Development of mathematical and physical models for studying high-voltage resistive dividers in digital voltage transformers

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Developing digital current and voltage transformers is an important task within the conceptual framework of innovative electric power development (intellectual power systems with active adaptive grids – IPS AAG). Resistive dividers are promising primary voltage converters. In the present study, we developed and examined a high-voltage divider containing resistive elements with solid-state insulation. The use of solid-state insulation in a transformer creates additional thermal resistance obstructing heat removal from resistive elements. Warming of resistive elements alters their resistance and thus lowers the accuracy of voltage measurement by the resistive divider. To reduce the impact of resistive element warming it is necessary to select resistors with a minimal temperature resistance coefficient (TCR), maximum surface area for increased heat transfer, and also maximum resistance to reduce heat release. However, increased resistive element resistance increases the impact of electrical displacement current and leakage current in transformer insulation, limiting the accuracy class of voltage transformers intended for open switchgear operation.

In view of the above, the task of developing and researching transformers based on resistive dividers is aimed at determining optimal resistance of resistive elements and their relative position, taking into account the distribution of thermal and electromagnetic fields to achieve maximum measuring accuracy. The resistive elements, their position and parameters specify and determine electromagnetic and thermal field levels, rendering our task one of iteration and interaction.

The target functions for designing a voltage divider may be written down as follows:

$$\begin{aligned}
&TKC \to \min; \\
&\Delta T \le 30^{\circ}C; \\
&\lambda_{герм} \to \max; \\
&I_C^k \to \min; \\
&U_{доп} \ge U_{гроз.имп.}; \\
&E < E_{доп},
\end{aligned} \qquad (1)$$

where ТКС (TRC) – temperature resistance coefficient of resistive elements; ΔT – resistive element warming relative to ambient temperature; $\lambda_{герм}$ – sealant heat conductivity; I_c – capacitive current; $U_{доп.}$ – permissible resistive divider voltage; $U_{гроз.\ имп.}$ – lightning impulse test voltage for the corresponding transformer class according to GOST 1516.3-96; E - electric field voltage.

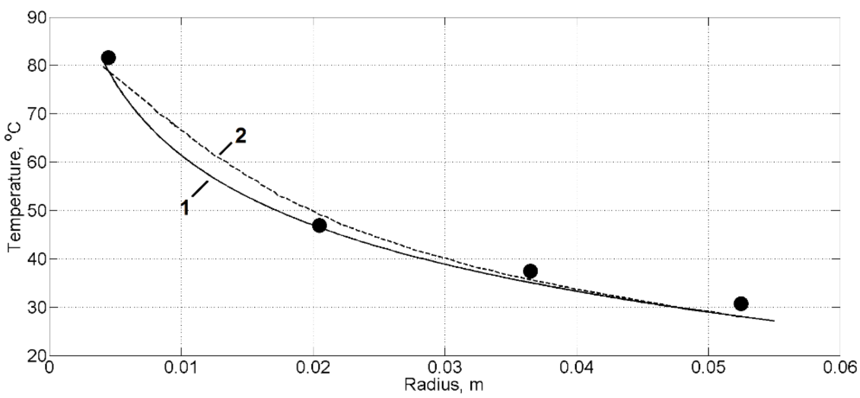
In the present study we developed methods of analysing the thermal and electromagnetic fields of a resistive divider to serve as the basis for calculating optimal design for resistive voltage dividers. The analysis methods are based on numerical simulation of thermal and electromagnetic fields using the finite elements method. For mathematical simulation of transformer thermal state, we used the thermal conductivity equation recorded in a cylindrical coordinates system:

$$\frac{\partial T}{\partial t} = a\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2}\right] + \frac{q_v}{c \cdot \rho}, \tag{2}$$

where T – temperature, r, φ, z – coordinates (z axis coincides with cylinder axis), t – process time, a – heat conductivity coefficient, q_v –heat source, related to heat release in resistive elements, c – heat capacity, ρ – density

Mathematical models of resistive divider thermal fields were verified with experimental data obtained from research involving an experimental prototype (Fig. 1).

a)



b)

Fig. 1. Photograph of experimental prototype (a) and dependence of established radial temperature distribution in the transformer's central part (b): 1 – results of calculation with COMSOL Multiphysics; 2 – results of modified method calculation, dots – results of experimental measurements

To analyse the impact of electrical displacement currents on voltage measuring accuracy (taking into account leakage currents in resistive divider insulation) we developed sequential computation methods with preliminary calculation of partial and parallel computations via the induced currents. Partial capacitances were calculated on a mathematical model of the transformer based on solution of the Laplace equation written for the electrical field:

$$-\nabla \cdot \varepsilon_0 \varepsilon_r \nabla \varphi = 0, \tag{3}$$

where ε_0 – vacuum dielectric permittivity, Φ/m; ε_r – relative dielectric permittivity, Φ/m; φ – electrical potential, V.

The second calculation method is based on a quasi-static resistive divider model, solving the following equation:

$$-\nabla \cdot \left(\left(\sigma + \mathrm{j}\omega\varepsilon_0\varepsilon_\mathrm{r} \right) \nabla\varphi \right) = 0\,, \tag{4}$$

where σ -electrical conductance, Siemens/m; j – imaginary unit number; rate of phase change, rad/s; φ – потенциал, V.

The methods of calculating electrical displacement and leakage currents permit computation of amplitude and phase errors of a resistive voltage divider and research into dynamic proceses.

Mathematical models were verified by alaytical formulae and tested experimentally. They enable us to analyse thermal and electrical fields with subsequent optimisation of resistive divider design.