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Computer Aided Model for a Low Voltage Varistor with Increased Thermal Stability

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***Abstract*— Metal Oxide Varistors are a very common power electronic device, applied for efficient overvoltage protection at any voltage level. This piece of equipment has a high non-linear current response function of the applied voltage, and, it provides a relatively high heat absorption capacity in case of accidental overvoltage pulse (shock)s. The crossing response current is clearly activated by temperature of that device, and, by consequent, overheating could be disastrous. Actual researches must be carried out both for a new more performant material as well as for new technical solutions for the design of all equipment integrating them, by studying heat extraction and heat transfer inside a new complex varistor device. Our article proposes a totally new device, used basically for low voltage applications, having a supplementary metal mass added to the body of that varistor, shaped as small disk. It actions like a heat pump immediately after the voltage pulse (shock) and as additional radiators at the end of the heating process caused by a transitory overvoltage. A CAD solution combined with a finite element model, followed by some experimental results are also presented, for confirming the performance of that newly design. By placing additional metal alloy masses inside a new varistor structure it will have a higher heat pumping and dissipation capability, in order to reduce temperature stress and all aging effects.**

Keywords*— *CAD Model, Low Voltage Varistor, Increased Thermal Stability

I. INTRODUCTION

Nowadays, Metal Oxide Varistors are often used for overvoltage protection equipment on a large industrial scale. All low voltage sensitive electronic devices are totally exposed to a lot of overvoltage aggressions, caused mostly by lightning (as transitory overvoltage) or caused by internal power network faults (as permanent overvoltage) [1].

The Metal Oxide Varistors are made of a mixture of semiconductor ceramic materials, most of them oxides. The relation between their crossing current and their applied voltage is essentially non-linear and their response time is extremely short, faster than the dielectric breakdown caused by the residual lightning voltage stroke on the sensitive and protected equipment. They have also a relatively high level of energy absorption capacity, but, having a risk of overheating for long time, due to their current which is highly influenced by temperature. Controlling their temperature is crucial for maintaining them in long service.

The current crossing throughout a varistor is highly depending on temperature, as for all semiconductor materials. In case of consecutives lightning strokes applied to the power grid, or in case of a longtime overvoltage, we noticed also an increased risk of overheating for the varistor itself [2].

When temperature increases (also due to environmental causes), the current increases too, due to electrical resistance reduction. An avalanche reaction could possibly appear in this case, with fatal and expensive consequences both for the protection as well as for the protected fragile piece of electronic or electric equipment [3].

Heat quantity produced inside the mass of that varistor is important in any case, and, by consequent, the design of an adequate technical solution, in order to control heat dissipation or evacuation, is mandatory for any varistors involved, at all voltage levels.

There are many practical and simple technical solutions applied mostly to increase the energy absorption capability (capacity) in case of a temporary lightning pulse (shock) (radiators, coating, etc.), not all of them being so effective. Today there is no analytical model which could describe a complex overvoltage incident, both from the electrical as well as the thermal point of view. Only the experimental procedures are suitable for this task [4].

This article describes only models and measurements made in case of the permanent overvoltage service. This permanent (long term) overvoltage service is not completely described in today's literature. In this situation, the varistor is exposed to a longtime accidentally occurring overvoltage, not so high, but enough destructive for the sensitive protected equipment. Heat (heat power, per time unit) produced inside the varistor (only by Joule effect) is provided by:

$$P_{dez} = U \cdot I = U \cdot A(U) \cdot T^2 \cdot e^{-\frac{q_e \cdot \Phi(U)}{k \cdot T}} \tag{1}$$

Heat (heat power, per time unit) evacuated by convection and radiation to the environment is provided by [6]:

$$P_{dis} = \alpha \cdot S_l \cdot (\theta - \theta_a) \tag{2}$$

where:

- I – crossing current;
- U - applied voltage;
- S_l – complete external heat exchange surface;
- $\Phi(U)$ – voltage height of semiconductor's junction potential barrier;
- Θ – varistor's own temperature;
- Θ_a – environmental temperature;
- T – absolute temperature, on Kelvin scale;
- k – Boltzmann's constant;
- $A(U)$- a parametric function depending on voltage and electric field intensity;
- q_e – electric charge of an electrone;
- α – the combined convective and radiative heat exchange coefficient;

There is a typical intersection of these two graphs (P_{dis} and P_{dez}) given by (1) and (2), providing two equilibrium points. The situation in which these two graphs do not intersect each other at all is the situation of a permanent fatal overheating regime (when heat produced inside the varistor is too high to be evacuated in the environment) [5].

Thermal stability (and energy adsorption), for a specified varistor, was analyzed only by taking in consideration the temperature of that varistor as the main perturbation, as a direct consequence of the overvoltage exposure [6].

II. ADDITIONAL METAL MASS PRINCIPLE

As previously explained, the most important issue concerning heat absorption capacity is to maintain the varistor inside the so-called "thermal stability" envelope, by carefully limiting its service temperature [7].

The high voltage exposure of a certain varistor also to a high energy pulse (shock) wave is caused by a short-time overvoltage, (process considered as adiabatic, due to its extremely short time). It means that the whole energy $Q=W$, produced by Joule effect remains stored inside its own mass, causing an important increase of its natural temperature $\Delta\theta_1$. It's necessary that this temperature increase to not over-pass the temperature stability equilibrium limit, so all heat produced inside the varistor could be dissipated in the environment [8].

The equation of for the varistor temperature increase $\Delta\theta_1$ due to the Q heat stored inside, is:

$$W = Q = m_v \cdot c_v \cdot \Delta\theta_1 \tag{3}$$

In practice, after a brief adiabatic process, the whole heat produced inside that varistor by Joule effect, Q, is stored and kept inside the varistor mass m_v, having the c_v specific mass heat. Heat quantity Q is given by the overvoltage specificity, so it could not be changed, and c_v is a specific material parameter, which could be slightly increased for higher heat absorption, but with drastic consequences, mostly for the electrical properties of that material. It is considered as a specific constant for a certain varistor type/ material [9].

An efficient and original technical solution (patented in Romania, by the authors), which is strongly recommended for thermal stability control of a certain varistor, consists in attaching some additional masses (made of a conductor material, metal or metal alloy) on the varistor itself These additional metal based masses must have an excellent thermal and electrical contact with the varistor. The main principle of this idea is briefly synthesized in Fig. 1.

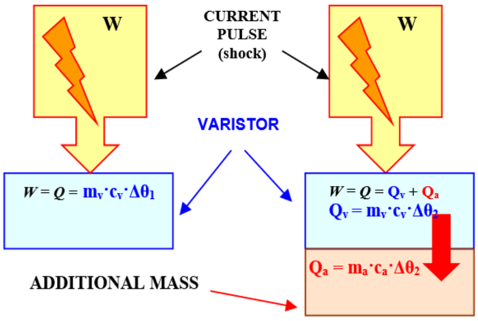

Fig. 1. The additional metal mass principle

The solution of this additional metal mass consists essentially in dividing the heat quantity produced by Joule effect inside the active part of the varistor, $Q=W$, in two different fractions. One of these fractions, called in this paper as Q_v ($Q_v = m_v \cdot c_v \cdot \Delta\theta_2$), remains stored inside the varistor, and the other fraction, called Q_a ($Q_a = m_a \cdot c_a \cdot \Delta\theta_2$) is naturally sent to and stored inside the additional mass which is well thermo-coupled with the varistor. Of course, m_a is the additional metal mass and c_a is its own specific mass heat. In this situation, the corresponding relation is:

$$W = Q = Q_v + Q_a = (m_v \cdot c_v + m_a \cdot c_a) \cdot \Delta\theta_2 \tag{4}$$

Equation (4) is valid and correct because:

- The electrical resistance of that additional mass is nine times smaller than the smallest varistor resistance obtained for the best conduction mode, and, by consequent, the additional mass is a passive conductor, which is not modifying any electric property of the assembly. The heat produced by Joule effect inside this additional mass is totally negligible, and, by consequent, the varistor is considered the only heat source.
- The thermal link between the varistor and the metal additional mass (in our tests is brass) is very well welded, so heat is changed very fast and uniform between those two structural different pieces. By consequent, both pieces involved will have the same temperature increment, $\Delta\theta_2$.
- This thermal conduction process is considered as fully adiabatic, very rapid, and we can correctly apply the energy conservation principle [10].
- It is obvious that the newly obtain temperature increase $\Delta\theta_2$ is smaller then previous $\Delta\theta_1$, as given by (4). This simple additional mass is acting, in fact, like a quick and passive "heat pump", extracting instantaneously a part of the excessive heat stored inside the varistor itself and, by this effect, decreasing its temperature and placing the whole assembly inside a possible thermal stability area.

It is mandatory also to explain that, because of the shape and geometry of these supplementary masses, the whole heat dissipation surface is increasing (not as much as in the case of large dedicated radiators). During the permanent service regime, these additional metal masses could be assimilated as radiators (which is not their main role), having a reduced contribution to the heat dissipation balance. By taking in consideration all these ideas, we can reduce, with a few degrees Celsius, the whole varistors' temperature. But, having a relatively small additional heat dissipation surface, we cannot consider them as dedicated true radiators.

III. COMPUTER BASED MODEL FOR THERMAL STABILITY ASSESSMENT

The main advantages of placing additional metal masses welded on the varistors could be proved only by using some geometries and numerical models, easily combined and verified by a set of experimental results, in order to perform confirmation of the proposed modeling hypothesis.

All CAD and numerical design procedures were performed at the POLITEHNICA University of Timisoara, Romania. The experimental part was performed at the LAPLACE Laboratory, from the PAUL SABATIER University in Toulouse, France.

All design solutions, simulations and measurements described inside this paper were carried out by using a set of regular 30 mm diameter commercial disk varistors, taken from the market (VARSI V250K30). These devices have reduced 3 mm height and they are applied mainly for a standard 230 V RMS European low voltage (domestic or similar) power supply installations. The varistors involved are not fully covered in epoxy resin, having only the small lateral edge coated with insulator, for about 1 mm. Two Ag alloy based electrodes are deposed by a special solvent technique on both sides. This configuration, having a single varistor alone is called the "A" configuration, in our article.

The additional metallic mass used was a small cylinder made of industrial brass, having a 20 mm diameter and a height of 5 mm. The newly proposed configuration, with a varistor and an additional mass on only one side, centered, is named, in our current article, the "B" configuration.

Analysis based on finite elements software is, nowadays, a powerful tool used for modeling heat transfer, as well as electric or magnetic field problems. For a complete CAD modeling, we used the FLUX 2D software, which provided excellent results for pieces having cylindrical symmetry.

The maximum numerically estimated temperature inside that model for configuration A (for 5300 points network) is:

$$\theta_e = \theta_a + \tau_e = 25 + 9.95 = 34.95\ ^\circ C \qquad (5)$$

The maximum numerically estimated temperature inside that model, for configuration B (for 5300 points network) is:

$$\theta_e = \theta_a + \tau_e = 26 + 6.38 = 32.38\ ^\circ C \qquad (6)$$

In Fig.2 and Fig.3 we will describe briefly the results of the finite elements approach, at 1 min (60 s) after the overvoltage pulse (shock), for each configuration considered below:

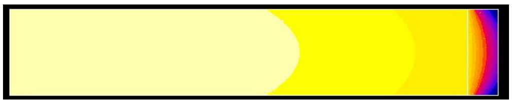

Fig. 2. Temperature repartition for configuration A

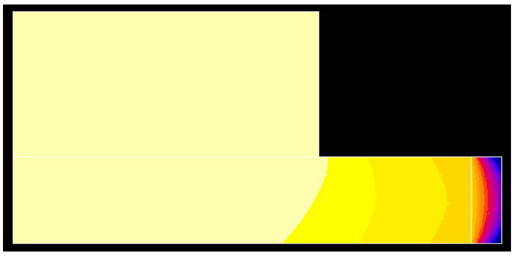

Fig. 3. Temperature repartition for configuration B

The maximal temperature obtained for configuration A was 32.84 ˚C and the minimal one was 31.77 ˚C, with a step of 0,09 degrees Celsius for each colour, from yellow to magenta. The time variation graph of the temperature, for a certain random point, located on the top side, where *H = 3 mm* and having a *R = 12 mm* radius from the axis, belonging to the configuration A, is shown in Fig.4.

The maximal temperature obtained for configuration B, in the same conditions, was around 31.41 ˚C and the minimum was 30.62 ˚C, with a step of 0,07 degrees Celsius for each colour. The time variation of the temperature for that randomly specified point, located on the top side (*H = 3 mm*) having a *R* = 12 mm radius, on the configuration B, is shown in Fig.5.

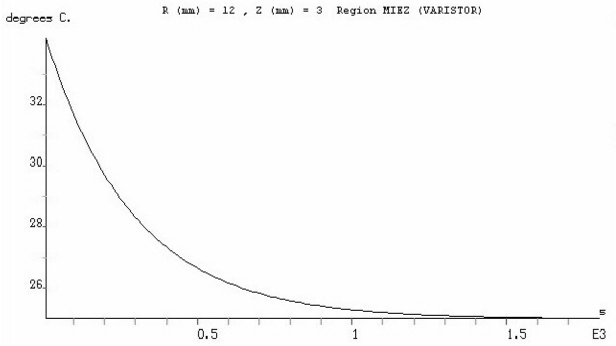

Fig. 4. Time variation of temperature for a point on configuration A

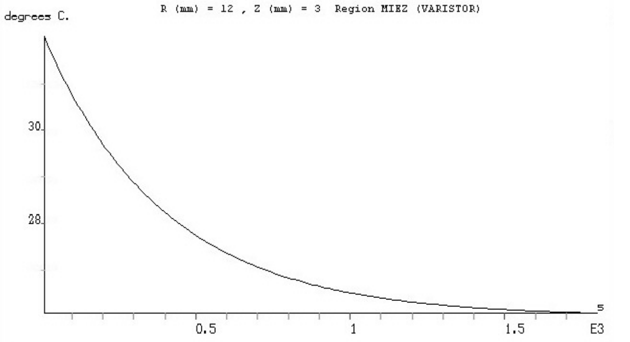

Fig. 5. Time variation of temperature for a point on configuration B

These graphs are only software estimations for the temperature. They must be verified in practice.

IV. EXPERIMENTAL RESULTS

Each considered configuration was submitted to an overvoltage test pulse (shock), by using a dedicated standard 8/20 pulse (shock) generator, located at the LAPLACE Laboratory, in Toulouse France. The maximum real measured temperature θ for the same random point, numerically and theoretically considered before (3 mm, 12 mm), belonging to the first configuration A was:

$$\theta = 34{,}44\ ^{\circ}\mathrm{C} \tag{7}$$

We notice that relation (5) offers a very good estimation compared to (7). The time evolution of the temperature, during the "after pulse" cooling process, for the same previous randomly chosen point, is shown in Fig.6. That considered point reference was also used for the other B configuration, too. The maximum physically measured temperature θ, on the same considered point position (3 mm, 12 mm), located on configuration B was:

$$\theta = 32{,}13\ ^{\circ}\mathrm{C} \tag{8}$$

The cooling process graphs are placed below:

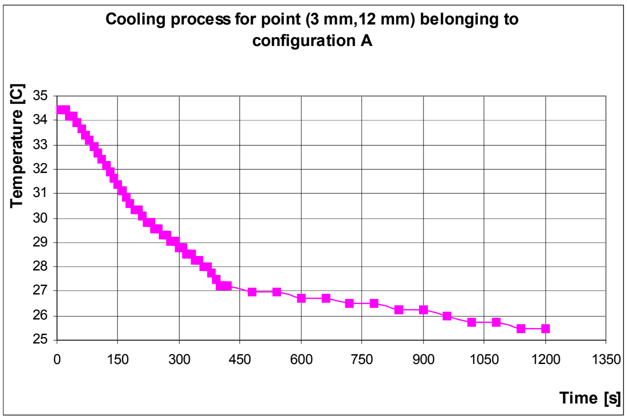

Fig. 6. Cooling process time graph for a point located on configuration A

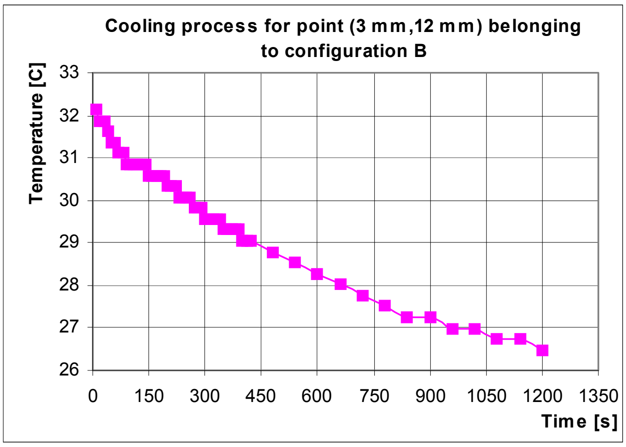

Fig. 7. Cooling process time graph for a point located on configuration B

Equation (6) offers an excellent estimation when compared to (8). The time evolution of the temperature during the cooling process, considered for the same point of configuration B, is described in Fig.7.

All overvoltage pulses applied here were standardized 8/20 μs ones, provided by a current pulse generator. All measurements were carried out for at least 60 seconds after applying that current pulse. We observed a very good correspondence between the estimated numerical values and the measured results. These are commonly made measurements which are proving the correct hypothesis considered.

V. CONCLUSIONS

After all these studies and taking also in consideration all incidents in service history, we noticed that there is a major risk of overheating a MOV varistor, during both permanent or pulse (overvoltage shock) service regime, because the crossing resulted current throughout that varistor is activated by its temperature.

The newly introduced thermal stability concept is an important issue for the quality assessment of a certain MOV varistor. By eliminating any potential overheating risk, the experiments performed in this paper, are safely placing the varistor inside the thermal stability envelope, in order to avoid its irreversible destruction and, also, to verify the efficiency of the newly proposed technical solution, with additional metal masses.

Potentially, there are plenty of technical solutions concerning the reduction of any overheating risk. From our point of view, the most efficient one involves improvements on the quality of the varistor material itself, which is a study dedicated for chemical or material specialists.

The new and original solution proposed here by the authors, conceived only for existing materials and equipment, consists in an additional metal (brass) mass welded on the varistor surface, which acts like a real heating pump, extracting part of the heat from the electrical active area of the varistor and relocating this heat in corresponding fractions, between the two pieces of equipment (varistor and mass).

This original solution detailed here is part of our Romanian Patent, RO 117052 B, practically proved to be efficient by reducing the varistor temperatures compared to the single varistor configuration. This technical solution offers us a high energy absorption capability, placing the active varistor inside the stability reserve area, for all normal overvoltage pulses (shocks). We observed a very good correspondence between the theoretical estimated models and the measured results. There is a slightly, almost two degrees Celsius difference between the numerical estimated temperature computed by using finite elements model and the real measurements, which is tolerable from the heating point of view (tens of degrees are critical in our case).

This simple principle of additional masses could be successfully applied in industry in order to manufacture "high energy absorption capacity" low voltage varistors or even sensors, suitable mostly for low voltage power or telecommunications applications. We strongly recommend this new varistors for frequent lightning protection.

The use of new and modern surge protection equipment is mandatory also in the field of any automation system or equipment, operating on large areas, especially in the Power and Energy domain.

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