A&QTR-R 2004 (THETA 14)
2004 IEEE-TTTC – International Conference on Automation, Quality and Testing, Robotics
May 13 – 15, 2004, Cluj-Napoca, Romania

THE STUDY OF TEMPERATURES DISTRIBUTION FOR CAPACITOR-TYPE BUSHING

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Abstract: The heating calculation of the dismountable path of current for capacitor-ype bushing for transformer, both in short time and long time duties is studied. The calculation of the heating in short time duty is valid for bushings with simple insulation (oil or SF6), but it can be also taken into account for the capacitor-type bushings, because the influence of the temperature variation in insulation can be neglected due to the very short time. The equation of temperature variation for some duties is established, the heating of insulation being also influenced by this. The calculation of the heating in long time duty and also of the thermal flux is neglected, but taking in consideration the Joule losses in terminal and the dielectric losses in capacitor, their variation with the temperature, too.

Key words: bushing, capacitor, thermal flux, dielectric losses

1. GENERAL

The capacitor-type bushings from the transformers are connected to the winding either by a solid bar (especially for currents higher than 1250 A) or by a dismountable cable located at the end of the bushings.

For insulations type RBP, the rated load is the current leading to a temperature of the hot spot of 120^{0}C maximum, when the lower end of the bushing is immersed in oil with a temperature of 90^{0}C.

2. HEATING CALCULATION

2.1. Heating calculation for short-time duty

The calculation is valid for the bushings with simple insulation (oil or SF6), but it can be also taken into account for capacitor-type bushings because, due to the very short time, the influence of the temperature variation in insulation can be neglected. The heat transfer in the conductors in which the current flows, used at the capacitor-type bushings, is studied. The equation of temperature variation for several duties of the bushings, which will influence the insulation heating too, is set.

Heat stored in conductor

Due to the flowing of the current I, in the conductors used at the bushings for transformers, a quantity of heat given by the relation from below is generated

$$Q = 0{,}24 \cdot R \cdot I_s^2 \cdot t \tag{1}$$

where: $R = \rho \cdot \frac{l}{A}$; for $l = 1$ $R = \frac{\rho}{A}$

$I_s = 25 \cdot I$ is the short time current

ρ = resistivity of the conductor material

l = length of the conductor through which the current flows

A = conductor area $= \frac{\pi \cdot d_e^2}{4}$

In the electric conductor, the stored heat will be:

$$q_{el} = m \cdot c \frac{d\theta}{dt} = A \cdot \gamma \cdot c \frac{d\theta}{dt} \tag{2}$$

where: m = conductor weight

c = specific heat of the conductor material

γ = density of the conductor material

A part of the heat Q is dissipated by conduction, convection and radiation.

$$q_p = \beta \cdot \theta \cdot p \tag{3}$$

where: β = convection and radiation coefficient

p = conductor perimeter $= \pi \cdot d_e$

By replacing, it results the heat stored in the conductor for t = 2 seconds (in short time thermal duty, when the thermal current limit provides the rise of the current path temperature to the highest value).

$$A \cdot \gamma \cdot c \frac{d\theta}{dt} = 0{,}24 \cdot I_s^2 \cdot \frac{\rho \cdot 4}{A} - \beta \cdot \theta \cdot p \tag{4}$$

$$d\theta = 0{,}96 \cdot I_s^2 \cdot \frac{\rho}{c \cdot A^2 \cdot \gamma} dt - \frac{\beta \cdot \theta \cdot p}{c \cdot A \cdot \gamma} dt \tag{5}$$

Taking into account the temperature influence on the resistivity, it results:

$$\rho = \rho_0 \cdot (1 + \alpha \cdot \theta) \tag{6}$$

where: α = coefficient of resistivity variation with temperature

ρ_0 = resistivity at initial temperature

$$d\theta = 0{,}96 \cdot I_s^2 \cdot \frac{\rho_0}{c \cdot A^2 \cdot \gamma} dt + 0{,}96 \cdot I_s^2 \cdot \frac{\rho_0}{c \cdot A^2 \cdot \gamma} \cdot \alpha \cdot \theta dt - \frac{\beta \cdot \theta \cdot p}{c \cdot A \cdot \gamma} dt \tag{7}$$

Designating: $\varepsilon = 0{,}96 \cdot I_s^2 \cdot \frac{\rho_0}{c \cdot A^2 \cdot \gamma}$ and

$$-\eta = 0{,}96 \cdot I_s^2 \cdot \frac{\rho_0}{c \cdot A^2 \cdot \gamma} \cdot \alpha - \frac{\beta \cdot p}{c \cdot A \cdot \gamma}$$

It results: $$d\theta = \varepsilon dt - \eta \cdot \theta dt \tag{8}$$

Respectively: $\frac{d\theta}{dt} + \eta \cdot \theta - \varepsilon = 0$ (9)

The solution is under the form: $\theta = U \cdot e^{-\eta t}$, which is substituted in (9) and it is got:

$\frac{dU}{dt} \cdot e^{-\eta t} - U \cdot \eta \cdot e^{-\eta t} + \eta \cdot U \cdot e^{-\eta t} - \varepsilon = 0$, that is

$$\frac{dU}{dt} \cdot e^{-\eta t} - \varepsilon = 0; \; dU = \varepsilon \cdot e^{+\eta t} dt \quad (10)$$

The equation (10) is integrated: $\int dU = \varepsilon \cdot \int e^{\eta t} dt$ and it is obtained:

$$U = \frac{\varepsilon}{\eta} \cdot e^{\eta t} - \frac{\varepsilon}{\eta} = \frac{\varepsilon}{\eta} \cdot \left(e^{\eta t} - 1\right)$$

with $U = \theta \cdot e^{\eta t}$, it results: $\theta = \frac{\varepsilon}{\eta} \cdot \left(1 - e^{-\eta t}\right)$ (11)

As an application, the variation of the conductor temperature for oil-oil and SF6 –SF6 bushings is given in Figure 1, using the computing program MATHLAB.

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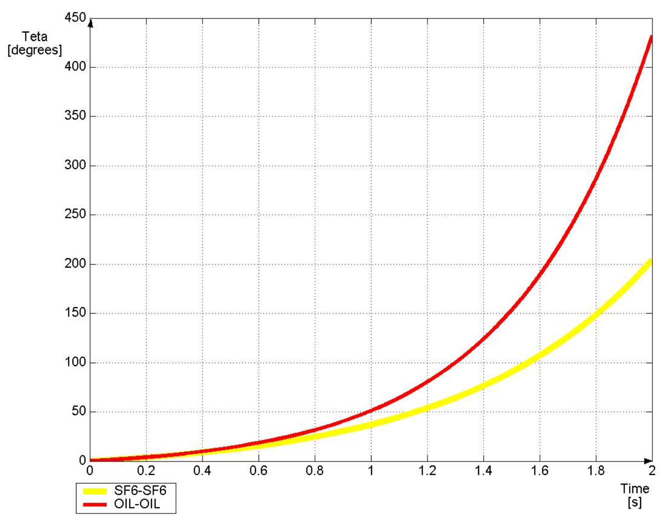

Figura 1 – Variation $\theta = f(t)$

2.3. Calculation of heating in long-time duty and capacitor-type bushing thermal stability

The calculation is done in a covering manner, supposing that the axial thermal flux is neglected, but taking into consideration the Joule losses in terminal and the dielectric losses in capacitor, also their variation depending on temperature. The outer temperature is considered to be given: θ_e.

The calculation model is shown in Figure 2. The current I_N flows through the terminal having the diameter d_e, generating per unit of length the Joule losses:

$$P_0 = k_r \cdot \rho_0 \cdot (1 + \alpha_0 \cdot \theta_0) \cdot \frac{4}{\pi \cdot d_e^2} \cdot I_N^2 \quad (12)$$

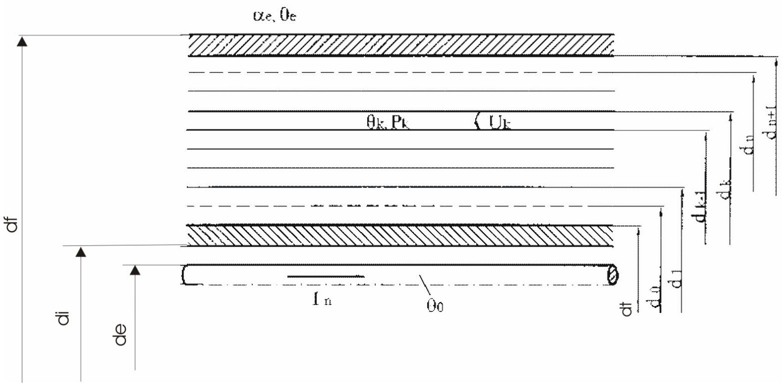

Figure 2 – Calculation model for capacitor-type bushing

Here, k_r is the skin effect factor, ρ_0 is the resistivity of the terminal material, α_0 is the temperature coefficient at 0^0 C, and θ_0 is the terminal temperature in ^{0}C.

The incrementing factor of the solid cylindrical circular conductor resistance is calculated taking into account the complex inner impedance of the cylindrical conductor.

NOTE – For bushings with rated currents up to 2500 A, the skin effect in the current path can be neglected.

Coming back to the Figure1, the terminal is placed in the guiding pipe having the inner diameter d_i. In the remained gap, there is oil with thermal conductibility $\lambda_u \approx 0.16$ W/m ^{0}C. It results a thermal resistance per unit of length:

$$R_0 = \frac{1}{2 \cdot \pi \cdot \lambda_u} \cdot \ln \frac{d_i}{de} \approx \frac{1}{\pi \cdot \lambda_u} \cdot \frac{d_i - d_e}{d_i + d_e} \tag{13}$$

Towards the environment, the terminal is edged by a flange having the outer diameter d_f and it transmits the heat to the environment with temperature θ_e, with a release factor α_e (having the size grade of 16 – 32 W/m^2 C). It results a thermal resistance per unit of length:

$$R_e = \frac{1}{\pi \cdot \alpha_e \cdot d_f} \tag{14}$$

If the bushing flange is fixed on the transformer tank, it can be considered $R_e \approx 0$, and as θ_e it is considered the maximum temperature of the oil at the level of the transformer cover ($\theta_e \approx 90^0$C).

The so-called capacitor-type bushing consists in n layers numbered 1....n, from inside towards outside. The layer with rank k is located between the diameters d_{k-1} and d_k, it has an average temperature θ_k, the voltage U_k is applied to it, and the dielectric losses per unit of length P_k are developed in this layer. The geometrical permeance per unit of length of the layer k is noted Λ_k

$$\Lambda_k = \frac{2\pi}{\ln \frac{d_k}{d_{k-1}}} \approx \pi \cdot \frac{d_k + d_{k-1}}{d_k - d_{k-1}}, \ k \in (1, n) \tag{15}$$

Then, the dielectric losses per unit of length of the layer k are expressed as:

$$P_k = p_d \cdot \Lambda_k \cdot e^{\sigma(\theta_k - \theta_d)} \cdot U_k^2, \ k \in (1, n) \tag{16}$$

where p_d represents the volume density of the dielectric losses at the reference temperature θ_d and at the unit of electric field strength, and σ is the temperature coefficient of the specific losses exponential variation.

NOTE – In general, it is valid the equation:

$$p_d = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r \cdot tg\partial \tag{17}$$

where f is the frequency, ε_0 is the vacuum permitivity, ε_r is the relative permitivity of the dielectric and ∂ is the loss angle.

The voltage U_k applied to the layer results from the voltage U_m applied to the bushing

$$U_k = U_m \cdot \frac{S_k}{\sum_{i=1}^{n} S_i},\ k \in (1, n) \tag{18}$$

where by S_k it was noted the elastance of the layer k.

$$S_k = \frac{1}{\varepsilon_0 \cdot \varepsilon_k \cdot \Lambda_k \cdot l_k},\ \ k \in (1, n) \tag{19}$$

By ε_k it was noted the relative permitivity of the dielectric from the layer k, which can depend on the temperature according to the relation:

$$\varepsilon_k = \varepsilon_d \cdot e^{\zeta(\theta_k - \theta_d)},\ k \in (1, n) \tag{20}$$

and ε_d is relative permitivity of the dielectric at the reference temperature θ_d, and ζ is the temperature coefficient.

The thermal resistance of the layer k is expressed by the relation:

$$R_k = \frac{1}{\lambda \cdot \Lambda_k},\ k \in (0, n+1) \tag{21}$$

where λ is the thermal conductibility of the dielectric; for cylinders made of paper lacquered with resin $\lambda = 0.16$ W/m ^{0}C.

The diagram for the calculation of bushing heating is given in Figure 3:

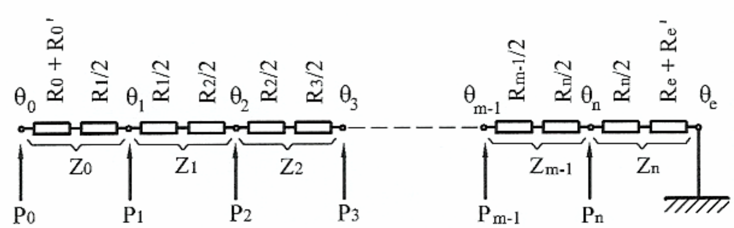

Figure 3 – Diagram for calculating the capacitor-type bushing

It is noted:

$$Z_0 = R_0 + R_0^{'} + \frac{R_1}{2};\ Z_k = \frac{R_k + R_{k+1}}{2}, k \in (1, n-1);\ Z_n = \frac{R_n}{2} + R_e + R_e^{'} \tag{22}$$

where by R_0’ and R_e’ there were noted the thermal resistances of the possible buffer layers, without voltage, from the inside and outside of the bushing,.

The temperatures are immediately determined by means of the relation:

$$\theta_k = \theta_{k+1} + Z_k \cdot \sum_{i=0}^{k} P_i,\ k \in (0, n) \tag{23}$$

Because the losses depend on the temperature, directly or by means of the voltage distribution on layers, the solving of (23) is done by a computing program and it is resumed in an iterative manner, each time correcting the losses in accordance with the previously calculated temperatures, until a stationary solution (fixed point) is got.

The computing program is used also for the temperature distribution in the capacitor-type insulation, having as boundaries the heat source (current path) and the immersion medium (hot oil). The diagram of the distribution for a particular case of the 123 kV, 1600 A capacitor-type bushing is shown in Figure 4.

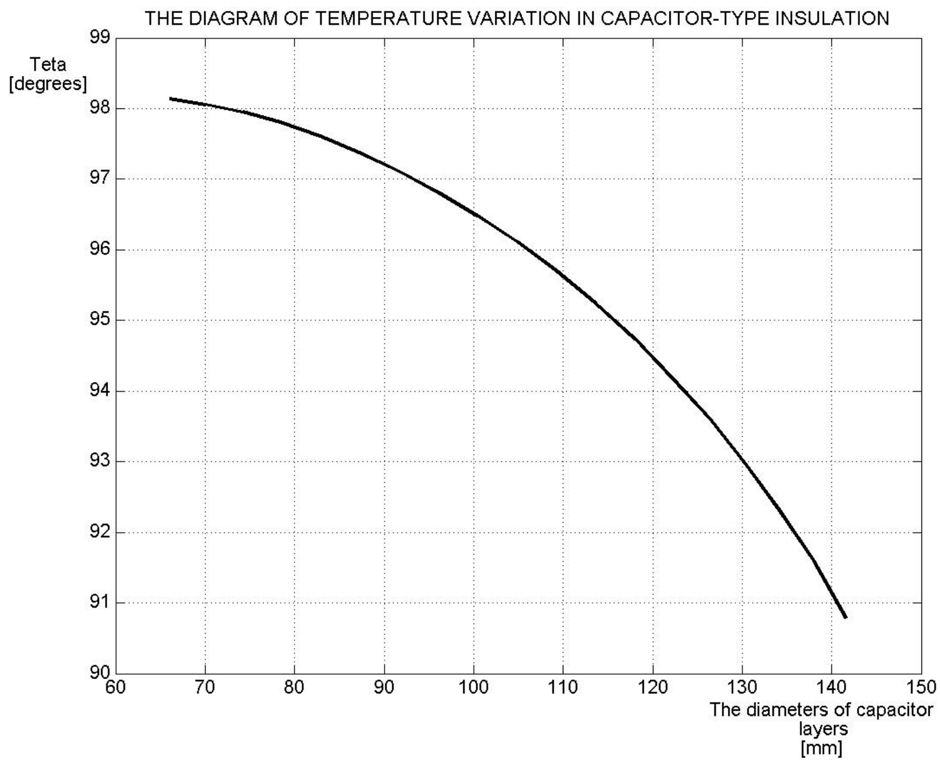

Figure 4 - The diagram of temperature distribution in 123 kV, 1600 A capacitor-type bushing

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