International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

K.128
(01/2018)

SERIES K: PROTECTION AGAINST INTERFERENCE

Surge protective component application guide – metal oxide varistor (MOV) components

Recommendation ITU-T K.128

ITU-T

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Surge protective component application guide – metal oxide varistor (MOV) components

Summary

Recommendation ITU-T K.128 describes metal oxide varistor (MOV) construction, non-linearity modelling, impedance properties, equivalent circuit, element temperature distribution, time factors, degradation and failure modes, operation states and application examples. These surge protective components (SPCs) are intended for the protection of exchange and outdoor equipment, subscriber or customer equipment and telecommunication lines from surges.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T K.128	2018-01-13	5	11.1002/1000/13451

Keywords

Application examples, degradation, metal oxide varistor, modelling, non-linearity index, operating states, surge, voltage limiter.

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

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Introduction

Recommendation ITU-T K.128 provides application guidance for the components covered by Recommendation ITU-T K.77, *Characteristics of metal oxide varistors for the protection of telecommunication installations*. This application guide provides two levels of information; overview and in-depth technical analysis.

Recommendation ITU-T K.128

Surge protective component application guide – metal oxide varistor (MOV) components

1 Scope

This Recommendation in the surge protective component application guide series covers metal oxide varistor (MOV) voltage limiting components These surge protective components (SPCs) are clamping type overvoltage protectors [b-ITU-T K.96]. These SPCs are used for the protection of power supply circuits and signal circuits of telecommunication installations against overvoltages. Guidance is given on construction, characteristics, ratings and application examples.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T K.77] Recommendation ITU-T K.77 (2009), *Characteristics of metal oxide varistors for the protection of telecommunication installations*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined in [ITU-T K.77]:

3.1.1 applied voltage ratio (R_{ap}): Ratio of d.c. voltage or peak of a.c. voltage applied on the MOV to the varistor voltage U_N.

3.1.2 clamping voltage (U_{cla}): Maximum peak voltage across the MOV measured under conditions of a specified waveform impulse with current peak I_P. If there is both a front peak and rear peak on the voltage waveform, the rear peak voltage is defined as the clamping voltage.

NOTE – For an individual MOV, peak voltages shall be measured in two directions, and the larger value of the two is referred to as the clamping voltage of this MOV.

3.1.3 clamping voltage ratio (R_{cla}): Ratio of the clamping voltage U_{cla} to the varistor voltage U_N ($R_{cla} = U_{cla}/U_N$).

3.1.4 combination impulse (1.2/50-8/20): Impulse with open-circuit voltage of 1.2/50 µs (T_1/T_2) and short-circuit current of 8/20 µs (T_1/T_2), which is expressed by "voltage peak/current peak".

NOTE – Unless otherwise specified, the effective impedance shall be 2 Ω, which is the quotient of the open-circuit voltage peak U_P and the short-circuit current peak I_P.

3.1.5 current peak de-rating curve: Curves expressing the relationship of the three variables of I_P, n, τ, where I_P is impulse current peak, τ is the impulse width, and n is average application numbers of the impulse that the MOV can withstand in terms of specified pass criterion. The current I_P shall be de-rated with the increasing of τ and/or n, that may be represented by equations 3-1 and 3-2.

$$\lg I_g = A - a \lg n \ (\tau = \text{constant}) \qquad (3\text{-}1)$$

$$\lg I_g = B - b \lg \tau \ (n = \text{constant}) \tag{3-2}$$

Where A, a, B and b are four constants which depend on the type and manufacturing of the MOV, also A and a depend on τ values, B and b depend on n values.

NOTE – Equations 3-1 and 3-2 agree well with the actual characteristics of MOV when $n \geq 10$, while for n less than 10, I_P deviated from these equations.

3.1.6 current de-rating fraction (F_I): Ratio of impulse current peak I_P (n, τ) to the maximum discharge current $I_{\max}$.

$$F_I = I_P(n,\tau) / I_{\max}$$

3.1.7 effective resistance: Ratio of the rear peak voltage to the applied impulse current peak of the specified waveform, unless otherwise specified, 8/20 impulse current shall be used.

3.1.8 effective linear resistance (R_V): Linear component of the effective resistance determined by the high-impulse-current method.

NOTE – The linear resistance of the MOV may be determined by the high-frequency-signal method, infrared method and high-impulse-current method, but they may give different results.

3.1.9 effective non-linear resistance (R_Z): Non-linear component of the effective resistance which can be expressed by equation 3-3

$$R_Z = A_1 \cdot I_P^{(\beta - 1)} \tag{3-3}$$

where:

- A_1 is the virtual clamping voltage at 1 A of specified impulse
- β is the non-linearity current index

3.1.10 endurance at maximum operating temperature: Property to operate at maximum operating temperature and maximum continuous operating voltage (MCOV) for 1000 h.

NOTE – Unless otherwise specified, the maximum recommended operating temperature is 85°C.

3.1.11 front peak voltage (U_F): Maximum voltage across the MOV occurring at the initial time of an applied impulse current of specified waveform and peak value. The front peak voltage represents a time-dependent modification of the highly non-linear conduction process responsible for varistor action.

3.1.12 high (low) voltage varistors: The varistors of varistor voltage $U_N \geq 82$ V are called high voltage varistors, and those of varistor voltage smaller than 82 V are named low voltage varistors.

3.1.13 impulse: Unidirectional wave of voltage or current without appreciable oscillation.

Six impulses are used in this Recommendation: current impulse 8/20, 10/350, 10/1000, 2-ms rectangular wave, electrostatic discharge, and 1.2/50-8/20 combination impulse.

3.1.14 impulse current peak ((I_P (n,τ)): Repetitive impulse current peak which can be applied for application numbers (n) with impulse width τ.

3.1.15 impulse width (τ): Normalized impulse duration which is the ratio of the waveform area to the impulse peak, by means of τ any waveform of impulse can be converted into an equivalent rectangular wave.

3.1.16 informative characteristics: Characteristics of a metal oxide varistor (MOV) which are of significance for applications and should be provided by manufactures, but they are not covered by an acceptance inspection programme, for example: V-I characteristics, V-I characteristics of low field region, current peak de-rating curve, temperature de-rating curve.

3.1.17 leakage current a.c. (I_{La}): Current passing through the metal oxide varistor (MOV) with the maximum a.c. voltage U_C applied on it, and at a specified temperature, it may be r.m.s value or peak value.

3.1.18 leakage current d.c. (I_{Ld}): Current passing through the metal oxide varistor (MOV) with the maximum d.c. voltage U_{DC} applied on it, and at a specified temperature.

3.1.19 long (short) duration impulse: An impulse with an impulse width $\tau \geq 100$ μs is called a long duration impulse, in contrast, an impulse of $\tau < 100$ μs is called a short duration impulse.

NOTE – In this Recommendation, a long (short) duration impulse is denoted by the letter "L" ("S")

3.1.20 maximum continuous operating voltage (MCOV) (U_C (U_{DC})): Maximum a.c. r.m.s. voltage U_C or maximum d.c. voltage U_{DC} which can be applied continuously at a temperature of 25°C. U_C shall be a substantially sinusoidal voltage (less than 5% total harmonic distortion).

3.1.21 maximum discharge current ($I_{\max}$): The maximum allowable crest value of impulse current with 8/20 waveform for two applications.

3.1.22 metal oxide varistor (MOV): Component made of ZnO and a few additives whose conductance, at a given temperature, increases rapidly with the voltage increasing over a certain voltage range. It is also known as a voltage-dependent resistor (VDR).

3.1.23 nominal discharge current (I_n): The crest value of impulse current with 8/20 waveform that is intended for clamping voltage measurement of the metal oxide varistors (MOVs) for power circuit use.

3.1.24 non-linearity current index (β): Slope of the volt-ampere characteristic when the effective linear resistance is much smaller than the effective non-linear resistance. It is always less than 1. For the convenience of calculation, equation 3-4 may be used.

$$\beta = \frac{\lg(U_{cla1}/U_{cla2})}{\lg(I_{P1}/I_{P2})} \tag{3-4}$$

NOTE – For most commercially available metal oxide varistors (MOVs), it is considered that the effective linear resistance is much smaller than the effective non-linear resistance when the 8/20 current density J_P is less than 320 A/cm^2.

3.1.25 rated dissipation power (P_m): Maximum allowable average power dissipation when subjected to the stress of successive impulses and at the temperature of 25°C.

3.1.26 rated impulse energy (W_{tm}): Maximum single impulse energy which can be absorbed by the metal oxide varistor (MOV) for a specified waveform. Unless otherwise specified, a 2 ms rectangular current impulse or 10/1000 current impulse shall be used.

3.1.27 rear peak voltage (U_R): Maximum voltage across the metal oxide varistor (MOV) occurring at the time behind the front peak with an application of impulse current of specified waveform and sufficient peak values.

3.1.28 temperature de-rating curve: Graphical representation of parameters de-rating against temperature.

NOTE – Typical parameters are maximum continuous operating voltage U_C (U_{DC}), maximum discharge current $I_{\max}$, nominal discharge current I_n, impulse current peak $I_P(n,\tau)$, rated dissipation P_m, and rated impulse energy W_{tm}.

3.1.29 temporary overvoltage (TOV) (U_T): a.c. voltage (r.m.s) or d.c. voltage that the metal oxide varistor (MOV) can withstand; U_T exceeds the maximum continuous operating voltage U_C or U_{DC}.

3.1.30 temporary overvoltage (TOV) withstanding capability: The specified TOV stress that a metal oxide varistor (MOV) should be capable of withstanding, and evaluated by the energy absorbed by the MOV and element temperature of the MOV under this stress.

NOTE – This property of the MOV is intended to match the operation of thermal disconnectors of the surge protective devices (SPDs) that use the MOV.

3.1.31 unit thickness voltage: Ratio of varistor voltage U_N to the thickness of the metal oxide varistor MOV element, expressed in "V/mm".

NOTE – The peak values of long duration impulse and impulse energy that the MOV is able to withstand depend strongly on the unit thickness voltage of the MOV.

3.1.32 varistor voltage (U_N): Voltage, at specified d.c. current, used as a reference point in the component characteristic, unless otherwise specified, 1 mA d.c. current shall be used.

3.2 Terms defined in this Recommendation

None.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AVR	Applied Voltage Ratio
DSB	Double–Schottky-Barrier
EMF	Electromotive Force
ESD	Electrostatic Discharge
GDT	Gas Discharge Tube
LPF	Low Pass Filter
LVR	Limiting Voltage Ratio
MCOV	Maximum Continuous Operating Voltage
MOV	Metal Oxide Varistor
PO	Protected Object
PS	Power Source
PTE	Protected Terminal Equipment
SB	Schottky Barrier
SMD	Surface Mounting Device
SPC	Surge Protective Component
SPD	Surge Protective Device
TOV	Temporary Overvoltage
VDR	Voltage-Dependent Resistor

5 Conventions

None.

6 Construction

6.1 Introduction

A metal oxide varistor (MOV), sometimes simply called a varistor, is a voltage limiting SPC. Generally, the voltage limiting characteristic comes from the use of a ZnO ceramic element, although other compounds like $S_r T_i O_3$ and $S_n O_2$ can be used.

NOTE – Early documents such as [b-Wang] page 14 and [b-Wang] page 18, referred to the varistor as a "voltage dependent resistor (VDR)", and described the varistor as a "component, whose conductance, at a given temperature, increases rapidly with voltage". Subsequent studies found that during pulse conditions the varistor's conductance decreases with increasing voltage, however the conductance of an MOV is monotonically increasing with current (page 38, [b-Panasonic]).

6.2 Packaging

Figure 1 shows some commonly used component form factors. Depending on the component terminals, form factors can be classified as leaded disc type (including wire, strap and screw terminal) or leadless type for surface mount technology.

The ceramic element inside an MOV may be made from either a single-layer disc (see Figure 1 (a)) or multi-layer chip, called a multi-layer varistor (MLV) (see Figure 1 (b)). Sometimes several MOV components may be combined into one package to form an MOV array or multi-unit MOV (see Figure 1 (c)).

Additionally, there are some special structures for unique applications. For example, a so called "ring shape noise suppression varistor" which is placed on the rotational axis of micro-motors to absorb surge voltages that occur during periods of phase voltage transition of the rotor windings (see Figure 1 (d)).

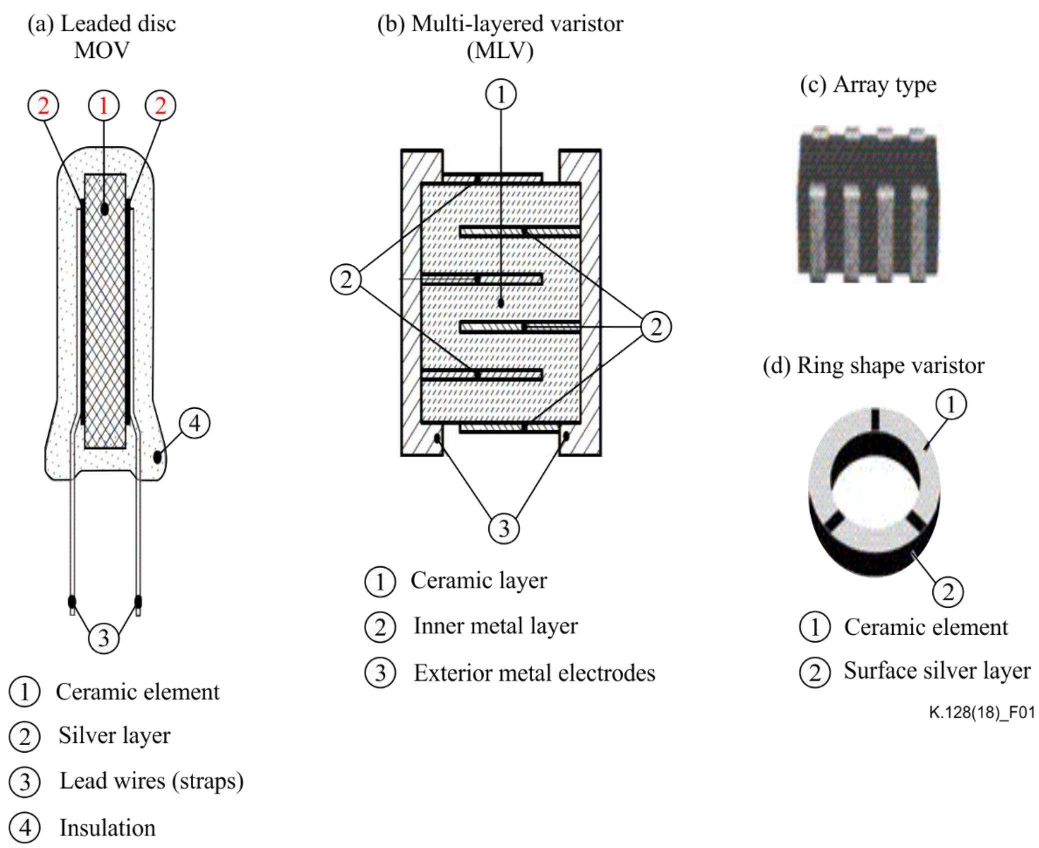
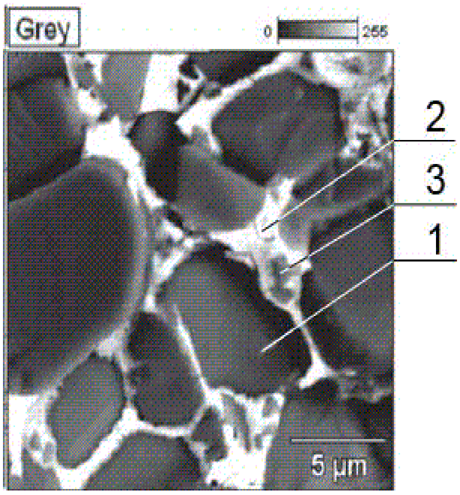


Figure 1 – MOV form factors

6.3 Ceramic element structure

The nonlinear V-I relationship of an MOV is due to its microstructure. MOVs are made primarily of ZnO powder, to which is added a small quantity of additives (about 10% in weight) such as Bi, Sb, Co, Mn, and others. The powder mix is made into a semiconducting ceramic element with typical ceramic processes. Figure 2 shows an electro-micrograph picture of the ceramic body, from which three substance phases can be found; ZnO crystal grains, grain boundary phase and some minute insulating grains mainly at triple points.



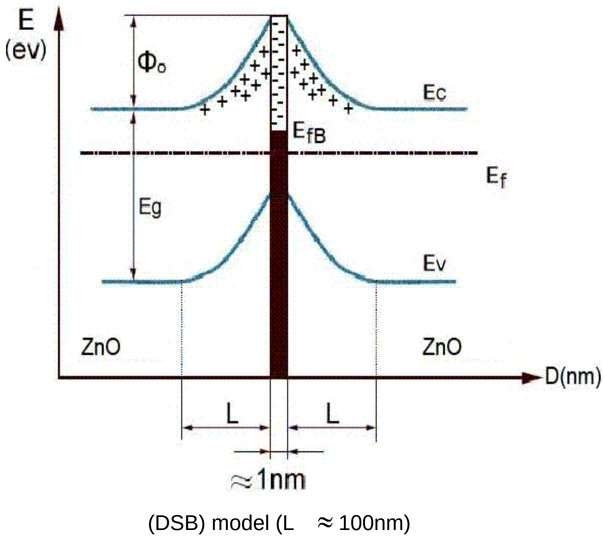
1 —ZnO crystal grain ，

2 一grain boundary phase,

3 —minute insulating grains

Figure 2 – Picture of the microstructure

The ZnO grains in MOV ceramics are n-type semiconductor having a resistivity as low as (0.1～1) Ω-cm, which means it is a good conductor. The grains play three major roles in MOV operations: electric conduction, heat conduction, and energy absorption. The average size of the ZnO grains range from less than 10 μm to more than 100 μm for commonly used MOVs.



(DSB) model (L ≈ 100nm)

Figure 3 – Double Schottky Barrier (DSB)

At an intimately contact portion of two grains, there is a very thin inter-granular film that is about 1 nm thick, see Figure 3. Within this film there are a very large number of electrons which are trapped from the adjacent ZnO grains resulting in space charge (or depletion) regions at each side of the 1 nm-film, hence an electrostatic potential barrier is built up in ZnO surface at each side, which control the current flow through the ceramic body. These types of barriers are Schottky Barriers (SBs) and not PN-junction barriers. The value of electrostatic potential of the SB is typically 3.2 V to 3.4 V for a ZnO-Bi_2O_3-based varistor, or 1.4 V for a ZnO-$P_{r2}O_3$-based varistor, which is almost independent of the ceramic formulations and fabricating processes.

The microstructure of two adjacent ZnO-grains plus their inter-granular film can form a Double–Schottky-Barrier (DSB) resulting in a symmetric V-I characteristic in two directions. This microstructure may be considered as an MOV-cell, or a micro-varistor, and an MOV component can be considered as many MOV-cells connected in series and parallel.

The DSB model can well describe many important behaviours of MOVs in low current range including high temperature-sensitivity of the non-linear resistance, but the DSB model fails to comprehend high impulse current operation, which is quite insensitive to temperature. A few improved models have been reported, but they lack consensus at the present time.

6.4 Ceramic element as a network

The MOV's ceramic element may be considered a three-dimensional network with a large number of MOV-cells acting in series-parallel connections between the two electrode layers. Accordingly, the macro-properties of an MOV should be the statistical representation of all MOV-cells inside the network. From this understanding the following points can be deduced:

In a ceramic block of a given average grain size, the series numbers of MOV-cells, as well as its voltage ratings, are roughly proportional to the thickness of the block. In a ceramic block of a given thickness, the series numbers of MOV-cells, as well as its voltage ratings, are roughly inversely proportional to the average grain size of the block. In a ceramic block, the paralleled numbers of MOV-cells, as well as its current ratings, are roughly proportional to the area of the metal electrode surface on the block. Combining above points, it is concluded that the power and energy handling capabilities of an MOV will be roughly proportional to the volume of its ceramic block.

Figure 2 shows that the grain size varies from grain to grain, and their physical electrical and thermal properties as well, which result in an uneven distribution of the current density and the temperature rise inside the block during a period of current flowing.

7 Modelling MOV non-linearity

7.1 Nonlinearity index

7.1.1 Introduction

The nonlinearity index α or β coefficients characterize the MOV V–I non-linearity.

The following two equations express the voltage-current characteristic of an MOV

$$U = CI^{\beta} \tag{5}$$

$$I = DU^{\alpha} \tag{6}$$

where:

- I – the current that flows through the MOV
- U – the voltage across the MOV at the current I
- β – current nonlinearity index
- α – voltage nonlinearity index
- α= 1/β
- C and D – constants

A linear resistor has β=α=1. A non-linear resistor that is voltage limiting has β＜1， α＞1 and a non-linear resistor that is current limiting has β＞1， α＜1.

The nonlinearity index α varies with the MOV body temperature and the MOV current level, but the variation behaviour is very different between low and high current levels owing to the different conduction mechanisms.

7.1.2 Physical meaning of voltage nonlinearity index α

From equation 6, equation 7 for α can be derived

$$\alpha = \frac{U/I}{dU/dI} = \frac{R_V}{R_d} \tag{7}$$

where:

static resistance $R_V = U/I$

dynamic resistance, or increment resistance $R_d = dU/dI$

Equation 7 shows that voltage nonlinearity index α is a ratio of the static resistance to its dynamic resistance.

7.1.3 Geometric meaning of current nonlinearity index β

From equation 5, equation 8 can be derived which signifies the slope of the logarithmic curve $\log U = f(\log I)$. Equation 9 is the reciprocal of equation 8

$$\beta = \frac{\log U_2 - \log U_1}{\log I_2 - \log I_1} = \frac{\log(U_2/U_1)}{\log(I_2/I_1)} \tag{8}$$

or

$$\alpha = \frac{\log(I_2/I_1)}{\log(U_2/U_1)} \tag{9}$$

These two equations give an average value of α or β in a current range of [I_2, I_1], usually the DC-α is defined in a current range of [1 mA, 0.1 mA]. Sometimes the current range of [2*I*, *I*] is defined, and the α obtained is denoted as "α_{2I}".

7.1.4 Nonlinearity index α variation in standby

The low current standby operation region of an MOV is temperature sensitive and the α-value decrease dramatically with increasing temperature, see Figure 4.

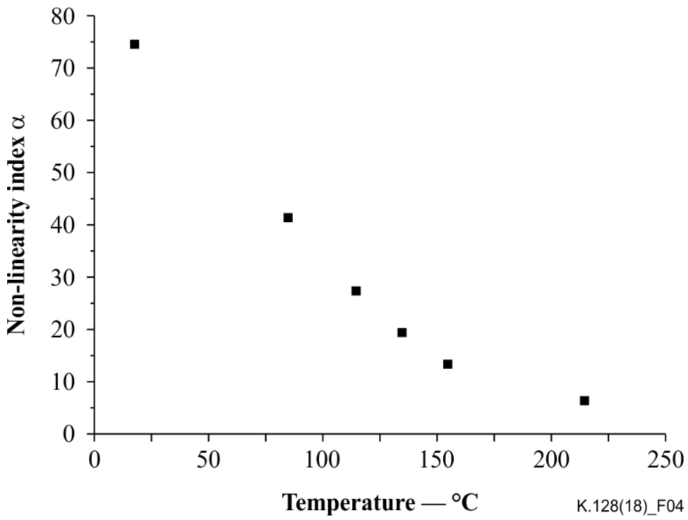


Figure 4 – Example of standby α decreasing with increasing temperature

The low current region dependency of α is shown in Figure 5. Over the current range shown the α-value continuously rises with current, meaning that the level of nonlinearity will also increase. At some current level the α-value will peak then fall. For MOVs with a $U_{1mA} \geq 75$ V, their highest α-value in low DC region ranges between 20 to 100.

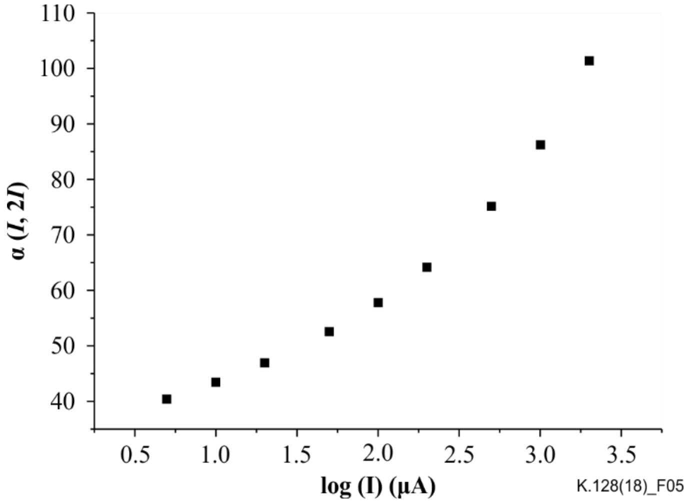


Figure 5 – Example of α (*I*, 2*I*) increasing with increasing current

7.1.5 Nonlinearity index α variation in voltage limiting

Figure 6 shows that the index α_{2I} (*I*, 2*I*) of a φ14 mm, U_{1mA}=738 V MOV falls as the 8/20 current peak current increases. The MOV limiting voltage *U* increases with increasing current. Example spot values are for *I*=200 A, *U*=1.2 kV and α_{2I}=60, while for *I*=8 kA, *U*=2.6 kV and α_{2I}=8. Generally, the MOV's lowest value of α_{2I} at its maximum rated 8/20 current falls towards 2 to 3.

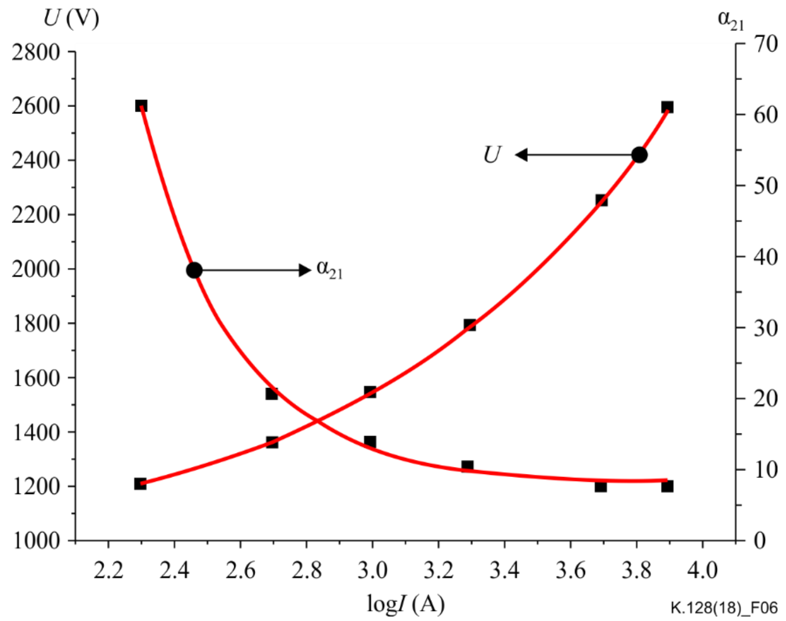


Figure 6 – MOV voltage (*U*) and α_{21} variation with 8/20 peak current (200 A to 8 kA)

7.2 Resistance formula

7.2.1 General

[b-Panasonic], page 38, first reported a resistance formula of an MOV, from which a set of V-I characteristic formulas can be easily deduced. The formulas have been successfully used for solving engineering MOV and MOV-type surge protective device (SPD) calculation problems, owing to the following advantages.

- Applicable to DC, AC, and impulse operation of the MOV.
- Applicable to a wider current range of greater than two decades.
- Has sufficient accuracy, usually 3%.
- The test and calculation steps to determine formula's constants are easy to do.

7.2.2 MOV resistance R measurement aspects

The MOV resistance R is the quotient of the MOV measured voltage to the measured current value through it. Measurements should observe the following:

- For DC and AC power frequency measurements, there is time delay (Δt) after the tested MOV being powered before readings stabilise. The time Δt varies mainly with the current density. Generally, measurements should be made after a Δt of 0.1 s.
- For DC and AC power frequency measurements, some polarization of the current and voltage values should be taken into account. The polarization is dependent on current density. To average out the polarisation, the average of the plus and minus measurements should be used.
- For impulse and AC power frequency measurements, the voltage and current measurements should be peak values, but these values may not occur at the same instant of time.

7.2.3 MOV resistance formula

Equation 10 shows the resistance formula that can be used to predict the MOV V-I characteristic over a wide current range.

$$\log R = A_0 + A_1 \log I + A_2 (\log I)^2 \tag{10}$$

Where: A_0, A_1 and A_2 are constants that are dependent on the characterised MOV part number. The formula shows that the resistance of an MOV varies with the current in a monotonic manner.

7.2.4 V-I characteristic from the MOV resistance formula

Equation 10 may be modified to plot the V-I characteristic as follows:

Add log$I$ to both sides of equation 6

$$\log R + \log I = A_0 + (1 + A_1)\log I + A_2 (\log I)^2 \tag{11}$$

The product of R and I is the varistor voltage U giving:

$$\log U = A_0 + \log I (1 + A_1 + A_2 \log I) \tag{12}$$

Raising both sides to the power of 10 and substituting $B = 1 + A_1 + A_2 \log I$ gives:

$$U = 10^{A_0} I^B \tag{13}$$

The B factor is not a constant but dependent on log$I$.

A similar treatment can give the I-V equation 14:

$$I = 10^y \tag{14}$$

Where $y = \dfrac{-(1 + A_1) + \sqrt{(1 + A_1)^2 + 4A_2 \cdot \log(U / 10^{A_0})}}{2A_2}$

Further manipulation can give the voltage ratio, k_v, equation, which is used for comparison purposes.

$$k_v = \frac{10^{A_0}}{U_1} \times I^B \tag{15}$$

Again $B = 1 + A_1 + A_2 \log I$ and U_1 refers to the varistor voltage of the MOV

The double-current index α_{2I} can be expressed as

$$\alpha_{2I} = \frac{1}{\left(B_I + (0.301 + \log I) A_2\right)} \tag{16}$$

where:

B_I is the B value at the given current I

7.3 MOV V-I characteristic graphs

7.3.1 Traditional MOV V-I graphs

A V-I characteristic can be described by mathematical equations (formulas) or a list of values or a graph of voltage against current. Until the MOV resistance equation and its derived V-I formula were introduced, there was not an equation that could describe the V-I relationship of an MOV over a wide range of current values.

Commonly published V-I graphs are typically generic and do not illustrate the MOV characteristics for DC, AC or impulse source types. Figure 7 [b-Wu] and Figure 8 (page 39, [b-Panasonic]) are two examples of such MOV V-I graphs.

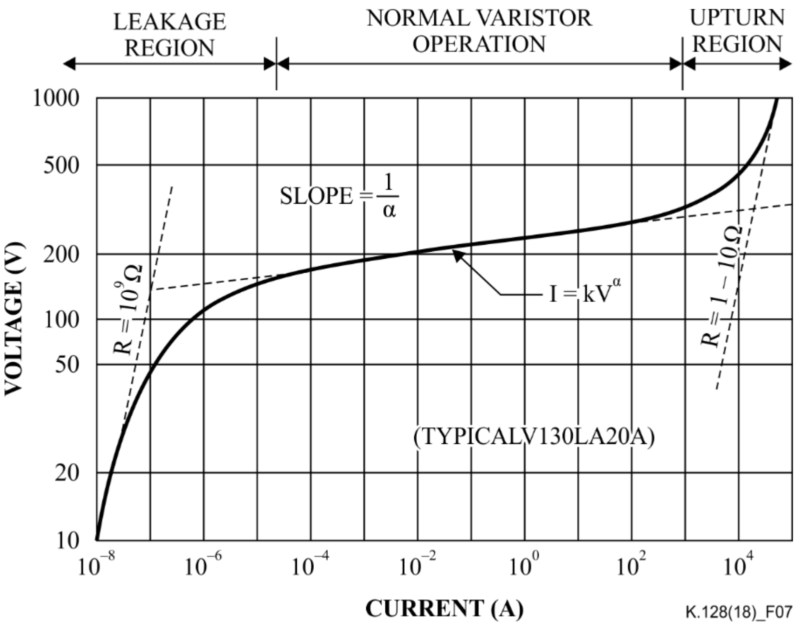


Figure 7 – Common example of an MOV V-I graph cited in many papers

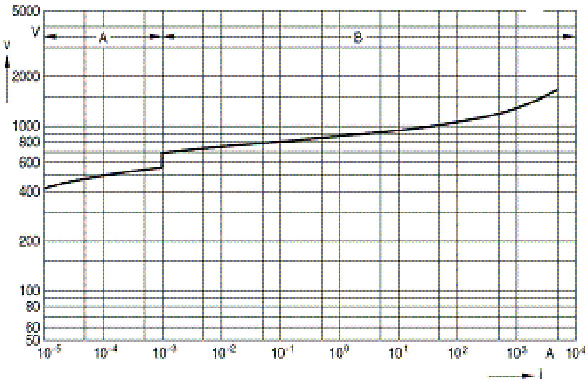


Figure 8 – Data sheet example with "A" leakage current and "B" limiting voltage regions marked

Figure 7 shows a single smooth V-I characteristic over the entire current range. This is not reality as there should be separate segments for DC, AC and impulse current operation. Equation 6, $I = DU^{\alpha}$, gives a smooth MOV V-I characteristic, but it cannot represent the characteristic over a large range of current. One reason is α varies, a range of 20 to 5 can occur. Also, the note that "R=1 Ω to 10 Ω" is probably unrealistic and "R < 0.1 Ω" would be more reasonable.

Figure 8 splits the characteristic into "A" for DC conditions and "B" for AC and impulse conditions. However, in the "B" part, there is a lower limit value for an 8/20 impulse current peak, due to the capacitance of the MOV. Hence, the lower "B" range limit of 1 mA is unlikely as an 8/20 impulse current value.

7.3.2 Segmented DC, AC and impulse MOV V-I characteristics

See [b-Xu].

Because the operating current range of an MOV can cover about 10 decades, there really needs to be three V-I characteristics: at low currents a DC characteristic, at medium current an AC characteristic and at high currents an impulse current characteristic. Figure 9 is an example of these three characteristics.

The V-I characteristics are normalised to the 1 mA MOV voltage by using k_v equation 11. The actual equation 11 values are:

DC characteristic: (I=10 μA to10 mA), $k_V=0.781I^B$ with B=0.06372–0.00866log$I$

AC characteristic: (I=3 mA to 10 A), $k_V=1.081I^B$ with B=0.01592+0.0003log$I$

Impulse characteristic: (I=200 A to 20 kA), $k_V=2.297I^B$ with B=–0.19552+0.04671log$I$

The values of non-linearity index α for the DC and AC characteristics are shown in Figure 9.

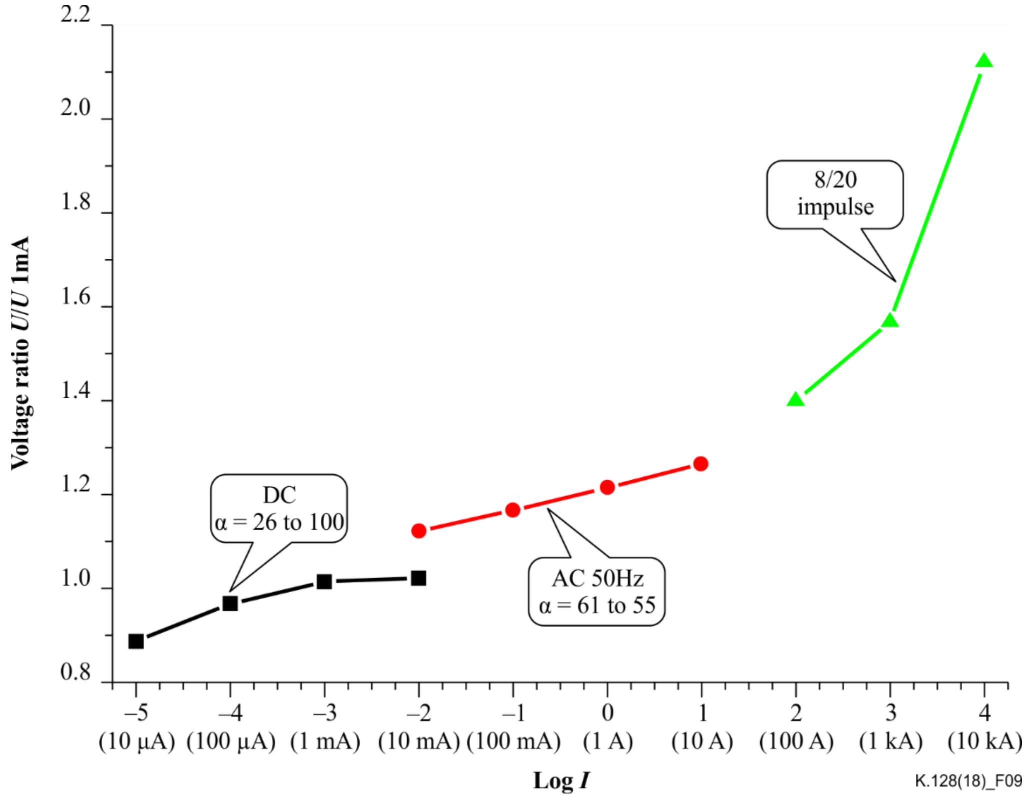


Figure 9 – MOV DC, AC and impulse characteristics

The MOV impulse characteristic will depend on the type of impulse used for the characterisation. Figure 9 shows an 8/20 impulse characteristic. Figure 10 is an example of how the characteristic varies for a 2 ms pulse and impulses of 1/5, 4/10 and 8/20. The Figure also shows how the peak voltage increases as the impulse current front time decreases for a given peak current.

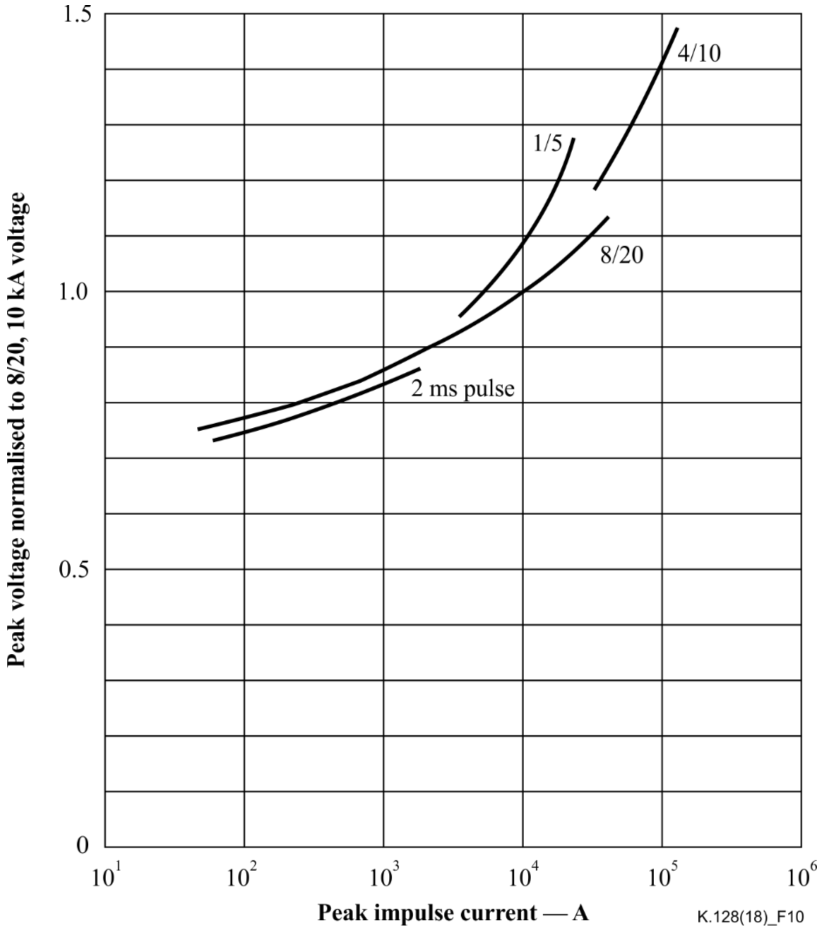


Figure 10 – Example impulse V-I characteristics for various impulse waveshapes

7.4 Other non-linear resistance effects

Unlike linear resistors the MOV shows peak displacement and negative dynamic resistance under particular conditions.

Negative dynamic resistance is when the voltage varies in an opposite direction to that of the current (–d*R*=-du/di or du/–di), see Figure 11. Peak displacement is when the voltage peak occurs at a different time point from that of the current peak, see Figure 12.

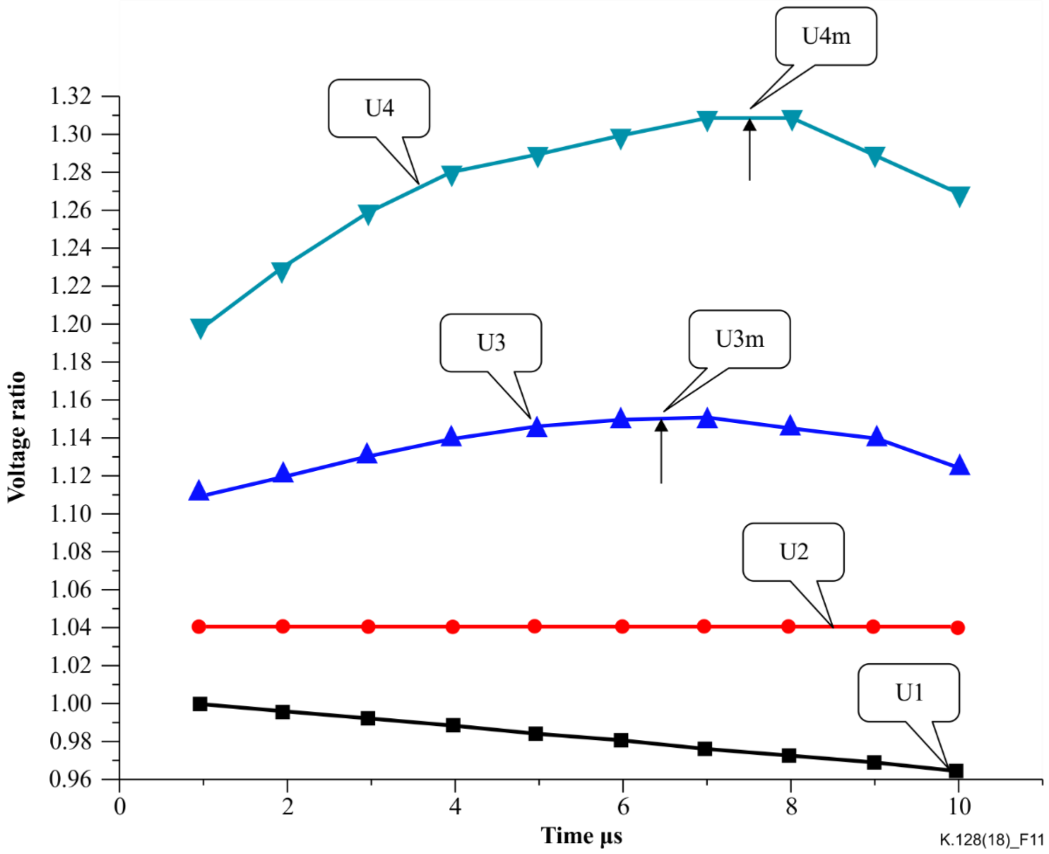


Figure 11 – MOV voltages, U_1, U_2, U_3 and U_4, during 8/20 impulse currents of I_{P1}<I_{P2}<I_{P3}<I_{P4}

Figure 11 shows four voltage plots (U_1, U_2, U_3 and U_4) of the same MOV which was subjected to a stepped 8/20 impulse current with the peak values of $I_{P1} < I_{P2} < I_{P3} < I_{P4}$. The MOV voltage was sampled in 1 µs steps over the time range of 1 µs to 10 µs. The MOV voltage waveforms varied in three ways depending on the current peaks, In Figure 11 the MOV voltage is normalised to U_1 at 1 µs.

– The lowest current MOV voltage U_1 shows a continuous decaying voltage waveform which is a negative incremental dynamic resistance characteristic.

– During the second current step, I_{P2}, the MOV voltage U_2 shows a constant voltage level, which is a zero-incremental dynamic resistance characteristic.

– At the two highest current steps the MOV voltages U_3 and U_4 show a voltage increase at first till reaching a peak value (U_{3m} and U_{4m}) followed by a decrease.

This 8/20 impulse test behaviour implies three things:

1) Peak displacement – the 8/20 impulse current peak is at the 10 µs but the MOV voltage peak occurs before, for U_{3m} this happened at 6.3 µs and for U_{4m} the peak happened at 7.5 µs.

2) Negative increment resistance – in the time interval between voltage peak and current peak, the voltage value going down while the current going up.

3) The MOV voltage peak time moved towards current peak time as the peak current increased (comparing the positions of U_{3m} and U_{4m}).

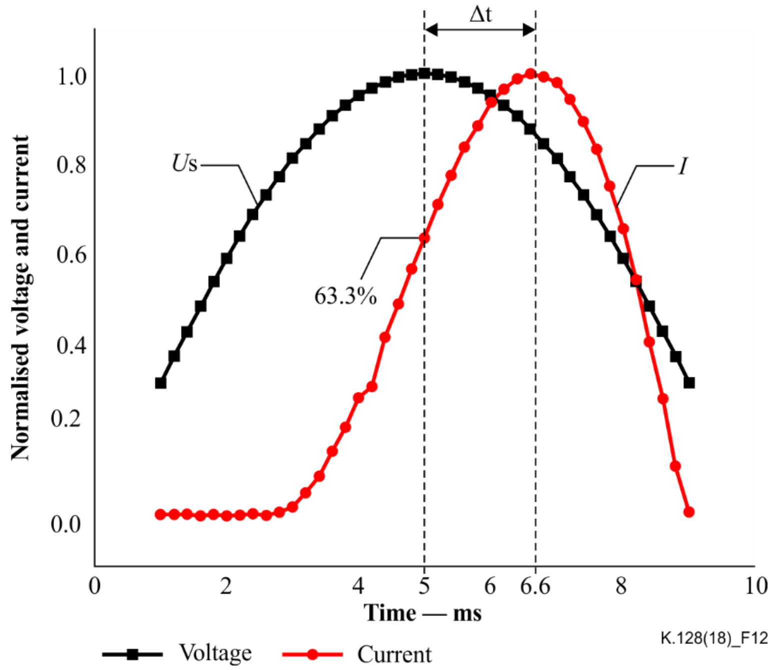


Figure 12 – Normalised MOV voltage and current under AC conditions with voltage source *U*S

Figure 12 for AC conditions shows similar MOV behaviours to the impulse conditions in Figure 11.

– Peak displacement – Current peak occurs later than voltage peak by a time Δt.

– Negative dynamic resistance during the time interval Δt.

– Current waveform distortion – current waveform is no longer a sine wave. The current waveform is asymmetric with a rising duration being longer than its falling duration.

These behaviours are due to the MOV resistance non-linearity and are mathematically explained in Appendix I.

8 Impedance properties and equivalent circuit

8.1 General

Like other electronic components, the behaviour of an MOV in electrical circuits can be represented by its equivalent circuit model. The equivalent circuit model used will depend on the application being simulated. The model showed in Figure 13 is applicable for DC and AC circuit analysis, while the Figure 14 model is applicable for impulse circuit analysis.

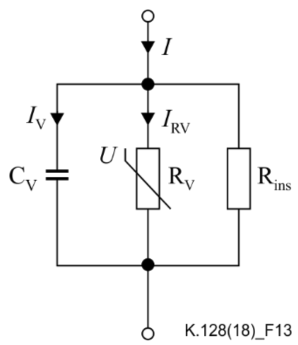


Figure 13 – Equivalent MOV circuit model for impulse analysis

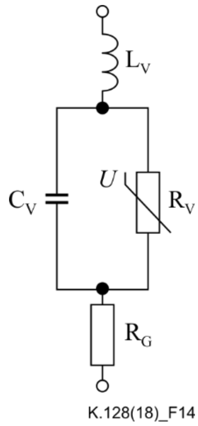


Figure 14 – Example photograph of surface temperature distribution together with spot temperatures (°C) for a bare ceramic element

The components of Figure 13 and Figure 14 are discussed in following clauses.

8.2 Non-linear resistance R_V

R_V represents the MOV non-linear resistance which varies from a very low value at high currents to a value approaching infinity at very low currents. When an applied voltage on the MOV is far below its U_{1mA}, the R_V value approaches infinity. In this case R_{ins} is the dominant resistance and the MOV can be considered as a linear high value resistor. At the opposite end of the current range, when a high value of impulse current is conducted, R_V approaches zero and the MOV can be regarded as a low value linear resistor.

8.3 Leakage resistance R_{ins}

R_{ins} is the net linear resistance of parallel components of volume insulation resistance and side surface insulation resistance. For quality MOVs, the R_{ins} value is much higher than the standby operation value of R_V and so can be omitted. However, R_{ins} might be included in situations when the MOV is exposed to a wet environment that could result in the side surface leakage current to increase steadily with time.

8.4 Capacitance C_V

As covered in clause 6.3, the MOV-cell consists of a grain boundary layer (insulator) being sandwiched between two ZnO grains (conductor) which forms a capacitor. The actual MOV capacitance, C_V, is the result of the MOV ceramic element being a network of many capacitor-cells connected in series and in parallel. The MOV capacitance, C_V, will be inversely proportional to varistor voltage and proportional to the ceramic element area rather than the thickness of its ceramic body.

8.5 Linear resistance R_G

The high current resistance, R_G, consists mainly of ZnO grain resistances, the ceramic surface to silver layer to metal termination contact resistance and the terminal lead resistance. Normally R_G is quite low, in the order of milliohms, but needs to be taken into account at high impulse currents when the non-linear resistance R_V approaches the R_G value.

8.6 Inductance L_V

The MOV's inductance, L_V, increases the MOV impulse limiting voltage at high rates of current change, *di/dt*, by $L_V \times (di/dt)$. The inductance of MOV's ceramic element is extremely small. The main component of L_V is the terminal lead inductance, which is about 1 nH/mm. For general lightning protection applications, the L_V voltage of a standard leaded type MOV is not a major factor. Including L_V should only be considered when the di/dt of the specified impulse current is far greater than that of the rated 8/20 impulse. The external circuit wiring connections to the MOV can represent much higher values of series inductance and their $L \times (di/dt)$ contribution can greatly increase the net in-circuit limiting voltage.

9 Ceramic element current and temperature distribution

9.1 Introduction

An ideal MOV would have a uniform current density in the ceramic element, resulting from a uniform material resistivity. However, such a result would require a uniform microstructure with identical grains and grain-boundaries in dimension, orientation, chemistry, thermal and electrical properties. Unfortunately, limitations of current ceramic processes lead to an inhomogeneous microstructure of the ceramic element, and therefore, the resistivity variations, resulting in uneven current distribution inside the ceramic element.

Uneven current distribution causes an uneven temperature distribution and lowers almost all properties of the MOV. Improving the uniformity of the material forming the MOV ceramic element is a continuous challenge for manufacturers.

There are two common methods used to evaluate the uniformity of microstructure: "photograph method" and "spot electrode method".

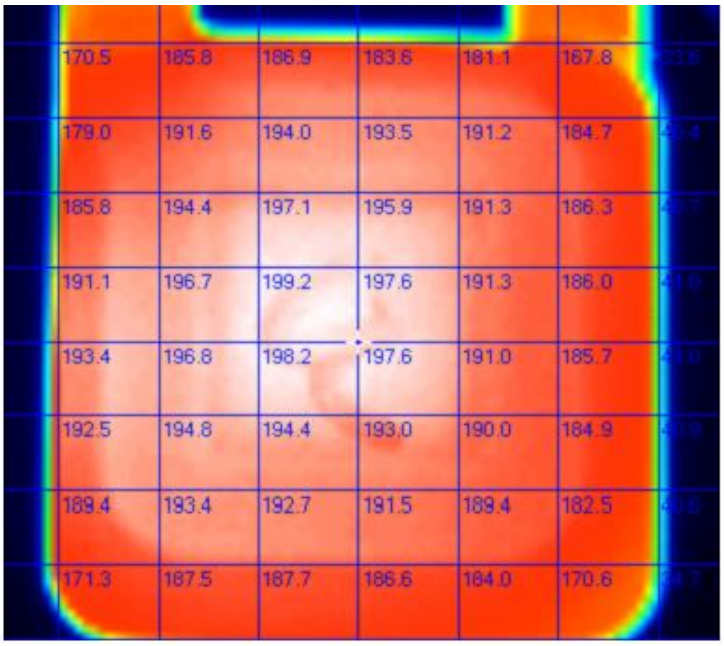


Figure 15 – Example photograph of surface temperature distribution together with spot temperatures (°C) for a bare ceramic element

The photograph method is used to check bare discs (without insulation coating). The photograph in Figure 15 was taken after the bare disc had been exposed to a power frequency source for a while. In order to measure the degree of un-uniformity, a parameter of "non-uniformity factor (F_U)" is defined:

$$F_U = \frac{T_{max} - T_{min}}{T_{AV}} \times 100\% \qquad (17)$$

Where: T_{max}, T_{min}, and T_{AV} refer to the highest, lowest and average temperature respectively on the surface.

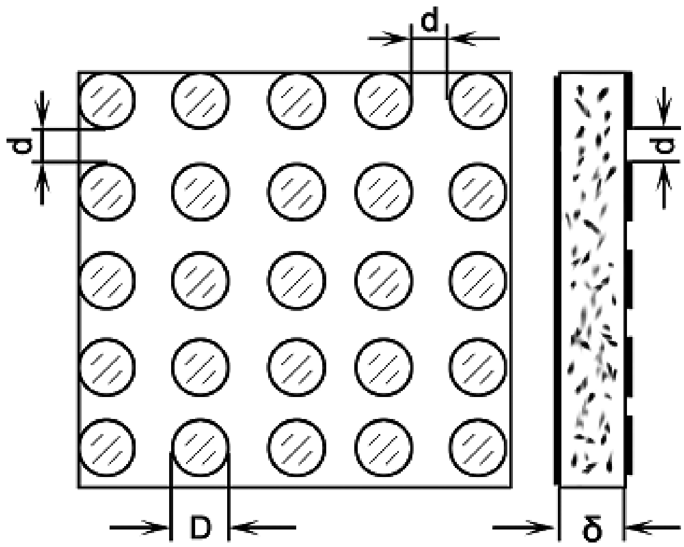


Figure 16 – Ceramic element with full electrode on one side and spot electrode on other side

The spot electrode, usually silver paste electrode, is applied on one surface of the ceramic element, while the other surface is full electrode, see Figure 16. The gap "d" between two spot electrodes is made to be not less than the ceramic element thickness δ. Then voltage measurement at a specified current (say10 μA) is made between each spot and the full electrode. At last the voltage un-uniformity factor (F_U) shall be calculated by replacing the temperature with the voltage in equation 17.

9.2 Thermal properties

The capabilities of an MOV to withstand surge impulse stresses, temporary overvoltage (TOV)-stresses, and temperature-voltage stresses, are closely connected with its thermal properties. Well-known electrical analysis techniques and parameters such as Ohm's law, capacitance, resistance (conductance), charge, voltage and current can be used for in equivalent form for thermal Ohm's law, specific heat capacity, thermal conductivity, and temperature. The mechanical coefficient of thermal expansion also needs to be considered.

9.2.1 Thermal Ohm's law

If an object (O_{bj}), as shown in Figure 17, is considered as an electric conductor, the electrical parameters will conform with the electrical Ohm's law, equation 18; while if it is considered as a thermal conductor, the thermal parameters will conform with the thermal Ohm's law, equation 19.

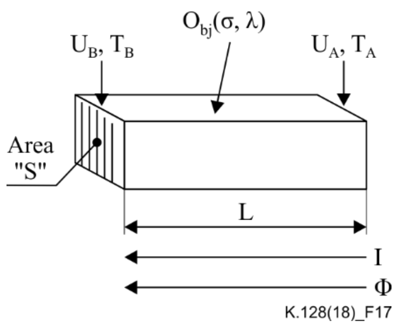


Figure 17 – Electrical and thermal relationships for a conducting block

$$I = \sigma \cdot \frac{S}{l} \cdot (U_A - U_B) \text{ (Electric Ohm's law)} \quad (18)$$

where:

I = current

σ = electric conductivity (A/V-cm)

S = area

l = length

U = voltage

$$\Phi = \lambda \cdot \frac{S}{l} \cdot (T_A - T_B) \text{ (Thermal Ohm's law)} \quad (19)$$

where:

Φ = heat flow (J/s)

λ = thermal conductivity (W/K-cm)

S = area

l = length

T = temperature

9.2.2 Specific heat capacity: c≈0.84J/g-K≈4.54J/cm^3

It takes 0.84 J of heat energy to raise the temperature of one gram of MOV ceramic by 1 degree, or 4.54 J per one cm^3 in volume (density 5.4 g/cm^3). This parameter, is used to calculate the temperature rise of an MOV ceramic element as a result of a current impulse or vice versa.

9.2.3 Thermal conductivity: λ≈0.057 W/cm-K=0.057 J/cm-K-s

Thermal conductivity λ is a material constant, which for MOV ceramic elements is roughly 0.057 J/cm-K-s, about 1.4% of that of copper. Such poor conductivity is one of the major causes responsible for an MOV to catch fire when thermal breakdown occurs.

9.2.4 Coefficient of thermal expansion

MOV ceramics has a small value of coefficient of thermal expansion, which is roughly 3×10^{-6}/K, about 1/5 of that of copper, therefore proper design coordination between an MOV ceramic element and its copper electrode is needed.

9.2.5 Current concentration (hot spotting)

Current concentration signifies a dynamic process of the interaction between electric effects and thermal effects in MOV bulk. This interaction shown below can be regenerative with condition 5 becoming the new condition 1:

1) Hot spot heat generation is greater than the heat dissipated.

2) Temperature increases.

3) MOV resistance reduces.

4) Higher current density due to more current from power source and hogging current from higher resistance areas.

5) Temperature further increases.

There are two outcomes here; a thermally stable condition with the generated heat equalling the dissipated heat or thermal runaway because the heat dissipation capability is less than the heat generation.

Factors effecting this process are:

- Level of ceramic element inhomogeneity.
- Duration of impulse current or TOV stress – longer durations increase current concentration.
- MOV temperature coefficient of resistance.
- Non-linearity (α-value) – higher α-value increases current concentration.
- Geometric shape and dimensions of the MOV – larger size and ratio of area to thickness increases current concentration.
- Voltage supply source impedance – low values increases current concentration.

9.2.6 Thermal stability and thermal breakdown

When current concentration occurs, there are two possible outcomes; thermal stability or thermal runaway. If an MOV has a fixed voltage U_{ap} applied and is in an ambient temperature of T_a, the outcome MOV depends mainly on the temperature, T, relationship between the MOV generated power P=f (T) and dissipated power Q=f (T) capability as shown in Figure 18 [b-Ding].

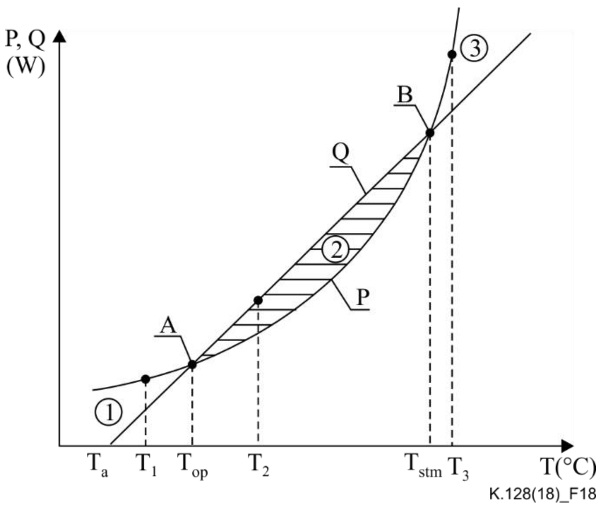


Figure 18 – Generated (P) and dissipated (Q) power versus temperature (T)

The power P =f (T) and Q=f (T) can be expressed in the equations below

$$P = U_{ap} \cdot I(T) \tag{20}$$

where:

$I(T)$ = current as a function of temperature

$$Q = \lambda \cdot S \cdot (T - T_a) \tag{21}$$

where:

λ = component thermal conductivity

S = component surface area

T_a = ambient temperature

The curve of equation 20 is approximately exponential due to a decreasing resistance of the MOV body with its temperature rising, meanwhile the applied voltage U_{ap} remains unchanged. The curve of equation 21 is approximately linear because the total surface area S and thermal conductivity λ are constant for a given MOV product and its installation.

Figure 18 shows two stable operating points where curves P=f (T) and Q=f (T) intersect at "A" and "B". The lower intersection point A represents a condition of thermal equilibrium where the generated power is equal to the dissipated power. Under this condition the MOV operates at a temperature of T_{op}. The second intersection point B represents the maximum allowable MOV temperature. If the MOV temperature increases above T_M then a thermally unstable condition exists where the generated MOV heat exceeds the system capability to dissipate the heat energy and thermal runaway will result. The temperature difference $\Delta T=T_M-T_{op}$ represents the maximum temperature rise, caused by surge energy absorption.

This has been a simplistic treatment of thermal stability and further comments are:

Without a point of intersection of the P=f (T) and Q=f (T) curves, stable operation of an MOV will be unobtainable.

For clarity, Figure 18, uses linear scales for power temperature. A more accurate assessment is possible if the scales were logarithmic to cover the possible range of powers and temperatures.

10 Time factors

10.1 Initial response to an impulse

Response time is a depreciated term for two reasons:

1) There is no MOV standard definition or test for such a parameter.

2) It is extensively used as a meaningless marketing tool with such feature headlines as "Response time < 0.5 ns (theoretical)"

The significant time intervals where various aspects of an MOV need to be considered are:

- MOV ceramic element ≤ 0.5 ns
- Leaded MOV components with two 25 mm leads ≤25 ns
- Leadless surface mount type MOVs ≤0.5 ns

As most common surges have front times of 500 ns or more the effects of the above list are not significant.

Figure 18 shows a leaded MOV current and voltage as a result of an applied voltage step, where the voltage step, U_m, is greater than the MOV's limiting voltage U_{VB}. From MOV's equivalent circuit of Figure 14 following current and voltage waveshapes can be predicted. During the time that the MOV voltage is below U_{VB} the most significant current flow will be the capacitive current (i_C) charging the MOV's capacitance. Only when the voltage reaches a certain threshold, U_1 at instant t_1, does the resistive current, i_R start to become significant. After t_1 the non-linear resistive current quickly increases for little increase of the voltage because the non-linear MOV resistance is rapidly decreasing. The total current passing the MOV is the sum of i_C and i_R. The delayed occurrence of the resistive current and the lead inductance results in a voltage over-shoot U_{OS}, which is the difference between the peak voltage value, U_P, and the stable MOV limiting voltage U_{VR}. of the MOV.

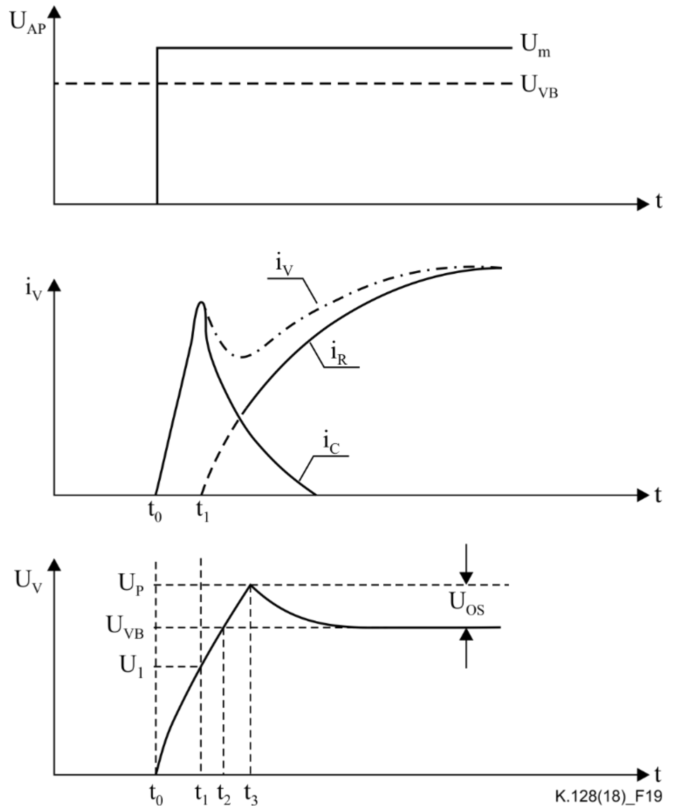


Figure 19 – MOV current and voltage resulting from a pulse step

Generally, a greater current rate of rise, di/dt, will result in a higher peak voltage, U_P. Figure 20 shows the results from a circular ceramic of diameter φ 20 mm U_{1mA}= 620 V MOV having a 100 A current step applied. The step front or rise time, t_R, was varied from 0.4 µs to 80 µs. The results confirm a di/dt sensitivity. At 250 A/µs (t_R=0.4 µs) U_P is 12% greater than the 13 A/µs (t_R=8 µs) U_P value. At 1.3 A/µs (t_R=80 µs) U_P is 9% less than the 13 A/µs (t_R=8 µs) U_P value.

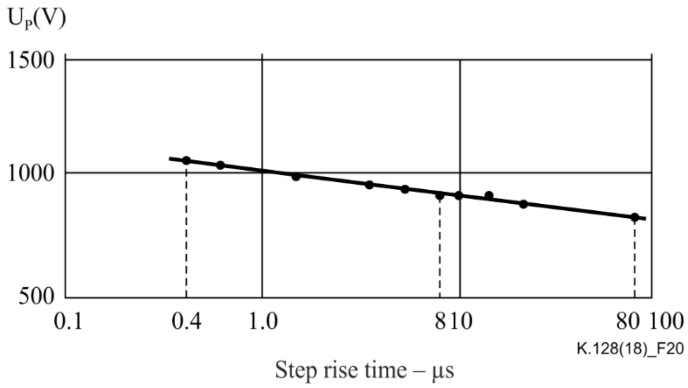


Figure 20 – MOV UP variation with 100 A step rise time

10.2 AC power frequency currents

Protecting mains powered equipment is a major application for MOVs. Incorrect selection of MOVs for this application can lead to MOV failure and result in safety hazards. Thus, it is important that designers understand how MOVs perform under AC power frequency conditions.

As indicated in Figure 19, the current flowing through an MOV consists of two components: capacitive current (I_C) and resistive current (I_{VR}) when a power frequency voltage U_S is applied on it. The amplitude of I_C is roughly proportional to the applied voltage ratio R_{avr} (a ratio of the applied voltage peak to the U_{1mA} of the MOV), while the current peak of I_{VR} is roughly proportional to $(R_{avr})^{\alpha}$

(typical non-linear index α=25 to 80). When the waveshape of I_C is a sinewave, while the waveshape of I_{VR} is pulse-like, therefore the shape of total current of MOV varies greatly with the variation of R_{avr}, as shown in Figure 21.

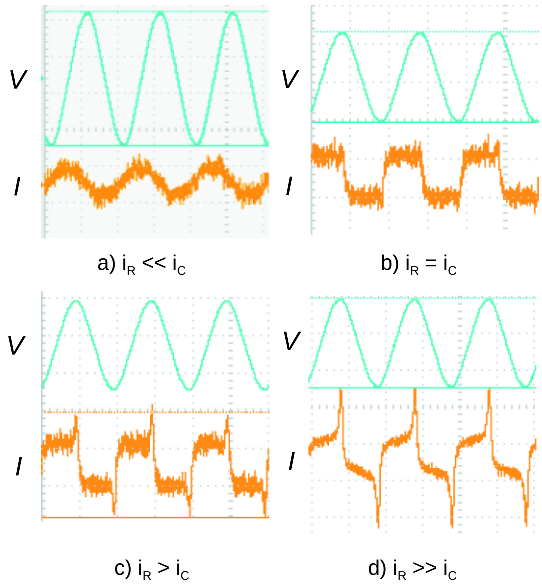


Figure 21 – Current waveforms for various i_R i_C ratios

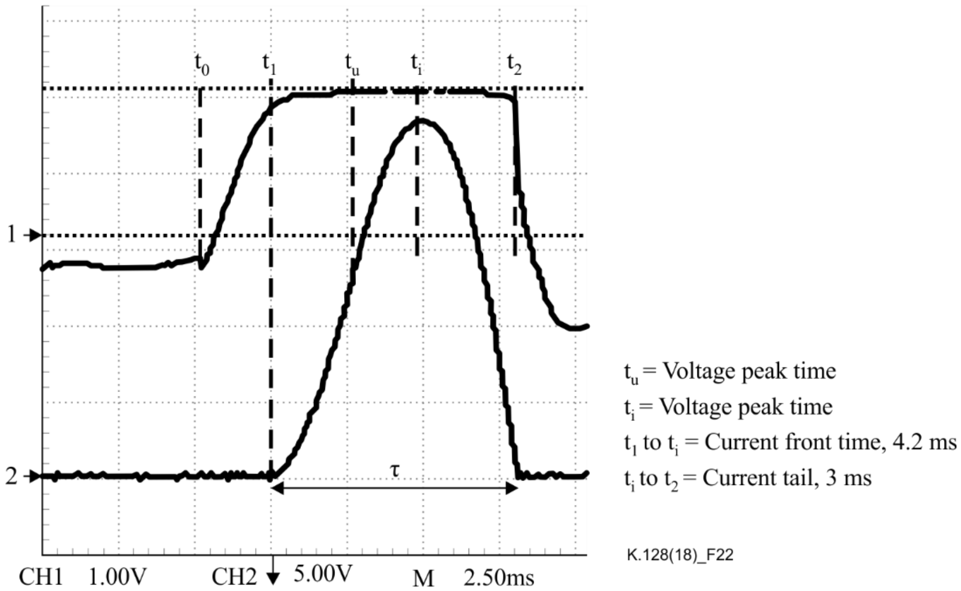


Figure 22 – MOV voltage and current half cycle 50 Hz waveforms

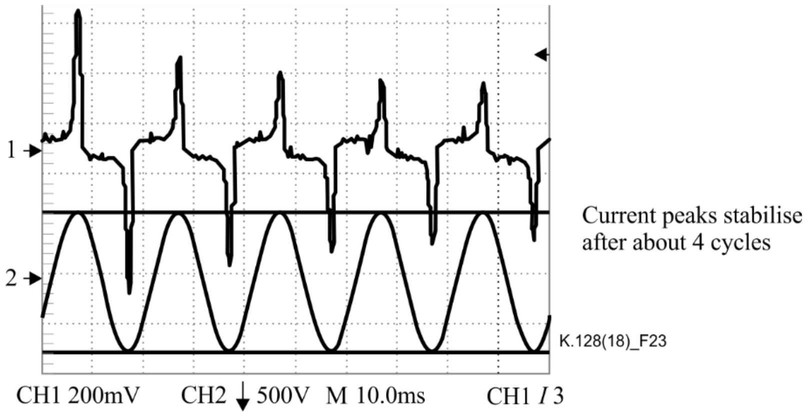


Figure 23 – First few cycles after AC voltage applied

Clause 6.4 and Figure 22 illustrate peak displacement of the voltage and current waveforms. In Figure 22 the current peak point at t_i occurred after the voltage peak point t_u by about 1.8 ms

Despite having a sinusoidal voltage being applied to the MOV, the current through the MOV is nothing like a sinewave, as shown in Figure 22, where the front duration of the current is longer than its tail duration.

As indicated in Figure 23, there is an initial transient period of current peaks after application of the sinewave voltage to an MOV, the first current pulse having the highest peak value, after which the peak values decrease and approach a stable state after about 3 to 4 cycles.

It can also occur where there is some difference between positive and negative current peaks which is called "polarization".

Hence, for AC peak or watts loss measurement, it is reasonable to take an average value of the plus and the minus peaks of the same cycle at four cycles after the voltage is applied.

The power loss (P) of a linear component is the product of the voltage (U) on it multiplied by the current (I) through it ($P=U\times I$). This simple formula cannot be used with a non-linear component such as an MOV unless the voltage and current are DC values.

Calculation of AC power loss is complex because, at higher current levels, the current waveform is asymmetrical triangular like pulse with a reasonably constant limiting voltage during conduction time, see Figure 22. Fortunately, with modern digital oscilloscopes it is easy to multiply and average the recorded waveforms of voltage and current to given the AC power loss. A very approximate estimate of the power loss at higher currents can be made from the formula $P=0.35\times I_P\times U_P$.

11 Degradation and failure modes

11.1 Stresses that may cause degradation

Degradation is an undesired departure in the operational performance from the expected performance. The term "degradation" can apply to temporary or permanent failure. The major stresses that may produce MOV degradation and/or failure include following items:

- Combined stresses of continuous operation voltage and temperature (*U/T* stresses)
- Impulse current stress (factors are peak value, duration, repetition times, interval between impulses, and polarity)
- Climatic conditions

The characteristics that may be used to evaluate degradation are

- Varistor voltage (U_{1mA})

- Limiting voltage
- Resistive current or watt loss
- Nonlinearity index (α value)

The most common characteristic used is a percentage change of U_{1mA}.

11.2 Impulse current degradation

The results shown in this clause are for a single polarity impulse life test where the end of life criteria was a 10% fall in U_{1mA}. Figure 24 and Figure 25 show how the degradation affected the low and high current indexes. The "Before" curve is prior to the start of life test and the "After" curve is measured following the life test.

The curves in Figure 24 show that the DC small current region the index α_{2I} drops dramatically in both directions after the life test, with a larger reduction in opposite polarity to the impulse current.

The curves in Figure 25 demonstrated that the impulse life test had little effect on impulse V-I characteristic.

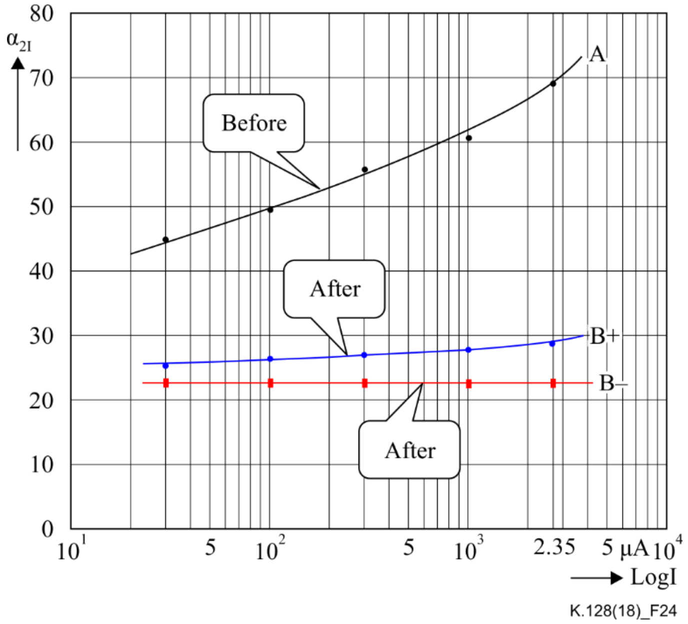


Figure 24 – Low current (30 µA to 2.35 mA) α_{2I} change pre- and post-impulse current life test

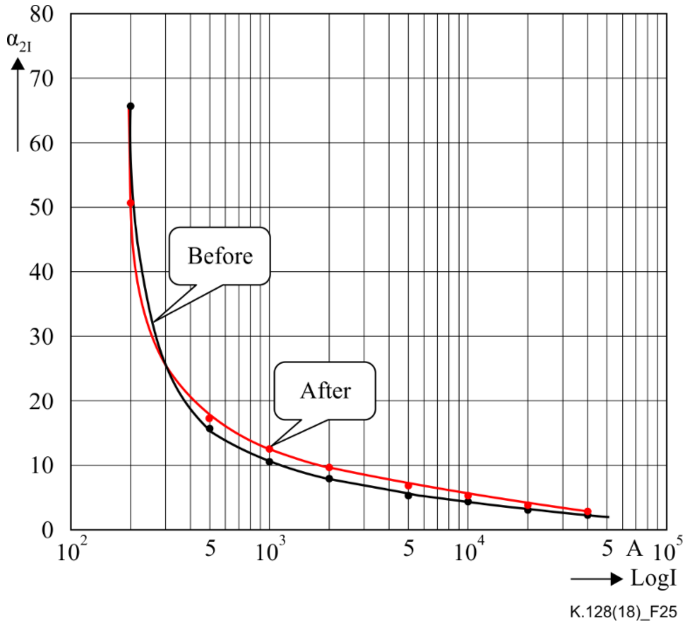


Figure 25 – Low current (200 A to 40 kA) α_{2I} change pre- and post-impulse current life test

11.3 Failure criteria

Two types of failure criteria are presently adopted for reliability evaluation of an MOV: "parameter degradation criteria" and "physical destruction criteria"

Parameter assessment for degradation criteria can be in the following areas:

1) Varistor voltage U_{1mA} has decreased by more than 10% of the initial value.

2) Residual/limiting voltage U_{res} at a specified impulse current has increased by more than 10% of the initial value.

3) Leakage current or watt-loss shows a steady increase.

Residual voltage always changes upwards when an MOV being subjected to repetitive impulse stresses, despite the varistor voltage (U_{1mA}) going down. The increase of the residual voltage is ordinarily about +3% when the U_{1mA} has dropped by –10%. Therefore, a "+10% increase of the limiting voltage" is never observed.

There are various potential MOV physical failure modes, which are determined by correlation between stresses and MOV design, as well as processing. Figure 26 shows some typical physical destructions with labels linked to the reasons below:

1) Thermal puncture (breakdown) hole in the ceramic bulk.

2) Etched silver layer.

A part of the silver layer adjacent to the metal lead (plate) has been melted by repeated or high-level impulse current, or by flashover. This type of destruction is difficult to detect via an ordinary electrical test, making it necessary to remove the coating for a visual inspection.

3) Cracking of insulation coating or separation.

Rapid temperature change or repeated impulse stresses are more likely to produce cracking of the insulation coating.

4) Cracking of the ceramic bulk.

5) A layer of ceramic bulk parted from the bulk.

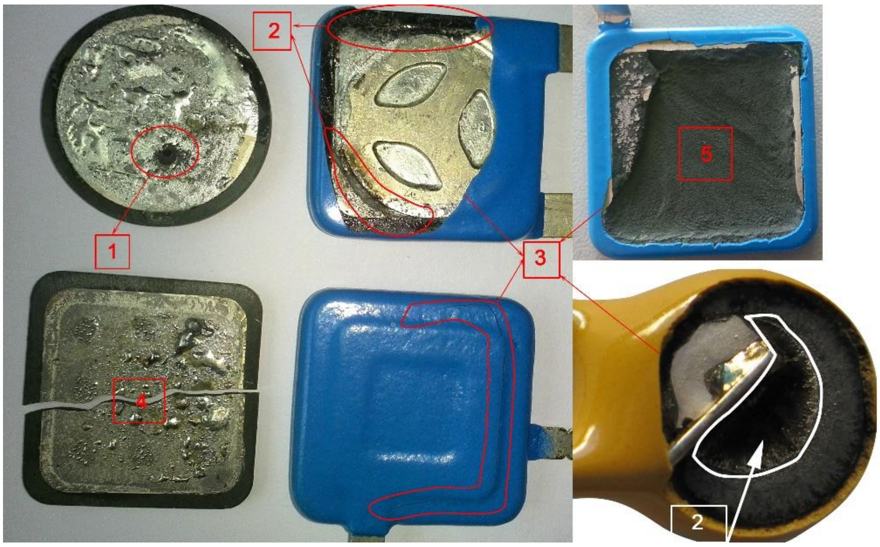


Figure 26 – Various MOV physical destructions

11.4 Additional MOV behaviours and effects

The major MOV behaviours and effects have been covered earlier. This clause covers second-order behaviours and effects, which may be met in MOV testing.

For example, the application and removal of a voltage to an MOV produces transient discharge currents that persist on a time scale extending from 10 ns to about 30 h. This behaviour cannot be explained by the DSB model.

It has been proved that there is polarization and de-polarization current in the MOV ceramics. The word "polarization" refers to a process of producing a relative displacement of positive and negative bound charges in the grain boundary phase (see clause 6.3) by applying an electric field. Parallel leakage paths are created with Schottky barrier-controlled current flow.

Another behaviour that is caused by variation of trap density at the grain boundary depletion layer, which affects the time-dependent stability of an MOV.

12 Operation states and related performances

In this clause, an MOV's typical operational states and related characteristics and ratings are discussed. The discussion includes parameter definitions and test methods, as well as application considerations.

12.1 Typical operation states and basic requirements

The MOV is a surge protection component, which functions by limiting impulse overvoltage and diverting the impulse current.

In an application, the MOV operation state can be in three modes: standby, voltage limiting and TOV-endurance.

In its entire service life, an MOV should meet some basic requirements that are requested by the operation states. These requirements are represented by related characteristics, ratings and parameters, as listed in Table 1.

Table 1 – Typical operational states and performances

<table>
<tr><th>Standby operation state</th><th>Surge suppression state</th><th>TOV endurance state</th></tr>
<tr><td colspan="3">Electrical stresses imposed on MOV</td></tr>
<tr><td>Maximum continuous operating voltage (MCOV)</td><td>MCOV or
Specified impulse current</td><td>TOV</td></tr>
<tr><td colspan="3">Ratings and parameters</td></tr>
<tr><td>varistor voltage U_n
U_n-tolerance δU_n
voltage gradient V/mm
MCOV
standby watt loss P_0 and its stability, or
resistive leakage current I_{LR} and its stability
capacitance C_V
Temperature dependence of V-I characteristics
Endurance test under U/T stresses (1000hrs)</td><td><u>Impulse limiting performance</u>
limiting voltage U_{LiM}
nominal discharge current I_n
capability of impulse current diversion
response time t_{res}
voltage overshoot Δu_{OV}
<u>impulse handling capability</u>
Max. discharge current of short / long impulse $I_{MS,}$ / I_{ML}
Repeated discharge current of short / long impulse $I_{MS,}$ / I_{ML}
Average impulse power P_{av}
Maximum impulse energy E_{max}</td><td><u>MOV component</u>
TOV endurance voltage U_{TOV} or
TOV withstanding energy E_{TOV}</td></tr>
<tr><td colspan="3">Characteristic formulas and curves</td></tr>
<tr><td>V-I characteristic formula or curves for AC or DC</td><td>V-I characteristic formula or curves of impulse life</td><td>V-I characteristic formula or curves of current peak vs voltage peak</td></tr>
</table>

12.2 Operational performances related to standby operation state

12.2.1 Varistor voltage U_n (U_{1mA}), tolerance δU_n, voltage gradient V/mm

Varistor voltage U_n, also named DC reference voltage, is used to signify the transition point between the insulation state and conduction state of an MOV. According to the product specification, U_n is measured at DC 1 mA ±10%, after a conduction period of 20 ms to 50 ms, independent of MOV size.

Varistor voltage U_n is usually used as a reference voltage, for example:

- Applied voltage ratio (AVR)=U_{ap} / U_n, where U_{ap} refers to the peak of AC voltage or DC voltage to be applied on the MOV. The AVR is used to express the severity of applied voltage upon an MOV.
- Limiting voltage ratio (LVR)=U_{mp} / U_n, where U_{mp} refers to the peak of the limiting voltage on the MOV. at a specified impulse current passing through it. The LVR is used to express the capability of suppressing surge voltage of the MOV
- Change rate of varistor voltage $\Delta U_n=(U_{n1}-U_{n0})/U_{n0}$, where U_{n0} and U_{n1} refer respectively to the measured varistor voltage before and after test, for the most test items of MOV, ΔU_n is used as a pass (failure) criteria. In the case of regular checks on field MOVs, ΔU_n (with respect to the initial value of U_n) is often used as a criterion of degradation, if the ΔU_n is beyond a specified value, the MOV should be replaced.

Lack of size sensitivity means that U_n is measured at different current density for different sizes. However, some important properties of MOV, such as temperature coefficient of voltage and current and the degree of degradation, are much sensitive to the current density, in this respect, the varistor voltage U_n may be defined as such a voltage that is measured at a specified current density, for example 0.1 mA/cm^2.

Tolerance of varistor voltage (δU_n) is an important parameter for MOV selection, the top value of the δU_n is usually limited by the maximum limiting voltage, while its low-end value is limited by the permitted degradation during the service life when taking the variation of system voltage into account.

Voltage gradient (V/mm) refers to varistor voltage per unit thickness. This parameter has three effects on MOV selection: generally, higher gradient means lower energy handling capability, lower cost, and better voltage limiting property (lower limiting voltage ratio).

The voltage gradient of most commercial MOVs ranges from about 100 V/mm to 220 V/mm for medium and high varistor voltage units.

12.2.2 Maximum continuance operating voltage U_M

The rating MCOV signifies such a voltage that may be applied continuously at a specified temperature.

At the discovery time of ZnO varistor, AC MCOV (U_{Mac}) was so defined that the peak of U_{Mac} shall be equal to or less than the lowest U_n of the specified tolerance, which is $0.9U_{n0}$ (U_{n0} is nominal varistor voltage) in case of ±10% tolerance,

$$U_{Mac} = \frac{0.9U_{n0}}{\sqrt{2}} \approx 0.64U_{n0} \tag{22}$$

As for system voltages other than AC source, including DC source, the MCOV shall be such a voltage value under which the MOVs generate about the same watt loss as that at U_{Mac}, based on this rule, the equation 23 was derived by experiments

$$U_{Md.c} \approx 1.3U_{Ma.c.} \tag{23}$$

From above discussion, the users should be aware that a particular magnitude of U_{Mac} and U_{Mdc} are affected by U_n-tolerance.

MCOV is not measurable, its conformity is evaluated by the following tests:

- Reliability screen test in the course of processing.
- Endurance test under MCOV and specified temperature.
- Operation duty test: MOV shall be thermally stable under MCOV which is applied on the samples immediately after specified impulse test.
- Life test.

12.2.3 Standby watt loss P_0, resistive leakage current I_{LR}, total leakage current (rms) I_L

These three parameters are related with MCOV. Generally, measurement of P_0, or I_{LR} is sufficient, P_0 being most easy to measure. The total leakage current (rms) I_L should be controlled for those MOVs that are intended to be connected to protective earth in the application.

12.2.4 Capacitance C_V

The MOV capacitance, C_V, has the following dependences:

- The value of C_V is about inversely proportional to varistor voltage rather than to bulk thickness.
- The value of C_V may be critical to the application. To understand the need requires analysis of circuit in which the MOV to be used in.
- The MOV C_V value has some "memory effect", where any previous MOV electrical stress will affect a subsequent measured C_V value. Normally, there can be a reduction in the measured capacitance value by 10% or more, therefore C_V measurement should be the first test of a series tests.

12.2.5 Temperature dependence of the V-I characteristics

Knowing the temperature dependence of an MOV V-I formula is of great benefit to users and producers, who can then predict the voltage/current values at any temperature ranging e.g., from 20 °C to 160 °C, if the room temperature of U_n is known, see the example below.

This example uses an MOV of φ 20 mm, U_{n0}=620 V, U_{n0}=627.8 V, having a DC V-I formula given in equations 24 to 27, which are expressed as a normalized voltage ratio $[VR]_{nom}$ in a current range of 1 μA to 10 mA in a temperature range of 20 °C to 160 °C.

$$[VR]_{nom} = \frac{V_{T,I}}{V_n} = A_0 \times I^{(A_1 + A_2 \times \log I)} \tag{24}$$

$$A_0 = 0.9 - 0.0013 \times T - 1.83 \times 10^{-5} \times T^2 \tag{25}$$

$$A_1 = 0.039 - 7.85 \times 10^{-4} \times T + 1.73 \times 10^{-5} \times T^2 \tag{26}$$

$$A_2 = -0.037 + 8.57 \times 10^{-5} \times T - 2.36 \times 10^{-6} \times T^2 \tag{27}$$

Where: $V_{T,I}$ is the voltage of the unit at ambient temperature T (°C) and current I (μA). V_n is the varistor voltage of the unit at room temperature.

Question

What is the voltage of an above type of unit that has been heated to 115 °C, when an MOV current of 100 μA flows, if its U_n at room temperature is 627.8 V?

Solution

Putting T=115 °C into equations 25, 26 and 27, give A_0=0.508, A_1=0.178, A_2=–0.025

Putting (A_0=0.508, A_1=0.178, A_2=–0.025, I=100 μA) into equation 24 give $[VR]_{nom,}$=0.889

The answer voltage is 0.889×627.8=558.1 V.

12.3 Operational performances related to surge suppression state

When an MOV provides surge protection it has to meet two requirements; sufficient surge impulse current capability and an acceptable peak voltage limiting.

12.3.1 Protection capability

The MOV should voltage limit the expected surges down to a level that is within the protected object (PO) capability. Besides the obvious surge voltage capability of the PO in some cases the resulting surge current taken by the PO needs to be considered. In most cases the input impedance of the PO in parallel with the MOV is much higher than the equivalent resistance of the MOV during surges only; therefore, the peak voltage needs to be considered. When the input impedance of the PO is low, such as with a rectifier system, then the surge current taken by the PO needs to be considered.

The "Maximum limiting voltage" at specified surge current is the usual parameter for evaluating voltage limiting capability of an MOV. The interaction between the MOV and PO in terms of surge current division it not commonly done because the PO surge impedance is often not known.

12.3.2 Impulse withstand capability

In functioning as a surge protective component, the MOV has to withstand the specified current surges. Surge durations vary from short (high current) ones to long (low-current) ones. Generally, an 8/20 current is regarded as short impulse, while 10/1000 or 10/350 or 2 ms rectangular currents are regarded as wide impulses. Different impulse durations and applications have different effects on MOVs, making it necessary to have ratings for "maximum single impulse current" and "repetitive impulse current" specified separately for short impulse (denoted "S") and for wide impulse (denoted "L").

The ratings classifying impulse withstanding capability include:

1) Maximum impulse current (one time)–$I_{MS,}$ I_{ML}.
2) Repeated impulse current (10 or 15 times) $I_{RS,}$ I_{RL}.
3) Rated impulse power P_0 (test current-wide impulse).
4) Maximum impulse energy E_M (test current-wide impulse).

The four test items mentioned above are covered by acceptance testing and delivery testing that is performed on a few selected samples. During the manufacturing processing, all semi-finished units should have to pass impulse aging and screening tests. The main aim of impulse aging and screening testing is to discover and reject those units that may be premature failures, and to further improve the impulse endurance of good quality units.

12.4 Operational performance related to TOV endurance state

MOVs that are intended for power circuits uses should have ratings and characteristics related to the TOV condition. Unfortunately, at present there is no consensus on what those component parameters are. For AC power systems, [b-IEC 60364-4-44] provides generic safety requirements for electrical installations in the event of voltage disturbances and electromagnetic disturbances. Here are two component proposals coming from manufacturing companies.

- TOV endurance voltage, U_{TOV}

The specified maximum power frequency voltage, U_{TOV}, is applied to the MOV for 5 s +0.5 s, –0 s followed by the 15-min application of the MOV MCOV, which shall show a decreasing temperature as it recovers from the U_{TOV} stress. The transition from U_{TOV} to MCOV shall be less than 100 ms.

This rating is intended for co-ordination with AC power system values.

- TOV withstanding energy, E_{TOV}

This rating is the average energy, E_{TOV}, deposited into an MOV prior to it going into thermally runaway when a specified AC power frequency source is applied. The AC source has a voltage that is able to producing an initial current of about 0.2 A/cm^2 into the MOV together with a prospective short-circuit current of ≥10 A. The energy value shall be measured with an accuracy of ±3%. The test is performed on three samples, the average energy of the three shall be not less than the specified E_{TOV} value.

12.5 Impulse life

12.5.1 Impulse life curves and impulse life equations

The impulse life curves of MOV, also termed impulse peak current de-rating curves, expressed the quantitative relationship between three variables of maximum impulse current peak (I_P), equivalent rectangular pulse width (τ), and impulse life numbers (n). Generally, the τ ranges from 20 µs to 10 ms, the n ranges from 1 time to 10^6 times

It has been demonstrated that the accumulated failure rate of MOV's impulse life tests is in accordance with the Weibull distribution function, from which three variables of characteristic life can be obtained which are termed respectively:

1) Median life n_{med}, at which half of the units concerned failed.
2) Average life n_{av}, an average value of the life times among all units concerned.
3) Guaranteed life n_{gua}, or minimum life times among all units concerned

Therefore, there are three types of impulse life characteristic, which may be expressed as curves or as equations.

Figure 27 and Figure 28 show example of impulse life curves which are identical, but expressed with different coordinates. Figure 27 shows against time $\log I_P = f(\log\tau)_{n-C}$ is straight lines of good linearity, but Figure 28 shows against repetitions (n) the linearity of the line $\log I_P = f(\log n)_{\tau-C}$ is poor when n is less than 100.

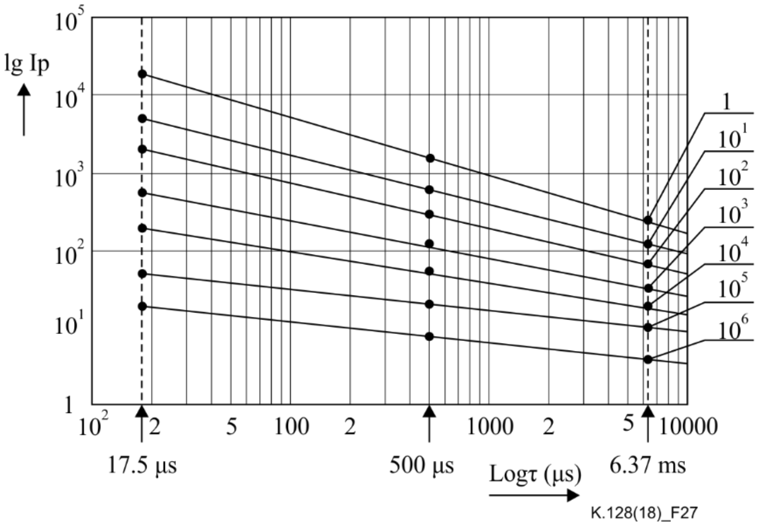


Figure 27 – Impulse life curves expressed as log*I*P = f (logτ), *n*=constant

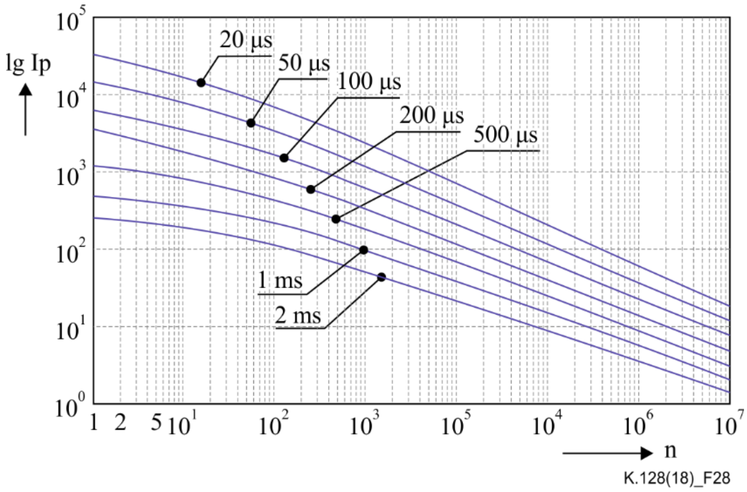


Figure 28 – Impulse life curves expressed as log*I*P= f (log *n*), τ=constant

The curves in Figure 27 can be expressed as equation 28,

$$LogI_P = B_{\mathrm{n}} - b_n \log\tau = B_n - \log\tau^{b_n}, n = cons\tan t \tag{28}$$

The curves in Figure 28 can be expressed as equation 29

$$LogI_P = A_\tau - a_\tau \log n = A_\tau - \log n^{a_\tau}, \tau = cons\tan t \tag{29}$$

It is clear that all impulse life characteristics of an MOV can be expressed by the two equations of 28 and 29, or in other words, by the four variables of A_τ, a_τ, B_{n}, b_{n}. The aim of the impulse life test is to establish life data, and from the results the four variables can be obtained via calculations

12.5.2 Procedure for determination of MOV's impulse life characteristics

The key steps of this procedure are listed below:

The impulse life test plan should cover

1) Three impulse waveforms for the life test

   which are τ_S= 20 µs, τ_M= 200 µs, τ_L=2000 µs.

2) Two peak current for each waveform used

   The high-level current peak I_H corresponds roughly to n=100 at interval Δt= 60 s, The low-level current peak I_L corresponds roughly to n=10,000 at interval Δt= 20 s,

This means 6 sample groups shall be tested under the stress conditions of [$\tau_{(S)}$, I_H], [$\tau_{(S)}$, I_L], [τ_M, I_H], [τ_M, I_L], [τ_L, I_H], [τ_L, I_L], with each group consisting of 20 samples.

3) All samples shall be of the same design (including nominal varistor voltage, voltage gradient, and sizes), using the same materials and the same manufacturing processes.

Perform impulse tests to failure and analyse the results

1) Failure criteria

   varistor voltage in any direction has dropped by more than 10%, and/or

   breakdown or flashover happened during impulse applications.

2) Testing of each group is completed when all group samples have failed.

3) Fit the test result data of each sample group to the Weibull distribution function to find the three life times n_{med} , n_{med} , n_{gua}

4) Calculate the six n values obtained from six groups of sample for four variables of A_τ , a_τ , B_n , b_n , herein n refers to any one of the [n_{med} , n_{med} , n_{gua}]

13 Application examples

13.1 Introduction

MOVs are used in a vast number of electric and electronic applications. This clause covers a few of the most common applications which are:

- Operation principles of overvoltage suppression and surge current diversion.
- Classification in terms of application and basic requirements for protective systems.
- Circuit connection mode.
- Field check and replacement.

13.2 Operation principles of a basic overvoltage protective system

13.2.1 Basic overvoltage protective system

The basic overvoltage protective system with power distribution can be considered as consisting of four elements: system voltage source, impulse overvoltage source, protective component(s) (MOV) and the PO. To achieve PO protection, the MOV used must satisfy the PO and system needs.

13.2.2 The principle of voltage suppression

In an overvoltage protective system, the MOV is always connected in parallel with the POs. According to The venin's theorem, the system source and impulse source are represented by a series combination of an equivalent electromotive force (emf) and source impedance (Z_S), making emf=U_0+U_{OV}. In most cases, the input impedance of the PO is much higher than the effective resistance of the MOV during the impulse, hence little impulse current enters the PO. Under such circumstances, the voltage on the MOV (U_V) and the impulse current peak passing the MOV can be found by use of a graphic method or by solving the two equations below:

$$U_V = U_{V0} \times I_V^{\,B} \quad \text{(MOV's impulse V-I formula)}$$

$$U_V = U_S - I_V \cdot Z_S \quad \text{(Load line of source resistance)}$$

13.2.3 The principle of surge current diversion

When the input impedance of the protected object, PO, is comparable with the MOV's resistance during the impulse, there must be some impulse current entering the PO. The three current components of I_S, I_{VR} and I_{PO} can be easily measured for example in case of Figure 29, which is a standard AC to DC power circuit.

In order to suppress incoming impulse overvoltages that may occur at AC input port, an MOV (VR) of Φ=14 mm, U_{n0}=430 V is installed. In this case, the measured input resistance of the PO was 1.76 Ω. If the 8/20 current is applied to the AC input port, then the current share between VR (I_{VR}) and the PO (I_{PO}) can be calculated after the resistance formula of the VR has been established.

VR resistance formula

$$R_{VR}=10^y$$

where:

$$y=2.96-1.18\times\log I+0.0565\times(\log I)^2$$

Input resistance $R_{in}=R_{PO}=1.76$ Ω

For the outcome of the calculation, see Table 2.

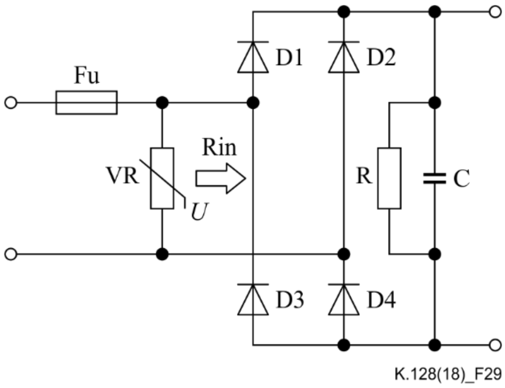


Figure 29 – Impulse overvoltage protection using MOV VR

Table 2 – Current sharing between VR and PO

Current, I_{VR} (A)	20	50	100	200	500	1000	2000	3000
Voltage V_R (V)	662.9	656.5	669.9	699.8	768.7	848.2	958.2	1014
$I_{P.O}=V_R/1.76$	376.6	373	380.6	397.6	436.8	481.9	544.5	591.1
$I_S=I_{VR}+I_{P.o}$	396.6	423.0	480.6	597.6	936.8	1482	2544	3591
Ratio I_{VR}/I_S	0.05	0.12	0.21	0.33	0.53	0.67	0.79	0.84
Ratio I_{PO}/I_S	0.95	0.88	0.79	0.67	0.47	0.33	0.21	0.16

It is clear that at the low end of the incoming impulse current, that most of it enters into the PO, which may cause electromagnetic compatibility (EMC) problems or harm other components which is not desirable.

13.3 Classification of applications of MOV's and standards requirements

At present, there is no definite classification for MOVs; according to their main usages, MOVs may be roughly used for:

- Electric power system protection against both lightning and switching surges. This application area is vast and varied.
- Signal and data networks.
- Electrostatic discharge suppression, especially the surface mount type SMV MOV.
- Absorbing magnetic field energy when motors or generators are turned off.
- Noise suppression of micro-motors (ring-shape varistor).
- Transient equi-potential bonding of normally unearthed conductors.
- Other special utilization

In term of protective effects, the overvoltage protective systems using MOVs play an important role of ensuring protected object(s) meet three types of standard requirements:

1) Insulation coordination requirements (e.g., [b-IEC 60664])
2) Surge immunity requirements (e.g., [b-IEC 61000-4-5] and [ITU-T K.77])
3) Safety requirements (e.g., [b-IEC 62368-1])

13.4 Connection modes of MOV in application circuits

13.4.1 Protective circuits for two-wire system

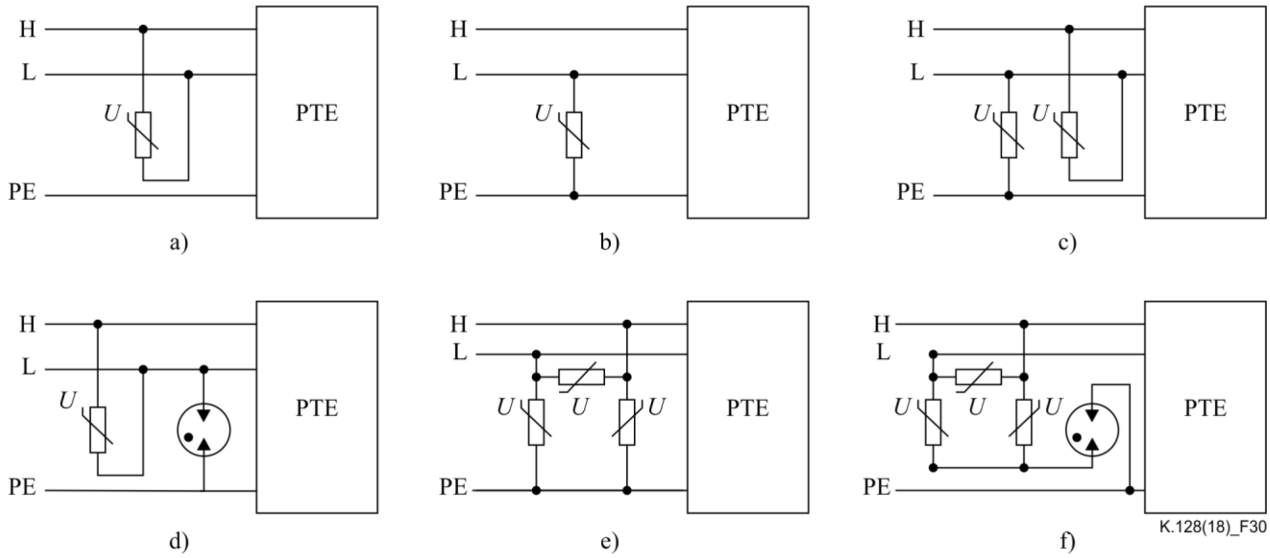


Figure 30 – Two-wire powering system protective circuits (H=live, L=neutral, PE=protective earth, PTE=protected terminal equipment)

13.4.2 Special functions of MOV in electric and electronic circuits

Besides limiting transient overvoltages, an MOV can also be used as a special circuit component, three instances are given below:

1) MOV functions as a voltage stabilizer in high voltage and small current DC circuits.
2) MOV functions as a voltage sensing component.

In Figure 31 the MOV VR functions as a voltage sensing component in an AC constant current circuit that drives a constant current into the load via an L-C-L network. The VR is in OFF state in normal operation, in case of open-circuited of the load, the voltage U_{out} goes up greatly and the VR turns conduction that drives a control circuit to turn off the switch S1.

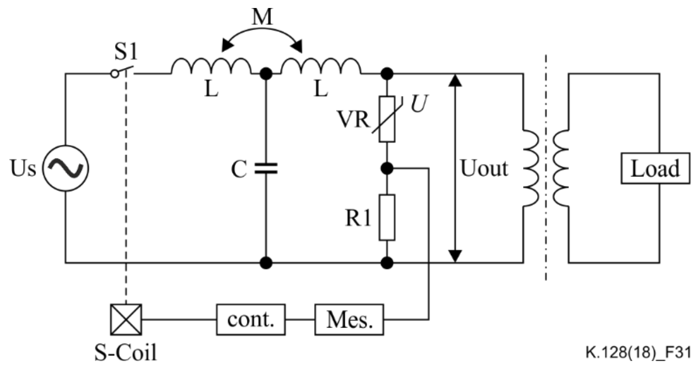


Figure 31 – Varistor VR acts as the voltage sensing component to stabilise the voltage

3) MOV functions as a voltage equalizer, Figure 32 is an example.

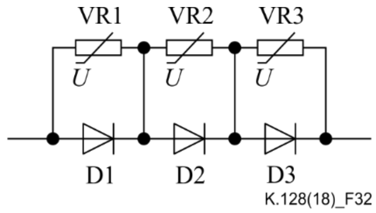


Figure 32 – MOVs equalising the reverse diode voltages of a series diode chain

13.5 Quantitative relationship between voltages of the MOV for power circuitry protection

Figure 33 shows the relationship between the different voltage parameters relevant to MOV power circuit protection. Unless otherwise specified these parameters should meet the criteria given by equations 30 to equation 34.

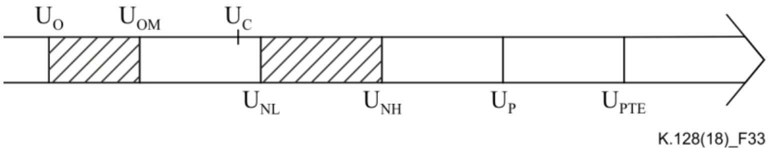


Figure 33 – MOV voltage parameters relevant to power circuit protection

U_{PTE} – Max. allowable surge voltage on the protected equipment

U_P – Protection level of the varistor used

U_{NH} – Top limit of the varistor voltage tolerance

U_{NL} – Low limit of the varistor voltage tolerance

U_C – Maximum continuous voltage AC

U_{OM} – Possible maximum value of the system voltage

U_O – Nominal system voltage

1) The protection level U_P of the MOV and the maximum permitted surge voltage U_{PTE} of the protected terminal equipment (PTE) should be in accordance with equation 30. The factor (0.8～0.9) aims to counteract the effects of residual voltage increment cause by MOV's degradation and by the voltage on the connecting wires between the MOV and the PTE.

$$U_P \leq (0.8\sim0.9)U_{PTE} \tag{30}$$

2) The top limit U_{NH} of the varistor voltage tolerance and the protection level U_P of the selected MOV should be in accordance with equation 31.

$$U_{NH} < U_P / R_{RES} \tag{31}$$

Where: R_{RES} is the residual voltage ratio of the selected MOV at specified pulse peak which is available from pulse V-I characteristic formulae of the MOV.

3) From viewpoint of production, at least 5% tolerance should be allowed for varistor voltage, so that:

$$U_{NL} < 0.95\ U_{NH} \tag{32}$$

4) From viewpoint of service life, the low limit U_{NL} should be not less than the MCOV

Power frequency circuitry: $U_{NL} \geq 1.41 U_C$

DC power circuitry: $U_{NL} \geq U_{CD}$

Other power circuitry: $U_{NL} \geq U_{Cx}$

5) According to clause G.10.2 of [IEC 62368-1], the MCOV of an MOV should be not less than 1.25 times U_R, the U_R refers to the rated voltage of protected equipment or the upper limit of the rated voltage range.

$$U_C \geq 1.25 U_R \tag{33}$$

Generally speaking:

$$U_C \geq k U_{0M} \ (k > 1) \tag{34}$$

Where: U_{0M} is the possible maximum value of the system voltage, the factor k depends on the voltage stability of the system into which the MOV being connected, the smaller system voltage variation corresponding to smaller factor k.

There are two basic conflicts involved in application design of MOVs:

- Conflict 1: low limiting voltage needs high non-linearity
  - high energy rating needs low non-linearity
- Conflict 2: long service life and high reliability under MCOV and TOV stresses needs high varistor voltage U_N,
  - low limiting voltage needs low U_N

Therefore, there has to be a trade-off between them.

13.6 Series connection and parallel connection examples

13.6.1 Series connection

MOVs are connected in series to have a higher voltage rating, or to achieve higher performance.

In Figure 34 most of TOV event voltage will occur across VRL, while during an impulse event most of the voltage will be across VRh due to conduction of the gas discharge tube (GDT).

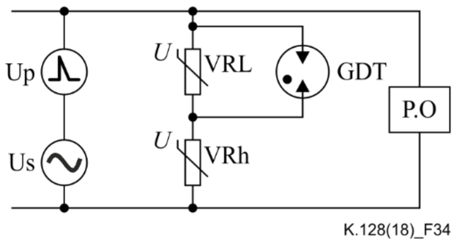


Figure 34 – Improved TOV endurance by series connection of high α MOV (VRh) and a low α MOV (VRL)

13.6.2 Parallel connection

Parallel connection of one or more units is often used in MOV technology, the aim of which is:

- to reduce residual voltage, or
- to increase the withstanding ratings of impulse current or energy, or
- to provide back-up protection, or
- to provide special performance.

The paralleled units may or may not be identical. The prime requirement of a parallel assembly is to achieve the correct current sharing between each individual unit so that the rated values are not exceeded for the entire service life. A design approach can be to calculate, using the V-I characteristic formulas, the current sharing over a range of impulse voltages to check that the specified ratings are not exceeded and the required current capability is achieved. The example below shows how this is done.

In this example the parallel assembly consists of two units that have the below impulse V-I formulas for a 8/20 current peak range of 30 A to 20 kA. The maximum allowable current peak is 40 kA 8/20 for Unit 1, and 3.5 kA 8/20 for Unit 2.

Unit 1, 34 mm×34 mm, U_{n0}=620V, $U_1 = 1702 \cdot I_1^{B_1}$, $B_1 = -0.247 + 0.0544 \times \log I$

Unit 2, φ10 mm, U_{n0}=560V, $U_2 = 1091 \cdot I_2^{B_2}$ $B_2 = -0.181 + 0.0666 \times \log I$

Using equation 35, two V-I formulas result from either using x_1 or x_2 for x. Using eight selected voltages from 950V to 1650V, the current sharing of the two units can be calculated. The results are given in Table 3

$$I = 10^x \tag{35}$$

where:

$$x_1 = \frac{0.247) + \sqrt{(0.247)^2 + 4 \times 0.0544 \times \log(U/1702)}}{2 \times 0.0544} \tag{36}$$

$$x_2 = \frac{0.181 + \sqrt{(0.181)^2 + 4 \times 0.0666 \times \log(U/1091)}}{2 \times 0.0666} \tag{37}$$

Table 3 – Calculated current sharing

Impulse voltage （V）	Current in Unit 2 I_2 （A）	Current in Unit 1 I_1 （A）	Total current $I_2 + I_1$ （A）	Current ratio I_1/I_2
950	216.1	958.9	1175	4.43
1050	422.9	2591.	3014	6.13
1150	695.4	4974	5669	7.15
1250	1037	8201	9238	7.91
1350	1449	12344	13792	8.52
1450	1932.	17461	19393.	9.04
1550	2488.	23600.	26089	9.48
1650	3117.	30802.	33919	9.88

It is seen from Table 3 that:

- If the total current is about 26 kA (greater than the expected maximum value of 20 kA), the current in Unit 2 is less than 2.5 kA while its rating being 3.5 kA, so it is safe.
- The current ratio of Unit 1 to Unit 2 is increasing with total current increasing.

Appendix I

Peak displacement and negative dynamic resistance

(This appendix does not form an integral part of this Recommendation.)

These peak displacement and negative dynamic resistance behaviours are due to the MOV non-linearity and can be mathematically explained by [b-Wang], page 56.

In the case of the peak displacement as current (*I*) through an MOV is a time variable, its resistance (*R*) is also a time variable, making the voltage rate (d*U*/dt) expression:

$$\frac{dU}{dt} = \frac{d(I \times R)}{dt} = R\frac{dI}{dt} + I\frac{dR}{dt} \tag{I.1}$$

If $R\frac{dI}{dt}$ is plus, $I\frac{dR}{dt}$ must be minus, or vice versa.

At current peak point $\frac{dI}{dt}$ must be zero, hence

$$\frac{dU}{dt} = I\frac{dR}{dt} \tag{I.2}$$

At voltage peak point $\frac{dU}{dt}$ must be zero, hence

$$R\frac{dI}{dt} + I\frac{dR}{dt} = 0 \tag{I.3}$$

Equation I.2 and equation I.3 cannot be fulfilled at the same time instant, which why the peak displacement happens.

For the case of the negative dynamic resistance the following incremental equation can be written:

$$du = d(i \times r) = r \cdot di + i \cdot dr \tag{I.4}$$

Taking dr always having an opposite sign of di into account, the following conclusions can be reached:

If $|r \cdot di| < |i \cdot dr|$, then du and di are in the opposite sign, i.e., negative dynamic resistance.

If $|r \cdot di| = |i \cdot dr|$, then du =0, the voltage remains unchanged despite the current variation.

If $|r \cdot di| > |i \cdot dr|$, then du and di are in the same sign, i.e., positive dynamic resistance, which is the expected MOV operation.

The above discussions show that both the peak displacement and the negative dynamic resistance are the result of the MOV's resistance non-linearity.

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Printed in Switzerland
Geneva, 2018