Application of characteristic equation of ZnO non-linear resistor

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Abstract

The characteristic equations of ZnO non-linear resistor(MOV) were firstly presented in China Periodical "Electronic Components and Materials" in 2012.[1]

Since then they have been successfully used by many engineers to solve problems related to lightning protection by using of MOV and MOV-based SPD. In this paper the method to determine the equations and the mathematical expression of the equations are reviewed. Then four examples are given to illustrate how to solve the practical engineering problems by using these equations.

Keywords: ZnO non-linear resistor(MOV)
Resistance characteristic equations
V-I characteristic equations
Coordination of two MOVs

1. The method to determine the characteristic equations of an MOV and their mathematical expression

The method and the equations have been described in the Zhang, Shu and Wang paper [1] and are summarized below.

The method involves four steps:

(1)Test MOV samples to obtain *n*-pairs of data [I_i-U_i] over a specified current range, *n* can be from 3 to 10 in general.

(2) Calculate resistance for each data pair, $R_i=U_i / I_i$

(3) Calculate resistance fitting equation of [log*R*=f(log*I*)] by using the data of [$R_1,R_2 \ldots R_n$] and [$I_1,I_2 \ldots I_n$] in accordance with second-order polynomial function. Then the three equation parameters A_0, A_1, A_2 can be obtained, which are, respectively, the constant item, coefficient of the first order item and second order item.

(4)the resistance equation and *V-I* equation are expressed as follows,

①Resistance equation

$\mathrm{Log}(R)=A_0+A_1 \log(I)+A_2 [\log(I)]^2$ (1.1a)

or

$R=10^{A0}\times I^b$, $b=A_1+ A_2 \log(I)$ (1.1b)

②Voltage equation

$\mathrm{Log}(U)=A_0+(1+A_1) \log(I)+A_2 [\log(I)]^2$(1.2a)

or

$U=10^{A0}\times I^B$, $B=(1+A_1) + A_2 \log(I)$ (1.2b)

This equation is applicable to calculate the voltage when the current *I* is known.

③Current equation

$I=10^y$

$$y=\frac{-(1+A_1)+\sqrt{(1+A_1)^2+4A_2\cdot\log(U/10^{A0})}}{2A_2}$$ (1.3)

This equation is applicable to calculate the current *I* when the voltage *U*is known

④Voltage ratio equation

$k_V=\frac{10^{A0}}{U_{1mA}}\times I^B$ $B=1+A_1+A_2\times logI$

(1.4)

Where "U_{1mA}" is the varistor voltage

⑤ Voltage non-linear index α_{2I}

$\alpha_{2I}=\frac{1}{B_1+(0.301+\log I)\times A_2}$

(1.5)

Where α_{2I} denotes the voltage non-linear index of an MOV over the current range of (I～$2I$).

2. The characteristic equations used for co-ordination between cascaded surge protection

It is a common practice to install two or more cascaded MOVs for lightning surge protection, see Figure 1.

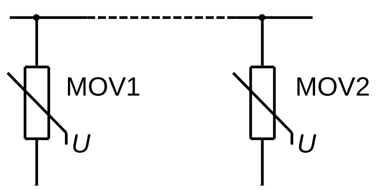

Figure 1 Cascaded MOVs

For example, MOV1is installed in 240V power incoming port of a building, while MOV2is installed in 240V power supply circuit of an instrument. In such a case the two MOVs have to be coordinated to fulfill following requirements [2].

⑴The two MOVs should withstand the expected incoming surge stress, that means the ratings of two MOVs should be respectively larger than their imposed maximum surge current.

⑵ The clamping voltage across the№2-MOV should be less than a specified level *Up*.

It is difficult to meet above two requirements. But with the proposed characteristic equations of the MOVs, it becomes easy. The following five-step procedure should be used when two MOVs need to be coordinated.

⑴ Identify the surges expected to occur at the installed position of theMOV1,for both long and short waveshapes because they have different stress on the MOV.

The long waveshape surge is usually represented by 10/1000, 2ms pulse, or 10/350 test currents, while the short surge by an 8/20 impulse current.

⑵Identify the maximum allowable clamping voltage on MOV2.

⑶ Make a preliminary choice of the two MOVs according to the ⑴ and ⑵, then get the *V-I* characteristic equations of the two MOVs, and their surge current ratings for long and short surge waveshapes. Generally these data could be available from the manufacturers, or otherwise via sample testing.

⑷ Calculate surge current sharing between the two MOVs, following is an example:

①expected maximum incoming surge current is 8/20-20kA.

② the preliminary selected MOVs and their *V-I* characteristic equations are given below,

MOV1: 34×34mm, U_{1mA}=620V, allowable maximum 8/20 surge current 40kA, itsequation parameters of the *V-I* characteristic: A_0=3.231, A_1=-1.247, A_2=0.05436

MOV2:φ 10mm,U_{1mA}=560V, allowable maximum 8/20 surge current 3.5kA, itsequation parameters of the *V-I* characteristic:A_0=3.038, A_1=-1.1812, A_2=0.06662

③ Because the two MOVs were connected across the 240V power line, if the impedance of the connection conductors between the two MOVs could be negligible, hence the clamping voltages U_{cla} on the two MOVs were considered to be the same, then a few arbitrary selected values of U_{cla} were listedin the column (a) of the Table I.

The surge currents respectively following through the two MOVs at each clamping voltage U_{cla} were calculated according to the parameters of the *V-I* characteristics showed in ②, and the outcomes of the calculation were listed in column (b) for MOV1 and column (c) for MOV 2.

TABLEI

Current share between two MOVs

U_{cla} (V)	I_{P1} (A)	I_{P2} (A)	$I_{P1}+I_{P2}$ (A)	I_{P1}/I_{P2}
(a)	(b)	(c)	(d)	(e)
950	958.9	216.1	1175	4.43
1050	2591.	422.9	3014	6.13
1150	4974	695.4	5669	7.15
1250	8201	1037	9238	7.91
1350	12344	1449	13792	8.52
1450	17461	1932	19393	9.04
1550	23600	2488	26089	9.48
1650	30802	3117	33919	9.88

It becomes clear that with increasing of the incoming surge current, the current share through the MOV2 decreasing. And at the expected maximum incoming surge current (I_{p1}+I_{P2})of 8/20-20kA, the current through the MOV2 is less than its allowable value (2.5kA). that is to say it is safe.

The same calculations as for 8/20 incoming surges can be applied to long waveshape surges as well.

Ifone or both calculation results for short and long surge waveshapes showed that the rating coordination requirements are not fulfilled, then a different pair of MOVs needs to be selected and the step ② and ③ repeated.

3.The characteristic equations application for MOV assembly of parallel connection

Parallel connection of MOVsoccurs for one or more of the following purposes:

① higher surge current rating
② higher surge energy rating
③ lower clamping voltage
④ providing backup surge protection

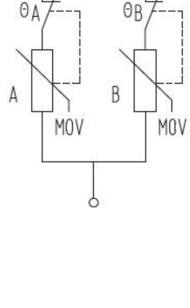

Figure 2. Assembly consists of two discs with thermal disconnectorsfor backup MOV

The assembly consists of two or more MOV discs whichusually, but not always, having the same part number. Ideally an assembly of two discs has double surge current rating and double energy rating when compared with the single disc, but its clamping voltage reduction (δU_{cla}) varies depending on the voltage non-linear index ∝of the disc, as showed in Table II, which indicated that with increasing of the surge current peak, theclamping voltage reduction caused by two paralleled discs will increase due to corresponding reduction of ∝value of the disc

TABLEII

Clamping voltage reduction (δU_{cla})

∝	δU_{cla}, %
20	3.4
10	6.7
5	12.9
2	29.3

It is mentioned that a reliable MOV surge protector should be so designed that the protection function shall be maitaned all the time which is achieved by use of an assembly consists of two discs, A and B, with thermal disconnectors, as shown in Figure2. This design is also termed a backup protection circuit because if one disc fails, it is disconnected from the circuit, but the other still play the surge protection role, and the disconnection can create alarm signal or visual indication.

The key point for above mentioned assembly lies in that each disc in it should shares the same portion of current as a surge imposed on the assembly, which means the *V-I* property of each disc was the same, but it was an ideal situation, as a matter of fact, it isimpossibleeven if the discs are of the same part number and same U_{1mA}.Therefore a realistic goal may be that within an interested clamping voltage range, the deviation of the impulse resistance (and surge current as well) between the paralleled discs being within a specified limit(for example 10%).

Examplevalues are given below.

- TwoMOVdiscs
  34x34mm-621-135V/mm
  Measured U_{1mA}: A-660V
  B-660V

- 8/20 surge current test
  A-15.4kA/1560V, 30kA/1880V
  B-15.4kA/1600V, 30kA/1920V

- Calculate the resistance (mΩ)
  A-1560V-101.3 , 1880V-62.7
  B-1600V-103.9, 1920V-64

- Consider the *V-I* property as linear within the current range of (15kA～30kA),write the equations *R=f(U)* by using of above voltage-resistance data
  A-*R*=289.6-0.1207x*U* (3.1)
  B-*R*=303.4-0.1247x*U* (3.2)
- If clamping voltage rangeof interest is 1500V to 1700V), then in that voltage range the MOV currents should be as the same as possible. Table III lists resistances of the two MOVs.

TABLE III

Resistance(*R*)of the two discs

Voltage (V)	A-*R* (mΩ)	B-*R* (mΩ)	A+8 (mΩ)
①	②	③	④
1500	108.6	116.4	116.6
1600	96.5	103.9	104.5
1700	84.4	91.4	92.4
1700	84.4	91.4	92.4

- Inserting a coordination linear resistor of8(mΩ) into MOV A to raise its total resistance to the values as showed in column ④ of Table III, helps to equalize the two paralleled discs of the resistance values and results in thecurrent sharing being within 1%.

4. The resistance equation used for finding the current following through the object to be protected by the MOV[3]

Figure.2. showed a commonly used a.c to d.c power supply circuit, a 50Hz/240V voltage is fed to its input port. The MOV VR is installed to suppress incoming surges.

When the circuit is subjected to the required surge test the capacitor C failed attimes. On a careful inspection, we found that the capacitor C has been damaged by over-current rather than by over-voltage. As the capacitor C fails as a result of the applied surges, the surge let-through current must be exceeding the capacitor surge withstand capability. The equivalent input resistance R_{in} of the rectifier arrangement in conjunction with the MOV, VR, U_{cla} allows too much let-through current, I_C in the capacitor.

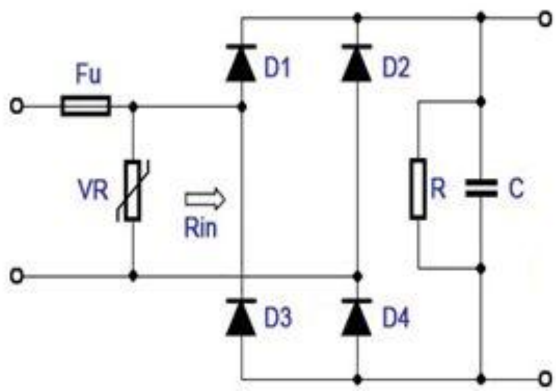

Figure.2. A rectifier and filter circuit protected by MOV(VR) against lightning

This problem has been solved with following steps:

① The surge current withstanding of the capacitor C was ascertained to be 8/20, 600A.

② The equivalent input resistance of the protected circuit Rin=1.76Ω that was measured by applying a surge current of 8/20, 100A without the MOV, VR, (the measured voltage being 176V)

③ An MOV of Φ14mm, U_{n0}=430V was used for VR in Figure3, its resistance equation from testing can be expressed as follows:

$R_{VR}=10^y$

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

④ Calculations for surge current flowing into the capacitor C,

TABLE IV
Calculations related Fig. 2

I_{VR} A	V_{VR} V	I_C A	I_S A	I_{VR}/I_C
100	670	381	481	0.26
200	700	398	598	0.50
500	769	437	937	1.14
1000	848	482	1482	2.07
2000	958	545	2544	3.67

Note:
I_{VR}- Supposed current passing thru the VR
V_R- Voltage on the VR at I_{VR} （$V_R=I_{VR}\times R_{VR}$, where the R_{VR},see the equation in ③）
I_C-Current pouring into the C(=V_R/1.76)
I_S-Total current(=$I_{VR}+I_C$)
I_{VR}/I_C-Current ratio

⑤ Conclusion

The design criteria was that the current pouring into the C shall be no more than 600A at maximum incoming surge *I*s=1500A. Table 3 indicated that this criteria has been fulfilled.

5. The characteristic equations used for finding the maximum clamping voltageamong an interested MOV group

The goal of MOV clamping voltage test is to determine the highest value among an MOV product distribution, which is represented by the tested samples. Because the MOV clamping voltage is closely related to its varistor voltage U_{1mA}, those units that having top tolerance value of U_{1mA} will have the highest clamping voltage among the MOV product distribution. But it is very difficult to pick up such units during sampling procedure. Hence it is necessary to convert a sample's measured clamping voltage values to the highest value of the product represented by the samples, which could not be done until the presentation of MOV's *V-I* characteristic equations [1].

Now this problem can be solved by using following steps,

- Samples:

Three samples shall be selected from the interested group , their varistor voltage (U_1) shall differ from each other by 3% or more, for example:

An MOV group of 34x34mm, nominal U_1=470V.

TABLEV
Selected samples

U_{1L}=458.9V	δU_{1L}=-2.36%
U_{1M}=476.2V	δU_{1M}=+1.32%
U_{1H}=494.2V	δU_{1H}=+5.15%

- Measure the clamping voltages of the three samples over a 8/20 current range of 500 A to 50 kA, and calculate clamping voltage equation coefficients as shown below,

$U_{claL}=923xI^B$, $B=-0.1893+0.04872\times\log(I)$
$U_{claM}=959xI^B$, $B=-0.1822+0.04652\times\log(I)$
$U_{claH}=1034xI^B$, $B=-0.1872+0.04666\times\log(I)$

- Calculate clamping voltages at selected surge currents by using above clamping voltage equations, as showed in Table VI.

TABLE VI
Clamping voltages at 4 arbitrary selected surge currents

I_p A	U_{claL} V	U_{claM} V	U_{claH} V
10K	917.8	993.7	1028
20K	1128	1145	1181
30K	1243	1255	1293
40K	1336	1344	1293

- If the clamping voltage at 8/20, 20kA is specified, the three clamping voltage values (1128 V, 1145 V and 1181 V) shall be fitted to the three tolerance values (-2.36, +1.32, +5.15), see Table V, for fitting equation of second-order polynominal equation, which yielded following equation:

$U_{cla}=1137+5.282\delta U_1+0.6365\delta U_1^2$ (Eq.5.1)

From this equation, we can say that the MOV unit of nominal U_1 (δU_1=0) among the inspected group has the nominal clamping voltage of 1137V at 8/20, 20kA, and the MOV unit of the maximum U_1 tolerance (δU_1=+10%) has the clamping voltage of 1253V.

6. Summary

The resistance equations and *V-I* characteristic equations are useful engineering tools for the application and fabrication of MOV components and MOV-based SPDs, These equations permit an accurate quantitative analysis to be done over a current range of a several order of magnitude.

The voltage and current parameters are traditionally used for measurements and calculations related with MOVs, but engineering practice in recent years demonstrated that the resistance parameter may be more appropriate solution for analyzing some problems.

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Background

Since the first publication of the paper related to MOV's V-I characteristic equations in 2012 in China, they have been widely accepted by experts from both China and abroad.The first international presentation of the paper was made in 8th APL conference in 2013 in Soul, Korea.

And now the equations have been accepted by the three

International Standard organizations (IEC-TC40, IEC-SC37B, and ITU-T/K)。

Inrecent year the Engineers in surge protection circle have solved many practical engineering problems by use of the equations, some of which are given in this presentation.