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THERMAL AGEING OF POWER CABLE COMPONENTS THROUGH PENETRATIONS

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Abstract. ***The power cables passing through penetration leads to growth of the thermal ageing mechanisms rate. The paper presents the results of the laboratory tests when the real environmental service conditions for penetration are simulated comparison with the result of the thermal computation of the power cables heating and of the temperature influence evaluation of temperature increase of the power cable components on the cable lifetime. For this particular case, a power cable with PVC insulation, we estimated a lifetime decrease about 20 years referring to lifetime (30÷40 years) for location in air.***

Keywords: thermal, ageing, power cable, penetrations, thermal calculus, lifetime.

1. INTRODUCTION

The power cables used in electric low voltage (0.6/1 KV) wiring have a wide variety, differing from structural and dimensional point of view.

The main components for power cables from low voltage circuits are, [1]: conductor, insulation, filler, shield and cable jacket. The paper is referring only to those cable components having an organic structure.

The materials, used for electric insulation and the cable jacket, are formulated organic compounds. They are made of primary polymers or of copolymer and additives that provide a material with specific properties, [2]. These additives are mainly the (anti-oxidants, fire - retardants, thermal stabilizers), mineral fillers, plasticizers, pigments, etc. Some complex compounds may contain up to ten or fifteen different constituents. Variations in formulation can affect both the activation energy and rate of thermal ageing. Of these materials commonly used are cross-linked polyethylene (XLPE), ethylene propylene based elastomers (EPR/EPDM) and polyvinyl chloride (PVC).

The power cables are exposed at different environmental conditions. The most important factors are the temperature, the presence of oxygen, the relative humidity, the influence of the biological factors (fungi) and their mixed action. Mechanical influences should also be considered (e.g. vibration for cables connected to running machine) paying them the same attention, connection/disconnection operations during maintenance and installation anomalies where bending stresses are excessive.

The environmental condition for service will induce chemical and/or physical processes at the molecular level of the material. All these processes generated by these factors are characteristic for ageing mechanism. The effect at macroscopic level is a slow and irreversible in the properties of the material (electrical, mechanical) which can lead to functional failure of the cable.

For assessment of the electric cable lifetime are required knowing of the working condition (temperature, radiation). Further, for the power cable, without heating due to environment are required to take into account the losses of power generated by turn of the electric current, losses converting into heat. These losses are proportional to electric resistance of the cable wires, at the operating temperature and with long regime current in conductors (Joule’s effect).

The heat is conducting to the outer jacket of the cable by conduction and therefrom through air by convection and radiation. The conducting of the heat to air leakage is similar to electric current flow phenomenon through finite conductivity environment, defined by the Ohm’s law.

By analogy, the converted heat is proportional to difference in temperature between the conductors and the environment and inverse ratio to thermal resistances amount of cable jackets and of the environment.

Writing the energy balance equations between the quantity of heat generating inside cable and the quantity of heat delivered to the environment by cable it is consisting in starting point of the heating calculus for power wire cables.

The energy balance equations from [3] are transformed such as allowing a graphical resolution. Knowing the environmental temperature and thermal characteristics of the cable jacket materials are required.

The Excel software is using as calculus system, in [4], to determine thermal resistance of the environment. The uncertainty inserted by the applied terminal conditions is not shown.

The determination of the cable wires heating, using the SPICE software, for a certain current is proposed in [5]. The thermal resistances of the environment are inserted as a variable factor, dependent on the difference in temperature between the cable surface and the environment. The physical characteristics of the dry air (thermal conductivity - λ, viscosity - ϑ, thermal extension factor - β), taken from [6], are used. Knowing the thermal characteristics of the cable jackets material (specific thermal resistance) and the geometrical configuration of the cables are required.

The heating values of the electric cables determined by two calculus methods, based on the measurement the environment temperature and temperature of the cable surface, respectively, are shown comparatively in [7]. The fluctuations inserted by type, the number, the material, the thermocouples arrangement and the effect of the conductors cross section are, also, shown.

The heating calculus of the high voltage cable for dynamic condition is shown in reference [8], of transformation the current value. The equations for thermal balance are written in Cartesian coordinates and are solving for a certain limit conditions. For different types of cable are shown the differences between the calculated values and the measured one, for the cable temperature.

To solve the thermal balance equations is proposing in references [9] and [10] using Finite Element Method.

The thermal balance equation is written in Cartesian coordinates in reference [11], and the limit condition and an adapted hypothesis are settled for its resolution. The coefficients of heat transfer by convection and radiation from the cable surface to the environment are determined for a temperature large range of the air surrounding the electric cable. The values for the air characteristics are from technical literature.

For the high voltage cables, a mathematic model for determination of the electric losses on the electric cable sheathing, which is converted into heat, is developed in reference [12]. The differences between the values calculated with this model and those resulted according to IEC Standard are shown.

In this paper, is proposed a computational procedure for heating determination of the electric cable conductors using Excel software. Knowing the temperature of the cable components is allowing the assessment of the power cable lifetime.

Outer diameter and thickness of steel pipe through penetrations are shown in the reference [12]. These are according to STAS 530-2/80. Inner diameter of pipe need is 1.5 x cables electric diameter.

2. SIMULATION OF REAL CONDITIONS FROM PENETRATIONS IN LABORATORY

Basic diagram of the experimental plant for simulation in laboratory of the real conditions for thermal ageing of the low power cable insulation from penetrations is shown in the Figure 1.

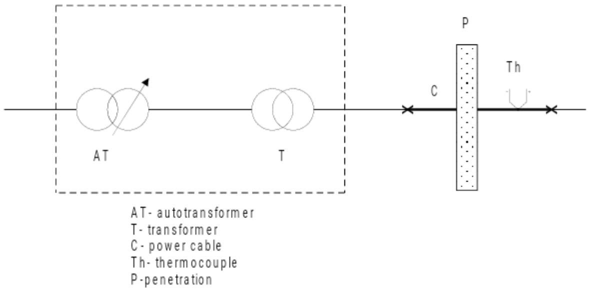

Figure 1. Basic diagram of the plant for simulation of the conditions from penetrations

For testing in laboratory condition of all types of power cables section (the maximum cross section of the conductors is 400 mm^2), we need a single-phase transformer (T) which provides a maximum current of 1000 A with an adjustable voltage of 0 │6V. It is required an autotransformer (AT) with an adjustable voltage of 0...230V and a minimum current of 26 A.

The cable sample for simulation in laboratory of the thermal ageing of insulation passing through concrete penetrations consists in a CYY 3x25; 0.6/1KV type power cable of 4.5 m length.

The steps to make cable samples were:
- the resistance insulation has been measured between each conductor and the other two conductors series connected;
- the three conductors’ series connected of the test cable;
- have been measured the electric resistance of the three series connected conductors with a four-wire multimeter, the value of 0.0013 ∧ being;
- a hole with 5 mm diameter worked out through cable jacket and insulation, placed on equal spaces referring to cable ends;
- a Fe-Ct thermocouple head set in the 5 mm diameter hole, in contact with the Cu conductor;
- a Fe-Ct thermocouple head set in contact with the jacket of the cable sample, near the 5 mm diameter hole.

The return conductor is made of the same cable type with the test cable having 4 m length, the three conductors being in parallel.

To simulate passing through penetrations has built a parallelepiped concrete block, sized 400 x 300 x 400 mm (L x l x h), having a central channel worked out with a protection pipe (42 mm inner diameter, 48 mm outer diameter and 300 mm length, steel made) passing through it.

The steps to make the installation assembling to simulate the thermal ageing in laboratory condition of the insulation were the following:
- the sample has been passed through the protection pipe, without contact of the cable and pipe walls, the thermocouples being placed at equal spaces referring to the pipe ends;
- the pipe ends having plugs by adding plaster;

- the sample connected to the terminals of the transformer using the return conductor, the transformer has supplied with power using a autotransformer and a starter, control and overheating protection equipment of the transformer in a short-circuit case;
- the voltage adjusted at the sample terminals using the autotransformer so that the current value, measured with a current clamp-on meter, being of 106 A;
- the temperature recorded at the jacket and Cu conductor level with a Hydra data acquisition system.

A passing through penetration of power cables is shown in the Figure 2.

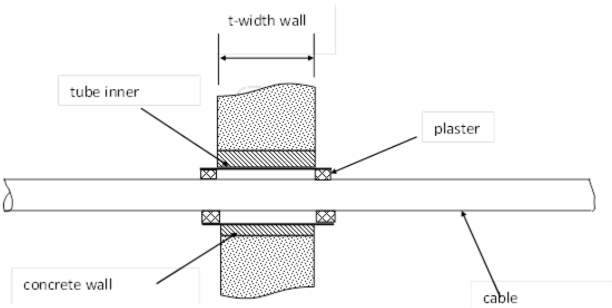

Figure 2 Image to simulate passing through penetrations of power cables

3. EVALUATION OF THE POWER CABLE HEATING. THERMAL CALCULUS

The conductors of the electric circuits are heating under Joule - Lenz (RI^2t) effect and from surrounding hot assemblies. The energy losses resulted in the metallic jackets and in dielectric are negligible for the low power cables and industrial usage, [3].

Heat flow (thermal current) is transferred through conduction of heat toward the outer jacket of the cable and further to the interface between the environment where the cables are laid-down (land, duct, and water) and air. Beginning from this surface the heat is changed in air by convection and radiation phenomena.

The continuous conduction phenomena of the heat flow from the sources inside of the cable and dissipation of energy in the atmosphere it is analogue with the phenomena of the electric current flow in the finite conductivity environment. Thus, considering two cylindrical concentric surfaces with radius r_1 and respectively r_2 and length l, having the temperatures θ_1 and θ_2 ($\theta_1 > \theta_2$), according to the Figure 3, the constant heat flow W_Σ through surface Σ (analogue to the Ohm law) will be:

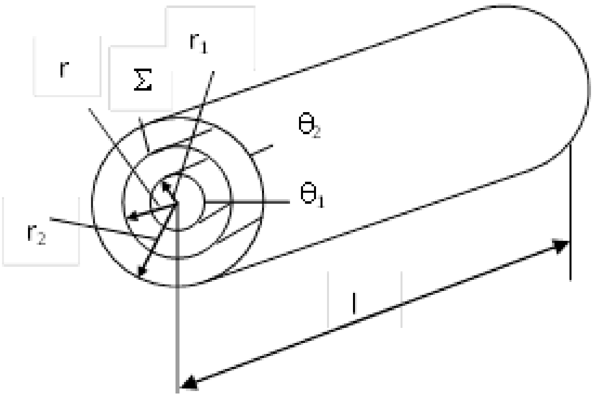

Figure 3 Conduction of heat in the cylindrical space ($\theta_1 > \theta_2$)

$$W_\Sigma = \frac{(\theta_1 - \theta_2) \cdot l}{R_{T\Sigma}} \quad (1)$$

where: $R_{T\Sigma}$, [grd/W] is the total thermal resistance of the circuit (thermal) considered;

$$R_{T\Sigma} = \frac{\rho_T}{2\pi l} \cdot \ln \frac{r_2}{r_1} \quad (2)$$

where: ρ_T, [grd m/W] is the specific thermal resistance. The equation (1) allowing us to determine “the temperature drop” TΣ for a particular case of a power cable passing through penetration. The calculus relation is following:

$$n \cdot \left(W_1 - W_{cu}\right) \cdot \left(\sum_i R_{T_i}\right) = \theta_{cu} - \theta_{air} \quad (3)$$

where: n is the number of active conductors of the cable; W_1 [W/m] is the Joule specific losses in one conductor (in unit of time and on unit of length of the cable); W_{Cu} [W/m] is the thermal flow transferred through conduction along of the conductor, from penetration toward the remainder cable (from the hot area toward the less hot area); R_{Ti} [grd.m/W] is the specific thermal resistances (on the unit of length of the cable) corresponding to:
R_{T1} - insulation of the cable;
R_{T2} - outer jacket;
R'_{T3} - space between outer jacket and the protection duct corresponding to conduction effect;
R''_{T3} - space between the outer jacket and the protection duct corresponding to radiation effect;
R_{T4} - protection duct;
R_{T5} - concrete wall;
R'_{T6} - convection effect on the wall surface;
R''_{T6} - radiation effect on the wall surface.

4. THE CALCULUS OF THE LINEAR THERMAL RESISTANCES R_T

The linear thermal resistances R_T can be calculated using the following equations, [4]:

R_T appropriate to unit length (of 1 m) is interest of versus its live wire axis is named linear thermal resistance of the thermal circuit. The losses of power W_1 are also counted on length unit of cable and on time unit.

R_T for the conductor's insulation and the filling material:

$$R_{T1} = \frac{\rho_{T1}}{2\pi} \cdot G \quad (4)$$

$$G = f\left(N, \frac{\delta}{\delta_i}, \frac{\delta_i}{d_c}\right) \quad (5)$$

where: G is the shape coefficient of the cable, d_c is the wire diameter, ρ_{T1} is the thermal resistivity of the wire insulation material.

The G shape coefficient value, depending on the conductor's number N of the cable and the value of ratio between the thickness of the wire cable insulation δ_i and the wires diameter d_c and of the ratio between filling material thickness δ and the conductor insulation thickness δ_i, is graphically described in [3].

R_T of the second layer, the outer jacket:

$$R_{T2} = \frac{\rho_{T2}}{2\pi} \cdot \ln \frac{d_e}{d_{mi}} \quad (6)$$

where: d_{me} is the outer diameter of the cable jacket, d_{mi} is the inner diameter of the outer jacket, ρ_{T2} is the thermal resistivity of the cable jacket material.

The thermal linear resistance of the air surrounding cable for thermal flow transmission through to the conduction phenomenon can be calculated using the following equations:

$$R'_{T3} = \frac{\rho_{T3}}{2\pi} \cdot \ln \frac{d_{ti}}{d_{mi}} \quad (7)$$

where: d_{me} is the outer diameter of the cable jacket, d_{ti} is the inner diameter of the tube, ρ_{T3} is the thermal resistivity of the air surrounding cable.

The thermal linear resistance of the air surrounding cable for thermal flow transmission through to the radiation phenomenon can be calculated using the following equations:

$$R''_{T3} = \frac{1}{\pi \cdot d_{me} \cdot a_r} \quad (8)$$

where: α_r is thermal radiation coefficient:

$$a_r = \varepsilon_i K \frac{(273+\theta_s)^4 - (273+\theta_a)^4}{\Delta\theta_s} \quad (9)$$

where: ε_i is the emission coefficient of the cable surface, K = 5.77 W/m^2 K^4 is the Boltzmann's constant, $\Delta\theta_s = \theta_s - \theta_a$ is the difference in cable surface temperature θ_s and air surrounding temperature θ_a.

The linear thermal resistance R_{T4} can be calculated using the following equations:

$$R_{T4} = \frac{\rho_{T4}}{2\pi} \cdot \ln \frac{d_{te}}{d_{ti}} \quad (10)$$

where: d_{te} is the outer diameter of the tube, ρ_{T4} is the thermal resistivity of the tube material.

The linear thermal resistance of the concrete can be calculated using the following equations:

$$R_{T5} = \frac{\rho_{T5}}{2\pi} \cdot \ln \frac{2 \cdot t}{d_{te}} \quad (11)$$

where: t is the thickness wall; ρ_5 is the thermal resistivity of the wall material in grd.m /W.

The thermal flow transmission through air surrounding wall is own mainly to the conduction and radiation phenomenon. The linear thermal resistance R_{T6}, can be calculated using the following equations:

$$R_{T6} = \frac{1}{\pi \cdot X \cdot (a_{cv} + a_r)} \quad (12)$$

where: α_{cv} and α_r are thermal convection and radiation coefficients.

According to [14], thermal convection coefficient can be calculated using the following equations:

$$a_{cv} = \frac{\lambda \cdot N_u}{X} \quad (13)$$

where: λ is the thermal conductivity, X – is the height of the concrete wall, Nu = f (Gr, Pr), is Nusselt number.

The Nusselt number can be calculated using the following table:

Table 1. Nusselt number at natural convection, [15]

Gr x Pr	Nu
to 5 . 10^2	1,18 (Gr x Pr)^{0,12}
to 2 . 10^7	0,5 (Gr x Pr)^{0,25}
to 10^{17}	0,135 (Gr x Pr)^{0,33}

where: G_r, P_r is Grashof's criterion and Prandtl's criterion.

$$G_r = \frac{g \cdot \beta}{\vartheta^2} \cdot X^3 \cdot \Delta\theta_s \quad (14)$$

where: g is the gravitational acceleration, ϑ is kinematic viscosity, β is the thermal coefficient of expansion of the environment.

$$\beta = 1/(273.15 + \theta_{a\_med}) \quad (15)$$

where: θ_{a_med} is the average air temperature.

$$\theta_{a\_med} = \frac{\theta_s + \theta_a}{2} = \frac{\Delta\theta_s}{2} + \theta_a \quad (16)$$

The environment thermal linear resistance depends on physical properties of the air surrounding cable (λ, ϑ and Pr). The physical properties of dry air: ϑ, λ, P_r, as per [14], are selected for an average value of the air surrounding the power cable θ_{a_med}.

Thermal radiation coefficient can be calculated using the equation 9. The value emission coefficient of the concrete wall surface, [3], is 0.9.

5. THE CALCULUS OF THE THERMAL FLOWS

According to [4], the losses of energy W_1 generating by Joule effect in cable conductors are calculated by following relation:

$$W_1 = R \cdot I^2 \quad (17)$$

where: I, [A], is the electric current through conductor in lasting regime, R[Ω/cm] is the alternating current linear resistance, on the conductor's length unit, at θ_c temperature, [3].

$$R = R_{20}[1 + \alpha_{20} \cdot (\theta_c - 20)] \quad (18)$$

where: R_{20} is the electric resistance at 20°C, α_{20} [1/grd] is the coefficient of fluctuation of the electrical resistivity related to temperature at 20°C.

$$R_{20} = \frac{\rho_{20} \cdot l}{s} \quad (19)$$

where: ρ_{20} [Ω mm^2/m] is the resistivity of the material at temperature of 20°C, measured in direct current, l is the conductor length, S is the conductor cross section.

The thermal flow, transmitted from penetration to the rest of the cable through conductor (conductor temperature in penetrations higher conductor temperature outside penetration), are calculated by following relation:

$$W_{cu} = \frac{2 \cdot \lambda \cdot s \cdot (\theta_{c-p} - \theta_{c-a})}{L} \quad (20)$$

where: λ [W/m⊕grd] is the thermal conductivity of the copper, s [m^2] is the conductor cross section, θ_{c_p} – the conductor temperature in penetration, θ_{c-a} is the conductor temperature outside penetration, L is the length of cable in whence there is the thermal flow transferred through conduction along of the conductor, from penetration toward the remainder cable.

6. THE RESULTS

6.1. The verification on procedure for heating determination

The values have been measured and determined for a three phase CYY3x25 type cable, at a cable supplied with allowable lasting voltage I=109 A.

Table 2 shows the air - penetration comparative distribution of the temperature values of the isothermal surfaces inside of the cable, measured values.

Table 2. A comparative air - penetration distribution of the temperature inside of the power cable measured values, for 109 A

Time (min)	θshe air	θcu air	θshe pen	θair
0	59.5	72.5	71.9	28.3
15	59.8	72.9	72.1	28.2
30	60.0	73.1	72.4	28.2
45	60.1	73.3	72.5	28.2
60	59.9	73.1	72.8	28.1
75	59.8	73.1	72.6	28.2
90	60.1	72.9	72.8	28.0
105	59.5	72.8	72.6	27.9
120	59.1	72.6	72.7	28.0
Average	59.7	72.8	72.6	27.8

The analysed cable was of low voltage, 06/1kV, tip PVC, 3x25 mm +16 mm^2 and the conductor diameter d_c of 0.0063 m, the filling material thicknesses δ_i=0.0015m and the insulating thick δ=0.003 m:
- For ρ_{T1} = 6 W/m·K, [16], G=0.9, according to [3], the results is R_{T1} = 0.86 K·m/W.
- For ρ_{T2} = 6 W/m·K, d_{me} = 0.0236 and d_{mi} = 0.0192 m, the results is R_{T2}= 0.197 K·m/W.
- For ρ_{T3} = 37 W/m·K, d_{ti} = 0.042 m, results R_{T3}'= 3.22 K·m/W, R_{T3}'' = 1.84 K·m/W.
- For ρ_{T4} = 0.0204 W/m·K, d_{te} = 0.05 m, results R_{T4}= 0.0006 K·m/W.
- For ρ_{T5} = 0.6451 W/m·K, t= 0.4 m, results R_{T5}= 0.255 K·m/W.
- For X=0.4m, θ_a=28°C; P_r=0.71; λ=0.0267W/m·K, υ =16.6·10^{-4} m^2/s/s; results R_{T6}= 0.19 K·m/W.
- For R_{20}=0.00071Ω; α_{20}=0.00393; I = 109A; θ_c = 78.9 ºC, results W_1 = 10.5 W/m; W_{cu}=2.4 W/m.

Table 3 shows the conductor cable temperature values comparative for air - penetration, the calculated and measured values, also.

Table 3. A comparative air – penetration temperature conductor of the power cable

	θ_{cu_pen} [°C]	θ_{cu_air} [°C]	I [A]	θ_{air} [°C]
By measured	79.6	72.8	109	28.0
By calculus	78.9	73.5		

The temperature difference of the insulation between calculated value and measured value is about 1 ^{0}C.

6.2. The temperature influence on power cable lifetime

An extended exposure of the power cable components to a high temperature is resulting in non-reversible degradations of the mechanical and electrical properties of the formulated organic compounds and implicit of the functional properties of the cable. Under heat effect, the organic compounds are becoming rigid and porous, losing the aspect and colour by oxidation, the effects of the hydrolysis and depolymerisation phenomena.

Using the Arrhenius low, we assess the lifetime (t_1) for a power cable in the long-term regulated service regime with a specific temperature (T_1). The calculus equation is following:

$$t_1 = t_2 \cdot e^{-\frac{E_a}{R} \cdot \frac{T1 - T_2}{T_1 \cdot T_2}} \quad (21)$$

where: R [cal/grad·mol] = 1.987 is the gas constant, E_a = 23000 [cal/mol] is the activation energy for PVC.

Table 4 shows the air - penetration comparative distribution of the temperature values of the isothermal surfaces inside of the cable, calculated values. The values have been determined for a three phase CYY3x25 type cable, at a cable supplied with a maximum allowable lasting voltage (70 A).

Table 4. A comparative air - penetration distribution of the temperature inside of the power cable

Isothermal surface	Temperature [^{0}C]	
	penetration	air
Environment	28.0	28.0
Concrete wall	31.7	-
Tube - inner	34.1	-
Jacket	44.0	39.9
Insulation	45.8	42.2
Conductor	48.4	45.5

We assumed a known lifetime (t_2 = 0.36 years) for a service thermal accelerated ageing regime with a characteristic temperature (T_2 = 368.75 K).

Applying the above methodology of the thermal calculus and lifetime assessment, in the Table 5 are shown the results obtained, air/ penetration comparatively, for a CYY 3x25 type power cable in a long-term service regime, Imax = 70A).

Table 5. The air - penetration comparative values for power cable lifetime

Cable properties	[M.U]	Air / penetration comparative values	
Insulation temperature	[°C]	45.5	48.4
Lifetime	[years]	50.1	36.1

7. CONCLUSIONS

Passing through penetration of the power cable leads to increase the thermal ageing mechanisms rate due to temperature growth of the power cable components about 3 ^{0}C, for it evaluating a power cable lifetime decrease of about 14 years.

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