2 Selection procedure

2.1 Overvoltage types and sources

Overvoltages are distinguished according to where they originate.

2.1.1 Internal overvoltages

Internal overvoltages are those overvoltages that originate in the actual system which is to be protected, e. g. through

– inductive load switching
– arcing
– direct coupling with higher voltage potential
– mutual inductive or capacitive interference between circuits
– electrostatic charge
– ESD.

With internal overvoltages the worst-case conditions can often be calculated or traced by a test circuit. This enables the choice of overvoltage protective devices to be optimized.

2.1.2 External overvoltages

External overvoltages are those overvoltages that affect the system which is to be protected from the outside, e. g. as a result of

– line interference
– strong electromagnetic fields
– lightning
– ESD.

In most cases the waveform, amplitude and frequency of occurrence of these transients are not known or, if so, only very vaguely. And this, of course, makes it difficult to design the appropriate protective circuitry.

There have been attempts to define the overvoltage vulnerability of typical supply systems (e. g. industrial, municipal, rural) so that the best possible protective device could be chosen for the purpose. But the scale of local differences makes such an approach subject to uncertainty. So, for reliable protection against transients, a certain degree of “overdesign” must be considered.

Therefore the following figures for overvoltage in 230-V power lines can only be taken as rough guidelines:

– amplitude up to 6 kV
– pulse duration 0,1 µs to 1 ms

Where varistors are operated directly on the line (i. e. without series resistor), normally the type series S20 should be chosen. In systems with high exposure to transients (industrial, mountain locations) block varistors are to be prefered.

Requirements are stipulated in IEC1000-4. Severity levels are specified in the respective product standards (table 1 in 3.2).
Tables 2a and 2b in 3.2.4 show the selection of varistors for surge voltage loads according to IEC1000-4-5 as an example.

2.2 Principle of protection and characteristic impedance

The principle of overvoltage protection by varistors is based on the series connection of voltage-independent and voltage-dependent resistance. Use is made of the fact that every real voltage source and thus every transient has a voltage-independent source impedance greater than zero. This voltage-independent impedance Z_{source} in figure 13 can be the ohmic resistance of a cable or the inductive reactance of a coil or the complex characteristic impedance of a transmission line.

If a transient occurs, current flows across Z_{source} and the varistor that, because $v_{source} = Z_{source} \cdot i$, causes a proportional voltage drop across the voltage-independent impedance. In contrast, the voltage drop across the SIOV is almost independent of the current that flows.

Because

$$v_{SIOV} = \left(\frac{Z_{SIOV}}{Z_{source} + Z_{SIOV}} \right) v \qquad \text{(equ. 8)}$$

the voltage division ratio is shifted so that the overvoltage drops almost entirely across Z_{source}. The circuit parallel to the varistor (voltage V_{SIOV}) is protected.

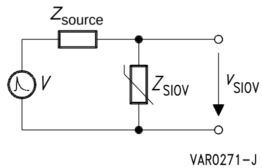
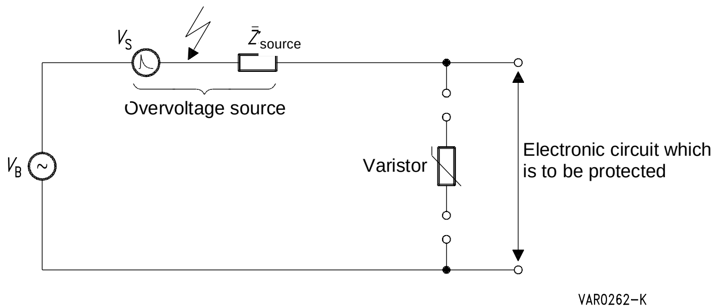


Figure 13 Equivalent circuit in which Z_{source} symbolizes the voltage-independent source impedance

Figure 14 shows the principle of overvoltage protection by varistors:

The intersection of the “load line” of the overvoltage with the *V*/*I* characteristic curve of the varistor is the “operating point” of the overvoltage protection, i. e. surge current amplitude and protection level.



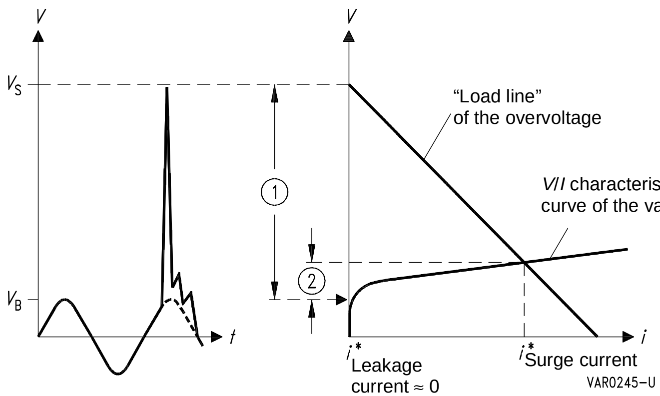


Figure 14 Principle of overvoltage protection by varistors

The overvoltage (1) is clamped to (2) by a varistor.

V_B operating voltage

V_S superimposed surge voltage

For selection of the most suitable protective element, one has to know the surge current waveform that goes with the transient. This is often, and mistakenly, calculated by way of the (very small) source impedance of the line at line frequency. This leads to current amplitudes of unrealistic proportions. Here one has to remember that typical surge current waves contain a large portion of frequencies in the kHz and MHz range, at which the relatively high characteristic impedance of cables, leads etc. determines the voltage/current ratio.

Figure 15 shows approximate figures for the characteristic impedance of a supply line when there are high-frequency overvoltages. For calculation purposes the characteristic impedance is normally taken as being 50 Ω. Artificial networks and surge generators are designed accordingly.

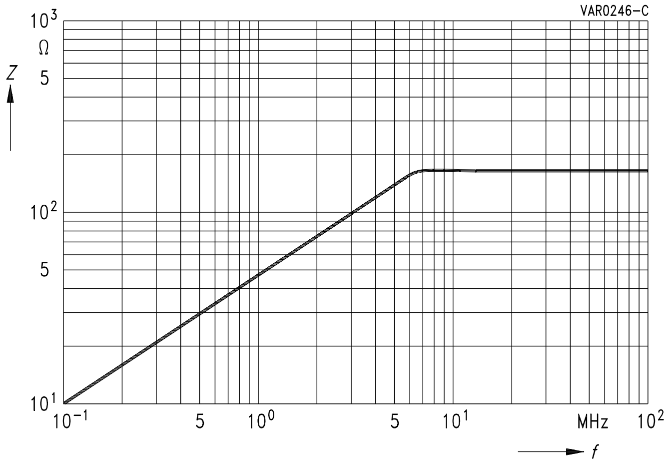


Figure 15 Impedance of a supply line for high-frequency overvoltages

2.3 Areas of application for varistors

A wide selection of components is available to cover very different requirements for protective level and load capability. Straightforward conditions of use and an attractive price/performance ratio have made SIOVs from S+M successful in just about every area of electrical engineering and electronics. The table below summarizes them:

Telecommunications
Private branch exchanges
Telephone subscriber sets
Telephone pushbutton modules
Teleprinters
Answering sets
Power supply units
Transmitting systems
Fax machines
Modem
Cellular (mobile) phones
Cordless phones

Industrial controls
Telemetering systems
Remote control systems
Machine controls
Elevator controls
Alarm systems
Proximity switches
Lighting controls
Power supply units
Ground fault interrupters
Gas heating electronics
Electronic ballasts

Power electronics
Bridge rectifiers
Brake rectifiers
Electric welding
Electric vehicles
Switch-mode power supplies
High-power current converters
DC/AC converters
Power semiconductors

Power engineering
Transformers
Inductors
Motor and generator windings
Transmission line lightning arresters

Automotive electronics
Central protection of automotive electrical systems
Load-dump protection
Anti-skid brake systems
Trip recorders
Radios
Motor controls
Generator rectifiers
Central locking systems
Trip computers
Wiper motors
Power window systems
Airbag electronics
Carphones
Seat memories

Traffic lighting
Traffic signals
Runway lighting
Beacon lights

Medical engineering
Diagnostic equipment
Therapeutic equipment
Power supply units

Data systems
Data lines
Power supply units
Personal computers
Interfaces

Stepped protection
Microelectronics
EMI/RFI suppression
EMP/NEMP protection

Entertainment electronics
Video sets
Television sets
Slide projectors
Power supply units
HIFI equipment

Household electronics
Washer controls
Dimmers
Lamps
Quartz clocks
Electric motor tools
Thermostats

If semiconductor devices like diodes, thyristors and triacs are paralleled with SIOVs for protection, they may do with lower reverse-voltage strength. This leads to a marked cost reduction and can be the factor that really makes a circuit competitive.

2.4 Series and parallel connection

2.4.1 Series connection

SIOV varistors can be connected in series for more precise matching to uncommon voltage ratings or for voltage ratings higher than those available. For this purpose the types selected should be of the same series (i. e. same diameter). The maximum permissible operating voltage in series configuration is produced by adding the maximum DC or AC voltages of the varistors.

2.4.2 Parallel connection

Metal oxide varistors can be connected in parallel in order to achieve higher current load capabilities or higher energy absorption than can be obtained with single components. To this end, the intended operating point in the surge current region (see section 1.5) must be taken into account.

2.4.2.1 Medium operating region

If an operating point is chosen from the derating fields that is in the highly non-linear medium region of the *V*/*I* characteristic (e.g. current of up to 1 kA in figure 46), a current distribution may result that leads to negation of the intended purpose.

Example surge current i^* = 1 A in figure 16:

In the worst case, 2 varistors may have been chosen for parallel connection with the first having a *V*/*I* characteristic curve corresponding to the upper limits and the second having a *V*/*I* characteristic curve corresponding to the lower limits of the tolerance band. From the region boundary a) one can see that then a current of 1 mA flows through the first varistor and a current of 1 A flows through the second varistor. The energy absorptions of the two varistors are in the same ratio. This means that if unselected varistors are used in this current region, current distributions of up to 1000:1 may render the parallel connection useless. In order to achieve the desired results, it is necessary to match voltage and current to the intended operating point.

2.4.2.2 High-current region

In this region, the current values are closer together due to the bulk resistance of the varistors. Region b) in figure 16 shows that in the worst case, the current ratio is approx. 15 kA:40 kA, which is a considerably better result than in the medium operating region. Accordingly, parallel connection can increase the maximum permissible surge current for 2 block varistors, e. g. from 40 kA to 55 kA for B40K275 varistors.

The graphical method in accordance with figure 16 can only provide guideline values, since the deviation of the individual varistors from the standard non-linear values is not taken into consideration. In practice, the individual varistors must be measured for the current region for which parallel operation is envisaged. If this region is within the two upper decades of the maximum surge current, then the varistors should be measured at 1 % of the maximum current in order to prevent the measurement itself reducing the service life of the varistor. Example: using B40K275, maximum permissible surge current 40 kA. The measurement should take place using 400 A with surge current pulse 8/20 µs.

The effort required for measurements of this kind will make the parallel connections an exception. The possibility of using a single varistor with a higher load capacity should always be preferred, in this example this would be a type from the B60, B80 or PD80 series.

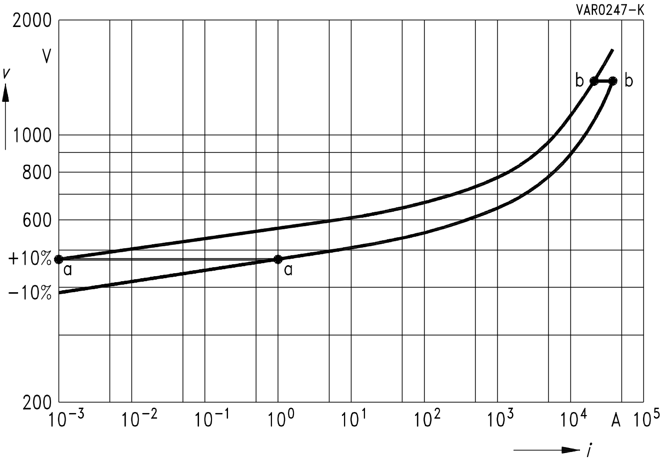


Figure 16 Tolerance band of the SIOV-B40K275

2.5 Selection guide

The choice of a varistor involves three main steps:

- Select varistors that are suitable for the operating voltage.
- Determine the varistor that is most suitable for the intended application in terms of
  a) surge current
  b) energy absorption
  c) average power dissipation
  (for a and b also estimating the number of repetitions).
- Determine the maximum possible voltage rise on the selected varistor in case of overvoltage and compare this to the electric strength of the component or circuit that is to be protected.

To ensure proper identification of circuit and varistor data, the following distinction is made:

– Maximum possible loading of varistor resulting from the electrical specifications of the intended location.
  Identification: *
– Maximum permissible loading of varistor limited by its surge current and absorption capability.
  Identification: max

So the following must always apply:

$i^* \leq i_{max}$ (equ. 9)
$W^* \leq W_{max}$ (equ. 10)
$P^* \leq P_{max}$ (equ. 11)

2.5.1 Operating voltage

Maximum permissible AC and DC operating voltages are stated in the product tables for all varistors. To obtain as low a protection level as possible, varistors must be selected whose maximum permissible operating voltage is the same as or as little as possible above the operating voltage of the application.

Non-sinusoidal AC voltages are compared with the maximum permissible DC operating voltages so that the peak or amplitude of the applied voltage does not exceed the maximum permissible DC voltage.

When selecting, you must allow for the plus tolerance of the operating voltage (European supply systems according to IEC 38: 230 V + 6 % = 244 V, at the latest, from the year 2003 on: 230 V + 10 % = 253 V) because power dissipation in a varistor rises sharply with too high an operating voltage.

Note:
Of course, you may also select any varistor with a higher permissible operating voltage. This procedure is used, for example, when it is more important to have an extremely small leakage current than the lowest possible protection level. In addition, the service life of the varistor is increased. Also the type for the highest operating voltage may be selected in order to reduce the number of types being used for different voltages.

2.5.2 Surge current

Definition of the maximum possible operating voltage in the previous step will have narrowed down the choice of an optimum SIOV to the models of a voltage class (e. g. those whose designation ends in 275 for 230 V + 10 % = 253 V). Then you check, with reference to the conditions of the application, what kind of load the SIOV can be subjected to.

Determining the load on the varistor when limiting overvoltage means that you have to know the surge current which is to be handled.

2.5.2.1 Predefined surge current

Often the surge current is predefined in specifications. After transformation into an equivalent rectangular wave (figure 19, page 46) the suitable varistor type can be selected with the aid of the derating curves.

2.5.2.2 Predefined voltage or network

If the voltage or a network is predefined, the surge current can be determined in one of the following ways:

Simulation

Using the PSpice simulation models of the SIOV varistors, the surge current, waveform and energy content can be calculated without difficulty. In these models, the maximum surge current is deduced for the lower limit of the tolerance band, i. e. setting TOL = – 10.

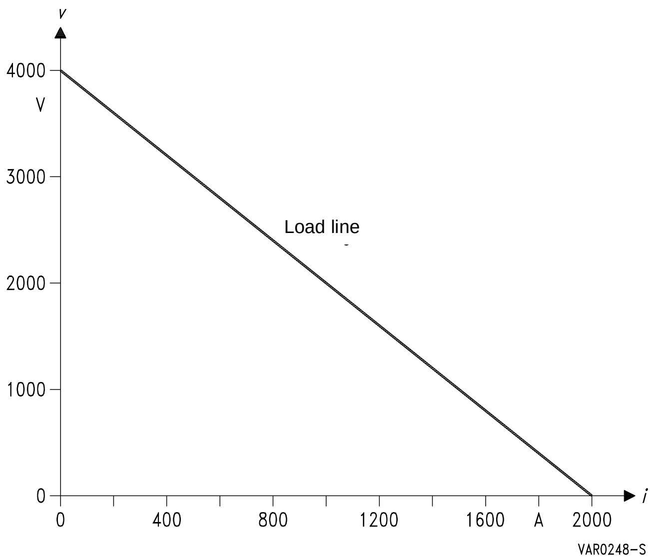
Test circuit

The amplitude and wave form of the surge current can be determined with the aid of a test circuit (example shown in figure 29, page 65). The dynamic processes for overvoltages require adapted measuring procedures.

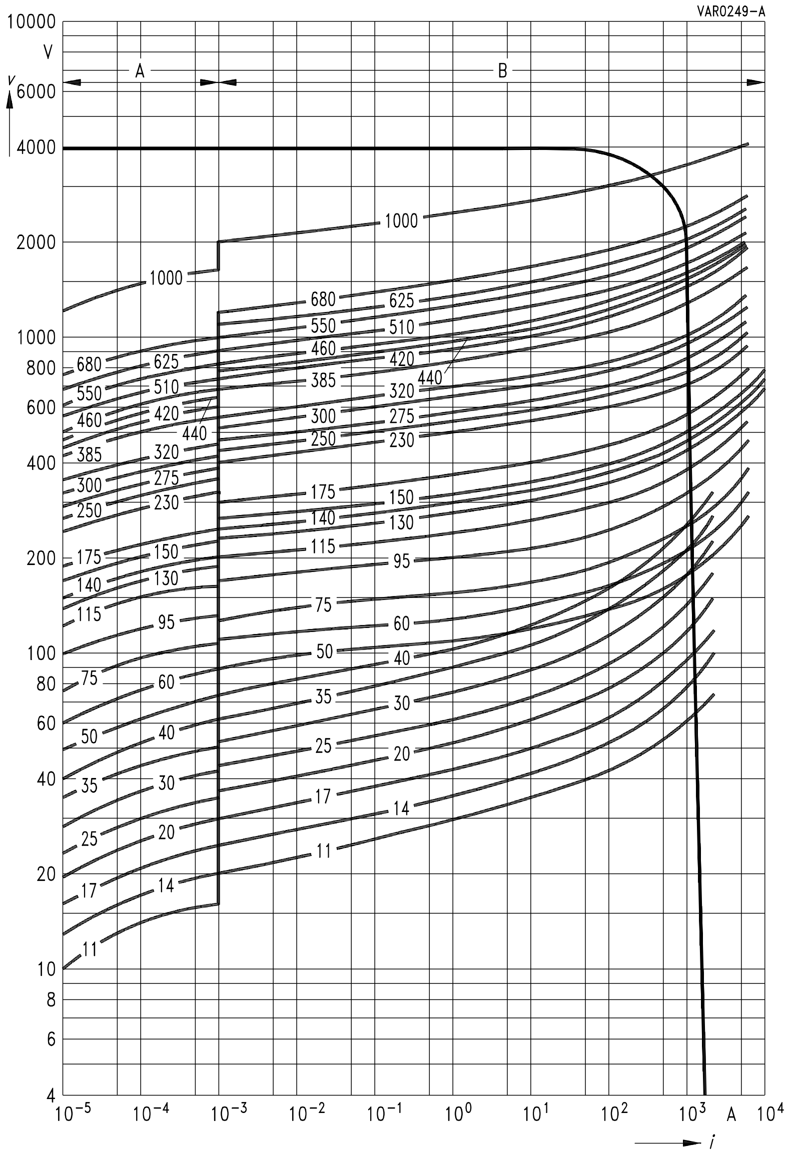
Graphic method

As shown in figure 17, the overvoltage can be drawn into the *V*/*I* characteristic curve fields as a load line (open circuit voltage, short circuit current). At the intersection of this “load line” with the varistor curve selected to suit the operating voltage, the maximum protection level and the corresponding surge current can be read off. The wave form and thus the energy content cannot be determined by this method.
Since the *V*/*I* characteristic curves are drawn in a log-log representation, the “load lines” in figure 17b are distorted to a curve.

17a



17b



Figures 17a and b *V*/*I* characteristic curves SIOV-S20 with the load line drawn in for a surge current amplitude 4 kV with Z_{source} = 2 Ω

Mathematic approximation

The surge current is determined solely from the source impedance of the surge voltage (V_s). By subtracting the voltage drop across the varistor (from the *V*/*I* curve) you can approximate the maximum surge current as follows:

$$i = \frac{V_s - V_{SIOV}}{Z_{source}} \qquad \text{(equ. 12)}$$

See 3.2.4 for an example.

Switching off inductive loads

If the transient problems are caused by switching off an inductor, the “surge current” can be estimated as follows:

The current through an inductance cannot change abruptly, so, when switching off, a current of the order of the operating current must flow across the varistor as an initial value and then decay following an e function. The path taken by the current during this time is referred to as a fly-wheel circuit (see figure 23, page 51).

The time constant $\tau = L/R$ that can be calculated from the inductance and the resistance of the fly-wheel circuit (including varistor resistance) shows how long the current requires to return to the 1/e part (approx. 37%) of its original value. According to theory, τ is also the time that the fly-wheel current must continue to flow at constant magnitude in order to transport the same charge as the decaying current.

So the amplitude of the “surge current” is known, and its duration is approximately τ (figure 18).

τ depends on the value of the inductance and the resistances of the fly-wheel circuit, generally, therefore, on the resistance of the coil and the varistor. The latter is, by definition, dependent on voltage and thus also current and so, for a given current, it has to be calculated from the voltage drop across the varistor (*V*/*I* characteristic).

$$\tau \approx \frac{L}{R_{Cu} + R_{SIOV}} \ [\mathrm{s}] \qquad \text{(equ. 13)}$$

L	[H]	Inductance
R_{Cu}	[Ω]	Coil resistance
R_{SIOV}	[Ω]	SIOV resistance at operating current

R_{SIOV} increases as current decreases. So τ is not constant either during a decay process. This dependence can be ignored in such a calculation however.

For comparison with the derating curves of the current you can say that $\tau = t_r$ (see example 3.1).

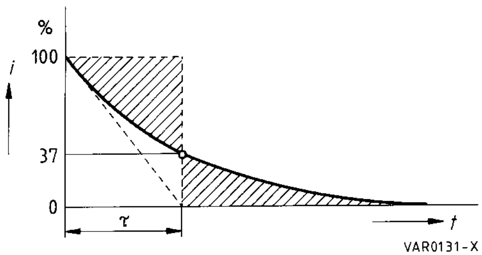


Figure 18 Time constant of fly-wheel circuit

2.5.2.3 Comparison: determined surge current / derating curve

The maximum permissible surge current of the SIOV depends on the duration of current flow and the required number of repetitions. Taking these two parameters, it can be read from the derating curves. It is compared to the maximum possible surge currents in the intended electrical environment of the varistor.

From the derating curves one can obtain maximum figures for rectangular surge current waves. For correct comparison with these maximum permissible values, the real surge current wave (any shape) has to be converted into an equivalent rectangular wave. This is best done graphically by the "rectangle method" illustrated in figure 19.

Keeping the maximum value, you can change the surge current wave into a rectangle of the same area. t^*_r is then the duration of the equivalent rectangular wave and is identical to the "pulse width" in the derating curves. (The period T^* is needed to calculate the average power dissipation resulting from periodic application of energy.)

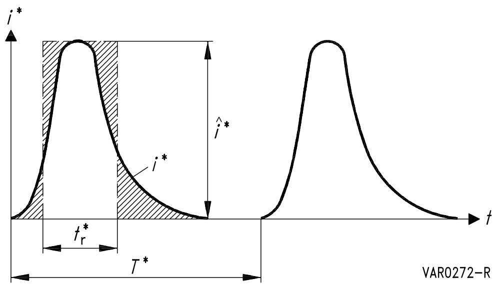


Figure 19 "Rectangle method"

If the pulse load $\int i^* dt$ is known, then t_r can be calculated using the following equation:

$$t^*_r = \frac{\int i^* d\,t}{\hat{i}^*} \qquad \text{(equ. 14)}$$

2.5.3 Energy absorption

When a surge current flows across the varistor, there will be absorption of energy. The amount of energy to be absorbed by the varistor can generally be calculated by equation 6.

Calculation method

Often, the energy absorption can be read directly from a storage oscilloscope or can be calculated from the voltage/current curve using numerical methods. An example for W^* = 100 J is shown in figure 30, page 66.

Simulation

Determination of the energy absorption by simulation (PSpice) is even more convenient.

Graphic method

Otherwise equation 6 can be solved graphically with sufficient accuracy by using the rectangle method. $i^*(t)$ is converted as in figure 19 and multiplied by the highest voltage appearing on the varistor according to equation 15:

		$\hat{v}^*$	[V]	(equ. 15)
$W^* = \hat{v}^* \, \hat{i}^* \, t^*_r$	[J]	$\hat{i}^*$	[A]	
		t^*_r	[s]	

$\hat{v}^*$ can either be derived from the *V/I* characteristic as the value matching $\hat{i}^*$, or likewise be determined with the aid of an oscilloscope as the maximum voltage drop across the varistor.

Switching off inductive loads

If transients are caused by interrupting the current supply of an inductor, the worst-case principle can be applied to calculate the necessary energy absorption of a varistor. The energy to be absorbed by the varistor cannot be greater than that stored in the inductor:

$W^* = {}^1/_2 \, L \, i^{*2}$	[J]	L	[H]	(equ. 16)
		i^*	[A]	

This calculation will always include a safety margin because of losses in other components. See 3.1 for an example.

Discharging of capacitances

The statements made for inductances also apply for capacitances. This means that the load placed on the varistors in many of the tests according to IEC 1000-4-X can be estimated.

Comparison: determined energy input / maximum permissible energy absorption

To check the selection requirement $W^* \leq W_{max}$ (equation 10), you have to determine the maximum permissible energy absorption for the intended varistor. This can be calculated by equation 17 as a function of time the energy is applied (t_r) and the number of repetitions from the derating curves:

$$W_{max} = v_{max} \, i_{max} \, t_{r\,max} \qquad \text{(equ. 17)}$$

v_{max} is derived from the *V/I* characteristic of the intended varistor type for the surge current i_{max}. $t_{r\,max}$ can be taken as being the same as t^*_r, because W_{max} is to be calculated for the given time of current flow.

2.5.4 Average power dissipation

The actual power dissipation of a varistor is composed of the basic dissipation P_0 caused by the operating voltage and, possibly, the average of periodic energy absorption. If metal oxide varistors are chosen from the product tables in agreement with the maximum permissible operating voltages, P_0 will be negligible.

Periodic energy absorption produces an average power dissipation of:

$$P^* = \frac{W^*}{T^*} = \frac{v^*\, i^*\, t^*_r}{T^*} \; [\mathrm{W}] \qquad \begin{array}{llll} W^* & [\mathrm{J}] & i^* & [\mathrm{A}] \\ T^* & [\mathrm{s}] & t^*_r & [\mathrm{s}] \\ v^* & [\mathrm{v}] & & \end{array} \qquad \text{(equ. 18)}$$

W^* takes the value of a single absorption of energy.
T^* is the period of figure 19.

By solving this equation for T^* it is possible to calculate the minimum time that must elapse before energy is applied again without exceeding the maximum permissible average power dissipation of the varistor:

$$T_{\min} = \frac{W^*}{P_{\max}} \; [\mathrm{s}] \qquad \begin{array}{ll} W^* & [\mathrm{J}] \\ P_{\max} & [\mathrm{W}] \end{array} \qquad \text{(equ. 19)}$$

Note:
Metal oxide varistors are not particularly suitable for “static” power dissipation, e. g. voltage stabilization. There are other kinds of components, like zener diodes, designed primarily for this kind of application.

The PowerDisk has been specially developed for periodic pulse trains with high continuous load ratings.

2.5.5 Maximum protection level

The maximum possible voltage rise in the event of a current surge is checked with the aid of the *V*/*I* curves or PSpice models. This figure can be read directly from the curve for a given surge current (for worst-case varistor tolerances). If the voltage value thus obtained is higher than acceptable, the following possibilities may assist in reducing the protection level:

- Choose a type with a larger disk diameter
  The protection level is lower for the same surge current because the current density is reduced.
- Better matching to the operating voltage by series connection
  Example: 340 V AC
  Here, according to the first step in selection, a standard SIOV with the end number “385” would normally be chosen. But if two SIOVs with the end number “175” are connected in series, the response of a 350-V varistor is obtained.
- Choose a tighter tolerance band
  A special type is introduced that only utilizes the bottom half of the standard tolerance band for example. This would mean a drop in the protection level by approx. 10 %.
- Insert a series resistor
  This reduces the amplitude of the surge current and thus the protection level of the varistor.

Note:
If the protection level obtained from the *V*/*I* curve is **lower** than required, one can change to a varistor with a higher protection level, i. e. higher end number in its type designation. This has a favorable effect on load handling capability and operating life. The leakage current is further reduced.
If necessary, the number of different types used can be reduced.

2.5.6 Selection by test circuit

The maximum permissible ratings of varistors refer to the amount of energy that will cause the varistor voltage to change by maximally ± 10 %.

Figures 20 and 21 show typical curves for the change in varistor voltage of metal oxide varistors when energy is repeatedly applied through a bipolar or unipolar load. You often find an increase of a few percent to begin with, and for a unipolar load there are also polarization effects. This is seen in figure 22 for the leakage current. Such phenomena have to be considered when interpreting measured results.

So, in test circuits, one starts with determining the varistor voltage for every single type as accurately as possible (at a defined temperature). It is advisable to check the change in varistor voltage from time to time, making sure that the temperature is the same. By extrapolation of the measured results to the intersection with the –10 % line a guide value for the lifetime of varistors is obtained.

Figure 46, for example, can be taken to be measured results that follow curve 1 of figure 20. The mean tends towards the horizontal, corresponding to point 1 in figure 20. Although 100 loads of 500 A (8/20 µs) are the maximum permissible number of load repetitions for S14K150 according to the derating curves, the measured results indicate that a substantially higher number of loads can be handled in individual cases. Figure 46 gives proof of the high reliability of SIOV varistors.

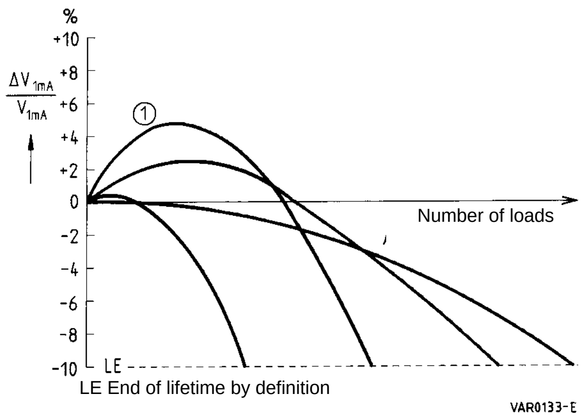
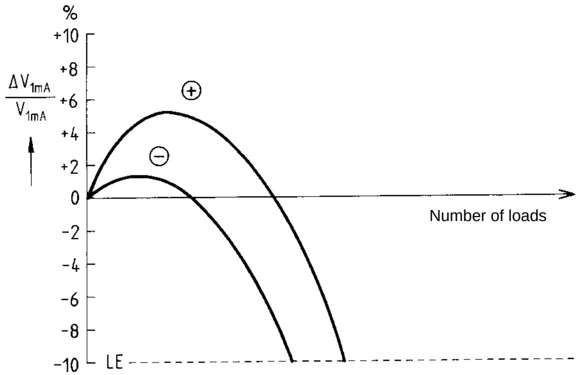
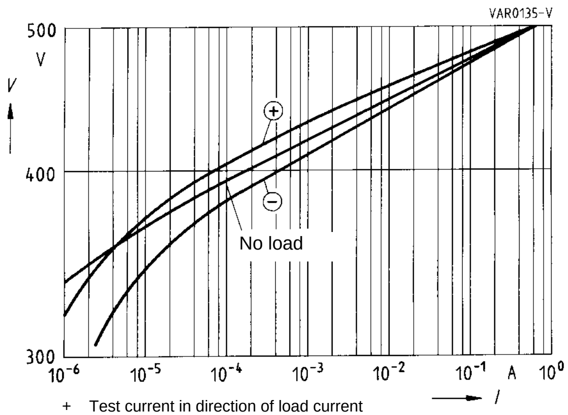


Figure 20 Typical curves for change in varistor voltage when metal oxide varistors are repeatedly loaded



LE End of lifetime by definition
\+ Test current in direction of load current
– Test current in opposite direction to load current

Figure 21 Typical polarization effect for unipolar loading of metal oxide varistors



\+ Test current in direction of load current
– Test current in opposite direction to load current

Figure 22 Typical polarization effects of leakage current for unipolar loading of metal oxide varistors