Metal-oxide varistor:
a new way to suppress transients

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Significance
Part 6: Textbooks, tutorials and reviews
Part 7: Mitigation techniques

Trade press announcement of the introduction to the U.S. market of Metal-Oxide Varistors intended for incorporation in original equipment manufacturers (OEM) equipment, with discussion of the principle of operation, background information on the origin of transients, and application information.

It is noteworthy that this announcement was released as early a October 1972, aimed at electronic OEM equipment but the corresponding announcement (with research results) of the availability of MOV-based surge arresters for the utility market was published much later, via the IEEE Transactions paper of March 1977 by Sakshaug et al., "*A New Concept in Station Arrester Design*" – see the file "New concept" in the annex of Part.7 of this Anthology.

Metal-oxide varistor: a new way to suppress transients

Able to withstand peak currents of hundreds of amperes, the small disk-shaped metal-oxide type of varistor dissipates negligible standby power while guarding against power-line surges and turn-on transients

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☐ Although it belongs to the established family of reliable varistor protection devices, the recently introduced metal-oxide type of varistor is adding a new dimension to the technology of protecting circuits and components. Trademarked as the GE-MOV and MOV varistor by General Electric Co., the metal-oxide-type varistor offers the advantages of nanosecond switching speeds and small size, while being able to handle current surges on the order of hundreds of amperes.

Like other varistor transient suppressors, the new varistor has a nonlinear voltage-current characteristic that makes it useful in voltage-regulation applications. And because its nonlinear V-I curve is very steep—steeper than that of most other varistors—it can pass widely varying currents over a narrow voltage range. In some applications, using the device allows a circuit to be redesigned with fewer components.

At low applied voltages, the metal-oxide-type varistor looks like an open circuit because its unique two-phase material assumes the properties of an insulator. When applied voltage exceeds rated clamping voltage, the device effectively becomes a short circuit, protecting the component that it shunts.

The unit, moreover, requires very little standby power, making it useful for guarding semiconductors. Steady-state power dissipation is typically a fraction of a milliwatt, as compared to the hundreds of watts dissipated by some other varistor devices.

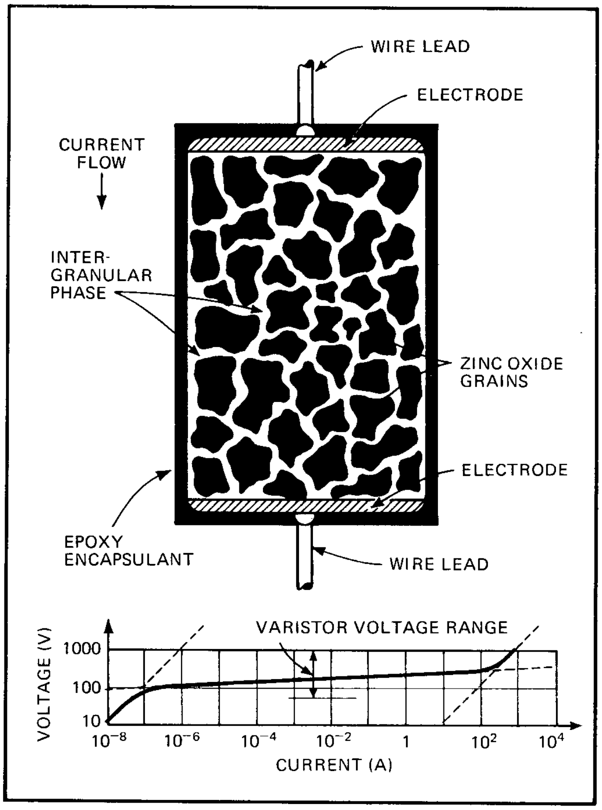
At present, operating voltage ratings for MOV-brand series VP varistors range from 140 to 1,400 volts peak, watt-second ratings from 10 to 160 joules, and continuous power ratings range from 0.5 watt to 1.3 w. Units are priced from less than $1 to $14 in 1,000-unit lots.

An inside look

The metal-oxide-type varistor (Fig. 1) has an encapsulated polycrystalline ceramic body, with metal contacts and wire leads. Zinc oxide and bismuth oxide, the essential ingredients, are mixed with proprietary powdered additives, and then pressed into disks and sintered at a temperature greater than 1,200°C.

Because the bismuth oxide is molten above 825°C, it assists in the formation of a dense polycrystalline ceramic through liquid-phase sintering. During cooling, the liquid phase forms a rigid amorphous coating around each zinc oxide grain, yielding a microstructure of zinc oxide grains that are isolated from each other by a thin continuous intergranular phase. It is this complex two-phase microstructure that is responsible for the nonlinear characteristic.

The voltage across a metal-oxide-type varistor and the current through it are related by the power law, $I = kV^n$, where k is a constant. Exponent n, which is



1. Properties. Two-phase material in body of metal-oxide-type varistor acts as insulator for low applied voltages and as conductor for transients that exceed device's clamping voltage. Bistable intergranular phase containing bismuth oxide surrounds each conductive zinc oxide grain. Idealized V-I curve illustrates unit's nonlinear behavior in varistor voltage range.

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also referred to as alpha (α), typically has a value between 25 and 50 or more, leading to the idealized V-I curve of Fig. 1. Over a wide current range, the voltage remains within a narrow band that is commonly called the varistor voltage.

Many properties of the varistor can be directly related to the microstructure and the properties of the two phases. As shown in Fig. 1, the unit's idealized V-I curve consists of two linear segments for extremely low and extremely high currents, and a nonlinear segment in the varistor voltage range.

At low applied voltages, the device's linear characteristic can be attributed primarily to leakage current through the intergranular phase. Device behavior is roughly that of an insulator, indicating that low applied voltages cause a high electric field across the intergranular phase and a low field within the zinc oxide grains.

In the varistor voltage range, the intergranular phase becomes nonlinear, and current through it increases rapidly as the voltage is raised slowly. The conduction mechanism that affects the nonlinear characteristic is now under investigation and is thought to be space-charge-limiting or tunneling phenomena. For extremely high currents, the resistance of the intergranular layer becomes less than that of the zinc oxide grains, causing the V-I curve to tend towards linearity again.

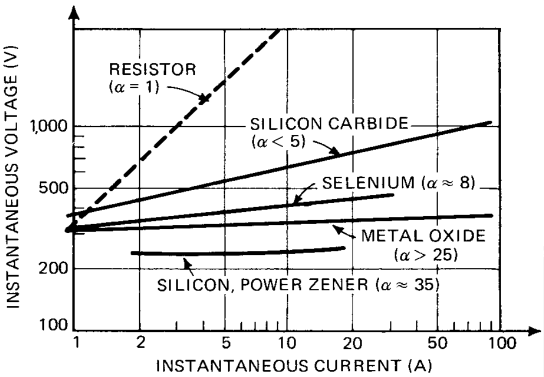
Comparing transient suppressors

A comparison of the volt-ampere characteristic of the metal-oxide-type varistor to that of other voltage suppressors yields the graph shown in Fig. 2. A number of varistor devices are represented, including silicon, selenium, silicon-carbide, and metal-oxide types. A point-of-reference curve for a linear ohmic resistor is also shown. The higher a device's alpha is, the better is its voltage suppression capability.

The parameters of some of the most widely used transient voltage suppressors are summarized in the table of Fig. 2. (The commercial voltage ratings reflect peak values; they must be divided by 1.41 to obtain root-mean-square values.) It should be noted that selenium suppressors are normally supplied as a single package of several series-connected plates, so that the selenium voltage rating is not that of a single plate. The other varistor data, however, reflects single-unit ratings.

Metal-oxide-type varistors can also be connected in series to increase clamping-voltage rating. Moreover, they can serve in a structural mode as well as an electrical one, for instance, by replacing the spacer between switch contacts to allow approaching arcless switching commutation, especially in dc applications.

One of the most important considerations when choosing a protection device is its steady-state power dissipation. In the case of varistors, the higher the alpha or exponent, the lower will be the standby loss. For example, if a varistor is shunted across a load, protecting it at a 300-V level in the presence of a 2,000-V transient with a surge impedance of 10 ohms, a steady-state power dissipation is required of the varistor, since it is connected continuously to the 117-V rms line. For the silicon-carbide varistor, which has a typical alpha of 3,



2. Suppressor comparison. V-I curves of various varistor transient suppressors and linear ohmic resistor show that characteristic for metal-oxide-type varistor is nearly horizontal because of its high alpha (^{a}) value. (All varistors obey power law, $I = kV^{\alpha}$.) Table compares some key specifications for several popular surge protectors. Shortly, clamping-voltage range will be broader for 9MOV varistors.

TYPICAL SURGE SUPPRESSOR PARAMETERS								
TRANSIENT SUPPRESSOR	PEAK IDLE CURRENT (mA)	MAX CURRENT - 1 ms - (A)	PEAK POWER - 1 ms - (kW)	PEAK ENERGY - 1 ms - (joules)	EFFECTIVE CLAMPING RATIO AT 10 A	WEIGHT (grams)	VOLUME (cm^3)	COMMERCIAL PER-DEVICE VOLTAGE RANGE (V)
MOV-brand varistors (26.21 mm OD)	1	65	18	18	2.0	5	4.4	140 – 1,400
Selenium (25.4 mm sq)	12	30	9	9	2.3	35	20	35–700
Zener, 6-cell cluster (38 mm sq)	0.05	20	7.7	7.7	1.50	30	24.5	14–165
Zener, single (DO-13 case)	0.005	5.7	1.65	1.65	1.65	1.5	0.5	1.8–300
Spark gap (8 mm OD)	–	<100	50	50	2.55 (100 V/μs)	1.5	0.6	150 MIN

the necessary steady-state dissipation will be 660 w. On the other hand, a metal-oxide-type varistor with an exponent of 30 will dissipate only 0.1 milliwatt.

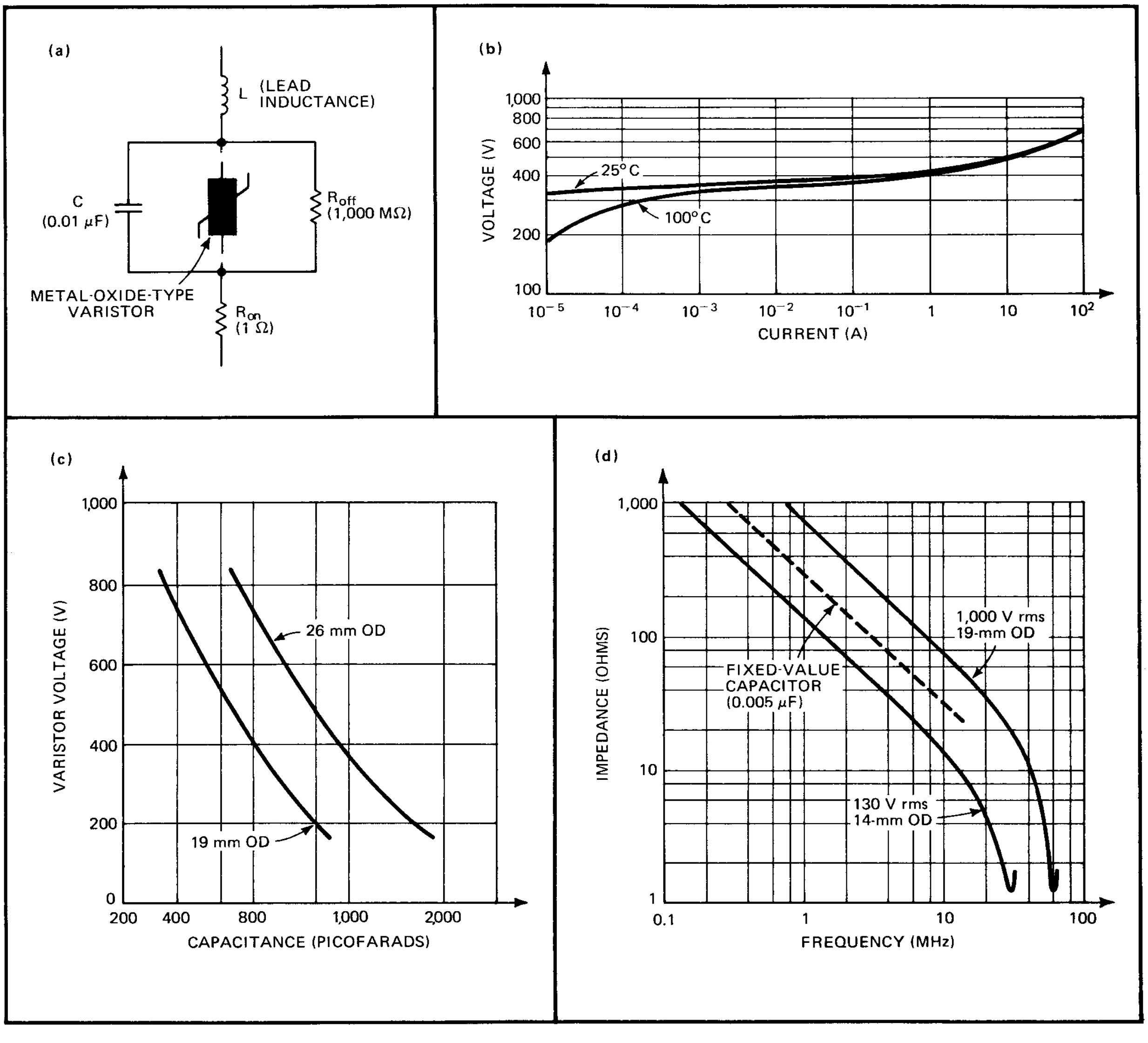
Examining device behavior

Fig. 3a shows the simplified equivalent circuit for the metal-oxide-type varistor, as well as its schematic symbol; representative capacitance and resistance values are used. The low-current-level resistance, R_{off}, is due primarily to the resistivity of the intergranular phase. Capacitance C can be attributed to the very thin dielectric of the intergranular phase; it becomes a fairly significant factor for the varistor's dynamic characteristic. The high-current-level resistance, R_{on}, is due to the intrinsic resistivity of the zinc oxide grains; it represents the unit's limiting resistance. The component values in the figure are for a typical MOV-brand series VP device.

As indicated in Fig. 3b, the device's V-I curve ordinarily exhibits a slightly negative voltage temperature coefficient, in the order of 0.01%/°C to 0.05%/°C for the series VP varistors. At very low current levels, this coefficient is substantially larger but does not affect the normal operating range. Maximum steady-state power dissipation for a disk with 3 square centimeters of total surface area is usually 1 w in a 70°C free-convection ambient environment.

Typical capacitance curves are depicted in Fig. 3c for units with differing diameters. Device capacitance influences high-frequency impedance properties, as shown by the plots of Fig. 3d for two production units—

3. Electrical behavior. Equivalent circuit (a) of metal-oxide-type varistor contains high-resistance element to model device's insulator state and low-resistance element for conductor state. Temperature rise from 25°C to 100°C produces only small negative voltage shift in V-I curve (b). Device capacitance (c), which is due to dielectric/conductor intergranular phase, depends on varistor size and voltage rating. Above frequencies of about 10 megahertz, varistor impedance (d) becomes nonlinear because device capacitance increases.



one with a 130-v rms rating, and the other with a 1,000-v rms rating. A point-of-reference curve for a fixed 0.005-microfarad capacitor is also included.

When a fast-rising surge is applied to a metal-oxide-type varistor, its capacitance immediately makes it appear as a low impedance. After the capacitance becomes fully charged, the unit simply operates at the point predicted by its V-I characteristic.

Tracing the origin of transients

Transient surges originate from a variety of sources. Regardless of whether electrical circuits operate from ac or dc sources, they are often plagued by voltage transients that are either generated within the circuit itself or transmitted into the circuit from external sources.

One of the most common sources of transients in power distribution systems is the L(di/dt) voltage caused by transformer magnetizing currents as the transformers are switched within either a feeder utility system or an industrial plant's own distribution system. Residual lightning surges are another source of concern. These surges can be thought of as an overflow on the main lightning arrestors with which most consumer, commercial, and industrial distribution systems are protected at the interface between the utility and the user's distribution systems. Still other sources can be found in homes themselves, resulting from equipment that is connected to the utility system.

Even a small synchronous line clock in the home can be subjected to a number of surges within just a 24-hour period. In fact, with the introduction of more automatic switching functions and complex electrical equipment into the home, line surges are becoming more frequent. And oddly, the better and newer the wiring and installation, the less inherent protection is provided by spillover occurring in poorly wired outlets, switches, and fixtures, and the greater the resulting impressed voltage level on connected equipment.

Using metal-oxide-type varistors

When a stepdown transformer is switched on, it can impress severe transients on any components connected to its secondary winding due to its interwinding capacitance. Installing a metal-oxide-type varistor, as shown in Fig. 4a, can eliminate this startup transient.

Another source of component failure, which is sometimes overlooked, can occur in the conventional transistor series-pass voltage regulator (Fig. 4b). When the circuit is turned on, the capacitor appears to be a short circuit, and the transistor is exposed to the full unregulated bus voltage. Placing a metal-oxide-type varistor across the transistor allows a soft current rise to pass through the regulator without the usual voltage surge.

Semiconductors can be protected with the new varistor, resulting in a design with fewer components, because the device can improve the electrical properties of the circuit in which it is installed. As an example, consider the output stage of small line-operated radio (Fig. 4c) that requires high-voltage transistors and an associated RC network to withstand the voltage spikes generated by distortion during overload.

The oscilloscope traces of transistor stress show the voltage transient that occurs with normal RC suppression but is dramatically reduced with varistor suppression. Because of this significant transient reduction, the circuit can be redesigned with fewer parts. (The third scope trace displays varistor current.)

Choosing the right varistor

Selecting the correct metal-oxide-type varistor is a simple, logical procedure. First, find the device with a peak operating voltage rating that is close to, yet higher than, the normal peak ac-line voltage. Next, determine or estimate the energy level of the transient to be suppressed. This energy level is usually determined by the energy term, $LI^2/2$, where I is the peak magnetizing current flowing in inductance L, which stores the transient energy in its field. In the case of transformers, I may be considered the peak exciting current.

The expected transient current level must be found next. (Peak feeder transformer magnetizing current, reflected to the secondary, is often used to estimate the peak transient current.) Then, the varistor unit can be selected that has the proper ratings for recurrent voltage, clamping voltage, and energy level.

In the case of dc applications, varistor steady-state power dissipation should be checked. Be sure to derate the device's energy rating if power dissipation demands will elevate the varistor case temperature above 85°C. For applications where repetitive transients may be encountered, calculate the expected watt-seconds per pulse and multiply this figure by the pulse repetition rate to determine the additional steady-state power dissipation required. And finally, make certain that the unit can comply with such ambient environmental factors as operating and storage temperatures.

Looking ahead

The next major developments for MOV-brand varistors will revolve around package changes to enhance applications versatility and improve heat transfer. Future packages will be available in a variety of mounting schemes—for example, a bolt-down version with or one without heat-transfer capability that could be directly fastened to chassis, brackets, bus bars, and heat exchangers. Low-inductance pill-shaped packages that are compatible with pressure-mounted thyristors are also being considered. Another possibility is a finned package for direct air convection and forced cooling.

Since metal-oxide-type varistors can be made rather thick, they should be available in the near future with kilovolt ratings. MOV-brand series VP units are currently being developed to cover the clamping voltage range of 30 V to 10 kV. □

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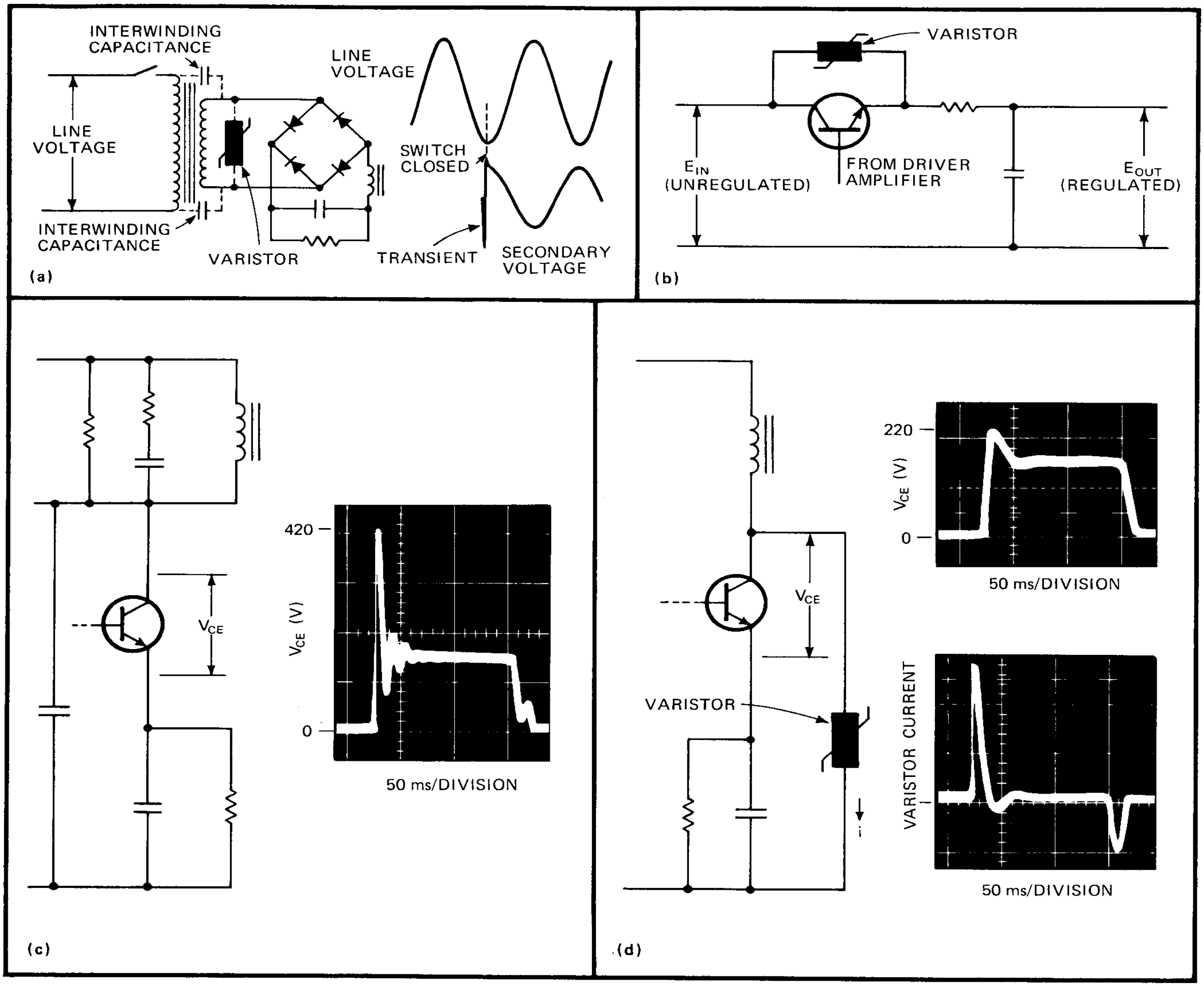

4. Applications. Switching transient on step-down transformer (a) can be prevented from damaging components by placing varistor across secondary winding. In (b), varistor protects transistor in series-pass regulator circuit from possible turn-on transient. Guarding transistor in radio output stage (c) with varistor permits circuit on left to be redesigned with fewer components, as shown on right. Scope traces depict voltage across unprotected transistor (left) and protected transistor (right), as well as varistor current (right).

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