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

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Recommendation ITU-T K.128

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), intended for the protection of exchange and outdoor equipment, subscriber or customer equipment and telecommunication lines from surges.

Keywords

metal oxide varistor; voltage limiter; modelling; non-linearity index; operating states; surge; degradation; application examples

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Recommendation ITU-T K.128

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

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.

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. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

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

3. Definitions

This Recommendation uses the following [K.77] terms:

3.1 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 .

3.2 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.

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

3.4 combination impulse (1.2/50-8/20): Impulse with open-circuit voltage of 1.2/50 μ s (T_1/T_2) and short-circuit current of 8/20 μ s (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 .

3.5 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.

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

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

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.

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

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

3.7 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.

3.8 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.

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

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

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

3.10 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.

3.11 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.

3.12 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.

3.13 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.

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

3.15 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.

3.16 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.

3.17 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.

3.18 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.

3.19 long (short) duration impulse: An impulse with an impulse width $\tau \geq 100 \mu\text{s}$ is called a long duration impulse, in contrast, an impulse of $\tau < 100 \mu\text{s}$ is called a short duration impulse.

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

3.20 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).

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

3.22 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).

3.23 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.

3.24 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.

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

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/cm².

3.25 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.

3.26 rated impulse energy (W_m): 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.

3.27 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.

3.28 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} .

3.29 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} .

3.30 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.

3.31 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.

3.32 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.

4. Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

ESD	Electrostatic Discharge
GDT	Gas Discharge Tube
LPF	Low Pass Filter
MCOV	Maximum Continuous Operating Voltage
MOV	Metal Oxide Varistor
PO	Protected Object
PS	Power Source
SMD	Surface Mounting Device
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 surge protective component (SPC). Generally, the voltage limiting characteristic comes from the use of a ZnO ceramic element, although other compounds like $SrTiO_3$ and SnO_2 can be used.

NOTE— Early documents [b-Wang 1], [b-Wang 2] referred to the varistor as a “voltage dependent resistor (VDR)”, and described 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 MOV is monotonically increasing with current [b-Panasonic 1].

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, 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)).

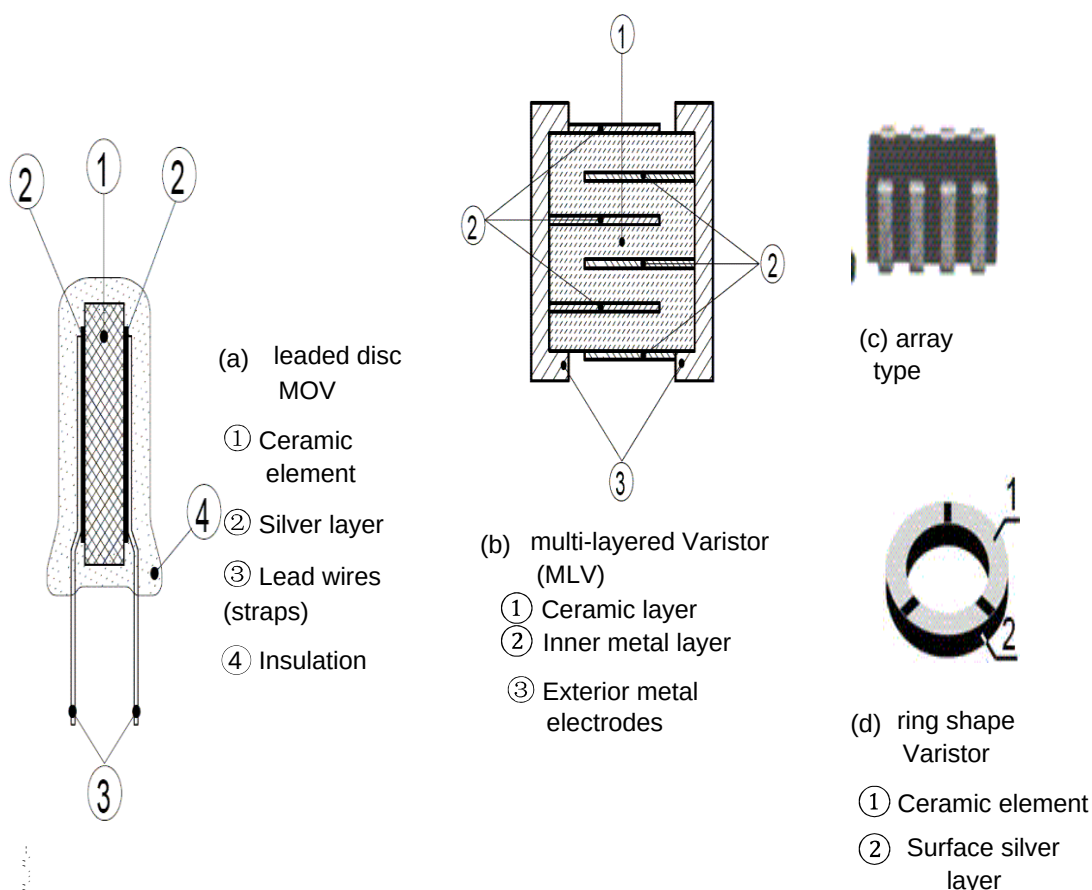
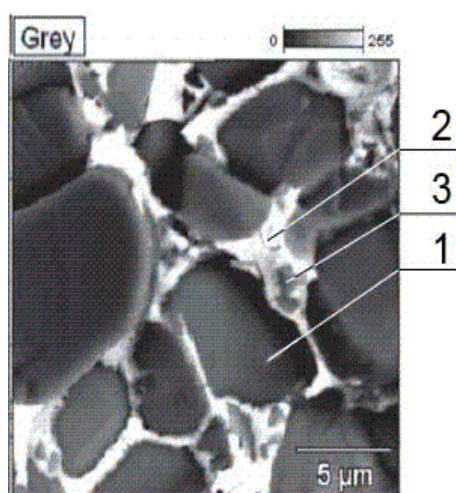


Figure 1—MOV form factors

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 —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, that means it is a good conductor. The grains play three major roles in MOV operations, i.e. electric conduction, heat conduction, and energy absorption. The average size of the ZnO grains range from less than 10 μ m to more than 100 μ m for commonly used MOVs.

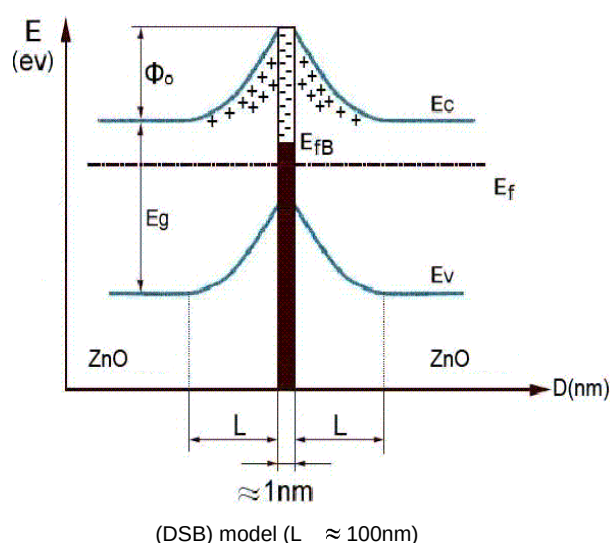


Figure 3— Double Schottky Barrier (DSB)

At an intimately contact portion of two grains, there is a very thin inter-granular film that is about 1nm thick, see Figure 3. Within this film there are very large number of electrons which are trapped from the adjacent ZnO grains resulting in a space charge (or depletion) regions at each side of the 1nm-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 Barrier (SB) 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-Bi₂O₃ based varistor, or 1.4V for a ZnO-P₂O₃ based varistor, which is almost independent of the ceramic formulations and fabricating processes.

The micro structure 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 micro structure 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 MOV 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

$$U = CI^\beta \quad (5)$$

$$I = DU^\alpha \quad (6)$$

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, $\alpha = 1/\beta$, C and D – constants.

A linear resistor has $\beta = \alpha = 1$. A non-linear resistor that is voltage limiting has $\beta < 1$, $\alpha > 1$ and a non-linear resistor that is current limiting has $\beta > 1$, $\alpha < 1$.

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

$$\alpha = \frac{U/I}{dU/dI} = \frac{R_v}{R_d} \quad (7)$$

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

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

or

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

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 $[1\text{mA}, 0.1\text{mA}]$. Sometimes the current range of $[2I, I]$ is defined, and the α obtained is denoted as “ α_{2I} ”.

7.1.4 Nonlinearity index α variation in stand-by

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

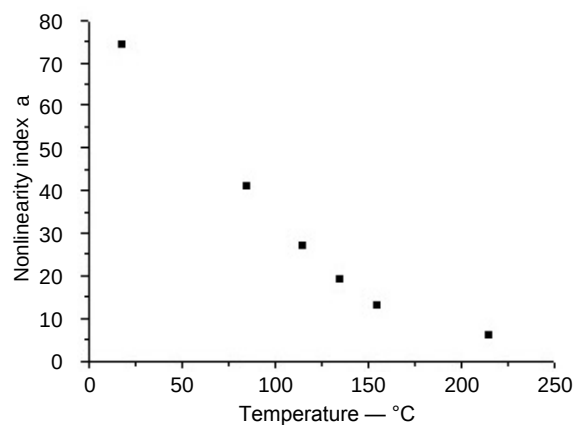


Figure 4—Example of stand-by α decreasing with increasing temperature

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 d.c. region ranges between 20 to 100.

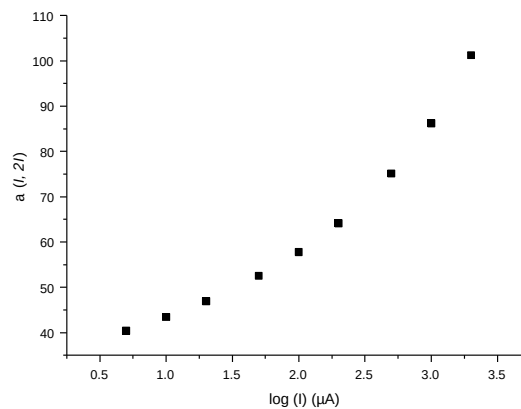


Figure 5—Example of $\alpha(I, 2I)$ increasing with increasing current

7.1.5 Nonlinearity index α variation in voltage limiting

Figure 6 shows that the index $\alpha_{2I}(I, 2I)$ of a $\phi 14$ 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 $\alpha_{2I}=60$, while for $I=8$ kA, $U=2.6$ kV and $\alpha_{2I}=8$. Generally, the MOV's lowest value of α_{2I} at its maximum rated 8/20 current falls towards 2 to 3.

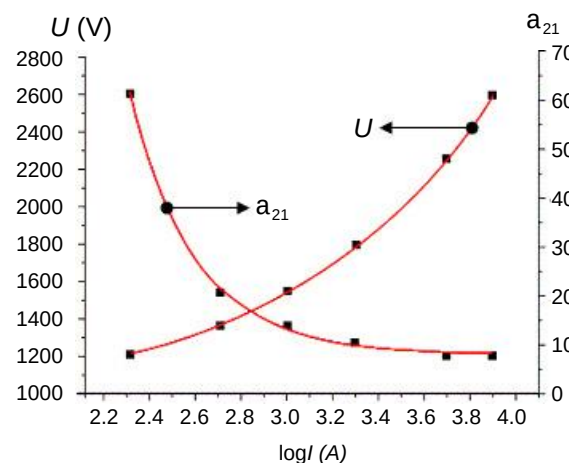


Figure 6—MOV voltage (U) and α_{2I} variation with 8/20 peak current (200 A to 8 kA)

7.2 Resistance formula

7.2.1 General

Reference [b-Panasonic 1] 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 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.