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Forward

This document is the third draft of the Application of Metal Oxide varistor (MOV) which is one part of “Handbook on Application of Surge protective Components and Surge Protective Devices (K.appspc.)”

The first draft of the Application of Metal Oxide Varistor TD 522 has been discussed during the WP1 meeting in Geneva on November 2010. The contribution C 295 which proposed modifications on TD 522 has been discussed during the WP1 meeting in Geneva on April 2011.

After April 2011 meeting, the editor prepared the second draft, the proposals in C295 are accepted, and some comments from Chinese Engineers also included.

Some new achievements in varistor technology have been added to this third draft.

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Part 1 Physical and electric foundations

1.1 What is MOV?

MOV is an semiconducting compound component made by using ceramic technology, its main materials are metal oxides, therefore commonly called metal oxide varistor (MOV).The primary property of this kind of component is that its resistance decreases rapidly with increasing current following through it and having a basically symmetrical nonlinear volt-amp(V-I)characteristic, like a pair of back-to-back connected zener diodes. The Table 1.1 showed an example, the resistance of this MOV sample drops from 9MΩ to 0.21Ω as the current through it increases from 10μA to 1000A that corresponds to a current range of about 8 decades, while the voltage variation only 2.3-fold, hence the MOV is a nonlinear component of voltage stabilizing or voltage limiting type. Therefore the main application fields of the MOV are as lightning arresters and surge protective devices in low voltage systems

Table 1.1 Example of an MOV‘s resistances (Type14D101)

Note ：The current refers to d.c, if I≤1mA, or to 8/20 impulse if I≥1A,

Current , I	10μA	100μA	1mA	1A	10A	100A	1000A
Voltage, U	90V	96V	100V	125V	155V	178V	210V
Resistance ,R	9MΩ	960kΩ	10kΩ	125Ω	15.5Ω	1.78Ω	0.21Ω

Figure 1.1 makes a comparison of V-I property between MOV and linear resistor, It is seen that the voltage of a linear resistor varies with the current linearly, while the V-I curve of an MOV can be divided up into two segments: when the voltage U is lower than “U_{BR}”, the current I is very small and the MOV behaves as if an insulator, when the voltage is higher than “U_{BR}”, the current goes up quickly with a small increment of the voltage, so it behaves as a conductor. The transition point between the two segments is termed as “ breakdown point ”, and the voltage “U_{BR}” is named “breakdown voltage”. It is noted that the voltage at the current of 0.5mA/cm^2 or 1mA/cm^2 is termed as breakdown voltage in research works, while the voltage at 1mA d.c.(U_N or U_{1mA}) is termed “varistor voltage” or “d.c. reference voltage” in product data sheets.

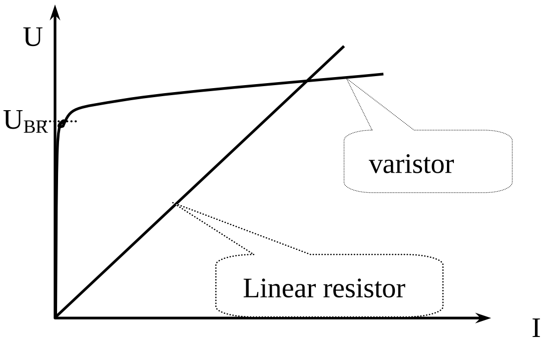


Figure 1.1 A comparison of V-I properties between MOV and linear resistor

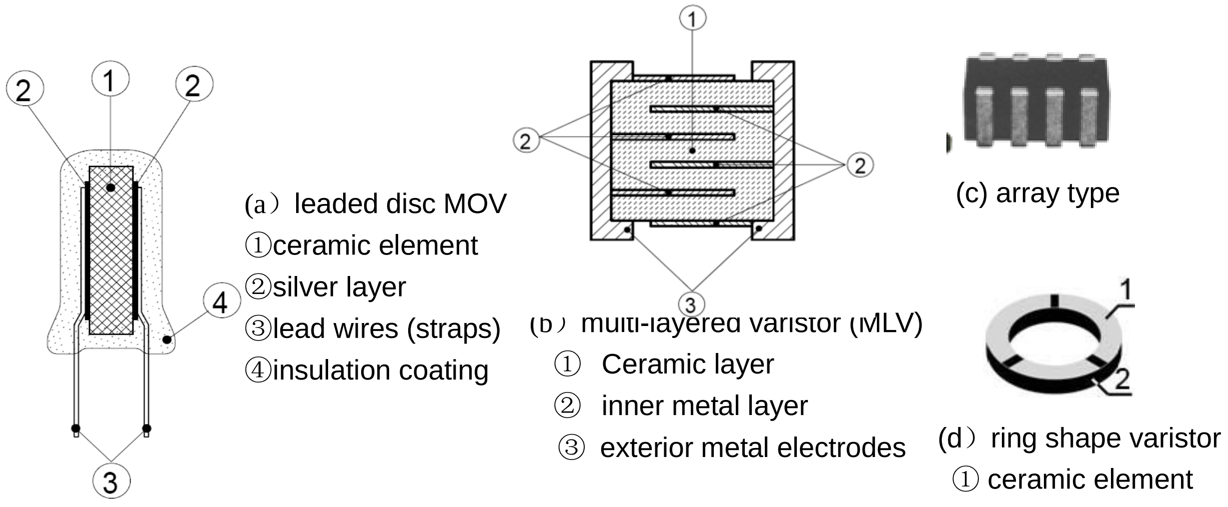
An MOV can be made of different types of materials such as ZnO, $S_r T_i O_3$, and S_nO_2, but the following discussion will focus solely on the ZnO-type, for the remaining types are negligible in markets

1.2 Macro-structures of MOV

Figure.1.2 shows some commonly used structures. According to the connection terminals, the MOV can be divided into leaded disc type (including wire, strap and screw terminal) and leadless varistor (SMV) for surface mount technology.

The ceramic element inside an MOV may be made from a single-layer disc or multi-layer chip, accordingly it is called single-layer variator (SLV) or multi-layer varistor (MLV). Sometimes several MOV components may be combined into one package which is called MOV array or multi-unit MOV.

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.



(a）leaded disc MOV
①ceramic element
②silver layer
③lead wires (straps)
④insulation coating

(b）multi-layered varistor (MLV)
① Ceramic layer
② inner metal layer
③ exterior metal electrodes

(c) array type

(d）ring shape varistor
① ceramic element
② surface silver layer

Figure 1.2 Typical structures of MOVs

1.3 Microstructure and origin of the nonlinearity

The special electric properties of nonlinearity of the MOV are the direct result of its microstructure. MOVs are made primarily of ZnO powder, and small quantity of additives (about 10% in weight) such as Bi, Sb, Co, Mn, and others. These powders of raw materials are made into an semiconducting ceramic body via typical ceramic processes. Figure 6.1.3 showed an electro-micrograph of the ceramic body, from which three substance phases can be found, they are ZnO crystal grains, grain boundary phase and some minute insulating grains mainly at triple points.

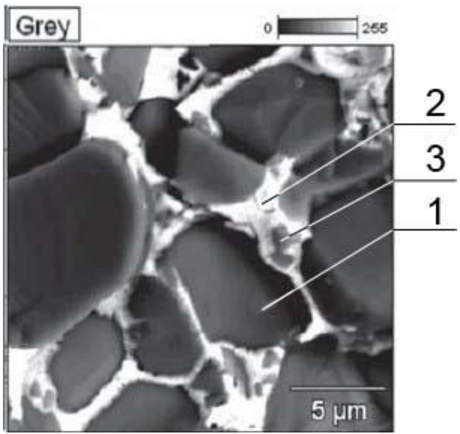


Figure 1.3.1 Typical microstructure
.1－ZnO crystal grain，
2－grain boundary phase,
3 -minute insulating grains

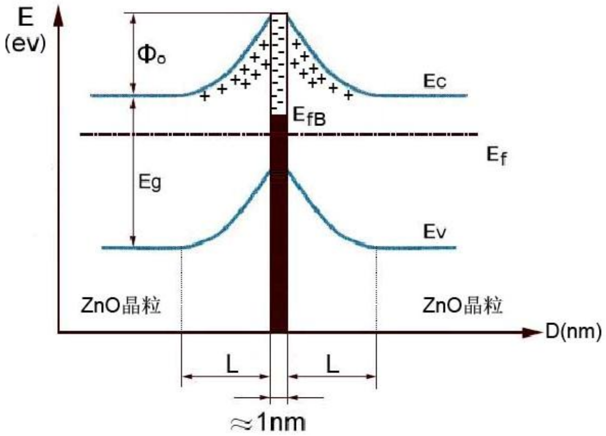


Figure 1.3.2 Double Schottky Barrier (DSB) model (L≈100nm)

The ZnO grains is n-type semiconductor having a resistivity as low as 1Ω-cm, that is a good conductor. The grains play three major roles in ceramic body: electric conduction, heat conduction, and energy absorption. The average size of the ZnO grains range from less than 10μm to more than 100μ m which control the voltage per mm thick.

At the intimately contact portion of two grains, electrostatic potential barriers are built-up, which form a highly insulating (electro-statically repulsing) region not more than 100 nm thick on each side of the ca. 1nm thick interface, see .Figure 6.1.3.2. These potential barriers are Schottky Barrier (SB) rather than PN-junction barrier. Because there is one SB on each side of the interface, so it is named Double Schottky Barrier (DSB)model.

The DSB model signifies that a ZnO-grain boundary-ZnO structure forms a micro-MOV unit whose breakdown voltage U_B is typically 3.2～3.4 V for a ZnO-Bi_2O_3 based varistor, or 1.4V for a ZnO-$P_{r2}O_3$ based varistor. It is should be stressed that the U_B is almost independent of ceramic formulations and fabricating processes.

1.4 Macro-properties- statistical representation of a large number of micro-MOV

MOV’s ceramic body may be considered to be a three-dimensional network with a large number of micro-MOV-unit acting in series-parallel combination between the two electrode layers. Accordingly, the macro-properties of an MOV should be the statistical representation of all micro-MOV-units inside the network. From this understanding of the MOV the following points are deduced:

1) The varistor voltage of an MOV component depends on the average size of ZnO grains and the thickness of the ceramic body. The smaller grain size and the thicker ceramic body result in more number of micro-MOV-units connected in series, and the higher varistor voltage accordingly.

2) The current handling capability of an MOV is roughly proportional to its surface area of metal electrode due to the number of paralleled micro-MOV-units can be deemed to be proportional to this area.

3) From the above points of 1) and 2), it is concluded that the power and energy handling capabilities of an MOV will be roughly proportional to the volume of the ceramic element. That is why the pulse energy absorption rating of MOV is much greater than that of P-N junction semiconducting devices, because the energy is dissipated by entire volume of the ceramic body, rather than by P-N junction alone in a P-N junction device.

Therefore a careful attention should be paid to the three significant parameters when making a choice of MOV which are varistor voltage, surface area of metal electrode, and thickness of the ceramic body (or voltage per mm thick)

1.5 Parameters to characterize non-linearity of a component

One of the following two equations expresses the voltage/current relation of a resistive component

$$U = CI^{\beta} \qquad (1.5.1)$$

$$I = DU^{\alpha} \qquad (1.5.2)$$

Where *I* – the current flows through the resistive component

U –the voltage across the resistive component at the current I

β – current index

α– voltage index ，α=1/β

A and D – constants

The resistive component with β=α=1 is named linear resistor or Ohm resistor，that with β≠α≠1 is a non-linear resistor or a non-Ohm resistor，that with β＜1，α＞1 is a voltage limiting type non-linear resistor；that β＞1，α＜1 is a current limiting type non-linear resistor。

From equation （1.5.2），the equation （1.5.3）can be deduced

$$\alpha = \frac{U/I}{dU/dI} = \frac{R_V}{R_d} \qquad (1.5.3)$$

Where：$R_V = U/I$ is named static resistance，$R_d = dU/dI$ is named dynamic resistance，or increment resistance。That means the voltage non-linear index α is a ratio of the static resistance to its dynamic resistance that is the physical meaning of α value.

Usually the V/I characteristic of MOV is expressed in $\log U = f(\log I)$ version, and the current index β signifies the slop of the curve $\log U = f(\log I)$,and the voltage index α signifies the reciprocal of the slop of the curve $\log U = f(\log I)$,see equation (1.5.4), that is the geometric meaning of α value

$$\beta = \frac{\lg U_2 - \lg U_1}{\lg I_2 - \lg I_1} = \frac{\lg(U_2/U_{1)}}{\lg(I_2/I_1)}, \quad \alpha = \frac{\lg(I_2/I_1)_{)}}{\lg(U_2/U_1)} \qquad (1.5.4)$$

It is mentioned that the equation (1.5.4) gives an average value of α or β in a current range of [I_2,I_1], usually d.c-α signifies the average α in the current range of［1mA～0.1mA]. Sometimes the range of [2I,I]] is defined, and such an α is denoted as “α_{2I}”.

1.6 Resistance formula, V-I characteristic formula and curves

The paper[] first presented a resistance formula of MOV, from which a V-I characteristic formula was easily deduced, and the related characteristic curves are plotted. They have been successfully used for practical engineering calculations regarding MOVs and SPDs due to following advantages

① It is applicable to d.c, a.c, and impulse operations of MOV.

② It can cover a current range of wider than two decades.

③ The deviations of the formula values from the measured values of voltage and current are generally less than 3%.

④ The test and calculation steps for determination of the formula constants are easy to do.

1)Resistance formula

The term of “Resistance” herein refers to a ratio of defined voltage value to defined current value of an MOV according to the following definitions

○d.c resistance: both the defined voltage value and defined current value shall be steady values

○ power frequency resistance: both voltage and current shall be steady average value of the plus peak and minus peak of the same cycle (Note:The voltage peak occurs at a different instant from that of the current peak)

○ impulse resistance: the voltage and current values shall be read at the same instant

The resistance formula (1.6.1) is a least-square fitting equation fitted to polynomial of logarithmic resistance (logR) versus logarithmic current (logI). It is obtained from n -pairs of tested values of voltage and current,the n shall be 3 at least, usually 5-9.

$$\log R = A_0 + A_1 \log I + A_2 (\log I)^2 \qquad (1.6.1)$$

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Where: A_0, A_1 and A_2 are constants that vary depending on particular MOV product(s)

2) V-I characteristic formula

By adding (logI) to both sides of equation (1.6.1), the V-I characteristic formula as equation (6.1.2) can be obtained

$$U = 10^{A_0} \times I^B \qquad B = 1 + A_1 + A_2 \lg I \qquad (1.6.2)$$

The formula (1.6.2) is used in case of the current value being known and the voltage value unknown, while in an opposite case, the formula(1.6.3) shall be used.

$$\mathrm{I} = 10^y \qquad y = \frac{-(1+A_1) \pm \sqrt{(1+A_1)^2 + 4A_2 \cdot \log(U/U_R)}}{2A_2} \qquad (1.6.3)$$

Sometimes the voltage ratio formula of $K_V = U/U_{1mA}$ is convenient for comparison purpose, in this case the formula (1.6.4) applies

$$k_v = \frac{10^{A_0}}{U_{1mA}} \times I^B \qquad B = 1 + A_1 + A_2 \lg I \qquad (1.6.4)$$

The formula of voltage non-linear index in a current range of [I, 2I], denoted as α_{2I} ,is also given ,as equation (1.6.5)

$$\alpha_{2I} = \frac{1}{B_I + (0.301 + \lg I)A_2} \qquad (1.6.5)$$

Where: B_I is the B value at the given current I.

3) V-I characteristic curves

Before presentation of above formulas the V-I property of an MOV were demonstrated solely by V-I characteristic curves, some of which are found to be not appropriate or incorrect based on today's understanding of the MOV, however they have been accepted by many engineers and leading to some mistakes, two prevailing curves are showed as Figure 1.6.1 and Figure 1.6.2 , and what inaccuracies with them are indicated as below

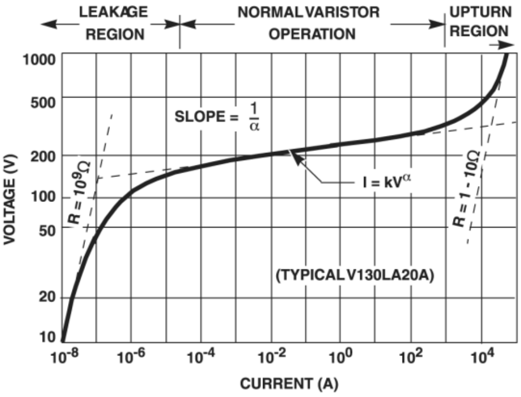


Figure 1.6.1, An early V-I curve cited by many previous papers [5]

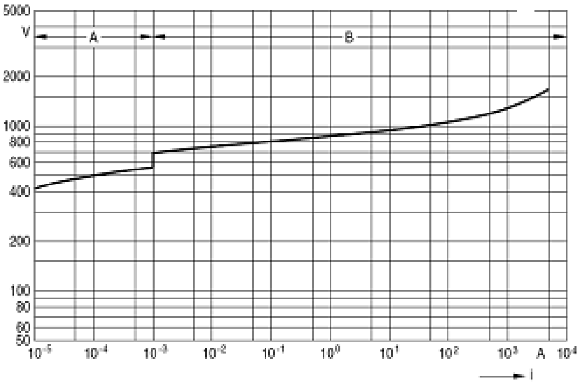


Figure 1.6.2 Max. leakage current ("A") and Max. clamping voltages ("B") in MOV's data sheet

① Generally the curve segment of leakage region is obtained by d. c. testing, while the segment of normal operation region is obtained by 8/20 impulse testing, it is impossible for the two segments connected with each other smoothly.

② There is a low limit value of available 8/20 surge current due to capacitance of MOV itself, hence a 8/20 voltage limiting property starting from 1mA pea (Figure 5) is impossible. For example, an MOV of 34×34mm ,U_{1mA}=600V, has a capacitance of about 1500pF, an average current of 90mA is needed to charge this capacitor up to 600V during 10μs (the front time of an 8/20 pulse).

$$I = C\frac{du}{dt} = 1500\times10^{-12}\times\frac{600}{10\times10^{-6}} = 90(mA)$$

Therefore to test this piece of MOV at the peak level less than 90 mA (8/20) will be impossible.

③The equation "$I=kV^{\alpha}$"(Figure 1.6.1) is not a sound formula for describing the V-I characteristic of entire normal operating region ,in which the α may vary from about 20 to 5 for most MOV.

④ The note of "R=1～10Ω" in Figure 1.6.2 is an error, because the right end point of the curve corresponded to a current of more than 10^4A, and a voltage of 1000V ,which signifies a resistance of less than 0.1Ω.

Practical V-I characteristic curves

What is practical characteristic curve like? Figure 1.6.3 gave an example. For the convenience of making a comparison, the voltage is scaled in voltage ratio $K_V=U/U_{1mA}$. Three curves are given which were tested respectively with d.c. current ranging from 10μA to 10mA , a.c.50Hz voltage source ranging from 3mA to 10A in peak, and 8/20 impulse current ranging from 200A to 20kA in peak. The V-I characteristic formulas available from the above tests are as below.

*For d.c curve : $K_V=0.781\times I^B$, B=+0.06372-0.00866×logI (current I in μA)

*For a.c. 50Hz curve : $K_V=1.081\times I^B$, B=+0.01592+0.0003×logI (current I in mA)

* For 8/20 impulse curve: $K_V=2.297\times I^B$, B=-0.19552+0.04671×logI (current I in A)

The values of non-linearity index α are also given in Figure 1.6.3 For example, the a.c. 50Hz curve has an α≈61 at low current end (a few mA), and an α≈55 at high current end (a few A).The highest value of α, which may be greater than 100, lies in a d.c. current range of several mA to tens of mA.

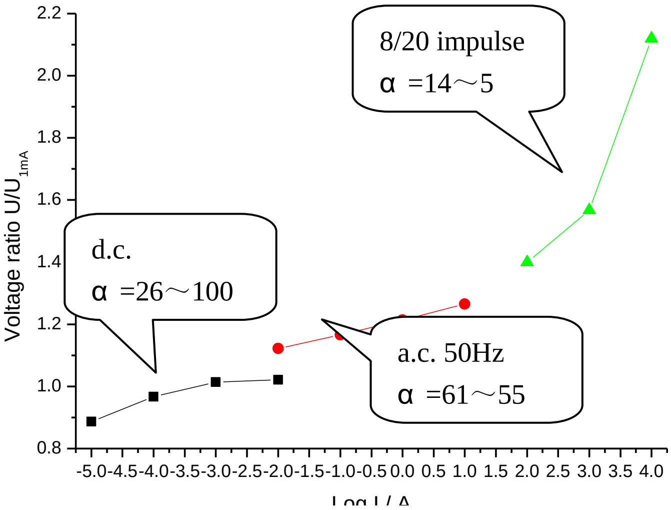
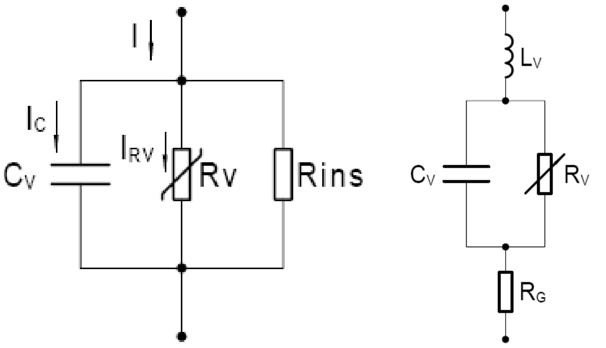


Figure 1.6.3 Practical V-I characteristic curves. The voltage is scaled in voltage ration $K_V=U/U_{1mA}$

1.7 Equivalent circuit

Similar to other electronic components, the main behavior of an MOV in electrical circuits may be represented by an equivalent circuit model. According to the need of circuit analysis, a few models have been reported, the models as Figure 1.7.1 are commonly used. Figure 1.7.1(a) is used for d.c. and AC analysis while Figure 1.7.1(b) is used for impulse behavior analysis. The components of the equivalent circuit are described below.



（a） suitable for d.c, and a.c （b）suitable for impulse

Figure 1.7.1 Equivalent circuit models of MOV

Non-linear resistance R_V

R_V is a representation of the non-linear resistance of an MOV which varies over a range of (0～∞). When an applied voltage is far below U_{1mA} of the MOV, R_V approaching "∞". When an impulse current peak is beyond about 6000A/㎝^{2}, R_V approaching zero.

Leakage resistance R_{ins}

R_{ins} consists of two parts in parallel, one is the leakage current through the volume of the ceramic body, and the other is the leakage current over the side surface of the ceramic body. For a good quality product ,R_{ins} should be so high that it can be omitted at standby operation state. However it has to be considered in such cases when the MOV is either exposed to a wet environment, or there is improperly matching of the ceramic materials with encapsulation material which can result in electro-chemical reactions between the two, causing the side surface leakage current to increase steadily with time.

Capacitance C_V:

It is known that a ZnO-ZnO grain boundary has some capacitance, the capacitance C_V of an MOV is the statistical representation of many grain boundary capacitors connected in series and in parallel. The value of C_V is inversely proportional to varistor voltage rather than inversely proportional to the thickness of the ceramic element ,as it is in an ordinary ceramic capacitor.

Linear resistance R_G:

The R_G consists mainly of ZnO grain resistances, secondary the contact resistance between "ceramic surface－silver layer －metal terminals". The R_G is quite low, ordinarily in milliohms , it should be taken into account only if the current is beyond （1000～2000）A·㎝$^{-2}$ where the non-linear resistance R_V dropped to such low values as small as R_G.

Inductance L_V:

The inductance of MOV's ceramic itself is extremely small. The L_V of an MOV consists mainly of terminal inductance which is about 1nH per mm lead wire. As for general lightning protection applications, the terminal inductance of standard leaded type of MOV may be not a concern The surface mount type MOV has an Inductance less than 1.5nH in total. It is mentioned that for most ordinary applications, the voltage increment of the leaded type MOV could be disregarded, but for the di/dt of the impulse current is far greater than that of 8/20 impulse.

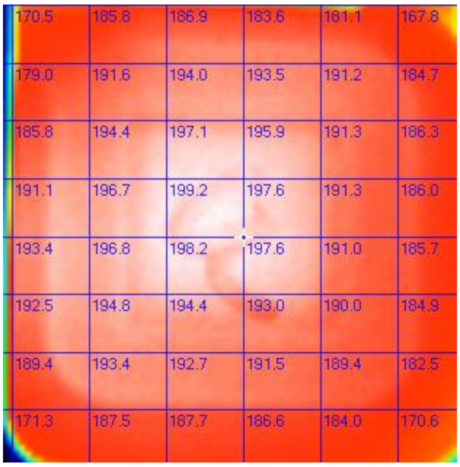
1.8. Current distribution inside ceramic body

Current distribution inside the ceramic body of an MOV is not uniform caused by limitations of present ceramic technology. Both current density and temperature vary from point to point within MOV body when an electric stress applied on it. Figure 1.8.1 and Figure 1.8.2 gave direct evidences for such an uneven distribution.

Figure 1.8.1 was a paper record taken from an experiment by sandwiching a very thin paper between two cut surfaces of a φ 32mm varistor ceramic, and followed by an impulse current test of 8/140μs-2kA . The current burns on the thin paper indicated locations with the high current density, while the non-scorched parts on the paper indicated locations with little or no current fllowing.

The thermal photograph as Figure 1.8.2 was taken from an MOV surface after it had been heated by applying a 50Hz a.c. current for a while .Any change in temperature from region to region correlates with varying current densities.

Figure 1.8.1 An experiment to show current diatribution whin a varistor



170.5	185.8	186.9	183.6	181.1	167.8
179.0	191.6	194.0	193.5	191.2	184.7
185.8	194.4	197.1	195.9	191.3	186.3
191.1	196.7	199.2	197.6	191.3	186.0
193.4	196.8	198.2	197.6	191.0	185.7
192.5	194.8	194.4	193.0	190.0	184.9
189.4	193.4	192.7	191.5	189.4	182.5
171.3	187.5	187.7	186.6	184.0	170.6

Figure 1.8.2 Surface temperature (℃) on an MOV

An uneven current distribution can harm varistor’s handling capabilities of power and energy, and it is also the origin of current concentration within MOV ceramic body.

Moreover the users should aware that the higher the α value is, the severer uneven current distribution will be. For example, if there are two portions (a) and (b) on the same varistor disc, and their varistor voltage is $U_{1mA\,(a)}=1.01U_{1mA\,(b)}$, then the current ratio of the two can be determined by equation (1.8.1) .

$$\frac{I_b}{I_a} = \left(\frac{U_{1mA(a)}}{U_{1mA(b)}}\right)^{\alpha} = (1.01)^{\alpha} \qquad (1.8.1)$$

If α=20, the current ratio will be $1.01^{20}\approx1.2$, If α=60, the current ratio will be $1.01^{60}\approx1.82$. In other words, to improving current uniformity inside the ceramic body, two aspects should be concerned, i.e, lessening both the voltage differences from point to point over the ceramic surface, and α value of the ceramic body.

1.9 Thermal properties of ZnO ceramic body

To know thermal parameters of ZnO ceramic body is indispensible for understanding the operations of MOV, particularly heat capacity, heat conductivity, and thermal coefficient of expansion

Heat capacity (c) is about 0.84J/G.K., which means a 0.84 J-energy is needed to raise the temperature of one- gram MOV body by 1K, By using this figure we will be able to know the temperature rise of an MOV if the energy deposited into the MOV body is known, or vice versa.

The ZnO ceramic body has a quite small heat conductivity which is about 0.057 W/cm.K

(0.057J/cm.K.s), roughly 1.5% of copper's heat conductivity. Such poor heat conductivity will aggravate the current concentration effect and thermal runaway of ZnO ceramic body.

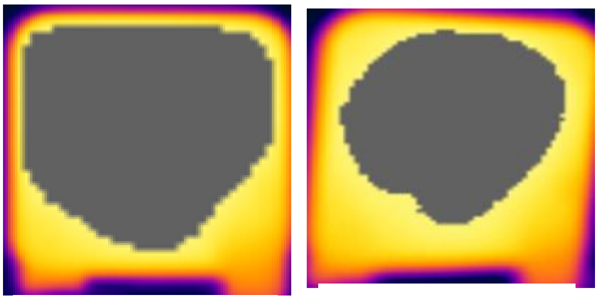
It is also a difficult problem that the ZnO ceramic body thermally matches its metal terminations properly due to the thermal coefficient of expansion of the former being only 18% of the latter ,which is the main cause of the ceramic body cracking or it being parted from its metal termination during repeated impulse current test or ambient temperature rapid change.

1.10 Current concentration effect

Current concentration signifies a process of an uneven current distribution being aggravation with time, via an interaction between electro-effects and thermo-effects. Generally, MOVs have a positive current temperature coefficient and a negative voltage temperature coefficient. This generates a positive feedback interaction between the variations of current and temperature at the "hot spot" on the MOV body, since a higher current causes a higher temperature which in turn causes an even higher current , so that more and more current pouring into the hot spot resulting in an increasing temperature and a decreasing area of the hot spot,

The behavior of current concentration effect is observed whenever the MOV subjected to impulse current stress or to power frequency current stress .

1) impulse current stress
The hot portion on an MOV body will have smaller area after having been exposed to an impulse of 10/350 than that exposed to an 8/20 impulse, despite of the same energy deposited into the MOV body. This is due to the longer duration of 10/350 current allowing the current concentration to develop. Figure 1.10.1 provided an evidence for this conclusion.



8/20- 40.8kA 1700V
1214J 88℃ portion

10/350-2. 76kA/920V
1270J 87℃ portion

Figure 1. 10. 1 Hot portion (within 5K) of an MOV
（34x34,U_{1mA}=513.6V）exposed to impulses

2) power frequency current stress
The temperature of the hot portion, caused by power frequency current stress, is rising with time, while the area is decreasing with time appearing a shrinkage process. A typical example is showed in Figure 1.10.2. The experiment was performed as that a sample of MOV (34×34mm, U_{1mA}=511V) was energized with a 50Hz a.c. voltage source, then

measuring the current peak (I_P) ,and the surface temperature at the moment of 27、50、and 78s after voltage application. The outcomes were as below.

current peak: I_P = 111、120、173 mA

maximum temperature of the hot portion: T_{max}= 83. 3、128. 8、189. 8 ℃

hot portion area ratio (%) : 61.0、58. 4、36. 4 %

Note: Hot portion area ratio was the ratio of the area of T_{max} ～(T_{max}-5K) to the total area.

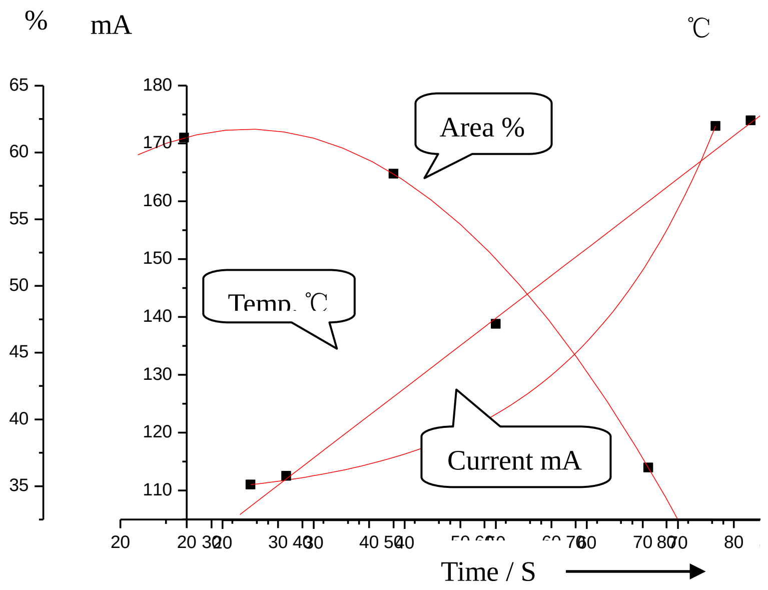


Figure 1.10.2　An example of current concentration effect with a.c. stress

In summary, the progression of the current concentration effect of an MOV is governed mainly by the following five factors: ① Initial uneven current distribution caused by an inhomogeneous microstructure of the MOV ceramic; ② time duration of impulse current or TOV stress applied; ③ voltage or current temperature coefficient and non-linearity (α-value) of the MOV ceramic; ④ geometry of the MOV ceramic (large size and big ratio of diameter to thickness may cause severe current concentration); ⑤ source impedance, because high source impedance will limit the current increasing pouring into the hot portion.

1.11 Thermal stability and thermal breakdown.

There are two possible ending of the current concentration progression, one is thermal stability and the other is thermal breakdown. They are mainly controlled by heat generation characteristic P= f(T) and heat dissipation characteristic Q= f(T), see Figure 1.11.1

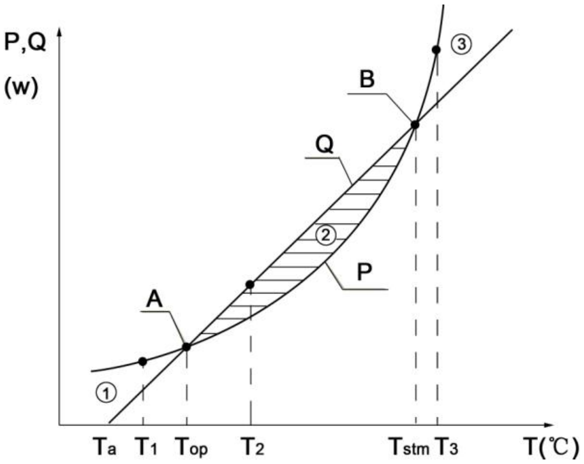


Figure1.11.1 heat generation characteristic P= f (T)
heat dissipation characteristic Q= f (T)

In Figure 1.11.1 the “T” refers to the temperature of the MOV body with a voltage stress U_{AP} applied on it, and T_a is an environment temperature. Because the resistance of the MOV decreases with its increasing temperature T, while the voltage U_{AP} remains unchanged, so that the heat generation power P increases with T in about an exponent manner, while the heat dissipation power Q increases with T in roughly a linear manner. Under proper conditions there are two intersection points “A” and “B” that divide the curves into three operation regions ①、②、③.

Within region ①, for example if $T=T_1$, because of P>Q at this point, the body temperature of the MOV goes up continually until $T=T_{OP}$ (point A) ,and at point A, we have P=Q, hence the body temperature remains unchanged.

As for region ②, for example if $T=T_2$, because of P<Q, the body temperature goes down continually until $T=T_{OP}$ (point A). That means the point A is a stable thermally equilibrium point.

While for region ③, for example if $T=T_3$, because of P>Q, so that the hot spot temperature will become higher and higher, along with the shrinkage of hot spot area, at last the hot spot being punctured. That means the point B is an instable thermally equilibrium point.

It is noted that, there may be only one, or none intersection point of the two curves if the environment temperature T_a and/or the applied voltage U_{ap} are too high, and in this case an proper operation mode of the MOV will be unavailable.

The characteristic curves like Figure 1.11.1 is of significance for thermo-protected MOV.

1.12 linearization of V-I characteristic

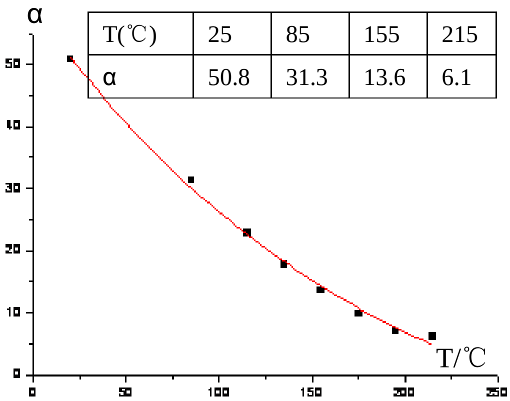
So called “linearization” signifies such a variation of the V-I characteristic of an MOV ,that its voltage index α is going down which may be or may not be recoverable. Three commonly seen linearization behaviors are presented as below.

1）Linearization caused by rising temperature

Figure 1.12.1 showed the index α（$U_{1mA}/U_{0.1mA}$, d.c.）of an MOV going down as its temperature (T) going up. It is reversible.

2) Linearization caused by a high impulse current

Figure 1.12.2 showed the index α_{2I}(I ,2I) of an MOV (φ14mm, U_{1mA}=738V) going down as the 8/20 current peak going up from 200A to 8kA. The variation of related residual voltage (U) was showed as well. It is seen that I≈200A, U≈1200V, α_{2I}≈60, while I≈8000A, U≈2600V, α_{2I}≈8. It is also reversible.



T(℃)	25	85	155	215
α	50.8	31.3	13.6	6.1

Figure 1.12.1 α ($U_{1mA}/U_{0.1mA}$) dropping with rising temperature (T)

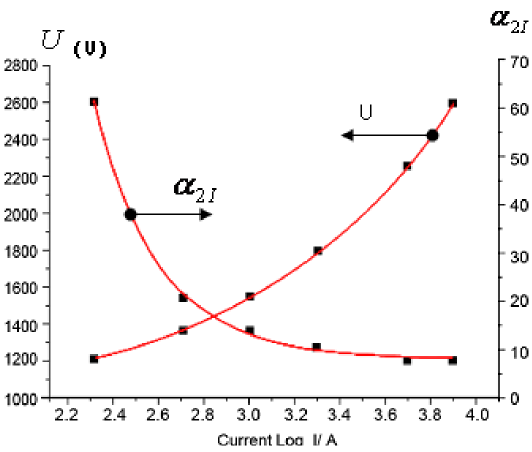


Figure 1.12.2 Residual voltage (U) and index α_{2I} vary with 8/20 current peak of (200A～8000A).

(34×34mm, U_{1mA}=644V) under such conditions that the impulse polarity remained unchanged, the interval between impulses was 25min, life-end criterion was the voltage U_{1mA} having fallen by -10% after the test, then two V-I characteristic formulas were detected respectively at d.c in a range of 30μA～2.35mA, and at 8/20 impulse in a peak range of 200A～40kA ,the index α_{2I} showed in Figure 1.12.3 and Figure 1.12.4.

The curves in Figure 1.12.3 demonstrated that in the d.c current region the index α_{2I} drops dramatically in both directions after the impulse life test, with a more severe drop in opposite direction (LT_-) than that in the same direction as the impulse (LT_+).

The curves in Figure 1.12.4 demonstrated that in high level impulse current region the index α_{2I} are roughly the same before and after the impulse life test.

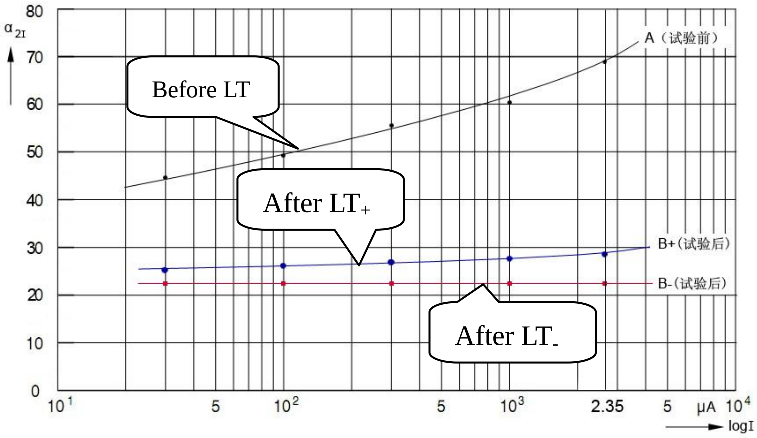


Figure1.12.3 Index α_{2I} vs d.c. current (30μ A～2.35mA)

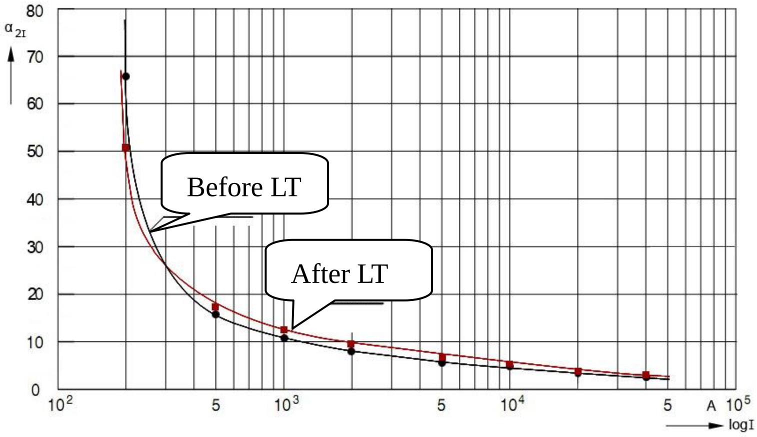


Figure 1.12.4 Index α_{2I} vs 8/20 current (200A～40kA)

1.13 Properties of an MOV with power-frequency voltage applied

It is known that MOV is a type of non-linear resistor, many properties of which are quite different from that of a linear resistor, unfortunately some engineers treat MOV as if it was a linear resistor that leaded to some mistakes, hence giving more attention to such kind of matters is needed Herein seven topics are discussed

1）Current waveform

As indicated in Figure 1.7.1, MOV has an inherent capacitance, hence the total current flowing through it, with a power frequency voltage U_S applied on it, shall be the sum of a capacitive current (I_C) and a resistive current (I_{VR}). Since the value of I_C is roughly proportional to the U_S , but the resistive current peak is proportional to the $(U_S)^{\alpha}$,therefore the shape of the total current waveform varies greatly with the ratio of I_{VR} to I_C .Figure 1.13.1 and 1.13.2 showed the total current waveform respectively at ($I_{VR} \approx I_C$) and at ($I_{VR} >> I_C$)

2) Peak displacement

The specification IEC61643-11,2011 (P.34, item E) described a method to determine the resistive current peak of an MOV which is powered by a voltage source of sine wave. According to this method, the resistive current peak should be the current value at the moment of source voltage crest, but that is wrong as demonstrated in Figure 1.13.3. The source voltage crest lies in “ t_u”(for\

f =50Hz, t_u=5ms), but the resistive current crest t_i lies in a position which is behind the t_u.

The same behavior can be observed whatever waveform of the source voltage is, which is termed "Peak displacement".

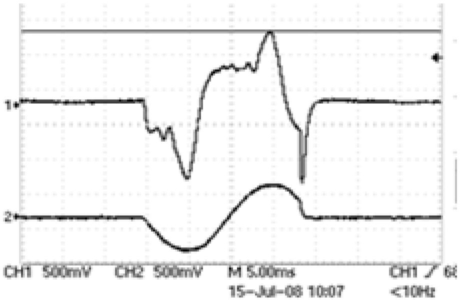


Figure 1.13.1 ,Total current (1)
source voltage (2)
(The tail of (2) was cut-off by SSR)

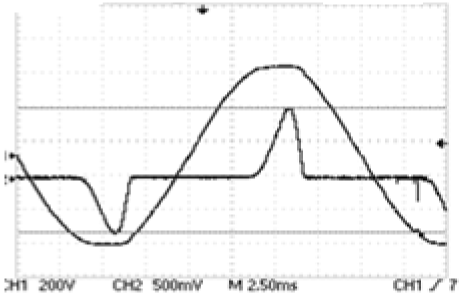


Figure 1.13.2，Resistive current pulse (Peak=104mA) and voltage on the MOV

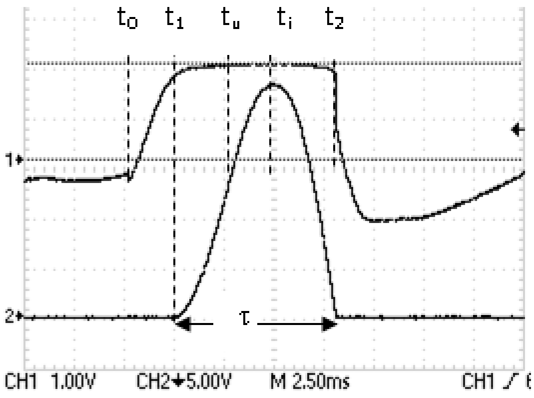


Figure 1.13.3 Time features of the waveforms

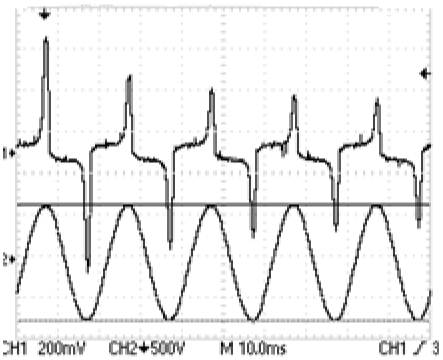


Figure 1.13.4 Stabilizing behavior of current and its asymmetry between plus and minus

3) Non-linear distortion

As indicated in Figure1.13.3, the current waveform flowing through MOV is no longer a sine wave under condition of the applied source voltage being sine wave. It becomes asymmetry with a rising duration apparently being longer than its falling duration, and the curvature of the rising curve is minus, while that of the falling curve is positive.

4) Transition and polarization

As indicated in Figure1.13.4 ,there is a transition period of the current peaks after application of the sine voltage, the first current pulse has maximum peak value, then falling and approaching to a stable peak value after a transition period of about 3～4 cycles.

It is also observed that there is some difference of the positive current peaks from the negative current peaks which is so called "polarization"

Many experiments have proved that a high current level has a small transition period, a small difference between the first peak value and the stable peak value, and a less polarization.

According to the above knowledge, when speaking of current peak or power loss of an MOV, it may be reasonable to take an average value of the plus one and the minus one of the same cycle that shall be the fourth cycle after voltage application or the behind.

5) Is the equation “P=U×I” applicable to MOV ?

The power consumption (P) of a component is the product of the voltage (U) on it multiplied by the current (I) through it (P=U×I). It seems quite simple,however, great care has to be taken when applying it to a non-linear component such as an MOV. Generally, the formula P=U×I is applicable to an MOV if U/I being d.c. values, or instant values of the same instant, but it is inapplicable to an MOV powered by a.c, sine-source if the U/I being peak values, or rms values ,or average values。Unfortunately an instrument was found on the market that gave the power loss of a ZnO block according to $P=U_{rms}\times I_{rms}$.

It is known that the general formula of power (P) deposited in a component shall be the formula (1.13.1) which applies to any waveform of cycle voltage and current.

$$P=\frac{1}{T}\int_0^T i(t)\cdot u(t)\cdot dt \qquad (1.13.1)$$

Where T is a cycle duration of voltage and current. The rms value of voltage (U_{eff}) and current (I_{eff}) shall be calculated according to the equation (1.13.2)

$$U_{eff}=\sqrt{\frac{1}{T}\int_0^T u^2 dt} \qquad I_{eff}=\sqrt{\frac{1}{T}\int_0^T i^2 dt} \qquad (1.13.2)$$

Apparently, $P \neq U_{eff} \times I_{eff}$ whenever the waveform u(t) and/or i(t) are non-sine wave

6) What are the ratio values like between peak、rms 、and average ?

As for a linear resistor powered by a cycle source of sine waveform，the ratio values between peak , rms , and average are fixed as below

$$\frac{rms}{peak}=\frac{1}{\sqrt{2}}, \qquad \frac{average}{peak}=\frac{2}{\pi}, \qquad \frac{rms}{average}=\frac{\pi}{2\sqrt{2}}\approx 1.114 \qquad (1.13.3)$$

But for MOV these ratio values will vary with voltage /current levels, source impedance , as well as non-linearity of the MOV. For the purposes of having a general idea of these ratio values, Table 1 made a comparison between linear resistor and MOV, as well as a comparison between an MOV energized by voltage source and current source.

.

Table 1.13.1 A comparison between linear resistor and varistor

	I_{aver} / I_{peak}	I_{rms} / I_{peak}	Power coefficient (k_p)
Linear resistor	0.637	0.707	$P=0.5\times I_P\times U_P$, ($k_p=0.5$)

MOV, voltage source of sine	0.362	0.524	$P=0.35\times I_P\times U_{P,}$ ($k_p=0.35$)
MOV, current source of sine	0.452	0.826	$P=0.446\times I_P\times U_P$ ($k_p=0.446$)

7) How to measure resistive current and capacitive current of an MOV ?

As indicated above the current flowing through an MOV consists of a non-linear resistive current I_V and a capacitive current $I_{C.}$.They are usually termed “leakage current” or “stand-by current” if the applied voltage on the MOV being its maximum continues operation voltage (MCOV) or less.

Under a.c operation conditions, resistive leakage current I_V and capacitive leakage current I_c are fundamental parameters to MOV’s operation ， and to be tested quite often, especially the stability of the I_V is a key factor for evaluation of degradation of an MOV.

It is noted that in case of applied voltage U_{ap} on the MOV being not greater than its MCOV, the level of the I_V is much smaller than I_c , so it is quite difficult to directly measure I_V, but to measure power loss is quite easy by feeding the total leakage current signal and the voltage signal to an multiplier. According to the integration equation (1.13.4), the power generated by capacitive current is zero , that is to say the effect of the capacitive current can be automatically rejected at the output of the multiplier. Figure 1.13.5 showed this rule directly, the capacitive power waveform includes plus and minus half-cycle and they are equal in value, so the integration of that is zero. In this figure the “peak displacement” (Δt) was stressed.

$$\int_0^T i_c \cdot u_{ap} \cdot dt = \int_0^T I_{cm} Sin\omega t \cdot U_{cm} Cos\omega t \cdot dt = 0 \qquad (1.13.4)$$

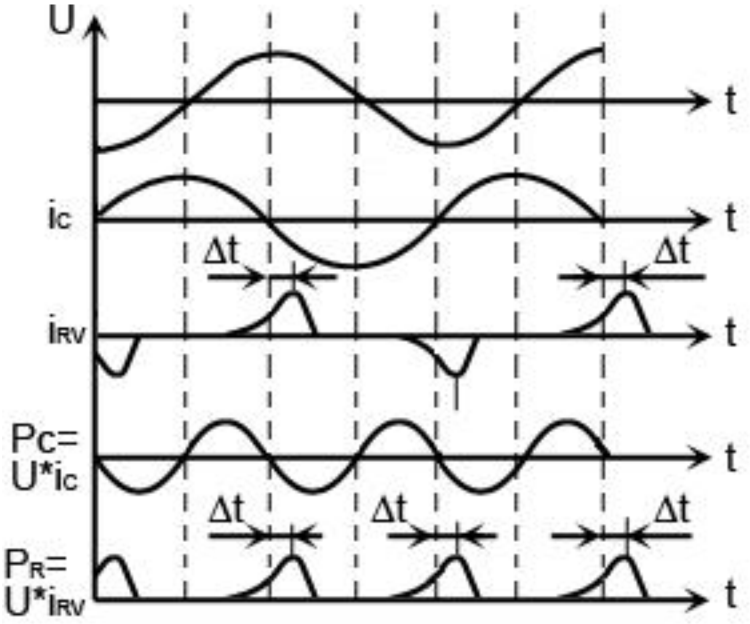


Figure 1.13.5, The effect of capacitive current can be automatically rejected by a multiplier for power loss test. Δ t=peak displacement

When capacitive current value of an MOV is needed it can easily be obtained by measuring capacitance at first and then to do the calculation according to equation (1.13.5)

$$I_C = 314 \cdot C_V \cdot U_{ap} \qquad (1.13.5)$$

1.14 Response performance to impulse

There are four topics related to the performances of an MOV responding to an impulse, which are discussed as below.

1) Physical behavior of an MOV responding to impulse

On application of a step voltage that is greater than the breakdown voltage of an MOV sample, the initial current charges the inherent capacitance (i_C) of the sample, see figure 1.14.1, whose voltage goes up starting from “0”, but no resistive current i_R flows through the ceramic body until a definite voltage U_0 is reached, after that the i_R goes up starting from “0”, at the same time the non-linear resistance goes down starting from infinite value.

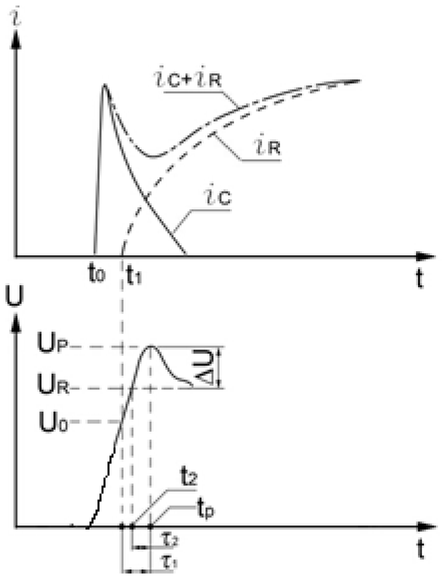


图 1.14.1 Response to a step voltage which is greater than the varistor voltage of the MOV

It is this time lag of the resistive current and non-linear resistance that result in voltage over-rising to such a value U_m that is greater than the stable residual voltage U_R ,after that the voltage starting to drop and approaching to its stable U_R that depending on the resistive current level. The voltage difference of (U_m - U_R)= ΔU is termed voltage overshoot, and the time span of ($t_1 \sim t_m$) is termed response time τ_{res} in MOV data sheet. Two parameters of response time τ_{res} and voltage overshoot ΔU (sometimes $\Delta U / U_R$ is used) are used to characterize the response performance of an MOV..

2) The response time of ZnO ceramic body to an impulse

The response time of ZnO-ceramics itself responding to a fast impulse is so small that unable to be determined by today's instrument, but by comparison method, it is surely less than 0.5ns

3) Response time of leaded type MOV

The response times is about 20ns or less measured from ordinary leaded type MOVs with two leads of 25 mm in length. That's why MOV data sheets give a response time of ≤25ns. However most surge over-voltages that occur in electrical and electronic systems possess a rise time of about 0.5μs. That is to say MOV's response time is roughly 20-times faster than the most surges.

4) A greater current rate (di/dt) will give rise to a higher voltage peak.

The following experiment proved that a greater current rate (di/dt) gives rise to a higher voltage peak (a greater voltage overshoot) and a less response time

The tested sample was an MOV of φ20mm U_{1mA}=620V which was exposed to several current impulses with a constant peak value of 100A, but the front period (t_R) of the current impulses being changed from 0.4μs to 80μs. The voltage peaks(U_P)were measured and ploted in Figure 1.14.2. The outcome of this experiment is like that ;the voltage peak U_P at t_R= 0.4μs is higher than the U_P at t_R= 8μs by about 12%, and that the U_P at t_R= 80μs is lower than the U_P at t_R= 8μs by about 9%.

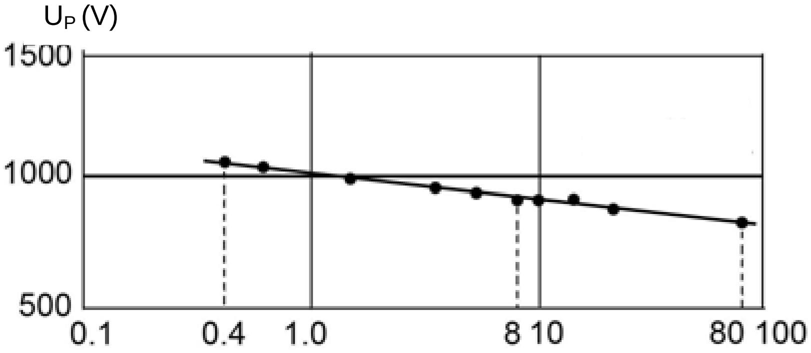


Figure 1.14.2 voltage peak increases with current rate（dI/dt）[5]

1.15 An explanation of peak displacement and minus increment resistance

1) An explanation of peak displacement

AS the discussion in 6.1.13, MOV has such a behavior that its current peak is always behind the voltage peak, no matter what waveform of test current is. Someone considered that it might be caused by an inductance, but by author's understanding of the MOV, this property results mainly from the non-linearity of the resistance. Because the resistance R of an MOV can be expressed as

(1.15.1)

$$R = f(I, dI/dt) \qquad (1.15.1)$$

If the current I is a time-dependent variable, the R must also be a time-dependent variable, therefore we have

$$\frac{dU}{dt} = \frac{d(IR)}{dt} = R\frac{dI}{dt} + I\frac{dR}{dt} \qquad (1.15.2)$$

It should be noted that if $\frac{dI}{dt}$ is"+"(current going up) , $\frac{dR}{dt}$ must be"—"(Resistance going down), or vice versa . At the instant of the current peak, dI/dt=0, so we have

$$\frac{dU}{dt} = I\frac{dR}{dt} \qquad (1.15.3)$$

At the instant of voltage peak, dU/dt=0, we also have

$$\left|I\frac{dR}{dt}\right| = \left|R\frac{dI}{dt}\right| \qquad (1.15.4)$$

According to equation (1.15.2), there is no such an instant for an MOV at that both dI/dt=0 and dU/dt=0 being met, That is why the voltage peak does not coincide with the current peak.

2) An explanation of minus increment resistance

There are two situations in which an MOV has minus (negative) increment resistance that were described in Figure 1.15.1, and Figure 1.15.2

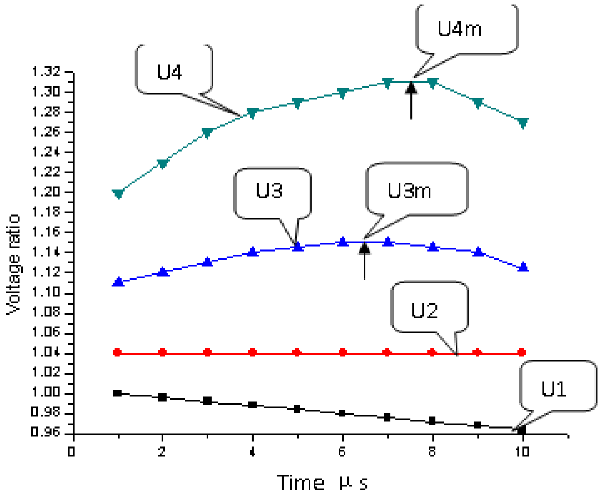


Figure 1.15.1 Voltage waveform in the front span of 8/20 impulse at the current peak respectively of $I_{P1} < I_{P2} < I_{P3} < I_{P4}$

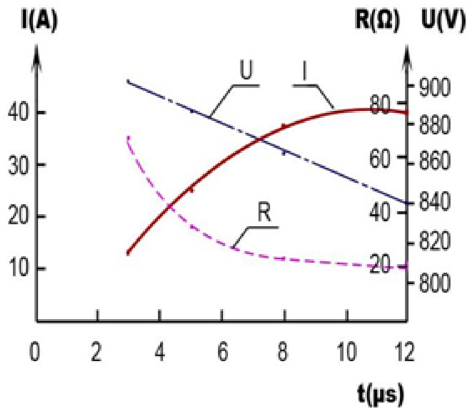


Figure 1.15.2 Waveform of 8/20 current (I) of peak=40A, voltage (U),and (U/I), in the front span of (I). Sample 34x34mm

Figure 1.15.1 demonstrated four voltage waveforms (U_1,U_2,U_3,U_4) of an MOV sample in a span of the front time of 8/20 impulse currents which flowed through the sample, the peaks of the currents were $I_{P1} < I_{P2} < I_{P3} < I_{P4}$. In order to have a clear seeing, the initial overshoot of the voltage waveforms were omitted , and the voltage was expressed in voltage ratio letting the initial value of the U_1 to be "1.0". there is no doubt that in the span the current increases simply, and its resistance simply decreases accordingly, but there are three possibilities of the voltage variation across the sample, which are governed by the peak values of the 8/20 impulses:

* at low level of 8/20 current peaks, say about amperes per cm^2, a continuous decaying voltage waveform (U_1) and a negative (minus) increment resistance are observed. In order to show this behavior clearly Figure 1.15.2 described anther experiment

* at some greater current levels the voltage may remain unchanged in the span (U_2), despite the current being steadily rising.

* at further greater current level, say hundred amperes per cm^2, the voltage increase at first till reaching its crest value U_m followed by a decreasing variation (U_3 and U_4), in the time span of "peak displacement", for example behind U_{3m} or U_{4m} in the Figure 1.15.1, and Figure 1.15.2, sample behaves a negative (minus) increment resistance as well.

The above behavior can be explained like that. Because

$$du = d(i \times r) = r \cdot di + i \cdot dr \qquad (1.15.5)$$

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

*if $|r \cdot di| < |i \cdot dr|$, du and di are in the opposite sign ,i.e. an negative increment resistance.

*if $|r \cdot di| = |i \cdot dr|$, du =0 ,the voltage remains unchanged despite the current variation

*if $|r \cdot di| > |i \cdot dr|$, du and di are in the same sign that is the most situations of MOV operations.

Part 2 Ratings and parameters, failure mode and service life

2.1 typical operation states and related ratings and parameters

2.2 varistor voltage $U_{n,}$ tolerance $\delta U_{n,}$ voltage gradient V/mm

2.3 Max. continuance operating voltage (MCOV) U_M

2.4 standby power loss $P_{0,}$ resistive leakage current $I_{LR,}$ total leakage current (rms) I_L

2.5 capacitance C_V

2.6 impulse protection performance — class current, nominal discharge current (I_N), clamping voltage U_{cla}, clamping voltage ratio $R_{cla.}$

2.7 Impulse current handling capabilities

2.8 average impulse power P_{av}, Max. impulse energy E_{max}

2.9 The key to MOV's impulse tests

2.10 TOV handling energy E_{TOV}

2.11, thermal stable applied voltage ratio R_{apT} , thermal stable temperature(T_V)

2.12, Holding temperature (T_h) of TPV

2.13 Interrupting current range I_B of TPV

2.14 Failure mode

2.15 Life tests and life expectancy

Part 2 Ratings and parameters, failure mode and service life

Herein the “rating” refers to either a limiting capability or a limiting condition beyond which damage to the MOV may occur

2.1 Typical operation modes and related ratings and parameters

In order to have a better understanding of the ratings and parameters, connecting them with the operation modes of MOV is needed. According to the electrical stresses imposed on MOV during its service life, three typical operation modes should be distinguished, particularly for those MOVs that are connected into power circuits, as Table 2.1.1.

Table 2.1. Three typical operation modes and their performances

Standby operation mode	Surge suppression mode	TOV endurance mode
electrical stresses imposed on MOV		
MCOV	①MCOV ②Specified impulse current	TOV
Ratings and parameters and		
① *varistor voltage U_n *U_n-tolerance δ U_n *voltage gradient V/mm ② * MCOV ③ *standby power loss P_0 and stability *resistive leakage current I_{LR} and stability *total leakage current I_L ④ capacitance C_V	Impulse limiting performance ① clamping voltage U_{cla} (class current I_{cls} (nominal discharge current I_n) ② response time t_{res} voltage overshoot Δ u_{OV} impulse handling capability ①Max. discharge current (short)$I_{MS,}$ (long) I_{ML} ②repeated discharge current (short)$I_{MS,}$ (long) I_{ML} ③average impulse power P_{av} ④Max. impulse energy E_{max}	component ① TOV handling energy E_{TOV} TOV test voltage U_T ②thermal stable applied voltage ratio R_{apT} (@25℃) TPV ① , Holding temperature (T_h) of TPV ② Interrupting current range I_B of TPV
Characteristic formula and curves		
①d.c. V-I formula ②a.c. V-I formula ③life hours under MCOV&T_M	①impulse V-I formula ②impulse life	

2.2 varistor voltage $U_{n,}$ tolerance δ$U_{n,}$ voltage gradient V/mm

varistor voltage U_n, also named d.c. reference voltage, is used to signify the transition point between insulation state and conduction state of an MOV

In MOV product data sheet , the U_n is measured at d.c.1mA±10% for a period of (20ms～50ms) before taking reading .The test voltage on the MOV shall be rising from a low value to U_n, a constant current source of d.c.1mA at a standby voltage that is much higher than U_n is not allowed.

The U_n is usually used as a reference of product, for example “applied voltage ratio

R_{ap}=U_{ap} / U_n” is used to signify the strength of applied voltage U_{ap} on the MOV. “residual voltage ratio $R_{res} = U_{res} / U_{n}$, ”（$U_{res}$ = residual voltage, or named as limiting voltage）is used to signify the capability of the MOV to limit surge voltage. The U_n degradation rate [δ U_{nD}] signifies the degree of degradation which is equal to a change rate of current U_n value during the service to the initial U_n value, hence it is encouraged to mark the initial U_n value on the product which is intended to be used for an important application.

It is mentioned that since the test current is 1mA, no matter what diameter of the product is, and so the U_n means a different current density for different dimension MOVs, however some important properties of MOV, such as temperature coefficient of power frequency voltage, the degree of degradation etc. are much sensitive to the current density, therefore, if necessary, the same test current density, $0.5mA/cm^2$ is quite common, should be used to test varistor voltage, and based on such voltage values, a comparison between MOVs which have different sizes could be properly made.

U_n-tolerance δU_n has a close connection with application performances, for example the maximum limiting voltage is determined by the MOVs whose U_n being equal to the top tolerance value, and the most severe degradation under MCOV stress is often seen from the MOVs whose U_n being equal to the lowest tolerance value. Therefore to pay more attention to tolerance δU_n is necessary.

The current specifications and data sheets have not included the parameter of “voltage

gradient V/mm”, but it has to be considered whenever selecting an MOV .As indicated in section 1.4 “the power and energy handling capabilities of an MOV will be roughly proportional to the volume of the ceramic element.”, therefore the parameter of V/mm has a big effect on long-duration impulse current rating and TOV-endurance , but a less effect on short-duration impulse (8/20) current rating. Moreover the MOV of high V/mm has a little good voltage limiting property（low limiting voltage ratio） and lower cost.

The available voltage gradient V/mm lies in the range of about 100V/mm to 220V/mm for those MOVs that have U_n greater than 80V.

2.3, Max. continuance operating voltage(MCOV) U_M

The MCOV signifies such a voltage that may be applied continuously at a specified temperature. At the discovery time of the MOV, the a.c.MCOV (U_{Mac}) was so defined that the peak of the U_{Mac} shall be equal to or less than the low limit of varistor voltage tolerance, in case of ±10%U_n (herein U_n refers to nominal value) the low limit is $0.9U_n$ hence we have:

$$U_{Mac} = \frac{0.9U_n}{\sqrt{2}} \approx 0.64U_n \qquad (2.3.1)$$

At d.c. MCOV (U_{Mdc}) the MOV shall generate the same power loss as that at U_{Mac}, based on this rule, the equation (2.3.2) was found via experiments

$$U_{Md.c} \approx 1.3U_{Ma.c.} \qquad (2.3.2)$$

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

MOV Products which conform to specified MCOV should be evaluated by following tests:
1) The power loss or resistive current of the products shall be stable with time and not greater than the specified value under the specified MCOV stress and temperature.

2) The products shall pass the specified life test under the specified MCOV stress and temperature.
3) The products shall pass the specified impulse tests immediately followed by application of MCOV for a specified time without thermal runaway..

2.4 standby power loss $P_{0,}$ resistive leakage current $I_{LR,}$ total leakage current (rms) I_L

These three parameters always connected with MCOV, as stated above. A few points are added below.

Generally to measure one of standby power loss $P_{0,}$ and resistive leakage current $I_{LR,}$ is sufficient for the purposes, but the standby power loss $P_{0,}$ is the first choice, see 1.13.7)

The total leakage current (rms) I_L should be controlled for those MOVs that are connected to ground in application fields.

2.5 capacitance C_V

As regards capacitance C_V of an MOV following points should receive user's attentions
1) The value of C_V is about inversely proportional to varistor voltage.
2) The current specifications of MOV specify up limit of C_V, that means a lower C_V is preferable, but a bigger C_V may have a beneficial effect to some application purpose, for example, for a series combination of GDT and MOV, a bigger C_V will reduce the breakdown voltage of the combination. However a bigger C_V can store more electric charges acquired during the last impulse, if it can't be fully discharged before next impulse coming, it may affect limiting voltage for the next impulse.
3) The capacitance C_V has some "historic effect", that is to say any previous electrical stress applied on the MOV will affect a later measurement of the $C_{V,}$ ordinary lessening the measured capacitance value by 10% or more, therefore a recovery treat shall be allowed

2.6 impulse limiting performances, class current, nominal discharge current (I_N), clamping voltage U_{cla}, clamping voltage ratio $R_{cla.}$ Highest value protection level

The impulse limiting performances of an MOV include two aspects:
  1) limiting voltage (clamping voltage)
  2) impulse response parameters —response time t_{res}, voltage overshoot Δu_{OV}
Since the t_{res}, and Δu_{OV} are steady, a routing test of them is not needed

According to the MOV's specification and data sheets ,the limiting voltage shall be tested at " class current" which is an 8/20 impulse current of peak $I_P \approx 33A/cm^2$, but SPD specifications defined a test current of 8/20 that is named "nominal discharge current I_N" ,whose peak $\approx 2000A/cm^2$

In the past there were two major problems with limiting voltage control as below:
1) The so called “max. clamping voltage curve” in manufacturer’s data sheets provided the clamping voltage values which may be much different from that of actual MOV-products
2) The current specifications of MOV described clamping voltage measurement on the samples only, but for type test and quality control purposes, the highest clamping voltage of the lot which is represented by the samples should be evaluated.

To solve the above problems, the manufactures of MOV are encouraged to provide their users with the impulse V-I characteristic formulas of delivered products.

To solve the above problems, the manufactures of MOV are encouraged to provide their users with the impulse V-I characteristic formulas of delivered products which are simple, convenient and accurate to use. There are two kinds of formula—one is applicable to a particular product lot which gives an accurate limiting voltage value of ±3%, and the other is general formula which gives approximate limiting voltage values ,say ±8%. An instance is below:

One manufacturer of MOV provided an impulse V-I characteristic formula (expressed in limiting voltage ratio) as equation (2.6.1) that is applicable to their φ10mm MOVs of U_n=200V～860V, the deviation of the calculated value from the practical value being usually within ±8%

$$R_{cla} = \frac{U_{cla}}{U_n} = 2.89 - 1.57 \times \log I + 0.45 \times (\log I)^2 \qquad (2.6.1)$$

To evaluate the deviation of this equation, one sample was taken from the lot, its varistor voltage was 582V, the limiting voltage ratios were tested at 8/20 impulse currents of

100A～3000A. .Table 2.6.1 made a comparison between calculated ratios by using equation (2.6.1) and actually tested ratios. This instance proved that using V-I characteristic formula is simple, convenient and accurate as compared with V-I curves showed in data sheet. When more accurate formula is needed, individual formula for a narrow range of U_n should be determined.

Table 2.6.1 a comparison between calculated ratios and actually tested ratios

8/20 current peak ,A	100	300	1000	2000	3000
Calculated R_{cla}	1.55	1.76	2.23	2.61	2.87
Actually tested R_{cla}	1.5	1.7	2.07	2.41	2.67
Deviation %	3.3	3.7	7.7	8.3	7.6

2.7 Impulse current handling capabilities

An MOV performs two major functions of limiting impulse overvoltage and diverting impulse current which result in degradations of MOV’s properties. The severity of an impulse implies five factors which are current peak I_P, duration (equivalent square wave width τ),successive impulse numbers n, interval between individual impulses, and impulse polarity (positive, negative)

Since a short duration impulse ($\tau < 100\mu s$) has quite a different effect on the MOV from that of a long duration impulse($\tau > 100\mu s$), therefore the specification IEC61051-1 described impulse handling capability separately for short and long duration impulses, the waveform of the former is 8/20 impulse, while the latter, 10/1000 or 2ms square wave .In order to evaluate the impulse handling capability of an MOV, both Max.(single) discharge current test and repeated discharge current test (n=10) shall be carry out..That is to say, for a complete evaluation of Impulse current handling capability of an MOV, four sample groups in total should be subjected to test ,8/20 impulse test only is insufficient for the evaluation, in fact an MOV of good 8/20 impulse handling capability may have, or may have not a good handling capability at long duration impulses.

It is mentioned that different specifications may define different impulse tests for the evaluation of the Impulse current handling capabilities, for example, according to the specification IEC61643-331, the MOV in class II SPDs, shall be subjected to ,at least ,n=17 times of 8/20 impulse at the nominal discharge current I_n (including two times of residual voltage measurement)

In addition, the impulse current test may be carried out with or without a.c. operation voltage applied. They are named “powered test” or “unpowered test” respectively. Currently there are two methods of powered test, the first is like that, an impulse current is superposed on a previously applied power voltage on the tested piece at a specified phase angle ,see figure 2.7.1. The second is that applying specified impulse at first followed by power voltage application within, say, 10ms. As far as MOV is concerned, no any noticeable difference between the two test outcomes was found, and the second method allows the test to be performed without coupling and /or de-coupling networks which are necessary for the first method where an extra discharge following the intended discharge is often seen, as was showed in Figure 2.7.1, which may lead to an erroneous overload to the tested piece, so that the second method is strongly recommended.

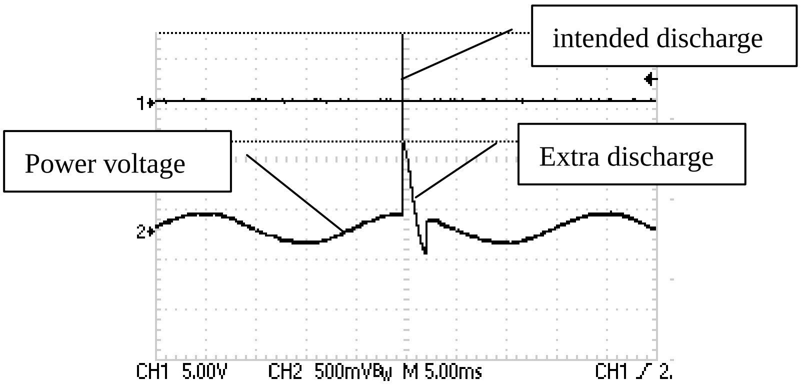


Figure 2.7.1 Extra discharge caused by de-coupling network during powered test on an MOV

2.8 average impulse power P_{av}, Max. impulse energy E_{max}

The parameter of average impulse power P_{av},is used for impulse life test . For example, if a sample of 34x34 mm U_n=470V is subjected to 8/20-5000A life test , then the interval between individual impulses Δ t should be 49.6s, as below.

$$\Delta t = \frac{E_P}{P_{av}} = \frac{R_{res} \times U_n \times \tau \times I_P}{P_{av}} = \frac{1.69 \times 470 \times 17.5 \times 10^{-6} \times 5000}{1.4} = 49.6(s)$$

Where: E_P is the energy (J) deposited into the sample per each impulse. P_{av} is rated average impulse power, herein is 1.4W for 34x34 mm MOV. R_{res} is residual voltage ratio of the sample at specified 8/20-5000A current, herein is 1.69, Sample's U_n=470V, the equivalent square wave widthτ of 8/20 impulse is $17.5x10^{-6}$(s)

It is noted that due to the increased numbers of Wind turbines and photovoltaic installations, the ac/dc converters increased rapidly, their operation voltage have cyclic impulse-like waveforms, the average impulse power of that is an major concern.

Whenever turning off a powered inductor, its stored energy has to be discharged by an energy absorber such as an MOV, in this case the Max. impulse energy E_{max} of the MOV should be coordinated to the stored energy of the inductor.

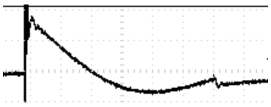
2.9 The key to MOV's impulse tests

The key to performing impulse tests on the MOVs should be fully understood and obeyed, particularly the following five aspects:

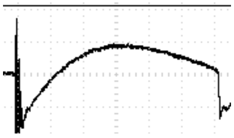
1）The tests involve high voltage and high current, and are inherently hazardous ,every operators are cautioned that never for one moment to overlook safety .The safeguards indicated in the related documents must be fully obeyed

2) Kelvin connections (four-terminal connections) must be used to connect DUT(device under test) so that the contact resistance and the resistance of connection wires are removed from the measured voltage values, in addition, the two potential connections must be placed at the specified points, ordinary at faraway end points of the terminals

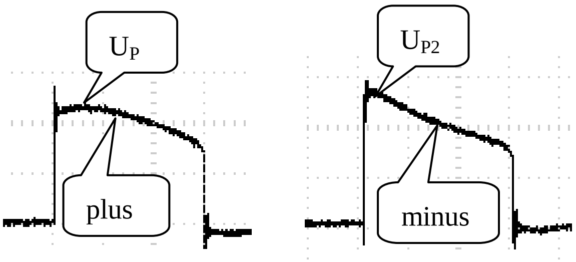
3) Voltage divider for impulse voltage measurement shall be free from interference caused by discharge current. Otherwise, up to 10% or even higher error in voltage reading may occur.



a) In phase



b) out of phase



1, free of interference

2, interfered

Figure 2.9.1 interference Voltage waveform

Figure 2.9.2 residual voltage waveform on MOV

It is k generated due to discharge of 8/20 impulse current i_S , if the voltage divider is placed in the space where the magnetic field exists, an interference voltage u_S will be inevitably generated on the divider via the mutual inductance M between the divider and the magnetic field as below:

$$u_S = -M \frac{di_S}{dt} \qquad (2.9.1)$$

Figure 2.9.1 shows waveforms of interference voltages on the divider which was measured via such method that the lead which normally joins the divider to the live end of the test object was disconnected from this point and connected instead to the earthed end of the test object, but maintaining approximately the same loop .The voltage measured under this condition, when the 8/20 impulse generator is discharged, may have two shapes as showed in Figure 2.9.1, which depends on the position and direction of the divider.

Figure 2.9.2 makes a comparison between a normal voltage waveform (left) without interference and being interfered voltage waveform (right) on the same sample at the same discharge current peak, but the normal one was obtained in condition that the voltage divider was placed far away from the current discharge loop, while the right was obtained where the voltage divider was placed nearby the discharge loop. The following three distinct features can be seen from Figure 2.9.2:

①The peak value of the interfered waveform(U_{P2}) greater than that of the normal one (U_{P1}) by about 15%.

②The time position of the (U_{P2}) moved ahead

③The curvature of the U_{P2} top curve is negative, but that of the normal one is positive.

④ The two waveforms have the same voltage value at the instant of the current peak where $di_S / dt = 0$,hence the interference $u_S = 0$

It is noted that the interfered voltage waveform (Figure 2.9.2, right) can be obtained by superposing the interference voltage (Figure 2.9.1 a)) onto the normal voltage waveform (Figure 2.9.2, left). Moreover, if the out of phase interference voltage (as 2.9.1b)) superposed ,the shape of MOV’s residual voltage waveform will change accordingly.

To sum up, the interference can be found by carefully looking at the residual voltage waveform and can be eliminated by placing the voltage divider far away from the magnetic field of the discharge current and perpendicular to the magnetic field.

4) Properly match the impedance of tested MOV up with the impedance of the impulse generator, the waveforms of tested MOVs are affected strongly by the matching degree of these impedances. In addition to that the equivalent impedance of an MOV can vary greatly with the current levels flowing through it, so that the observed waveforms of the tested MOVs will vary accordingly.

5) A careful observation of the voltage and current waveforms is needed during the impulse tests since some light or weak flashover or breakdown of the tested MOV cannot be found by a visual inspection after the impulse test, but they are surely seen from

abnormal waveform.

Besides a longer observation time than the impulse duration is advised , for example, 100 μ s observation time for 8/20 impulse test is defined by some specifications, since some abnormal phenomena may occur after the normal discharge through the tested MOV.

2.10, TOV handling energy E_{TOV}

Total energy deposited into an MOV prior to its thermal runaway during the specified TOV test voltage U_T being applied on it and at ambient temperature of 25 ℃

The measured energy E_{TOV} shall be equal to or greater specified value.

2.11, thermal stable applied voltage ratio R_{apT} , thermal stable temperature(T_V)

At ambient temperature of 25 ℃, the maximum voltage ratio of applied voltage U_{ap} on MOV to its varistor voltage U_n($R_{apT}=R_{ap}/U_n$) when the MOV lies in thermal stable state, the temperature of the MOV body in this state (T_{VS})is thermal stable temperature

The parameters of R_{apT} and T_{VS} are application information according to which the user can know the operation state of an MOV.

2.12, Holding temperature (T_h) of TPV

The maximum temperature of the thermo-protected MOV(TPV) at which its thermo-disconnect device will not interrupt during a specified time under specified conditions

2.13 Interrupting current range I_B of TPV

A current range, whenever the current flowing through the TPV lies in this range, the TPV is interrupted safely under the condition that the source voltage being equal to 2 times MCOV of the TPV

At present a type of TPV having an Interrupting current range of 50mA to 100A is available.

2.14 Failure mode

The outcomes from both field statistics and laboratory experiments have demonstrated that the stresses that result in performance degradations and failures of MOV include mainly ①impulse discharge currents
②normal continuous system voltage
③temporary overvoltage of the system
④high environment temperatures
⑤other environmental conditions such as rapid temperature change,

The failure modes of MOV products may be distinguished in terms of application performance or physical destructions

Three performance parameters are ordinarily used as failure criteria which are as below

① varistor voltage U_n has decreased by more than 10% with respect to the initial value.

② residual voltage U_{res} has increased by more than 10% with respect to the initial value.

③ leakage current or power loss drifts upwards.

It is noted that the second failure criteria (residual voltage criteria) has not been seen prior to the fist failure criteria (varistor voltage criteria) having been met, therefore as a matter of fact only the first and the third criteria are effective.

The failure modes of physical destruction which were encountered quite often are as below

①cracking of the insulation coating
This type of destruction is often found whenever the MOV is subjected to rapid ambient temperature change or repeated impulse current. It is due to different expansion rates between the coatings and the metal terminals.

② etched silver layer
A part of silver layer adjacent to the metal lead has been etched by melting during passing a high impulse current.This destruction mode cannot be discovered via electrical measurements in most cases, therefore the coatings should be removed for visual examination.

③parting of the silver layer from the metal lead or from the ceramic body

④cracking of ceramic body due to localized over-heating or due to thermo-elastic stresses during high current impulses。

⑤thermal puncture of ceramic body（See 1.11）

⑥flashover from high dielectric stresses at rim or surface of the ceramic body

2.15 Life tests and life expectancy

At present some users request that the MOV shall function normally for 20 years. In order to evaluate MOV’s service life, the life tests on the MOV samples have to be carried out so that the life expectancy can be obtained. The first purpose to perform life tests lies in establishing the failure rate distribution of the tested sample size, from which the life data, such as average life, or mid-position life, or guarantee life, can be found, the second purpose of the life tests lies in establishing the relation between the life and the severity of the stresses, based on which the life expectancy of the products represented by the tested samples can be made under a given set of stresses.

The service life of MOV includes two aspects which are treated independently, i.e. the life under a

combined stresses of continuous voltage and temperature, and the life under impulse current stress. The former is expressed in hours (h), and the latter is expressed in impulse numbers(n),

2.15.1 ,Basic technical ideas regarding to Life tests and life expectancy

The previous research works reported the following outcomes which formed basis of performing life tests and evaluating life expectancy of the MOV

① Standard IEC60099-4,Edition1.2, addressed that “The Arrhenius law has provided good confidence on life expectancy of metal- oxide blocks”. The voltage/temperature tests described in this document were at 115℃ and at corrected maximum continuous operating voltage for 1000h. The document also indicated that “ In general, it is not acceptable to increase the test temperature above 115℃ as it may change the physics of aging, rending the Arrhenius law non-applicable”

②The document[ ] indicated that “most of today’s established materials show a decreasing power loss with time and the decrease normally is higher at higher test temperatures. Hence these stable materials show a behavior just opposite to an Arrhenius-type law,

③ The paper[ ] and the IEC material[ ] reported that the failure rate distribution of the impulse life test at 8/20 and 10/350 impulse current is in accordance with Weibull distribution from which the average life data and guaranteed life data can be obtained

④The so called “ impulse current peak de-rating characteristic curves”, as showed in IEC 61051-2, and manufacturer’s data sheets, gave the characteristic curves of $I_P = f(\tau,n)$, herein, I_P —impulse current peak，τ —equivalent impulse width, n —times of impulse application which is based on the Life end criteria that “the varistor voltage having decreased by equal to or greater than 10% with respect to the initial measured value. These curves, in fact, are impulse life curves, but what is the test procedure of these curves is not described.

⑤ The book [ ] addressed the impulse life expectancy $\overline{N}$ (in year) as equation (2.15.1)

$$\overline{N} = \frac{[As]_{MOV}}{[As]_{EXP}} \qquad (2.15.1)$$

Where: $[As]_{MOV}$ is the “ampere-second resource” of used MOV. $[As]_{\exp}$ is the expected ampere-second consumption per year at the place where the MOV is intended to be installed.

2.15.2 Procedures for life test and life expectancy

Based on the above basic ideas and the present practices of MOV-circle, the procedure as below is presented for life test and life expectancy of the MOV

① voltage/temperature life tests and life expectancy

In terms of MOV, the severity of voltage stress signifies applied voltage ratio of $R_{ap}=U_{ap}/U_n$ rather than the absolute voltage value, herein U_{ap} refers crest value of a.c. voltage or d.c voltage that is applied on the tested sample, and the U_n is measured varistor voltage of each MOV-sample.

The life test shall be carried out on nine groups of sample, and each group of sample shall be subjected to a combination of voltage/temperature stress, as showed in Table 2.15.2.1. Usually d.c. voltage is used for this test due to its more severe than a.c.voltage. The number of each sample group is ordinary 20 pcs, or more. The life-end criterion is that the power loss of tested piece is going up to a specified value, say 2-times of initial measured value.

Table 2.15.2.1 Voltage/temperature stress combinations for nine sample groups

Applied voltage ratio R_{ap}		1.0	0.9	0.8	
Environment Temperature T(℃)	95 (A)	G(10A)	G(09A)	(G08A)	Eq.(V1)
	105 (B)	G(10B)	G(09B)	(G08B)	Eq.(V2)
	115 (C)	G(10C)	G(09C)	(G08C)	Eq.(V3)
		Eq.(T1)	Eq.(T2)	Eq.(T3)	

Note: G(10A) is Code of sample group ,and the tested life figure of this group shall be placed here. Eq.(T1) is Code of fitting equation

Each group of sample shall be tested till every sample of total 20pcs has reached life-end criterion,

An analysis of the 20 life-time figures of each sample group shall be conducted for failure rate distribution function (try Weibull distribution at first) from which the average life(in hours), mid-position life, or guarantee life of the group shall be found, and it is then being noted into Table 2.15.2.1

The three life figures of the same R_{ap} shall be fitted to the three temperatures to yield three equations Eq(T1), Eq.(T2),and Eq.(T3),

The three life figures of the same temperature shall be fitted to the three Applied voltage ratio R_{ap} to yield three equations Eq.(V1), Eq.(v2),and Eq.(v3),

By use of the above six equations, the life expectancy under other combinations of voltage-temperature stress can be found.

② impulse life tests and life expectancy

The procedures of impulse life tests and life expectancy are quite similar to that of voltage/temperature stresses but for stress combination of nine sample groups and the life-end criterion. The stress combination for nine sample groups shall be as Table 2.15.2.2, and the life-end criterion is that the varistor voltage has decreased to 90% of the initial measured value.

Table 2.15.2.2 Impulse stress combinations for nine sample groups

Impulse current peak		$0.5I_M$	$0.25I_M$	$0.1I_M$	
Impulse current width (μ s)	17.5 (A)	G(50A)	G(25A)	(G10A)	Eq.(8-20)
	500 (B)	G(50B)	G(25B)	(G10B)	Eq.(10-350)
	6370 (C)	G(50C)	G(25C)	(G10C)	Eq.(10ms)
		Eq.(50)	Eq.(25)	Eq.(10)	

Note: 8/20-17.5μ s, 10/350-500μ s,, 10ms-sine-6.37ms.

I_M-maximum discharge current of 8/20 or10/350 or 10ms-sine.

Part 3 Application guide

Part 3 Application guide

3.1 three-step method for application design

The users are advised to follow three-step method for MOV’s application design

Step -1 Try your best to ascertain properties and requirements of three aspects.
MOV is a link in an overvoltage protection chain, it should be considered from the chain system of view which includes three other links, i.e. impulse source, normal system voltage source, and protected objects. Sometimes their properties and requirements are not quite clear, especially related with lightning protection. In this case the users should try their best to ascertain initial data related to MOV application design.

Step-2 Make a choice of right MOV product taking account of related properties, safety and cost

Step-3 .Conduct a laboratory test to discover and correct deficiencies of the initial design till having a satisfaction with the design

3.2 circuit principle of overvoltage protection by MOV

The circuit principle of overvoltage protection by MOV can be described by Figure 3.2.1, the protective component MOV is always connected in parallel with the protected object(s) (PO),the input impedance Z_{PO} paralleled with MOV. Based on Thevenin theorem, the system source and the surge source can be represented by an equivalent source voltage U_S and source impedance Z_S connected in series. In case of a surge impinging the equivalent source voltage U_S is the sum of normal system voltage U_0 and surge voltage U_{OV}. It is noted that the source impedance Z_S and the input impedance Z_{PO} are linearity in most cases, while the equivalent impedance of the MOV is non- linearity. For such type of circuit, that includes both linearity and non-linearity components, graphical method is commonly used to determine the current and voltage values in it, as showed in Figure 3.2.1,

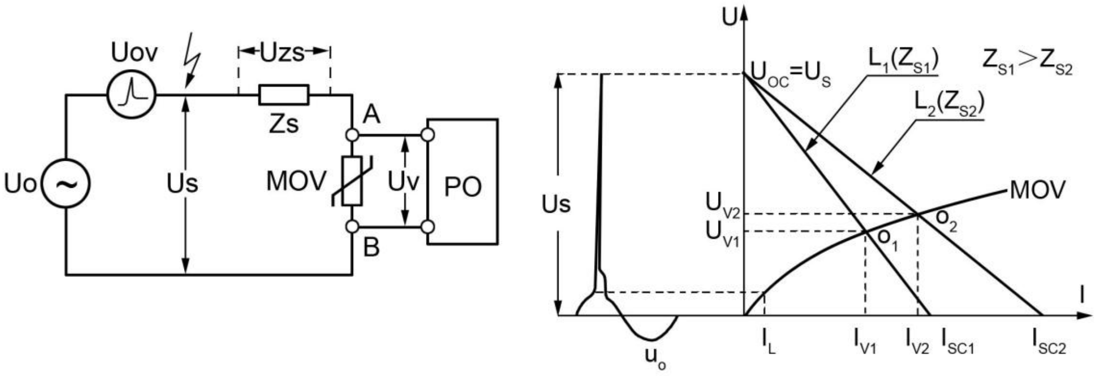


Figure 3.2.1 Description to The circuit principle of overvoltage protection by use of MOV

In case that the resistance of the MOV is far lower than the $Z_{PO,}$ during the period of the surge. the circuit current I_{V1} or I_{V2} can be found from the intersection O_1 or O_2, where the V-I characteristic of the MOV, is intersected by load line Z_{S1} or load line Z_{S2} respectively. herein $Z_{S1} > Z_{S2}$, which resulted in $U_{V1} < U_{V2}$,that is to say a greater source impedance Z_S will result in a lower residual voltage because more part of surge voltage dropped on the source impedance $Z_{S.}$ Therefore an important point should be recognized that the effectiveness of voltage limiting function by an MOV depends not only on MOV's property, but on the source impedance Z_S as well.

It should be aware of such situation where the input impedance of protected objects may lower than equivalent resistance of the MOV, for example, in many power supply circuits , the MOV is installed just before the rectifier diodes and filter capacitors, in this case there may be a large surge current pouring into the capacitors during the impulse , therefore both limiting protections against the voltage on the capacitors and the current through the capacitors shall be taken in to consideration.

3.3 effects of MOV on the systems to which the MOV is installed

From systems engineering point of view, MOV is a link in an overvoltage protection system, it should exert as little influence as possible over the other links in the system except for its normal surge suppression functions. These influences shall be less than the permitted limits as defined by related standards.

3.3.1 Capacitance effects

1) The capacitive current caused by MOV connected between mains and earth, may trip the residual current device mis-open which being installed upper side of the MOV. This current I_C also raise the potential of the earth conductors by a value of (I_C x R_G) (R_G is the earthing resistance of the earth conductors)

2) The capacitance C_V of an MOV can cause loss of higher frequency signals, or alter the frequency performance of the system which should be taken into consideration when the system being signal and/or data system

3) An oscillation may be excited by surges in a loop including capacitance C_V and inductance L of conductors.

4) Due to electric charge storage effect of the $C_{V,}$ the residual charge gained from the last conduction of the MOV may change the breakdown voltage of a series combination of MOV and GDT.

5) Resistive current of MOV is delayed to take place by the $C_{V,}$, when an MOV responds to a fast impulse

6) The capacitance C_V of an MOV is beneficial for noise rejection.

3.3.2 Effects of non-linear current and voltage

MOV is a component of non-linearity which gives rise to non-linearity distortions of the current through it and the voltage across it that contain some harmonic waves, and may spread to some sensitive circuits via various coupling mechanisms, therefore attention should be paid to their effects especially for signal and data systems.

3.3.3 Effects of high surge current discharge by MOV

There are at least four effects resulting from high surge current discharge by MOV.

1) Raising the potential of grounding conductors that may cause discharge between the

grounding conductors and nearby circuits.

2) Interfering with nearby circuits via capacitive, inductive, resistive coupling and spatial radiation.

3) Generating significant heat that might melt small conductors

4) Generating large electro-dynamic forces that might break small wires or cause displacement of the parts.

3.3.4 Harm to the system caused by short-circuited failure of an MOV

A short-circuited failure of an MOV forced the system to stop functioning and, worst of all ,it may lead to catch fire, especially in power supply system,where the MOV shall be treated as an arcing PIS (Potential ignition sources) according to the safety standard IEC62368-1：2010, clause G.10.3.

3.4, A series or parallel combination of MOV, and coordination of multi-stage protection.

A series or parallel combination of one or more units of MOV is often used in order to have a high voltage, current, and/or energy rating which are beyond that of an individual unit, or to provide back-up protection, or to form a new performance or a new function by combining two or more units of different property MOVs. Some key points of view relating to these problems are discussed below.

3.4.1 reliability-screening and performance stabilization of each individual unit intended for series or parallel combination

Before being put into the series or parallel combinations, the MOV shall pass two types of test to stabilize performances of the units, and to screen out those units that have interior defects which may lead to a premature failure.

The first test is " voltage - temperature aging test" at a specified temperature (T_s) and a specified voltage (U_s), for a specified period (t_s), during which those units shall be rejected that showed a steady increasing power loss or the value of which having changed beyond a specified limit. The test parameters of [T_s, $U_{s,}$ t_s] depend on the design and manufacturing processes of the tested MOV .An example is that T_s=125℃, $U_{s,}$= (0.7～1.0)U_{Mdc} (Maximum d.c. operating voltage), and t_s=6h.

The second test is " impulse current aging test" at a specified current peak, usually (0.3～0.5)$I_{max,}$ one shot each for positive and negative direction, the current waveform should be both a short duration impulse (say 8/20) and a long duration impulse (say 10/350, or 10-ms sine wave). Any unit, which showed varistor voltage having dropped by more than a specified limit, shall be rejected.

It is noted that all units that have passed the above tests have a more stable parameters and an improved impulse handling capability in comparison with untested units

3.4.2 series connection

A series combination of MOV (Figure 3.4.1) is often intended for having a high voltage rating. It should be mentioned that the d.c and power frequency voltage of the combination U_{ab} is the sum of that of each unit in it, but this rule is not applicable to an impulse operation state due to the effect of inherent capacitance C_{V1} and $C_{V2,}$ as well as the effect of stray-capacitance to the ground,C_{S1} and $C_{S2.}$

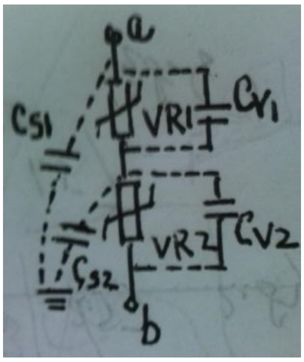


Figure 3.4.1 Two units of MOV connected in series

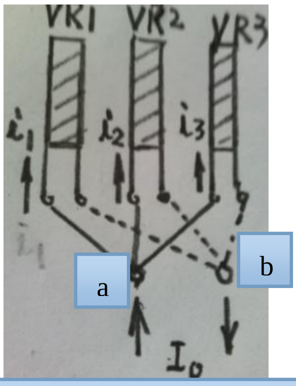


Figure 3.4.2 Three units of MOV connected in parallel

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3.4.3 parallel connection

A parallel combination of one or more units of MOV is often used , 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 form a special performance, in which each individual unit may be identical to or different from each other. Figure 3.4.2 showed a parallel combination of three units.

The key to achieve the goal by use of a parallel combination is that the total current I_0 shall be shared out between each individual unit in accordance with the design requirements throughout its entire service life, that is to say the current difference between individual current ($I_{1,}$ I_2, $\cdots I_n$) at the same voltage shall be within the designed limits during the entire life. If a unit shares a current which is beyond its specified share, then more and more shares of the current will pour into this unit which eventually fails at first.

To resolve such kind of problems, the V-I characteristic formula of MOV can be a right tool. An example is given below to show the calculation method for the current shares.

Three units of 34x34mm MOV were selected from a production batch, the voltage U_{1mA} of which were 458.9V(L), 476.2V(M), and 794.2V(H) respectively. Their V-I characteristic formulas at 8/20 impulse current were as below that were obtained by tests on them

$$U=10^y, \quad y=\frac{0.19\pm\sqrt{0.0361+0.1995\times\log(U/926.1)}}{0.09764} \qquad \text{(Sample L)}$$

$$U=10^y, \quad y=\frac{0.1854\pm\sqrt{0.03436+0.1879\times\log(U/971.45)}}{0.0939} \qquad \text{(Sample M)}$$

$U=10^y$,　　(Sample H)

The following Table was obtained from calculations by use of above formulas

Table 3.4.1 The currents in the parallel combination of three units (L,M.H)

Residual Voltage, V	8/20 current peak (A)					Ratio of Diff. to total
	Sample L	Sample M	Sample H	Total	difference	
700	1212	802	427.5	2442	784.5	32%
800	3321	2651	1948	7920	1373	17%
900	6677	5758	4602	17037	2075	12%
1000	1143	10349	8627	20119	2836	9.3%
1100	17830	16617	14216	48663	3614	7.4%
1200	25901	24721	21528	72150	4373	6%

Generally a right design for parallel combination of MOVs can be found via four steps:

* Step one -- Performance stabilizing process of the MOV-products which are intended for parallel combination
* Step two--Determine the V-I characteristic formulas of the stabilized MOVs.
* Step three--Establish the right parameters of the MOVs to be paralleled via calculations
* of the V-I characteristic formulas

Step four--

e current thru each unit in accordance with the design requirements. The aims of parallel commonly impulse current or energy, or providing back-up protection .The types and parameter ratings of each unit among the parallel combination may be the same or not, the key point lies in that the V-I characteristic of each unit should be known (provided by the manufacturer or tested by user itself),so that the current distribution among the parallel combination can be calculated and in accordance with the design requirements.

There is an ordinary situation where multiple MOVs worked in parallel but often being ignored, that is in a production or laboratory room, many equipments and instruments powered by the same phase of power frequency source, but different types of MOV being installed at the mains circuits of the equipments and instruments, in case that the phase of power source invaded by surge voltage, the surge current thru each MOV may differ considerably ,that may lead to failure of some MOVs. To avoid such type of failure, a co-ordination of such paralleled MOVs is necessary.

As for surge overvoltage protection ,multi-stage protection systems are often seen, for example，the MOV installed in power distributor and the MOV at the mains input of a powered equipment formed a two–stage surge protective system. It is necessary to co-ordinate the V-I characteristics of all MOVs in the multi-stage system ,so that no MOV(s) will be over-loaded by all expected surges happened in the system. An instance was given as below to show the method of coordination calculations.

For a power frequency source of 220V/50Hz, the two-stage protection as mentioned above was used. The MOV of the first stage was 34×34mm U_N=620V, maximum surge current rating 8/20-40kA.The MOV of the second stage wasφ 10mm, U_N=560V,maximum surge current rating 8/20-3.5kA. The maximum surge current at the installed field of power distributor was expected to be 8/20－20kA。The purpose of coordination calculations lies in that in case of 8/20－20kA happened at power distributor, whether or not the MOV of φ10mm, U_N=560V will be overloaded. The most severe situation lies in no any impedence between the two MOVs, i.e. the two MOVs being treated as parallel connection directly. The V-I characteristics of the two MOVs were as below:

1st. stage MOV (34×34mm)：$U = U_R \cdot I^B = 1702 \cdot I^B$， $B = -0.247 + 0.05436 \times \log I$

2nd stage MOV (φ 10mm)：$U = U_R \cdot I^B = 1091 \cdot I^B$， $B = -0.1812 + 0.06662 \times \log I$

Calculate the currents thru the two MOVs at given voltages of 950V～1650V by use of equations of（6.20）and（6.21）,the results of calculations were listed in Table 1. It is seen from Table 1 that :① If the total surge current is about 26kA (greater than the expected maximum value of 20kA), the current thru the 2nd stage MOV (φ10mm) less than 2.5kA，but its rating being 3.5 kA, so it is safe. ② The current ratio of 1st stage to 2nd stage is increasing with total current increasing.

Table 1 Current distribution of two stages

Residual Voltage （V）	Current thru MOV-φ10 I_2 （A）	Current thru MOV-34×34 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

3.5 Special functions of MOV in electric and electronic circuits

The basic and the most important functions of MOV lie in limiting transient over voltages for the purposes of the insulation coordination and /or EMC immunity. In addition to that some special circuit functions may be performed simply and /or at a low cost via utilizing MOV, Some of them are showed below

1) MOV functions as a voltage stabilizer in high voltage and small current d.c. circuits

2) MOV functions as a voltage sensing component

Figure 3.2.1 gives an example in which a varistor VR functions as a voltage sensing component to protect the circuit from being breakdown. The function of this circuit lies in driving a constant current into the load via the L-C-L network, the magnitude of the load current is roughly proportional to the source voltage U_S. The VR is in OFF state in normal operation of the circuit, in case of open-circuited of the load, the voltage U_{out} goes up and the VR turns conduction followed by switching off the source voltage U_s by a feedback system.

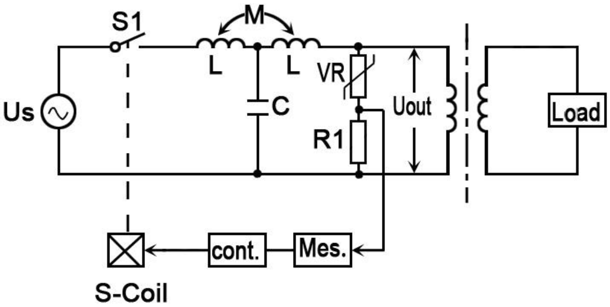


Figure3.5.1 The varistor VR functions as a voltage sensing component

3) MOV functions as a voltage equalizer, Figure 3.2.2 is an example

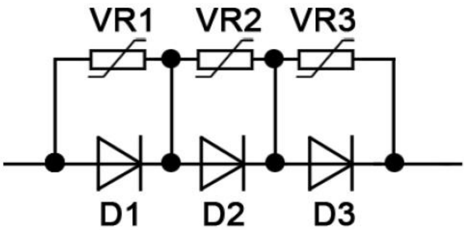


Figure 3.5.2 Equalizing the reverse voltage on each diode in a series diode chain

4) MOV functions as a voltage coupling (dropping) component. The circuit of Figure 3.2.3 is intended to test the load voltage at a constant current $I_L = |U_R| / R_Y$, in this case the voltage potential at point V_Z is zero; if I_L greater than $|U_R| / R_Y$, the voltage potential at point V_Z is positive, the base current of the transistor T goes upwards ,and the resistance of the T goes downwards causing the current I_1 to increase, which ,in turn ,forcing the current I_L to decrease, and vise verse. In this circuit the VR functions as a voltage dropping component .in order to lessen the power loss of the transistor T, and allow this circuit to operate at higher voltage than the permissible voltage of the transistor T.

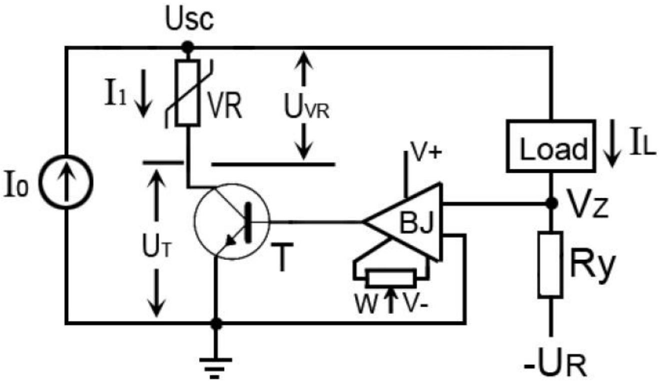
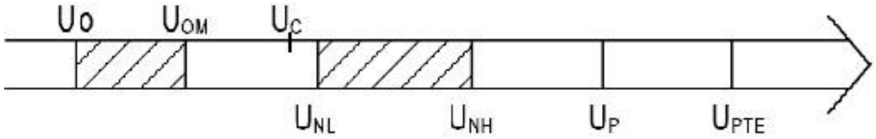


Figure 3.5.3 A circuit for varistor voltage U_{1mA} test by using VR as a voltage dropping component

capacitors shall be

3.6 basic quantitative relationships between a few voltages

There are several voltages involved in the power circuitry protection by use MOV as illustrated in Figure 3.5.1, the voltages should be in accordance with equation（3.5.1）～ equation（3.5.8）.



U_{PTE} — Maximum permitted surge voltage of the PTE
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 a.c.
U_{OM} — Possible maximum value of the system voltage
U_O — Nominal system voltage

Figure 3.5.1 Relations between the voltages as MOVs being used for power circuitry protection

1) The protection level U_P of the MOV and the maximum permitted surge voltage U_{PTE} of the PTE should be in accordance with equation (6.21). The factor (0.8～0.9) aims to counteract the effects of residual voltage increment cause by MOV's degradation and by the voltage drop on the connecting wires between the MOV and the PTE.

$$U_P \le (0.8\sim0.9)U_{PTE} \qquad (3.5.1)$$

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 (6.22).

$$U_{NH} < U_P / R_{RES} \qquad (3.5.2)$$

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 the point of view of MOV's normal production, at least 5% tolerance should be allowed for varistor voltage, i.e. the low limit U_{NL} should be in accordance with equation (6.23).

$$U_{NL} < 0.95\, U_{NH} \qquad (3.5.3)$$

4) From the point of view of the service life, the low limit U_{NL} of the varistor voltage tolerance should be no less than the MCOV (see 6.3.6):

Power frequency circuitry: $U_{NL} \ge 1.41 U_C$ (3.5.4)
d.c.power circuitry : $U_{NL} \ge U_{CD}$ (3.5.5)

other power circuitry: $U_{NL} \geq U_{Cx}$ (3.5.6)

Note: Equation (6.24.1) and equation (6.20) are the same.

5) According to the standard IEC62368-1,clause G10.2, the MCOV of an MOV should be no less than 1.25 times U_R, the U_R refers to the rated voltage of protected equipments or the upper limit of the rated voltage range.

$$U_C \geqslant 1.25U_R \qquad (3.5.7)$$

Generally speaking: $U_C \geqslant kU_{0M}$ ($k > 1$) (3.5.8)

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.

It is often the case that the equations of (6.21）～（6.25）can not be met at same time, because there is such a conflict that low residual voltage requests low varistor voltage U_N, but high reliability under system voltage and TOV stresses request high varistor voltage U_N, so that there is a trade-off between the two, and some special measures have to be used sometimes, for example using larger size MOVs to reduce residual voltage.

3.7 field installation and field routing inspection

3.8 safety measures

3.10 application data Table