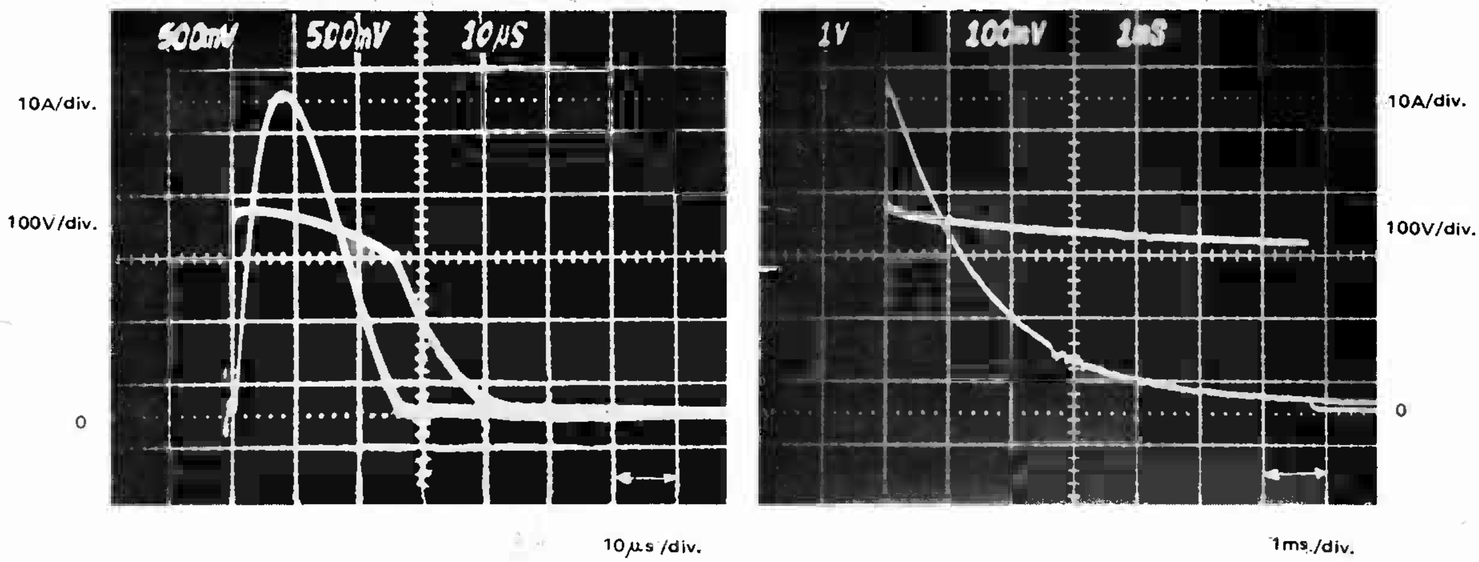

FIGURE 7.4: (V130LA10) VARISTOR VOLTAGE FOR THE INITIAL CYCLES OF 60 HZ OPERATION AT A PEAK CURRENT OF 1.0 mA

Third, it is normal for the varistor voltage-current characteristic to become slightly asymmetrical in polarity under application of dc electrical stress over time. The varistor voltage will increase in the same direction as the polarity of stress, while it will be constant or will decrease in the opposite polarity. This effect will be most noticeable for a varistor that has been subjected to unipolar pulse stresses or accelerated dc life tests. Therefore, to obtain consistent results during unipolar pulse or operating life tests, it is essential to provide a polarity identification for the test specimens. However, for initial readout purposes, this effect usually is insignificant.

### *7.3.2 Maximum Clamping Voltage, $V_C$*

As discussed in Chapter 3, the clamping voltage of a varistor is best defined in terms of the current impulse impressed on the varistor, rather than in terms of applied voltage. Two typical current impulses that may be used to define the varistor clamping voltage are the 8 / 20$\mu$s and the 10 / 1000$\mu$s pulses. Figure 7.5 shows typical varistor test waveforms for these two impulses.

The clamping voltage of a given model varistor at a defined current is related by a factor of the varistor voltage. Therefore, a test of the nominal varistor voltage against specifications may be sufficient to provide reasonable assurance that the maximum clamping voltage specification is also satisfied. When it is necessary to perform the $V_C$ test, special surge generators are required. For shorter impulses than 8 / 20$\mu$s, precautions must be observed to avoid an erroneous "overshoot" in the measurement of the clamping voltage. Section 7.6 gives general information on surge generators; a brief description of the "overshoot" effect follows.



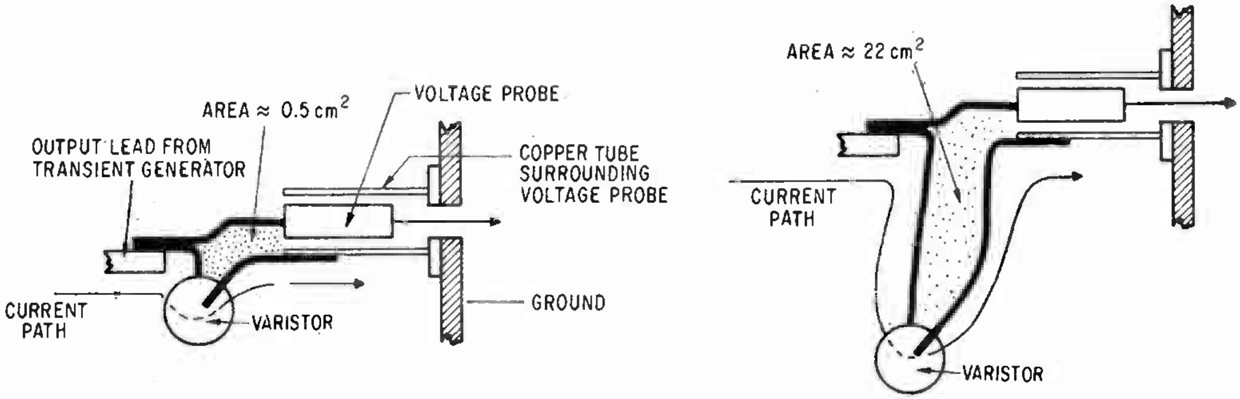

a) 8 / 20$\mu$s wave $I_P$ = 50A, $V_P$ = 315V

b) 10 / 1000$\mu$s wave $I_P$ = 50A, $V_C$ = 315V

FIGURE 7.5: TYPICAL CLAMPING VOLTAGE TEST WAVEFORMS
(GE-MOV®II VARISTOR TYPE V130LA10A)

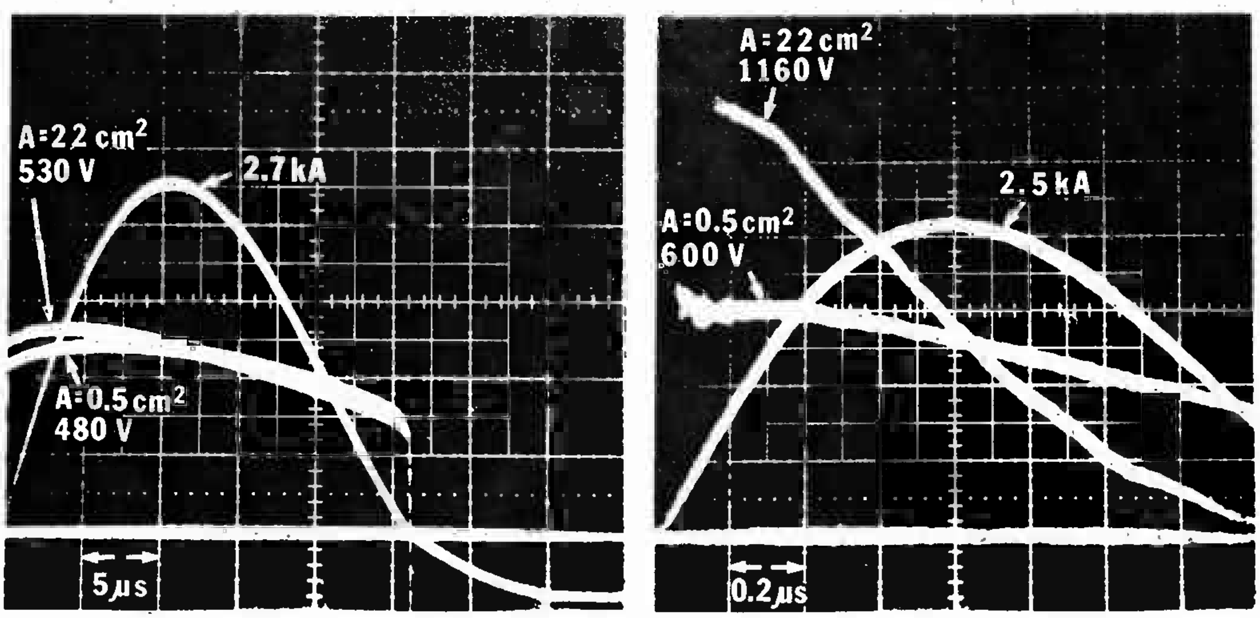
The GE-MOV®II Varistor specification sheets show the V-I characteristic of the devices on the basis of maximum voltage appearing across the device during a current pulse of 8 / 20$\mu$s. If current impulses of equal magnitude but faster rise are applied to the varistor, higher voltages will appear across the device. These higher voltages, described as "overshoot," are partially the result of an intrinsic increase in the varistor voltage, but mostly of the inductive effect of the unavoidable lead length. Therefore, as some applications may require current impulses of shorter rise time than the conventional 8$\mu$s, careful attention is required to recognize the contribution of the voltage associated with lead inductance.[1]

The varistor voltage, because of its nonlinearity, increases only slightly as the current amplitude of the impulse increases. The voltage from the lead inductance is strictly linear and therefore becomes large as high current amplitudes with steep fronts are applied. For that reason, it is impractical to specify clamping voltages achieved by lead-mounted devices with current impulses having rise times shorter than 0.5$\mu$s, unless circuit geometry is very accurately controlled and described.




a) Minimal Loop Area

b) Excessive Loop Area




c) Current Rise of 8μs

d) Current Rise of 0.5μs

**FIGURE 7.6: EFFECT OF LEAD LENGTH ON "OVERSHOOT"**

To illustrate the effect of lead length on the "overshoot," two measurement arrangements were used. As shown in Figures 7.6a and 7.6b, respectively, 0.5 cm$^2$ and 22 cm$^2$ of area were enclosed by the leads of the varistor and of the voltage probe.

The corresponding voltage measurements are shown in the oscillograms of Figures 7.6c and 7.6d. With a slow current front of 8μs, there is little difference in the voltages occurring with a small or large loop area, even with a peak current of 2.7kA. With the steep front of 0.5μs, the peak voltage recorded with the large loop is nearly twice the voltage of the small loop. (Note on Figure 7.6d that at the current peak, L di/dt = 0, and the two voltage readings are equal; before the peak, L di/dt is positive, and after, it is negative.)

Hence, when making measurements as well as when designing a circuit for a protection scheme, it is essential to be alert to the effects of lead length (or more accurately of loop area) for connecting the varistors. This is especially important when the currents are in excess of a few amperes with rise times of less than 1μs.

With reasonable care in maintaining short leads, as shown in Figure 7.6a, it is possible to describe the "overshoot" effect as an increase in clamping voltage relative to the value observed with

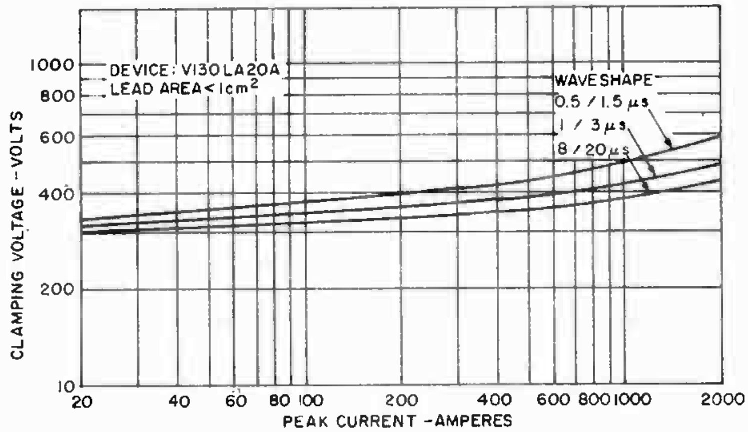



**FIGURE 7.7: TYPICAL "OVERSHOOT" OF LEAD-MOUNTED VARISTOR WITH STEEP CURRENT IMPULSES**

a 8 / 20$\mu$s impulse. Figure 7.7 shows a family of curves indicating the effect between 8 and 0.5$\mu$s rise times, at current peaks ranging from 20 to 2000A. Any increase in the lead length, or area enclosed by the leads, would produce an increase in the voltage appearing across the varistor terminals – that is, the voltage applied to the protected load.

### *7.3.3 DC Standby Current, $I_D$*

This current is measured with a voltage equal to the rated continuous dc voltage, $V_m$(dc), applied across the varistor. The circuit of Figure 7.1 is applicable where current sensing resistor R2 has a value of 1000Ω. The test method is to set the voltage supply, E1, to the specified value with switch S1 closed and S2 in the V. position. Then S2 is placed in position I and S3 in position, $I_D$. S1 is then opened, the test device is inserted in the test socket, and S1 is closed. The DVM reading must be converted into current. For example, if a maximum standby current of 200$\mu$A is specified, the maximum acceptable DVM reading would be 0.200V.

The measurement of dc standby current can be sensitive to the device behavioral phenomena of "break-in" stabilization and polarization of the V-I characteristics, as described in Section 7.3.1. If the device under test has prior unipolar electrical history, polarity indicators should be observed and test values interpreted accordingly.

The value of dc standby current also can be sensitive to ambient temperature. This is unlike varistor characteristics measured at currents of 1mA or greater, which are relatively insensitive to ambient temperatures. With $V_M$(dc) around 85% of $V_N$, Figure 7.8 shows the typical dc standby

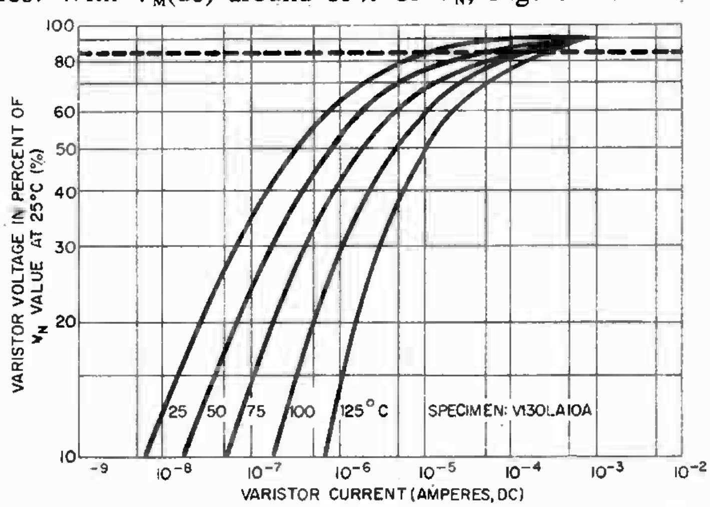



**FIGURE 7.8: TYPICAL TEMPERATURE DEPENDENCE OF DC STANDBY CURRENT VARISTOR TYPE – V130LA10A**

current of a model V130LA10A varistor in the order of 10 or 20$\mu$A at room temperature. $I_D$ increases to about 80$\mu$A at 85°C, the maximum operating temperature without derating.

### *7.3.4 Capacitance*

Since the bulk region of a GE-MOV®II 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®II Varistor is a function of its voltage and energy ratings. The voltage rating is determined by device thickness, and the energy rating is directly proportional to volume.

GE-MOV®II Varistor capacitance can be measured through use of a conventional capacitance bridge and is found to vary with frequency, as shown in Figure 7.9. Typically, capacitance measurements are made at 1 MHz. Dissipation factor also is frequency-dependent, as shown in Figure 7.10.

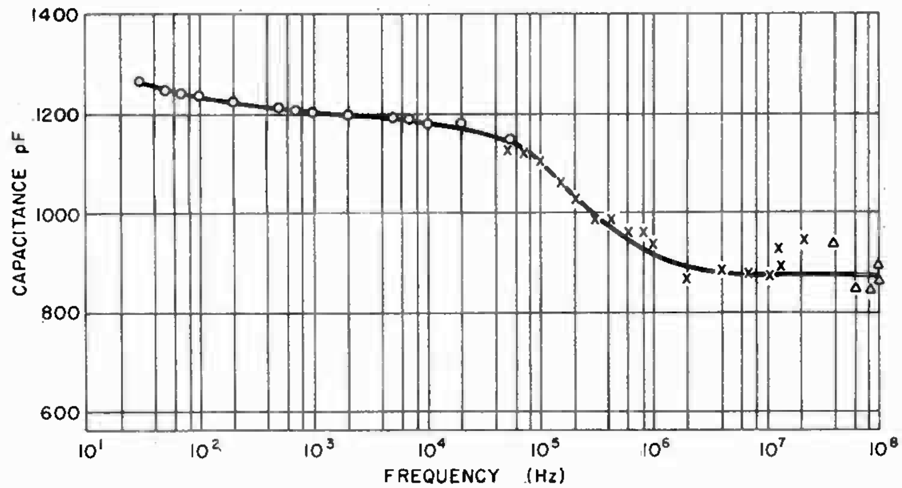



**FIGURE 7.9: CAPACITANCE VARIATION WITH FREQUENCY**

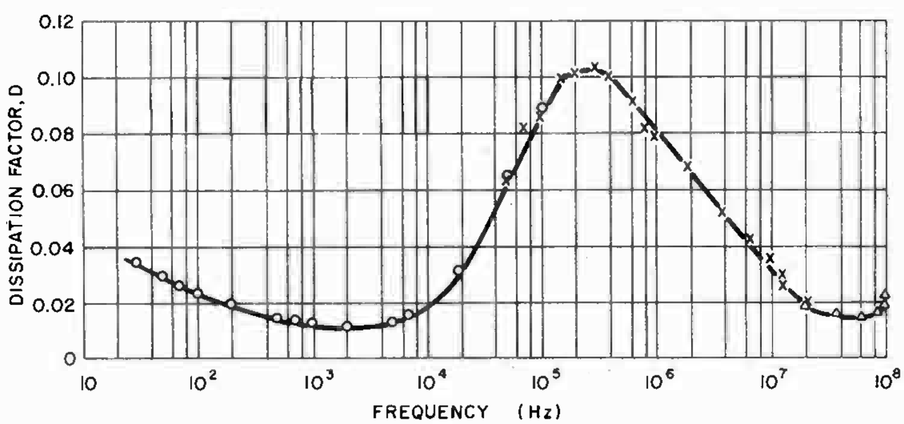



**FIGURE 7.10: DISSIPATION FACTOR VARIATION WITH FREQUENCY**

When measured with a dc bias, the capacitance and dissipation factor show little change until the bias approaches or exceeds the $V_N$ value. Furthermore, the capacitance change caused by an applied voltage (either dc or ac) may persist when the voltage is removed, with the capacitance gradually returning to the prebias value. Because of this phenomenon, it is important that the electrical history of a GE-MOV®II Varistor be known when measuring capacitance.

### *7.3.5 Miscellaneous Characteristics*

A number of characteristic measurements can be derived from the basic measurements already described, including the nonlinear exponent (alpha), static resistance, dynamic impedance, and voltage clamping ratio. These characteristics are derived characteristics in the sense that they are found by computation per the defining equations given in Chapter 3. The data, however, may be obtained by measurement methods similar to those already given for nominal varistor voltage and maximum clamping voltage. These miscellaneous characteristics may be useful in some cases to enable comparison of GE-MOV®II Varistors with other types of nonlinear devices, such as those based on silicon carbide, selenium rectifier, or zener diode technologies.

## 7.4 VARISTOR RATING ASSURANCE TESTS

### *7.4.1 Continuous Rated RMS and DC Voltage [$V_m$(ac) and $V_m$(dc)]*

These are established on the basis of operating life tests conducted at the maximum rated voltage for the product model. These tests usually are conducted at the maximum rated ambient operating temperature, or higher, so as to accelerate device aging. Some test results are given in Chapter 8. Unless otherwise specified, end-of-lifetime is defined as a degradation failure equivalent to a $V_N$ shift in excess of $\pm 10\%$ of the initial value. At this point the device is still continuing to function. However, the varistor will no longer meet the original specifications.

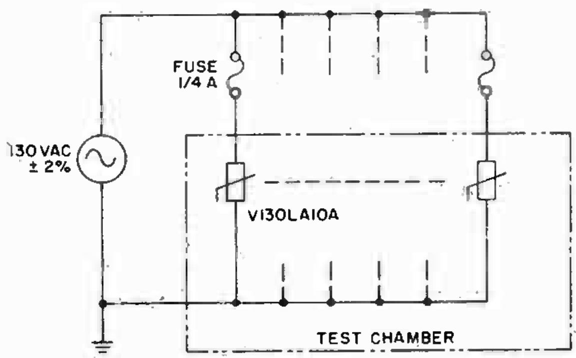



**FIGURE 7.11: SIMPLIFIED OPERATING LIFE TEST CIRCUIT**

A typical operating life test circuit is shown in Figure 7.11. If the varistor is intended principally for a dc voltage application, then the ac power source should be changed to dc. It is desirable to fuse the varistors individually so testing is not interrupted on other devices if a fuse should blow. The voltage sources should be regulated to an accuracy of $\pm 2\%$ and the test chamber temperature should be regulated to within $\pm 3$°C. The chamber should contain an air circulation fan to assure a uniform temperature throughout its interior. The varistors should receive an initial readout of characteristics at room ambient temperature – i.e., 25 ±3°C. They should then be removed from the chamber for subsequent readout at 168, 500, and 1000 hours. A minimum of 20 minutes should be allowed before readout to ensure that the devices have cooled off to the room ambient temperature.

### *7.4.2 Transient Peak Current, Energy, Pulse Lifetime, and Power Dissipation Ratings*

Special surge generator equipment is required for testing. Data on commercially available equipment is given in Table 7.3, and an example test circuit is described in Section 7.6. Since high energy must be stored at high voltages to perform these tests, especially on larger sizes of GE-MOV®II Varistors, the equipment is necessarily expensive and must be operated using adequate safety precautions.

The peak current rating, $I_{tm}$, of GE-MOV®II Varistors is based on an 8 / 20$\mu$s test impulse waveshape. The specifications inlcude a maximum single value in the ratings table. A pulse lifetime rating graph defines the peak current rating for longer impulse duration as well, such as for a 10 / 1000$\mu$s wave. A family of curves defines the rated number of impulses with a given impulse duration and peak current. End-of-lifetime is as previously defined, $\pm 10\%$ shift in the nominal varistor voltage.

Energy rating, $W_{tm}$, is defined for a 10 /1000$\mu$s current impulse test wave. This waveshape has been chosen as being the best standard wave for tests where impulse energy, rather than peak current, is of application concern. A direct determination of energy requires that the user integrate over time the product of instantaneous voltage and current. Such integration is cumbersome to perform, and the integration feature is not generally available in surge generation equipment.

However, peak voltage and current are readily measured with available equipment. Therefore, the energy rating can be tested indirectly by applying the rated peak impulse current of a 10 / 1000$\mu$s waveshape to the test specimen. Then, the energy dissipated in the varistor can be estimated from the known pulse waveshape. For a 10 / 1000$\mu$s waveshape the approximate energy is given by the expression $E = 1.4 V_C I \tau$. See Chapter 4 for a discussion of energy dissipation for various waveshapes.

For example, a model V130LA10 varistor has a single pulse rating for a 10 / 1000$\mu$s impulse waveshape of about 75A peak, and a maximum clamping voltage at 75A of about 360V. Thus, the computation of estimated energy dissipation is 38J.

The transient power dissipation rating, $P_{tam}$, is defined as the maximum average power of test impulses occurring at a specified periodic rate. It is computed as the estimated energy dissipation divided by the test pulse period. Therefore, varistors can be tested against this rating by applying two or more impulses at rated current with a specified period between pulses. For example, a model V130LA10A varistor has a pulse lifetime rating of two 10 / 1000$\mu$s test impulses with a peak current of about 65 A. The estimated energy dissipation per pulse computed as per the preceding example is about 30J. If a period of 50s is allowed after the first test pulse, the estimated average power dissipation can be computed as about 0.6W, which is the specification rating. It should be noted that GE-MOV®II Varistors are not rated for continuous operation with high-level transients applied. The transient power dissipation rating is based on a finite number of pulses, and the pulse lifetime rating of the varistor must be observed. See Figure 7.12

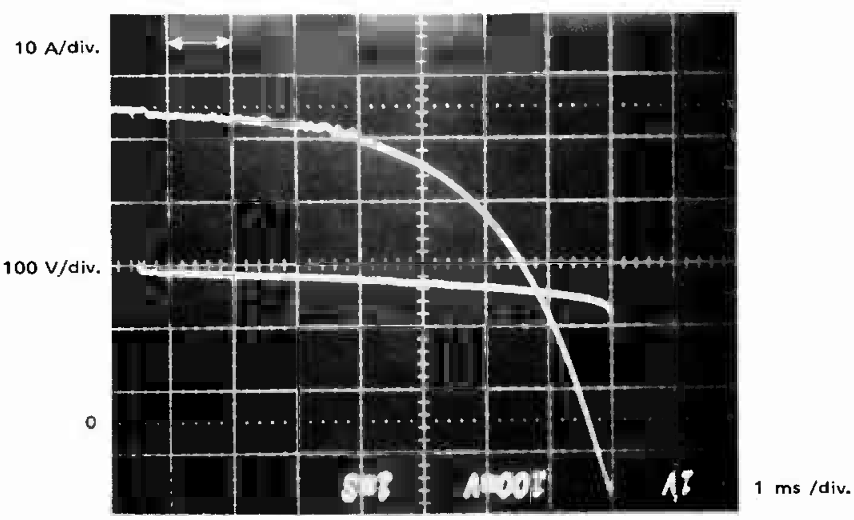



FIGURE 7.12: SURGE TEST WAVEFORMS

10 / 1000 $\mu$s WAVEFORM

Table 7.1 outlines a suggested program of testing to verify varistor transient and pulse lifetime ratings with a minimum of expensive, time-consuming testing. New specimens should be used for each test level and failure judged according to the specification criteria.

**TABLE 7.1**

**TESTING OF TRANSIENT CURRENT, ENERGY, PULSE LIFETIME, AND POWER DISSIPATION RATINGS**

| TEST PARAMETER | NO. PULSES @ RATED CURRENT (ALTERNATING POLARITY) | TEST WAVESHAPE (μs) | MINIMUM PULSE PERIOD (s) |
|---|---|---|---|
| Maximum Peak Current | 1 (same polarity as readout) | 8 / 20 | NA |
| Pulse/Energy Life, Power Dissipation | 2 | 10 / 1000 | 50 |
| Pulse Life | 10 | 8 / 20 | 25 |
| Pulse Life | 100 | 8 / 20 | 12 |

### *7.4.3 Continuous Power Dissipation*

Since GE-MOV®II Varistors are used primarily for transient suppression purposes, their power dissipation rating has been defined and tested under transient impulse conditions. If the devices are to be applied as threshold sensors or coarse voltage regulators in low power circuits, then a dissipation test under continuous power is more appropriate. This continuous power test will aid the user in determining if the device is suitable for his specific application.

A circuit for continuous power dissipation testing is shown in Figure 7.13. The dc power supply voltage should be set to a value of approximately twice the nominal varistor voltage of the product model under test. In that case, nearly constant power dissipation is maintained in the varistor. Since the circuit transfers nearly equal power to the series resistor and varistor-under-test, the series resistor value is simply chosen to achieve the test design value of power dissipation. In Figure 7.13 a nearly constant power dissipation of about 0.6W is obtained.

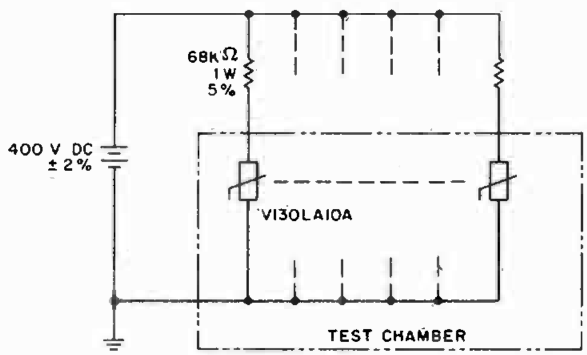



**FIGURE 7.13: CONSTANT POWER LIFE TEST CIRCUIT**

## 7.5 MECHANICAL AND ENVIRONMENTAL TESTING OF VARISTORS

### *7.5.1 Introduction*

Many tests have been devised to check the reliability of electronic components when subjected to mechanical and environmental stresses. Although individual equipment makers may specify their own tests on component purchase documents, these tests are often based on an equivalent MIL-STD specification. Therefore, it is convenient to summarize these tests in MIL-STD terms. Since the ratings of GE-MOV®II Varistors may vary with product series and model, the test conditions and limits should be as specified on the applicable detail specification.

GE-MOV®II Varistors are available in a high reliability series. This series incorporates most standard mechanical and environmental tests, including 100% pre-screening and 100% process conditioning. Details are provided in Chapter 9.

### *7.5.2 UL Recognition Tests*

GE-MOV®II Varistors have been tested by Underwriters Laboratories, Inc. (UL) and have been recognized as across-the-line components, varistor type, UL E75961. The tests were designed by UL and included discharge (withstand of charged capacitor dump), expulsion (of complete materials), life, extended life, and flammability (UL492) tests.

## 7.6 EQUIPMENT FOR VARISTOR ELECTRICAL TESTING

### *7.6.1 Introduction*

Most tests of GE-MOV®II Varistors can be performed with relatively simple circuits and inexpensive equipment on the laboratory bench. However, large users with versatile automatic test systems available may find it more economical to program these systems for the low-current varistor tests. As noted previously, medium or high-current impulse testing will require specialized test equipment. Table 7.3 is a partial listing of available test equipment and systems that can be used for varistor testing. It is intended as a guide only to illustrate the generic type of equipment offered commercially.

### *7.6.2 Impulse Generators*

A convenient method of generating current or voltage surges consists of slowly storing energy in a capacitor network and abruptly discharging it into the test varistor. Possible energy storage elements that can be used for this purpose include lines (lumped or distributed) and simple capacitors, depending on the waveshape desired for the test. Figure 7.14 shows a simplified schematic for the basic elements of an impulse generator.

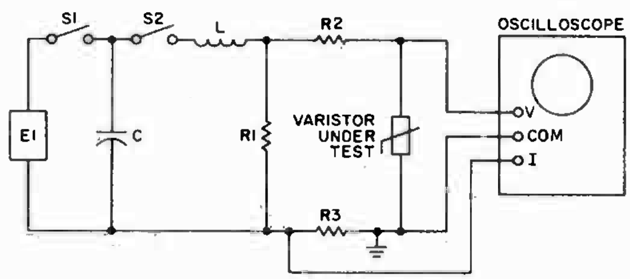



FIGURE 7.14: SIMPLIFIED CIRCUIT OF SURGE IMPULSE GENERATOR

The circuit is representative of the type used to generate exponentially decaying waves. The voltage supply, E1, is used to charge the energy storage capacitor, C, to the specified open-circuit voltage when switch S1 is closed. When switch S2 (an ignitron or a triggered gap) is closed, the capacitor, C, discharges through the waveshaping elements of the circuit into the suppressor device under test. With capacitances in the order of 1$\mu$F to 10$\mu$F and charging voltages of 10kV to 20kV, the typical 8 / 20$\mu$s or 10 / 1000$\mu$s impulses can be obtained by suitable adjustment to the wave shaping components L, $R_1$, and $R_2$, according to conventional surge generator design.[2,3,4,5]

### *7.6.3 Measurement Instrumentation*

Transient measurements include two aspects of varistor application: (1) detection of transients to determine the need for protection, and (2) laboratory measurements to evaluate varistor performance. Transient detection can be limited to recording the occurrence of transient overvoltages in a particular system or involve comprehensive measurements of all the parameters which can be identified. Simple detection can be performed with peak-indicating or peak-recording instruments, either commercial or custom-made. Table 7.4 gives a partial listing of such instruments.

Laboratory instruments and field detection with comprehensive instrumentation can involve substantial investment, primarily associated with oscilloscopes, cameras, and calibrated sensors. A detailed discussion of these systems is beyond the scope of this manual; rather, the major oscilloscope manufacturers should be consulted, as well as the available literature.

**TABLE 7.3 — AVAILABLE EQUIPMENT FOR VARISTOR TESTING***

| TYPE & MANUFACTURER | MODEL | FEATURES |
|---|---|---|
| **High Voltage Test Systems**<br>E. Haefely and Co., Ltd.<br>Basel, Switzerland<br>U.S. Distributor:<br>Rhode & Schwarz Sales Inc.<br>14 Gloria Lane<br>Fairfield, NJ 07006 | P12/P6R<br>7CL-6/P6T<br>P35/CP70<br>CP360<br>CP1500 | Voltage Surges: 1.2/50, 0.5/700, 10/700, 100/700, 0.5/100kHz and NEMP up to 35kV<br>Current Surges: 8/20, 20/60, 10/1000$\mu$s up to 50 kA |
| **Storage Curve Tracer**<br>Tektronix, Inc.<br>P.O. Box 500<br>Beaverton, OR 97005<br>315-455-6661 | 577/177<br>(Also can use 576) | AC & dc tests up to 1600V peak, with safety interlock, storage display mode |
| **Auto Capacitance Bridge**<br>General Radio<br>300 Baker Ave.<br>Concord, MA 01742<br>617-369-4400 | 1687 | 1MHz test frequency, 3 measurements/sec, .01% accuracy, digital display, programmable control, IEEE testing. |
| **Varistor Test System**<br>Mastech, Inc.<br>478 E. Brighton Ave.<br>Syracuse, NY 13210<br>315-478-3133 | 222F<br>342 | 0-2000V, up to 10mA dc, 100 mA pulse, digital readout, front panel programming<br>0-100kV at 10A. Front panel programming. IEEE Standard 4888 |
| **Semiconductor Test Systems**<br>Teradyne, Inc.<br>183 Essex St.<br>Boston, MA 02111<br>201-334-9470 | T57<br>or<br>Z27 | 0-1200V, up to 10mA, computer operated, line printer output, multiple test stations, data analysis software, tape cartridge |
| **Pulse Generator**<br>Cober Electronics, Inc.<br>7 Gleason Ave.<br>Stamford, CT 06902<br>703-327-0003 | 605P | 2.2kV, 20kW peak power, pulses 0.3$\mu$s — 10ms, variable PRF or can amplify external input |
| **Surge Generator & Monitor**<br>KeyTek Instrument<br>220 Grove St.<br>Box 109<br>Waltham, MA 02154<br>617-272-5170 | System 1000, including Model 424<br>Model 711 | 6kV, up to 5000A, further expandable, selectable waveshapes (8 / 20, 10 / 1000, etc.), measures & displays peak V & I across test device.<br>Peak biased differential high voltage probe. IEEE testing. |
| **Pulse Generator**<br>Velonex<br>Varian Div.<br>560 Robert Ave.<br>Santa Clara, CA 95050<br>408-727-7370 | 360 | 2.5kV, 10A, pulses, up to 300$\mu$s wide, variable PRF, variable rise-fall available, plug-ins for higher peak I |

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

TABLE 7.4 — AVAILABLE TRANSIENT DETECTION EQUIPMENT*

| MANUFACTURER | MODEL | FEATURES |
|---|---|---|
| **Storage Oscilloscopes:** | | |
| Tektronix<br>P.O. Box 500<br>Beaverton, OR 97005 | 466<br>7834 | 100MHz, 3000 div/μs speed, portable<br>Multimode storage, 400MHz, 5500 div/μs |
| **Peak Recording Instruments:** | | |
| Micro-Instrument | Memory Voltmeter Model 5203 | 20MHz, records, displays voltage levels up to 2kV |
| Bermar<br>Box 1043<br>Nashua, NH 03061<br>603-888-1300 | Memory Voltmeter MVM-108 | Displays peak voltage, >0.5μs pulses up to 8kV |
| Dranetz<br>2285 So. Clinton Ave.<br>So. Plainfield, NJ 07080<br>201-287-3680 | Model 606 | Prints out peak voltages, >0.5μs duration pulse |
| KeyTek<br>Box 109<br>Waltham, MA 02154<br>617-272-5170 | 424 Surge Generator & Monitor | Displays peak voltages, >0.5μs duration |
| Industronic<br>115 Pleasant St.<br>Mellas, MA 02054<br>617-376-8146 | Zap Trap | Measures peak voltages, >2μs duration |
| Trott<br>9020 Wehrle Dr.<br>Clarence, NY 14031<br>413-634-8500 | TR745A | Detects 0.3μs pulses, up to 3000V |

## 7.7 TEST WAVES AND STANDARDS

The varistor test procedures described in this chapter have been established to ensure conformity with applicable standards,[6] as well as to reflect the electromagnetic environment of actual circuits[7] which need transient protection. Chapter 1 presented an overview of the transient environment; some additional background is presented in this section concerning generally accepted assumptions about this environment.

### *7.7.1 Test Waves*

A number of test waves have been proposed, to be applied to various electronic "black boxes," in order to demonstrate capability of survival or unimpeded performance in the environment. Table 7.5 is a partial listing of these test waves presented to illustrate the variety of proposals rather than to be an exhaustive listing.

TABLE 7.5 – PARTIAL LISTING OF EXISTING OR PROPOSED TEST WAVES

| ORIGIN | DESCRIPTION | | TYPICAL APPLICATION |
|---|---|---|---|
| | WAVESHAPES | AMPLITUDE | |
| ANSI, IEC. | • 1.2 / 50$\mu$<br>• 8.0 / 20$\mu$s | Specified voltage<br>Specified Current | Power apparatus |
| IEEE Std. 472<br>Guide for Surge Withstand Capability (SWC) | • 1.25MHz repetitive at 60Hz<br>• 6$\mu$s decay to 50%<br>• 150$\Omega$ source impedance | 2.5kV Peak | Low-voltage ac circuits and control lines in substation equipment |
| IEEE Std. 587-1981<br>Guide on Surge Voltage in Low Voltage ac Power Circuits | • .5$\mu$s - 100kHz<br>• 1.2 / 50$\mu$s voltage<br>• 8 / 20$\mu$s current | Dependent on location | Low-voltage ac circuits and signal lines. |
| Ground Fault Interrupters | • 0.5$\mu$s rise<br>• 100kHz ring<br>• 2nd peak $\geqslant$60% first<br>• 50$\Omega$ source impedance | 3kV and 6kV | High impedance circuit of ground fault interrupters. |
| IEEE Std. 465.1<br>Test Specifications for Gas Tube Surge Protective Devices | Three requirements:<br>• 10 / 1000$\mu$s current<br>• 8 / 20$\mu$s current<br>• Linear voltage ramp of 100, 500, 5000, 10,000 V/$\mu$s until spark-over | <br>50 to 500A<br>5 to 20kA | Telephone protectors |
| FCC Docket 19528 | • Metallic<br>– 10 / 560$\mu$s<br>– 100A short-circuit current<br>• Longitudinal<br>– 10 / 160$\mu$s<br>– 200A short-circuit current | 800V Peak<br><br>1500V Peak | Communications equipment |
| FCC Section 68.302<br>Title 47, Telecommunications | • 2 / 10$\mu$s<br>– 1000 A short-circuit capability | 2500V Peak | Line-powered communication equipment |
| Rural Electrification Administration Spec. PE-60 | • 10 / 1000$\mu$s voltage<br>• 100V/$\mu$s rise | 3$\sigma$ of Protector level | Telephone electronics |
| Nuclear Electromagnetic Pulse (NEMP) | • Rectangular pulse 3 ns to 10$\mu$s<br>• Damped sinewave $10^1$ to $10^3$ Hz | 0.1 to 1000A<br><br>1.0 to 100A | Evaluation of components |
| NASA Space Shuttle | • Damped sinewave 125 kHz<br>• Unidirectional<br>– 2 / 100$\mu$s<br>– 300 / 600$\mu$s | $E_{OC}$ – 50V<br>$I_{SC}$ – 10A<br>$E_{OC}$ – 50V<br>$I_{SC}$ – 10A<br>$E_{OC}$ – 0.5V<br>$I_{SC}$ – 5A | Space Shuttle electronics |
| MIL-STD-704 | • Envelope specified, max. duration 50$\mu$s | 600V Peak | Military aircraft power |

A proposal also has been made to promote a transient control level concept[5] whereby a *few* selected test waves could be chosen by common agreement between users and manufacturers. The intent being that standard test waves would establish certain performance criteria for electronic circuits, without resorting to a multiplicity of test waves, each attempting to simulate a particular environment.

*7.7.2 Source Impedance*

The effective impedance of the circuit which introduces the transient is an extremely important parameter in designing a protective scheme. Impedance determines the energy and current-handling requirements of the protective device.

Historically, the approach to transient withstand capability was to apply a voltage wave to a device and to ascertain that no breakdown occurred. Typically, the device offered high impedance to the impulse, so that no significant current would flow (unless breakdown occurred), and the source impedance was unimportant. But if a transient suppressor is applied, especially a suppressor of the energy-absorbing type, the transient energy is then shared by the suppressor and the rest of the circuit, which can be described as the "source."

As in the case of waveshapes, various proposals have been made for standardizing source impedances. The following list summarizes the various proposals intended for ac power lines:

1. The Surge Withstand Capability (SWC) standard specified a 150 Ω source.
2. The Ground Fault (UL-GFCI) standard is 50 Ω source.[11]
3. The Transient Control Level (TCL) proposals of Martzloff et al[7] include a 50 Ω resistor in parallel with a 50 $\mu$H inductor.
4. The installation category concept of IEEE Standard 587-1980 implies a range of impedances from 1 to 50Ω as the location goes from outside to inside.
5. The FCC regulation for line-connected telecommunication equipment implies a 2.5Ω source impedance. However, the requirement of the FCC is aimed at ensuring a permanent "burning" of a dielectric puncture and does not necessarily imply that the actual source impedance in the real circuits is 2.5Ω.
6. There is no agreement among the above proposals on a specific source impedance. Examining the numbers closer, one can observe that there is a variance between 2.5 ohms to about 50 ohms. Going back to IEEE Standard 587 — by using the OCV (open circuit voltage) and SCI (short circuit current) for the different location categories, one can calculate a source impedance.

Any practical power circuit will always have some finite impedance due to the resistance and inductance of the power line and distribution transformer. Figure 7.15 shows representations of the impedance between line and ground on typical 120 V and 220 V systems in residential systems.

The impedance of industrial or commercial systems generally supplied by underground entrances, or a separate substation of relatively large kVA rating, tends to be low, and the injection of any lightning transients occurs at a remote point. This results in lower transient peaks than those that can be expected in residential circuits, but the energy involved may be, in fact, greater. Therefore, transient suppressors intended for industrial use should have greater energy-handling capability than the suppressors recommended for line-cord-powered appliances.

Clearly, the industry standards have not been able to agree on a single value of the source impedance, for several reasons. When a transient suppressor is being selected for a particular application, there is a need for engineering judgment based on a knowledge of the function, and the capability of the device.

| | |
|---|---|
| CATEGORY A RING WAVE | 6kV / 200A = 30Ω |
| CATEGORY A IMPULSE | 10kV / 10kA = 1Ω |
| CATEGORY B RING WAVE | 6kV / 500A = 12Ω |
| CATEGORY B IMPULSE | 6kV / 3kA = 2Ω |

FIGURE 7.15: SOURCE IMPEDANCE AT DIFFERENT LOCATION CATEGORIES IN LOW VOLTAGE AC SYSTEMS (TO 600V).

## REFERENCES


1. Fisher, F.A., "Overshoot — A Lead Effect in Varistor Characteristics," Report 78CRD, General Electric, Schenectady, N.Y., 1978.
2. Heller, B. and A. Veverka, *Surge Phenomena in Electrical Machine*, ILIFFE Books Ltd., London, 1968.
3. Greenwood, Allen, *Electrical Transients in Power Systems,* Wiley Interscience, New York, 1971.
4. Craggs, J.D. and J.M. Meek, *High Voltage Laboratory Techniques,* Buttersworth Scientific Publications, London, 1954.
5. Martzloff, F.D., *"Transient Control Level Test Generators,"* Report 77CRD241, General Electric, Schenectady, N.Y., 1977.
6. Test Specifications for Varistor Surge-Protective Devices, IEEE Std. C62.33, 1982
7. Martzloff, F.D., and F.A. Fisher, "Transient Control Level Philosophy and Implementation — The Reasoning Behind the Philosophy," 77CHI224-5EMC, Proceedings of the 2nd Symposium on EMC, Montreux, June 1977.
8. *"Standard for Safety: Ground Fault Circuit Interrupters,"* UL943, Underwriters Laboratories, May 12, 1976.
9. "Longitudinal Voltage Surge Test #3," Code of Federal Regulations, Section 68.302(e), Title 47, Telecommunications.

chapter 8

# VARISTOR RELIABILITY

## 8.1 INTRODUCTION

The GE-MOV®II Varistor is a rugged, reliable voltage transient suppressor designed to improve the reliability of electronic systems. Proper system design, with the GE-MOV®II Varistor, as detailed in other parts of this manual, will clamp transient voltages to a level compatible with long-life of the electronic system. To assure GE-MOV®II Varistor reliability, General Electric performs extensive process and quality control monitoring. This is accomplished via a combination of 100%, periodic, and lot testing. Both parametric and reliability characteristics are controlled in this manner.

Every year, over 1.7 million device hours of maximum rating and accelerated reliability test data is accumulated. In addition, a continuous product improvement research program is in effect to provide the user with an optimal product. As a result of these programs, extensive reliability data and reliability prediction models have been generated.

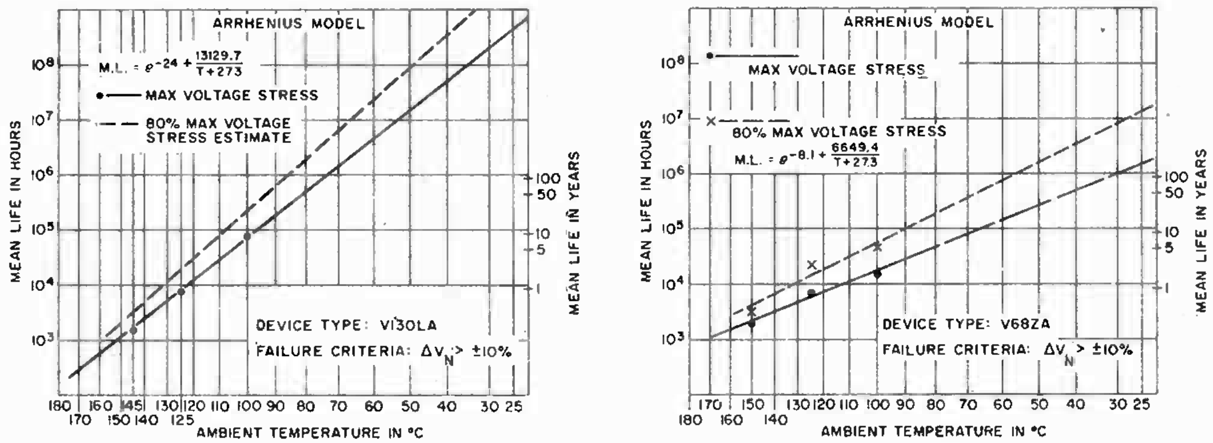
Two types of GE-MOV®II Varistors are being manufactured at present; a "line voltage" type (above 100V RMS) and a "low voltage" type (below 100V RMS). Reliability evaluation has been conducted on both types under the conditions summarized below:

| Test Condition | Stress |
|---|---|
| Voltage | ac Bias |
| | dc Power |
| Temperature | 100°C |
| | 125°C |
| | 145°C |
| Energy | Pulse |
| Storage | 125°C |
| Humidity | 40°C, 95% RH |
| Mechanical | Solderability |
| | Terminal Strength |
| | Shock |
| | Vibration |

As improved products, processes, and test procedures evolve, the applicability of past data to reliability assessment changes. Thus, the data presented in this chapter represents a "snapshot in time" of data applicable to the GE-MOV®II Varistors being manufactured now and for the anticipated future. The test data has been generated at very high stress levels, at or beyond maximum ratings, to confirm the product's ability to meet these ratings and to obtain the most information in the shortest time period. Results of ac voltage and dc power bias tests have allowed the generation of models which provide expected life as a function of stress.

## 8.2 AC BIAS RELIABILITY

The majority of the applications for the GE-MOV®II Varistor are as transient suppressors on the ac line. The varistor is connected across the ac line voltage and biased with a constant amplitude sinusoidal voltage. If the varistor current increases with time, the power dissipation will also increase, with the ultimate possibility of thermal runaway and varistor failure. Because of this possibility, an extensive series of statistically designed tests have been performed to determine the reliability of the GE-MOV®II Varistor under ac bias combined with temperature stress. This test series contained over one million device hours of operation at temperatures up to 145°C. The average duration of testing ranges from 7000 hours at low stress to 495 hours at high stress. The results of this test have shown the GE-MOV®II Varistor to be an excellent fit to the Arrhenius model, i.e., the expected life is logarithmically related to the inverse of the absolute temperature (MTBF $= e^{c + K/T}$). The definition of failure is a shift in $V_N$ exceeding $\pm 10\%$. Although the GE-MOV®II Varistor is still functioning normally after this magnitude of shift, devices at the lower extreme of $V_N$ tolerance will begin to dissipate more power. As previously explained, this could ultimately lead to failure. This choice of failure definition, in combination with the lower stresses found in applications, should provide life estimates adequate for most design requirements. Figure 8.1 illustrates the Arrhenius model plot for the line voltage and the low voltage GE-MOV®II Varistor.




(a) Line Voltage GE-MOV®II Varistor

(b) Low Voltage GE-MOV®II Varistor

**FIGURE 8.1: ARRHENIUS MODELS OF VARISTOR MEAN LIFE VS. TEMPERATURE**

This type of statistical model allows a prediction of the reliability level that can be expected at normal operating temperatures. The usual ambients are well below the temperature levels chosen for accelerated testing. For example, a V130LA10 operating at 130V ac in a 55°C environment has a mean life, from Figure 8.1(a), of about 10,000,000 hours (≈ 1140 years!). Using the equation gives a more precise estimate of 9,152,824 hours (1045 years). Note that at lower bias voltage even longer mean life is expected. Although the V130LA and V68ZA type devices are specifically described, the results are representative for all GE-MOV®II Varistors. Additional evidence of the conservative ratings of the GE-MOV®II Varistor is the absence of systematic or repeated field failures in over seven years of product use. All field failures of the GE-MOV®II Varistor to date have been caused by misapplication or by exceeding the transient energy capability of the varistor.

It is noted the mean life curves have a steep slope. This indicates a high activation energy. As operating temperature is decreased, the mean life increases rapidly. Also, as the voltage stress is lowered, life will increase as well. The maximum stress curve represents the worst-case condition of a model at its lowest voltage limit operated at the maximum allowable rating. In usual practice, the median of a population of devices will operate closer to the 80% voltage stress curve.

For some applications the circuit designer requires other stability information to assess the effects of time on circuit performance. Figures 8.2, 8.3, and 8.4 illustrate the stability of additional GE-MOV®II Varistor parameters when operated at maximum rated voltage and 100°C for 10,000 hours (≈ 1.15 years). The graphs indicate upper decile, median and lower decile response, furnishing useful design information on the stability of $V_N$, standby power drain, and the nonlinear exponent ($\alpha$).

## LONG TERM GE-MOV®II VARISTOR STABILITY AT HIGH TEMPERATURE AND MAXIMUM VOLTAGE

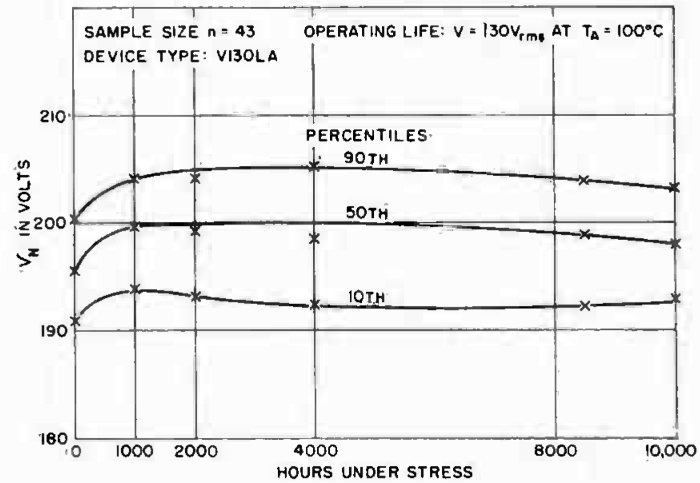



**FIGURE 8.2: VOLTAGE STABILITY**

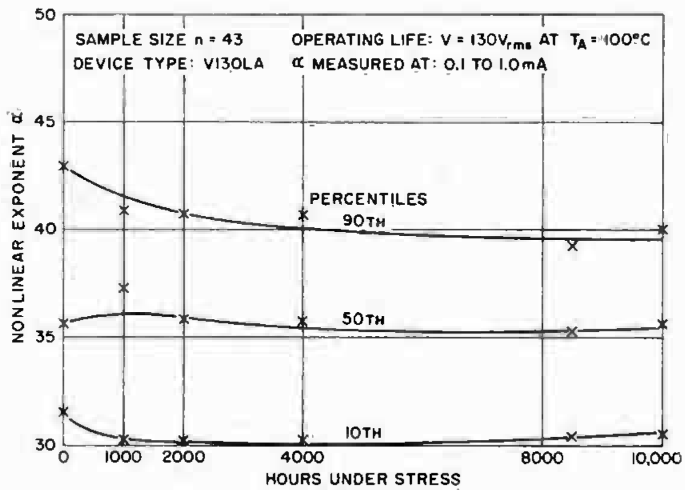



**FIGURE 8.3: NONLINEAR EXPONENT STABILITY**

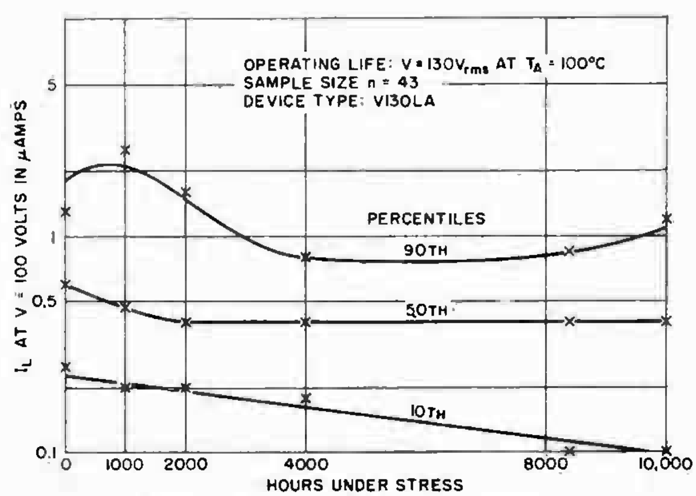



**FIGURE 8.4: LEAKAGE STABILITY**

## 8.3 DC BIAS RELIABILITY

GE-MOV®II Varistors are also applied across dc power lines where transient impulses may occur. This application is more frequent for the low voltage devices. The varistor is designed to have high reliability when the dc bias voltage is below $V_N$ where the current is on the order of microamperes and little average power is consumed. This operation is analogous to the ac bias condition.

Varistors can operate reliably under power dissipation from intermittent transient pulses. Ratings are provided in the specifications for this type of service. Operation is not characterized for *continuous power dissipation* since transient applications generally do not require this capability. The stress under continuous power dissipation can be severe and its effects are shown below for design guidance.

### *8.3.1 DC Bias Voltage Tests*

The application of a constant dc voltage within device ratings to the GE-MOV®II Varistor results in a low stress. A high degree of stability is desired, similar to the ac voltage bias, as the danger of increasing power dissipation with time exists. Life tests of GE-MOV®II Varistors on constant dc voltage bias at accelerated test conditions have been conducted. Measurements indicate stability is at least comparable to the results of ac voltage tests. The data is illustrated in Figure 8.5.

Failure criteria on this test is defined as a $\pm 10\%$ shift in $V_N$. No units exceeded this failure limit during the 3000-hour accelerated test. It should be noted that the polarity of parameter readout is the same as the polarity of the stress.

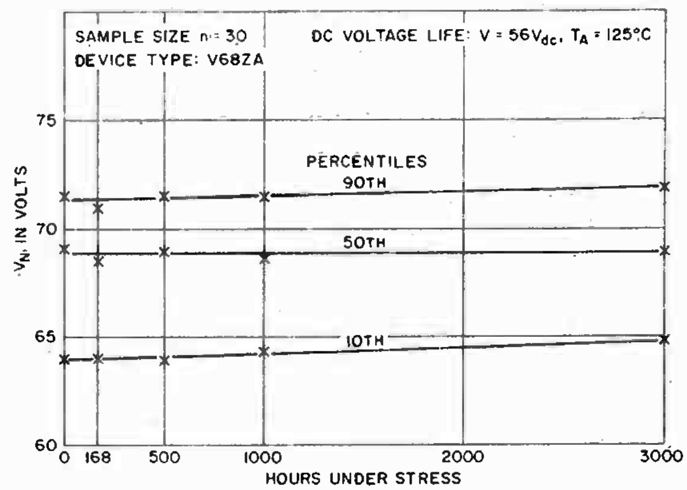



**FIGURE 8.5: ACCELERATED DC VOLTAGE LIFE**

### *8.3.2 DC Power Tests*

Application of a constant current to the varistor results in nearly a constant power condition. In practice, a constant power life test can be implemented easily, using a current limiting resistor and a voltage source about twice $V_N$. At significant power levels compared to the rating, the varistor bias is above $V_N$ (usually 1mA). The long-term response is characterized by a continuing increase in leakage current, especially noticeable at low voltages. This is illustrated in Figure 8.6. The test is at a high stress compared to the normal application levels. The change in leakage causes $V_N$ to fall gradually with time. This is illustrated by Figures 8.7 and 8.9 showing $V_N$ vs. time.

The response to dc power life may be put into further perspective by analysis of a series of accelerated temperature tests. These tests were run on low voltage products at stress temperatures of 55°C, 100°C, 125°C, and 145°C. The change in low voltage leakage current was selected as the most sensitive indicator of degradation and was plotted against time. Device end-of-life was defined at a leakage current limit of $100\mu A$. The mean life results were found to be a good fit to the Arrhenius model as shown in Figure 8.8. Self-heating caused by device power dissipation was added to the ambient temperature of the test. This Arrhenius model can be used to predict mean life at normal operating temperatures by extrapolation of the curve. For example, at 55°C operating ambient, a mean life of 2,400,000 hours (271 years) continuous operation is projected.

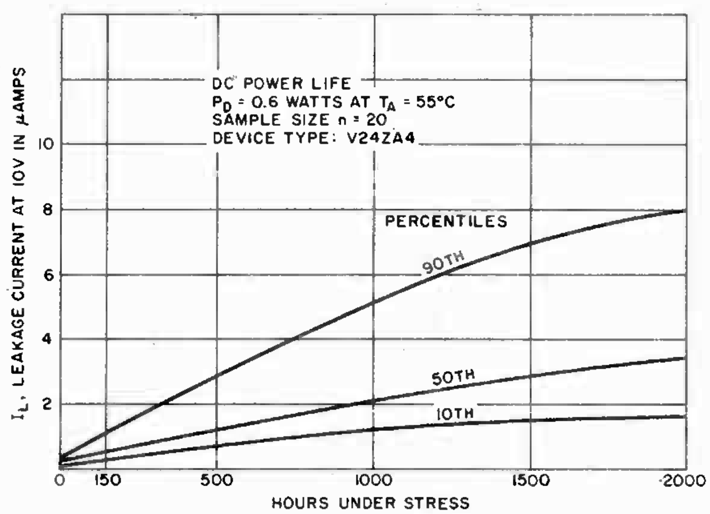



**FIGURE 8.6: ACCELERATED DC POWER LIFE. LEAKAGE CURRENT VARIATION FOR LOW VOLTAGE VARISTOR**

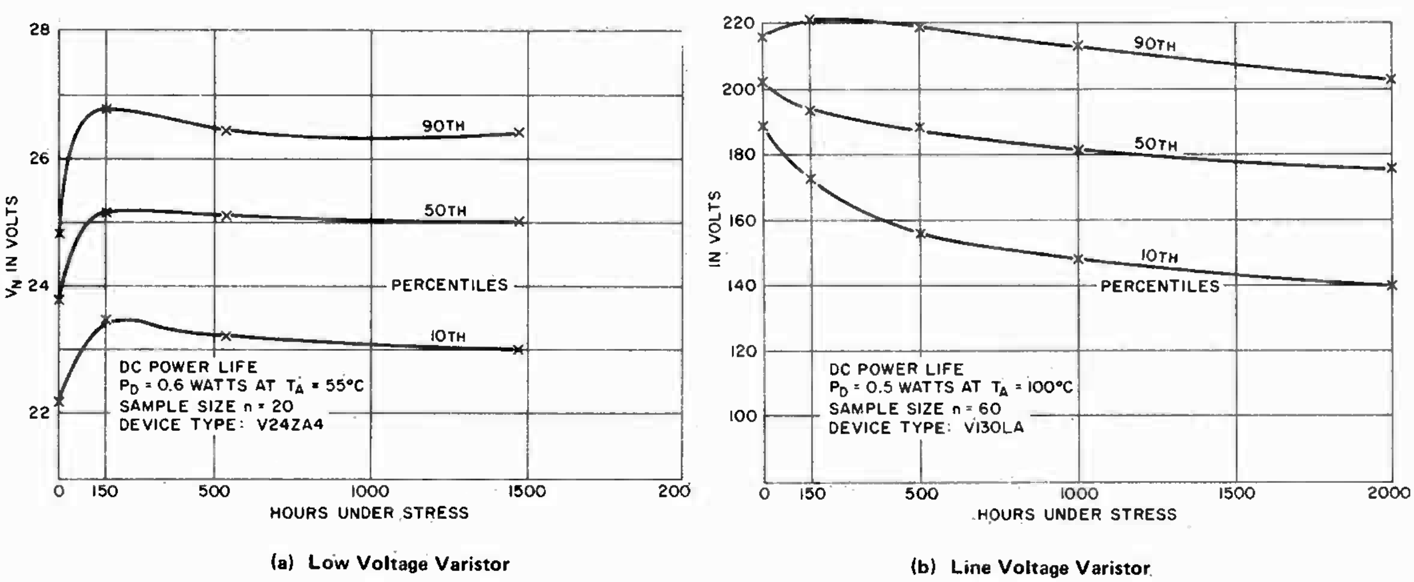



**FIGURE 8.7: ACCELERATED DC POWER LIFE, $V_N$ VARIATION**

With judicious derating to a modest power level, the varistor may be used at continuous power dissipation on a dc line. These applications are limited and highly specialized as the device is intended primarily for intermittent, transient service.

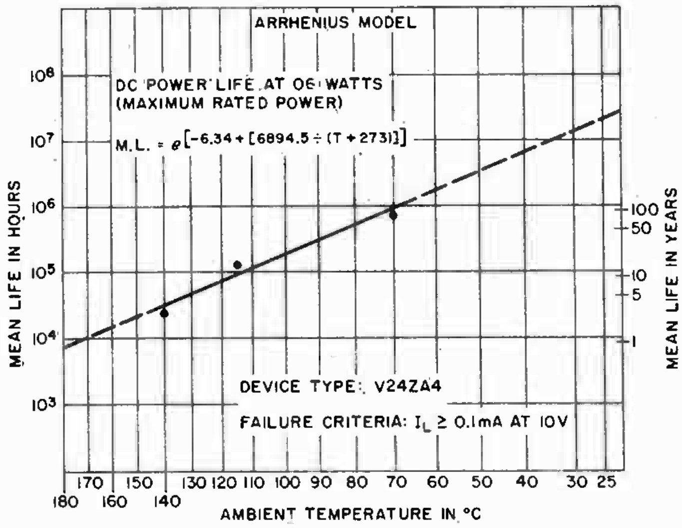
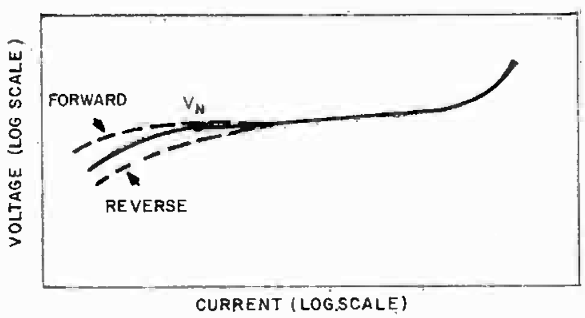


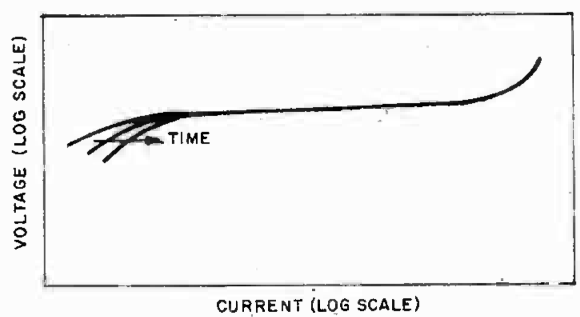

**FIGURE 8.8: RELIABILITY MODEL DC POWER LIFE**

## 8.4 PULSE ENERGY CAPABILITY

The ability of the GE-MOV®II Varistor to absorb large amounts of transient energy is the key to its utility. No other suppressor device combines equal performance with the same economic advantage. Pulse energy is absorbed throughout the bulk of the device. The effect of pulse stress is to shift the low current end of the V-I characteristic as illustrated in Figure 8.9. With sufficient stress (unipolar) the curve will become asymmetrical as shown in Figure 8.9(a). Other forms of electrical or temperature stress affect the low current region as well. The general response to most stress is a shift of the low current V-I segment to the right. That is the main reason for the consistent use of the failure definition as a change in $V_N$ of $\pm 10\%$.




**(a) Unipolar Pulse And dc Stress Response**




**(b) General Response To Stress With Time**

**FIGURE 8.9: EFFECT OF STRESS WITH TIME ON V-I CHARACTERISTIC**

At voltages above $V_N$, little change is observed in response to pulsing or other types of stress. The varistor will continue to provide adequate clamping protection after stressing, up to the point of catastrophic failure. At catastrophic failure the device exhibits a short-circuit punch-through. It takes an extremely high energy pulse to cause this type of failure which is a melting of the ceramic body. More frequently, it is ac current from the power line that causes the pulse-weakened device to go into thermal runaway.

Voltage stability at several conditions of peak current, impulse duration, and temperature is summarized in Figure 8.10 for the V130LA20A model. These results are typical of the excellent pulse capability observed in all sizes of devices. No significant difference is noted between 25°C and 75°C testing.

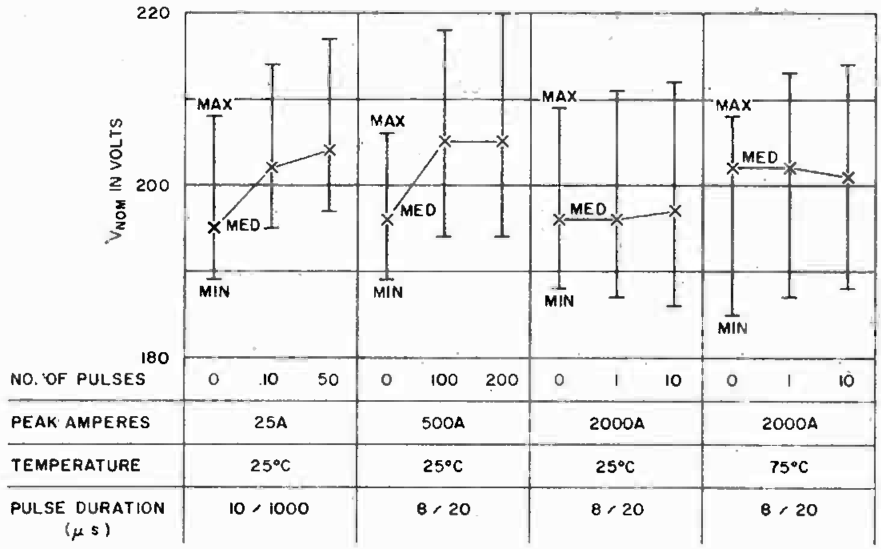



**FIGURE 8.10: TYPICAL PULSE TEST STABILITY, V130LA20A MODEL**

**7 mm**

| Peak Current | 5A | | 100A | | 400A | | 400A | | 1000A |
|---|---|---|---|---|---|---|---|---|---|
| Temperature | 25°C | | 25°C | | 25°C | | 75°C | | 25°C |
| Waveshape | 10 / 1000 | | 8 / 20 | | 8 / 20 | | 8 / 20 | | 8 / 20 |
| No. of Pulses | 10 | 50 | 100 | 200 | 1 | 10** | 1 | 10** | 1 |
| No. Tested | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| No. Failed* | 0 | | 0 | | 0 | | 0 | | 0 |

**14 mm**

| Peak Current | 25A | | 500A | | 2000A | | 2000A | | 4000A |
|---|---|---|---|---|---|---|---|---|---|
| Temperature | 25°C | | 25°C | | 25°C | | 75°C | | 25°C |
| Waveshape | 10 / 1000 | | 8 / 20 | | 8 / 20 | | 8 / 20 | | 8 / 20 |
| No. of Pulses | 10 | 50 | 100 | 200 | 1 | 10** | 1 | 10** | 1 |
| No. Tested | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| No. Failed* | 0 | | 0 | | 0 | | 0 | | 0 |

**20 mm**

| Peak Current | 50A | | 1000A | | 4000A | | 4000A | | 6500A |
|---|---|---|---|---|---|---|---|---|---|
| Temperature | 25°C | | 25°C | | 25°C | | 75°C | | 25° |
| Waveshape | 10 / 1000 | | 8 / 20 | | 8 / 20 | | 8 / 20 | | 8 / 20 |
| No. of Pulses | 10 | 50 | 1 | 10 | 1 | 10** | 1 | 10** | 1 |
| No. Tested | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| No. Failed* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

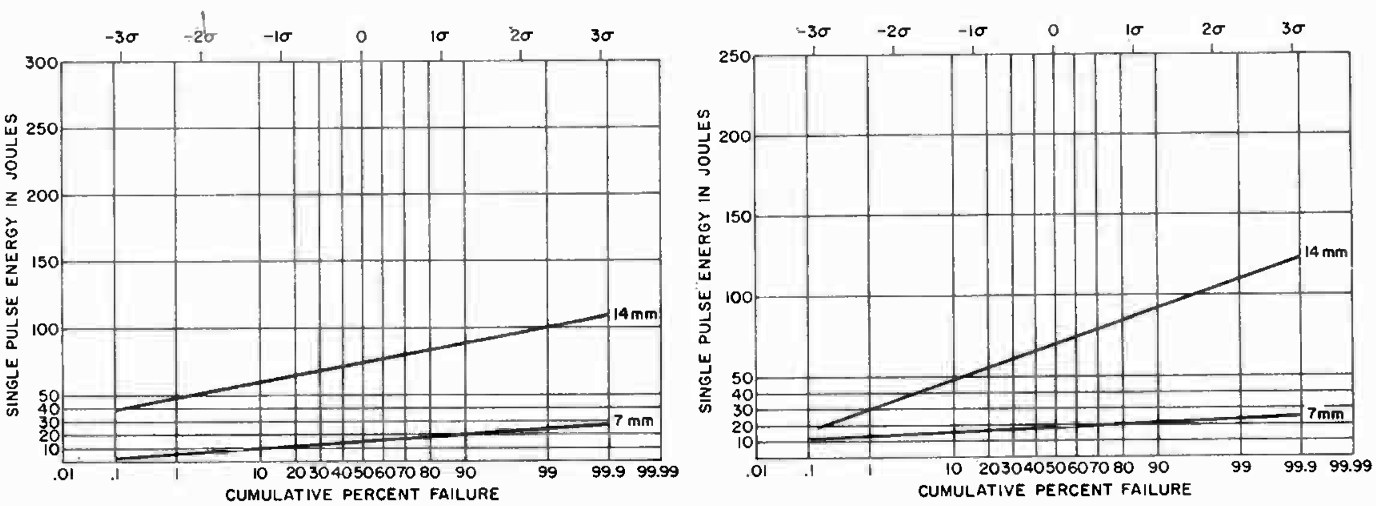
*Catastrophic Failure Definition.

**Designates 5 times the rated value.

**FIGURE 8.11: V130LA PULSE CAPABILITY SUMMARY**

Figure 8.11 provides further details on the pulse current capability of the line voltage models for exponential pulses (reference Figure 3.18). This chart indicates how well units survived peak currents at rated levels of pulsing and at an over-rated condition of pulsing.

Data defining energy withstand capability is presented in Figure 8.12 for the low voltage varistor (V68ZA types) and for the line voltage varistor (V130LA types). These curves show a statistical estimate of the energy to failure distribution. The distributions are shown on normal probability paper where the estimated percentiles of failure can be obtained. The surge test method uses a quasi-current source to apply a single surge of 8 / 20$\mu$s energy stress after which the rated continuous voltage is applied, 130V RMS for line voltage units and 40V RMS for low voltage devices. The failure mode was a catastrophic punch-through of the ceramic body occurring after the surge stress and during application of rated voltage. Thus, the immediate cause was thermal runaway on rated voltage induced by overheating from surge energy absorption. A post-test readout of non-failed devices showed no significant degradation of V-I characteristics.

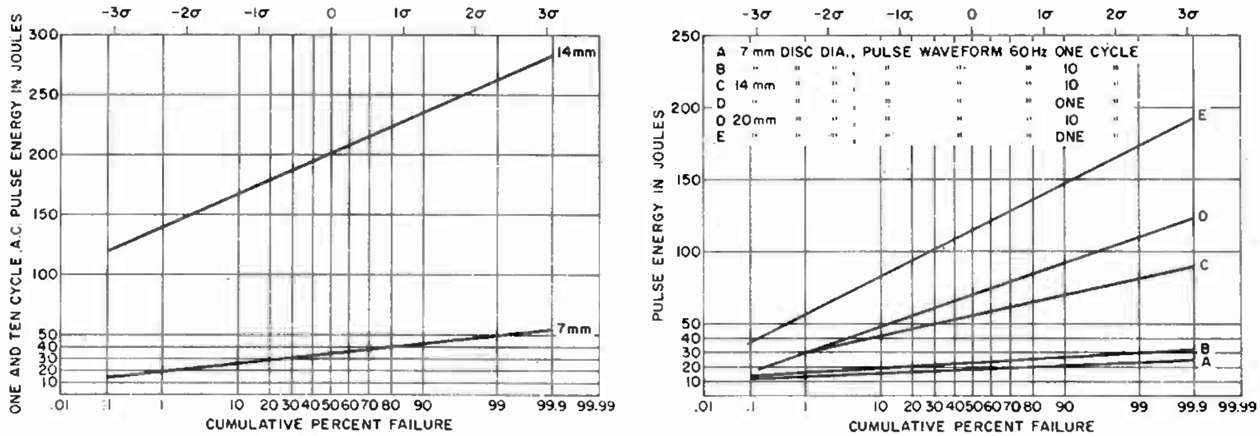



(a) Low Voltage Varistor (Type V68ZA) (b) Line Voltage Varistor (Type V130LA)

FIGURE 8.12: PULSE ENERGY CAPABILITY TO SINGLE PULSE OF 8 x 20 $\mu$s

The distribution curves reflect the conservatism of the GE-MOV®II Varistor energy ratings. For example, 7mm and 14mm line voltage devices (V130LA types) are rated at 8J and 30J respectively. Figure 8.12 indicates a statistical estimate at these energy levels of not more than 1% of the population failing.

Pulse energy testing also has been performed at 60 Hz for single cycle and ten cycle surges. This test simulates conditions possible in ac line applications, especially in crowbar circuits and when used in conjunction with spark gaps to enhance turn-off. In these tests the pulse energy application is immediately followed by maximum rated ac voltage. The results also are presented on a normal probability graph as distributions of energy vs. percent failure. Figure 8.13 illustrates low voltage and line voltage varistor performance.




(a) Low Voltage Varistor (Type V68ZA)

(b) Line Voltage Varistor (Type V130LA)

FIGURE 8.13: 60 Hz SURGE ENERGY CAPABILITY

## 8.5 MECHANICAL RELIABILITY AND INTEGRITY

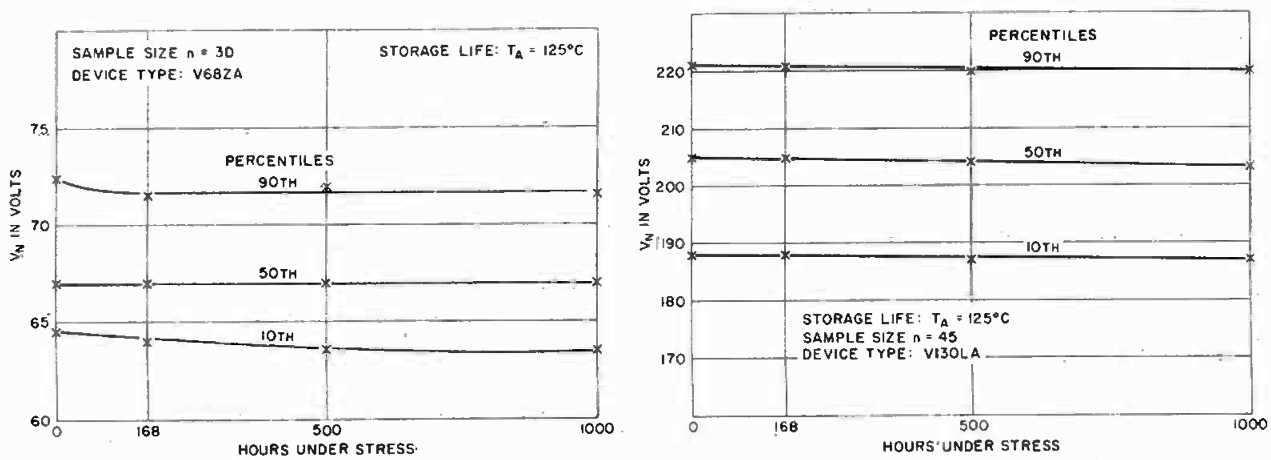
The GE-MOV®II Varistor is constructed by encapsulating a solid piece of ceramic in a rugged, plastic body. This rugged construction, when subjected to the normal military standard mechanical tests, again illustrates the conservative design philosophy. Figure 8.14 tabulates the testing performed and typical results measured. No significant differences are noted between radial and axial devices or low voltage and line voltage types. It should also be noted that the plastic encapsulant complies with the flamability requirement of Underwriter Laboratories standards (UL492).

| MILITARY TEST | METHOD | CONDITION | RESULTS (FAILURES/SAMPLE) TYPE OF PACKAGE | |
|---|---|---|---|---|
| | | | RADIAL | AXIAL |
| Solderability | MIL-STD-750 Method 2026.2 | 230°C, 5 Sec. Dip 95% Wetting | 0/15 | 0/25 |
| Terminal Strength | MIL-STD-750 Method 2036.3 | 3 Bends, 90°C Arc 8 Oz. Weight | 0/15 | 0/25 |
| Thermal Shock | MIL-STD-202E Method 107D | -55°C to 85°C 5 Cycle | 0/25 | 0/25 |
| Mechanical Shock | MIL-STD-750 Method 2016.2 | 1,500 g's 5 Drops $X_1, Y_1, Z_1$ | 0/50 | 0/25 |
| Vibration, Variable Frequency | MIL-STD-750 Method 2056 | 20 g's 100 – 2000 Hz $X_1, Y_1, Z_1$ | 0/50 | 0/69 |

FIGURE 8.14: MECHANICAL TEST RESULTS ON GE-MOV®II VARISTOR PACKAGES

## 8.6 ENVIRONMENTAL AND STORAGE RELIABILITY

The construction of the GE-MOV®II Varistor ensures stable characteristics over the wide variety of environments in which electronic equipment is stored, shipped, and operated. Stress testing of the GE-MOV®II Varistor confirms the stability of low voltage and line voltage types subjected to high temperature storage and accelerated humidity stress. Figure 8.15 presents 1000-hour stability life data at 125°C storage conditions.

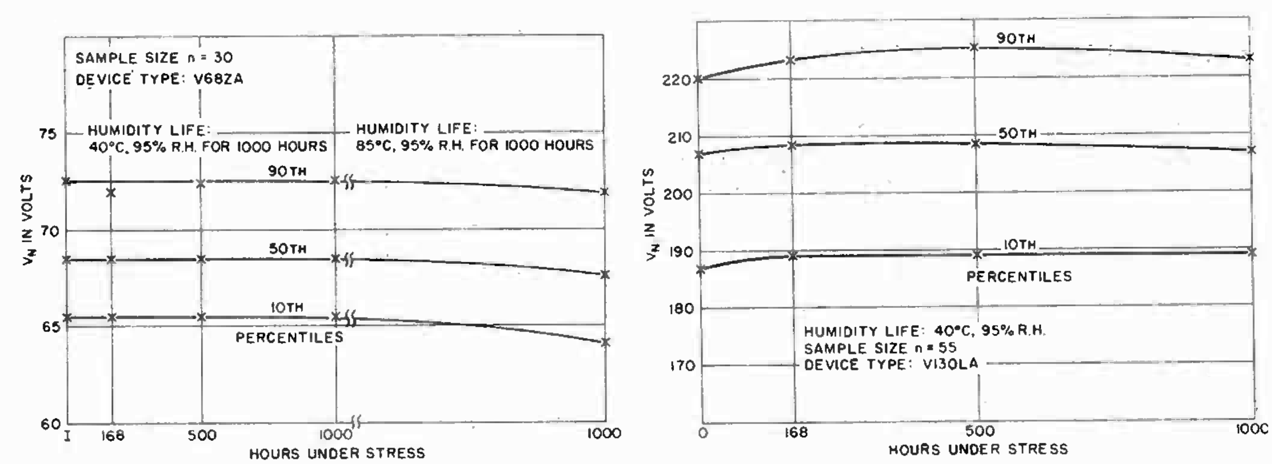



(a) Low Voltage Varistors

(b) Line Voltage Varistors

FIGURE 8.15: ACCELERATED STORAGE LIFE

Figure 8.16 illustrates 1000-hour stability life during accelerated humidity testing. Note that the low voltage varistor type has been subjected to two tests sequentially. The normal 40°C, 95% R.H., 1000-hour test was followed by the very severe 85°C, 95% R.H. test. Excellent stability is observed through this combined testing sequence.




(a) Low Voltage Varistors

(b) Line Voltage Varistors

FIGURE 8.16: ACCELERATED HUMIDITY LIFE

## 8.7 SAFETY

The GE-MOV®II Varistor may be used in systems where personnel safety or equipment hazard is involved. All components, including this semiconductor device, have the potential of failing or degrading in ways which could impair the proper operation of such systems. Well-known circuit techniques are available to protect against the effects of such occurrences. Examples of these techniques include fusing and self-checking. Fault analysis of any systems where safety is in question is recommended. Potential device reaction to various environmental factors has been discussed throughout this section. These and any other environmental factors should be analyzed in all circuit designs.

Should the varistor be subjected to surge currents and energy levels in excess of maximum ratings, it may physically fail by package rupture or expulsion of material. It is recommended that protective fusing be used as described in Chapter 4. If not fused, the varistor should be located away from other components or be physically shielded from them.

GE-MOV®II Varistors have received listing under an Underwriters Laboratories standard for across-the-line components, ULE75961, "Component — Transient Voltage Surge Suppressors."

If the system analysis indicates the need for a maximum degree of reliability, it is recommended that General Electric be contacted for a customized reliability program.

It is stressed that most GE-MOV®II Varistor parameter and reliability testing requires the use of voltages of a magnitude that is hazardous. When GE-MOV®II Varistor testing is contemplated, provisions must be made to insure personnel safety.

Notes

# chapter 9

# GE-MOV®II METAL OXIDE VARISTORS FOR TRANSIENT VOLTAGE PROTECTION: SPECIFICATIONS

GE-MOV®II is the latest result in metal oxide varistor technology, offering a significantly higher energy capability and an improved voltage clamping characteristic.

GE-MOV®II Varistors are voltage dependent, symmetrical, metal oxide semiconductor devices which perform similary to back-to-back zener diodes in circuit protection. Their characteristics enable them to protect against high transient voltage spikes (when properly selected) to meet anticipated loads. When the protected equipment or circuit encounters high voltage spikes, the varistor impedance changes from a very high standby value to a very low conducting value, thus clamping the transient voltage to a protective level. The excess energy of the incoming high voltage pulse is absorbed by the GE-MOV®II Varistor, protecting voltage sensitive components against damage.

The protection afforded by the GE-MOV®II Varistors not only guards expensive and voltage sensitive equipment from physical damage, but also provides increased reliability in components that can encounter temporary functional failure from transient voltage of lower amplitude.

**FEATURES**

■ Wide Voltage/Energy Range ■ Excellent Clamp Ratio ■ Fast Response Time ■ Low Standby Power ■ No Follow-On Current ■ UL Recognized

## Special Products for Special Applications

**MA Series**

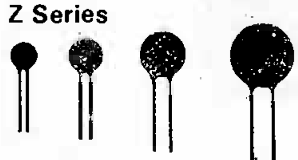
- Axial Package
- Wide Voltage Range
- Automatic Insertion

**P Series**

- Rigid Mountdown
- NEMA Creep and Strike Distance
- Quick Connect Terminal
- UL Recognized

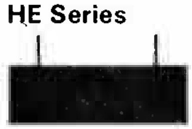
Due to our continuing program of product improvement, specifications are subject to change without notice.

**Z Series**



- Radial Package
- Low Voltage Operation

**HE Series**

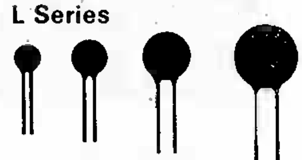


- Isolated Baseplate
- NEMA Creep and Strike Distance
- Rigid Terminals
- Low Inductance
- UL Recognized

**Hi Reliability Series**

- 100% Prescreened
- 100% Process Conditioning
- Meets Military Specifications

**L Series**



- Radial Package
- Line Voltage Operation
- UL Recognized

**C Series**

- Unpackaged Disc Form
- High Voltage Protection
- High Energy Capability

## CONCEPTS OF TRANSIENT VOLTAGE PROTECTION

Varistor characteristics are measured at high current and energy levels of necessity with an inpulse waveform. Shown below is the ANSI STD C62.1 waveshape, an exponentially decaying waveform representative of lightning surges, and the discharge of stored energy in reactive circuits.

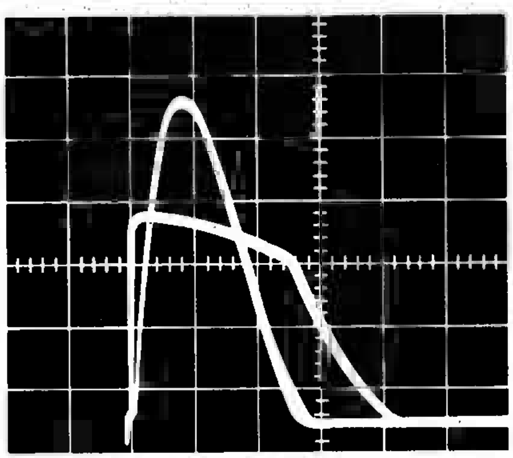
Based on industry practices, the 8 / 20$\mu$s current wave (8$\mu$s rise and 20$\mu$s to 50% decay of peak value) is used as a standard for current ($I_{TM}$) and clamp voltage ($V_C$) ratings shown in the specification tables and curves. Ratings for other waves of different decay times are shown specifically on the pulse life derating curves.

For the energy rating ($W_{TM}$), a longer duration waveform of 10 / 1000$\mu$s is used. This condition is more representative of the high energy surges usually experienced from inductive discharge of motors and transformers. GE-MOV®II Varistors are rated for a maximum pulse energy surge that results in a varistor voltage ($V_N$) shift of less than $\pm$(10% + 1V) of initial value.

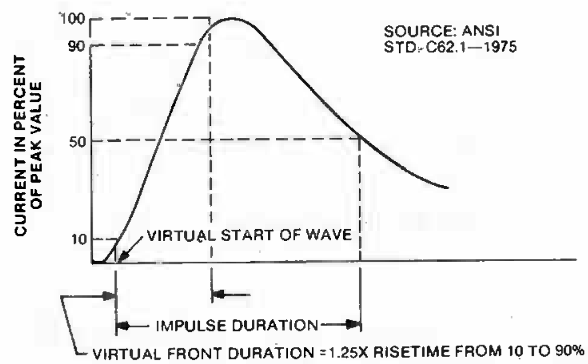
To determine the energy absorbed in a varistor the following equation applies:

$$E = KV_C I\tau$$

where I is the peak current applied, $V_C$ is the clamp voltage which results, $\tau$ is the pulse width and K is a contant. K values are 1.0 for a retangular wave, 1.4 for a 10 /1000$\mu$s wave, and 1.0 for a 8 / 20$\mu$s wave.




8 / 20$\mu$s Test Wave, $I_P$-50A, $V_C$-315V
V130LA10A




**Peak Current Test Impulse Wave**
**8$\mu$s front duration / 20$\mu$s (impulse duration) except as noted.**

Note that the rated energy ($W_{TM}$) and the energy absorbed in a varistor may not be identical. A specimen with lower clamping voltage will absorb less energy. This effect tends to be greatest at rated peak current ($I_{TM}$) with an 8 / 20$\mu$s wave.

It is important to note, as demonstrated by the above equation, that poorer varistors must absorb higher energy levels than the better performance varistors with lower clamp voltages, yet they actually provide less over-voltage protection. For that reason, energy ratings based on an 8/ 20$\mu$s pulse tend to overstate varistor capability. The 10 / 1000$\mu$s waveform consequently gives a more realistic energy rating value.

## SPEED OF RESPONSE

The measured response time of a varistor is influenced by lead configuration and length. In a typical application, the response time is shorter than the inductive lead effect. In a coaxial configuration, one could show response times of less than a few nanoseconds. (Ref: Proposed IEEE standard Varistor test specifications P165.3.)

## DEFINITIONS

| TERM | DEFINITION |
|---|---|
| DC VOLTAGE, $V_{m(dc)}$ | Maximum allowable steady state dc applied voltage. DC standby current, $I_D = 20\mu A$ typical, $200\mu A$ maximum at $T_A = 25°C$, except V18ZA to V36ZA 20mm size: $I_D = 200\mu A$ (TYP), 3mA max. |
| RMS VOLTAGE, $V_{m(ac)}$ | Maximum allowable steady state sinusoidal voltage (RMS) at 50-60Hz. If a nonsinusoidal waveform is applied, the recurrent peak voltage should be limited to $\sqrt{2} / V_{m(ac)}$. |
| ENERGY, $W_{TM}$ | Maximum allowable energy for a single impulse of 10 / 1000$\mu$s current waveform. Energy rating based on a $V_N$ shift of less than $\pm 10\%$, $\pm 1V$ of initial value. |
| PEAK CURRENT, $I_{TM}$ | Maximum allowable peak current for a single impulse of 8 / 20$\mu$s waveform with rated continuous voltage applied. See pulse lifetime rating curves for other conditions. |
| VARISTOR VOLTAGE, $V_N$ | Varistor peak terminal voltage measured with a specified current applied. For dc conditions, 1mA is applied for a duration of 20ms to 5s. For ac conditions 1mA peak 60Hz wave is applied. |
| CLAMPING VOLTAGE, $V_C$ | Maximum terminal voltage measured with an applied 8 / 20$\mu$s impulse of a given peak current. See V-I curves and table for product ratings of clamping voltage over the allowable range of peak impulse current. |
| CAPACITANCE | Typical values measured at a test frequency of 0.1 to 1.0MHz. Maximum capacitance is two times the typical value measured at 1MHz. |

## VARISTOR SAFETY PRECAUTIONS

Should the varistor be subjected to surge currents and energy levels in excess of maximum ratings, it may physically fail by package rupture or expulsion of material. It is recommended that protective fusing be used as described in the Transient Voltage Suppression Manual, 3rd Edition, Chapter Four. If not fused, the varistor should be located away from other components or be physically sheilded from them.

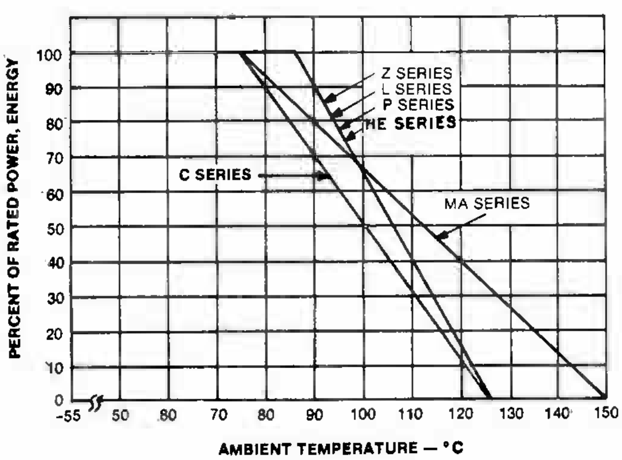
# VARISTOR PRODUCT FAMILY SELECTION GUIDE

Maximum Steady State Applied Voltage: 10, 15, 35, 75, 95, 130, 150, 225, 270, 420, 480, 550, 575, 750, 1100, 2000, 2500, 2800 (VRMS); 14, 20, 40, 100, 120, 180, 800, 970, 1400, 2500, 3000, 3500 (VDC)

| Peak Pulse Current (Amps) | Energy (Joules) | Series | Disc Sizes Packages |
|---|---|---|---|
| 40-100 | .07-1.7 | MA SERIES 10-373 VRMS 14-365 VDC | 3mm |
| 250-4500 | 6-35 | Z SERIES 6-115 VRMS 8-153 VDC | 7, 14, 20mm |
| 800-6500 | 7-360 | L SERIES 130-1000 VRMS 175-1200 VDC | 7, 14, 20mm |
| 6500 | 70-250 | P SERIES 130-660 VRMS 175-850 VDC | 20mm |
| 15,000-25,000 | 200-700 | HE SERIES 130-750 VRMS 175-970 VDC | 32mm |
| 50,000 | 1000-6500 | C SERIES 420-2800 VRMS 560-3500 VDC | 50mm Disc |

| SERIES | MA | Z | L | P | HE | C |
|---|---|---|---|---|---|---|
| Operating Ambient Temperature | +75°C | +85°C | +85°C | +85°C* | +85°C | +75°C |
| Storage Temperature | −55 to +150°C | −55 to +125°C | −55 to +125°C | −40 to +125°C | −40 to +125°C | −55 to +125°C |
| HiPot Encapsulation, Volts dc For 1 Minute | 1000 | 2500 | 2500 | NA | 2500 | NA |
| Voltage Temperature Coefficient | −0.03%/°C | −0.05%/°C | −0.05%/°C | −0.05%/°C | −0.05%/°C | −0.10%/°C |
| Insulation Resistance (MΩ) | >1000 | >1000 | >1000 | NA | NA | NA |

*Base Plate Temperature.
Solderability: Per mil std 202E, method 208C.




**Current, Power, Energy Rating vs. Temperature**

# HOW TO SELECT A GE-MOV®II VARISTOR

To select the correct GE-MOV® II Varistor for a specific application, determine the following information:

1. What is system RMS or dc voltage?

   A. Phase to Ground ____________.

   B. Phase to Phase ____________.

2. How will the GE-MOV®II Varistor be connected?

   A. Phase to Ground ____________.

   B. Phase to Phase ____________.

3. Calculate required varistor voltage at 10-25% above system RMS or dc voltage.

A. $V_{\text{Phase to Ground}} \times 1.1 =$ ____________.

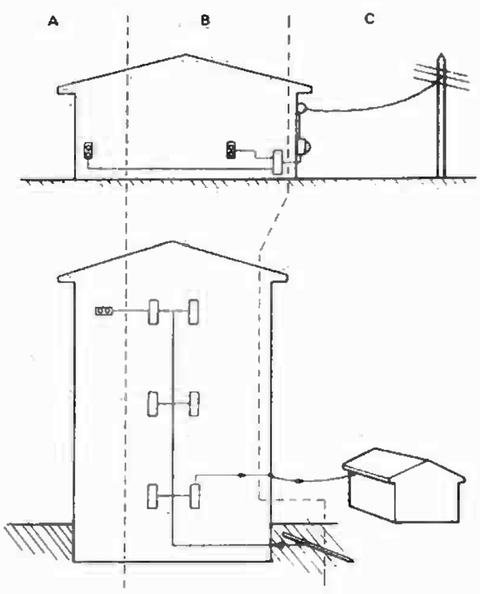
B. $V_{\text{Phase to Phase}} \times 1.1 =$ ____________.

The maximum continuous RMS or dc varistor voltage should be equal to or greater than either 3A or 3B. This maximum continuous RMS or dc varistor voltage can be found in the rating and characteristic tables $V_{m(ac)}$ or $V_{m(dc)}$.

4. Selecting the correct varistor voltage is reasonably straightforward, but selecting the proper energy rating is more difficult and normally presents a certain degree of uncertainty. Choosing the highest energy rating available is expedient, but usually not cost effective.

   As economic considerations enter the selection process, the worst case size of the transient, the frequency of occurrence, and the life expectancy of the equipment to be protected cannot be ignored.

   IEEE Standard 587 addresses these considerations and is reprinted in the *Transient Voltage Suppression* manual - *Third Edition.* From IEEE Standard 587 it becomes evident that *what* equipment or component to be protected is not as important as *where* this equipment is located in the electrical environment. IEEE standard 587 divides the electrical distribution system into 3 location categories. Figure 1 defines these location categories in detail.




A. Outlets and Long Branch Circuits
All outlets at more than 10m (30 ft) from Category B with wires #14-10
All outlets at more than 20m (60 ft) from Category C with wires #14-10

B. Major Feeders and Short Branch Circuits
Distribution panel devices
Bus and feeder systems in industrial plants
Heavy appliance outlets with "short" connections to the service entrance
Lighting systems in commercial buildings

C. Outside and Service Entrance
Service drop from pole to building entrance
Run between meter and distribution panel
Overhead line to detached buildings
Underground lines to well pumps

**FIGURE 1. LOCATION CATEGORIES**

## TABLE 1. SURGE VOLTAGES AND CURRENTS DEEMED TO REPRESENT THE INDOOR ENVIRONMENT AND RECOMMENDED FOR USE IN DESIGNING PROTECTIVE SYSTEMS

| LOCATION CATEGORY | COMPARABLE TO IEC 664 CATEGORY | IMPULSE | | TYPE OF SPECIMEN OR LOAD CIRCUIT | ENERGY (JOULES) DEPOSITED IN A SUPPRESSOR[3] WITH CLAMPING VOLTAGE OF | |
|---|---|---|---|---|---|---|
| | | WAVEFORM | MEDIUM EXPOSURE AMPLITUDE | | 500V | 1000V |
| | | | | | (120V System) | (240V System) |
| A. Long branch circuits and outlets | II | 0.5µs - 100kHz | 6kV | High impedance[1] | — | — |
| | | | 200A | Low impedance[2] | 0.8 | 1.6 |
| B. Major feeders short branch circuits, and load center | III | 1.2/50µs | 6kV | High impedance[1] | — | — |
| | | 8/20µs | 3kA | Low impedance[2] | 40 | 80 |
| | | 0.5µs - 100kHz | 6 kV | High impedance[1] | — | — |
| | | | 500A | Low impedance | 2 | 4 |

Notes: (1) For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.

(2) For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.

(3) Other suppressors which have different clamping voltages would receive different energy levels.

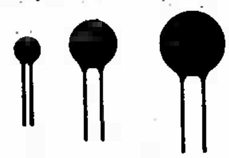
Table 1 shows the open-circuit voltage and short-circuit current of the transients which can be expected at location A and B.

The GE-MOV®II Varistor selected must first survive the worst case transient (see "Medium Exposure Amplitude" in Table 1) and, secondly, clamp the maximum open-circuit voltages to levels which will not damage equipment or components in the system to be protected.

5. Select proper location category, A or B.
6. Determine worst case transient current and voltage from Table 1.
7. Knowing the maximum continuous RMS or dc varistor voltage (from 3), determine maximum clamping voltage from V-I curve for the device selected using the worst case transient current found in 6.
8. Does this clamping voltage provide the required protection level? If not, repeat Step 7 using a higher energy-rated device. If this process proves to be ineffective, consult your local General Electric sales office for assistance.
9. In many cases the source of the transient is known. The transient energy can be calculated, and maximum clamping voltage can be determined from the V-I characteristic since the maximum pulse current or source impedance is known. Examples of these calculations can be found in the *Transient Voltage Suppression* Manual — *Third Edition*, Chapter 4.

# RATINGS AND CHARACTERISTICS TABLE: MA SERIES

| MODEL NUMBER | MAXIMUM RATINGS (25°C) | | | | CHARACTERISTICS | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | CONTINUOUS | | TRANSIENT | | | | | | |
| | DC VOLTAGE | RMS VOLTAGE | ENERGY (10 / 1000$\mu$s) | PEAK CURRENT (8 / 20$\mu$s) | $V_N$ VARISTOR VOLTAGE @ 1.0mA DC CURRENT | | | MAXIMUM CLAMPING VOLTAGE, $V_C$@ $I_P$= 2A (8 / 20$\mu$s) | TYPICAL CAPACITANCE |
| | $V_{m(dc)}$ | $V_{m(ac)}$ | $W_{TM}$ | $I_{TM}$ | | | | TEST $V_C$ | f = 0.1-1MHz |
| | VOLTS | VOLTS | JOULES (WATT-SEC) | AMPERES | MIN. | $V_N$ | MAX. | VOLTS | PICOFARADS |
| V18MA1B | 14 | 10 | 0.07 | 40 | 15.0 | 18 | 21.0 | 44 | 550 |
| V22MA1B | 18 | 14 | 0.10 | 40 | 19.0 | 22 | 26.0 | 51 | 410 |
| V27MA1B | 22 | 17 | 0.11 | 40 | 24.0 | 27 | 31.0 | 59 | 370 |
| V33MA1A | 23 | 18 | 0.13 | 40 | 26.0 | 33 | 40.0 | 73 | 300 |
| V33MA1B | 26 | 20 | 0.15 | | 29.5 | | 36.5 | 67 | |
| V39MA2A | 28 | 22 | 0.16 | 40 | 31.0 | 39 | 47.0 | 86 | 250 |
| V39MA2B | 31 | 25 | 0.18 | | 35.0 | | 43.0 | 79 | |
| V47MA2A | 34 | 27 | 0.19 | 40 | 37.0 | 47 | 57.0 | 99 | 210 |
| V47MA2B | 38 | 30 | 0.21 | | 42.0 | | 52.0 | 90 | |
| V56MA2A | 40 | 32 | 0.23 | 40 | 44.0 | 56 | 68.0 | 117 | 180 |
| V56MA2B | 45 | 35 | 0.25 | | 50.0 | | 62.0 | 108 | |
| V68MA3A | 48 | 38 | 0.26 | 40 | 54.0 | 68 | 82.0 | 138 | 150 |
| V68MA3B | 56 | 40 | 0.30 | | 61.0 | | 75.0 | 127 | |
| V82MA3A | 60 | 45 | 0.33 | 40 | 65.0 | 82 | 99.0 | 163 | 120 |
| V82MA3B | 66 | 50 | 0.37 | | 73.0 | | 91.0 | 150 | |
| V100MA4A | 72 | 57 | 0.40 | 40 | 80.0 | 100 | 120.0 | 200 | 100 |
| V100MA4B | 81 | 60 | 0.45 | | 90.0 | | 110.0 | 185 | |
| V120MA1A | 97 | 72 | 0.40 | 100 | 102.0 | 120 | 138.0 | 220 | 40 |
| V120MA2B | 101 | 75 | 0.50 | | 108.0 | | 132.0 | 205 | |
| V150MA1A | 121 | 88 | 0.50 | 100 | 127.0 | 150 | 173.0 | 255 | 32 |
| V150MA2B | 127 | 92 | 0.60 | | 135.0 | | 165.0 | 240 | |
| V180MA1A | 144 | 105 | 0.60 | 100 | 153.0 | 180 | 207.0 | 310 | 27 |
| V180MA3B | 152 | 110 | 0.70 | | 162.0 | | 198.0 | 290 | |
| V220MA2A | 181 | 132 | 0.80 | 100 | 187.0 | 220 | 253.0 | 380 | 21 |
| V220MA4B | 191 | 138 | 0.90 | | 198.0 | | 242.0 | 360 | |
| V270MA2A | 224 | 163 | 0.90 | 100 | 229.0 | 270 | 311.0 | 460 | 17 |
| V270MA4B | 235 | 171 | 1.0 | | 243.0 | | 297.0 | 440 | |
| V330MA2A | 257 | 188 | 1.0 | 100 | 280.0 | 330 | 380.0 | 570 | 14 |
| V330MA5B | 274 | 200 | 1.1 | | 297.0 | | 363.0 | 540 | |
| V390MA3A | 322 | 234 | 1.2 | 100 | 331.0 | 390 | 449.0 | 670 | 12 |
| V390MA6B | 334 | 242 | 1.3 | | 351.0 | | 429.0 | 640 | |
| V430MA3A | 349 | 253 | 1.5 | 100 | 365.0 | 430 | 495.0 | 740 | 11 |
| V430MA7B | 365 | 373 | 1.7 | | 387.0 | | 473.0 | 700 | |

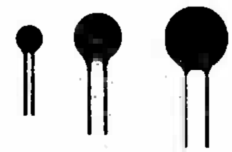


# RATINGS AND CHARACTERISTICS TABLE: Z SERIES

| MODEL NUMBER | MODEL SIZE DIA. (mm) | MAXIMUM RATINGS (25°C) | | | | CHARACTERISTICS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CONTINUOUS | | TRANSIENT | | | | | | | |
| | | RMS VOLTAGE | DC VOLTAGE | ENERGY (10 / 1000$\mu$s) | PEAK CURRENT (8 / 20$\mu$s) | VARISTOR VOLTAGE @ 1mA DC TEST CURRENT | | | MAXIMUM CLAMPING VOLTAGE, $V_C$ @ TEST CURRENT (8 / 20$\mu$s) | | TYPICAL CAPACITANCE |
| | | $V_{m(ac)}$ | $V_{m(dc)}$ | $W_{TM}$ | $I_{TM}$ | MIN. | $V_N$ | MAX. | $V_C$ | $I_P$ | f = 0.1-1MHz |
| | | VOLTS | VOLTS | JOULES | AMPERES | VOLTS | VOLTS | VOLTS | VOLTS | AMPS | PICOFARADS |
| V12ZA1 | 7 | 6 | 8 | 0.6 | 250 | 8.4 | 12 | 16.0 | 34 | 5 | 3000 |
| V18ZA1 | 7 | 10 | 14 | 0.8 | 250 | 14.4 | 18 | 21.6 | 42 | 5 | 2500 |
| V18ZA3 | 14 | | | 3.5 | 1000 | | | | 39 | 10 | 12000 |
| V18ZA40 | 20 | | | 80.0* | 2000 | | 18† | | 37 | 20 | 25000 |
| V22ZA1 | 7 | 14 | 18‡ | 0.9 | 250 | 18.7 | 22 | 26.0 | 47 | 5 | 2000 |
| V22ZA3 | 14 | | | 4.0 | 1000 | | | | 43 | 10 | 10000 |
| V24ZA50 | 20 | 14 | 18‡ | 100.0* | 2000 | 19.2 | 24† | 26.0 | 43 | 20 | 20000 |
| V27ZA1 | 7 | 17 | 22 | 1.0 | 250 | 23.0 | 27 | 31.1 | 57 | 5 | 1700 |
| V27ZA4 | 14 | | | 5.0 | 1000 | | | | 53 | 10 | 8500 |
| V27ZA60 | 20 | | 22 | 120.0* | 2000 | | 27† | | 50 | 20 | 18000 |
| V33ZA1 | 7 | 20 | 26 | 1.2 | 250 | 29.5 | 33 | 36.5 | 68 | 5 | 1400 |
| V33ZA5 | 14 | | | 6.0 | 1000 | | | | 64 | 10 | 7000 |
| V33ZA70 | 20 | 21 | 27 | 150.0* | 2000 | | 33† | | 58 | 20 | 15000 |
| V36ZA80 | 20 | 23 | 31 | 160.0* | 2000 | 32.0 | 36† | 40.0 | 63 | 20 | 12000 |
| V39ZA1 | 7 | 25 | 31 | 1.5 | 250 | 35.0 | 39 | 43.0 | 79 | 5 | 1200 |
| V39ZA6 | 14 | | | 7.2 | 1000 | | | | 76 | 10 | 6000 |
| V47ZA1 | 7 | 30 | 38 | 1.8 | 250 | 42.0 | 47 | 52.0 | 92 | 5 | 1000 |
| V47ZA7 | 14 | | | 8.8 | 1000 | | | | 89 | 10 | 5000 |
| V56ZA2 | 7 | 35 | 45 | 2.3 | 250 | 50.0 | 56 | 62.0 | 107 | 5 | 800 |
| V56ZA8 | 14 | | | 10.0 | 1000 | | | | 103 | 10 | 4000 |
| V68ZA2 | 7 | 40 | 56 | 3.0 | 250 | 61.0 | 68 | 75.0 | 127 | 5 | 700 |
| V68ZA10 | 14 | | | 13.0 | 1000 | | | | 123 | 10 | 3500 |
| V82ZA2 | 7 | 50 | 66 | 4.0 | 250 | 74.0 | 82 | 91.0 | 152 | 5 | 600 |
| V82ZA12 | 14 | | | 15.0 | 1000 | | | | 147 | 10 | 3000 |
| V100ZA3 | 7 | 60 | 81 | 5.0 | 250 | 90.0 | 100 | 110.0 | 180 | 5 | 500 |
| V100ZA15 | 14 | | | 20.0 | 1000 | | | | 175 | 10 | 2500 |
| V120ZA1 | 7 | 75 | 102 | 6.0 | 1200 | 108.0 | 120 | 132.0 | 205 | 10 | 200 |
| V120ZA6 | 14 | | | 22.0 | 4500 | | | | 210 | 50 | 1200 |
| V150ZA1 | 7 | 95 | 127 | 8.0 | 1200 | 135.0 | 150 | 165.0 | 250 | 10 | 170 |
| V150ZA8 | 14 | | | 30.0 | 4500 | | | | 255 | 50 | 1000 |
| V180ZA1 | 7 | 115 | 153 | 10.0 | 1200 | 162.0 | 180 | 198.0 | 295 | 10 | 140 |
| V180ZA10 | 14 | | | 35.0 | 4500 | | | | 300 | 50 | 800 |

*Energy rating for impulse duration of 30 milliseconds minimum to one half of peak current value.
†10mA dc test current.
‡Also rated to withstand 24V for 5 minutes.

**NOTE: Power dissipation of transients not to exceed 0.25, 0.6, 1.0 watts for sizes 7, 14 and 20mm respectively.**



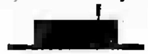
# RATINGS AND CHARACTERISTICS TABLE: L SERIES

Series L Varistors are listed under UL file #E75961 (supersedes E56579) as a UL recognized component.

| MODEL NUMBER | MODEL SIZE DIA. (mm) | MAXIMUM RATINGS (25°C) CONTINUOUS RMS VOLTAGE | DC VOLTAGE | TRANSIENT ENERGY (10 / 1000$\mu$s) | PEAK CURRENT (8 / 20$\mu$s) | CHARACTERISTICS VARISTOR VOLTAGE @ 1mA DC TEST CURRENT | | | MAXIMUM CLAMPING VOLTAGE, $V_C$ @ TEST CURRENT (8 / 20$\mu$s) | | TYPICAL CAPACITANCE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $V_{m(ac)}$ | $V_{m(dc)}$ | $W_{TM}$ | $I_{TM}$ | MIN. | $V_N$ | MAX. | $V_C$ | $I_P$ | f = 0.1-1MHz |
| | | VOLTS | VOLTS | JOULES | AMPERES | VOLTS | VOLTS | VOLTS | VOLTS | AMPS | PICOFARADS |
| V130LA1 | 7 | 130 | 175 | 7 | 800 | 184 | 200 | 255 | 390 | 10 | 180 |
| V130LA2 | 7 | | | 11 | 1200 | | | 228 | 340 | 10 | 180 |
| V130LA10A | 14 | | | 38 | 4500 | | | 228 | 340 | 50 | 1000 |
| V130LA20A | 20 | | | 70 | 6500 | | | 228 | 340 | 100 | 1900 |
| V130LA20B | 20 | | | 70 | 6500 | | | 220 | 325 | 100 | 1900 |
| V150LA1 | 7 | 150 | 200 | 8 | 800 | 212 | 240 | 284 | 430 | 10 | 150 |
| V150LA2 | 7 | | | 13 | 1200 | | | 268 | 395 | 10 | 150 |
| V150LA10A | 14 | | | 45 | 4500 | | | 268 | 395 | 50 | 800 |
| V150LA20A | 20 | | | 80 | 6500 | | | 268 | 395 | 100 | 1600 |
| V150LA20B | 20 | | | 80 | 6500 | | | 243 | 360 | 100 | 1600 |
| V250LA2 | 7 | 250 | 330 | 14 | 800 | 354 | 390 | 473 | 730 | 10 | 110 |
| V250LA4 | 7 | | | 21 | 1200 | | | 429 | 650 | 10 | 110 |
| V250LA20A | 14 | | | 72 | 4500 | | | 429 | 650 | 50 | 500 |
| V250LA40A | 20 | | | 130 | 6500 | | | 429 | 650 | 100 | 1000 |
| V250LA40B | 20 | | | 130 | 6500 | | | 413 | 620 | 100 | 1000 |
| V275LA2 | 7 | 275 | 369 | 15 | 800 | 389 | 430 | 515 | 775 | 10 | 100 |
| V275LA4 | 7 | | | 23 | 1200 | | | 473 | 710 | 10 | 100 |
| V275LA20A | 14 | | | 75 | 4500 | | | 473 | 710 | 50 | 450 |
| V275LA40A | 20 | | | 140 | 6500 | | | 473 | 710 | 100 | 900 |
| V275LA40B | 20 | | | 140 | 6500 | | | 453 | 680 | 100 | 900 |
| V300LA2 | 7 | 300 | 405 | 16 | 800 | 420 | 470 | 565 | 870 | 10 | 90 |
| V300LA4 | 7 | | | 25 | 1200 | | | 517 | 775 | 10 | 90 |
| V320LA20A | 14 | 320 | 420 | 90 | 4500 | 462 | 510 | 565 | 850 | 50 | 380 |
| V320LA40B | 20 | | | 160 | 6500 | | | 540 | 810 | 100 | 750 |
| V420LA20A | 14 | 420 | 560 | 90 | 4500 | 610 | 680 | 748 | 1120 | 50 | 500 |
| V420LA40B | 20 | | | 160 | 6500 | | | 720 | 1060 | 100 | 1000 |
| V480LA40A | 14 | 480 | 640 | 105 | 4500 | 670 | 750 | 825 | 1240 | 50 | 450 |
| V480LA80B | 20 | | | 180 | 6500 | | | 790 | 1160 | 100 | 900 |
| V510LA40A | 14 | 510 | 675 | 110 | 4500 | 735 | 820 | 910 | 1350 | 50 | 400 |
| V510LA80B | 20 | | | 190 | 6500 | | | 860 | 1280 | 100 | 800 |
| V575LA40A | 14 | 575 | 730 | 120 | 4500 | 805 | 910 | 1000 | 1500 | 50 | 370 |
| V575LA80B | 20 | | | 220 | 6500 | | | 960 | 1410 | 100 | 750 |
| V1000LA80A | 14 | 1000 | 1200 | 220 | 4500 | 1425 | 1600 | 1800 | 2700 | 50 | 200 |
| V1000LA160B | 20 | | | 360 | 6500 | | | 1650 | 2420 | 100 | 400 |

NOTE: Power dissipation of transients not to exceed 0.25, 0.6, 1.0 watts for sizes 7, 14 and 20mm respectively.

P Series, Base
Mount Style; 20 mm



HE Series, Base
Mount Style; 32 mm

# RATINGS AND CHARACTERISTICS TABLE: P/HE SERIES

Series Pa/HE Varistors are listed under UL file #E75961 (supersedes E56579) as a UL recognized component.

| MODEL NUMBER | MAXIMUM RATINGS (25°C) | | | | CHARACTERISTICS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CONTINUOUS | | TRANSIENT | | | | | | | |
| | RMS VOLTAGE | DC VOLTAGE | ENERGY (10 / 1000$\mu$s) | PEAK CURRENT (8 / 20$\mu$s) | VARISTOR VOLTAGE @ 1mA DC TEST CURRENT | | | MAXIMUM CLAMPING VOLTAGE, $V_C$ @ TEST CURRENT (8 / 20$\mu$s) | | TYPICAL CAPACI-TANCE |
| | $V_{m(ac)}$ | $V_{m(dc)}$ | $W_{TM}$ | $I_{TM}$ | MIN. | $V_N$ | MAX* | $V_C$ | $I_P$ | f = 0.1-1MHz |
| | VOLTS | VOLTS | JOULES | AMPERES | VOLTS | VOLTS | VOLTS | VOLTS | AMPS | PICOFARADS |
| V130PA20A | 130 | 175 | 70 | 6,500 | 184 | 200 | 243 | 360 | 100 | 2400 |
| V130PA20C | | | | | | | 220 | 325 | 100 | |
| V130HE150 | | | 200 | 20,000 | | | 228 | 365 | 300 | 4700 |
| V150PA20A | 150 | 200 | 80 | 6,500 | 212 | 240 | 284 | 420 | 100 | 2000 |
| V150PA20C | | | | | | | 243 | 360 | 100 | |
| V150HE150 | | | 220 | 20,000 | | | 268 | 425 | 300 | 4000 |
| V250PA40A | 250 | 330 | 130 | 6,500 | 354 | 390 | 453 | 675 | 100 | 1200 |
| V250PA40C | | | | | | | 413 | 620 | 100 | |
| V250HE250 | | | 330 | 20,000 | | | 429 | 690 | 300 | 2500 |
| V275PA40A | 275 | 369 | 140 | 6,500 | 389 | 430 | 494 | 740 | 100 | 1100 |
| V275PA40C | | | | | | | 453 | 680 | 100 | |
| V275HE250 | | | 360 | 20,000 | | | 473 | 760 | 300 | 2250 |
| V320PA40A | 320 | 420 | 160 | 6,500 | 462 | 510 | 565 | 850 | 100 | 1000 |
| V320PA40C | | | | | | | 540 | 800 | 100 | |
| V320HE300 | | | 390 | 20,000 | | | 539 | 860 | 300 | 1900 |
| V420PA40A | 420 | 560 | 160 | 6,500 | 610 | 680 | 790 | 1160 | 100 | 1200 |
| V420PA40C | | | | | | | 690 | 1050 | 100 | |
| V420HE400 | | | 400 | 25,000 | | | 748 | 1200 | 300 | 3000 |
| V480PA80A | 480 | 640 | 180 | 6,500 | 670 | 750 | 860 | 1280 | 100 | 1100 |
| V480PA80C | | | | | | | 790 | 1160 | 100 | |
| V480HE450 | | | 450 | 25,000 | | | 824 | 1320 | 300 | 2700 |
| V510PA80A | 510 | 675 | 190 | 6,500 | 735 | 820 | 963 | 1410 | 100 | 1000 |
| V510PA80C | | | | | | | 860 | 1280 | 100 | |
| V510HE500 | | | 500 | 25,000 | | | 910 | 1450 | 300 | 2400 |
| V575PA80A | 575 | 730 | 220 | 6,500 | 805 | 910 | 1050 | 1560 | 100 | 900 |
| V575PA80C | | | | | | | 960 | 1410 | 100 | |
| V575HE550 | | | 550 | 25,000 | | | 1005 | 1600 | 300 | 2200 |
| V660PA100A | 660 | 850 | 250 | 6,500 | 940 | 1050 | 1210 | 1820 | 100 | 800 |
| V660PA100C | | | | | | | 1100 | 1650 | 100 | |
| V660HE600 | | | 600 | 25,000 | | | 1160 | 1850 | 300 | 1900 |
| V750HE700 | 750 | 970 | 700 | 25,000 | 1080 | 1200 | 1320 | 2100 | 300 | 1700 |

*With 50-60Hz ac test, the maximum voltage for 1mA peak current is 5% higher.

**NOTE:** Average power dissipation of transients not to exceed 1.0-1.5 watts for PA/HE Series Varistors.

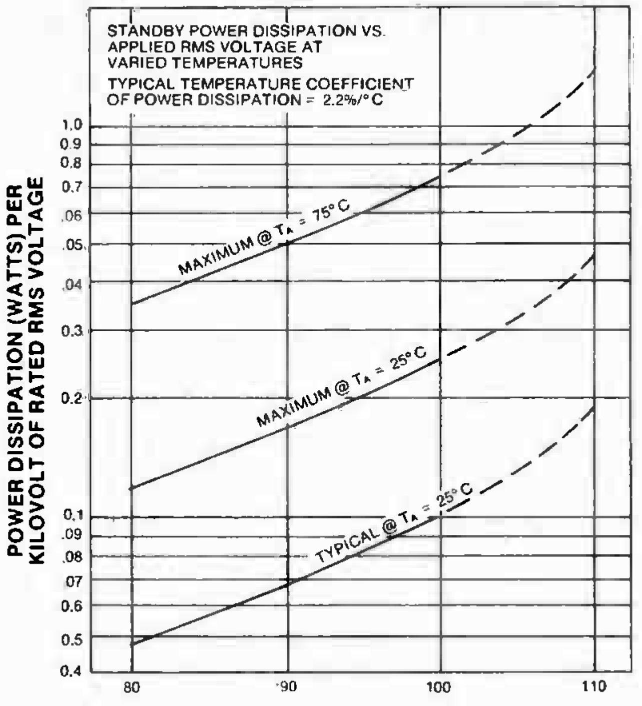
# RATINGS AND CHARACTERISTICS TABLE: C SERIES

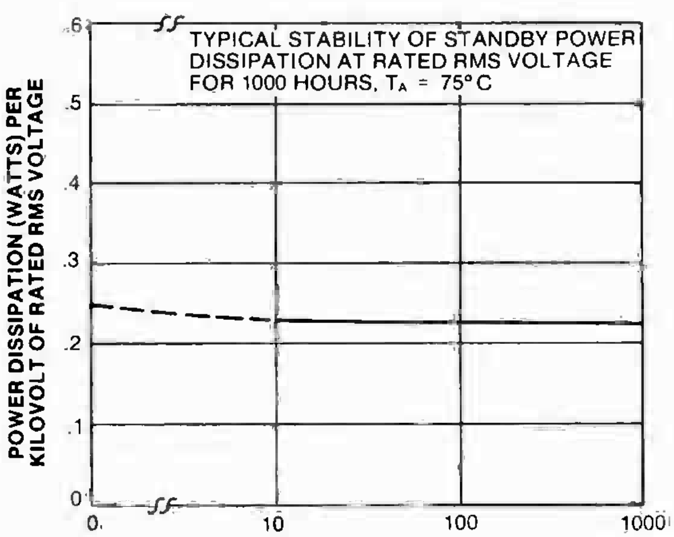
| MODEL NUMBER | MODEL SIZE DIA. (mm) | MAXIMUM RATINGS (25°C) | | | | CHARACTERISTICS | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CONTINUOUS | | TRANSIENT | | VARISTOR VOLTAGE ($V_N$) @ 1mA DC CURRENT | | | MAXIMUM CLAMPING VOLTAGE, $V_C$ @ 200 AMPS CURRENT (8 / 20$\mu$s) |
| | | RMS VOLTAGE | DC VOLTAGE | ENERGY (10 / 1000$\mu$s) | PEAK CURRENT (8 / 20$\mu$s) | | | | |
| | | $V_{m(ac)}$ | $V_{m(dc)}$ | $W_{TM}$ | $I_{TM}$ | MIN. | $V_N$ | MAX* | $V_C$ |
| | | VOLTS | VOLTS | JOULES | AMPERES | VOLTS | VOLTS | VOLTS | VOLTS |
| V421CA401 | 32 | 420 | 560 | 400 | 25,000 | 610 | 680 | 748 | 1180 |
| V421CA102 | 50 | | | 1000 | 50,000 | | | | 1140 |
| V481CA451 | 32 | 480 | 640 | 450 | 25,000 | 670 | 750 | 825 | 1300 |
| V481CA112 | 50 | | | 1100 | 50,000 | | | | 1250 |
| V511CA501 | 32 | 510 | 675 | 500 | 25,000 | 735 | 820 | 910 | 1420 |
| V511CA122 | 50 | | | 1200 | 50,000 | | | | 1370 |
| V571CA551 | 32 | 575 | 730 | 550 | 25,000 | 805 | 910 | 1000 | 1580 |
| V571CA142 | 50 | | | 1400 | 50,000 | | | | 1530 |
| V661CA601 | 32 | 660 | 850 | 600 | 25,000 | 940 | 1050 | 1160 | 1820 |
| V661CA152 | 50 | | | 1500 | 50,000 | | | | 1750 |
| V751CA701 | 32 | 750 | 970 | 700 | 25,000 | 1080 | 1200 | 1320 | 2070 |
| V751CA172 | 50 | | | 1700 | 50,000 | | | | 2000 |
| V881CA851 | 32 | 880 | 1150 | 850 | 25,000 | 1290 | 1500 | 1650 | 2570 |
| V881CA212 | 50 | | | 2100 | 50,000 | | | | 2500 |
| V112CA103 | 32 | 1100 | 1400 | 1000 | 25,000 | 1620 | 1800 | 2060 | 3200 |
| V112CA252 | 50 | | | 2500 | 50,000 | | | | 3100 |
| V142CA332 | 50 | 1400 | 1750 | 3300 | 50,000 | 2020 | 2200 | 2550 | 3900 |
| V172CA402 | 50 | 1700 | 2150 | 4000 | 50,000 | 2500 | 2700 | 3030 | 4500 |
| V202CA502 | 50 | 2000 | 2500 | 5000 | 50,000 | 2970 | 3300 | 3630 | 5500 |
| V242CA572 | 50 | 2400 | 3000 | 5700 | 50,000 | 3510 | 3900 | 4290 | 6600 |
| V282CA652 | 50 | 2800 | 3500 | 6500 | 50,000 | 4230 | 4700 | 5170 | 7800 |

*With 50-60Hz ac test, the maximum voltage for 1mA peak current is 5% higher.

**NOTE: Average power dissipation of transients not to exceed 1.5, 2.5 watts for sizes 32 and 50mm respectively.**

# STANDBY POWER DISSIPATION



# MECHANICAL AND ENVIRONMENTAL TESTING: HIGH RELIABILITY SERIES

The High Reliability GE-MOV®II Varistor is the latest step in increased product performance. Applications requiring guaranteed quality in extreme ambients can now be served. The new series of varistors are 100% prescreened and process conditioned to meet stringent mechanical and electrical requirements.

### 100% PRESCREEN

| | |
|---|---|
| Pre-encapsulation Inspection | Visual Inspection of Lead Frame and Disc Prior to Coating |
| Electrical | $I_L$ @ 10.0$\mu$A, $V_N$ @ 1mA dc, $V_C$ @ 100 Amp (8 / 20$\mu$s) |
| Final Inspection | Coating Integrity, Leads, Marking, Outline |

### 100% PROCESS CONDITIONING

| TEST NAME | TEST METHOD (MIL-750B) | DESCRIPTION |
|---|---|---|
| High Temperature Life | Method 1032.1 | 125°C, 24 Hr. Bake |
| Thermal Shock | Method 1051.1 | Air-Air; −55°C to 125°C, 5 Cycles |
| Constant Acceleration | Method 2006 | 20,000 G, $Z_1$ |
| Humidity Life | No Equivalent | 85°C, 85% RH, 168 Hr. Exposure |
| Burn-In | Method 1038, Cond B | 72 Hr., 85°C, Rated $V_{ACM}$ |
| Post Burn-In Screen | No Equivalent | $V_N$ and $V_C$ Screen, 10% POA |
| Visual Inspection | Method 2071 | Encapsulation, Marking, Outline, Leads |

### QUALITY ASSURANCE TESTS AFTER PROCESSING CONDITIONING

| | |
|---|---|
| ■ Electrical (Bi-Directional), $V_N$, $V_C$ | 0.65% AQL LEVEL II |
| ■ Dielectric BV (MIL-STD 202-301) | 0.65% AQL LEVEL I |
| ■ Capacitance @ 1MHz | 1.0% AQL LEVEL S-4 |
| ■ Solderability (Non Activated) | 1.0% AQL LEVEL S-4 |

### ADDITIONAL CAPABILITIES

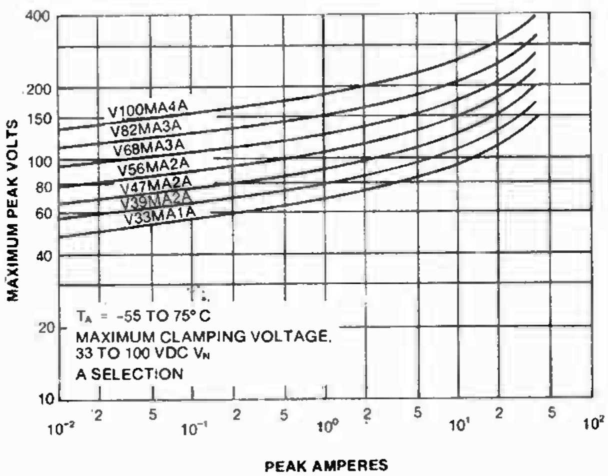
| TEST NAME | TEST METHOD (MIL-750B) | DESCRIPTION |
|---|---|---|
| Terminal Strength | Method 2036.3 | 3 Bends; 90° Arc; 16 oz. Weight |
| Shock | Method 2016.2 | 1500 G's; .5 ms; 5 pulses; $X_1$, $Y_1$, $Z_1$ |
| Variable Frequency Vibration | Method 2056 | 20 G's; 100-2000Hz; $X_1$, $Y_1$, $Z_1$ |
| Salt Atmosphere | Method 1041 | 35°C; 24 Hr.; 10-50 G/M²/Day |
| Soldering Heat | Method 2031 | 260°C; 10 Sec.; 3 Cycles; Test |
| Resistance to Solvents | MIL-202E, Method 215 | Marking Permanence; 3 Solvents |
| Flammability | MIL-202E, Method 111A | 15 Sec. Torching; 10 Sec. to Flame Out |

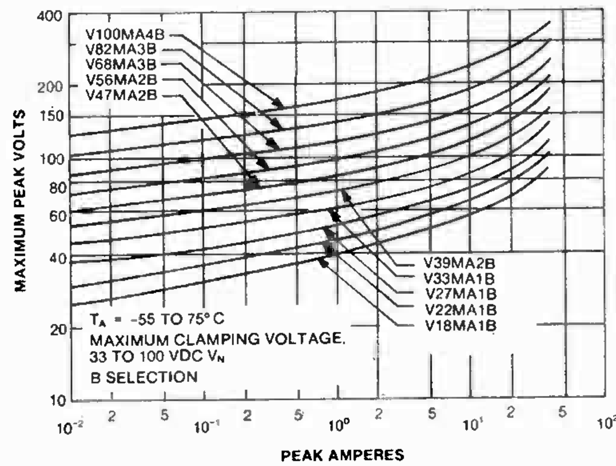
**Note:** High reliability varistors are rated to withstand a low temperature storage of −65°C.

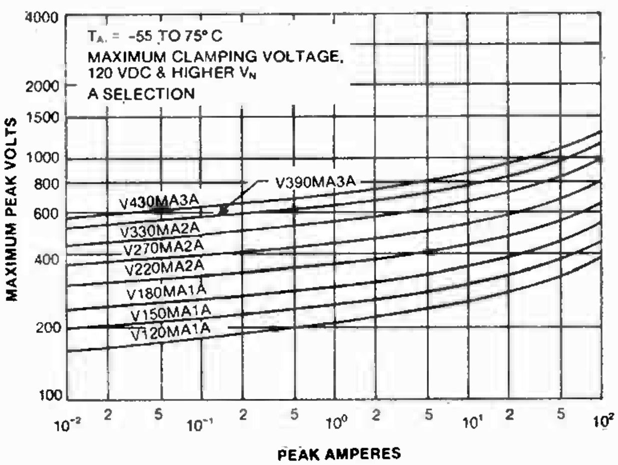
Please contact your local General Electric Sales Office for any specific high reliability requirement or for types presently available.

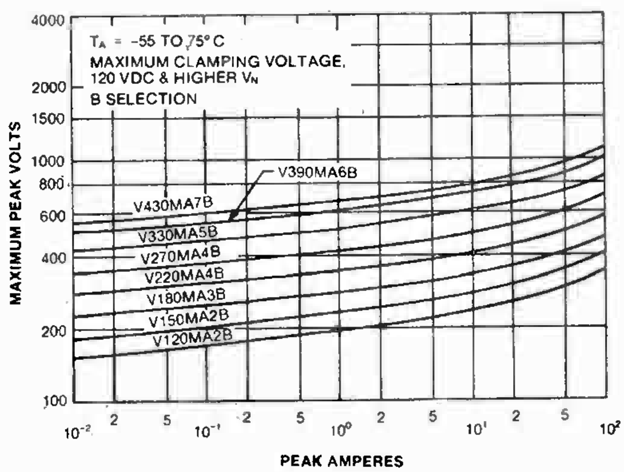
GE-MOV®II Metal Oxide Varistors
for Transient Voltage Protection

# TRANSIENT V-I CHARACTERISTICS: MA SERIES

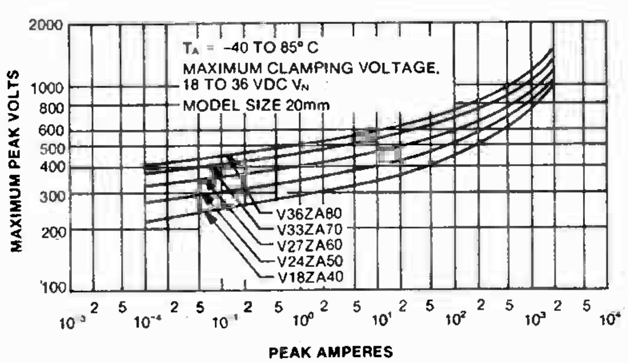


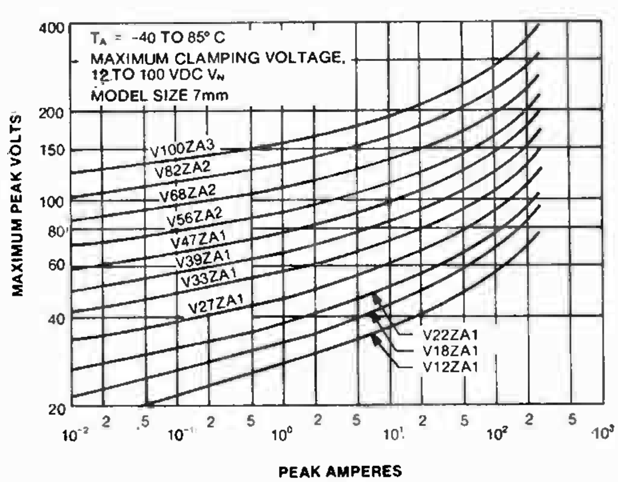



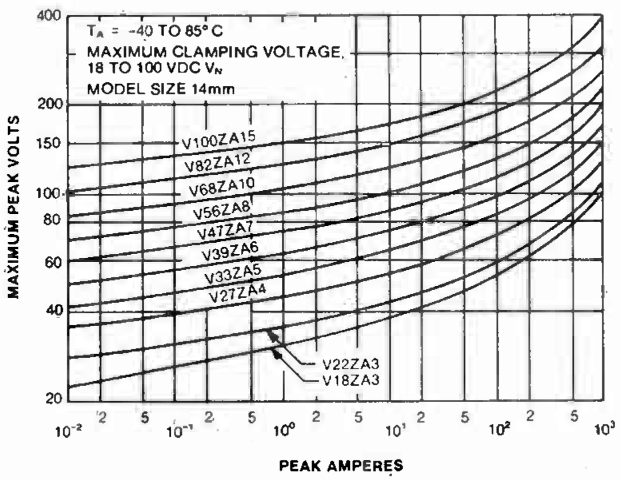



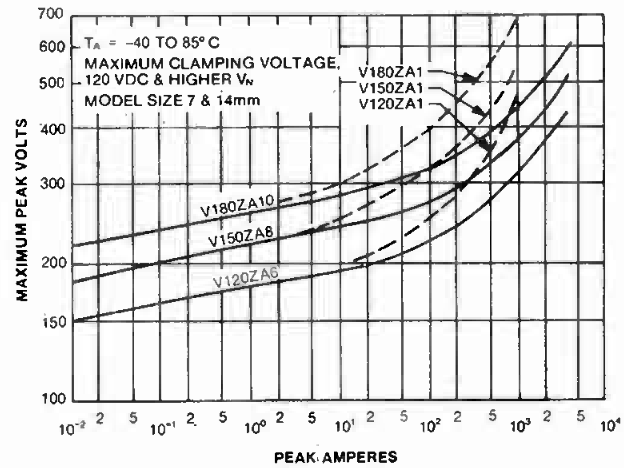

# Z SERIES



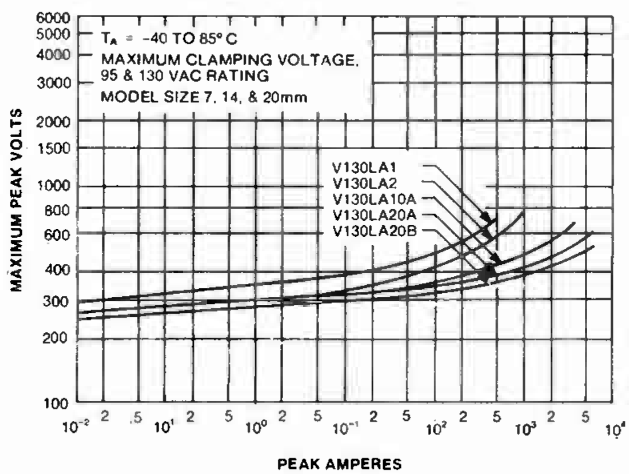



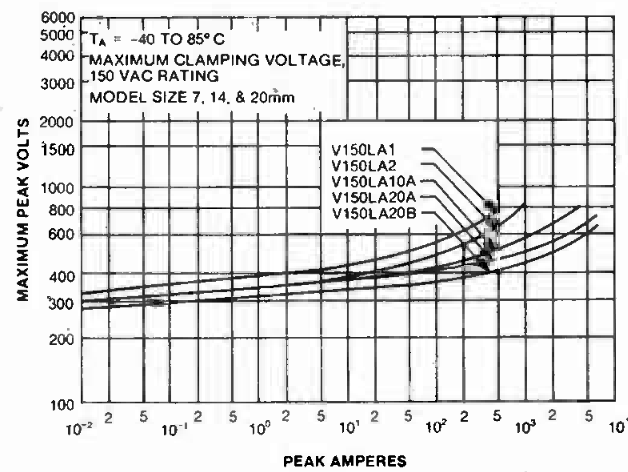
# TRANSIENT V-I CHARACTERISTICS: Z SERIES (cont'd)

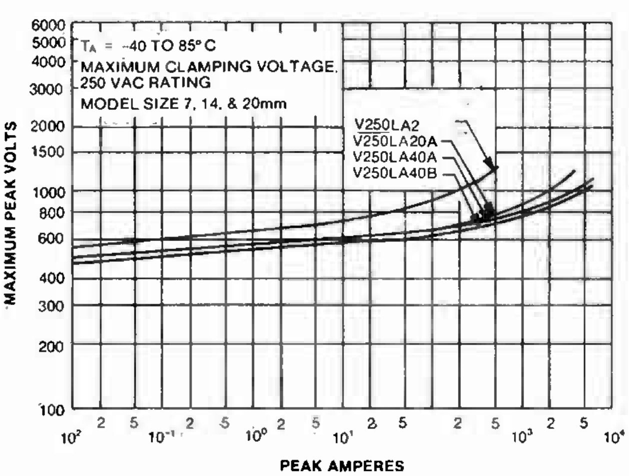


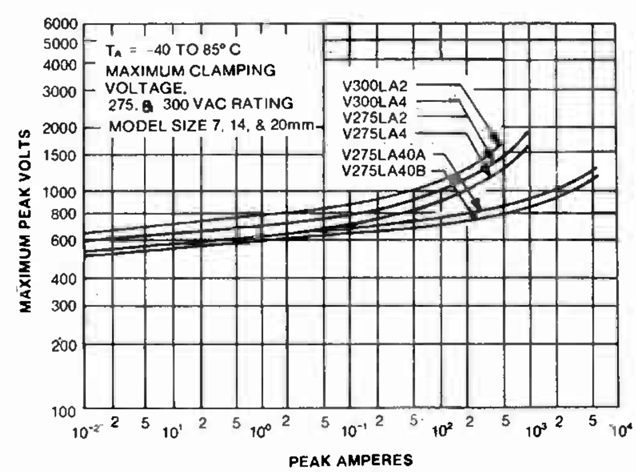




# L SERIES

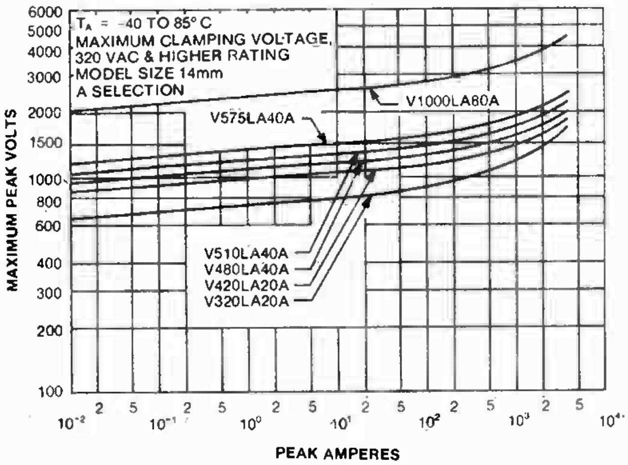


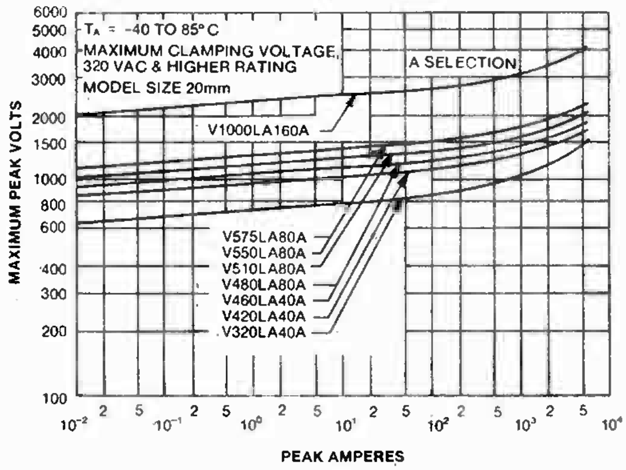



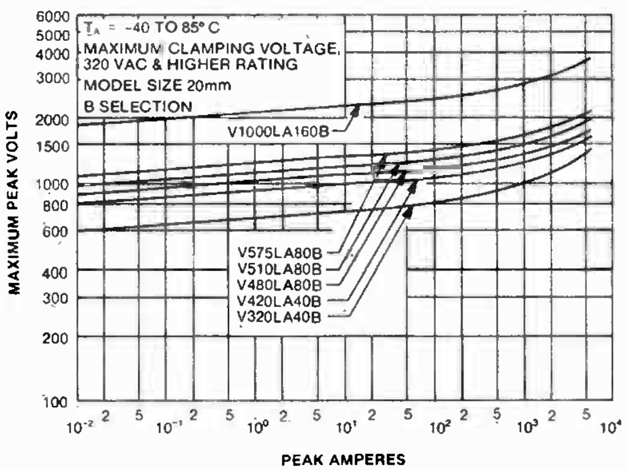



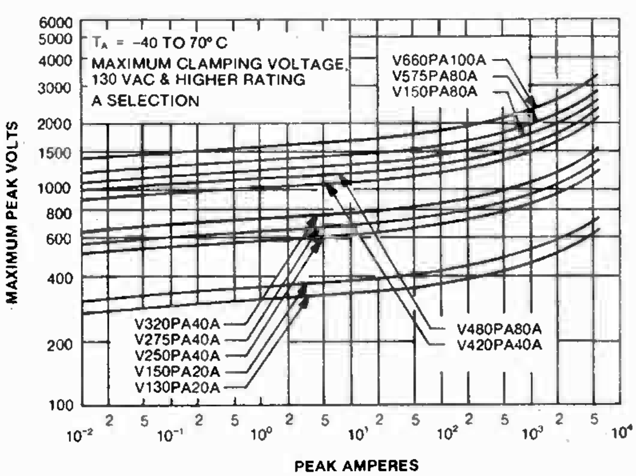
# TRANSIENT V-I CHARACTERISTICS: L SERIES (cont'd)

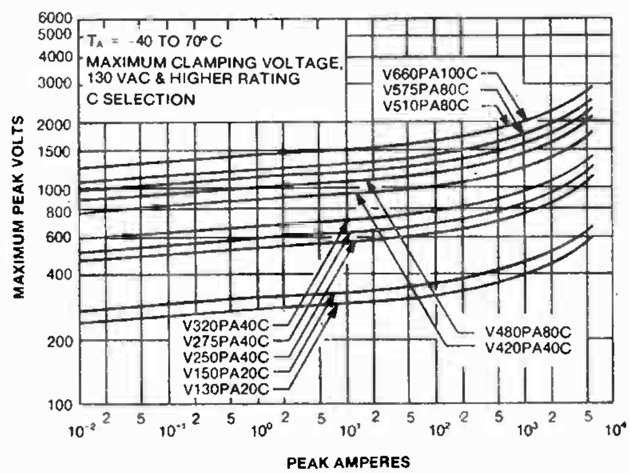


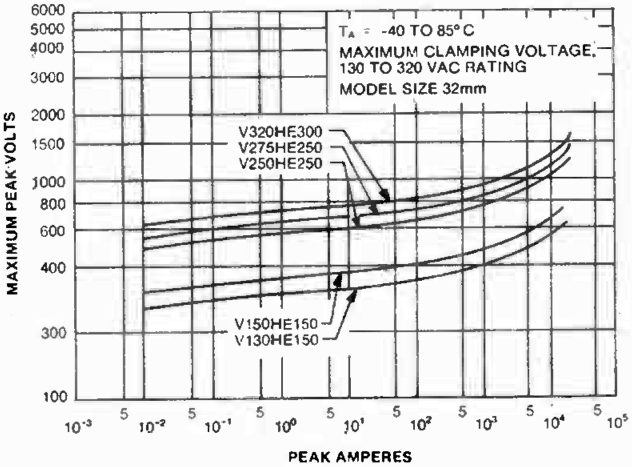



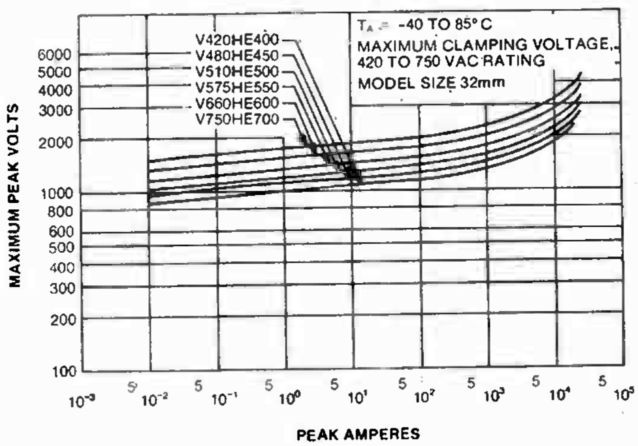

# P SERIES



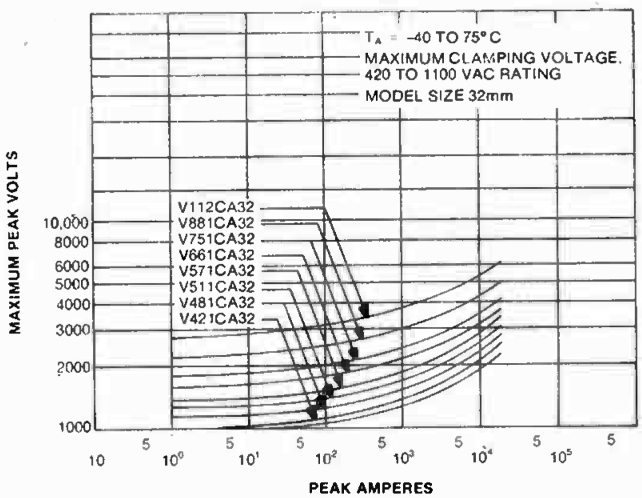



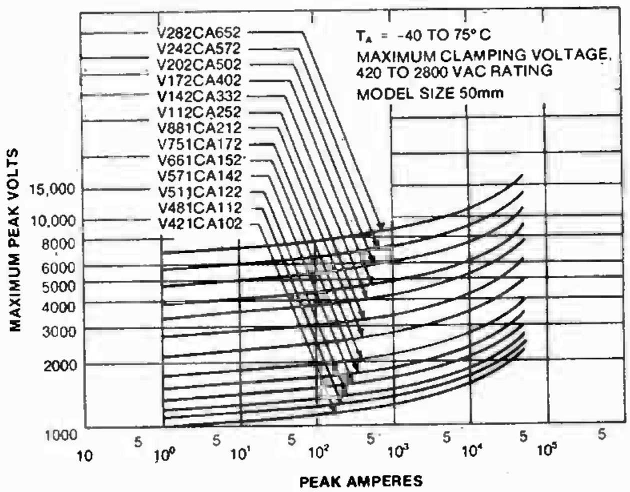
# TRANSIENT V-I CHARACTERISTICS: HE SERIES



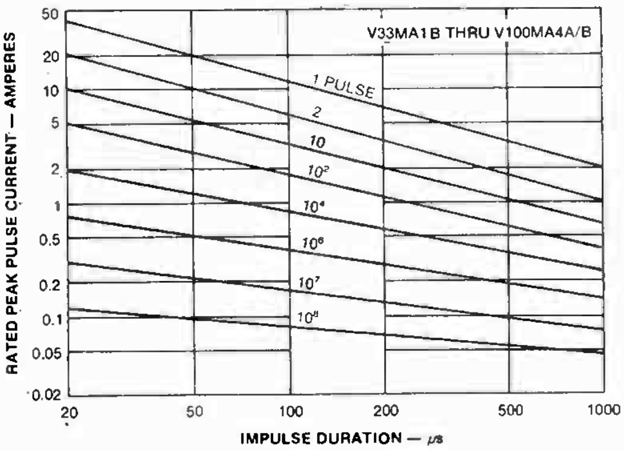



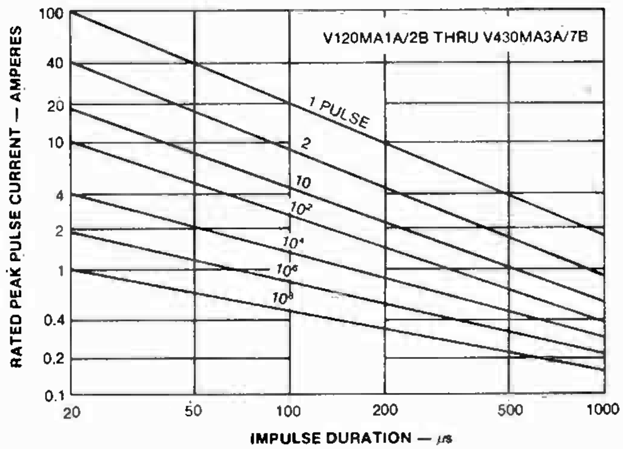

# C SERIES



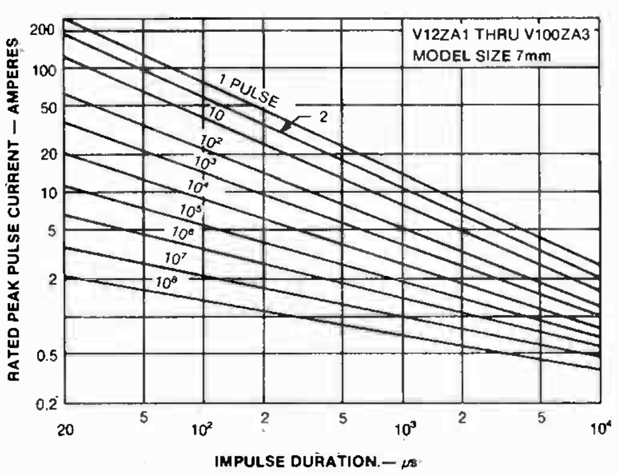



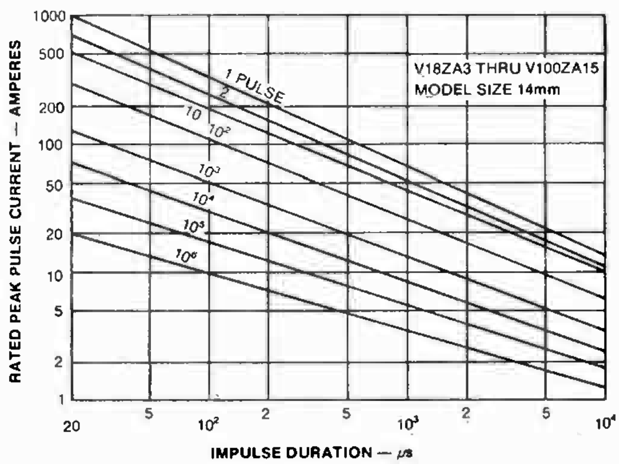
# PULSE LIFETIME RATINGS: MA SERIES

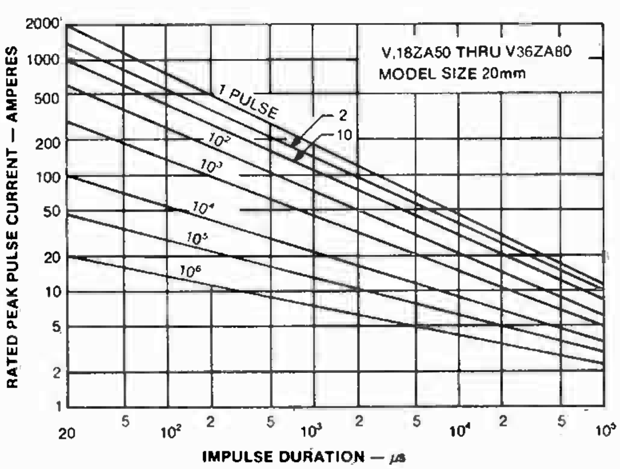


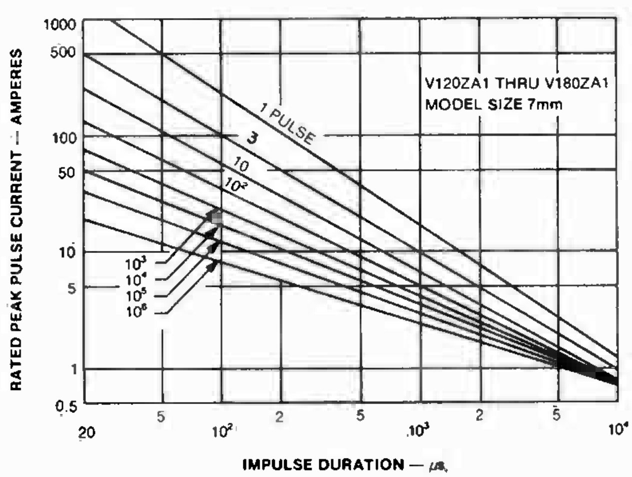




## Z SERIES

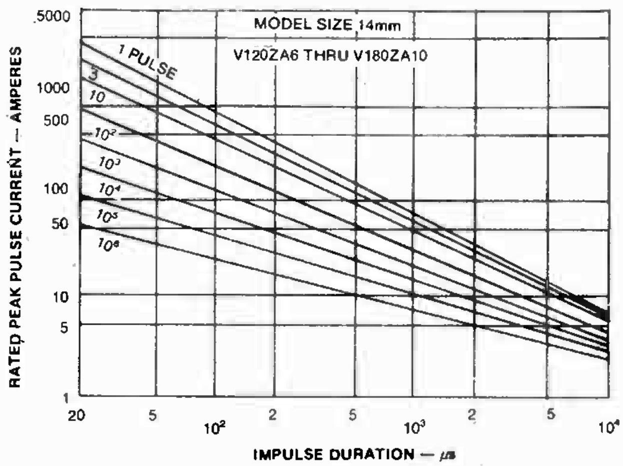


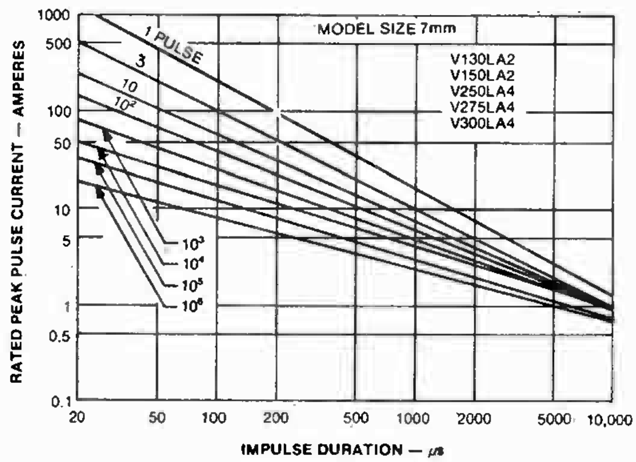
# PULSE LIFETIME RATINGS: Z SERIES (cont'd)

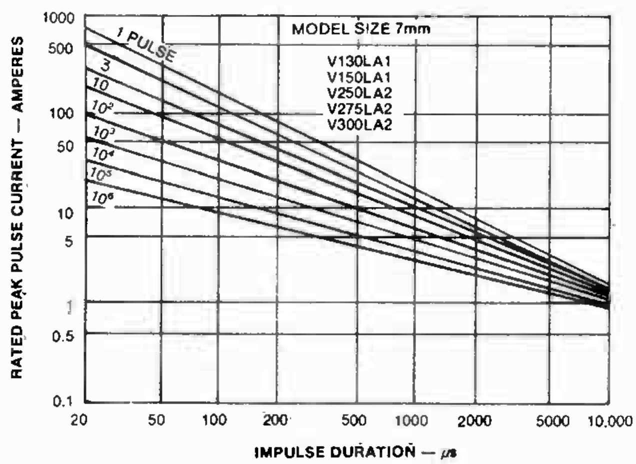


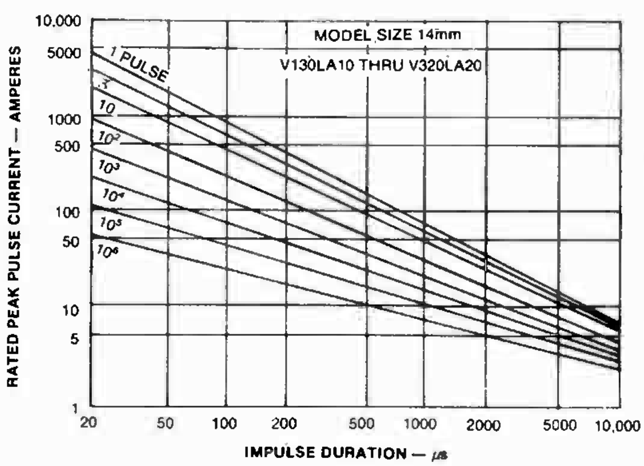

**NOTE:** End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere exceeding ±(10% +1V) of the initial value. This type of failure is normally a result of a decreasing $V_n$ value, but does not prevent the device from continuing to function.

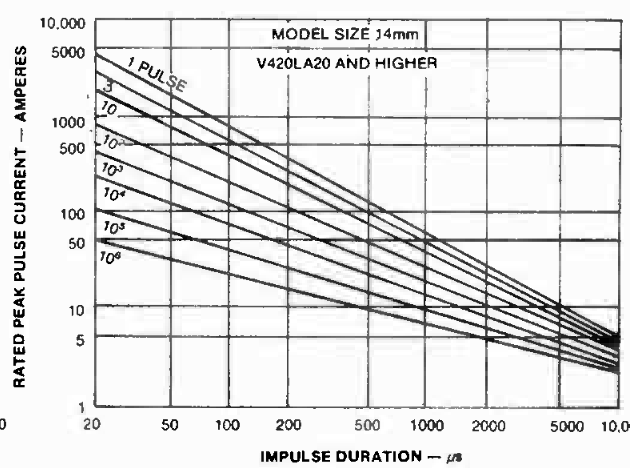
However, the varistor will no longer meet the original specifications. Note: for models V18ZA40, V24ZA50, V27ZA60, V33ZA70, V36ZA80 the applicable test current is 10mA.

# L SERIES

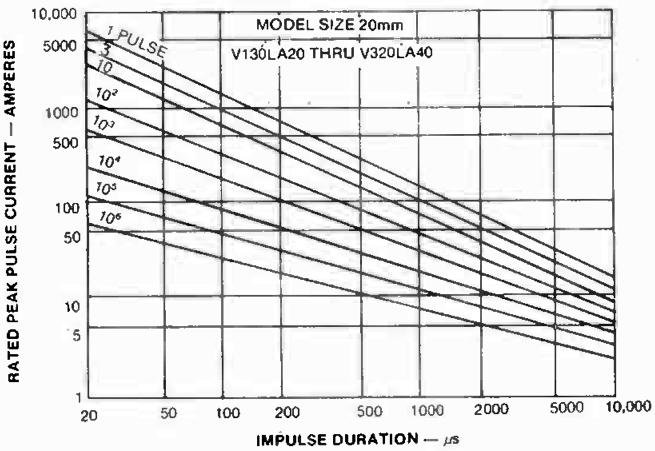


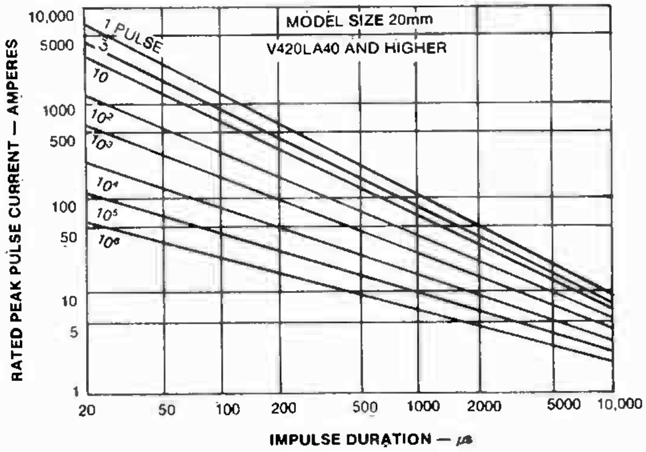



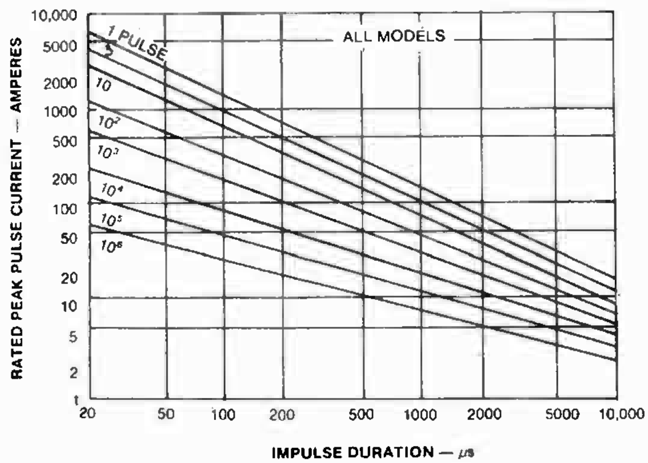



# PULSE LIFETIME RATINGS: L SERIES (cont'd)

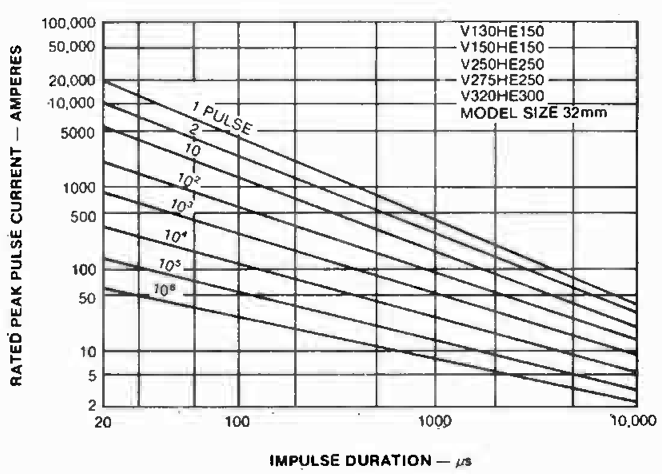



# P SERIES

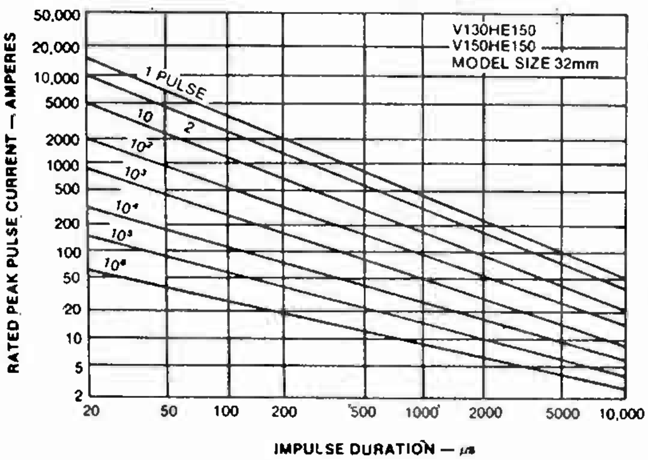


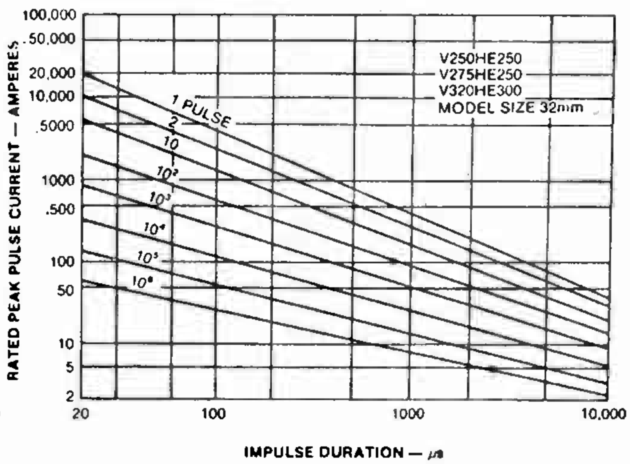

# HE SERIES

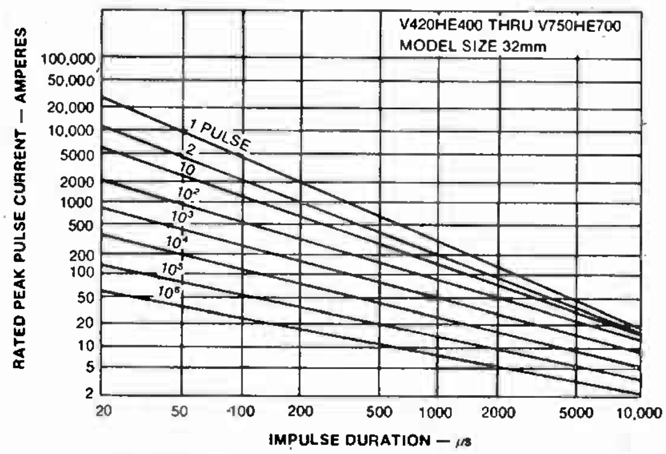



NOTE: End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere exceeding ± 10%, ± 1V of the initial value. This type of failure is normally a result of a decreasing $V_1$ value, but does not prevent the device from continuing to function. However, the varistor will no longer meet the original specifications.

# PULSE LIFETIME RATINGS: HE SERIES (cont'd)



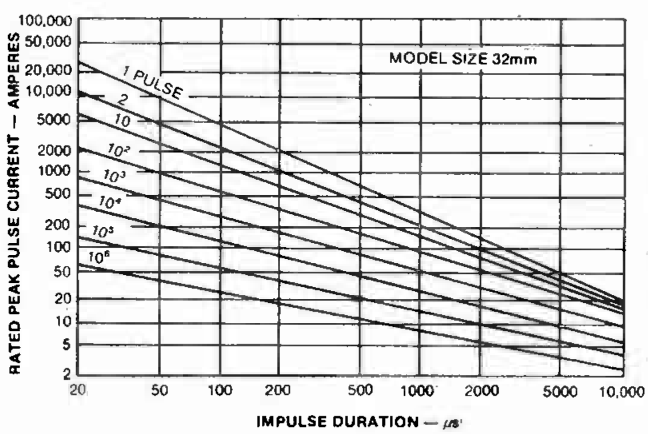



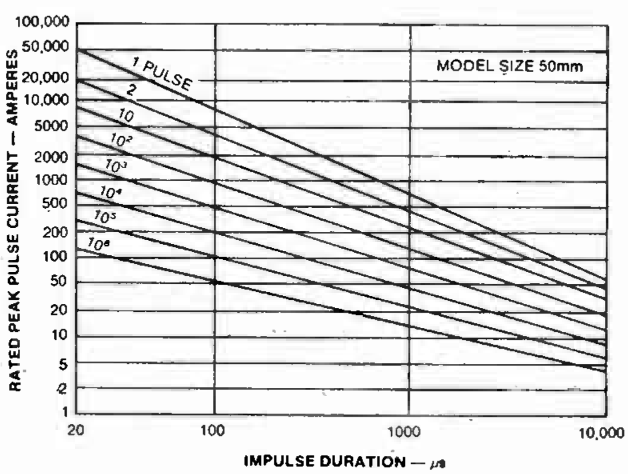




NOTE: End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere exceeding ±(10% + 1V) of the initial value. This type of failure is normally a result of a decreasing $V_1$ value, but does not prevent the device from continuing to function.

However, the varistor will no longer meet the original specifications.

# C SERIES

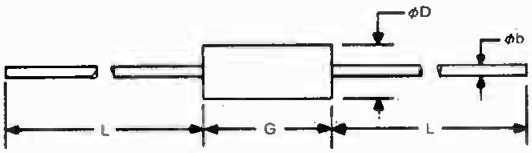



NOTE: End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere exceeding ±(10% + 1V) of the initial value. This type of failure is normally a result of a decreasing $V_1$ value, but does not prevent the device from continuing to function.

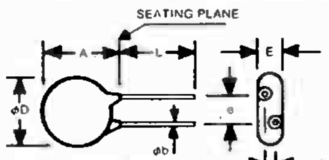
However, the varistor will no longer meet the original specifications.

# OUTLINES AND DIMENSIONS: MA SERIES




| SYMBOL | MILLIMETERS | | INCHES | |
|---|---|---|---|---|
| | MIN. | MAX. | MIN. | MAX. |
| ϕb | .60 | .83 | 0.024 | .033 |
| ϕD | 3.43 | 3.68 | .135 | .145 |
| G | 8.01 | 8.50 | .315 | .335 |
| L | 26.0 | 29.0 | 1.03 | 1.14 |

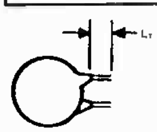
# Z AND L SERIES



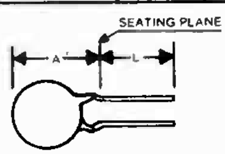

Standard Outline

| STANDARD OUTLINE DIMENSIONS | VARISTOR MODEL SIZE | | | | | |
|---|---|---|---|---|---|---|
| | 7mm | | 14mm | | 20mm | |
| | mm | in | mm | in | mm | in |
| A MAX. | 11.7 | 0.46 | 18.9 | 0.74 | 25.5 | 1.01 |
| ϕb MAX. | 0.68 | 0.027 | | | | |
| ϕb MIN. | 0.59 | 0.023 | | | | |
| ϕD MAX. | 10.0 | 0.39 | 16.4 | 0.65 | 22.5 | 0.89 |
| e MAX. | 8.5 | 0.33 | | | | |
| e MIN. | 4.0 | 0.16 | | | | |
| L MIN. | 25.4 | 1.00 | 25.4 | 1.00 | 25.4 | 1.00 |

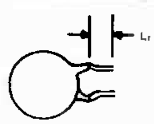
| STANDARD OUTLINE DIMENSIONS | MAXIMUM VARISTOR RMS VOLTAGE $V_{m(ac)}$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | V12ZA-V56ZA | | V68ZA-V160ZA | | V120ZA-V180ZA V130LA-V150LA | | V250LA-V575LA | | V1000LA | |
| | mm | in | mm | in | mm | in | mm | in | mm | in |
| $e_1$ MAX. | 3.8 | 0.15 | 5.5 | 0.22 | 3.8 | 0.15 | 5.5 | 0.22 | 9.0 | 0.35 |
| $e_1$ MIN. | 1.1 | 0.04 | 3.0 | 0.12 | 1.1 | 0.04 | 3.0 | 0.12 | 6.0 | 0.24 |
| E MAX. | 5.6 | 0.22 | 7.3 | 0.29 | 5.6 | 0.22 | 7.3 | 0.29 | 10.8 | 0.43 |




Trimmed Standard Lead



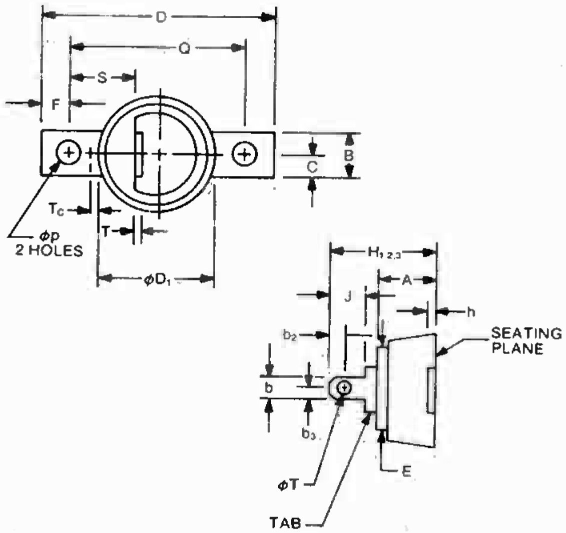

Crimped Lead




Crimped and Trimmed Lead

| AVAILABLE CHANGES | VARISTOR MODEL SIZE | | | | | |
|---|---|---|---|---|---|---|
| | 7mm | | 14mm | | 20mm | |
| | mm | in | mm | in | mm | in |
| Trim $L_T$ MAX. | 4.8 | 0.19 | 4.8 | 0.19 | 4.8 | 1.9 |
| Trim $L_T$ MIN. | 3.4 | 0.13 | 3.4 | 0.13 | 3.4 | 0.13 |
| Crimp A MAX. | 15.0 | 0.59 | 22.5 | 0.89 | 29.0 | 1.14 |

# OUTLINES AND DIMENSIONS: P SERIES

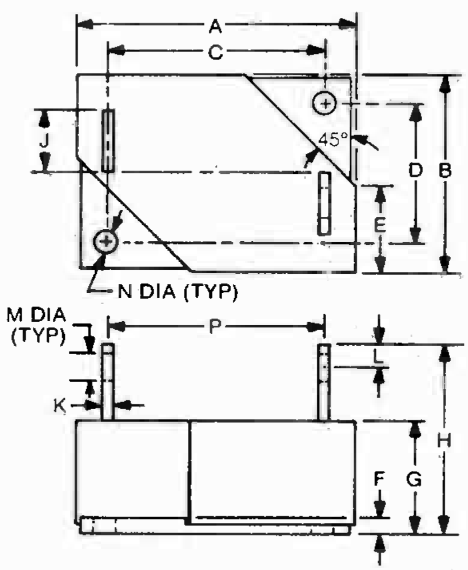



| SYMBOL | INCHES MIN. | INCHES NOM. | INCHES MAX. | MILLIMETERS MIN. | MILLIMETERS NOM. | MILLIMETERS MAX. | NOTES |
|---|---|---|---|---|---|---|---|
| A | | | .57 | | | 14.3 | |
| b | | | .26 | | | 6.6 | 1 |
| $b_2$ | | .16 | | | 4.1 | | |
| $b_3$ | | .13 | | | 3.2 | | |
| B | | | .51 | | | 12.9 | |
| C | | | .26 | | | 6.5 | |
| D | | | 2.61 | | | 66.2 | |
| $\phi D_1$ | | | 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 | |
| $\phi p$ | .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 | |
| $\phi T$ | .11 | | | 2.8 | | | |
| $T_c$ | | .13 | | | 3.2 | | 2 |

NOTES:

1. Tab is designed to fit ¼" 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)
   $H_3$ (420-660$V_{RMS}$ devices)
4. Electrical connection: top terminal and base plate.

# HE SERIES




| DIMENSION | MILLIMETERS | INCHES |
|---|---|---|
| A | 61 MAX. | 2.40 MAX. |
| B | 41. MAX. | 1.60 MAX. |
| C | 44.45 ± .75 | 1.75 ± .03 |
| D | 25.40 ± .75 | 1.00 ± .03 |
| E | 16.5 NOM. | .65 NOM. |
| F | 3.2 NOM. | .13 NOM. |
| G | 23 MAX. | .91 MAX. |
| H | 41 MAX. | 1.60 MAX. |
| J | 13 NOM. | .51 NOM. |
| K | 1.6 NOM. | .06 NOM. |
| L | 6.4 NOM. | .25 NOM. |
| M | 6.4 NOM. | .25 NOM. |
| N | 5.4 NOM. | .21 NOM. |
| P | 40.5 NOM. | 1.6 NOM. |

Maximum Weight ............................... 120 gm.

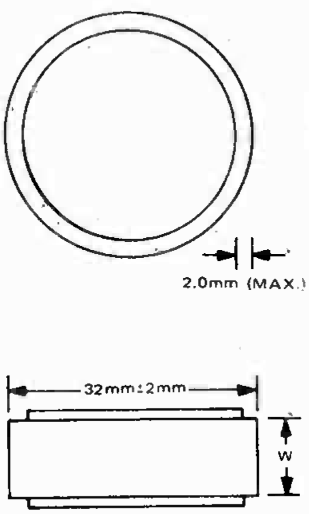
Minimum Strike and Creep Distance

Terminal to Terminal ........................... 1.4 in. (3.5 cm.)

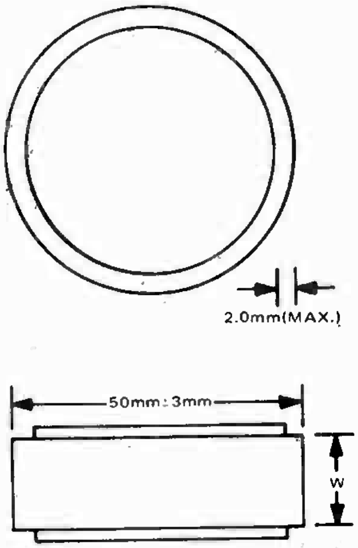
Terminal to Baseplate ........................... 0.80 in. (2.0 cm.)

# OUTLINE DIMENSIONS:
# C SERIES

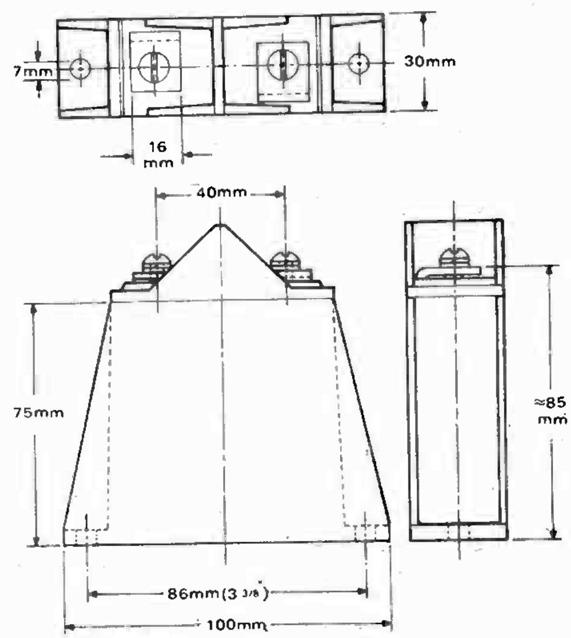
32mm




50mm



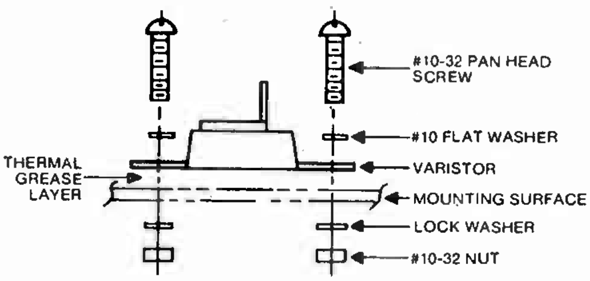

PACKAGE BELL TYPE*



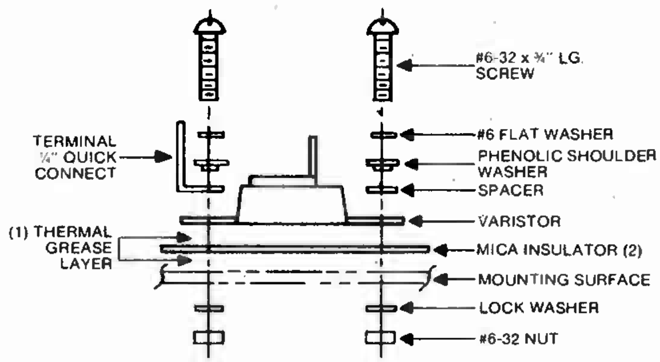

| $V_{ACM}$ (RMS) | Disc Thickness — W | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 32mm Models | | | | 50mm Models | | | |
| | mm | | Inches | | mm | | Inches | |
| VOLTS | MIN. | MAX. | MIN. | MAX. | MIN. | MAX. | MIN. | MAX. |
| 420 | 3.9 | 5.9 | 0.15 | 0.23 | 3.9 | 5.9 | 0.15 | 0.23 |
| 480 | 4.3 | 6.5 | 0.17 | 0.26 | 4.3 | 6.5 | 0.17 | 0.26 |
| 510 | 4.8 | 7.2 | 0.19 | 0.28 | 4.8 | 7.2 | 0.19 | 0.28 |
| 575 | 5.2 | 7.9 | 0.20 | 0.31 | 5.2 | 7.9 | 0.20 | 0.31 |
| 660 | 6.1 | 9.2 | 0.24 | 0.36 | 6.1 | 9.2 | 0.24 | 0.36 |
| 750 | 7.0 | 10.4 | 0.28 | 0.41 | 7.0 | 10.4 | 0.28 | 0.41 |
| 880 | 8.4 | 13.0 | 0.33 | 0.51 | 8.4 | 13.0 | 0.33 | 0.51 |
| 1100 | 10.5 | 16.3 | 0.41 | 0.64 | 10.5 | 16.3 | 0.41 | 0.64 |
| 1400 | — | — | — | — | 13.1 | 20.2 | 0.52 | 0.80 |
| 1700 | — | — | — | — | 16.3 | 23.9 | 0.64 | 0.94 |
| 2000 | — | — | — | — | 19.3 | 28.7 | 0.76 | 1.13 |
| 2400 | — | — | — | — | 22.8 | 33.9 | 0.90 | 1.33 |
| 2800 | — | — | — | — | 27.5 | 40.8 | 1.08 | 1.60 |

* For Further Information and Model Numbers, Contact Factory

# SUGGESTED MOUNTING OF THE P SERIES VARISTOR




## Typical Non-Isolated Mounting




## Typical Isolated Mounting

NOTES:

(1) GE G623, Dow Corning, DC3, 4, 340, or 640 Thermal Grease is recommended for best heat transfer.

(2) 1000-volt isolation kit containing the following parts can be ordered by part #A7811055.
- (1) MICA insulation 1" / 3.1" / .005" thick.
- (2) #6-32 / ¾ screw.
- (2) #6 flat washer.
- (2) Phenolic shoulder washer.
- (2) #6 internal tooth lock washer.
- (2) #6-32 nut.
- (1) ¼" quick connect terminal.
- (1) Spacer.

# SPECIAL PRODUCT MARKINGS

Standard marking on GE-MOV®II Varistors includes complete model number and date code. However, because of size limitations all 7mm radial types are marked with an abbreviated model number as follows:

**L Series**

| MODEL NUMBER | MARKING |
|---|---|
| V130LA1 | 1301 |
| V130LA2 | 1302 |
| V150LA1 | 1501 |
| V150LA2 | 1502 |
| V250LA1 | 2502 |
| V250LA4 | 2504 |
| V275LA2 | 2752 |
| V300LA2 | 3002 |
| V300LA4 | 3004 |

**Z Series**

| MODEL NUMBER | MARKING |
|---|---|
| V12ZA1 | 12Z1 |
| V18ZA1 | 18Z1 |
| V22ZA1 | 22Z1 |
| V27ZA1 | 272A |
| V33ZA1 | 33Z1 |
| V39ZA1 | 39Z1 |
| V47ZA1 | 47Z1 |
| V56ZA2 | 56Z2 |
| V68ZA2 | 68Z2 |
| V82ZA2 | 82Z2 |
| V100ZA3 | 100Z |
| V120ZA1 | 120Z |
| V150ZA1 | 150Z |
| V180ZA1 | 180Z |

# index

# index

# index

Semiconductor Products Department
General Electric Company
Auburn, NY 13021

GENERAL ELECTRIC

400.3 4/82 (50M) WP

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