The MOV computer models for thermal – electric analysis

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Abstract: The main theme of this article is the mechanical and the thermal resistance of zinc - oxide varistor for class I and II during the operation process against surge currents of nominal values declared by manufacturers. The article is focused on few computer and mathematical analysis of several models in overvoltage protection area. The first part consists from the modelling and the behaviour of varistor electric properties. The second part deals about the computer model for the thermal – electric simulation with finite element method.

Key words: *MOV, computer model, thermal breakdown, surge current, FEM.*

1. Introduction

The successful operation against the surge and pulse currents is defined by individual Slovak Technical Standards (STN EN 61643-11 a STN EN 61643-331). The industrial process of the sintered grains of metallic oxide ceramic allows applying this basic element in the overvoltage protection area. The technical standards exactly define the usage and operation process of this element in each class of overvoltage protection level for nominal values of currents. The big attention is focussed to the substantive usage of the mathematical and computer solution of many analyses presently. Such solutions have doubtless advantages, especially for new experiments and measurements. Of course there is necessary to compare the results of computer analysis with experimental measurements.

2. Metal oxide varistor

Varistor is non-linear resistor with symmetrical and non-linear V-I characteristic. Older types were made form SiC, now they are made from ZnO, which is mixture of metal-oxide in 95% share. The rest are admixtures for higher stability of varistor and for better non-linearity. The admixtures are Bi_2O_3, TiO_2, CoO, MnO and Sb_2O_3. The MOV are fabricated from sintered zinc oxide powder with admixtures to a ceramic part. The temperature of the fabrication process is 1250 – 1400 °C and it depends on the protection level of usage. Each zinc oxide grain of the ceramic acts as if it has a semiconductor junction at the grain boundary [1]. The VI characteristic of varistor is created from a few of thousand of connections of the diodes. Taking to the account the symmetrical VI characteristic, there is no rule to the direct of connection of varistor based surge arresters.
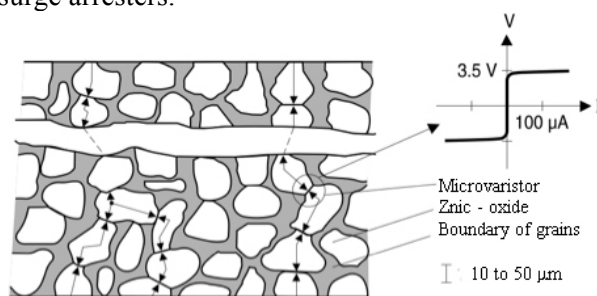

Fig. 1 The microstructure of zinc oxide varistor [2]

In case the voltage level is low, the varistor is almost in non-conducting mode and his resistance is substantive. When voltage rises up varistor crosses into conducting mode and the value of resistance is low. The resistance of varistor is muffling oscillations created during activity of overvoltage protection system [3].

$$I = kV^{\alpha} \qquad (1)$$

The characteristic of varistor is defined with the relation (1), where k is the constant of ceramic part (depends on a type of MOV), and the exponent α ($1 \leq \alpha \leq \infty$) defines the level of non - linearity. This characteristic is usually contained for values $\alpha > 20$. The exponent α is determined for VI characteristic or from relation (2):

$$\alpha = \frac{\log\left(\frac{I_2}{I_1}\right)}{\log\left(\frac{U_2}{U_1}\right)} \qquad (2)$$
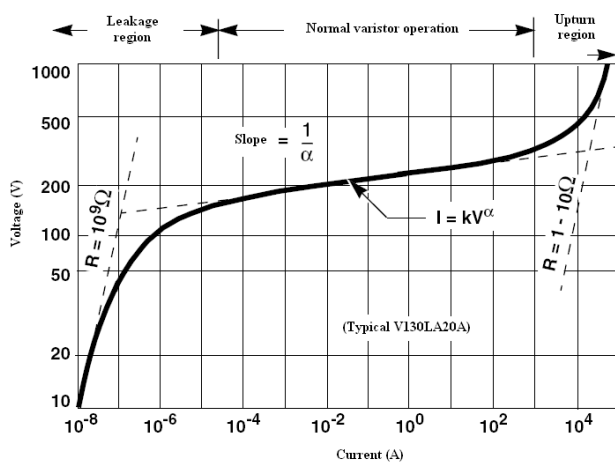
Fig. 2 VI characteristic of zinc oxide varistor

Just a few nanoseconds take crossing to conducting mode. This crossing into conductive mode caused by connection of overvoltage to varistor's clamps and transferring the energy of overvoltage to the ground creates the fundamentals of varistor protection level. The isolation of protected device is stressed by residual voltage caused by crossing pulse current through varistor. Between elementary electric characteristics belong: high capability, fast response time, ability to absorb high value of energy, small value of follow current, high value of transient current. The stability of VI characteristic depends on the material composition and the fabrication process (the temperature and the time of sintering, the quantity of flatling substance) [4].

3. Physical and stochastic models of lightning

The difference between physical and stochastic models is that physical models are generally focusing to simulation of propagation of the leader. The result of this analysis is set of equations for conservation of momentum, energy and continuity equation. Some models were used for derivation of parameters for practical utilize, for example U50 breakdown voltage, time of breakdown, calculation of pulse current and time of pulse current. On the other hand the complexity of physical models has several disadvantages such the absence of ability to reproduce the random behaviour of the propagation trajectory of leader. They are not preferred for analysis of lightning hit to buildings or study the efficiency of lightning protection system. The stochastic models are primary based on electric field. They use rules of probabilities to predict propagation of leader channels of lightning. The possibilities of reproducing random behaviour of trajectory of leader and the ability of 3-D simulating make them very suitable. There are used for study of lightning hits to objects and efficiency of overvoltage protection system [5].

4. The definition of operation process of MOV according the technical standard STN EN 61643-331

The basic properties and characteristic of metal oxide varistor are described in the technical standard STN EN 61643-331. They may be provided or not with electrodes, encapsulated or not in resin, and may be fitted with wires or brackets for connection purposes. They may be used alone or in conjunction with other MOV or other components in surge protective devices (SPDs – Surge Protective Device). The MOV is characterized with following parameters: clamping voltage V_c, maximum discharge current I_{max}, maximum continuous voltage V_M, standby current I_D and capacitance C_V.

The degradation fault mode of MOV: In this mode, an MOV has a nominal varistor voltage, of less than 90 % of a pretest voltage value. Since the nominal voltage is used as a basis of failure criteria, the selection of the test current can affect a failure evaluation. A typical value recommended for the test current is 1 mA. In the ***short – circuit fault mode***, the MOV resistance is permanently reduced to less than 100 Ω (≥ 10 mA) with 1 V [6].

5. The computer models of MOV for analysis of electric properties

IEEE model of varistor [7, 8] is probably the most accepted computer model. The main problem of mathematical simulations of electric circuits with varistor is related to the simulation of non - linear resistance for his V-I characteristic. Non - linear resistance was modelled as voltage controlled voltage source or voltage controlled current source. The varistor model with voltage controlled voltage source is shown on Fig. 3. The capacitance of varistor is omitted.

This method of modelling gives satisfactory results if the is one non - linear element. On the other hand, the IEEE varistor model has at least two non - linear elements in parallel combination.
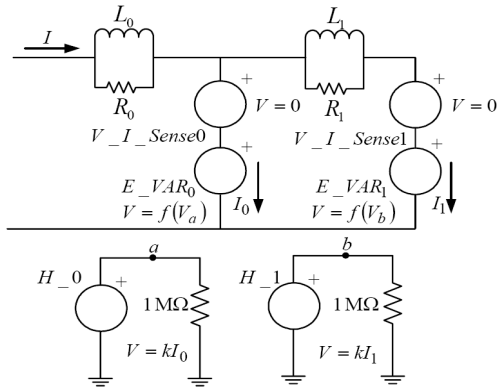
Fig. 3 The varistor model with voltage controlled voltage source

The current is divided between non-linear branches according the inductance L1 and the increase of surge pulse, at the moment when the current is applied to the model. While the time of rise, the inductance L1 blocks second branch. The first branch takes more current. Increased current of second branch is also limited by the inductance L1. When the current disappears, the second branch takes control over remains of current. The disadvantage is the equalization of potentials in both branches in case the current in first branch is disappearing. The solution can be to connect voltage controlled switch that reacts in case of current drop under specified value. The second problem is relevant to some parameters such as R1 a L1. The mathematic stability holds, but after eliminating pulse current is still current flowing in both parallel branches. In such case the solution can be to connect diodes to both branches to eliminate the flowing current. Of course, necessary is to locate the diodes for each direction of pulse current flow.
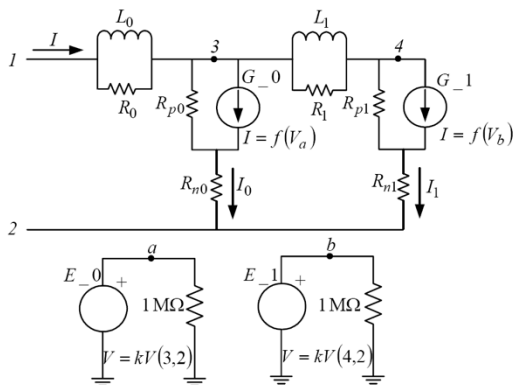

Fig. 4 The varistor model with voltage controlled current source

The alternative to above simulation model is the model with voltage controlled current source. This is typical solution since varistors are located between the phase and the ground. Current sources are defined with large internal resistance. According this fact the first branch cannot be short-circuited and numerical oscillations are avoided. In this model is the capacitance omitted too (Fig. 4) [9].

Realized simulations show some disadvantages of implementations. Depending on time of crest is surge pulse divided between resistances A0 and A1.

The shape of A0 and A1 curves is predefined and the simulation model is tuned with inductances L0 and L1 to agree with real MOV varistor. Resistances R0 and R1 keep the stability of model. The behavior of MOV varistor is simulated for pulse 8/20 μs (Fig. 5). The amplitude of pulse current is 10,6 kA for circuit parameters: LO = 29 nH, L1 =50nH, R0 =145Ω, R1 =100Ω, and rated voltage is Vn = 320 V. The result of simulation of dynamic characteristic is shown in Fig. 5.
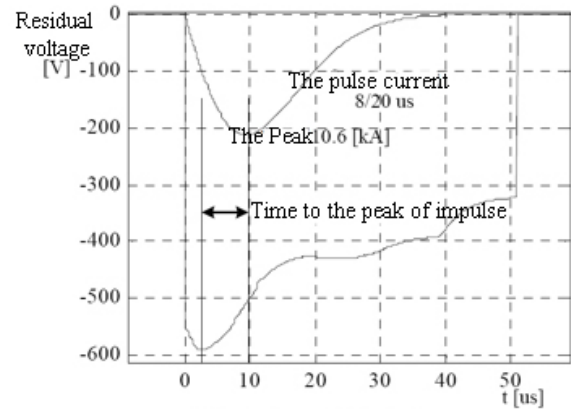
a) The Varistor residual voltage
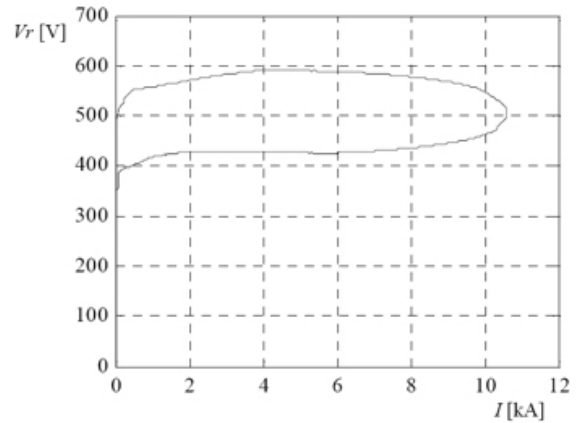
b) The dynamic characteristic of varistor

Fig. 5 The results of simulation for surge current pulse 8/20

As we can see, higher residual voltage requires higher value of inductance L1. The Value of inductance L1 has to be big enough to block the current flow through non-linear element A1. The characteristic of dividing of current between non-linear elements is shown in Fig. 6 [9].
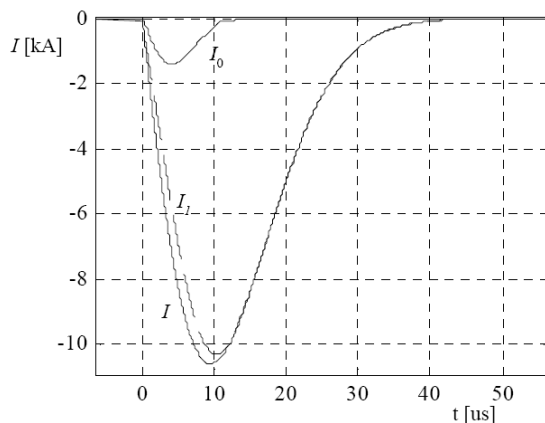

Fig. 6 The curve of current sharing between non – linear elements

Pinceti and Giannettoni proposed frequently dependent varistor model (Fig. 7) made on basics of simplified IEEE model [9]. Diaz and Fernandez made one more step ahead. The simplified solution (Fig. 8) of them can be determined from the manufacturer catalogues [10].
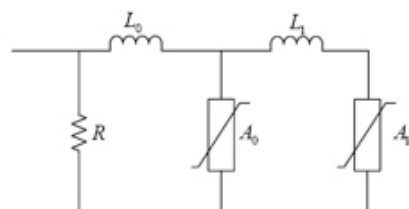

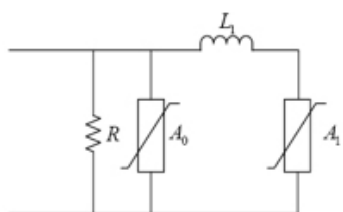Fig. 7 Pinceti & Giannettoni Model

Fig. 8 Fernandez & Diaz Model

Aleš Štagoj, Vladimir Murko and Andrej Pirih have attended to the problem about the ability of MOV to resist the high - energy lightning impulse discharge [11]. Their intention was to describe a new type of MOV, that can safely resists and takes under control the discharge much more higher than the energy of lightning impulse without destruction. The main disadvantage is no more the usage the MOV as surge protective devices in class I, but the degradation of electric properties caused by pulse stress.

The results of this study je clarifying of many advantages of MOV as lightning arresters in the comparison with spark gap systems – lower protection level, no follow current, sufficient surge current carrying capability. The combination of two stacks of varistor blocks (4 varistor on a block) in a commercially manufactured package (2xP75/4) can safely discharge high - energy lightning pulse I_{imp} = 100 kA [11].

The surge arrester model was designed as a combination of varistor blocks for same nominal voltage and current with non - homogeneous VI characteristic. This type of model satisfies the international technical standards IEC 60664 and IEC 62305. One of the points of such study is the equation (3). The equation estimates the number of required varistors for the correct function of SPD. The equation is a function of the electric charge of the lightning partial current and the tolerance given by the manufacturers.

$$n = \frac{(Qt_{max} - Q_{1max})}{Q_{1max}} \left(\frac{1 + tolerance}{1 - tolerance} \right)^{\alpha} + 1 \qquad (3)$$

SPD with varistor, as the basic element for class I, have a range of tolerance smaller then 2 %. The number of varistors in block is very important for such solution. The 1 mA test is very consequential for choosing the varistors into the blocks according the range of tolerance and the connections between them. The presented calculation is effective with the values given by manufacturers [12].

6. Modelling of non - linear Vi characteristic

One of the parameters what characterize the behaviour of varistor is the non – linear VI characteristic. This curve has a substantive influence on the indication of varistor properties during the operation process in surge current area. From the point of optimization the basic element, the modelling of non – linear VI curve is highly necessary. The non – linearity process depends on the ratio of admixtures. The model on Fig. 9 was created in Matlab Simulink. This model serves to generate the VI curve non – linear computer simulations, and it is able to eliminate the pre – selected harmonics [13].
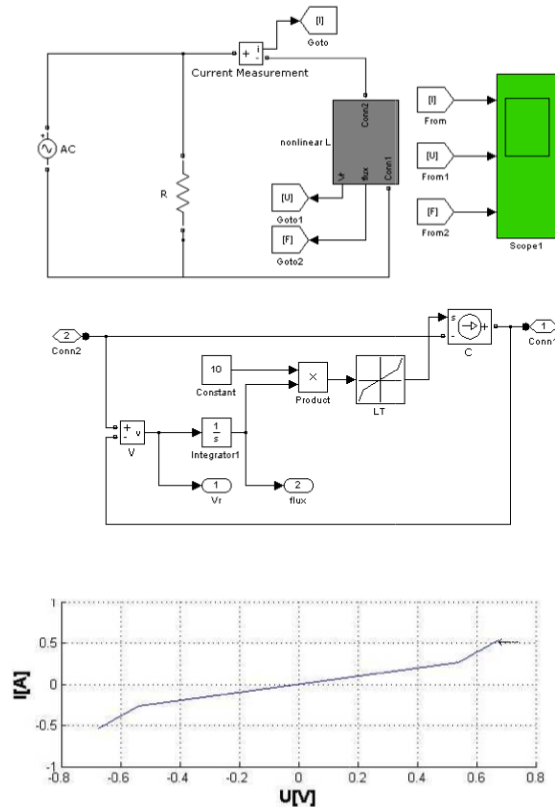
Fig. 9 The model of non / linear VI characteristic in Matlab Simulink and the simulation result [13]

7. The application of finite element method for thermal – electric analysis of zinc oxide varistor model

The main interest of this computer model for electric – thermal varistor simulations is an analysis of thermal changes in the core of ZnO ceramic, which is depended by created equivalent high enough voltage after surge current crossing (the shape of surge current is 10/350 μs). The priority of the model's electric-thermal analysis is to determine the possibilities how to minimalize the rate of damages caused by destruction effects of surge currents. The material inhomogeneity of ZnO ceramic, likewise its non-linear characteristic, is the problem part of the thermal breakdown modelling of this basic element.
For the analyses of the thermal dynamic processes is suitable the computer software Ansys – Workbench and Ansys – APDL. The principle is based on the Finite Element Method (FEM) for investigation not only the thermal dynamic processes. Because of the reduction of model calculating time of thermal and electric dynamic processes is used only the symmetrical half of MOV model (Fig. 10).
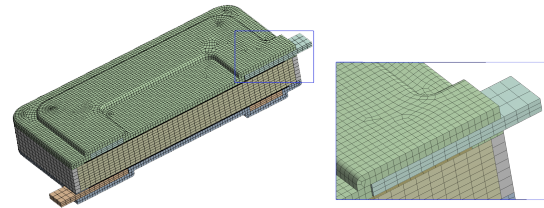

Fig. 10 The grid of finite element method for MOV model

Choosing very fine grid of finite elements is important to get the finest results of transient analysis. Each part of varistor model was meshed separately. The grid of whole system reaches almost 200 000 nodes.

Taking to the account the credibility of given model is highly necessary to compare the output simulation results with experimental measurement. The maximum amplitude of surge current (9 kA) was applied on the MOV model contacts for simulating of creating respond varistor voltage. The MOV is still in working mode (under voltage), so the beginning voltage value for minimum current value is 230 V (readable from VI characteristic).

The metal oxide varistor model is able to create high enough voltage to eliminate the surge current (Fig. 11). The problem coming with the simulation of overrun the nominal values of surge current with following electric breakdown. The breakdown is caused by extreme rising of a temperature, same as the change of the material structure in the core of varistor ceramic [14].
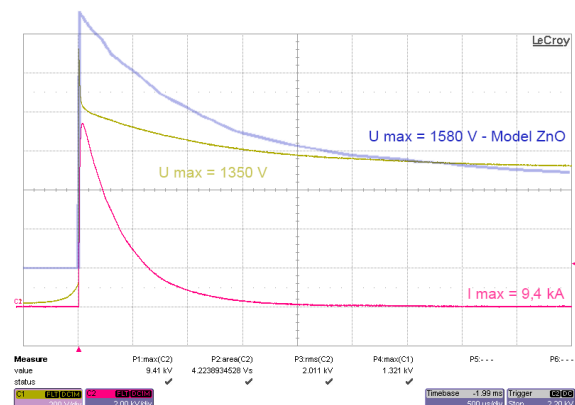

Fig. 11 The simulation results of surge current 9 kA

8. Conclusion

Computer simulation is one of modern analytic interpretation for solution of many different

problems. Taking to the account the direction of development in overvoltage protection devices area this method can be applied to elimination and effects of surge pulse. The replace of MOV varistor with adequately computer model is much - discussed subject. There are several replacements of MOV varistor or his electric parameters and also some solutions of coordination or cooperation of varistors. These models are modified in time.

The mathematical and computer solutions have unquestionable quantity of advantages and positives. One of them is the application of such methods for proposing the new model of metal oxide varistor with ZnO ceramic core for different analysis and simulations. The models are focused primarily on a high current area ($\geq$ 6 kA). Each of models solves specific characteristic of zinc oxide varistor. Some of them are suitable for electric simulations, and some for thermal analysis.

For the transient thermal – electric analysis the shape and amplitude of high enough respond voltages, same as the temperature changes in the core of varistor ceramic, are the basic monitored courses. The MOV model behaviour is reliable with only minor deviations (comparison with laboratory experiment). The temperature rising is evaluating clearly on theoretical assumptions.

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