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CONTINUOUS CURRENT RATING OF SELF-SUPPORTING INSULATED CABLE BUNCH WITHOUT COOLING BY FORCED CONVECTION

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ABSTRACT

This paper presents an analytical approach to the solution of continuous current rating of self-supporting insulated cable bunch, taking into account cooling by natural convection. Calculation of the heat transfer from the surface of the cable by natural convection is based on non-dimensional numbers.

A comparison is made between the current rating based on calculations in this paper and the current rating computed in accordance with IEC Publication. An important conclusion that comes from this comparison is that the results based on IEC Publication are too conservative. In order to verify the proposed analytical approach for continuous current rating of self-supporting insulated cable bunch without cooling by forced convection the calculated values are compared with the experimental results for both, the insulated circular conductor and self-supporting insulated cable bunch.

In this paper the coefficients of exposed projected areas for different forms of solar radiation are also presented.

1. INTRODUCTION

An investigation aimed to clarify realistic limitations concerning continuous current rating of self-supporting insulated cable bunches have been motivated by a wide application of these cables in distribution networks and their conservative design. In the first part of this investigation just the conditions of cooling by natural convection have been considered. This paper reports the results on that subject.

The results of investigations regarding influences of cooling by forced convection and short overloading (non-stationary conditions) will be reported later on.
The full utilization of the cable material is only possible if continuous current rating can be calculated taking into account convective heat transfer from the surface of the cable.
The calculation of the continuous current rating in [1] and [4] is based on heat transfer from the cable surface only by radiation.
Consideration regarding the heat transfer of the overhead lines conductor presented in [2] and [5] does not include the self-supporting insulated cable bunch.
This paper presents the analytical expression for the continuous current rating of self-supporting insulated cable bunch taking into account both, cooling by natural convection and heating by solar radiation. The verification of the expression is based on the experimental results in the case of natural convection and without solar radiation.

2. THEORY FOR SOLVING THERMAL STEADY STATE PROBLEMS

2.1 Basic Equation

The permissible current rating of an AC cable laid in free air can be derived from the expression for the temperature rise above ambient temperature and is given by:

$$I = \left[\frac{\vartheta_c - \vartheta_a - P_d\left[0.5T_1 + n(T_2 + T_3 + T_4)\right] - P_s T_{4r}}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3 + T_4)} \right]^{\frac{1}{2}} \tag{1}$$

where ϑ_c is the maximum operating temperature of the conductor, ϑ_a is the ambient temperature, R is the alternating current resistance per unit length of the conductor at its maximum operating temperature, n is the number of conductors in the cable, T_1 is the thermal resistance per unit length between one conductor and the sheath, T_2 is the thermal resistance per unit length of the bedding between the sheath and the armor, T_3 is the thermal resistance per unit length of the external serving of the cable, T_4 is the thermal resistance per unit length between the cable surface and the surrounding medium, T_{4r} is the thermal resistance per unit length of the cable in free air, adjusted to take into account solar radiation, λ_1 and λ_2 are ratios of the total losses in metallic sheaths and armor respectively to the total conductor losses, P_d are dielectric losses per unit length per phase, and P_s is the solar heating per unit length.
In this paper we shall particularly discuss the thermal resistances T_4 and T_{4r}, , and the solar heating P_s. Calculations for other variables are given in [1], [3], and [5].

2.2 Thermal Resistance Between the Cable Surface and The Surrounding Medium

The thermal resistance between the cable surface and the surrounding medium can be expressed in the form

$$T_4 = \frac{1}{\pi d_s \left(f_r k_{tr} + k_{tc} \right)} \tag{2}$$

where d_s is the overall diameter for one conductor of the self-supporting insulated cable bunch, f_r is the factor for the interchange of radiant energy between the surfaces of the conductors of the self-supporting insulated cable bunch, K_{tr} is the radiant heat transfer coefficient, and K_{tc} is the convective heat transfer coefficient.
The factor f_r for two long parallel circular cylinders according to [2], is given by

$$f_r = \frac{1}{\pi}\left\{\frac{\pi}{2} + \left[\frac{s^2}{d_s^2} + \frac{2s}{d_s}\right]^{\frac{1}{2}} - \left(1 + \frac{s}{d_s}\right) - \cos^{-1}\left[\frac{1}{1 + (s/d_s)}\right]\right\} \tag{3}$$

where s is the spacing. In the case of the self-supporting insulated cable bunch with three conductors, this factor is equal to 0.636.

The radiant heat transfer coefficient may be found from Stefan-Boltzmann law, as follows:

$$k_{tr} = \sigma_B \varepsilon_S \frac{(273 + \vartheta_S)^4 - (273 + \vartheta_a)^4}{\vartheta_s - \vartheta_a} \tag{4}$$

where σ_B is the Slefan-Boltzmann constant $\sigma_B = 5.6697 \cdot 10^{-8} Wm^{-2}K^{-4}$, ε_S is the emissivity of the cable surface, and ϑ_s is the cable surface temperature.

The convective heat transfer coefficient could be calculated by

$$k_{tc} = N_u \frac{\lambda}{d_s} \tag{5}$$

where N_u is the Nusselt number, and λ is the thermal conductivity of the fluid at the surface of the cable. The thermal conductivity for moderate temperatures can be approximated by

$$\lambda = 2.42 \cdot 10^{-2} + 3.6 \cdot 10^{-5}(\vartheta_s + \vartheta_a) \tag{6}$$

The Nusselt number for natural convection for the isothermal horizontal self-supporting insulated cable bunch could be expressed as

$$N_u = A(G_r P_r)^m \Phi \tag{7}$$

where G_r is the Grashof number, P_r is the Prandtl number, constants A and m are the functions of G_r, P_r and Φ is the ratio between the Nusselt number for the self-supporting insulated cable bunch to that for one circular cylinder.

The Grashof number for one circular cylinder is defined by

$$G = \frac{d_s^3 \cdot g \cdot (\vartheta_s - \vartheta_a)}{[0.5 \cdot (\vartheta_s + \vartheta_a) + 273]\nu} \tag{8}$$

where g is the acceleration due to gravity, and ν is the kinematics' viscosity of the fluid at the surface of the cable.

Kinematics' viscosity of the fluid at sea level for moderate temperatures is defined by

$$\nu(0) = 1.32 \cdot 10^{-5} + 4.75 \cdot 10^{-8}(\vartheta_s + \vartheta_a) \tag{9}$$

and at height H above sea level is defined by

$$\nu(H)=\nu(0)\cdot\left(1-6.5\cdot10^{-3}H/288.16\right)^{-5.2561} \tag{10}$$

The Prandtl number for moderate temperature can be expressed as

$$P_r=0.715-1.2510^{-4}\left(\vartheta_s+\vartheta_a\right) \tag{11}$$

2.3 Thermal Resistance of the Cable in Free Air Adjusted to Take Into Account Solar Radiation

The thermal resistance adjusted to take into account solar radiation can be expressed in the form

$$T_{4r}=\frac{1}{\pi d_s k_{tr}} \tag{12}$$

where the actual exposed surface area shall be expressed in relation to the heat input for different forms of solar radiation.

2.4 Solar Heating

The total solar heat input per unit length may be expressed as the sum from beam radiation, diffuse radiation, long-wave radiation and reflected radiation.
The heal input from the beam radiation is defined by

$$P_{SB}=\alpha_S d_S I_B f_{SB}\sin\eta \tag{13}$$

where α_S is the absorptive surface to short-wave radiation, I_B is the direct-beam short-wave radiation flux, f_{SB} is the coefficient of exposed projected area normal to the direct beam defined for each conductor, and η is the angle between the solar beam and the axis of the self-supporting insulated cable bunch.
The coefficient of the exposed projected area normal to the direct beam defined for each conductor of the self-supporting insulated cable bunch with three conductors is given by

$$f_{SB}=\frac{1+\sin\eta+\sin\left(60^\circ-\eta\right)}{3};0^\circ\langle\mu\langle60^\circ \tag{14}$$

$$f_{SB}\frac{1+\sin\eta}{3};60^\circ\leq\eta\leq120^\circ \tag{15}$$

$$f_{SB}\frac{1+\sin\eta+\sin\left(\eta-120^\circ\right)}{3};120<\eta<180^\circ \tag{16}$$

The heat input from the diffuse radiation is defined by

$$P_{Sd} = \alpha_S d_S f_{Sd} I_d \cos^2 \frac{\zeta}{2} \tag{17}$$

where I_d is the broad-band diffuse irradiance and ζ is the inclination of the cable.
The coefficient of the exposed surface area from the diffuse radiation defined for each conductor of the self-supporting insulated cable bunch with three conductors is given by

$$f_{Sd} = \frac{15\pi/36 + \pi/2 + 9\pi/36}{3} \tag{18}$$

The heat input from the long-wave radiation is defined by:

$$P_{SL} = \alpha_L d_S \cos^2 \frac{\zeta}{2}\left[f_{SL} I_L + f_{S\rho}\varepsilon_g \sigma_B (\vartheta_g + 273)^4\right] \tag{19}$$

where α_L is the absorptive surface to long-wave radiation, I_L is the downward flux of long-wave radiation, f_{SL} is the coefficient of downward-facing exposed surface area from long-wave radiation defined for each conductor, $f_{S\rho}$ is the coefficient of exposed downward-facing area from reflected radiation defined for each conductor, and ε_g is the emissivity of the ground.
The coefficient of the exposed downward-facing area from the reflected radiation defined for each conductor of the self-supporting insulated cable bunch with three conductors is given by:

$$f_{S\rho} = \frac{15\pi/36 + \pi/2}{3} \tag{20}$$

The coefficient f_{SL} is equal to the coefficient f_{sd}.
The heat input from the reflected radiation is defined by:

$$P_{S\rho} = \alpha_S d_S \rho_g f_{S\rho} \cos^2 \frac{\zeta}{2}\left(I_B(H)\sin H_S + I_d\right) \tag{21}$$

where ρ_g is the albedo of the ground.
Calculations for other variables are given in [2].

3. EXPERIMENTAL RESULTS

3.1 The Testing Samples

This paper reports new results obtained by testing the actual self supporting XLPE insulated cable bunches, rated voltages of 1 kV and 10 kV, insulated by filled cross linked polyethilene, type XL 3512 and HFDS 4201, respectively. The conductor screen and insulation screen for 10 kV XLPE insulated cable bunch were made of semioconducting layer, type HHDS 0592. The XLPE self supporting cable bunches, rated voltages of 1 kV and 10 kV, have the construction characteristics given in Table 1.

TABLE 1 – Construction characteristics of self-supporting XLPE cables

Geometric characteristics	1 kV No. of cores and cross section (mm^2)		10 kV No. of cores and cross section (mm^2)
	4x16	3x70x71.5	3x70
Conductor diameter (mm)	5.0	10.4/10.9	10.3
Insulated conductor diameter (mm)	7.4	14/14.5	18.1
Metal screen diameter (mm)	-	-	20.0
Sheathed core diameter	-	-	23.6
Cable diameter (mm)	18.0	24.0	59.0

Temperatures were measured and recorded by thermo-couples connected with the personal computer through the measuring instrument and RS 232 connection.
The calculated continuous current current ratings is determined numerically step by step, since the surface temperature of self-supporting insulated cable bunch is unknown.

3.2 One Insulated Conductor

The experiments for one insulated circular conductor are carried out with the conductor taken from the low and medium voltage self-supporting insulated cable bunches cross-sections 4x16 mm^2 and 3x70 mm^2, respectively.
The conductor and surface temperature changes in the case with constant current for the full heating-cooling cycle (ambient temperature-conductor maximum permitted temperature-ambient temperature) are presented in Figure 1 and Figure 2.
Comparative results for measured and calculated continuous current values, for maximum permitted conductor temperature of 90° C, are presented in Table 2. Calculated values in Table 2 are based on the theory given in Section 2 for natural convection.
The shape of curves in Figure 2 is caused by the lower initially adjusted value of continuous current (that does not correspond to the steady state conductor temperature of 90° C).

TABLE 2 – Continuous current for one insulated circular conductor

Conductor area (mm^2)	Ambient temperature ($^\circ$C)	Measured current (A)	Calculated current (A)
16	19.0	116.0	114.0
70	19.5	324.0	321.3

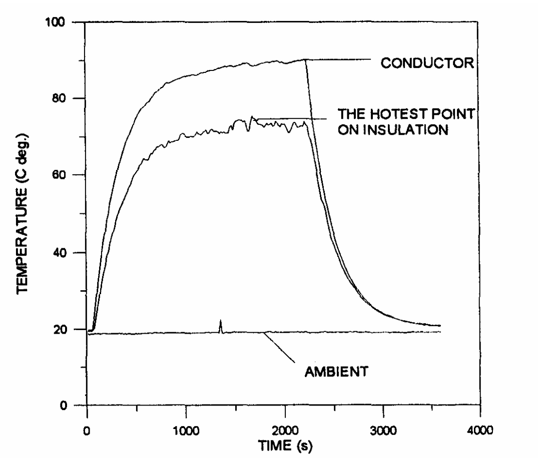

Figure 1 – Heating-cooling cycle for 1x16 m^2,1 kV

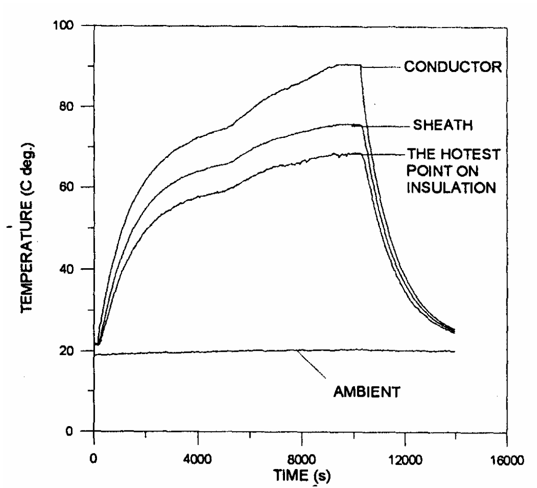

Figure 2 – Heating-cooling cycle for 1x70 mm^2, 10 kV

3.3 Self-supporting insulated cable bunches

The experiments for self-supporting insulated cable bunches arc carried out with the low voltage self - supporting insulated cable bunches cross-sections 4x16 mm^2 and 3x70+71.5 mm^2 and medium voltage self -supporting insulated cable bunch cross-section 3x70 mm^2.

In Fig. 3, Fig. 4 and Fig 5 The conductor and surface temperature changes in the case with constant current for the full heating-cooling cycle (ambient temperature- conductor maximum permitted temperature -ambient temperature) are presented in Figures 3, 4 and 5.

Comparative results for measured and calculated continuous current values, for maximum permitted conductor temperature of 90° C, are given in Table 3 . Calculated values in Table 3 are based on both, the theory given in Section 2 for natural convection (2.1), and the IEC Publication (2.2).

TABLE 3 – Continuous current for self-supporting insulated cable bunches

Self-supporting cable type	θ_a (ºC)	Measured current (A)	Calculated value		Φ
			I_1(A)	I_2(A)	
4x16 mm^2 1 kV	20	88.0	88.3	67.3	0.526
3x70+71.5 mm^2 1 kV	20	232.0	232.0	178.4	0.526
3x70 mm^2 10 kV	21	264.0	264.4	195.4	0.541

Table 3 also lists the values of the ratio between the Nusselt number for the self-supporting insulated cable bunch to that one for the circular cylinder (Φ). In order to establish general conclusion regarding the ratio Φ, much more experiments with different cross-sections of self-supporting insulated cable bunches are required.

The ratio Φ, in Table 3, have different values compared with the corresponding value of the natural convection coefficient given in [3]. The coefficient given in [3] has a constant value of 2/3 independently of the cable diameter. The values of the ratio Φ in Table 3 are lower than the corresponding values in [3], since in our case cable has four cores (where the fourth is a supporting one).

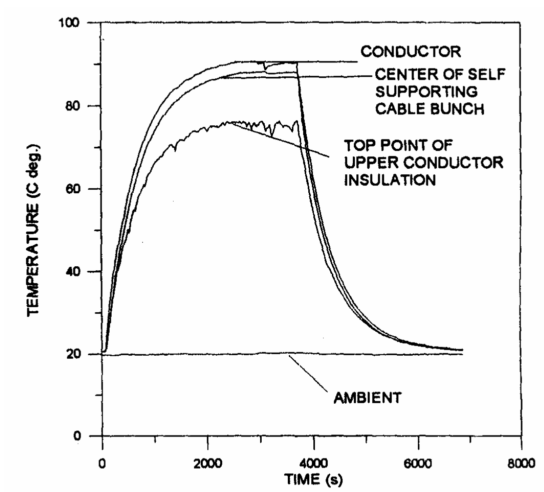

Figure 3 – Heating-cooling cycle for X00/0-A, 4x16 mm^2, 1 kV

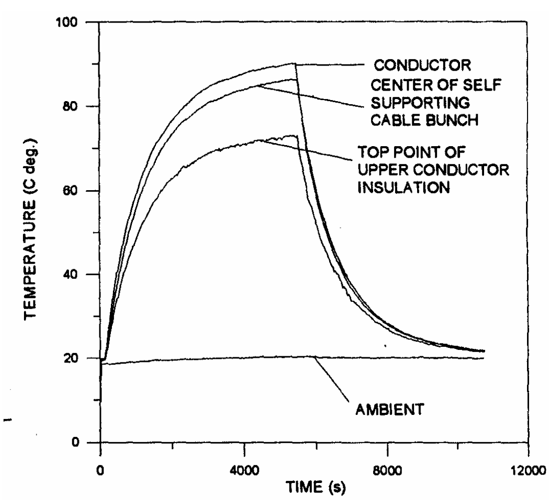

Figure 4 – Heating-cooling cycle for X00/0-A, 3x70+71.5 mm^2, 1 kV

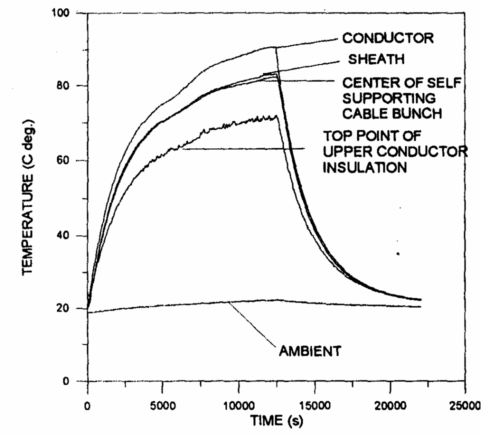

Figure 5 – Heating-cooling cycle for XHE 49/0-A, 3x70 mm^2, 10 kV

The time constants and other relevant data pertinent to the complete heating-cooling cycle can be evaluated from Figures 3, 4 and 5.

It is interesting to note that the temperature in the center of self-supporting cable bunch is higher than the temperature of the top point of upper conductor insulation.

4. CONCLUSION

In this paper an analytical approach to continuous current rating calculations of self-supporting cable bunch is presented and verified in comparison with experimental measurements. Analytical and experimental investigations have been performed taking into account cooling by natural convection only, whereas results with cooling by forced convection and with short overloading will be reported later on. The coefficients of exposed projected areas of self-supporting cable bunch for different forms of solar radiation are also presented.

The results verified in this paper show that self-supporting cable bunches can be utilized more effectively than it is recommended in the IEC Publication.

5. BIBLIOGRAPHY

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