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Some Technical Progress in Varistors made in China

In recent years a great progress in varistor technology has been achieved in China not only in fabrication technology but also in application fields and skills, as well as in some theoretical topics. In this presentation three topics are to be presented

1, Varistor's voltage-current (V-I) characteristic equations

2, Varistor's service life evaluation technology

3, Subjects to be studied for further step

Topic1 Varistor's voltage-current (V-I) characteristic equations

1.1 Early equations to describe the V-I characteristic

① Empirical equation

$I = A \cdot U^{\alpha}$ or $U = C \cdot I.^{\beta}$ (1.1)

Where : U is the voltage on the varistor as a current I I passes thru it.

A and C are constants which depend on individual varistor,

α is named voltage non-linearity index, $\alpha \geq 1$.

β is named current non-linearity index, $\beta \leq 1$. And $\beta = 1/\alpha$

This equation is applicable only to a narrow current range in which the α (β) value can be considered as a constant, therefore it is not commonly accepted

②Equivalent circuit equation

For general applications, the behavior of a varistor in electric circuits may be described by an equivalent circuit like Fig.1. Herein:

C_V - an inherent capacitance of the varistor,

R_V -non-linear resistance that varies from the infinite to zero with the current variation

R_G - series resistance consisting mainly of ZnO grain resistance

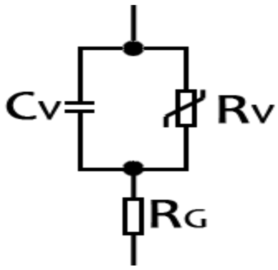


Fig.1 Equivalent circuit of a varistor

In most applications the resistance R_V being much smaller than the reactance of C_V , therefore the equation (2) can be deduced

$$U = I \cdot R_V + I \cdot R_G = CI^{\beta} + I \cdot R_G \qquad (1.2)$$

The deviation of the calculated values by using equation (2) from the measured values is big, usually 6%～10%, over a current range of two decades is considered, that's why it does not get a wide application as well.

1.2 What are the new V-I characteristic equations?

The new V-I characteristic equations were first reported in 2012 in China, and presented in 8th 2013 Asia-Pacific International Conference on Lightning, Jun. 26-28, 2013, Seoul, Korea, since then they have been increasingly utilized in engineering calculations due to their three remarkable features:

①Covering a current range of more than two decades.

②Deviation from the measured values being less than 5%.

③Easy to be available via testing and calculation

In fact the new V-I characteristic equations are 2nd-order polynomial fitting equations which can be obtained by fitting the resistance values of the varistor to their correlative current values. The forms of them are as below, they are to be used for different calculation purposes

①Resistance equation

$$\log(R) = A_0 + A_1 \cdot \log(I) + A_2 \cdot [\log(I)]^2 \qquad (1.1a)$$

or $$R = 10^{A_0} \times I^b \quad b = A_1 + A_2 \cdot \log(I) \qquad (1.1b)$$

② Voltage equation

$$\log(U) = A_0 + (1 + A_1) \cdot \log(I) + A_2 \cdot [\log(I)]^2 \qquad (1.2a)$$

or $$U = 10^{A_0} \times I^B, \quad B = (1 + A_1) + A_2 \cdot \log(I) \qquad (1.2b)$$

③ Current equation

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

④ Voltage ratio equation

$$k_v = \frac{10^{A_0}}{U_{1mA}} \times I^B \qquad B = 1 + A_1 + A_2 \lg I \qquad (1.4)$$

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

⑤ Normalized voltage ratio (k_{v0}) euation

$$k_{v0} = \frac{10^{A_0}}{U_{1mA0}} \times I^B \qquad B = 1 + A_1 + A_2 \cdot \log I \qquad (1.5)$$

Where "U_{1mA0}" is the nominal varistor voltage

1.3 Application examples of V-I characteristic equations

1.3.1 Calculate current shares in paralleled varistors and in multi-stage SPDs based on varistor technology

Example A

VR1, 34x34mm, U_{1mA}=585.6V, $U=1653 \times I^{B}$, B= -0.2536 + 0.05582 x lgI

VR2,34x34mm, U_{1mA}=649.6V, $U=1788 x I^{B}$, B=-0.2492+0.05452x lgI

Note: VR1 and VR2 were selected from the same production lot

Example B

VR1, 34x34mm, U_{1mA}=620V, $U=1702 \times I^{B}$, B= -0.247 + 0.05436 x lgI

VR2,φ 10mm U_{1mA}=560V, $U=1091 \times I^{B}$, B=-0.1812+0.06662x lgI

Example A				Example B			
Voltage (v)	**Current Thru VR1**	**Current thru VR2**	**Current ratio I_1/I_2**	**Voltage (v)**	**Current Thru VR1**	**Current thru VR2**	**Current ratio I_1/I_2**
950	1562.9	520.24	**3.00**	950	958.9	216.1	4.43
1000	2452.1	1138.2	**2.15**	1050	2591.	422.9	6.13
1100	4816.6	2810.3	**1.71**	1150	4974	695.4	7.15
1200	8036.9	5199.6	**1.55**	1250	8201	1037	7.91
1300	12182.	8389.4	**1.45**	1350	12344	1449	8.52
1400	17307	12443.	**1.39**	1450	17461	1932.	9.04
1500	23456.	17414.	**1.35**	1550	23600.	2488.	9.48
1600	30666.	23346.	**1.31**	1650	30802.	3117.	9.88
1700	38966.	30275.	**1.29**				
1800	48380.	38233.	**1.27**				

1.3.2 Determine the maximum limiting voltage among a product lot

As for an acceptance inspection of a lot of varistor products, the limiting voltage (U_{LV}) means the highest value of the $U_{LV,}$ among the lot .As for a type test, the value of U_{LV} should be the highest one among all units represented by the tested samples. Generally the higher the varistor voltage (U_{1mA}.) is, the greater the limiting voltage (U_{LV}) will be ,that is to say it is necessary to convert measured U_{LV} values from the tested samples into those varistor's U_{LV} that have the maximum varistor voltage U_{1mA}. in terms of specified tolerance . By use of V-I characteristic equations, we are in a position to do this conversion via an equation as below:

$$U_{LV} = a_0 + a_1 \cdot (\delta U_{1mA}) + a_2 \cdot (\delta U_{1mA})^2 \qquad (1.7)$$

An example is as below.

Varistor Size 34x34mm, nominal varistor voltage U_{1mA0}=470V, tolerance ±10%

Variations of limiting voltage according to the tolerance of varistor voltage

δ_{U1mA}%	-10	-8	-6	-4	-2	0	+2	+4	+6	+8	+10
U_{LV} (V)	1021	1026	1033	1040	1048	1057	1067	1078	1090	1102	1116

1.3.3 Determine the surge current into the object to be protected by varistor

It is well known that varistors possess two major functions that are limiting surge voltage and diverting surge current. In case that the impedance of the protected object is low enough as compared with varistor's resistance at surge current, the surge current into the protected object has to be evaluated by use of varistor's R-I equation (Equation 1.3). A typical example is showed below

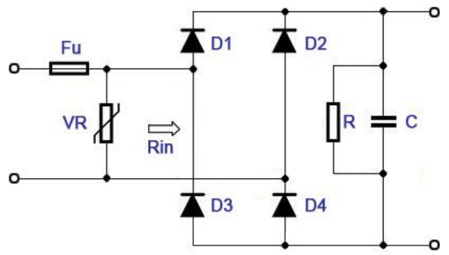


Fig.2 Surge current into the P.O.
VR—varistor Φ 14mm, U_{n0}=430V
resistance formula $R_{VR}=10^y$
$y=2.96-1.18\times \log I + 0.0565\times (\log I)^2$
Measured resistance of the protected object (P.O) $R_{in}=R_{PO}=1.76\Omega$

Current shares between VR and P.O

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

Topic 2 Service life evaluation technology

2.1 Market demands for life-rated varistors

① Varistors to be installed in very important equipments and locations should be life-rated

② aristors to be installed at those places where maintenance is hard to be available. Presently 20- years life is required by many users.

2.2.Varistor's service life involves two elements:

① Impulse current stress life, expressed in impulse numbers n.

② Voltage-temperature (U-T) stresses life (including humidity), expressed in time duration hrs.

The impulse current life shall be converted to time length according to the equation below

$$\overline{N} = \frac{[As]_P}{[As]_{EXP}} \qquad (1.10)$$

Where: $\overline{N}$ — expected service life in years.

$[As]_P$ —Varistor's amp-second resource that is able to be available by conversion from the impulse life

$[As]_{EXP}$ —Annual average Amp-second value of impulse current at installation locations.

2.3,Procedures and methods for evaluation of impulse current life

It is well known that varistor's impulse current life can be described as a set of curves like Figure 2.3.1 and Figure 2.3.2 showed, but there is a question herein that how to determine the n value of each curve?

Varistor engineers in china have proved that the failure rate of varistors subjected to impulse current stresses is in accordance with Weibull distribution, from which varistor's "median life" n_{med}, "average life" n_{av}, and "guaranteed life" number (n_{gua})are available. That means there are three types of life curves for one part Number of varistot product. Based on which the Procedures and methods for evaluation of impulse current life have been established

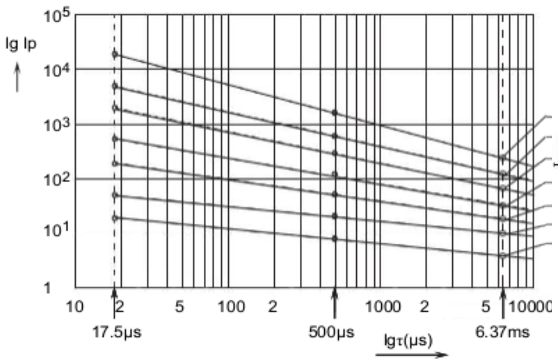


Figure 2.3.1, an example of impulse life curves logI$_P$= f (logτ) ,n=constant

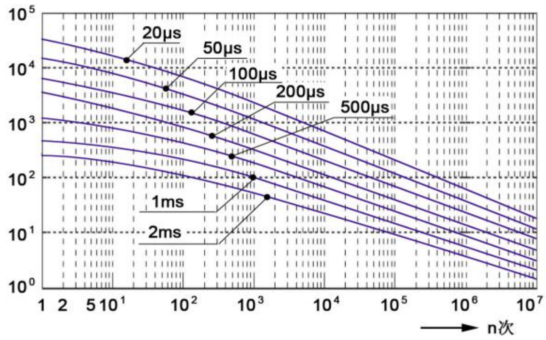


Figure 2.3.2 an example of impulse life curves logI$_P$= f (log n) ,τ =constant

2.4Procedures and methods for evaluation of U-T stress life

A Proposal of the procedures and methods for evaluation of U-T stress life has been made by varistor engineers in china, which is based on the standard MIL-STD-690D " Failure Rate Sampling Plans and Procedures". This life is described by MTTF （Mean Time to Failure)

The key points of proposed " Qualification test method for 20 years U-T stress life" are as below:

① MTTF=24x365x20=175.2(khrs)≈180(khrs)

② From MIL-STD-690D, Table 1:

Confidence Level=60%, Number of failures permitted C=0,

Qualified Failure Level M: 1%/1000h

Cumulative unit-hours of the life test : 91.6 k uh.

③ Samples

Samples for qualification tests shall be selected from a production run and produced with equipment and procedures normally used in production, and all lots produced during the production period are represented.

The varistor voltage deviations between samples among a sample group shall be within 1%, so that all samples of the group absorber an approximate same initial power loss

④, Test perio : 2000-hours, unless otherwise specified

⑤, Sample numbers may be either (a) or (b)

(a) N= (Total UH in Table 1) / 2000

(b) N_1+$N_{2,}$ N_1-tested under rated voltage/temperature stress

$N_{2.}$-tested under the accelerated stresses with acceleration factor AF.

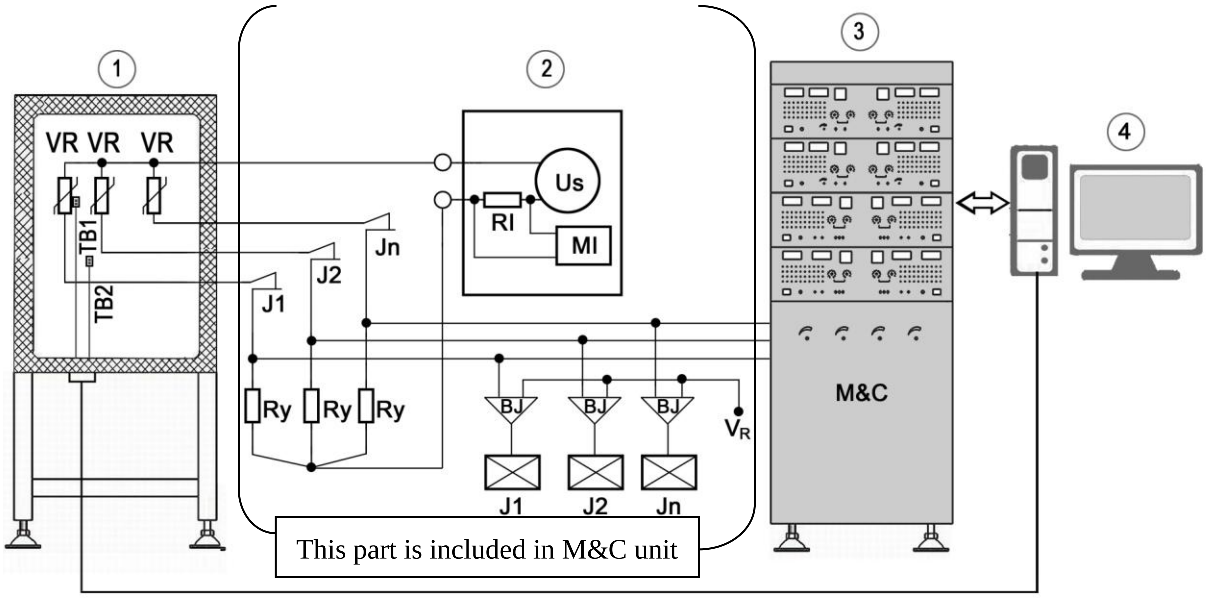
⑥ Failure criteria

A steady increase and beyond a specified limit of the power loss or current of the sample shall constitute a failure.

⑦Pass criteria for the qualification test

Number of failures shall not exceed 1.0.

⑧Test system



Test system

①--Test chamber at specified temperature

②--Test voltage source (a.c. or d.c. or other voltage source)

③—Measuring and control unit

④- Computer

VR—Tested varistors

TB1—Temperature sensor (attached on one sample surface of a sample size)

TB2—Temperature sensor (chamber temperature)

Ry—Current sensing resistor for each sample

J1,J2, …and BJ—Over current protection to turn OFF the sample when its current beyond a specified limit.

Topic 3 Subjects to be studied for further step

3.1 Effects of interactions between various stresses on the varistor’s life

3.2 Perform tests for determination of AF(Acceleration Factor) of various stresses

3.3 Study effects of continues current (C.C) on the varistor’s life. The c.c denotes a current the duration of which ranging from tens of millisecond to a few seconds

3.4 Effects of abnormal operation conditions on the varistor’s life, especially see environment, high temperatures, and high humidity.

3.5 Techniques of quick reliability screening

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