Towards the Prospection of an Optimal Thermal Response of ZnO Surge Arrester in HV Power System

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ABSTRACT (10 PT)

In order to understand the thermal and electrical properties of surge arrester under standard climatic conditions, it would be useful to evaluate the progression heating in its different elements. These last ones are constituted of heterogeneous materials which have physical and electrical nonlinear properties along the surge arrester. Temperature predicting solutions for zinc oxide ceramic blocks provide fundamental elements of the material electrothermal characteristics in view of the lifetime estimation. Electrothermal phenomenon analysis of surge arresters is based on determined parameter empirically models, using finite element method (FEM) simulated on COMSOL Multiphysics software which is a more precise approach compared to the existing models. In this paper, we develop a model to study the surge arresters behavior in both cases the steady state and overvoltage state (lightning). The obtained results are in adequacy with other published works that illustrate the energy handling dependence upon surge intensity current and the electrical and thermal phenomenon durations.

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1. INTRODUCTION (10 PT)

For a long time, MOA surge arresters based on silicon carbide have offered the best protection for all types of surges occurring on power networks. However, in the recent decades, these devices, have given way to surge arresters varistors based on zinc oxide (ZnO). Nowadays, these last are playing a major role in electrical protection systems and offer remarkable electrical properties such as; low response time, leakage current suppression, stability and reliability of electric systems, and high energy absorption capability. This high absorption capability of energy allows the sizing of surge arresters on all networks, from electronics to very high voltage power transmission (225 or 400 kV).

Which translates their energy limit beyond destruction for the two equipment protection types (overvoltages of Atmospheric origin ―lightning‖ and slow overvoltage switching surge) [1,2].
Furthermore, the response time of the ZnO varistors is very short, which makes the use of surge arresters possible for system protection against transient overvoltage with very steep fronts.

The Varistors are semiconductor devices made of polycrystalline ceramic, with a particular composition and microstructure [3]. They are variable and have a high nonlinear characteristic resistance to low applied voltage values. A varistor behaves like a high value resistance obeying the law Ohms but, above a threshold voltage, the device becomes highly conductive with low impedance to the high tensions. When the resistance becomes conductive, it maintains the applied voltage to a maximum value indicated by the protected system which can withstand it [4]. Indeed, the current-voltage relationship I(V) essentially reflects the quality of varistor from the non-linear and leakage current point of view [5].

The varistors are placed in a polymer or porcelain envelope so that it is not affected by moisture or pollution. The external enclosure of the surge arresters varistors offers insulation outside. These envelopes have traditionally been made of porcelain, but today the trend is towards the use of synthetic insulators [6]. A porcelain surge arresters contains a large amount of dry air or gas (nitrogen), while a synthetic surge arrester does not have all the gas included. This means that the internal conditions against the electric and thermic phenomena must be resolved differently for both designs [7].

In the design of electrical engineering, particularly in protection systems, thermal evaluation should be taken into account during operating cycles in order to increase the reliability of protection systems [8]. This paper presents the thermal-electric model developed to study the behavior of ZnO porcelain surge arrester. The development of this model is relatively complex, as it takes into consideration the non-linearity of the electrical characteristic of ceramics, the non-linearity of thermal phenomena, as well as the coupling of electrical and thermal phenomena during surge arresters operating. Two cases of ZnO surge arrester operation are examined; steady state and transient regime. Under normal operating conditions, ZnO surge arresters present low leakage current to ground. [9] When a surge arrester is subjected to a transient voltage, the ZnO elements absorb a large amount of energy and the temperature rises abruptly due to the unequal voltage distribution created by the surface leakage currents [4]. Materials temperature is strongly related to power dissipation and temporary overvoltage. Therefore, there is a coupling between electrical behavior active elements (ZnO varistors) and the thermal impact of the whole structure.

Furthermore, the applied voltage is below a threshold temperature, the varistors reach a point of balance. The heat generated by the losses is in balance with the heat dissipated via the surge arrester towards the ambient air. However, if the applied voltage exceeds this threshold, the current and the temperature have no balance point, and they will increase continuously until the destruction of the device. This phenomenon is called thermal runaway.

The protection against the thermal runaway is a problem of prediction in surge arrester elements electrothermal behavior. There is a certain temperature margin in which the arrester is stable. Therefore, if the instantaneous increase in temperature remains lower than the temperature difference of the margin, the arrester is stable. In other words; whether the ambient temperature or the applied voltage (field applied) change, this temperature margin may have other values, and consequently its value is not unique. If the voltage is moderated, the temperature of an element will reach its equilibrium to a level where the generated power is balanced by the dissipated power. However, if the applied voltage is very high (higher than a certain level), the thermal runaway takes place. [10].

The degradation in the surge arresters reduces the stability zone by moving the upper point towards higher temperatures, and the arrester degrades further. Thus, the aging effect creates a new operating point that will evolve until both stability limits are combined and the arrester can no longer dissipate (destruction). [11].

At the microscopic scale, the resistivity of a semiconductor material decreases as the temperature increases. This electrical property is due to the fact that thermal energy increases the charges carrier number. Since ZnO is an intrinsic semiconductor, the thermal energy is sufficient to excite electrons from the valence band to the conduction band. Therefore, the electrical conductivity is ensured by the holes created in the valence band and the electrons located in the conduction band. [12].

The leakage currents flowing through the surge arrester ZnO block can be divided into resistive leakage current and capacitive leakage current [13]. The leakage current density is measured for an electric field value close to the nominal operating conditions, for example 75% or 80% of the ES threshold field [14, 15]. The leakage currents magnitude is higher for surge arresters with higher energy class element [16]. Hence, the leakage current is related to the temperature increase in the ZnO block and it is sensitive to the distribution of the voltage in the block. [17]. Resistive leakage currents generate a Joule effect. The temperature increase in the ZnO block of the surge arrester [18,19], which will lead to molecules excitation, is due to the reduction of ZnO block internal resistance. In other words, the electrical losses in the ZnO varistors bloc of surge arrester, which depend on the leakage currents, are responsible for the temperature rising [20]. The thermal and electrical properties of the surge arrester ZnO block can be evaluated, when the resistive leakage current flows through it. Several techniques make it possible to calculate the resistive leakage current value from the total leakage current [21, 22, 23]. The resistive current reaches the value of the total current at the moment when the voltage is at its maximum. The increase in the resistive current is a result of the increase in varistor temperature, which does not necessarily leads to degradation or damage of the surge arrester [24].

The main idea of this work is the prediction of thermal state of ZnO surge arrester, in a complex physical environment. In this study we employ the COMSOL Multiphysics.

2. ELECTRIC PROPERTIES

The current-voltage characteristic is in general described by the following equation:

$$j = j_0 \left(-\frac{q\emptyset_b}{k_B T}\right)\left[1 - \exp\left(-\frac{qV_f}{pk_B T}\right)\right] \quad (1)$$

j is the electronic flux due to the electronic transport through potential barrier and j_0 is a constant which can be a function of the temperature and V_f is the direct bias potential [25,26].

The current density increment has two parts:

- One is due to the increase of the electric field at constant conductivity:
-

$$\sigma\,(E)\,dE \;=\; \left(\frac{J}{E}\right) dE. \quad (2)$$

- The second is due to the increase increment in non-ohmic material, it can be written as:
-

$$dJ = -\frac{J}{E} dE + \beta J dE \quad (3)$$

Therefore, the semi-empirical equation is:

$$J(E) = \sigma_0 dE \exp \beta E \quad (4)$$

σ_0: is the electrical conductivity at room temperature and it is calculated in the first ohmic region using the ohmic relation.[2]

The electric field and the temperature are interrelated. Furthermore, nonlinear factor is proportional to the voltage barrier height level. [27]

At low electrical fields ($\beta E < 1$) the Ohm's law will be:

$$J = \sigma_0 E. \quad (5)$$

At high fields, $\sigma\,(E) = \sigma_0 / E$, the conductivity is increased with the electric field exponentially:

$$\sigma(E) = \sigma_0 \exp \beta E \quad (6)$$

The characteristic V(I) must represent the non-linear conductivity and also temperature effect in the electric current low zone. V(I) is simulated by:

$$J(E,T) = J_0 \;\exp(N.T)\; \exp(B.E) \qquad A/m^2 \quad (7)$$

$$\sigma(E,T) = \sigma_0 \;\exp(N.T) \exp(B.E) \qquad S/m \quad (8)$$

where,

J_0, B, N, σ_0: constant.

E: Electric field at the terminals of the varistor [V/m].

T: Temperature in [K^0].

J: The current density [A/m^2].

Equations (7) and (8), which are used to represent the characteristic V(I), have the advantage of including both temperature effect and different electrical and physical quantities of materials.

In order to solve these equations, we proposed an algorithm to find the curve of electrical conductivity according to temperature and electric field (refer to Fig. 1).

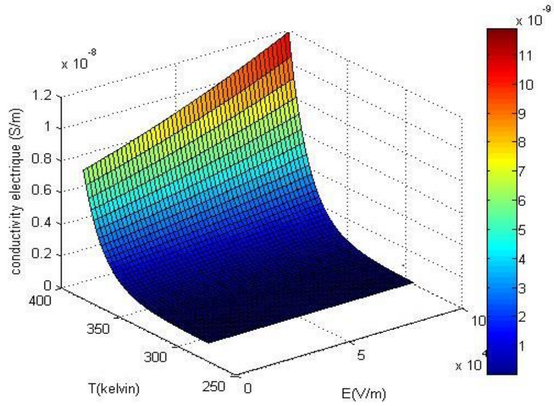


Figure.1. Electric conductivity as a function of temperature and electric field.

From Figure.1, the electrical conductivity of zinc oxide in the low current zone increases with the increasing of electric field and temperature.
The distribution of the temperature inside surge arrester influences the electric fields, likewise the distribution of the temperature between the individual elements of ZnO, both in normal operation and transient overvoltages, influences the voltage profile along the arrester. Therefore, a very complicated analysis is needed in the design of surge arresters. This analysis should cover mutual coupling between the thermal and electrical phenomena [28].
The heat diffusion equation takes the form [29].

$$D(T)\left(\frac{\partial^2 T'}{\partial r^2}+\frac{1}{r}\frac{\partial T'}{\partial r}+\frac{Q(r)}{k_0}\right)=\frac{\partial T'}{\partial t}, \quad (9)$$

where, : $D(T)=\frac{k(T)}{c_p}$, is the diffusivity.

Since the thermal conductivity k(T) depends strongly on temperature [29], the scaled temperature T’ is used,

$$T'(T)=\frac{1}{k_0}\int_{T_0}^{T}k(T). \quad (10)$$

The temperature T’ and the input heat Q presented in equation (1) depend on r (the radial distance from the disk center) and on t (time). The heat dissipates only radially by convection to air over the sidewall, since disks mounted in a surge arrester do not have significant axial heat conduction to neighboring disks [30, 31],

2.1. The corresponding boundary condition

$$\left.\frac{\partial T'}{\partial r}\right|_{r=R}=-\chi\left[T(T'(R,t))-T_A\right]^{5/4}, \quad (11)$$

Electrothermal simulation requires knowledge of physical parameters materials. Comsol Multiphysics has a database containing a set of numerical values for the different physical constants characterizing the materials. The values are taken directly from the literature [32].
The heat conduction equation in cylindrical co-ordinates for axial symmetry problems is:

$$\frac{k}{r}\frac{\partial T}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q=C_p\rho\frac{\partial T}{\partial t},\ r>0,\ t>0 \quad (12)$$

3. ELECTROTHERMAL MODELING OF ZNO SURGE ARRESTER

The general configuration as depicted in (Fig. 2) is a 2D diagram of ZnO surge arrester, represents the main components and their dimensions.
In this device, three types of material regions are present:
- The ZnO varistors column which has electrical characteristics μ_r and ε_r
- The covers at each end, and the joints among two adjacent varistors is made in aluminum with characteristics σ, ε_a, and μ_a

- The housing insulation material is made of porcelain σ_e, ε_e, and μ_e.

The whole model geometry is surrounded by a layer of air. The electrothermal surge arrester model is developed in finite element method (FEM); it can be divided into an electric model and a thermal model. It consists in coupling a thermal and electrical phenomenon.

The COMSOL Multiphysics software works on the heat flow and the electrical potential resulting from an imposed voltage that passes through a resistive material. It solves the equations system arising from the electric charge conservation and the thermal energy balance to calculate the temperature.

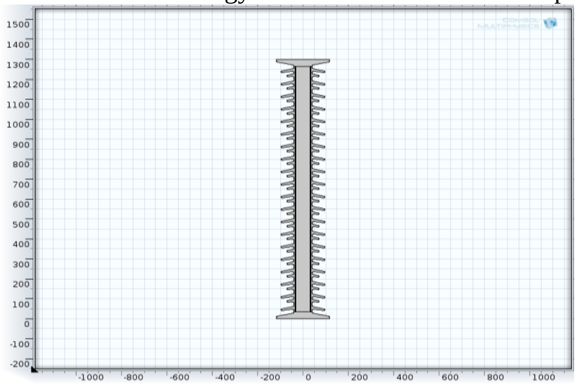


Figure. 2. Definition of geometry in COMSOL Multiphysics.

The equation of continuity: $-\boldsymbol{\nabla}.(\boldsymbol{\sigma\nabla}\ \mathbf{V}) = \mathbf{0}$ (13)

3.1 Electrical properties of the envelope

AR.RAHISHAM et al [23] proposed an FEM modeling of the surge arrester envelope (non-conductive regions). The approximation represented by a mathematical expression:

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}} = 0 \quad (14)$$

Since $\mathrm{E} = -\nabla \mathrm{V}$, and by applying the divergence to the Maxwell-Amperes law:

$$\nabla.\nabla \times \mathrm{H} = \nabla.\left[\mathrm{J} + \frac{\partial \mathrm{D}}{\partial \mathrm{t}}\right] \quad (15)$$

where, J = σ.E and $\mathrm{D} = \varepsilon_0\varepsilon_r$Eare the current density and the displacement vector respectively.

The potential distributions and the electric field are calculated in time domain as following:

$$-\nabla.\frac{\partial}{\partial \mathrm{t}}(\varepsilon_0\varepsilon_r\nabla.\mathrm{V}) - \nabla.(\sigma\nabla.\mathrm{V}) = 0 \quad (16)$$

In this expression, V is the potential, σ is the electrical conductivity, ε_0 is the permittivity of the vacuum, and ε_r is the relative permittivity of the material.

3.2. Heat Transfer

$$\boldsymbol{Q} = \boldsymbol{\rho}.\boldsymbol{cp}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} - \boldsymbol{\nabla}.(\boldsymbol{k\nabla T}) \quad (17)$$

The link between the two equations is the joule effect, defined by:

$$\mathrm{Q} = \mathrm{J}.\mathrm{E} = \sigma \mathrm{E}^2 \quad (18)$$

where, Q: is the heat flux (W / m^3).

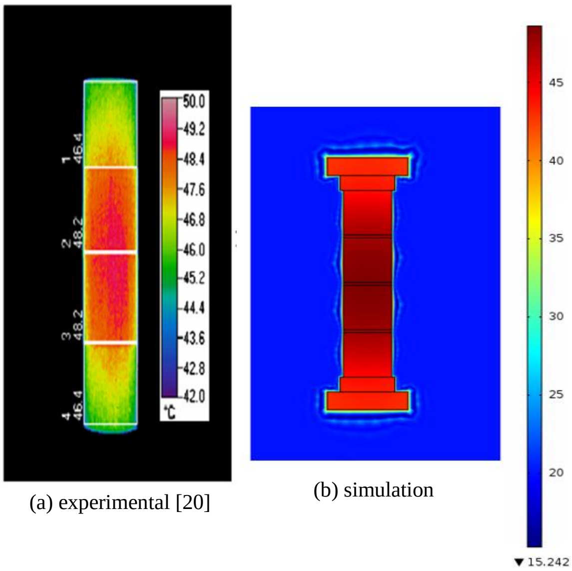
3.3. Model Validation

The developed model takes into account two different time constants are confronted. The thermal time constant is between 1h and 4h, while the time constant for electrical phenomenon is in the order of a few milliseconds. To calculate the thermal phenomena, the time step retained is about several dozen seconds. It should be noted that some adjustments are needed in the coupling of thermal and electrical phenomenon to observe their influences in ZnO varistor [33]. Moreover, under these conditions, the electrical study is assimilated to a continuous regime and its model contains only non-linear resistances. This representation is justified by the fact that electrical study has a dominant resistive behavior, which is mainly used to indicate high temperatures.

Su-Bong Lee, and al [20] applied a voltage of 18 kV with a normal frequency of 50 Hz on surge arrester (Fig. 3.a) for four hours. The obtained results are illustrated in Fig. 3a, and Fig.4a.

Fig. 3.b represents a simulation of the experimental work carried out by these researchers under the same boundary conditions:

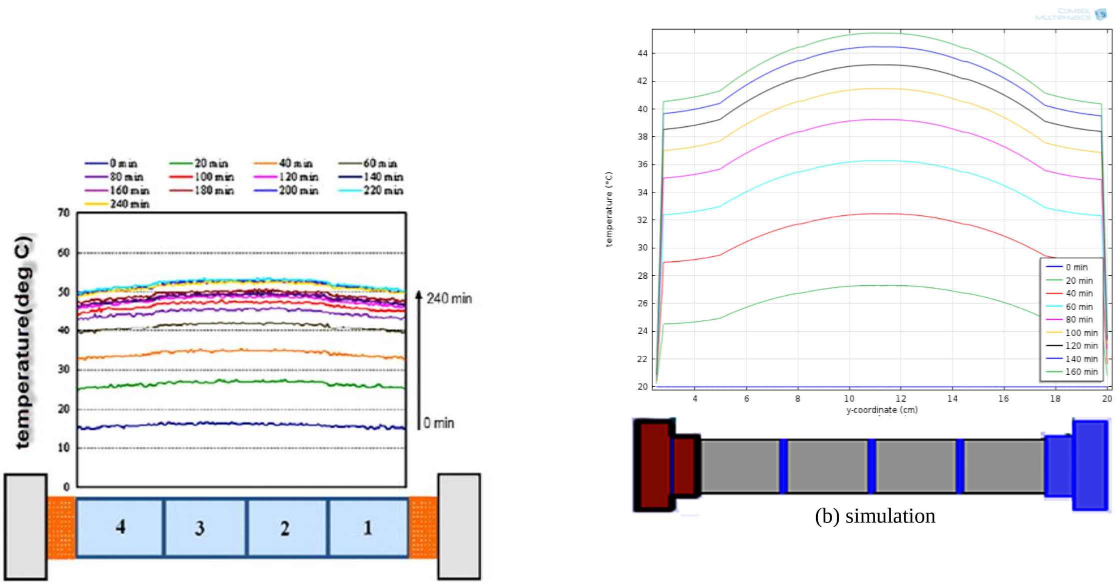
- The applied voltage 18 kV,
- The ambient temperature 20 C°.
- Heat convection coefficient h = 60 [W / m^2.K].
-



(a) experimental [20]

(b) simulation

Figure .3. Temperature distribution on the surge arrester after 4 hours



(b) simulation

(a) experimental [20].

Figure .4. Thermal profile of a surge arrester with time.

4. RESULTS AND DISCUSSIONS

The simulation results are shown in Fig. 3b and Fig. 4b. In Fig. 3.b, it can be observed that the temperature distribution is similar to the results obtained experimentally in Fig. 3.a.

It has been revealed that the temperature value in the electrodes is lower than in the middle. Accordingly, its maximum value is in the middle of the surge arrester (it reaches 50 C° experimentally and 48 C° by simulation).

In Fig. 4.b, the thermal profile along the surge arrester is represented as a function of time obtained by simulation. An increase of temperature is observed. From 80 minutes, the temperature difference between two successive periods of 20 minutes decreases. The temperature distribution of this simulation (Fig. 4.b) is close to the results obtained experimentally (Fig. 4.a). [20].

Furthermore, the general appearance is present in our results, although we do not have the identical parameters values that influence the electrical phenomenon and the heat dissipation.

This set of results (Fig.3 to 4.b) shows clearly a concordance between the results obtained from the two modeling which are different in the theoretical point of view.

The Comsol Multiphysics software allows us to perform calculations by solving the integral temperature equation by the finite element method, taking into account the nonlinear conductivity of ZnO. This calculation is rigorous and carried out without any simplifying hypothesis.

5. APPLICATION OF THE MODEL TO A 110 KV SURGE ARRESTER

5.1. Under continuos operating

Under continuous operating conditions, the applied voltage is 110 kV to top electrode, at room temperature of 20°C and the simulation time is 2 h 15 min. The obtained results are shown in the following figures.

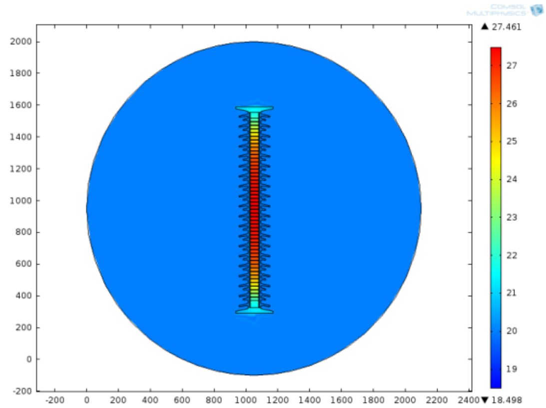


Figure .5. Temperature distribution after 2h15 minutes.

From Fig.5 the temperature value is maximum in the middle of the surge varistor and minimal at the electrodes. Thus, the surge arrester temperature varies between 20 C° and 27 C°, and it remains stable when the applied voltage is about 110 kV. The power loss created by the leakage current is equal to the heat emitted into ambient air.

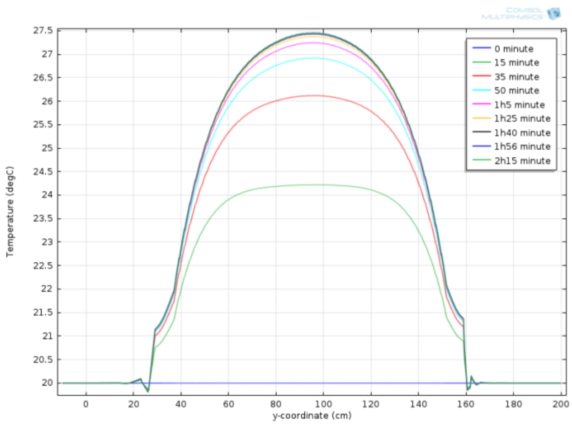


Figure. 6. Temperature profile along the arrester

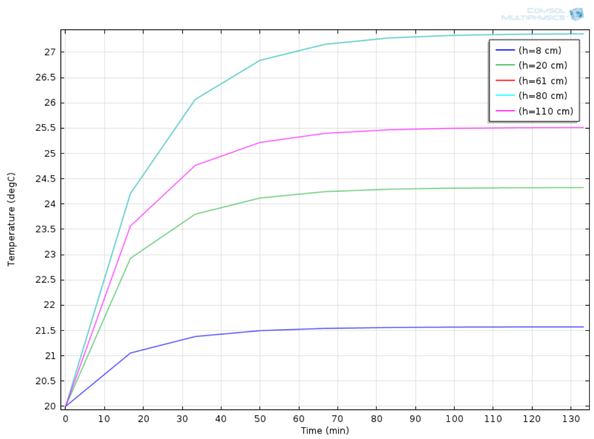


Figure. 7. Thermal profile along the surge arrester

Fig. 6 shows the thermal profile along the surge arrester under an applied permanent voltage of 110 kV for 2 hours and 15 minutes. The distribution of non-uniform heat in the varistors is observed. The ZnO varistor near the aluminum electrode is characterized by a lower temperature, because metallic electrodes

(Aluminum) that promotes the release heat on both ends. In addition, the general form of porcelain insulators causes a temperature increase to the maximum value in the middle of the surge arrester, due to the small amount heat released.
To determine temperature variation as function of time in the surge arrester, several points are chosen in different heights. The reference height is h = 0 at the low voltage electrode. The simulation results are shown in Fig. 7 which illustrates the influence of height on temperature as a function of time. It is obvious that the temperature in interval [0, 100 min] varies proportionally with time. However, from 100 minutes, the temperature value remains constant with time increase, due to the equilibrium between generated and dissipated power.
The study of the thermal balance of a varistor must be carried out in all its operating regimes, because the danger of thermal runaway may occur at any time [2].

5.2. Transient analysis
Surge arresters can be used in non-continuous mode, it is important to see the thermal behavior in the transient mode (lightning, maneuver).
A bi-exponential lightning voltage surge of 1.2 / 50 µs is applied; the waveform is given by equation 19:

$$V(t) = \eta \frac{aV_0}{\sqrt{a^2-1}}\left[\exp\left(-\frac{\left(a-\sqrt{a^2-1}\right)t}{b}\right) - \exp\left(-\frac{\left(a+\sqrt{a^2-1}\right)t}{b}\right)\right] \quad (19)$$

where, a= 6.9, b= 4.9 µs, η= 0.98, and V_0=110kV.

The simulation lasts for 60 minutes; the result of the temperature distribution on the surge arrester is shown in Fig.8 and Fig. 9.

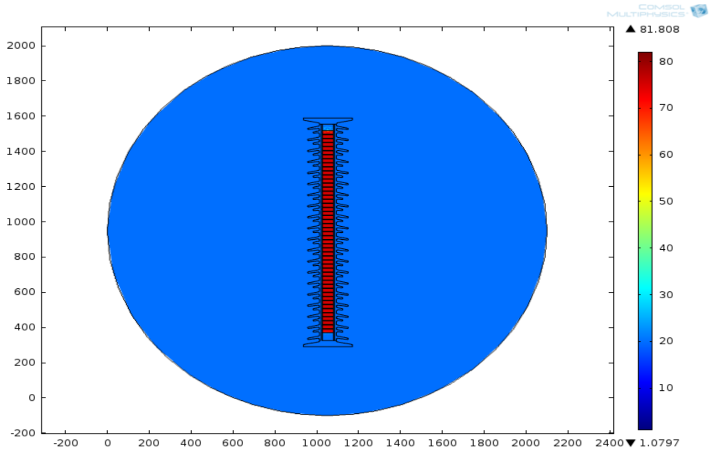


Figure.8. Temperature distribution on surge arrester after 60 minute.

At transient regime, the ZnO blocks temperature increases to 81 C° after 60 minutes. Fig.9 shows the thermal profile as a function of time. Temperature profile along the symmetry axis of the arrester, at the point of the medium under transient conditions, reaches 75 °C.

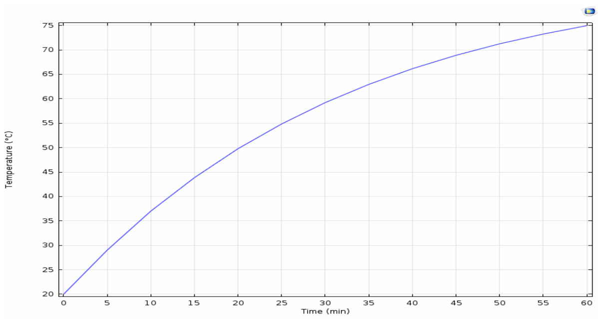


Figure.9. Thermal profile as a function of time (middle point).

When the temperature of the ZnO blocks exceeds the limit, it causes a thermal imbalance between the production of heat and that released which can lead to failures or thermal runaway.

It is concluded that the degradation phenomena and the thermal runaway of the ZnO surge arrester block are directly related to the heat lossless, which determines the generation and temperature dissipation processes.

5.3. Cooling under voltage

The transient regime results are exploited as initial state in the cooling study under voltage of steady state for 3 hours. The result of the simulation is shown in the fig. 10.

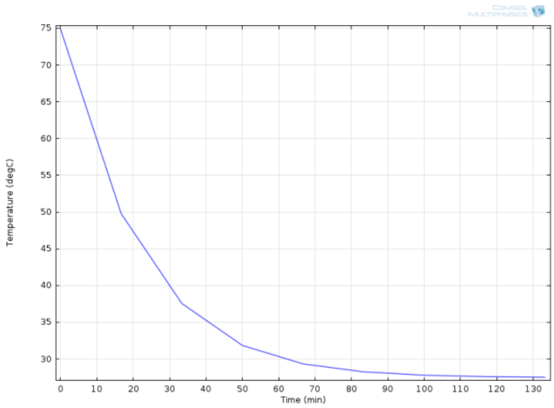


Figure. 10. Thermal profile as a function of time (middle point*)*

The characteristics of the thermal stability of this surge arrester can be determined from the amount of heat released directly by the surge arrester. The values obtained in the median part of ZnO varistors at ambient temperature of 20 °C, are illustrated in Fig. 10. The cooling rate is very low (it takes 130 mn) due to the low thermal conductivity. In addition, the heat can be dissipated to the housing surface with a low temperature gradient [34].

The distribution of heat as a function of time is given by:

$$T(t) = (T_0 - T_a)\exp(-t/\tau) + T_a \quad (20)$$

where,
τ : Constant of time.
T_a: Ambient temperature 20°C.
t: Heat release time
We set t = τ and introduce it into the previous equation, we obtain T = 40°C, we project this temperature value on the curve 18 to find τ = 68 min.
During the first minutes of cooling, extreme ceramics temperature decreases very rapidly due to the heat dissipation by conduction towards the covers, and the large heat capacity of these covers. The central part cools in a uniform way, because the covers influence is minimal, for the order of the initial heating magnitude. In that case, most of the central part heat is evacuated by radiation, convection and conduction between the ZnO column and the porcelain.

6. CONCLUSIONS

The surge arrester operations are simulated by an electrothermal study in order to predict its behavior under thermal factors influence. This is one of the vital characteristics of surge arresters that must ensure the proper power electrical network operating.
The work covered in this paper consists essentially of two main parts:
In the first part, we exploit COMSOL Multiphysics software to extract electrical and thermal properties of different materials used in the proposed model. This extraction is represented as functions of temperature for the thermal properties. Furthermore, an algorithm is developed to implement the nonlinear characteristics (electrical conductivity and thermal conductivity, thermal capacity) in this software.

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