Characterisation of surge suppressors

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Surges are a fact of life in electrical circuits, typically due to lightning but also to supply faults of various sorts. So it has become standard practice to incorporate protection into the interfaces of any electronic circuits that are likely to be susceptible; certainly the AC mains power supply, but also any other interfaces which connect to long distance cables that might be exposed, such as process instrumentation field wiring, DC power buses or telephone lines. The standardized EMC test for immunity to surges is IEC/EN 61000-4-5 and this is referenced in many product immunity standards, but even without this requirement, it is good practice to implement surge protection on critical interfaces. Data on surge prevalence in the real world can be found in "Guide on the Surge Environment in Low-Voltage AC Power Circuits", IEEE C62.41.1–2002.

There are three main types of surge suppressors that are available to electronic circuit designers: gas discharge tubes (GDTs), metal oxide varistors (MOVs) and silicon avalanche suppressors – zeners, sometimes referred to as transient voltage suppressors, transzorbs or transils, the latter being registered trademarks. The GDT is relatively rarely used except in certain well-defined applications like telephone lines and antenna leads, but the other two are in very common use and there is a large range from which to choose. They are placed in parallel with the transient source and their effectiveness depends on the ratio of their dynamic slope impedance Z_S to the transient source impedance Z_T.

The choice of device is dictated by circuit operating parameters: leakage current, capacitance and threshold voltage are important with respect to normal circuit operation; clamping voltage, follow-on current, energy capability and response time are important when the device is faced with a transient.

The device must be sized to hold off the maximum continuous operating voltage of the circuit, with a safety margin for tolerances, and to absorb the energy from any expected transient while maintaining a sufficiently low clamping voltage. The first requirement is fairly simple to design to, although it means that the transient clamping voltage may be more than twice the continuous voltage, and circuits that are protected by the suppressor must be able to withstand this. The second requirement calls for a knowledge of the source impedance and likely amplitude of the transients, which are often difficult to predict especially for external connections. On the other hand, IEC/EN 61000-4-5 (and other standards for specific environments) gives a clear specification for what will be applied as a test stress, and this allows the designer to make some reasonable attempt at quantifying the parameters.

All the manufacturers of suppressor devices give data on the necessary values that will enable a conservative design against the known test stress to be made. But what really happens when the test waveform is applied, and what would happen if the stress went outside the design margin in practice? These questions can’t easily be answered from the data sheet, but they should be of interest to any designer who is concerned about real-world performance of a product.

This article reports the results of some measurements made on a variety of surge suppressors, subjected to a surge stress up to 1kV according to IEC/EN 61000-4-5 and using the three source impedances specified in that standard. The waveform of the clamped voltage is shown for a range of devices, including low voltage MOVs, low voltage Zener types and high voltage MOVs, both surface mount and leaded. For the smaller devices, destructive overstress was applied in order to investigate the likely behaviour of the protection in this situation.

The surge stress

IEC/EN 61000-4-5 gives levels from 500V to 4kV peak voltage, with a voltage waveform of 1.2µs front time and 50µs half-time, and a current waveform of 8µs front time and 20µs half time. There are three levels of source impedance (Z_T above), depending on the mode of coupling: the most severe is an equivalent 2Ω line-to-line on power supply inputs, which would give a worst-case peak current of 2000A at the highest surge level. The other impedances are 12Ω for line-to-protective earth, on power supplies, and 42Ω line-to-earth on signal lines.

The energy content of transients and surges is not simple to define. The actual energy stored in the test generator is not all dissipated in the load. That proportion which is, depends on the ratio of the load and generator impedances. In general, a load such as a surge suppressor will be non-linear and will also have a time dependence related to the transient waveform.

As a practical approach, the energy that will be delivered by the generator into a defined resistive load can be calculated. Choosing a load which matches the output impedance, the voltage or current waveform is assumed to be maintained into this resistance with half the open circuit (or short circuit, for current) amplitude. In these cases the energy in Joules (watt seconds) is shown for the four standardized test levels in Figure 1 and is given by

$$W = \frac{1}{R} \cdot \int_0^T \left(\frac{V(t)}{2} \right)^2 dt \qquad\qquad W = R \cdot \int_0^T \left(\frac{I(t)}{2} \right)^2 dt$$

where V(t) and I(t) are the open circuit voltage and short circuit current waveforms, respectively.

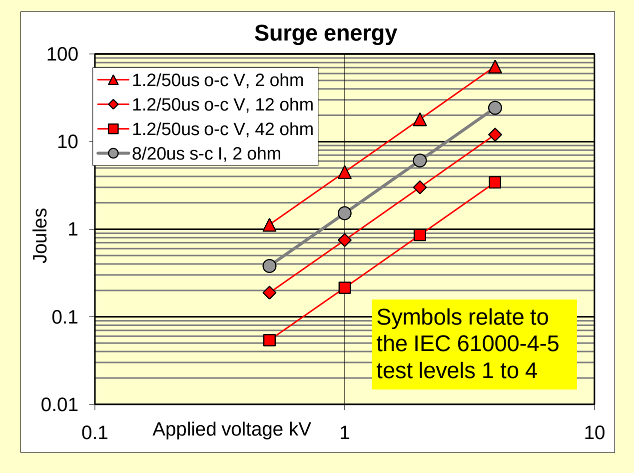

Figure 1. The energy in a surge

Figure 1 is for comparative purposes only – the real energy delivered to a particular device can only be calculated if the load impedance and characteristics, and the actual waveshape applied to this load, are known accurately.

The test circuit

A simple generator giving up to 1kV peak voltage with three selectable source resistances, approximating to the standard values, was used to characterise the devices. The device was placed across the terminals of the generator and the waveform was recorded with a 500MHz bandwidth storage oscilloscope. The short circuit current and open circuit voltage waveforms for a 500V peak level are shown below and these are reasonably representative of the standard waveforms.

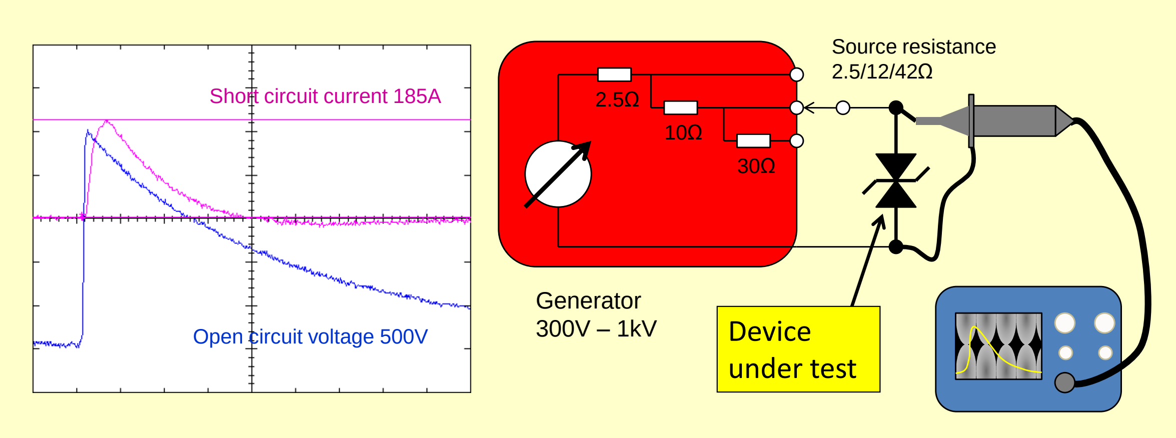

Figure 2. **The surge generator, waveform and setup**

This circuit doesn't add in the standing mains or DC supply voltage and therefore the results may not be fully representative of waveforms that would occur in a real circuit, but they do allow the main features of each type and level of device to be compared.

Specifications of suppressors

Comparison of competing devices is sometimes difficult because different manufacturers specify their key parameters in different ways. To begin with, the part number itself; it invariably refers to the rated voltage, but this might be the DC voltage, the AC RMS voltage, or the voltage at 1mA. The maximum pulse current is normally quoted for a double exponential waveform, but this might be the 10/1000µs telecom waveform or the 8/20µs combination (IEC 61000-4-5) waveform; the latter will allow a much higher current value. And the energy rating for MOVs (varistors) is sometimes quoted for a 2ms duration and sometimes for a 10/1000µs waveform. It is never specified in the same way for TVSs (avalanche devices), although you can derive it given the peak power derating curves; for instance for the devices investigated here, which are 600W parts, the curves derate the power to 400W for 2ms.

As stated above, the energy in a surge is not all deposited in the suppressor, so if you know something about the surge source, then it is better to use the expected peak current to define the size of device.

Test results

The devices that were tested – in most cases, several samples of each – are listed in table 1. The manufacturer's principal parameters are included for each.

In all the plots that follow, the voltage across the suppressor is shown at 50µs per division and with up to four curves, generally representing peak surge voltages of 300V, 500V, 750V and 1kV from the stated source impedance, in the order blue-purple-green-red. Not all devices in the table are shown in the plots – some have been omitted for brevity, where they have similar characteristics to the rest.

Table 1 Devices tested

Device	Manufacturer	Size	V_V @ 1mA	Rated DC V	Energy J	I_{max} A 8/20us	V_{cl} @ I
Leaded Transient Voltage Suppressor					* Derived from power spec		
SA30CA	Vishay (GS)	DO204	35	30	0.8 * (a)	10.5 (10/1000)	48.4@10.5
P6KE36A	Fairchild	DO15	36	29	0.8 * (a)	62	64.3@62
Surface Mount Transient Voltage Suppressor							
SMBJ13CA	STM	DO-214	14.4	13	0.8 * (a)	147	27.2@147
SMBJ33CA	STM	DO-214	36.7	33	0.8 * (a)	57	69.7@57
Surface Mount Metal Oxide Varistor							
CN1210K17G	Epcos	1210	27	22	1.7 (a)	400	44@2.5
CN2220K25G	Epcos	2220	39	31	9.6 (a)	1200	65@10
CN1206K30G	Epcos	1206	47	38	1.1 (a)	200	77@1
V14MLA0805V	Littelfuse	0805	18.1	14	0.3 (b)	120	32@1
V33MLA1206AXH	Littelfuse	1206	43.5	33	0.8 (b)	180	75@1
Leaded Metal Oxide Varistor							
V68ZA2	Littelfuse	7mm	68	56	3 (b)	250	135@2.5
ERZV07D680	Panasonic	7mm	68	56	3.3 (a)	500	135@2.5
ERZV07D101	Panasonic	7mm	100	85	6 (a)	1750	165@10
ERZV07D391†	Panasonic	7mm	390	320	25 (a)	1750	650@10
V100ZA3†	Littelfuse	7mm	100	81	5 (b)	1200	165@10
S14K150	Epcos	14mm	240	200	40 (a)	4500	395@50
S14K275	Epcos	14mm	430	350	71 (a)	4500	710@50
V275LA4	Littelfuse (GE)	7mm	430	369	23 (b)	1200	710@10
V250LA20AP	Littelfuse	14mm	391	330	72 (b)	4500	650@50
2381 592 52716	Vishay (BC)	5mm	430	350	12 (b)	400	695@5
Zener Diode							
1N5242B	-		12V	-	-	-	-

† = discontinued device

(a) = 2ms (b) = 10/1000µs

TVS devices

Plots of avalanche TVS performance are shown in Figures 3 - 5.

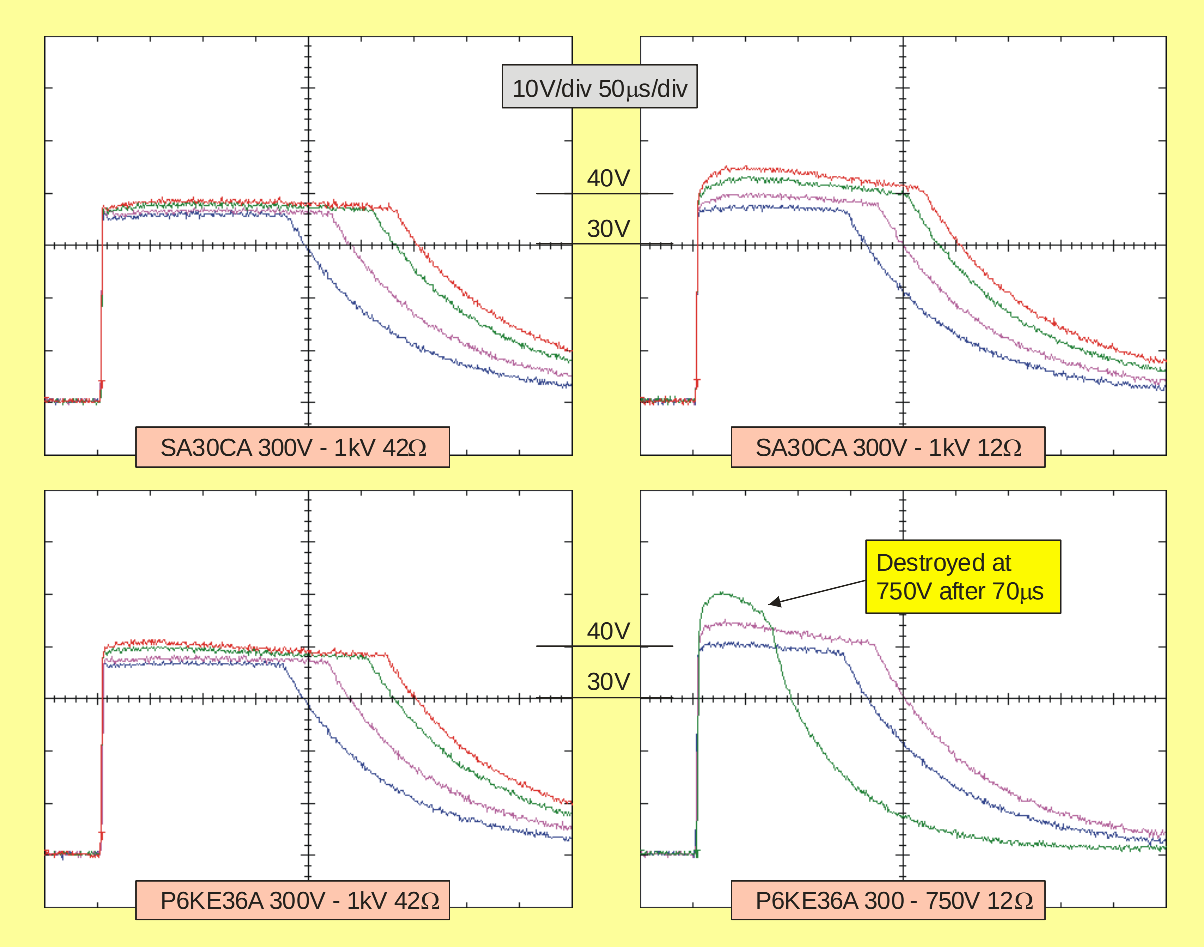

Figure 3. **Leaded devices**

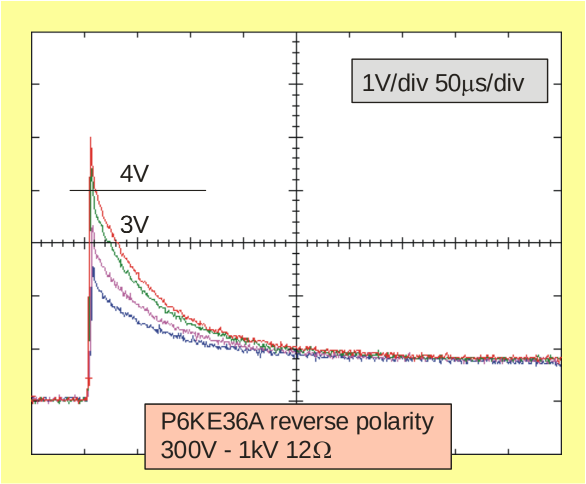

Figure 4. **Reverse polarity**

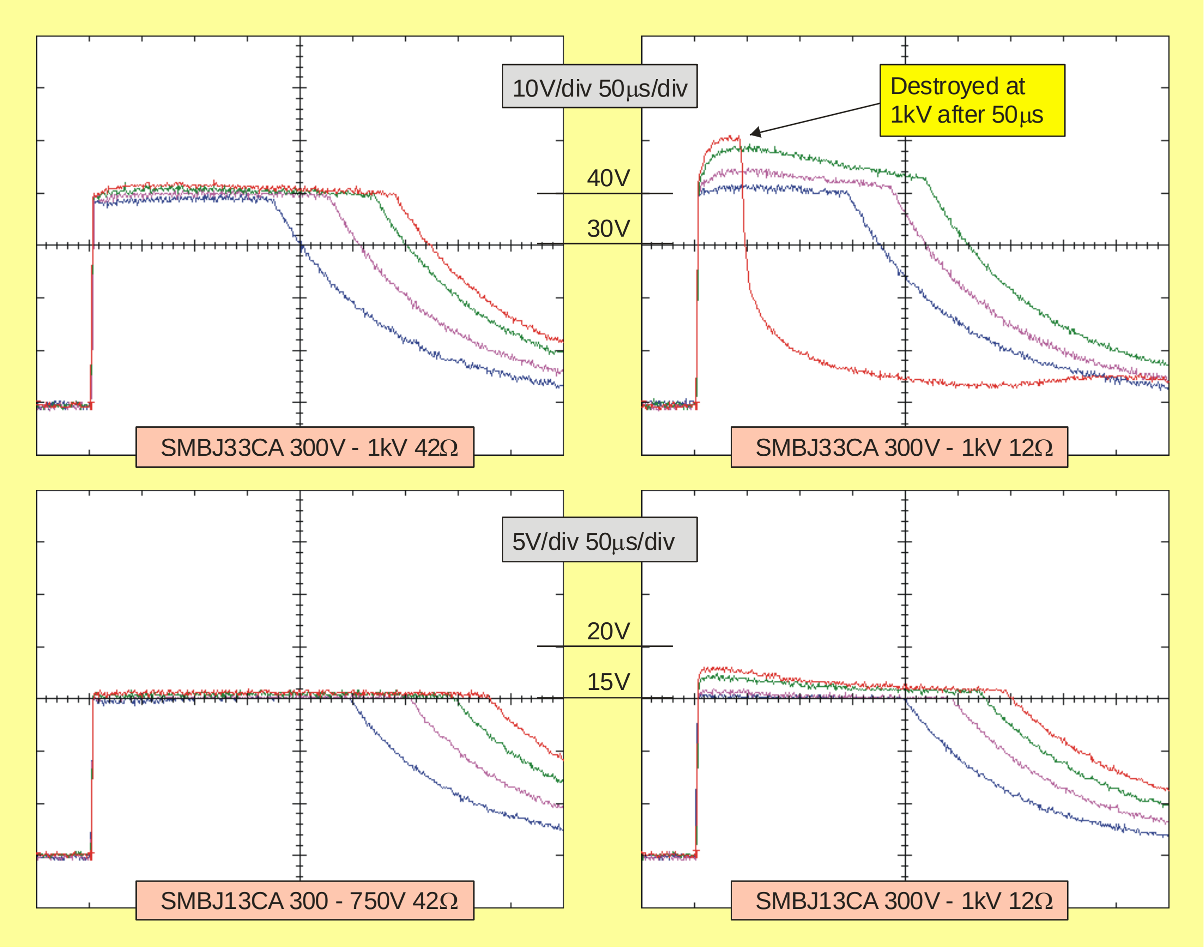

Figure 5. **Surface mount devices**

The most significant aspect of all these curves is the very flat nature of the clamping waveform. Given that the device is passing a current which, at least for the 42 ohm source impedance, follows the voltage waveform almost exactly, it is clear that once the knee is reached, the slope resistance above this point is very low. For the 12 ohm impedance the current is sufficient to increase the clamping voltage noticeably, and in the case of the SMBJ33CA a 1kV pulse is enough to destroy the device after 50µs with a peak voltage of 50V reached. Here the peak current is around 80A, for a device with a maximum quoted 8/20µs current of 57A. The same level doesn't destroy the SMBJ13CA, despite being virtually the same current waveform, since due to its lower clamping voltage the power dissipation is less than half. A 750V/12 ohm pulse is sufficient to destroy one sample of the P6KE36A, although the SA30CA device, despite having a slightly lower rated power capability, survived at 1kV; this discrepancy is harder to explain.

You can observe that, comparing the actual clamping voltages in each case with the specifications quoted in Table 1, the specification is noticeably more pessimistic than the measured value would imply.

Although these devices will clamp pulses within their capabilities effectively, they are easily destroyed once the dissipation exceeds their limit by only a small margin. This is a feature of avalanche devices: the actual breakdown occurs within a relatively small region of the silicon, which cannot withstand or conduct away the dissipated heat successfully. This distinguishes them from MOVs.

Figure 4 shows the waveform across a unipolar device in the reverse sense. This should be the normal forward voltage of a silicon p-n junction, but if you were expecting the usual 0.6V or so, think again: with the high current (80A) being passed by the device, the actual voltage approaches 5V at the peak with a 1kV 12 ohm surge.

Low-voltage surface mount MOVs

Figures 6, 7 and 8 show surface mount varistors. The most notable feature here is the sharp front-end peak, which is entirely absent from TVS waveforms, as well as the higher slope resistance, which makes the clamped waveform closer in shape to the applied surge voltage: remembering that with a series resistance of 12 or 42 ohms, the current waveform through the device is close to the open circuit voltage waveform.

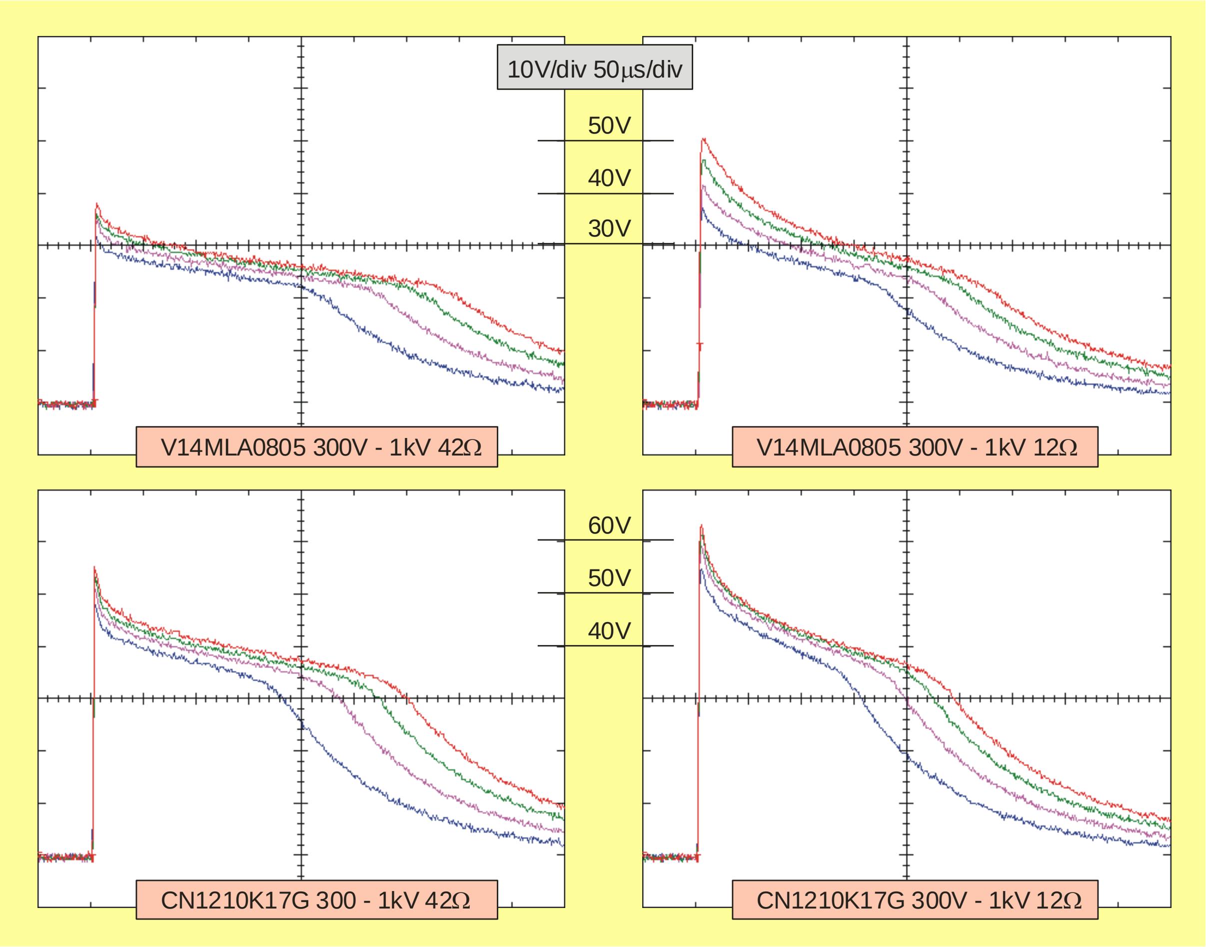

Figure 6. 14/17 V devices

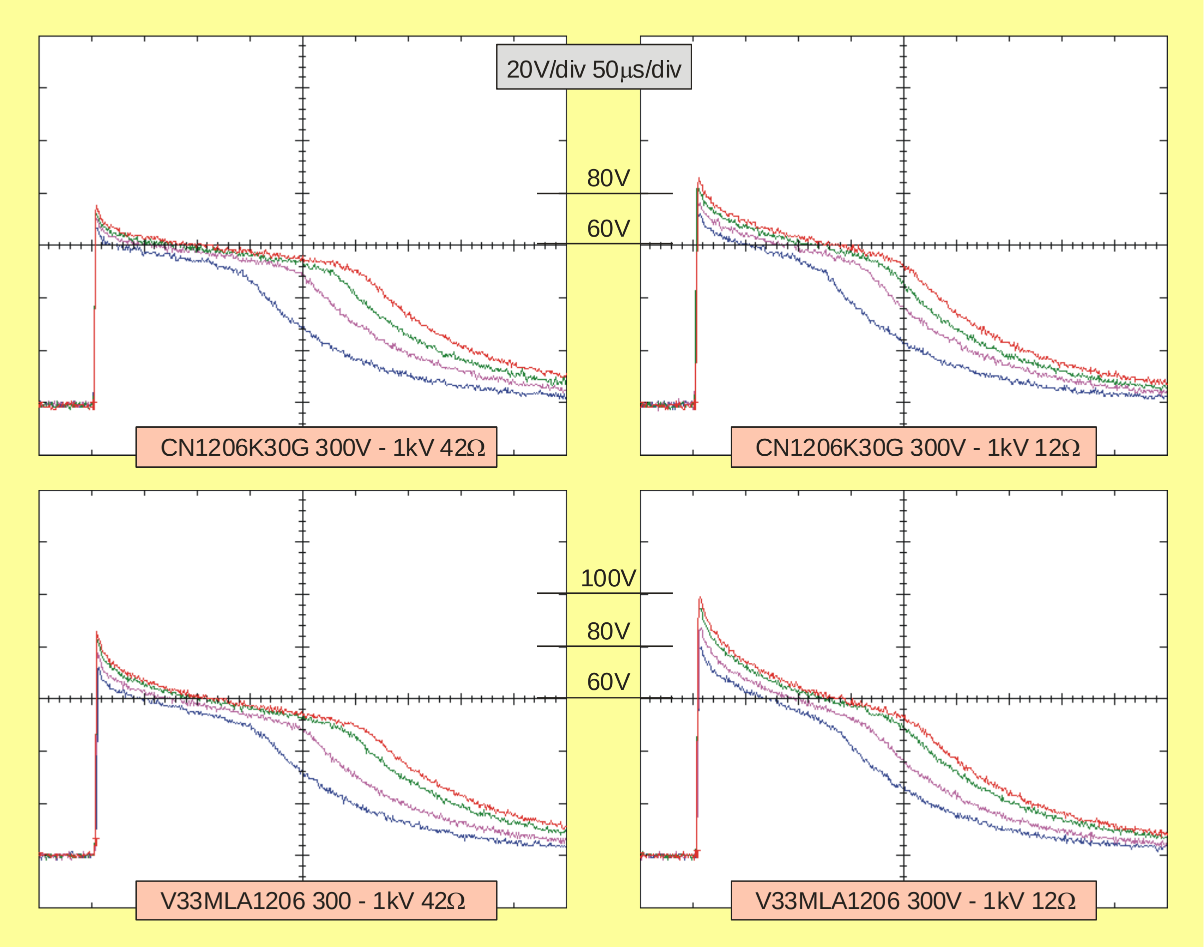

Figure 7. 30/33V devices

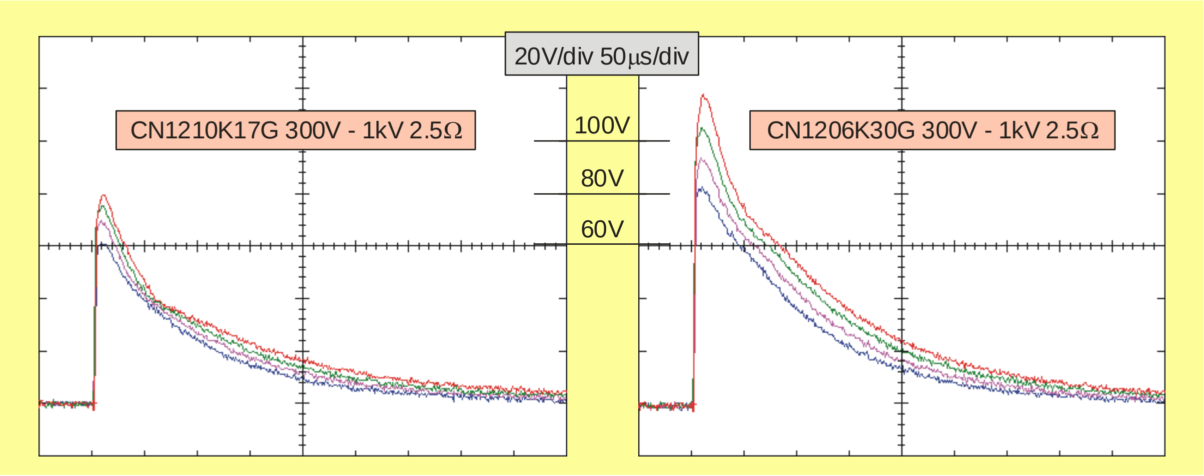

Figure 8. EPCOS devices at 2.5 ohms

Expecting to be able to test these devices to destruction, the two EPCOS parts were also subjected to surges up to 1 kV at 2.5 ohm source impedance (Figure 8). They weren't destroyed! Although the 30V 1206 part showed a peak voltage exceeding 100V, and a corresponding current which would have approached 400A (twice its quoted I_{max}), it was able to accept repeated pulses at this level without complaint. The 17V 1210 part was being operated just over its maximum rating.

This points up the advantage of the multilayer varistor: its interdigitated electrode construction within the mass of dielectric material. This results in excellent current distribution and the peak temperature versus energy absorbed is very low. The matrix of semiconducting grains combine to absorb and distribute transient energy, which reduces thermal stresses and enhances device reliability.

On the other hand, you can also see that the ratio of peak voltage compared to the rated operating voltage is much higher than the equivalent avalanche TVS, implying a greater slope resistance, as can indeed be found in the data for these devices.

Degradation of MOVs

One of the often-quoted disadvantages of varistor devices is that their characteristics are said to degrade with each transient they capture. It's hard to find authoritative data on this, and this study can hardly be said to be the last word, but to find out if there is anything in this belief, one sample of a 1206 device was subjected to 100 surges at its rated current. The device was a V33MLA1206 which has a rated maximum current of 180A; to achieve this a voltage of 450V was applied through the 2.5 ohm source impedance. The surges were applied at a rate of one every 10 seconds; no significant heating effect was observed on the device. Figure 9 shows the waveforms recorded at the first, 10th, 50th and 100th application. From this you can see that there is a roughly 5% increase in the peak clamping voltage. It's probably unfair to expect a properly selected device to see its rated current a hundred times in quick succession; but if this is a concern, allowing a 5% margin in the design for this aspect would probably be a reasonable approach.

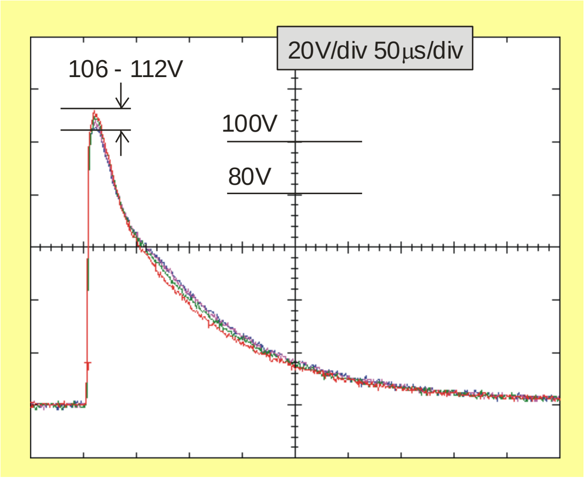

Figure 9. **Degradation of a V33MLA1206 over 100 surges**

High voltage leaded MOVs

Some higher voltage/higher energy MOVs were also tested. These are typically used for mains power supply or other AC clamping applications where the surges are expected to be a higher level than on signal or DC lines. Some curves are shown in Figures 10 and 11. Note that these are mostly taken at 2Ω source impedance as this will be the impedance presented across the lines in a mains test to IEC 61000-4-5. As the mains supply voltage is a greater proportion of the surge voltage, for the higher rated devices only the higher levels were applied.

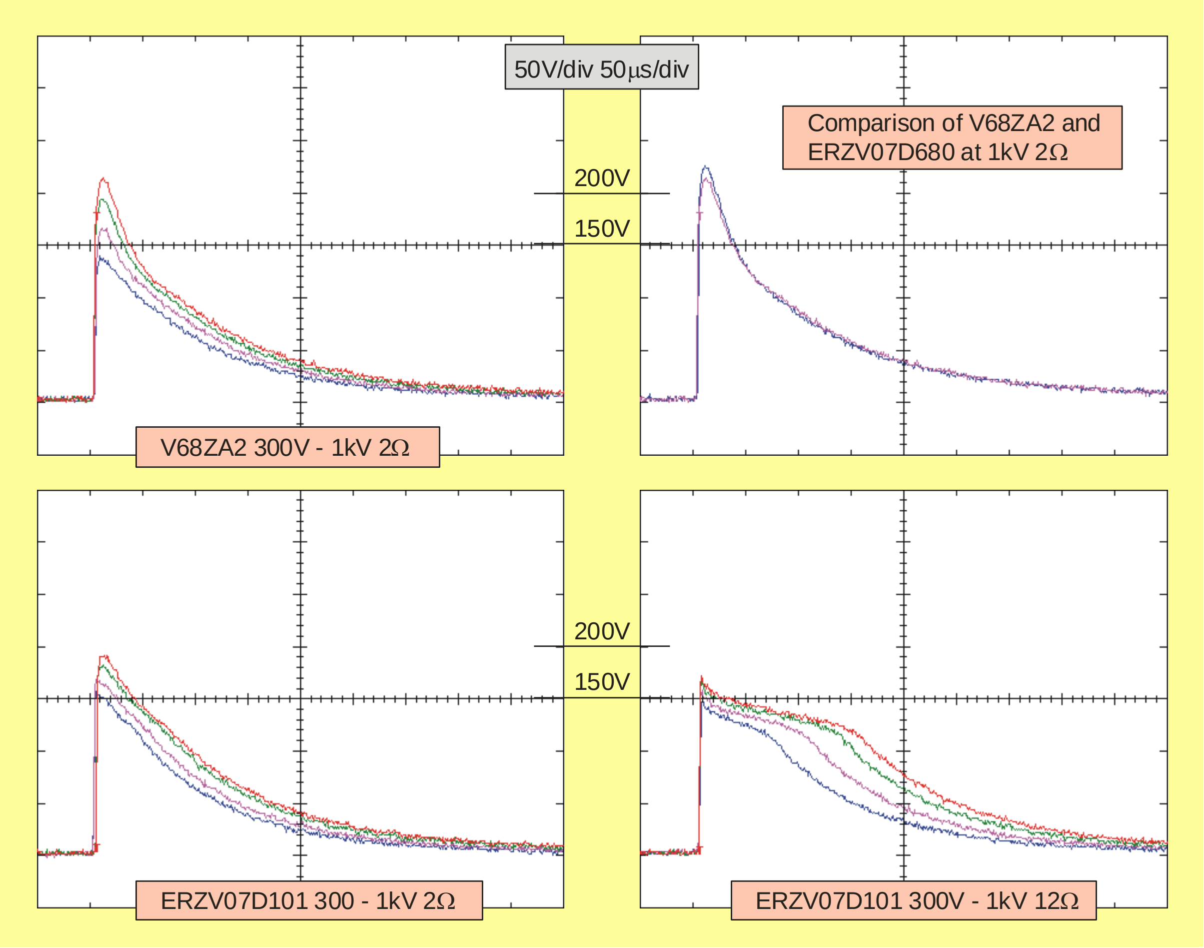

Figure 10. Less than 230V AC rated

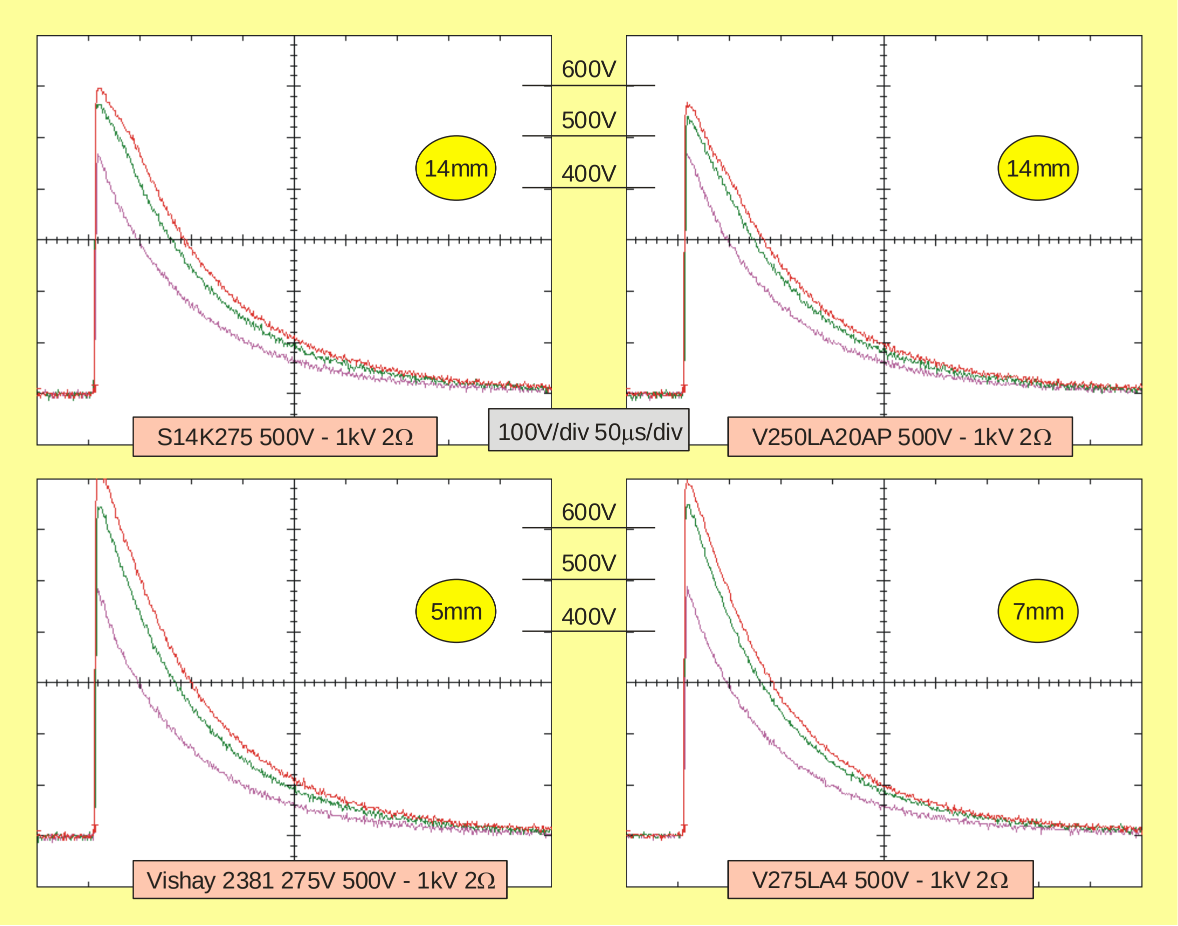

Figure 11. **230V mains application**

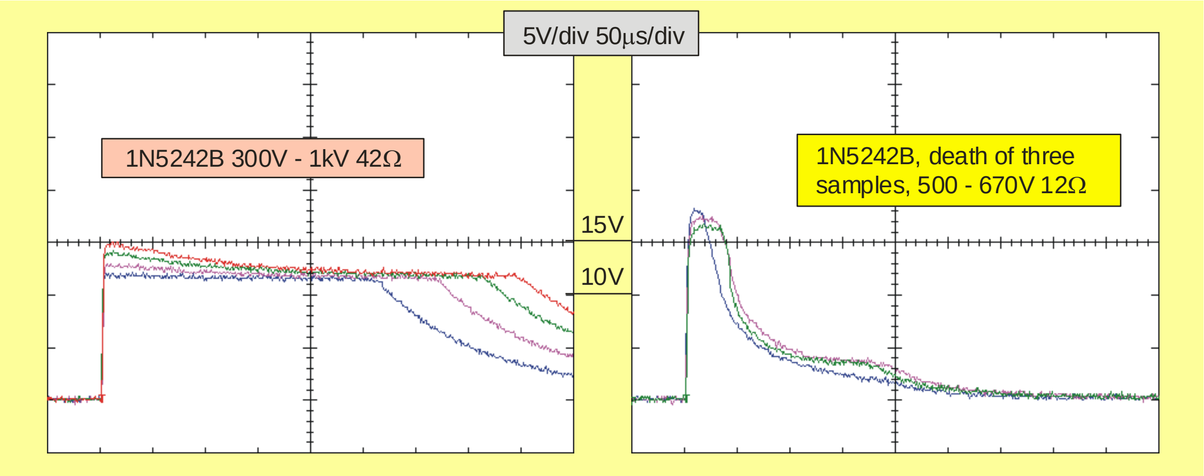

Figure 12. **12V Zener**

Ordinary Zeners

As a side exercise, a few samples of an ordinary 500mW 12V Zener diode (1N5242B) were tested in the same way. The plots are shown in Figure 12. It's clear that the zener will clamp similarly to a TVS, hardly surprising as it is the same avalanche breakdown mechanism. It's also clear that destruction occurs in the same way, and of course at a lower level, since the part is neither rated to withstand high-energy surges nor characterised for them. But if the design can ensure that sufficient series impedance is available to prevent a high surge current, a zener can be used to the same effect as the (usually more expensive) TVS.

Spread of clamping voltages

For units where there were several samples, the statistics of the clamping voltage at a specific surge level were collected. These are tabulated below.

Table 2 Spread of V_{CL}

Device	Manufacturer	Size	Quoted V_{CL} @ I A	Mean V_{CL}	**SD as % of mean**	@ Vsurge, Zsurge	No of units
Leaded Transient Voltage Suppressor							
SA30CA	Vishay (GS)	DO204	48.4@10.5	36.1	**0.4**	500V, 42Ω	4
				38.7	**0.4**	500V, 12Ω	
P6KE36A	Fairchild	DO15	64.3@62	37.7	**1.4**	500V, 42Ω	5
				51.1	**2.2**	1kV, 12Ω	
Surface Mount Transient Voltage Suppressor							
SMBJ13CA	STM	DO-214	27.2@147	16.0	**1.5**	500V, 12Ω	5
SMBJ33CA	STM	DO-214	69.7@57	45.5	**1.1**	500V, 12Ω	5
Surface Mount Metal Oxide Varistor							
CN1210K17G	Epcos	1210	44@2.5	57.6	**3.2**	500V, 12Ω	5
CN2220K25G	Epcos	2220	65@10	57.4	**1.5**	500V, 12Ω	5
CN1206K30G	Epcos	1206	77@1	77.5	**0.7**	500V, 12Ω	5
V14MLA0805V	Littelfuse	0805	32@1	40.9	**2.0**	500V, 12Ω	6
V33MLA1206AXH	Littelfuse	1206	75@1	90.6	**11.3**	500V, 12Ω	6
Leaded Metal Oxide Varistor							
V68ZA2	Littelfuse	7mm	135@2.5	211.8	**1.5**	1kV, 2Ω	5
ERZV07D680	Panasonic	7mm	135@2.5	220.0	**1.0**	1kV, 2Ω	5
ERZV07D391*	Panasonic	7mm	650@10	611.5	**0.9**	1kV, 2Ω	4
S14K150	Epcos	14mm	395@50	364.4	**0.8**	1kV, 2Ω	5
S14K275	Epcos	14mm	710@50	605.0	**1.1**	1kV, 2Ω	5
V250LA20AP	Littelfuse	14mm	650@50	572.0	**4.9**	1kV, 2Ω	4
2381 592 52716	Vishay (BC)	5mm	695@5	722.0	**0.2**	1kV, 2Ω	5
Zener Diode							
1N5242B	-	DO204	12V	12.6	**5.2**	500V, 42Ω	8

With a few exceptions, the clamping voltage is repeatable across samples (SD as % of mean) to around 1 or 2%. There was no obvious reason for the exceptions. It's also clear that in general it is hard to correlate the observed clamping voltage at a particular surge level with the manufacturers' quoted figure at a different current. Usually it seems that manufacturers' figures, even their published curves, are pessimistic (see earlier). And look closely at the measurements for the Epcos CN1210K17G and CN2220K25G parts. Although they are quoted at different levels, and the smaller 1210/17V part looks quite different to the larger 2220/25V one, when hit with the same 500V/12Ω surge their clamping voltage is virtually identical. That is, a larger device effectively has a lower slope resistance which allows it better clamping with a higher operating voltage.

In a couple of cases it was possible to compare different manufacturers' similar parts: look at the Littelfuse V33MLA1206AXH versus the Epcos CN1206K30G, and the Littelfuse V68ZA2 versus the

Panasonic ERZV07D680. In the first case there is substantial difference, but in the second case great similarity. They had virtually identical specifications in each case.

Conclusions

MOV devices have a high slope resistance and a greater peak clamping voltage, but are very robust and can take high energy repeatedly. Even small parts (1206 and smaller) are able to withstand severe surges without destruction, even though they may experience up to three times their rated stand off voltage.

TVS (Zener) devices have a low slope resistance and a very flat clamping profile at low energies, but are more easily destroyed by higher energy surges. These would generally be the preferred part if the source impedance is high but the downstream circuit withstand voltage is not, as in signal circuits. For a more comprehensive protection technique, the two types can be cascaded: first a MOV, which will catch the bulk of the transient energy but will have a fairly high let-through voltage, then a low value of series resistance, and finally a TVS which will clamp the remainder of the transient without having to dissipate much power.

Ordinary zeners will work but aren't characterised for surges; again, for signal circuits with some series impedance, they may well be adequate.

Consultancy and Training in Electromagnetic Compatibility