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The Experimental Determination of the Maximum Continuous Operating Voltage for a ZnO Based Varistor

ZnO based varistors are today frequently used for surge arresters. In order to obtain a better behavior of that piece of equipment, it is very important to know the continuous voltage limits accepted. This goal could be achieved only by making some experiments to evaluate the thermal limits of a certain varistor. This paper presents some original experiments made by the authors at the "Genie Electrique" Laboratory of the "Paul Sabatier" University in Toulouse, France. These experiments are original because they are taking in consideration the environmental temperature too, and they provide technical solutions for an optimal service of that equipment.

1. Introduction

Metal Oxide Varistors (also named ZnO varistors, due to their most important component) are today used for making state of the art surge arresters for all voltage levels, from domestic low voltage to high voltage transport lines. Their main goal is to protect any piece of electrical equipment against any type of over voltage which occurs on the power supplying network (technical incident, induced voltages or lightning stroke).

ZnO varistors are essentially ceramic poly-crystalline 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.

Like many other semiconductor devices, the current passing through that varistor is thermal 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. As long as the temperature increases (even the environmental temperature increases), the passing through current increases 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 for the protected equipment too.

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

2. The thermal stability of a ZnO based varistor

As a consequence of the thermo-activated current, the thermal stability of a ZnO based varistor could be analyzed in two different cases:

- 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.

This paper presents a method used to determine the maximum continuous operating voltage of a ZnO varistor, based on experimental results.

A parameter called "the load coefficient, C" is involved, in order to obtain some information about the voltage applied.

It is defined as:

$$C = V / V_N \quad (1)$$

Where V is the applied voltage and V_N is the nominal voltage for that varistor.

Our goal is to determine the maximum value of this coefficient (in fact the maximum continuous operating voltage V) for a certain varistor at a certain environmental temperature, different from the standardized one. This study could be made only in an experimental way.

3. Experimental procedure

All the measurements were made by the authors at the "Génie Electrique" Laboratory of the "Paul Sabatier" University in Toulouse, France. All the experiments were performed by using the same type of domestic appliance varistors, made by the Slovenian company ISKRA D.O.O. The catalog data for a disk varistor type **ISKRA V250D32S**, having a diameter of 32 mm and a height of 3 mm, are, according to the manufacturer [1]:

$$V_{\text{RMS}} = 250 \text{ V}, V_{\text{DC}} = 320 \text{ V}, P_{\max} = 1,2 \text{ W}, I_{\max} (8/20\mu\text{s}) = 25000 \text{ A}, W_{\max(2ms)} = 340 \text{ J}, V_N = 390 \text{ V}, \Delta_N = \pm 10\%, V_c = 650 \text{ V}, I_n = 200 \text{ A}, C = 2200 \text{ pF}$$

We notice that the producer already offers a maximum continuous operating voltage (a maximum value for the "C" coefficient) at an environmental temperature of 25 °C, defined, in permanent DC regime, as:

$$C_{\max} = \frac{V_{DC}}{V_N} = \frac{320Vd.c.}{390Vd.c.} = 0,82 \quad (2)$$

The first step is to verify this value provided by the manufacturer [2].

The experimental equipment is shown in Fig. 1 and the electrical schema of that device is shown in Fig. 2. The tested varistor is connected through two wires in order to avoid any thermal transmission. Two Pt high sensitive temperature sensors, with low delay, are placed on the two disk faces, near to the center of that disk. All experiments are made in a thermo – insulated controlled chamber shown in Fig. 1.

The elements of the experimental equipment are, as shown in Fig. 2:

- A FLUG-HP 64488 DC voltage source, programmed by a PC 486 computer, which can supply any DC voltage between 0 and 12500 V DC at a maximum current of 25 mA;
- A Keithley 619 DC digital micro ampere-meter which allows measurements between $1,9 \cdot 10^{-9}$ and $1,9 \cdot 10^{-3}$ A, having a precision class of 0,5%;
- A Racal Dana 6000 digital memory voltmeter used to measure the voltage difference between the faces of that disk varistor through a 1:1000 resistive voltage interface, having a precision class of 0,1%;
- Two usual portable multi meters (not shown in Fig. 2) used to measure the resistance of the Pt temperature sensors in order to obtain that temperature values.

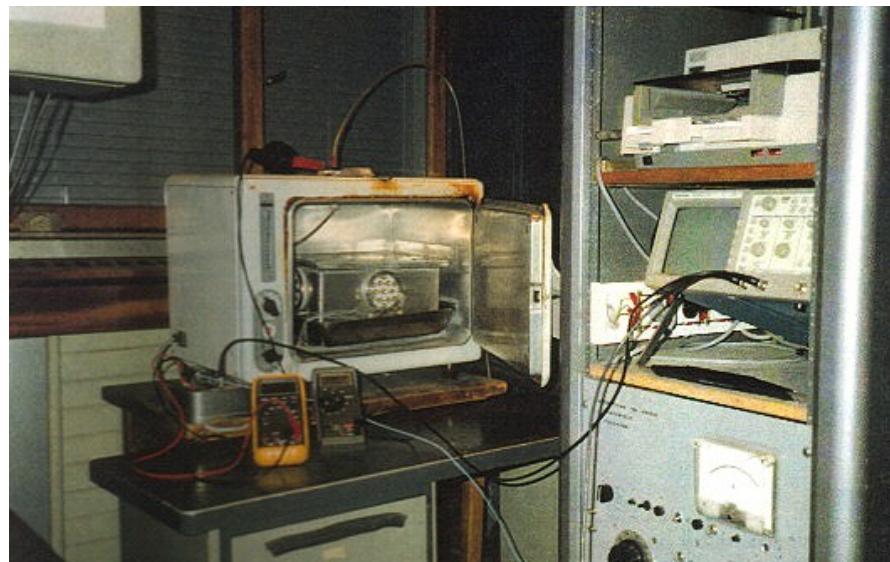


Figure 1. The experimental equipment

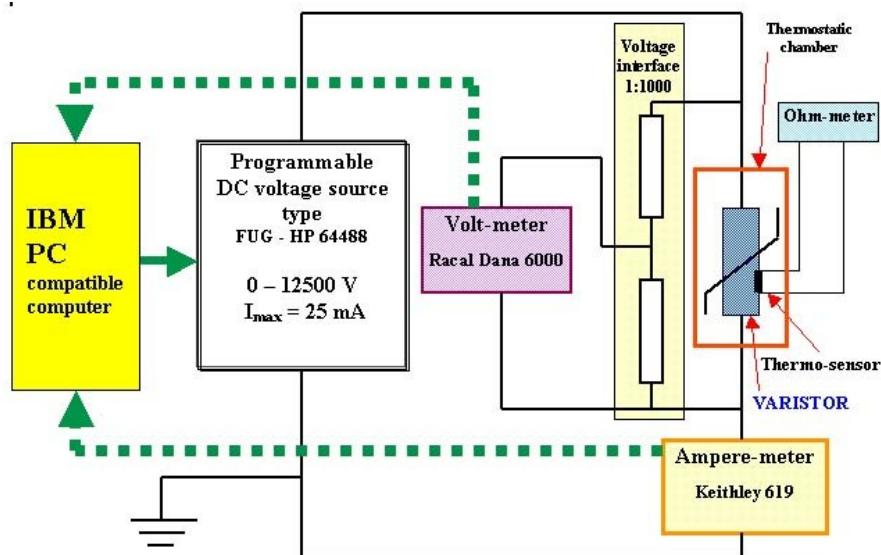


Figure 2. The electrical schema of the experimental equipment

That varistor was polarized at three different voltage levels [2]:

- 312 V DC, corresponding to $C = 312/390 = 0,8$, a value under the manufacturer limit;
- 320 V DC, corresponding to $C = 320/390 = 0,82$, the manufacturer limit;
- 345 V DC, corresponding to $C = 345/390 = 0,884$ – value over that limit.

The main purposes of these measurements were:

- to evaluate the thermal avalanche;
- to establish the maximum voltage for a certain environmental temperature
- to verify the thermal behavior of that varistor;
- to determine the critical current density for that temperature.

The evolution of varistors' supra-temperature (related to the environment one, $t_a = 25^\circ\text{C}$) is shown in Fig. 3, for all values of C [2].

We notice that for the producer recommended value $C= 0,82$, a steady regime is obtained with a supra-temperature of only $6,8^\circ\text{C}$.

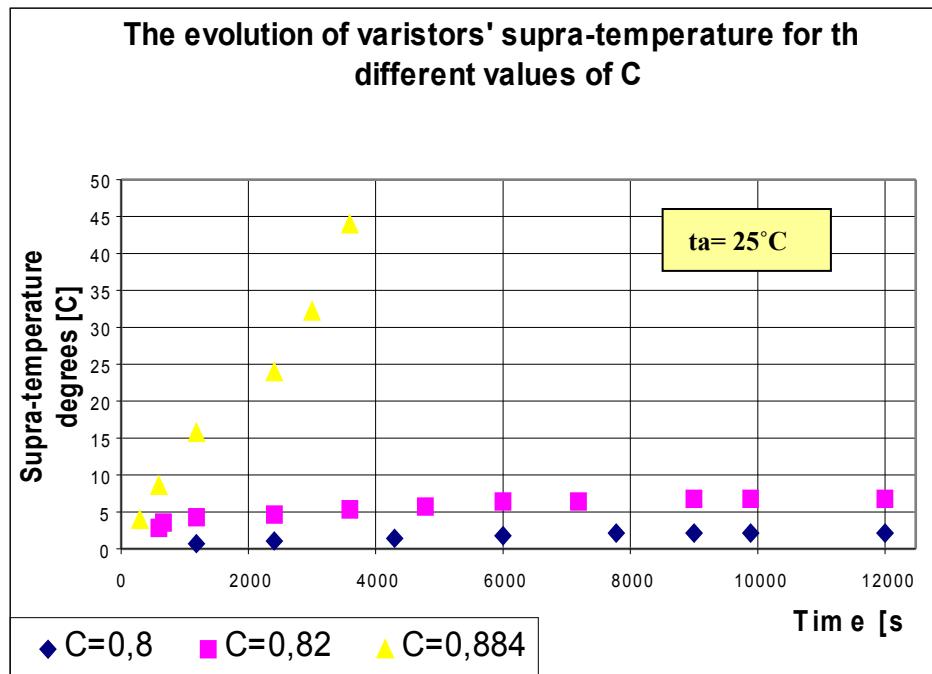


Figure 3. Time evolution for supra-temperature

For a higher value of the C coefficient, at the same value of the environmental temperature $t_a = 25^\circ\text{C}$, the increase of the supra-temperature of that varistor is exponential, in avalanche. The varistor was disconnected after 1

hour (3600 s) to avoid its destruction. It was having a supra-temperature of 44,1 °C at that moment.

The time related evolution of the crossing current (at $t_a = 25$ °C) is shown in Fig. 4, for all values of C [2].

We noticed that [2], [3]:

- for a coefficient $C = 0,8$, under the limit $C = 0,82$, the current is maintained constant arround 10^{-4} A;
- for a coefficient $C = 0,884$, over the limit, the current increases exponentially, with a higher risk of overheating and degradation.
- for a coefficient $C = 0,82$ ($V = 320$ V DC), the limit prescribed by the producer, the current remains stable arround $7,1 \cdot 10^{-4}$ A, even starting from $2 \cdot 10^{-4}$ A (value specified in its voltage-current chart).

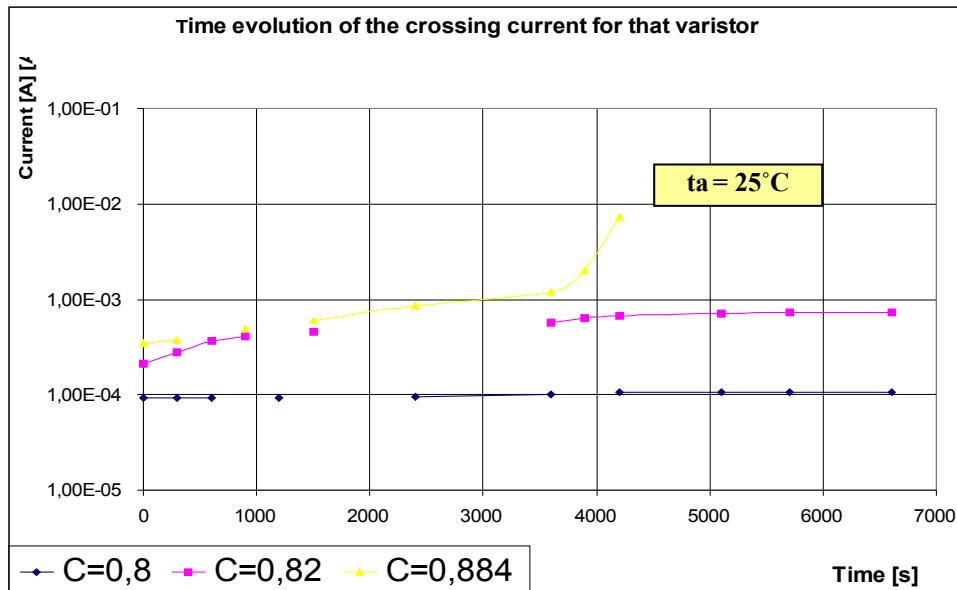


Figure 4. Time evolution of the crossing current

The limited value for the voltage (the limited coefficient C) provided by the manufacturer does not represent the voltage necessary to obtain the critical current density, beeing in fact inferieur to that value. The critical current density, at an environmental temperature of 25 °C, is obtain for a load coefficient arround 0,83 ...0,85, depending on the geometry of that varistor and his composition and structure [3].

According to some experimental data, for that specified varistor, we have some important values [1], [2], [3]:

- $\rho_a = 3,6 \cdot 10^5$ [$\Omega \cdot m$] (electrical per unit resistance);
- $\alpha_R = 3 \cdot 10^{-3}$ [degrees] (thermal resistance factor);
- $d = 3 \cdot 10^{-2}$ [m] (diameter).

For a temperature of 25°C , $\alpha \approx 1$ [W/(m²degree)] (thermal transmittance). The calculated critical density is obtained by using this equation [3]:

$$J_{cr} = \sqrt{\frac{\alpha \cdot l_p}{\rho_a \cdot \alpha_R \cdot A}} = \sqrt{\frac{4 \cdot \alpha}{\alpha_R \cdot \rho_a \cdot d}} \quad (3)$$

And it has a value of [2]:

$$J_{cr} = 1,448 [A/m^2] \quad (4)$$

By analyzing the expression of the critical current density, J_{cr} , gave by (3), we can observe that its value is influenced only by the de heat dissipation conditions by changing α by changing the diameter of the ZnO varistor disk [3].

The critical current density will be the same for all series of varistors of the same diameter, the absorbed energy being proportional with the volume (the height) of the varistor (cylinder or disk).

The evolution of the supra-temperature for the considered varistor for two different environmental temperatures $t_a = 25^\circ\text{C}$ and $t_a = 55^\circ\text{C}$ is shown in Fig. 5 [2].

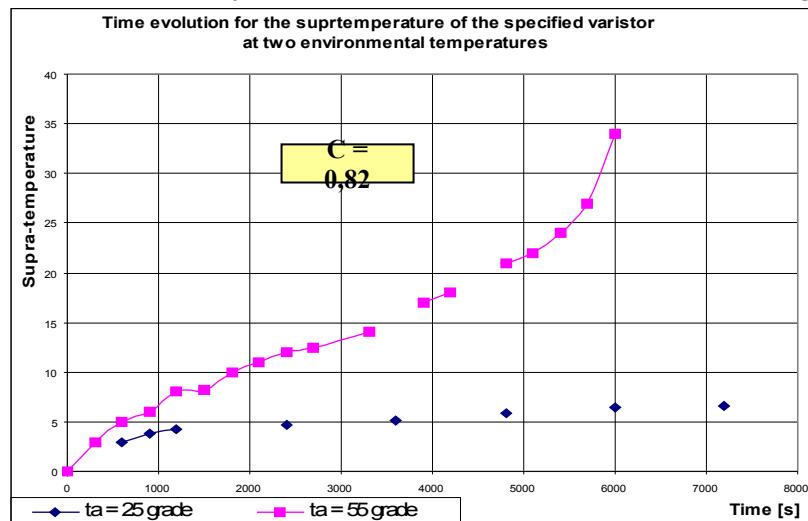


Figure 5. Time evolution for the supra-temperature for the considered varistor for two environmental temperatures

All the measurements were made at a voltage value of 320 V DC, which corresponds to the limited value for the "C" load coefficient, recommended by the producer as being $C = 0,82$.

The first value is placed under the environmental temperature limit and the second is placed over that. The limited value of the environmental temperature for a load coefficient $C = 0,8$ is about 40-45 °C. Over this value, the risk of thermal racing is higher. For a continuous service at the nominal voltage level ($C < 0,65$) there are no risks of thermal racing, overheating and fault even for an environmental temperature $t_a = 85$ °C (direct solar exposure of that piece of equipment) [2].

The time evolution of the crossing current for the two values of the environmental temperature is shown in Fig. 6 [2].

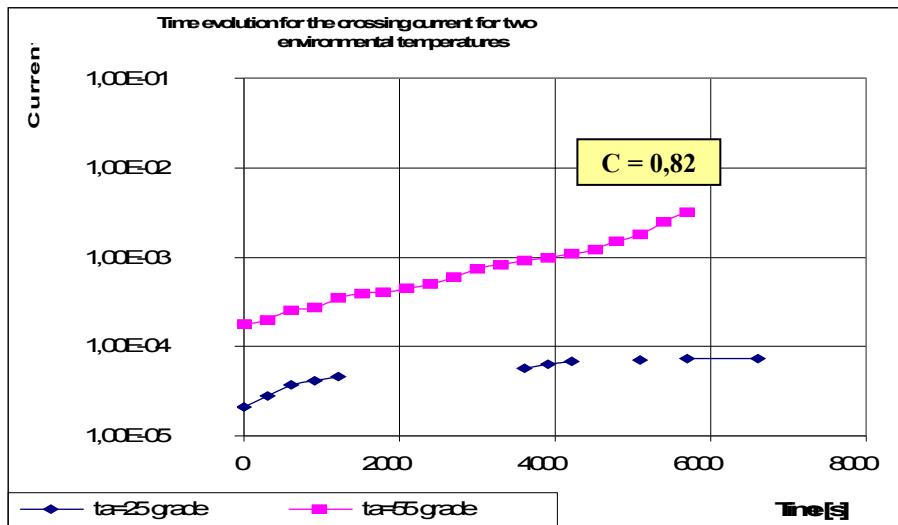


Figure 6. Time evolution of the crossing current for two environmental temperatures

We can observe that, in this case of a higher environmental temperature, the thermal racing occurs even for a load coefficient $C = 0,8$. The critical load coefficient is located around $C = 0,75$ for an environmental temperature of 55 °C. When passing over that value, the risk of over heating increases dramatically. So, we observe that [2]:

at $t_a = 25$ °C, $C_{cr} = 0,84$, and;

at $t_a = 55$ °C, $C_{cr} = 0,75$; (5)

By taking in consideration all these aspects, after all experimental determinations, we observed that all the critical values of the load coefficient have

a linear dependence of temperature, the line of that critical values passing by those two points gave by (5).

The equation of that line was experimentally determined as [2]:

$$C_{cr} = 0,915 - 3 \cdot 10^{-3} \cdot t_a \quad (6)$$

This line is presented in Fig. 7. For all points having the plan coordinates (C, t_a) located over the line, the thermal racing at that applied voltage V (load coefficient C) and that environmental temperature is inevitable. For all points having the plan coordinates (C, t_a) located under that line, the thermal racing does not occur, because the critical current density is not over passed.

All the points obtained before were represented in Fig. 7.

This linear relation between the critical load coefficient and the environmental temperature was verified not only for this type of varistors, but also for another low voltage varistors.

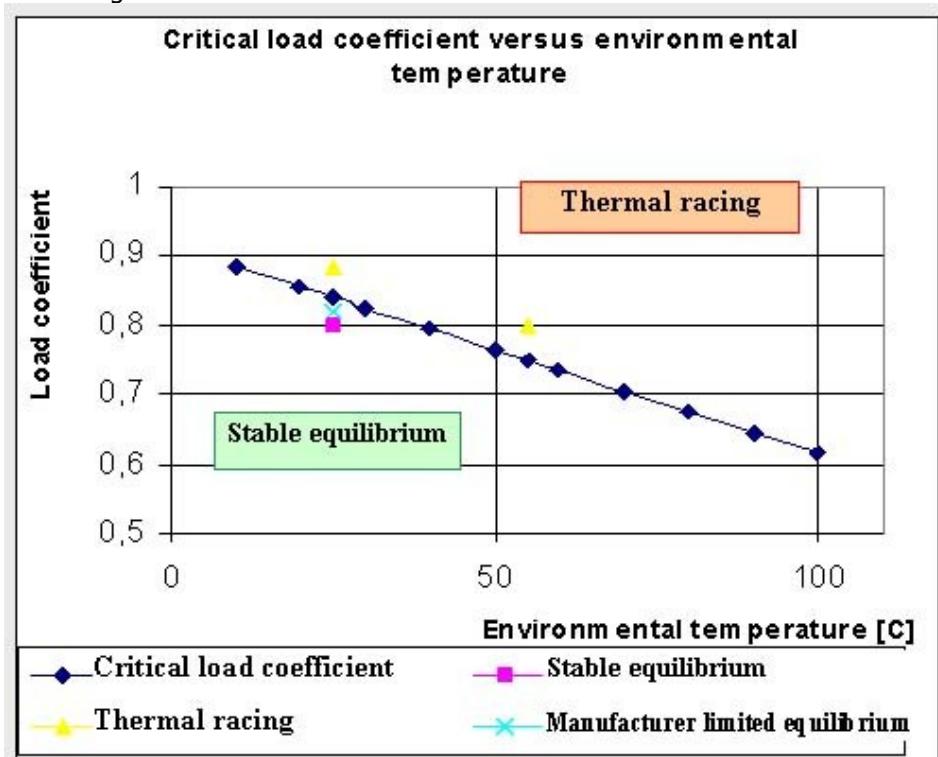


Figure 7. The relation between the critical load coefficient and the environmental temperature

It gives an answer to the question: "What is the maximum continuous DC operating voltage for a certain varistor at a certain environmental temperature?".

This method is very simple at involves no further equipment or supplementary costs. The designer, the producer or the simply user of a varistor could know its limits only by evaluating the equation (6) for a certain environmental temperature.

The climatically parameters of a varistor (or any other low voltage equipment which could or could not contain such a device) are specified by the IEC 68-1 and IEC 68-2-3 standards and also by CECC 42000 standards.

The storage temperature of such equipment must not over pass 60-70 degrees Celsius.

Not every varistor manufacturer offers data related to the environmental temperature of that device. Generally, all manufacturers gave data only for measurements made at an environmental temperature of 20 or 25 degrees Celsius. Surge arresters have to perform very well even at higher temperatures, due to excessive climate or direct solar exposure. This kind of measurements is not standardized [3].

4. Conclusions

This paper presents an experimental method used to determine the maximum continuous operating DC voltage for a ZnO based varistor at a certain environmental temperature. This kind of technical data is not always specified by the manufacturer but is necessary when using that device. We introduced a so-called "load coefficient" in order to obtain a much simplified expression for that relation.

By studying a certain disk type varistor we obtained a very simple linear equation which offers an answer to that question. This equation was verified for many other types of low-voltage ZnO based varistors, made by other producers and with other dimensions.

All the experimental procedures and all results are original and they are already applied by the Romanian low-voltage surge-arresters manufacturer PROTENERGO S.A. from Timisoara.

This equation gives a solution concerning the long term thermal stability of a varistor at a certain environmental temperature with no other further measurements and testing procedures, reducing the design time and costs for a low voltage surge-arresters made by using ZnO based varistors.

This study must be continued with an evaluation of the impulse regime thermal stability for completing all tests concerning the low voltage ZnO based varistors. These conclusions could be used even for medium and high voltage ZnO based varistors.

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