

POWERCET CORPORATION

METAL OXIDE VARISTORS

PROTECTIVE LEVELS, CURRENT AND
ENERGY RATINGS OF PARALLEL VARISTORS

PREPARED FOR
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SALT LAKE CITY, UTAH

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EXECUTIVE SUMMARY

Manufacturers of metal oxide varistors (MOVs) recommend that higher surge currents and energies than available in a single component can only be achieved by paralleling components whose characteristics have been carefully matched. This recommendation is contrary to the observations of a number of manufacturers who have built multiple MOV modules using unmatched components.

This study was done to evaluate the performance of both matched and unmatched parallel MOVs and compare them to a single larger component. For this purpose, the clamping voltage and surge current performance of two stacks of six parallel 18 mm diameter MOVs, one with matched and one with randomly selected components, were compared with that of a single 40 mm MOV. Tests were also done to verify the maximum surge current rating of the 18 mm components.

Results from these tests showed that 18 mm components could withstand several 8x20 μ s waveshape standard impulses with little change in characteristics at a 10 kA level. Current sharing in both matched and unmatched stacks was found to be good, and improved at higher currents. The current sharing in the unmatched stack was significantly better than predicted by manufacturers. This sharing improved with surge current magnitude and was not substantially worse than the matched stack at higher currents. It was concluded that the surge current and energy capabilities of a stack of six unmatched parallel 18 mm MOVs were equivalent to or possibly higher than a single 40 mm MOV.

The clamping voltage of both stacks of parallel 18 mm MOVs were similar and significantly better than the clamping voltage of a 40 mm MOV of the same voltage rating.

INTRODUCTION

Metal Oxide Varistors (MOVs) are solid state shunt surge protective devices that are widely applied on low-voltage ac circuits for the protection of wiring devices and sensitive loads by limiting transient overvoltages and diverting transient currents. To perform the desired function, the suppressor must be able to limit transient voltages to below specified levels and divert transient currents of specified current and waveshapes. It must not operate under normal power system conditions, and is required to automatically reset after operating on a transient. In order to handle larger surge currents and energies in practical surge suppressors, two strategies are possible – using single large varistors or parallel stacks of smaller units. The purpose of this report is to compare the merits of these two strategies.

VARISTOR TECHNOLOGY

Varistors consist of a ceramic compound consisting primarily of zinc oxide (ZnO) granules, doped with other compounds, principally the oxides of bismuth, cobalt, manganese, chromium and tin. The material is fabricated by mixing finely powdered constituents with a binder agent. This

mixture is pressed into thin disks and then fired in an oxidizing atmosphere at around 1200 degrees C. The two faces of the disk are then coated with an electrically conducting compound and terminals are attached by soldering. Finally, the whole assembly is coated with thin epoxy covering to provide electrical insulation and mechanical protection.

GENERAL PROPERTIES OF VARISTORS

The varistor consists of microcrystalline grains of low resistance zinc oxide that are surrounded by high resistance layers of the doping agents. Non-linear properties of the varistor are established at the grain boundaries throughout the whole varistor, which act as a series/parallel stack of diodes. At low voltages, the diodes are off and the varistor is a very good insulator. At high voltages, the diodes turn on and the varistor resistance drops markedly. The electrical properties of varistors are a function of the grain size as well as the relative proportion of the various doping agents. In addition to consistency of the mixture, uniform density must be achieved during the pressing and firing processes to assure optimum performance and current distribution.

The turn-on (and therefore rated) voltage of a varistor is determined by its thickness, which is the limiting factor in manufacturing low-voltage units. Varistors rated for use at lower voltages than around 50 V are difficult to manufacture. Varistors designed for use on North American power systems operating at 120 V ac are only about 1.5mm (1/16) inch thick. For these thin units, varistor diameters up to 20 mm are relatively easy to manufacture with good control of the thickness and density. Larger diameters (up to 60 mm) are available, but the difficulty of manufacture and therefore cost rises rapidly with increase in disk size.

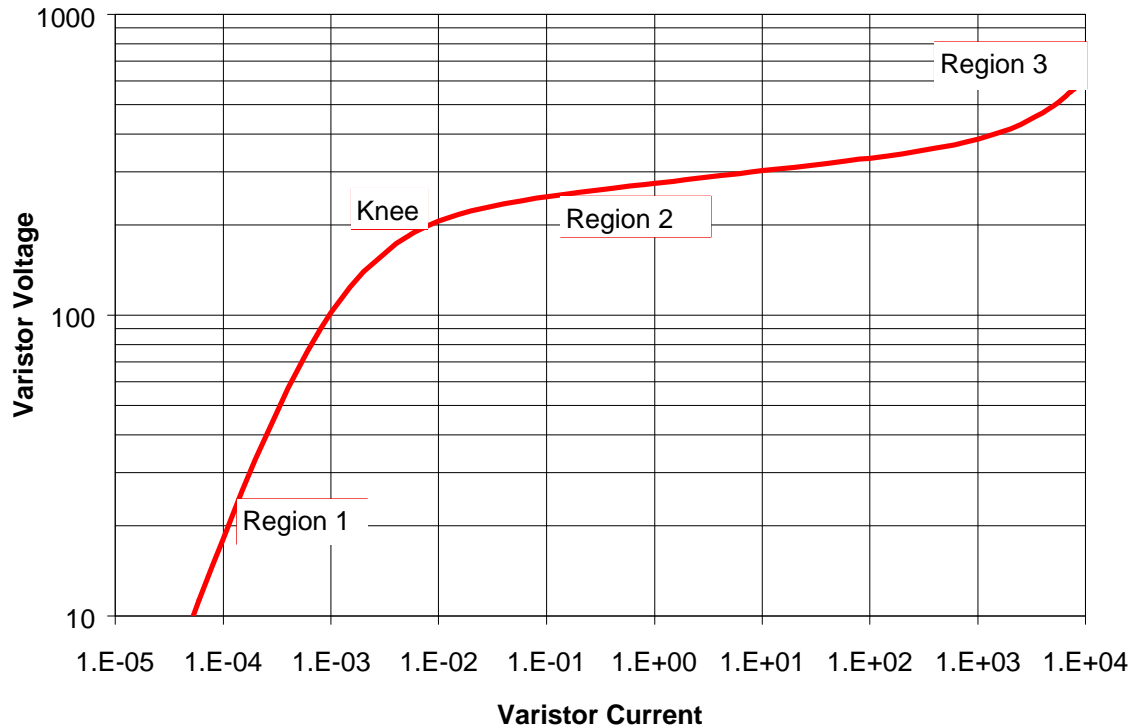
Since varistors always have some internal resistance, they dissipate some of the shunted transient current as heat. This heat is the limiting factor in the capability of a varistor to conduct current, and is obviously proportional to the area of the varistor as well as the waveshape of the current. Transient current limits for varistors lie in the range of 65 amps per square centimeter for 10x1000 μ s waves and 4 kA per square centimeter for 8x20 μ s waves. This translates into about 165 amps and 10 kA respectively for the most commonly used 18-mm units and about 815 amps and 50 kA for the larger 40-mm diameter varistors.

ELECTRICAL CHARACTERISTICS

Varistor electrical protection characteristics are best illustrated with a voltage-current curve. This curve plots the peak transient current in amperes along the X-axis and the peak varistor voltage along the Y-axis. Since the varistor operates over a wide range of currents, the X-axis is usually plotted logarithmically, as is occasionally the Y-axis. A typical curve for a 150-volt rated varistor of 18mm diameter, based on measured data using an 8x20 μ s transient current waveform, is shown in Figure 1 below.

The characteristic curve has three main regions. Region 1, at the lower left of the graph, represents the varistor in its "off" or passive state. Region 2 represents the active non-linear operation of the varistor in which the resistance falls rapidly with voltage and the "clamping" action is evident. Region 3 represents saturation, in which the resistance of the varistor reaches its lowest and constant value. The knee represents the transition between the "off" and "on" states of the varistor, and is referred to as the "nominal voltage" of the varistor. This is the voltage across the varistor under the application of a constant direct current. By convention, this current is 1 mA per square centimeter of disk area for large varistors (>60 mm diameter), and 1 mA for small varistors.

Figure 1: Typical Curve of 150-Volt Rated 18 mm Diameter Varistor

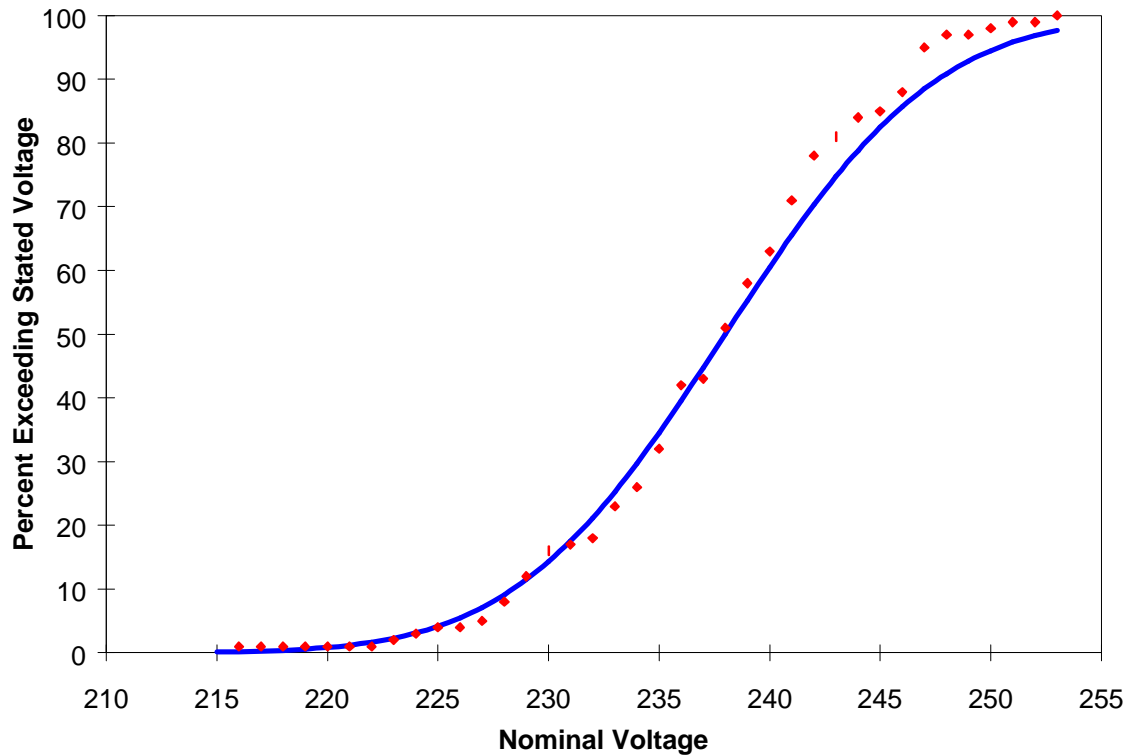


The actual clamping voltage of a varistor carrying transient currents differs from that under the application of direct currents, typically being a few percent higher. The nominal voltage is a good predictor of the clamping voltage under transient conditions, but not perfectly so. Varistors having the same nominal voltage will show variation in clamping voltage when carrying identical transient currents.

Measured using transient waveforms, the dynamic volt-current curves of varistors from the same batch have the same shape – that is they are parallel and do not cross. Since the separation between these dynamic curves is approximately dependent on the nominal voltage, this leads to the conclusion that the main difference between varistors results from minor differences in disk thickness or density.

If the variations within a batch are indeed the result of thickness or density resulting from chance manufacturing variances, the distribution of nominal (1 mA) voltages as well as the dynamic volt-current curves would be expected to be normal (Gaussian). The nominal voltage of 100 samples of 18mm varistors, rated for 150 V ac operation was measured, and the distribution plotted. This plot is shown, together with the best-fit normal curve in Figure 2.

Figure 2: Distribution of Nominal Voltage of 100 Varistors

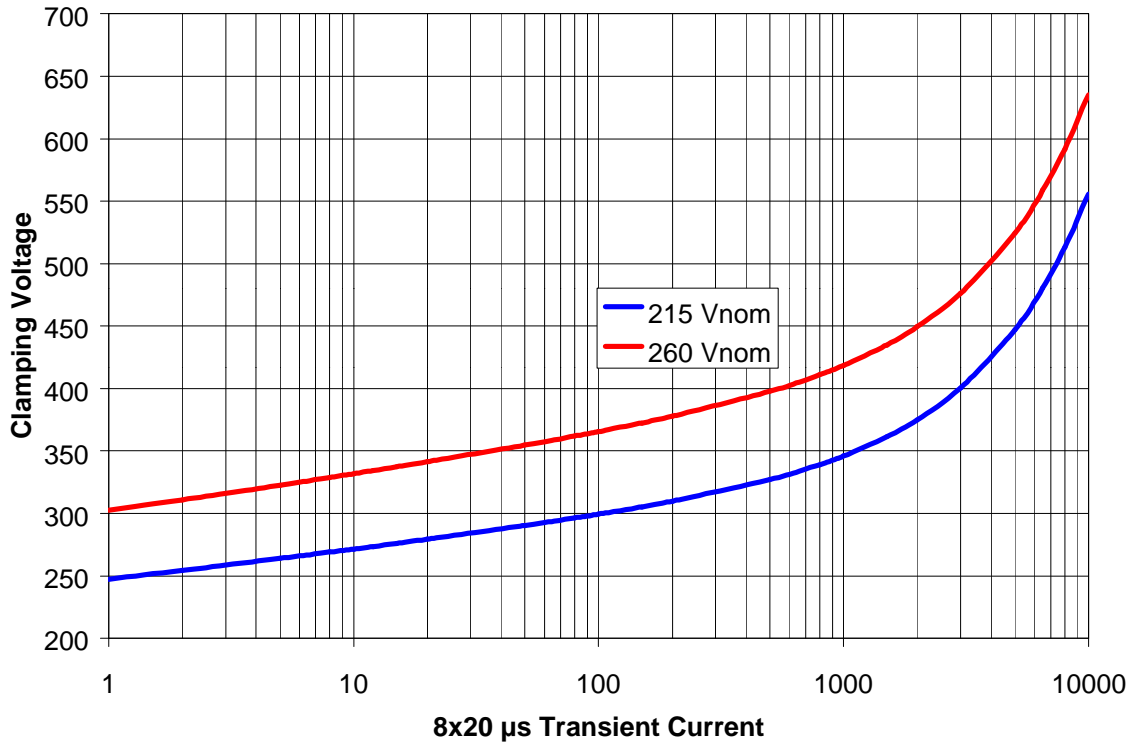


This shows, as expected, a closely normal curve, having a mean of 238 volts and a standard deviation of 7.5 volts. The nominal voltage of virtually all varistors would fall between the limits of 215 V and 260 V - a range of about $\pm 9\%$ from the mean. It may be assumed that the clamping characteristics would be similarly distributed, although in practice the distribution of clamping voltages may be somewhat better.

Since the nominal voltages appear to be distributed normally, it is quite easy to calculate the expected range of values of varistors in a parallel stack consisting of several varistors, assuming that they occur at random. It is also possible to calculate the probability that an individual stack of several varistors contains one of extremely high or low voltage rating.

A normal distribution has virtually no members above or below three standard deviations from the mean. This sets the expected upper and lower limits of varistor voltage for the population examined at 215 and 260 V respectively. Assuming that the nominal voltage and clamping curves are perfectly correlated, the clamping curves may be predicted from the nominal voltage. The volt-current curves for varistors having nominal voltages of 215 V and 260 V- the extreme ends of the distribution - are shown below in Figure 3.

Figure 3: Volt-Current Curves of High and Low Voltage Varistors



CURRENT SHARING OF PARALLEL VARISTORS

When varistors are connected in parallel, the voltage is the same across each varistor and the current through each individual unit will depend on its volt/current characteristic. Varistors having lower clamping voltages will conduct more current than those having higher clamping voltages. The difference in current will be very much greater than the difference in nominal voltages because of the non-linear varistor characteristics. The handbook of one manufacturer states that varistors may only be operated in parallel if their characteristics are closely matched, otherwise the current sharing between parallel devices could vary as much as 1000:1. Close matching varistors are often defined as those having voltage curves within 1% of each other.

Examination of Figure 3 enables an estimate of the largest difference between parallel varistors at each end of the voltage range. For a clamping voltage of 300 V, the lower varistor conducts 100 amps, while the higher one conducts only 1 amp— a ratio of 100:1. The sharing improves with current, however (Table 1). This shows that, even with the worst matched varistors from opposite ends of the statistical distribution, the current sharing is never worse than a ratio of 100, and over most of the range of interest it is less than 10. This is significantly better than the manufacturers predict.

CURRENT & ENERGY RATINGS OF PARALLEL VARISTORS

Table 1 Current Sharing in Two High and Low Voltage Parallel Varistors

Clamping Voltage	Current in 215 V Varistor	Current in 260 V Varistor	Ratio of Currents in Two Varistors
300	100	1	100
350	1050	40	26
400	3000	550	5.5
450	5000	2000	2.5
500	7500	4000	1.9
550	9500	6000	1.6

PERFORMANCE OF PARALLEL STACKS

Of more interest is the performance of a parallel stack of several varistors chosen at random from one batch, as this is the technique used by several manufacturers to manufacture high-current varistor modules. For this study, the performance of parallel stacks of six 18mm varistors was examined. The goal was to establish the following:

1. Does current sharing between unmatched varistors fall within acceptable limits?
2. What is the maximum current and energy rating of a parallel stack?
3. Does a parallel stack of unmatched varistors perform comparably to a single 40-mm unit?

Two experimental stacks were made – one with six varistors having nominal (1 mA) voltages matched within $\pm 1\%$, and the other with varistors chosen at random. Transient currents with a nominal $8 \times 20 \mu\text{s}$ were applied to each stack in turn and the currents through each varistor measured using Pearson high-frequency current transformers. After the response had been found at lower currents, the measurements were continued at higher currents on only the lowest and highest voltage clamping varistors in each stack.

The current values for the matched stack are shown in Table 2, together with the nominal voltage for the varistors used:

CURRENT & ENERGY RATINGS OF PARALLEL VARISTORS

Table 2 : Distribution of Current in Stack of Six Matched Varistors

Varistor Nominal Voltage	238 V	242 V	239 V	242 V	240 V	243 V
Test 1 Currents	59 A	42.5 A	58.5 A	51 A	41.2 A	46.4 A
Test 2 Currents	142 A	103 A	140 A	123 A	102 A	116 A
Test 3 Currents	277 A				212 A	
Test 4 Currents	383 A				302 A	
Test 5 Currents	491 A				397 A	
Test 6 Currents	596 A				492 A	
Test 7 Currents	705 A				588 A	
Test 8 Currents	1120 A				986 A	
Test 9 Currents	1930 A				1730 A	
Test 10 Currents	2960 A				2680 A	
Test 11 Currents	3960 A				3640 A	
Test 12 Currents	5920 A				5500 A	
Test 13 Currents	8020 A				7500 A	

It should be noted that, even though the MOVs were well matched, there was a difference between them, and the nominal voltage was not a perfect predictor of clamping performance.

The similar measurements for the unmatched stack are given in Table 3:

CURRENT & ENERGY RATINGS OF PARALLEL VARISTORS

Table 3 : Distribution of Current in Six Unmatched Varistors

Varistor Nominal Voltage	246 V	239 V	229 V	235 V	246 V	246 V
Test 1 Currents	35.8 A	36.2 A	103 A	72.2 A	25.2 A	21.2 A
Test 2 Currents	96.1 A	90.5 A	228 A	180 A	74.8 A	62.4 A
Test 3 Currents	149 A	135 A	315 A	254 A	123 A	128 A
Test 4 Currents	331 A	280 A	531 A	450 A	247 A	216 A
Test 5 Currents	654 A	536 A	908 A	805 A	494 A	460 A
Test 6 Currents			1600 A			988 A
Test 7 Currents			2060 A			1410 A
Test 8 Currents			2550 A			1900 A
Test 9 Currents			3640 A			3080 A
Test 10 Currents			4200 A			4000 A
Test 11 Currents			6160 A			6520 A

From the above, the ratio of the currents in the lowest and highest rated varistors in each stack may be compared. These data show that, although the current sharing is worse in the unmatched stack, it is nevertheless very good, particularly at the higher currents. Again, it may be seen that the nominal voltage was a reasonable, but not perfect, predictor of clamping performance.

The maximum current of a parallel stack is determined by the lowest clamping varistor. When the current through that varistor reaches its maximum limit, this represents the most conservative current limit for the parallel stack, since all other varistors will be conducting less current.

The maximum current of 8x20 μ s waveshape specified for 18-mm varistors by most manufacturers lies in the range between 7.5 kA and 10 kA. This limit is specified as that which a varistor may

conduct one time without any change in nominal voltage of more than 10% - the concern being that a reduction in nominal voltage may lead to varistor conduction under normal conditions leading to early failure.

In order to confirm the high current limits of modern production varistors for this study, ten varistors were exposed to impulses at the 10 kA level, and their nominal voltages recorded before and after. All ten varistors conducted a minimum of three impulses at or exceeding the 10 kA level with no major change in nominal voltage. In fact, in all units tested, the nominal voltage increased a few percent. The adoption of 10 kA as a one-time current limit for 18 mm varistors is therefore considered conservative.

Examination of the data from Figure 3 shows that a parallel combination of a 215 V varistor and a 260 V varistor would have a current limit of 17 kA if the current in the lower clamping varistor is limited to 10 kA. The worst possible combination of six varistors would comprise one 215 V and five 260 V units, an impossible combination to achieve in manufacture. Such a parallel stack would have a maximum 8x20 μ s current rating of 45 kA.

The randomly chosen stack described above, with data given in Table 3, would have a maximum 8x20 μ s current of nearly 59 kA, using the above limiting criterion. This is very close to the theoretical maximum of 60 kA, and well above the typical 50 kA rating of 40 mm varistors.

Since varistors in parallel stacks are chosen at random from the population, it may be expected that the performance of stacks will exhibit some variance. The stack measured is expected to be representative of that population. It is estimated that approximately two thirds of the stacks will perform close to the representative one examined, and that the maximum current capability of these stacks will exceed 55 kA. The remaining one third of stacks will have less well-matched varistors and contain at least one low-rated unit. The maximum current of these will be somewhat lower, but will still exceed 50 kA.

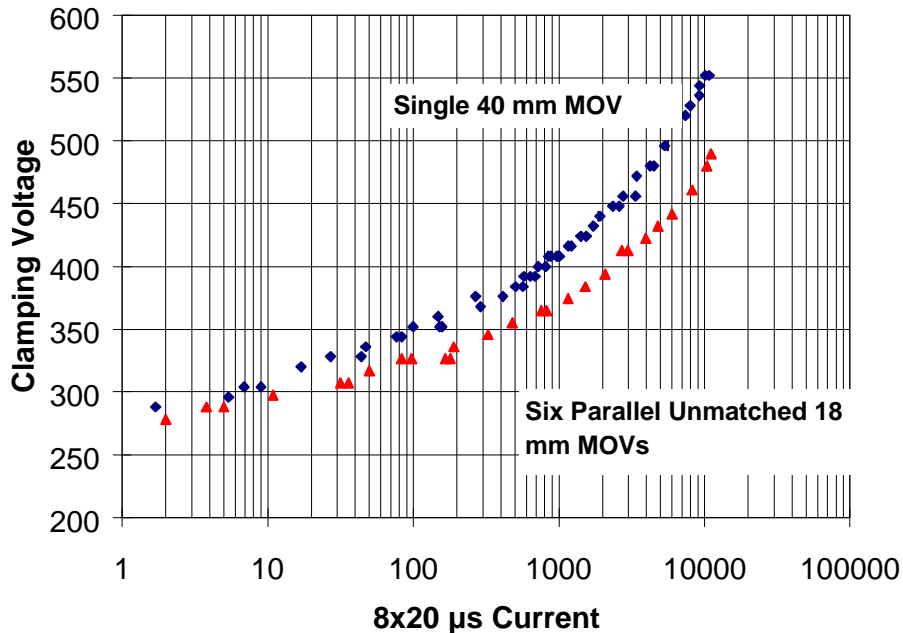
As mentioned above, the one-time 8x20 μ s current rating for 40 mm varistors is 40 kA, although this is also expected to be conservative, and most units should be capable of 50 kA.

It is concluded from these measurements that the current and therefore energy rating of a stack of six parallel unmatched set of 18 mm varistors is comparable to and may exceed those of a single 40 mm varistor.

CLAMPING VOLTAGE COMPARISON BETWEEN STACK AND SINGLE 40 MM UNIT

The clamping voltages of an unmatched stack of six varistors in a commercially manufactured package and a single 40-mm varistor were measured using 8x20 μ s currents from a few amps up to 15 kA. These data are shown in Figure 4.

Figure 4: Comparison between stack and single mov



The upper curve represents the measured data on the 40 mm varistor, the lower curve the measured data on the parallel stack of six 18 mm varistors. It can be seen that the clamping of the stack is significantly better than the single 40 mm unit, especially at higher currents.

DISCUSSION ON PERFORMANCE

A varistor may be considered to comprise four components – a variable resistor in parallel with a fixed resistor and a capacitor, and a third resistor in series with the other components. The first component represents the dynamic resistance of the varistor; the second represents the off resistance of the varistor (typically several hundred kilohms), the third represents the device, and the fourth represents the on or bulk resistance of the varistor (typically a small fraction of an ohm). These are shown schematically in Figure 5.

The important characteristics for surge protective purposes are the variable resistor characteristics and the value of the bulk resistance.

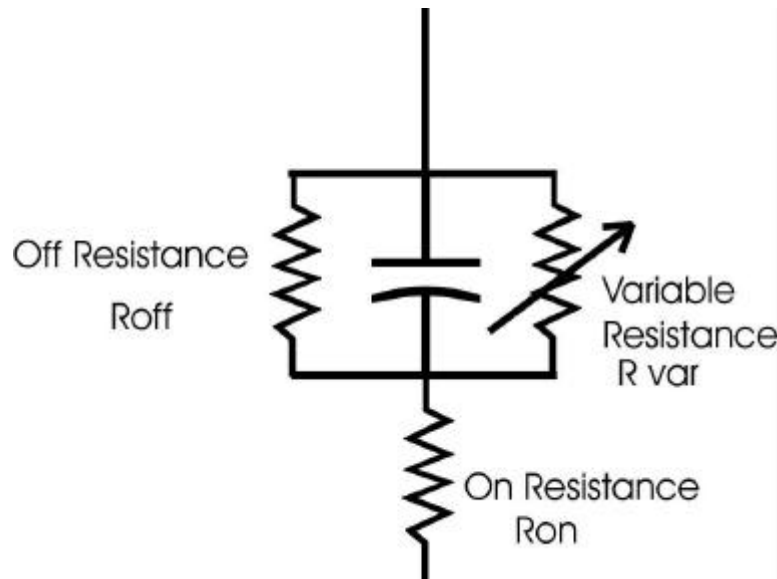
Examination of the measured data from the varistors shows that the variable resistor closely follows a power law, whereas the bulk resistance is constant. The values for these for the 40 mm and 18 mm varistors is as follows:

Variable resistor

$$R_{\text{var}} = 1.146 \times V_{\text{nom}} \times (I)^{-0.96}$$

This was found to be valid for both 18 mm and 40 mm units

Figure 5: Schematic of varistor equivalent circuit



This variable resistance has values that drop with surge current, as shown in Table 4 below:

Table 4: Variable resistance of MOVs

Varistor Current in amps	Variable Resistance in Ohms
0.001	208639.2
0.01	22876.83
0.1	2508.395
1	275.04
10	30.15754
100	3.306708
1000	0.362573
10000	0.039755

Bulk resistance of 40-mm units:

$$R_{on} = 33 \times V_{nom} \text{ in micro-ohms (mean value 0.008 ohms)}$$

Bulk resistance of 18-mm units

$$R_{on} = 92 \times V_{nom} \text{ in micro-ohms (mean value 0.022 ohms)}$$

These data show that the improvement in performance at higher surge currents achieved by paralleling varistors is substantially as a result of the reduction in resistance. The improvement, however, is not quite equal to the expected paralleling of six units. The effective resistance of a parallel stack of six varistors is closer to that of four in parallel than six. This suggests that some of the resistance ascribed to the bulk properties of the varistors may actually be in the connecting leads.

FAILURE MODES

Varistors suffer two failure modes – overheating due to excessive surge energy and overheating due to sustained power frequency overvoltages. In the first, the varistor suffers failure by cracking or shattering of the disk material as a result of the thermal shock. In the second, the varistor suffers a punch-through failure in which a track through the disk is established, eventually burning a hole in the disk.

In both failure modes, a single 40-mm varistor will be irreversibly damaged. If the units are fused correctly, such a damaged unit will be removed from service, leaving the circuit without protection unless redundant devices are provided.

In a stack of varistors, the lowest voltage units, which carry the highest current, are most likely to be damaged by an extreme surge and it is unlikely that all six in a stack would fail simultaneously. In the event of power-system overvoltage, only one of the lowest voltage varistors is likely to suffer from punch-through failure. If the varistors are provided with individual overcurrent or thermal protection, the stack has inherently better redundancy. Even without such individual component protection, the stack has a higher chance of retaining functioning protection after a severe power system event.

CONCLUSIONS

The performance of a stack of six unmatched 18-mm diameter varistors shows the following in comparison with a single 40-mm varistor of the same nominal voltage:

1. The maximum single-pulse current is 50 kA $8 \times 20 \mu\text{s}$ for both stack and single 40-mm varistor
2. The maximum single-pulse energy is comparable for the stack and single 40-mm varistor
3. The clamping performance of the stack is superior to the single 40-mm varistor
4. The clamping performance and maximum surge current capability of a stack of six matched varistors are not significantly different than those of the unmatched stack
5. Overstress failure modes of the stack offer advantages over the failure mode of the single 40-mm varistor