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ELECTROTHERMAL AND MECHANICAL STRESS OF HIGH VOLTAGE SURGE ARRESTERS

Abstract: In order to find out the influence of leakage current on Metal Oxide surge thermal and mechanical processes in metal oxide arresters were subject of research. Mathematical model of current and thermal flow and mechanical displacement field were proposed and computed using finite-element method. Computations were performed for arresters used for 22 kV voltage distribution networks at voltage levels of normal operation and ground fault.

Keywords: surge arresters, leakage current

1. Introduction

High voltage surge arresters without gaps present quality improvement in overvoltage protection. SiC varistors were replaced with metal oxide varistors (MOV). Nowadays, there are arresters manufactured by several producers, e.g. Raychem, ABB, tridelta, Acer, etc. offered on market.

It is important to say that faults occurred in early stages of installation of surge arresters. These faults are caused mainly by absorption of energy followed by thermal and mechanical overload. MOV are continually connected to operating voltage and additionally stressed by overvoltages. Overvoltages can be separated into the following groups: lightning transients, switching transients, temporary overvoltages. When lightning or switching transients occur, overload last for relatively short period (from microseconds to several milliseconds). During occurrence of temporary overvoltages overload can last for several hours depending on type of distribution system [1].

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2. Theoretical analysis

2.1. Thermal stability of MO surge arresters

At low voltages mainly capacitive current component flows through MOV. On the contrary, because of strongly non-linear current-voltage characteristic MOV become conductive at overvoltages. The number of ZnO varistors in surge arrester depends on residual voltage — there is need for decrease in number of ZnO varistors. On the contrary, due to long-term thermal stability there is demand for increase in number of ZnO varistors in surge arrester. Producer must take into account both long-term thermal stability and amplitude of residual voltage. Current-voltage characteristic of MOV is strongly non-linear, symmetrical and depending on temperature (increase in current due to increase in temperature). In Fig. 1, the dependence of ZnO varistors power loss P on temperature T at continuous operating voltage U_c is shown. Exponential increase in losses can be seen. Cooling of arrester is supplied by thermal flow Q to surrounding environment.
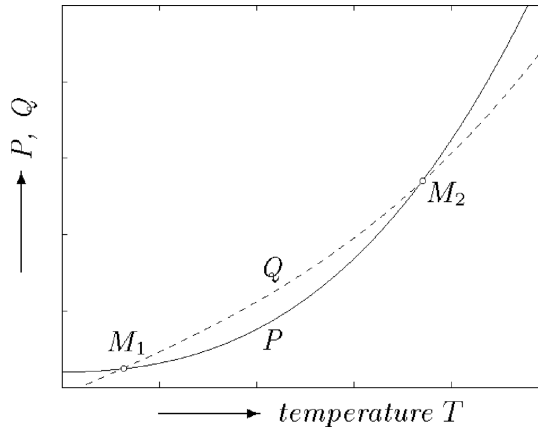

Fig. 1. *Power loss P of MOV and thermal flow Q radiated by active parts of surge arrester characteristics depending on temperature of MOV at continuos operating voltage U_c*

At high temperatures exceeding critical value (point M_2) statement $P > Q$ is valid. There is insufficient thermal transfer in this region. Temperature of MOV continuously grows and thermal damage follows. It is possible to provide stable operational conditions by suitable design and dimensions of arrester. Then $P < Q$ statement is valid and MOV are cooled till stable point M_1 is reached.

Thermal damage of MOV can also be caused by voltage higher than continuos operating voltage U_c. It is possible to overload the surge arrester by higher voltage for limited period provided not exceeding of period given by producer, see Fig. 2. (Curve a applies to an arrester that was not previously loaded; b applies to an arrester that was previously loaded with $E = 2,5\,\text{kJ/kV}\cdot U_c$, t is the duration of the overvoltage at the power frequency).
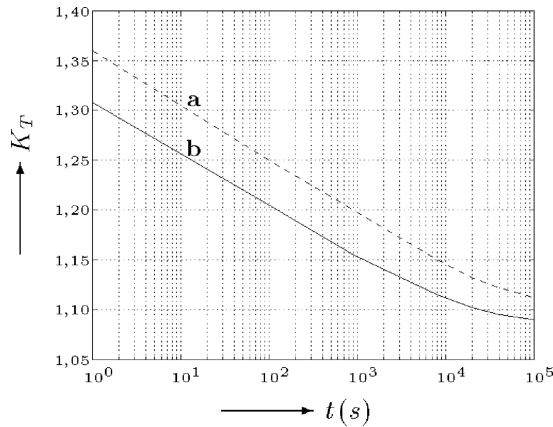
Fig. 2. *Withstand strength K_T against temporary overvoltages U_{TOV} as a function of the time t at an ambient temperature of $45°C$*

Next equation for withstand strength K_T against temporary overvoltages U_{TOV} is valid:

$$U_{TOV} = K_T U_c$$

The higher U_{TOV} value is, the higher power is absorbed. Even in this case point M_2 must not be exceeded so absorbed energy is limited. It means that with increase in value of K_T allowed duration t decreases.

2.2. Formulations in thermal flow analysis

In order to compute temperature distribution in MOV it is necessary to determine heat produced by leakage current. The problem of current distribution is described by Laplace's equation for scalar potential φ. For axisymmetric case it has the form [2]:

$$\frac{\partial^2 \varphi}{\partial r^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0$$

Electric field and the current density are expressed by the following equations:

$$
\begin{aligned}
E &= -\nabla\varphi \\
j &= \rho^{-1}E
\end{aligned}
$$

where ρ represents the resistivity of a conductor.

Joule heat produced in MOV by leakage current can be calculated using equation:

$$W = \int\limits_V j \cdot E dV$$

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Temperature field in MOV can be analysed solving heat transfer equation for axisymmetric case:

$$\lambda(T)\left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) = -q$$

where T is temperature in Kelvins, $\lambda(T)$ is heat conductivity and q represents volume power of heat sources. While solving the previous equation following boundary conditions must be fulfilled [3]:

- *Heat flux boundary condition*

$$F_n^+ + F_n^- = -q_n$$

where F_n is normal component of heat flux density, "+" and "−" superscripts denote quantities to the left and to the right side of the boundary. For inner boundary q_s denotes the generated power per unit area.

- *Convection boundary condition* is specified at outward boundaries:

$$F_n = \alpha(T - T_0)$$

where α is film coefficient and T_0 is temperature of contacting medium.

- *Radiation boundary condition* describes radiative heat transfer and is defined by the following equation:

$$F_n = k_{SB}\beta(T^4 - T_0^4)$$

where k_{SB} is Stephan-Boltzman constant, β is emissivity coefficient.

2.3. Mechanical stress

The displacement field is assumed to be completely defined by the two components of the displacement vector in each point δ:

$$\{\delta\} = \begin{Bmatrix} \delta_z \\ \delta_r \end{Bmatrix}$$

The axisymmetric problem formulation is described by strain tensor. The strain--displacement relationship is defined as:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_z \\ \varepsilon_r \\ \varepsilon_\varphi \\ \gamma_{rz} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial \delta_z}{\partial z} \\[2mm] \dfrac{\partial \delta_r}{\partial r} \\[2mm] \dfrac{\delta_r}{r} \\[2mm] \dfrac{\partial \delta_z}{\partial z} + \dfrac{\partial \delta_r}{\partial r} \end{Bmatrix}$$

The corresponding stress components:

$$\{\sigma\} = \begin{Bmatrix} \sigma_z \\ \sigma_r \\ \sigma_\varphi \\ \tau_{rz} \end{Bmatrix}$$

The equilibrium equations for the plane problems are:

$$\frac{1}{r}\frac{\partial(r\sigma_r)}{\partial r} + \frac{\partial(\tau_{rz})}{\partial z} = -f_r$$

$$\frac{1}{r}\frac{\partial(r\tau_{rz})}{\partial r} + \frac{\partial(\sigma_z)}{\partial z} = -f_z$$

where f_z and f_r are components of the volume force vector [2].

For linear elasticity, the stresses are related to the strains using relationship of the form:

$$\{\sigma\} = [D]\left(\{\varepsilon\} - \{\varepsilon_0\}\right)$$

where D is a matrix of elastic constants, and ε_0 is the initial thermal strain:

$$[D] = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \qquad \{\varepsilon_0\} = \begin{Bmatrix} \alpha \\ \alpha \\ \alpha \\ 0 \end{Bmatrix} \Delta T$$

where E denotes Young's modulus of the isotropic material; ν is a Poisson's ratio for isotropic material, α is a coefficient of thermal expansion for isotropic material and ΔT is the temperature difference between strained and strainless states.

3. Results

In order to calculate temperature field and corresponding mechanical stress a simplified design of a MOV was used. The model consisted of seven ZnO discs surrounded by porcelain housing which was separated from ZnO discs by air gap. Metal electrodes were used to carry electric current and to enclose whole design. Electrical and thermal properties of porcelain and metal and thermal properties of ZnO blocks were known from literature [1, 4]. Electrical properties of ZnO discs were found out experimentally [4].

The computations were carried out for following voltage levels: normal operation 12,7 kV (fig. 3), ground fault 22 kV (fig. 4) and increased voltage 26 kV (fig. 5). Additional computations were performed for arrester with increased conductivity of ZnO

disc representing a damaged arrester (conductivity 10 times higher) (fig. 6). Temperature steps modelled increase in ambient temperature with the height caused by warm air flowing from lower to upper parts of MOV. Difference between top and bottom was set to 5 K.

Results of computations show significant increase in the temperature of damaged surge arrester compared to three cases of non-damaged ones (from 315 to 392 K). Increased temperature causes increased mechanical stress, which value rose from 1,28 to 1,352 GN/m². Thin grey line in all pictures marked b represents change in shape due to increased temperature.
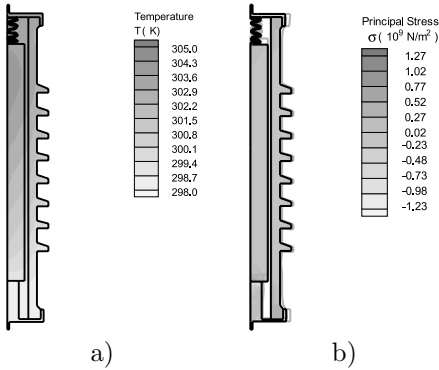

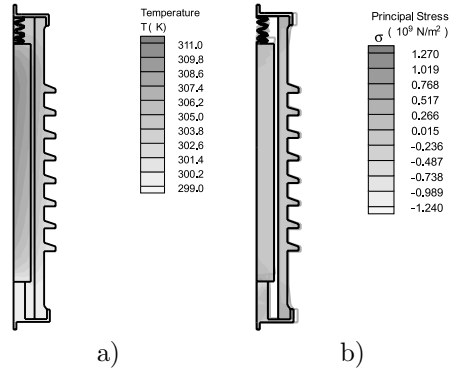**Fig. 3.** *Varistor at 12,7 kV, a) temperature field, b) stress distribution*

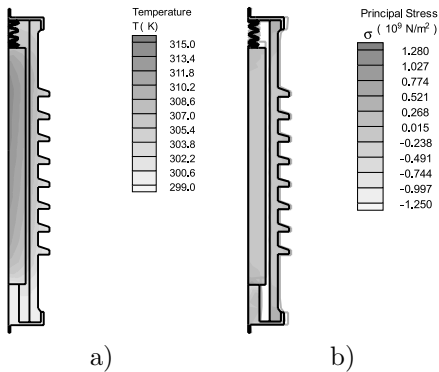**Fig. 4.** *Varistor at 12,7 kV, a) temperature field, b) stress distribution*

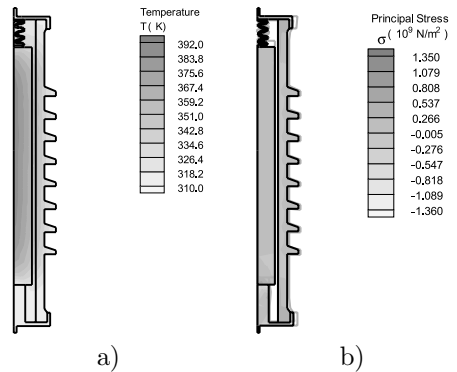**Fig. 5.** *Varistor at 26 kV, a) temperature field, b) stress distribution*

Fig. 6. *Varistor at 22 kV, a) temperature field, b) stress distribution*

4. Conclusion

Computation of temperature fields showed significant temperature differences across MOV which that can be increased during ageing under operation. Different temperatures of varistor columns and porcelain housing cause increase in mechanical stress. This can exceed the mechanical strength of porcelain housing could destroy arrester thermally.

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Elektrotermiczne i mechaniczne narażanie
wysokonapięciowych ograniczników przepięć

Celem badań było rozpoznanie procesów cieplnych i mechanicznych, związanych z prądami upływowymi w ogranicznikach przepięć z tlenków metali. W referacie zaproponowano stosowny model matematyczny, uwzględniający przepływ prądu i ciepła oraz przemieszczenia mechaniczne. Obliczenia przeprowadzono dla ograniczników zainstalowanych w liniach 22 kV, pracujących w normalnych warunkach operacyjnych oraz przy doziemieniach.