A Few Aspects Concerning the Modeling of Thermal Stability Control for a Low Voltage ZnO Varistor

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Abstract: - ZnO based varistors are today the most common technical solution for making state of the art surge arresters for all voltage levels, due to some advantages like a high non-linearity coefficient and a high energy absorption capacity. Due to their thermal activated conduction, the control of heat dissipation inside that semiconductor device is crucial for its service. Heat dissipation control could be done only by modeling the thermal and electrical status of the varistor in case of some special and original configurations. The new configuration proposed in this paper consists in a disc varistor with an additional brass mass used for heat extraction and dissipation. This paper presents the finite-element model used for the direct control of heat dissipation, as well as some experimental results.

Key-Words: - Thermal Stability Control Modeling, ZnO Varistor

1 Introduction
Modern surge-arresters are based on ZnO varistors. All electronic devices (including command and control equipment, industrial computers, PLCs etc.) are using low voltage varistors in order to protect those sensitive devices against any type of low voltage, mainly lightning strokes or induced overvoltages, both on power supply lines as well as on data lines.

ZnO varistors are essentially ceramic polycrystalline n – semiconductors. They are applied in modern technologies due to some important advantages such as: a high level of non-linearity for the current-voltage characteristic, a high energy absorption capacity and an excellent response time (less then 100 ns), which make them useful for protecting other sensible electronic devices.

Knowing the service limits for a certain varistor included into a protection, measuring or control equipment is important in order to obtain maximum performance and safety for a long term use of that protection equipment.

Another important aspect concerning ZnO varistors is improving their thermal behavior, by controlling the heat dissipation during permanent or shock regime.

2 Problem Formulation
Like many other semiconductor devices, the current passing through that varistor is thermally activated. So, for a high energy short time shock (like a violent lightning stroke) or for a long time over voltage (a technical incident), there is an increased risk of overheating [5].

As long as the temperature increases (even the environmental temperature increases), the passing through current increases too, due to the diminution of the electrical resistance. An avalanche phenomenon could occur any moment, with devastating consequences both for the surge arrester as well as for the protected equipment.

The heat produced inside the varistor is basically incontrollable, during a heavy duty permanent regime or after an extremely violent shock.

That’s why, finding an efficient method to control heat dissipation or a technical solution to improve the thermal behavior by enlarging the safety stability reserve is very important.

As a consequence of the thermo-activated current, the thermal stability of a ZnO based varistor could be controlled and analyzed in two different regimes [3]:

- the permanent service regime, when the varistor is exposed to a long time accidentally over voltage, not very high, but destructive for the protected equipment;
- the shock (voltage impulse) regime, when the varistor is exposed to an extremely short time over voltage, but with a very high value (like a lightning stroke), obviously destructive for any protected equipment.
The shock regime is generally specified by the surge arrester manufacturer by marking the energy absorption capacity of that device at a certain maximum voltage, in the case of a standardized shock wave form. Of course, that parameter is informal, no lightning stroke is like in standards and there are many other parameters involved (the environmental temperature, the varistors’ temperature, the wave form, etc.). There are many technical solutions to increase the energy absorption capacity in case of a voltage impulse (new materials, radiators, other cooling systems, etc.). Generally, ZnO varistors behaves according to manufactures specifications, due to large series of experimental tests made before. No mathematical model could predict such an incident; the experimental method is the only one to characterize that type of electrical faults. In this paper we will not discuss about the shock regime, but only about the long term over voltage regime.

The long term over voltage regime is generally not very well described.

The power produced inside the varistor has the expression [2],[3]:

\[
P_{dez} = U \cdot I = U \cdot A(U) \cdot T^2 \cdot e^{-\frac{q_s \Phi(U)}{kT}} \tag{1}
\]

The power dissipated in the environment has the expression:

\[
P_{dis} = \alpha \cdot S \cdot \left(\theta - \theta_a\right) \tag{2}
\]

Where:
- \(S\) – is the total dissipation surface;
- \(\Phi(U)\) – is the height of the potential barrier (as a function of the applied voltage);
- \(q_s\) – is the electrons’ charge;
- \(T\) – is the absolute temperature;
- \(k\) – is Boltzmann’s constant;
- \(\alpha\) – is the convective exchange coefficient;

The two curves (\(P_{dis}\) and \(P_{dez}\)) given by (1) and (2), could be intersected in one or two equilibrium points (E and U on Fig.1). The situation in which they do not intersect is corresponding to the situation of a permanent overheating regime (when the heat produced inside the varistor is too great to be dissipated in the environment).

In Fig.1 we have a complete overview of the system stability for a varistor. The thermal stability of a varistor is given by the intersection of the two curves \(P_{dis}\) and \(P_{dez}\). Point E (which is reached after a normal heating process caused by a small shock or a permanent accidental regime) is a stable equilibrium point. Any small increase in temperature (caused by the environment or the varistor itself) will place the system in a thermal stability reserve area, where it could dissipate more heat than it produces.

Point U is an instable equilibrium point. In fact, it gives the thermal stability limit for that varistor. Any increase in temperature after that point will place the system in the overheating area, where heat produced inside the varistor is higher than its heat dissipating capabilities. Any heat is considered as a power (heat in a time unit).

![Fig.1. The thermal stability control](image)

The thermal stability control for a certain varistor was analyzed only by taking in consideration the varistor temperature as the main perturbation [3].

### 3 Technical Solution for Thermal Stability Control

Maintaining the varistor inside the stability reserve area, by controlling its temperature is crucial for its performance.

As shown before, the passage through a varistor of a W shock wave, (the process is considered as adiabatic), imposes that the whole energy \(Q=W\), produced by Joule-Lentz effect remains inside its mass, producing by this way the increase of its temperature \(\Delta \theta\). It is suitable that this growth would not lead to the over-passing of the temperature equilibrium limit, so all heat located inside could be dissipated.

The value of the varistor temperature increases with \(\Delta \theta\) after having the Q heat accumulation[5]:

\[
W = Q = m_v \cdot c_v \cdot \Delta \theta \tag{3}
\]

It means that the whole heat \(Q\) is stored inside the varistor mass \(m_v\), having the \(c_v\) specific mass heat. \(Q\) is given by the shock specificity, so it could not be modified, and \(c_v\) is a specific material constant, which could be increased, but with fatal consequences on the material, especially concerning the electrical properties of that material. So, we consider it a constant for a certain varistor type.
The increase of the varistors mass \( m_v \), is possible in the limits imposed by the electric parameters, being known the fact that the height of the varistor is being fixed by the operational voltage level. The solution is not always economically justified (the price of the disc type varistor is increasing with the diameter and its performances) and it brings no significant improvements, because the heat still remains stored inside the active mass of the varistor.

An original technical solution used to control the thermal stability of the varistor consists in putting some additional masses on the varistor, these additional masses having a thermal contact with the varistor. The principle of this technical solution is shown in Fig.2.

![Additional Mass Principle](image)

**Fig.2. Additional mass principle**

The principle of additional masses usage consists in dividing the stockage of the heat produced inside the active part of the varistor, \( Q = W \), in two fractions. One fraction called \( Q_v \) (\( Q_v = m_v \cdot c_v \cdot \Delta \theta_1 \)) remains inside the varistor, and the other fraction \( Q_a \) (\( Q_a = m_a \cdot c_a \cdot \Delta \theta_2 \)) is pumped inside the additional mass which is thermo-coupled with the varistor. Of course, \( m_a \) is the additional mass and \( c_a \) is its specific mass heat.

Resuming, we have:

\[
W = Q = Q_v + Q_a = (m_v \cdot c_v + m_a \cdot c_a) \cdot \Delta \theta_2 \quad (4)
\]

Relation (4) is valid because:

- The process is fully adiabatic and we can apply the energy conservation principle.
- We can observe that \( \Delta \theta_2 \) is smaller then \( \Delta \theta_1 \), as given by (4). The additional mass is acting like a “heat pump”, taking instantaneously a part of the varistors heat and, by this way, reducing its temperature and placing it inside a possible stability area.

It is interesting that, because of the supplementary masses geometry, the heat evacuation surface is increasing (not as much as in the case of radiators). During the permanent regime, these additional masses can be assimilated to radiators, but with a reduced effect on the heat dissipation. By doing this, we can reduce, with a few degrees Celsius, the varistors’ temperature. But, having a reduced supplementary heat dissipation surface, we cannot call them radiators [4].

Classical star-shaped radiators are difficult to put on a varistor submitted to high voltage shocks, having many electric field concentrators on the edges. Only higher metal cylinders could be partially used as radiators, solution close to our one.

Many improvements could be done by acting on the material itself, in order to improve the heat parameters. But, it is a chemical research basically.

The material used by the authors for the additional masses is brass, having the following properties:

- A cheap material;
- It is easy to work;
- A good thermal conductor;
- A sufficiently high specific mass heat;
- A reduced electric resistivity;
- It could be welded on the varistors surface;
- The material parameters are well known and can be easily determined;
- It is found even in the construction of electrodes of some overvoltage protection equipments.

### 4 Thermal Stability Modeling

The advantage of using additional masses welded to the varistors could be proved only by using some numerical models combined with experimental results in order to obtain confirmation of the modeling hypothesis.

We will present some modeling results (followed by experiments) that we have done during the last years at the POLITEHNICA University of Timisoara, Romania, Power Systems Department.

The experiments were done at the LAPLACE (Génie Electrique) Laboratory, from the PAUL SABATIER University in France.
All measurements and models were performed by using 30 mm commercial disk varistors. They have a 3 mm height and they are designed for standard 230 V European low voltage (domestic) power supply lines. The varistors are not totally covered in epoxy resin, having only the lateral edge coated for 1 mm. Metal electrodes are deposed on both sides. This configuration (varistor alone) is called the “A” configuration.

The additional mass was a small cylinder made of brass, having 20 mm in diameter and a height of 5 mm. This configuration (varistor + additional mass on one side) is called the “B” configuration.

Finite elements analysis is a powerful tool for modeling heat transfer, as well as electric fields. For modeling, we have used the FLUX 2D software, which gave excellent results for our pieces, having a cylindrical symmetry [1].

The finite elements mesh for each configuration is shown in Fig.3 and Fig.4.

- the linear relation between the volume specific heat and temperature \( \theta \), [J/(m\(^3\)·C)]:
  \[ c_v = 3.516 \cdot 10^6 \cdot (1 + 8.33 \cdot 10^3 \cdot \theta) \]
- the mass density [kg/m\(^3\)]:
  \[ \rho = 5660 \]

For the epoxy resin [2], [3]:
- the thermal conductivity [cal/(cm · s · °C)]:
  \( \lambda = 0.15 \)
- the radiation heat exchange coefficient:
  \( \varepsilon_r = 0.9 \)
- the linear relation between the heat convection exchange coefficient and the temperature \( \theta \) [W/(m\(^2\)·C)], similar to the varistor:
  \[ \alpha_c = 9 \cdot (1 + 0.0166 \cdot \theta) \]
- the volume specific heat (constant, because the resin is not exposed to temperature variation), [J/(m\(^3\)·C)]:
  \[ c_v = 1.9 \cdot 10^6 \]
- the mass density [kg/m\(^3\)]:
  \[ \rho = 1300 \]

For the brass additional mass [3]:
- the thermal conductivity [cal/(cm · s · °C)]:
  \( \lambda = 0.26 \)
- the radiation heat exchange coefficient:
  \( \varepsilon_r = 0.2 \)
- the linear relation between the heat convection exchange coefficient and the temperature \( \theta \) [W/(m\(^2\)·C)]:
  \[ \alpha_c = 5 \cdot (1 + 0.02 \cdot \theta) \]
- the volume specific heat (constant, because the additional mass is not exposed to temperature variation), [J/(m\(^3\)·C)]:
  \[ c_v = 3.224 \cdot 10^6 \]
- the mass density [kg/m\(^3\)]:
  \[ \rho = 8400 \]

Simulations for configuration A were made for an environmental temperature \( \theta_e \) of 25 °C, and for configuration B, at 26 °C. The simulation were performed by considering that a certain impulse energy \( Q = 90 \) J (given, in fact, by a real shock generator) is transformed in heat, producing the rapid increase of temperature for each configuration (as we said before, this process is fully adiabatic). After absorbing that energy, each configuration is cooled down naturally, performing temperature estimation at any moment, in any point, until reaching the environmental temperature [3].

For configuration A, the overheating, \( \tau_e \), [°C], is:

\[ \tau_e = \frac{Q}{m_v \cdot c_v} = \frac{90}{12 \cdot 0.7534} = 9.95 \]

where:
- \( m_v = 12 \) g is the mass of the varistor;
- \( c_v = 0.7534 \) [J/(g · °C)], is the mass specific heat.

Fig.3. Finite elements mesh for configuration A

Fig.4. Finite elements mesh for configuration B
The maximum estimated temperature for configuration A is:
\[ \theta_e = \theta_a + \tau_e = 25 + 9.95 = 34.95 \, ^\circ\text{C} \quad (5) \]

For configuration B, the overheating, \( \tau_e \), [\(^\circ\text{C}\)], is:
\[ \tau_e = \frac{Q}{m_v \cdot c_v + m_{al} \cdot c_{al}} = \frac{90}{12 \cdot 0.7534 + 13.19 \cdot 0.383} = 6.38 \]

where:
- \( m_v = 12 \, \text{g} \) is the mass of the varistor;
- \( c_v = 0.7534 \, [\text{J/(g \cdot ^\circ\text{C})}] \), is the mass specific heat;
- \( m_{al} = 13.19 \, \text{g} \) is the mass of the brass;
- \( c_{al} = 0.383 \, [\text{J/(g \cdot ^\circ\text{C})}] \), is the brass specific heat.

The maximum estimated temperature for configuration B is:
\[ \theta_e = \theta_a + \tau_e = 26 + 6.38 = 32.38 \, ^\circ\text{C} \quad (6) \]

In Fig.5 and Fig.6 we show the finite elements simulation results, at 60 s after the shock, for each configuration:

![Fig.5. Temperature repartition for configuration A](image)

![Fig.6. Temperature repartition for configuration B](image)

The maximum temperature for configuration A was 32.84 \(^\circ\text{C}\) and the minimum was 31.77 \(^\circ\text{C}\), with a step of 0.09 degrees Celsius for each colour. Time variation of the temperature for a point located on the top side (\( H = 3 \, \text{mm} \)) having a \( R = 12 \, \text{mm} \) radius, belonging to configuration A, is shown in Fig.7.

![Fig.7. Time variation of the temperature for a point located on configuration A](image)

The maximum temperature for configuration B was 31.41 \(^\circ\text{C}\) and the minimum was 30.62 \(^\circ\text{C}\), with a step of 0.07 degrees Celsius for each colour. Time variation of the temperature for a point located on the top side (\( H = 3 \, \text{mm} \)) having a \( R = 12 \, \text{mm} \) radius, belonging to configuration B, is shown in Fig.8.

![Fig.8. Time variation of the temperature for a point located on configuration B](image)

These are only estimations for the temperature. They must be verified experimentally.

## 5 Thermal Stability Measurement

Each configuration was submitted to a voltage shock, by using a standard 8/20 shock generator. The shock generator is shown in Fig.9. It is located at the LAPLACE (Génie Electrique) Laboratory, from the PAUL SABATIER University in France.

![Fig.9. Shock generator](image)

Temperature was measured by putting Pt sensors soldered with silicone gel (a very good thermal conductor).

The maximum measured temperature \( \theta \) for the same point (3 mm, 12 mm), belonging to configuration A was:
\[ \theta = 34.44 \, ^\circ\text{C} \quad (7) \]

Relation (5) offers a very good estimation compared to (7). The evolution of the temperature during the cooling process, for the same point is shown in Fig.10.
The same point was considered for configuration B.

![Cooling process for point (3 mm, 12 mm) belonging to configuration A](image)

Fig. 10. Cooling process for a point located on configuration A

The maximum measured temperature $\theta$ for the same point (3 mm, 12 mm), belonging to configuration B was:

$$\theta = 32.13 \degree C$$  \hspace{1cm} (8)

Relation (6) offers a very good estimation compared to (8), too. The evolution of the temperature during the cooling process, for the same point is shown in Fig.11.

![Cooling process for point (3 mm, 12 mm) belonging to configuration B](image)

Fig. 11. Cooling process for a point located on configuration B

We observe a good correspondence between the estimated and the measured results.

6 Conclusions

Because current inside a varistor is thermo activated, there is a major risk of overheating during permanent or shock regime.

Only by taking in consideration the thermal stability concept, we can control the status of a varistor. In order to avoid any risk of overheating, the functional point of the varistor must remain inside the safety reserve area, as we noticed. The experiments described placed the varistor inside the thermal safety area, in order to avoid destruction and to verify the efficiency of the proposed technical solution.

There are many technical solutions concerning the overheating reduction. But the most efficient ones involved working to improve the varistor material itself, a job basically for chemical engineers. The original solution proposed by the authors, dedicated to existing material and equipment, consists in an additional mass welded on the varistor, which act like a heating pump, extracting heat from the active part of the varistor and relocating it between the two pieces. This solution proved to be efficient, offering more reduced temperatures compared to the single varistor one. This technical solution offers a high energy absorption capacity, placing the varistor inside the safety reserve area, for all normal voltage shocks. It is a natural form of heating self-control.

We observed a good correspondence between the estimated and the measured results.

This principle of controlling the thermal stability for a varistor, by improving the technical solutions for heat exchange, is applied to other industrial systems like chemical reactors, nuclear reactors (for example, the Chernobyl reactor exploded while functioning inside the overheating area, when heat produced inside was higher than heat dissipated, and the unstable equilibrium functional point, at the limit of the safety reserve area, was over passed). Of course, the scale of the events is not similar, but the principle is the same. And the main task (increasing power networks stability and reducing any fire or explosion risk) is similar too.

References: