ORNL/CP-95772

CONF-971201--

To be presented at Fall Meeting of the Materials Research Society, Boston, MA, December 1–5, 1997, and published in Proceedings:

COMPUTER SIMULATION OF ZnO VARISTORS FAILURES

M. Bartkowiak,* G. D. Mahan,* M. G. Comber,** and M. A. Alim+

*Solid State Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6030
and
University of Tennessee, Dept. of Physics and Astronomy,
Knoxville, TN 37996-1200

**Hubbell Power Systems, 210 North Allen Street
Centralia, MO 65240-1395

+Hubbell Incorporated, The Ohio Brass Company
8711 Wadsworth Road, Wadsworth, OH 44281

prepared by
SOLID STATE DIVISION
OAK RIDGE NATIONAL LABORATORY
Managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
under
Contract No. DE-AC05-96OR22464
with the
U.S. DEPARTMENT OF ENERGY
Oak Ridge, Tennessee

November 1997

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M. BARTKOWIAK*, G.D. MAHAN*, M.G. COMBER**, M.A. ALIM†
*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996-1200, and Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6030, bartkowiakm@ornl.gov
**Hubbell Power Systems, 210 North Allen Street, Centralia, MO 65240-1395
†Hubbell Incorporated, The Ohio Brass Company, 8711 Wadsworth Road, Wadsworth, OH 44281

ABSTRACT

A simple thermo-mechanical model is applied to evaluate the influence of the nonuniformity of ZnO varistor disks used in surge arresters on their energy handling capability. By solving heat transfer equations for a varistor disk with nonuniform electrical properties, we compute the time dependence of the temperature profile and the distribution of thermal stresses. The model can identify the energy handling limitations of ZnO varistors imposed by three different failure modes: puncture, thermal runaway, and cracking. It conforms to the available failure data, and explains the observation that energy handling improves at high current densities.

INTRODUCTION

Zinc oxide varistors are multi-component ceramic devices produced by sintering ZnO powder together with small amounts of other oxides. Highly nonlinear current-voltage (I-V) characteristics of ZnO varistors are used in electrical surge arresters. They protect electrical equipment from damage by limiting overvoltages and dissipating the associated energy. Therefore, the energy handling capability is crucial. It is defined as the amount of energy that a varistor can absorb before it fails.

There are three main failure modes of varistor elements: thermal runaway, puncture, and cracking. The leakage current, and consequently the Joule heating of a varistor, increase with temperature. Thus, if the temperature is raised above the thermal stability temperature T_s, power input may exceed heat dissipation, and thermal runaway occurs. In puncture, a small hole results from melting of the ceramic where high current is concentrated [1]. Nonuniform heating can also cause thermal stresses higher than the failure stress of the material and can lead to cracking [1, 2]. Currents in the nonlinear region of the I-V characteristics tend to concentrate into narrow paths. This current localization has been detected by applying small spot electrodes on the surfaces of varistors, by using infrared cameras [3, 4] and by electroplating techniques [5].

Measurements of the energy handling capability of varistors have been reported [1, 6, 7], but the nature of the failures is not well understood. Puncture has been studied by Eda [1], who showed that at high currents, a hot spot may reach about 800 °C and cause local melting. However, two important factors were omitted by Eda: (1) the influence of the upturn in the I-V characteristics, and (2) that thermal stresses may cause cracking before a puncture can take place.

ZnO varistors exhibit a complex dependence of the energy handling capability upon pulse magnitude and duration. Initially the energy handling capability decreases with increasing current, but, as first pointed out by Sakshaug et al. in [6], it *increases* again if the current becomes very high and the pulse duration becomes very short. It is the main purpose of the present paper to provide a fundamental explanation of the phenomenon. The explanation is of added interest because Ringler et al. [7] have recently shown that the energy absorption capability of varistors used in station-class arresters increases almost 4 times as the current level increases from 0.8 A_{peak} to 35 kA_{peak}. These tests are simulated in the present study, and the results are compared with the experimental data. The model is also used to evaluate the influence of the nonuniformity of varistor disks on their energy handling capability for current surges of various magnitudes and durations.

THERMO-MECHANICAL MODEL OF VARISTOR DISKS

Details of the thermo-mechanical model used in the present study have been presented elsewhere [8]. Here, only its brief description is presented in order to settle the terminology and define the basic concepts.

The behavior varistor disks is simulated by solving the coupled nonlinear equations of current conduction and heat diffusion to obtain the time and spatial dependence of the current density and of the temperature. The temperature dependence of the thermal conductivity [9] is taken into account in the heat diffusion equation. The boundary conditions include the assumption that the disks can dissipate heat only radially by convection to air through the sidewall, and that the ambient temperature is 20 °C. A model temperature-dependent I-V characteristic typical for high-voltage varistors is used in the simulations [8]. At $T = 293$ K, the breakdown field (i.e., the field at 1 mA/cm^2) is $F_b \approx 1870$ V/cm, the prebreakdown resistivity $\rho_{pb} = 5 \times 10^{11}\ \Omega$ cm, and the resistivity in the upturn region (i.e., the resistivity of the grains) is $\rho_{up} = 1\ \Omega$ cm. The coefficient of nonlinearity has the maximal value $\alpha_m \approx 50$. Nonuniformity of the varistor disk is simulated by assuming that a hot spot of diameter $2R_{hs}$ extends axially through the block at its center, so that the heat diffusion problem remains cylindrical symmetric. The breakdown voltage at the hot spot F_{bhs} is assumed p% lower than that for the rest of the varistor block, i.e., $p = (F_b - F_{bhs})/F_b$. The quantity p (expressed in percents) will be called *the hot spot intensity.* As follows from [1], typical varistor disks have hot spots with $p = 5\%$, but the intensity of hot spots in highly nonuniform disks can be as high as 10%. The small difference between the electrical properties of the hot spot, and those of its surroundings, causes high nonuniformity in the spatial distribution of the current, and thereby in the input power density due to Joule heating.

The temperature profile for the disk and its time evolution, is used to calculate the distribution of thermal stresses and to identify the cracking failure mode. To determine the maximum energy that can be absorbed by a varistor disk before it cracks, it is necessary to know the strength of the material. Its value strongly depends on the details of the ceramic processing used, on the presence of preexisting flaws, and on other factors, so that it may vary considerably for individual disks. Here, a simple assumption that the tensile strength of the varistor ceramic is $S_{ft} = 20$ kpsi [2] is used. Two types of failures are considered: (1) cracking at tension, when thermal tensile stress exceeds S_{ft}; and (2) puncture, when the temperature at the hot spot exceeds 800 °C [1].

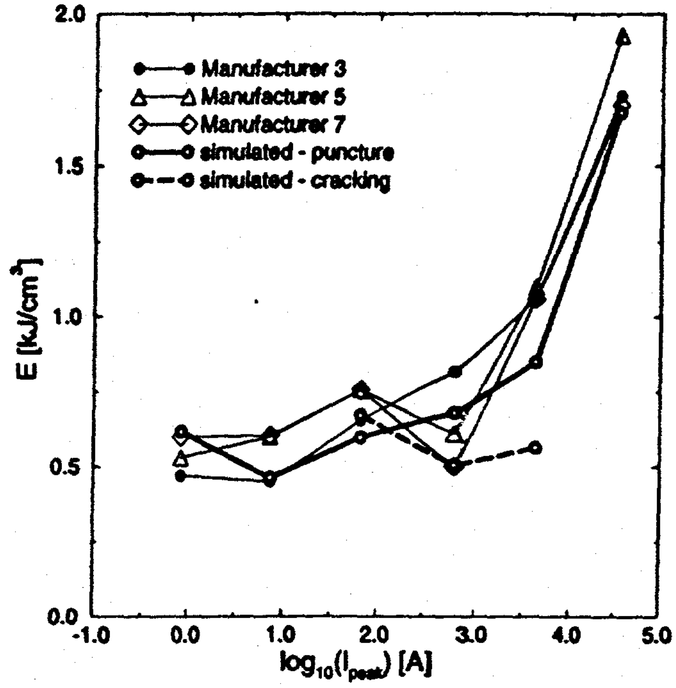

Figure 1: The simulated and mean measured [7] energy handling capabilities of station-class-arrester disks as a function of the peak test current.

SIMULATION OF THE EXPERIMENTAL DATA

Recently, Ringler et al. [7] measured the energy absorption capability of commercial varistor disks used in station-class arresters, at current levels ranging from 0.8 A_{peak} to 35 kA_{peak}. Here, the model described in the preceding section is used to simulate these experiments. A typical disk, 23 mm high and 63 mm diameter, is assumed to have a 1.2 cm diameter hot spot ($R_{hs} = 0.6$ cm), and the upturn resistivity $\rho_{up} = 1\ \Omega$ cm. The computed energy handling capabilities for puncture and cracking as functions of the peak test current are shown in Fig. 1, together with the measured mean values of the total energy to destroy varistor disks from three different manufactures. The same symbols and code numbers for manufactures as in [7] are used.

At low currents corresponding to 0.8 A_{peak} and 7 A_{peak}, the only possible failure mode (besides a thermal runaway) is puncture. This is consistent with the results of [7], where at these test currents the failure resulted in a single hole through the bulk ceramic, and no cracking or fragmentation failures were observed. At 600 A_{peak}, the tensile tangential stresses around the hot spot become higher than the strength of the varistor ceramic before the temperature at the hot spot reaches 800 °C. Therefore, the disks become likely to crack along lines branching out from the hot spot. Indeed, the most significant external damage was found in [7] for the currents at 600 A_{peak}. The simulations indicate that cracking remains the most likely failure mode also at 4 kA_{peak}. However, for very high current pulses of 35 kA_{peak}, the simulated thermal stresses never become high enough to cause cracking, and the disks fail either due to a puncture or due to overheating. This is again consistent with the data reported in [7].

Varistors from Manufacturers 5 and 7 exhibit an unexpected dip in energy absorption capability at 600 A_{peak}. This agrees surprisingly well with the simulated energy handling characteristic for cracking, and the agreement suggests that these disks crack on failure at 600 A_{peak}. On the other hand, the energy handling curve for puncture in Fig. 1 is in good agreement with the experimental data for varistors from Manufacturer 3. Apparently, the latter varistor disks have higher mechanical strength and are more likely to exhibit puncture than cracking.

The predicted cracking patterns, as well as the transition from the puncture failure mode at low current densities to cracking for high currents, are also in qualitative agreement with the experimental observations of Eda [1].

INFLUENCE OF THE NONUNIFORMITY

The assumptions that the disk had a 1.2 cm in diameter hot spot with the intensity $p = 5\%$ was used in the preceding section. The obtained excellent agreement between the simulated results and the corresponding *mean values* obtained from a statistical analysis of the experimental data [7] indicates that a *typical* disk indeed has such a hot spot. However, as shown in [7], the disks are not identical, and results from individual measurements may vary considerably. In particular, the disks can have different hot spots. In this section, the influence of the hot spot intensity on the energy handling capability is discussed. Thermo-mechanical behavior of the disks with 1 cm in diameter hot spots is simulated, assuming three different intensities: $p = 2.5\%$, 5%, and 7.5%. The energy handling characteristics of disks with these hot spots, obtained for the case of dc currents, are shown in the left panels of Fig. 2.

Of course, the disks with hot spots of higher intensity have lower energy handling capability. The minimum energy handling decreases from about 1 kJ/cm^3 for $p = 2.5\%$, to 450 J/cm^3 for $p = 5\%$, and 200 J/cm^3 for $p = 7.5\%$. Also, the region of the current densities for which the disks exhibit punctures extends to lower currents as the intensity increases. Simulations for the case of $p = 2.5\%$ show that the thermal stresses never become high enough to cause cracking, independently of the magnitude of the applied current. This shows that disks with hot spots of low intensities do not crack, and can only fail by puncture. Cracking caused by tensile thermal stresses in tangential direction is the dominating failure mode at high current densities for $p = 5\%$ and $p = 7.5\%$. Moreover, for higher p, the disks become more likely to crack also at lower current densities.

The size of the hot spot is another parameter that can significantly deviate from the typical value of about 1 cm. To evaluate its influence on the energy handling capability, station-class varistor disks having hot spots with $p = 5\%$, and three different diameters: 1 mm, 1 cm, and 2 cm are simulated. Their energy handling characteristics, obtained for a dc current flow, are shown in the right panels of Fig. 2. The value of the minimum energy handling only weakly depends on the size of the hot spot, and varies from about 650 J/cm^3 for the disk with a 1 mm hot spot, through 450 J/cm^3 when $2R_{hs} = 1$ cm, to 480 J/cm^3 for the disk with a 2 cm in diameter hot spot. These results indicate that the minimum energy handling is not a monotonic function of R_{hs}, and that it becomes lowest for disks with hot spots of an intermediate size. In all three simulated cases, the minimal E corresponds to a puncture, and moves towards lower current densities as the size of the hot spot increases. As follows from the data in Fig. 2, the disks are more likely to crack on failure when they have large hot spots. The disk with a 1 mm hot spot never cracks, whereas cracking is the dominating failure mode even at 1 A/cm^2 for the disk with $2R_{hs} = 2$ cm.

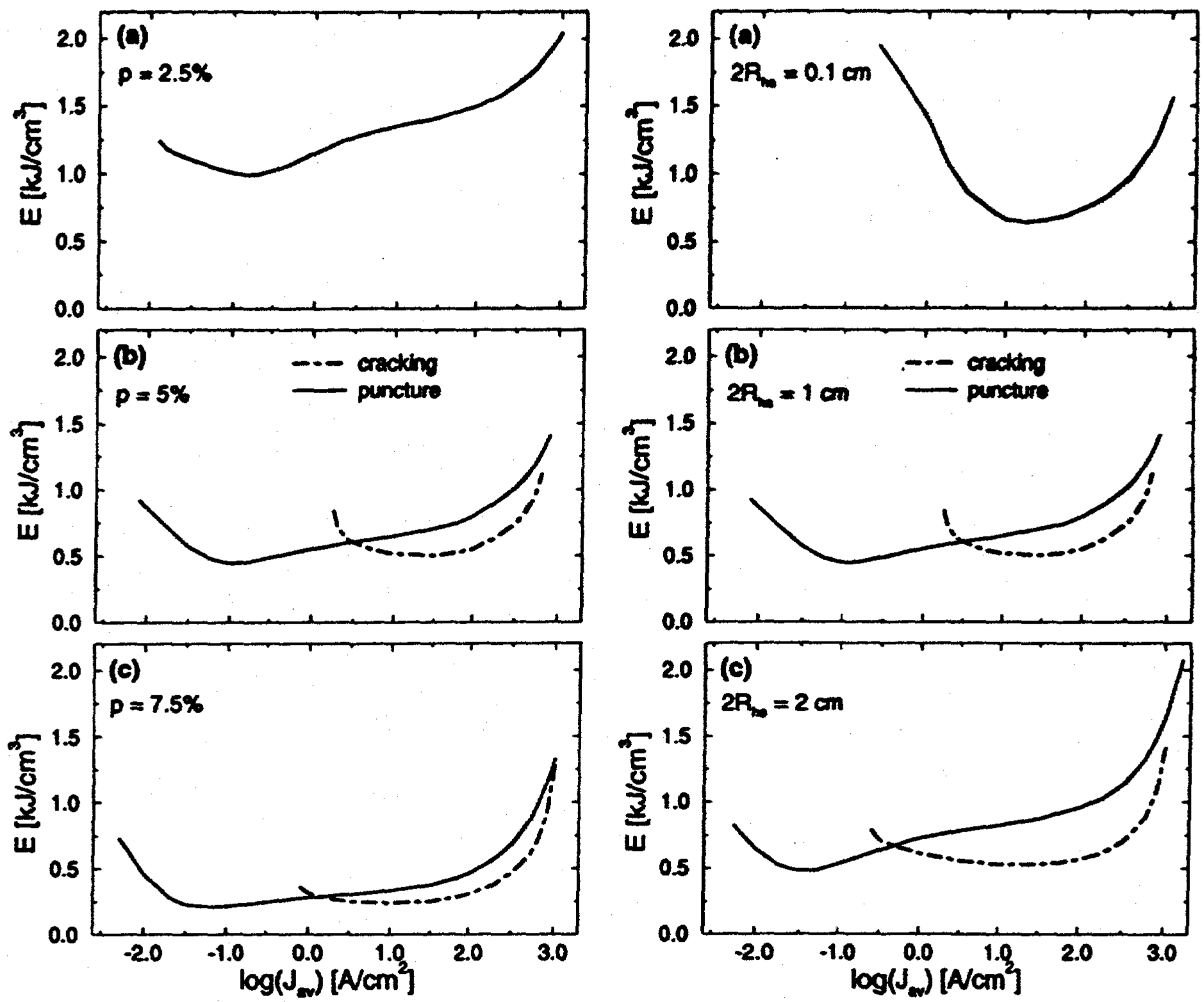

Figure 2: Energy handling characteristics of station-class varistor disks having 1 cm diameter hot spots with different intensities (left panels); and having hot spots of the intensity $p = 5\%$ and three different sizes (right panels)

CONCLUSIONS

A simple theoretical model can identify the energy handling limitations of ZnO varistors imposed by three different failure modes: puncture, thermal runaway, and cracking. The energy handling depends upon which of these failure modes is predominant for a current pulse. Each failure mode can be limiting, depending on the disk shape, its electrical uniformity, and the current magnitude.

The model conforms to the available failure data, and explains the observation of Sakshaug et al. [6] and Ringler et al. [7] that energy handling improves at high current densities. It can also be used to simulate thermo-mechanical behavior and estimate the energy handling capability of various types of varistor disks without performing destructive experiments.

Cracking and puncture are caused by a localization of the current, which causes local heating leading to nonuniform thermal expansion and thermal stresses. Puncture is most likely in varistor disks with low geometrical aspect ratio and when the current density has intermediate values. Cracking dominates at higher current densities and for disks with high aspect ratio. Puncture and cracking do not occur when the current is small, because the time evolution of the nonuniform heating is slow enough for the temperature distribution to flatten. They are also unlikely at very large currents corresponding to the upturn region of the I-V characteristic, since in this case the current becomes uniformly distributed. For low and very high current densities the most likely failure mode is thermal runaway.

The model is also applied to evaluate the influence of the nonuniformity of varistor disks used in surge arresters on their energy handling capability. Puncture is the dominating failure mode for slightly nonuniform disks, but cracking becomes more likely as the degree of nonuniformities increases.

ACKNOWLEDGEMENTS

The authors are indebted to F. Modine (ORNL) for stimulating discussions. This work was supported by the U.S. Department of Energy through the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the High Temperature Materials Laboratory User Program and by the Office of Basic Energy Science under contract DE-AC05-96OR22464, managed by Lockheed Martin Energy Research Corporation.

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