

Degradation is not likely in MOVs used within their specifications

# Metal Oxide Varistor Degradation

The purpose of this document is to provide an overview of the degradation process that can occur in metal oxide varistors (MOVs). MOVs are variable resistors primarily consisting of zinc oxide (ZnO) with the function of limiting or diverting transient voltage surges. MOVs exhibit a relative high energy absorption capability which is important to the long term stability of the device. The growing demand of ZnO varistors is due to the nonlinear char-



by Kenneth J. Brown

Photo 1

acteristics as well as the range of voltage and current over which they can be used. This range is far superior to devices composed of other materials that were used prior to the development of MOVs.<sup>1</sup>

If MOVs are used within their well-defined specifications, degradation due to the environment is not likely. How-

## Resistance of an MOV decreases as voltage magnitude increases.

ever, the environment that MOVs are used in is not well-defined. Low voltage ac mains are subject to lightning strikes, switching transients, voltage swells/sags, temporary overvoltages (TOVs) and other similar disturbances. Due to the variety of disturbances that MOVs are exposed to, degradation or failure are possible in many applications.

MOVs perform their intended function reliably and experience low failure rates when applied within their specified limits. For an MOV to operate without failure or degradation it must quickly dissipate absorbed energy and return to its standby operating temperature. The ability to dissipate energy to the environment will depend on the design of the environment itself—ambient temperature, ventilation, heat sinking, other component population and density, proximity of heat sources, weight of PCB conductor traces, presence of thermal cutoff devices, etc. Degradation and catastrophic failures may occur if an MOV is subjected to transient surges beyond its rated values of energy and peak current.

The life of an MOV is defined as the time required reaching a thermal

runaway condition. The relationship between ambient temperature and the life of an MOV can be expressed by Arrhenius rate equation,

$$t = t_0 \exp[E_a - f(V)]/RT$$

where :

(t) = the time to thermal runaway,

$t_0$  = constant,

R = constant,

$E_a$  = activation energy,

T = temperature in Kelvin,

and  $f(V)$  = applied voltage.

Most Arrhenius rate models impose increased voltage and/or elevated temperature to accelerate the reaction rate (i.e., degradation or time to thermal runaway) and do not adequately address the detrimental effects of surge history.<sup>2</sup> Surge history, especially transient surges beyond rated maximums, are perhaps the greatest single contributor to reductions in varistor voltage, increased standby leakage current, and ultimate thermal runaway. When increased voltage is applied for durations longer than microseconds, physical and chemical changes occur within the many boundary layers of a multi-junction MOV device. As with single-junction semiconductor devices, these changes occur on electronic and atomic scales at rates determined by the diffusion rates of structural defects—electrons, electron holes, and interstitial vacancies and ions. The MOV's joule heating increases rapidly and exceeds the MOV's ability to dissipate heat causing a thermal runaway condition and ending the MOV's effective life.

### Metal Oxide Varistors Description

MOVs are bipolar ceramic semiconductor devices that operate as nonlinear resistors when the voltage exceeds the maximum continuous operating voltage (MCOV). The term *varistor* is a generic name for voltage-variable resistor. The resistance of an MOV decreases as voltage magnitude increases. An MOV acts as an open circuit during normal operating voltages and conducts current during voltage transients or an elevation in voltage above the rated MCOV.

Modern MOVs are developed using zinc oxide due to their nonlinear characteristics and the useful range of voltage and current is far superior to silicon carbide varistors. The characteristic feature of zinc oxide varistors is the exponential variation of current over a narrow range of applied voltage. Within the useful varistor voltage range, the voltage-current relationship is approximated by the expression:<sup>2</sup>

$$I = AV^\alpha$$

where:

I = current in amperes,

V = voltage,

A = a material constant, and

$\alpha$  = exponent defining the degree of nonlinearity.

### MOV Failures

MOVs have a large, but limited, capacity to absorb energy, and as a result they are subject to an occasional failure. The significant MOV failure mechanisms include: electrical puncture, thermal cracking, and thermal runaway, all resulting from excessive heating, in particular, from non-uniform heating. Non-uniform joule heating occurs in MOVs as a result of electrical properties that originate in either the varistor fabrication process or in the statistical fluctuations of properties that generally occur in polycrystalline materials.<sup>6</sup>

There are three basic failure modes for MOVs used within surge protective devices.<sup>3</sup>

1. The MOV fails as a short circuit.
2. The MOV fails as an open circuit.
3. The MOV fails as a linear resistance.

Note: Small-diameter MOVs that initially fail short circuit are likely to fail as an open circuit due to the absorption of large continuous current within the MOV.

The short-circuit failure of an MOV is usually confined to a puncture site between the two electrodes on the disk. Large fault current can create plasma inside the ceramic, with temperatures high enough to melt the zinc oxide ceramic. This failure mode can be caused by long-duration overvoltage, such as switching from a reactive load or thermal runaway of the MOV connected to the ac mains.

Open circuit failures are possible if an MOV is operated at steady state conditions above its voltage rating. The exponential increase in current causes overheating and eventual separation of the wire lead and disk at the solder junction.

### Degradation of MOVs

It is well-known that MOVs experience degradation due to single and multiple current impulses. The test results documented in Mardira, Saha and Sutton show that MOVs can be degraded from an 8/20 $\mu$ s surge current at 1.5 times the rated MOV surge current. A 20 mm MOV with a 10 kA surge current rating will be degraded if a 15 kA single pulse surge current is applied.<sup>5</sup>

When MOVs degrade they become more conductive

after they have been stressed by either continuous current or surge current. MOVs generally experience degradation due to excessive surges exceeding the MOV's rating while in operation. However, many MOVs show no signs of degradation when operated below a specified threshold voltage. The degradation of MOVs is primarily dependent on their composition and fabrication, as well as their application or duty.

Degraded MOVs were found to have smaller average grain size and change in the diffraction peak position compared to a new sample.<sup>5</sup> The non-uniform temperature distribution in the material is due to the development of localized hot spotting during the current impulse and the dissolving in some other phases.

In high current conditions the zinc oxide junctions of the MOV begin to degrade resulting in a lower measured MCOV or turn-on voltage. As the degradation continues, and the MOV's MCOV continues to drop until it conducts continuously, shorting or fragmenting within several seconds.

One of the key parameters related to measuring degradation of a varistor is leakage current. Leakage current in the pre-breakdown region of an MOV is important for two reasons:

1. Leakage determines the amount of watt loss an MOV is expected to generate upon application of a nominal steady-state operating voltage.
2. The leakage current determines the magnitude of the steady-state operating voltage that the MOV can accept without generating an excessive amount of heat.

The total leakage current is composed of a resistive current and a capacitive current. The resistive component of current is thermally stimulated and is significant, since it is responsible for the joule heating within the device. The capacitive current is a function of the MOV's capacitance value and the applied ac voltage. If an MOV is subjected to an elevated voltage at a specific temperature, the internal current increases with time. Conversely, if the MOV is subjected to an elevated temperature at a specific applied voltage, the internal current increases with time. This phenomenon is accelerated by higher operating stress, and is further aggravated by elevated temperatures. The life of an MOV is primarily determined by the magnitude of the internal current and its increase in temperature, voltage, and time. As the current increases, the amount of heat (if not allowed to dissipate) can rapidly raise the temperature of the device. This condition may result in thermal runaway that can cause destruction of the MOV.

Tests were performed to induce thermal runaway.

## Pulse Rating Curves

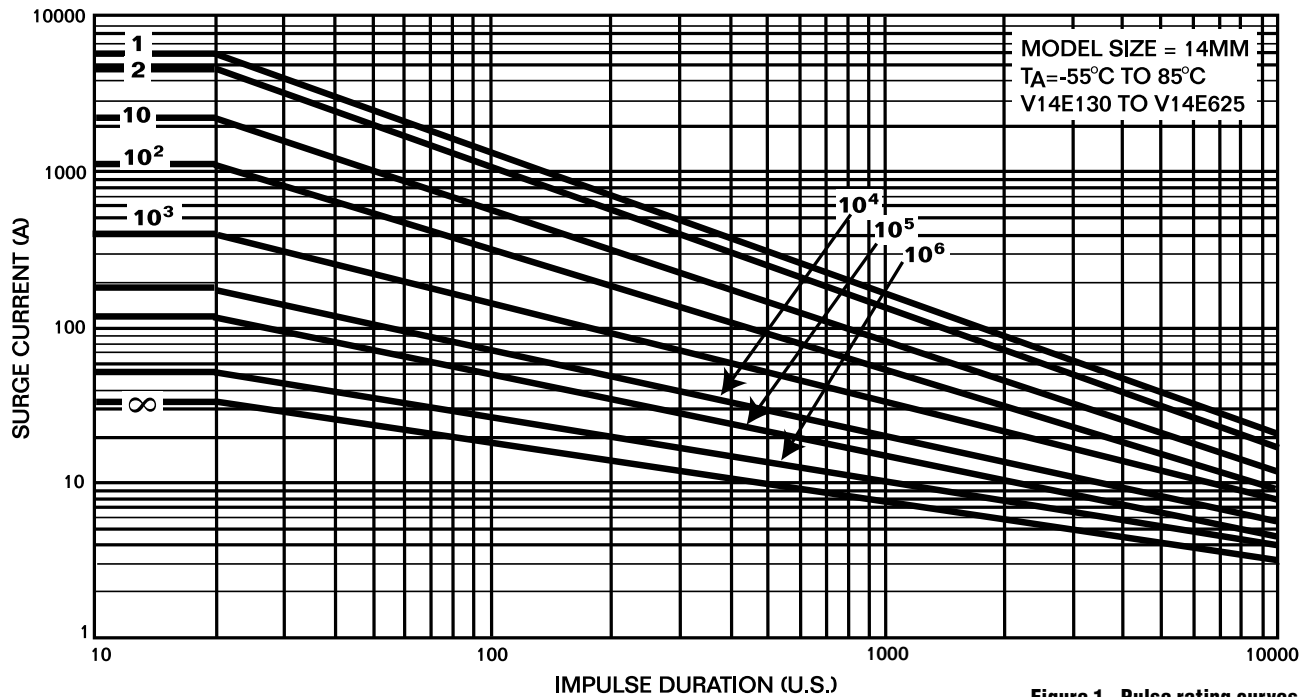


Figure 1. Pulse rating curves

Photo 1 is a 40 mm MOV with an MCOV rating of 130 volts ac. During the test 240 V ac were applied at 15 amps and the MOV ignited.

If an MOV is to operate without failure or degradation, it must quickly dissipate absorbed energy and return to its pre-pulse standby operating temperature. It also must have thermally stable leakage characteristics. The leakage current is significant because it determines the watt loss ( $I^2R$  heat) that will be generated at steady-state operating voltage.<sup>2</sup>

MOVs exhibit greater power dissipation at higher temperatures given a fixed voltage. This characteristic can lead to thermal run-away. If the increase in power dissipation of the MOV occurs more rapidly than the MOV can transfer heat to the environment, the temperature of the MOV will increase until it is destroyed.

MOVs degrade gradually when subjected to surge currents above their rated capacity. The end-of-life is commonly specified when the measured varistor voltage ( $V_n$ ) has changed by  $\pm 10$  percent.<sup>4</sup> MOVs usually are functional after the end-of-life, as defined. However, if an MOV experiences sequential surge events, each causing an additional 10 percent reduction of  $V_n$ , the MOV may soon reach a  $V_n$  level below the peak recurring value for the applied  $V_{rms}$ . When this state is reached the MOV draws in excess of 1 mA of current during each half-cycle of the sine wave voltage, a condition tantamount to ther-

mal runaway. In nearly all cases, the value of  $V_n$  decreases with exposure to surge currents. The degradation manifests itself as an increase in idle current at the maximum normal operating voltage in the system. Excessive idle current during normal, steady-state operation will cause heating in the varistor. Because the varistor has a negative temperature coefficient, the current will increase as the varistor becomes hotter. Thermal runaway may occur, with consequent failure of the varistor.

Littelfuse publishes varistor pulse rating curves that are shown in figure 3. The pulse rating curves plot the maximum surge current versus the impulse duration in seconds. It is noted that stresses above the conditions may cause permanent damage to the device.

### Power Dissipation Ratings

If transients occur in rapid succession, the average power dissipation is the energy (watt-seconds) per pulse times the number of pulses per second. The power generated must be within the specifications shown in the chart above. Operating values must be derated at high temperatures as shown in figure 2. Note the rapid drop in rated value at temperature greater than 85°C.

Varistors can dissipate a relative small amount of average power compared to surge power and are not suitable for repetitive applications that involve substantial amounts of power dissipation.

In the ANSI/IEEE C62.33 (1982) Standard for Surge Protective Devices the following is stated: "Single and lifetime pulse current ratings are appropriate tests of varistor surge withstand capability. In the absence of special requirements, energy ratings are recommended for use only as supplements to the predominant current ratings, and for application problems, which are more conveniently treated in terms of energy."<sup>7</sup>

**Mean Time Before Failure (MTBF)**

MTBF is a measure of the typical number of hours that a varistor will continuously operate, at a given temperature, before a failure will occur. Accelerated aging test techniques are used to understand and minimize the MOV degradation process.

To obtain MTBF value, accelerated aging testing techniques are used to acquire the necessary data accurately and reliably in a short period of time. The following is a brief explanation of how an accelerated aging test is performed:

1. Obtain 60-90 MOVs of the same production run.
2. Initially test the varistor voltage @ 1 mA, and the leakage current at the rated DC working voltage.
3. Place an equal count of 20-30 varistors in three separate temperature chambers that have the temperature set at 85°, 105°C, and 125°C.
4. Apply rated volts ac to the devices.
5. Every 100 hours remove varistors from testing chambers and measure the varistor voltage @ 1 mA, and the leakage current at the rated DC working voltage.
6. If the leakage current is greater than 100 uA (an arbitrary failure point) then remove the device from test and record the number of hours before failure.
7. Continue test until all devices have failed, or enough data has been collected to allow an accurate curve fit of the data.
8. Input data into a data analysis program and extrapolate the time before failure at other temperatures.

The amount of time required to perform this test can be long. Typically Maida tests its MOVs for 10,000 – 15,000 hours (416 – 625 days) before the test completes. The criteria used to signify a failure or the time between testing is arbitrary. The values shown in the procedure are what Maida uses to run

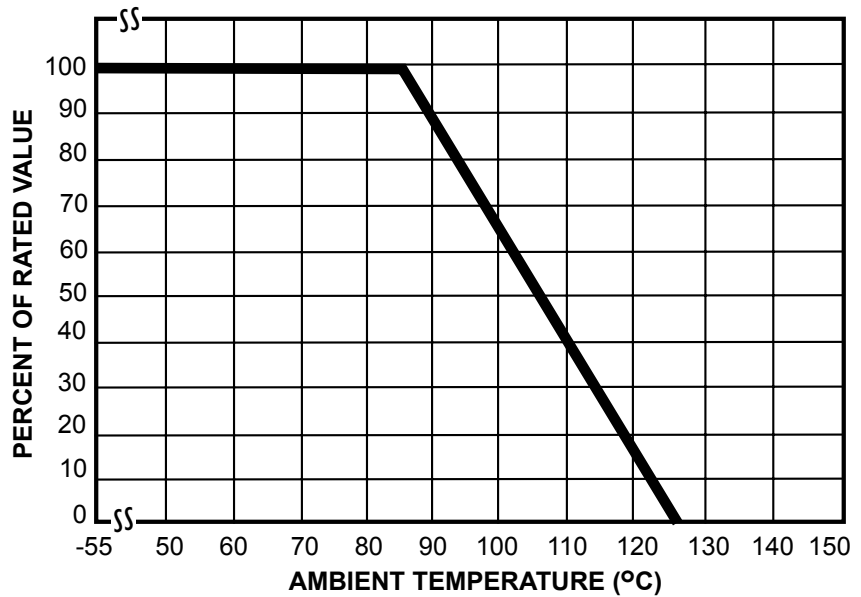


Figure 2. Current, energy and power derating curve.

its test. Other values can be used for these parameters if required.

Using the Arrhenius model, the data collected is imported into a spreadsheet and then exported into a curve-fitting program. Using the equations of the Arrhenius model, the MTBF for a given temperature is plotted and printed.

Accelerated testing has been used in reliability prediction models. Accelerated testing allows accurate reliability and failure rate estimation in a relatively short period of time. Failure rates obtained by subjecting electronic components to highly accelerated testing conditions are used to estimate failure rates under normal operating conditions.

Studies have shown that failure of many electronic components, and varistors in particular, are due to chemical degradation processes, which are accelerated by elevated temperature. The Arrhenius model has found wide application in accelerated testing technology. The Arrhenius model is applicable if:

1. The most significant stresses are thermal.
2. The expected mean life is logarithmically related to the inverse of temperature.

The model is generally described by the following equation:

$$ML = e^{A+B/T}$$

where:

ML: Mean life

A,B: Empirically derived constants from the life test data. The constant's values depend on the characteristics of the material tested and the method.

T: Absolute temperature in Kelvin

The expected mean life (ML) of a varistor under normal operating temperatures is calculated using the above equation. The constants A and B are calculated from the (ML vs. temp.) graph developed during the accelerated testing experiment. The following two equations make calculating A and B easier:

$$B = (\ln ML_1 / ML_2) (1 / T_1 - 1 / T_2)^{-1}$$

And,

$$A = \ln (ML_1) - B / T_1$$

T<sub>1</sub> and T<sub>2</sub> are high temperatures used during the accelerated testing, and ML<sub>1</sub> and ML<sub>2</sub> are the corresponding mean lives obtained from the accelerated test.

A varistor normally operates under 40°C, a standby current value less than 50 uA and a voltage (10-15%) less than the MCOV.

Mean life of an electronic component is the expected mean or average life of the component. Mean life is es-

timated by testing a sample of components for a period of time, then:

$$ML = \frac{\text{number of MOV hours on test}}{\text{number of failures at the time of estimation}}$$

$$ML = \frac{(\sum \text{failure time}) + (\text{test hours for surviving varistors})}{\text{number of failures}}$$

or,

$$ML = \frac{(\sum NF * TTF) + ((NVT-NF) * \text{hours on test})}{NF}$$

where:

NF: Number of failures

NVT: Number of varistors

TTF: Time to failure (hours)

The number of “varistor hours” on test at any time can be computed by adding the lives, in hours, of the

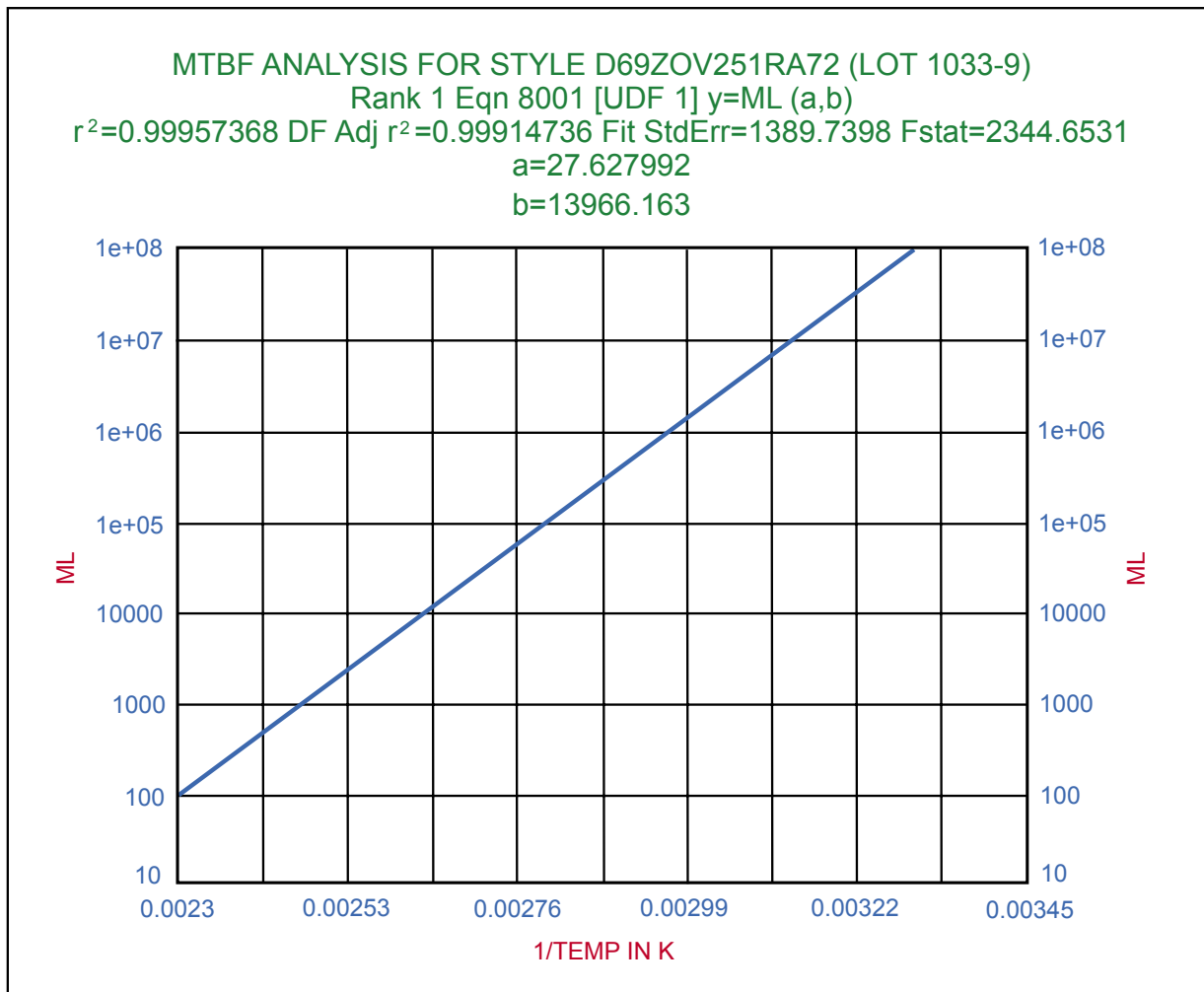


Figure 3. MTBF analysis for varistor style D69ZOV251RA72.

varistors that have failed up to the moment of estimation, to the lives, in hours, of the varistors observed that have not failed. The greater the number of item hours (testing time), the more confidence in the resulting estimates of mean life.

Figure 3 is an example of the MTBF Analysis completed recently for varistor Style D69ZOV251RA72.

The vertical axis (ML) is a label that signifies the mean life (or the average time before failure) of an MOV expressed in hours. The horizontal axis (1/TEMP IN K) is a label of the temperature expressed in the reciprocal of the temperature in Kelvin. As the reader can see from the example the ML, at  $0.00299^{-1}$  ( $61.5^{\circ}\text{C}$  or  $334.5^{\circ}\text{K}$ ), equals  $1\text{e}+06$  or 1 million hours. The ML, at  $0.0023^{-1}$  ( $161.8^{\circ}\text{C}$  or  $434.8^{\circ}\text{K}$ ), equals 100 hours.

Conclusion: MOVs are commonly used in a wide variety of lightning protection systems, low voltage surge arrestors, transient voltage surge suppressors (TVSS) and down line equipment which includes uninterruptible power supplies (UPS), televisions. It is important to understand the performance of such a widely used device since this knowledge can help to reduce failures and increase reliability of the power system. ✎

**Acknowledgement**

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**References**

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*Kenneth J. Brown currently holds the position of director of power quality engineering at Leviton Mfg. Co. He has an undergraduate in electronics engineering from the Ohio Institute of Technology and an MBA from West Coast University. He is currently chairman of the Technical Committee at NEMA 5-VS Low Voltage Surge Protective Devices. He has been involved in the design of surge protective devices for 8 years and prior to that he worked as a manager of subsystem development on the guidance section of an air-to-ground weapon system.*