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AUTHOR: MELTON, J.G., CTR-4

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Los Alamos National Laboratory
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J. G. MELTON

Los Alamos National Laboratory, Los Alamos, NM 87545

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J. G. Melton

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Nonlinear resistors can be used to improve the energy transfer efficiency of inductive energy storage systems that use resistive transfer elements. Improved energy transfer efficiency can result in significant cost savings in some large systems if the cost of the nonlinear resistor is less than the cost of the energy storage and charging hardware that the resistor replaces. This report describes experimental tests that were done to determine appropriate energy ratings for ZnO Metal Oxide Varistors (MOV's) for pulsed conditions from 10 to 20 ms long. Tests were performed first on single MOV units which were forced to failure in a small number of shots. Then several sets of matched pairs were operated under identical conditions to investigate current sharing and the statistics of failure. Test results show that the standard rating method used by manufacturers relating peak current, pulse length, and expected lifetime are adequate, but somewhat conservative. The manufacturers' energy ratings project to a very economical nonlinear transfer resistor.

INTRODUCTION

For many applications requiring the storage and rapid discharge of large amounts of electrical energy, inductive energy storage is more economical than capacitive energy storage. This is often true even though inductive energy storage is basically energy inefficient when a resistive energy transfer element is used. The maximum theoretical transfer efficiency is 25% when the load and the storage element are perfectly matched. A capacitive energy transfer element can be used to improve energy transfer efficiency to a theoretical maximum of 100%. However, the added expense of a capacitor bank will usually negate the economic advantage of using inductive storage.

Another approach to improve the energy transfer efficiency is to use a nonlinear resistive element. The nonlinear resistive element should have resistance that decreases as the current increases to produce a more constant driving voltage resulting in a higher peak current in the load and better energy transfer efficiency. However, at higher currents the resistance must increase as current increases. Otherwise current sharing between pairs of units is not stable.

If the cost of the nonlinear transfer resistor is low enough, a nonlinear transfer resistor can pay for itself by saving energy. In fact, in very large systems the increased efficiency could result in significantly reduced system costs through reduced energy storage requirements.

At Los Alamos National Laboratory, we are investigating nonlinear transfer resistors for possible use in a controlled fusion research experiment, ZETA, under development. ZETA will be a toroidal field pinch experiment similar in many features to Tokamak fusion research experiments using inductive energy storage. ZETA will store 180 MJ of magnetic energy before a shot. Due to geometrical constraints, the storage coil is not well matched to the plasma load. This results in an energy transfer efficiency of only 10% or about 18 MJ delivered to the plasma. Computer simulation has shown that the efficiency can be boosted to about 50% by use of a nonlinear transfer resistor. In this case, a more

energy efficient system could be built if an economical and reliable nonlinear resistor were available.

Zinc oxide metal oxide varistors (MOV's) are a promising candidate for this duty. Their service in the power distribution and transmission industry as lightning surge arrestors has proven them to be very reliable, economical, and rugged. Preliminary estimates, based on standard rating methods, suggest that the units for a 180-MJ resistor would cost about 0.2 ¢ per joule. This would be an acceptable price, even allowing considerable assembly cost. It compares to about 3 to 5 ¢ per joule for basic magnetic energy storage (magnet coils plus power supplies).

This report describes experimental tests to determine the feasibility of using ZnO MOV's as a transfer resistor in a repetitively pulsed application. First, several MOV units were tested individually to failure to determine roughly the maximum energy ratings. Then matched pairs of units operating in parallel were tested under similar conditions to determine statistics of failure and to investigate current sharing.

Results show that the standard rating methods used by manufacturers relating peak current, pulse length, and expected lifetime are adequate, though somewhat conservative. Test results on current sharing show that current sharing between matched pairs improves during a single shot, during a single run, and as the units age over several days. Both of these results are necessary for a large economical transfer resistor to be possible. The tests did not establish that the required reliability can be achieved, since only 40 units were tested. If the manufacturer's ratings for reliability are accurate at the 10⁻⁴ level of failure, then a large resistor would be sufficiently reliable to be economical.

EXPERIMENTAL TESTS

The nonlinear resistor elements selected for testing are commercially available ZnO metal oxide varistors produced for surge protection applications in the electrical power industry. They are 75 mm in diameter and either 23 or 35 mm thick. The energy rating for a disk of this size is typically 15,000 J. The voltage and current ratings of these units are a clamping voltage of about 5500 volts and a pulse surge current rating of about 10,000 amps. The single pulse short duration surge current rating is 20,000 amps. The nominal energy rating is 12,500 joules. The MOV units are rated for maximum temperature of 85°C. A rule of thumb for derating the expected lifetime at higher temperatures is that for a ten degree rise in temperature, the life expectancy is reduced by half.

The experimental facility used for testing the MOV's was a 10 kV high voltage test bay containing ten 1000 pF capacitors rated at 10 kV and associated power supplies for charging, control circuitry, and trigger circuitry for discharging. The capacitors through a selected load. Two different sets of load coils were used to control the discharge current and the pulse duration. The power supplies and controls are capable of charging and discharging the capacitor bank at 1 Hz and intervals, but in these tests the fastest repetition rate used was one shot every two minutes. The high voltage switch was an impact switch using a 20 A gun.

Individual MOV Tests

The initial tests were conducted to determine the maximum single pulse energy capacity of the selected units. Four different batches of MOVs were tested to destruction at different energies and pulse lengths.

Batch A consisted of four units tested at 27-kJ per pulse and a pulse length of 620 μ s. This energy is about 160% of the manufacturer's nominal energy rating. While these tests were in progress, we learned from outside sources that the failure mode for MOVs is different for long pulses than it is for short pulses, and the failure rate is greater. Consequently, we increased the pulse length, and all subsequent tests were conducted at pulse lengths of 15 to 22 ms.

Batch B consisted of five units tested at 27-kJ and 14.5 ms pulse length. Although five units were tested, only two units had failed after 40 shots. Contrary to the reports we had received, the longer pulse length produced a lower failure rate. So the energy per shot was increased in the next series of tests, in order to increase the failure rate.

Batch C consisted of five units tested at 31-kJ per shot (about 180% of rated energy) and a pulse length of 16 ms. The average number of shots to failure was 29 shots.

Batch D consisted of six units tested at 38-kJ per shot (220% of rated energy) and a pulse length of 19 ms. All six units failed in 20 shots or less.

Matched Pairs Tests

Having established in previous tests conditions that lead to early failure, we estimated conditions expected to cause failure in 100 to 1000 shots. We also modified the test fixture holding the MOV under test to hold two units in parallel. The current in each MOV was monitored individually to study current sharing by the units during a single shot and throughout the tests.

Batch E consisted of a single matched pair tested at 17-kJ per unit per shot and a pulse length of 17 ms. The pulse rate was chosen to be one shot every 5 minutes, which allowed the temperature to plateau at about 150°C. This pair of units survived for 3000 shots without failure. Since this test consumed six weeks of run time, which was too much time, it was necessary to increase the test energy once again in order to complete the test program in a reasonable time.

Batch F consisted of six pairs of matched units tested at 26-kJ per shot and a pulse length of 21 ms. Tests were run until one of the pair failed. Tests lasted between 184 shots and 1232 shots. After the failure, it was not possible to match the surviving unit to another fresh unit, so it was decided to retire the surviving unit, rather than continue the test on a single unit.

TEST RESULTS

The results of the tests to determine approximate energy ratings for individual units are summarized in Table 1. The number of shots presented for each group is the mean number of shots for that group.

Table 1
Summary of Tests Performed

GROUP	No. of Units	ENERGY (kJ)	Pulse Length (ms)	No. of Shots
A	4	27	620	29
B	5	27	14.5	40
C	5	31	16	29
D	6	38	19	20
E	2	17	17	3000
F	12	26	21	600

The results of the current sharing tests between paralleled units can be seen in Fig. 1. Plotted is the difference of the current in the two MOVs vs the average of the two currents. The current sharing between units which had been previously matched was within 10%.

DISCUSSION OF RESULTS

Energy Ratings

At the beginning of this work, it was not clear how to assign an energy rating for repeated high energy pulses. Although similar pulsed rating tests have been done,¹ the larger body of data exists for a.c. tests. The industry standard rating system is based on the ability to survive lightning strikes or other surges at infrequent intervals but for hundreds of years of continuous protective service. In surge protection service, the energy rating must be very conservative, as the surge arrestor must maintain its ability to protect expensive equipment. For applications other than circuit protection, if one is concerned only that the varistor itself not be destroyed, one might expect to exceed the standard energy rating by a large amount.

Maximum energy ratings for MOVs are stated in terms of a "defined failure criterion" that is generally well below the catastrophic failure level. The defined maximum energy is the amount of energy the units can withstand without the V-I characteristics of a certain percentage of the units being altered by a predefined amount.¹ For example, "Brand X" varistors are rated for a maximum pulse energy surge that results in a varistor voltage (V_v) shift of less than $\pm 10\%$ from initial value.²⁴

Similarly, lifetime is defined in terms of a defined failure criterion. It is defined to be the number of pulses the unit can sustain without the characteristics changing by a predefined amount. These ratings clearly are more conservative than ratings based upon catastrophic failure criteria.

The usual way of presenting the pulse capability data of an MOV is by curves of allowable peak current vs pulse length with the expected lifetime (number of pulses) as a parameter. A representative curve is shown in Fig. 2. Each curve, for example for 10⁴ pulses expected lifetime, is a straight line (on log-log graph paper) of the form $I t^\beta = \text{constant}$. Here I is the peak current, t is the pulse length, and the exponent β varies from about 1 for high energy pulses (corresponding to short life expectancy) to about 2 for curves for low energy pulses (longer life expectancy).

To relate energy rating to the exponent β , we note that if the voltage across the MOV were constant, then the line $I t^\beta = \text{constant}$ (that is, $\beta = 1$) would represent a curve of constant energy. Similarly, if the resistance of the MOV were constant, the line $I t^\beta = \text{constant}$ (that is, $\beta = 2$) would represent a curve of constant energy. In the published curves, the exponent β varies from 1 to 2. This means that the intuitive notion that failure rate is proportional to energy has some validity.

Figure 1
Sharing of Current During Pulse

The test results of Table I are shown plotted in Fig. 2. Each of the test series are plotted by test conditions, that is, peak current vs pulse duration. The number of shots achieved for series A, B, C, and D agree well with the number of pulses shown on the figure. Series E and F, however, achieved larger numbers of shots than shown on the figure.

When we tried to extrapolate from our short pulse results (series A) to set up similar test conditions, but for longer pulses of the same energy (series B), we found that the longer pulse resulted in a longer lifetime than expected. Failure for short pulses resulted in a puncture through the body of the MOV, while failure for long pulses resulted in a puncture within 2 mm of the edge. This effect has been observed before in aging tests conducted under a.c. conditions. The effect is consistent with short pulse failure being caused by thermal shock and long pulse failure being caused by chemical degradation occurring at the surface.

Current Sharing

The voltage-current characteristics of MOVs are so nonlinear that units in parallel will not share current equally unless they are matched beforehand. The units we tested are typed by the manufacturer in their standard quality testing at the factory. Each unit is pulsed to some standard current, and the voltage across the unit is recorded and stamped on the unit. The units we tested were pretested at the factory to 10,000 amps. The units operated in parallel were preselected to have the same stamped voltage value. This prematching was sufficient to give current sharing within 10% in our tests, except when the current was passing through the highly nonlinear region of the characteristics.

The current sharing for a single pulse can be seen in Fig. 1. Plotted is the difference factor vs the average current. The difference factor is defined to be the difference of the two currents divided by the sum of the two currents. The arrows indicate the path taken during the pulse. Both early and late during the shot, the sharing is not good, as one of the units is passing 90% of the current. During the main part of the pulse, however, the current is shared to within 10%.

The current sharing is also seen to improve during the pulse. If one of the units is drawing more current, its temperature increases more than that of the other MOV. Consequently, its resistance increases more, and the current begins to transfer to the other MOV. Therefore, the

Figure 2
Peak Pulse Current vs Pulse Duration

temperature dependence of resistance in the high current region of the voltage-current characteristic forces the currents to equalize. Similarly, as the temperature increases over the span of many shots, the current sharing improves.

During the course of the tests over several days, we noticed the current sharing improving. This trend was permanent and was probably a result of gradual deterioration of the ZnO material. It should be noted that although we could see signs of varistor aging, we were unable to detect any prior warning or precursor of failure.

Failure Statistics

The data of the F series of tests were analyzed using methods for incomplete failure data. The data, consisting of the number of shots to failure for the failed units and the differing number of shots on unfailed units, constitutes multiply censored failure data, and are best presented by means of a hazard plot, as in Fig. 3. The points are presented on a Weibull hazard plot. The shape factor for the line drawn through the points is 1.18, which means the distribution is slightly weighted toward early failures. However, it must be pointed out that the six points plotted represent a very small sample.

Since we were able to test only a small number of units, we must rely on the manufacturer's curves for information concerning reliability vs energy. Figure 4 is adapted from rating curves showing the cumulative failure vs fraction of rated energy. The principal point of interest is that if one wishes to operate at the 0.01% level of failure, the energy per pulse should be derated to about 0.1 times the rated energy.

Figure 3
Cumulative Hazard Plot for Series F MOV Failures

Figure 4
Cumulative Per Cent Failure
vs Fraction of Rated Energy

Multi-element Resistor

In order to get more data on the reliability of the MOV units, a nonlinear resistor was constructed and used in a switch test facility, whose purpose was to test vacuum interrupter opening switches. Two resistor units were built, each with 6 MOV discs in parallel and 4 discs in series. The nominal energy rating of the two resistors was 816-kJ total. They were operated in an application where they take over the current and absorb energy when a vacuum interrupter opens and interrupts current. The current interrupted was 50 kA. The resistor typically absorbed 300 kJ when the interruption took place. Each varistor disc absorbed 6250 joules. The peak current and pulse duration for a single MOV unit under this service is indicated on Fig. 2 by the symbol "SIFA." These resistor units have operated without failure for 1500 shots.

CONCLUSIONS

We found the pulsed energy rating of individual ZnO varistor units to be slightly higher than manufacturers' ratings. Derating is probably necessary to achieve the reliability required for assemblies containing a large number of units. The current sharing between paralleled units is sufficient to allow parallel operation of large numbers of units. The overall level of reliability required for operation of large numbers of units has not been proven by this study, but it seems to project to an economical nonlinear transfer resistor.

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