Temperature Response of OPGW with Armored Aluminum Covered Steel Wires – Aluminum Alloys Wires Submitted to Short-Circuit

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Abstract

The design of armored aluminum covered steel – aluminum alloys OPGW as focused in this paper requires the knowledge on the effect of each cable components on the temperature response effects caused by short-circuit. Aside from mechanical properties of cable components, the thermal properties of the cable materials has proved to play an important role in evaluating the maximum temperature achieved by the extruded tube. The same remark holds for cable components geometrical parameters. In previous papers presented at the 53 IWCS, 54 IWCS and 55 IWCS, analytical approaches were presented in order to solve the heat conduction problem describing the thermal effects due to short-circuit. Predicted results were reported for cases of armored aluminum covered steel wires (ACSW), as well as for armored aluminum covered steel wires – aluminum alloys wires (ACSW-AAW). As reported in previews papers, the predicted results are in good agreement with experimental results, for the case of armored galvanized steel wires. I the present paper, experimental results obtained from short-circuit tests of (ACSW-AAW) are presented and analyzed in comparison to the theory reported at 55 IWCS. Results show the advantages of the type of cable analyzed here in comparison with the cable ACSW. A sensitivity analysis with respect to cable components parameter is also presented.

Keywords: OPGW, short-circuit; unsteady heat-transfer.

1. Introduction

A novel design of OPGW manufactured with aluminum covered steel wires and aluminum alloy is reported in [1]. The authors pointed out the advantage of mixing aluminum covered steel wires and aluminum alloy wires to increase the current carrying capacity. The current carrying capacity of an OPGW depends mainly on the electric resistance of its conductor components, as is the case of the extruded aluminum tube and the armored wires. As is shown in [2, 3, 4], the maximum temperature achieved in the extruded aluminum tube depends not only on the electric resistance of the conductors, but also on the thermal contact resistance between the armored wires and the tube, and the thermal conductivity of the material of the armored wires.

The electric current of the OPGW focused here is assumed to be distributed in parallel association through the tube, the aluminum cover of the wires, and the steel wires themselves. Therefore, thermal effects caused by temperature gradients as well as by the covering layer thickness should be taken into account, in order to investigate the effect of the electric current on the temperature variation of each conductor with time. The present analysis has been reported in detail in [4], where it is assumed that the electric resistance of the wire is evaluated as a function of the average wire temperature over its cross section. However, only predicted results are reported in [4].

2. Basic Equations

In the present analysis the skin effects due to the intensive short-circuit current are neglected. The skin effect for an OPGW as focused here, according to [5, 6], may result in a temperature gradient around 10°C over the cross section of the extruded aluminum tube. This temperature gradient is around 4% of the maximum temperature expected in the aluminum tube. It is assumed here that the heat loss at the outer surfaces of the armored wires to the surrounding medium is neglected. The optic fibers gel inside the extruded aluminum tube is assumed to have very low thermally conductivity, so that the inner surface of the extruded tube can be consider to be insulated. The temperature gradient over the cross section of the tube is also neglected.

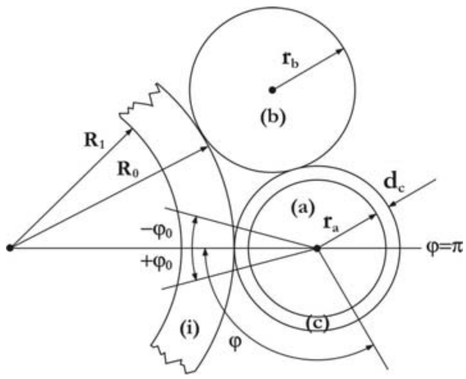

Figure 1. Cross section geometry of the OPGW

Both the aluminum covered wire (a) and the uncovered wire (b) are supposed to be in thermal contact with the tube, but in no thermal contact with each other. The effective thermal contact angle for both wires (a) and (b) is assumed equal to φ_o as shown in Figure 1. Only the basic differential equations in terms of the average temperatures of the aluminum tube and the armored wires will be presented here. The solution of the equations is presented in [4].

2.1 Aluminum Tube

The energy balance for the tube (i), by assuming no thermal gradient over the cross section of the tube is shown to be governed by the following dimensionless equation,

$$\frac{d\theta_i}{d\tau} = p_i\left(\theta_i, \overline{\theta}_a, \overline{\theta}_b, \overline{\theta}_c\right) - \frac{2}{\pi}\alpha_c \beta_c F_{oc}\phi_{oc}(\tau) - \frac{2}{\pi}\beta_b F_{ob}\phi_{ob}(\tau) \quad (1)$$

where $\theta = \frac{T - T_o}{T_o}$, $\tau = t/\Delta t_{sc}$, T_o is the initial temperature, Δt_{sc} is the short-circuit duration time, $\overline{\theta}_a$, $\overline{\theta}_b$, and $\overline{\theta}_c$ are the average temperatures over the cross section of wire core (a) and wire (b), and the aluminum covering layer (c), respectively. $F_{ob} = k_b \Delta t_{sc} / \rho_b c_b r_b^2$ is the Fourier number respective to wire (b), $F_{oc} = k_c \Delta t_{sc} / \rho_c c_c ((r_c + r_a)/2)^2$ is the Fourier number respective to the aluminum cover layer (c) of wire core (a), $\alpha_c = 2d_c/(r_a + r_c)$, d_c is the thickness of the covering layer (c),

$\beta_b = N_b \sqrt{1+\kappa_b^2}\, \rho_b c_b \pi r_b^2 / \rho_i c_i \pi (R_o^2 - R_1^2)$,

$\kappa_b = 2\pi(R_o + r_b)/L$ is the pitch ratio of wire (b),

$\beta_c = N_a \sqrt{1+\kappa_c^2}\, \rho_c c_c \pi \left(\frac{r_a + r_c}{2}\right)^2 / \rho_i c_i \pi (R_o^2 - R_1^2)$, $\kappa_c = \kappa_a$, $\kappa_a = 2\pi(R_o + r_a + d_c)/L$ is the pitch ratio of wire (a), $\phi_{oa} = \int_0^{\varphi_o} \phi_a(\varphi,\tau)d\varphi$, $\phi_a = q_a'' r_a / k_a T_o$, $\phi_{ob} = \int_0^{\varphi_o} \phi_b(\varphi,\tau)d\varphi$, $\phi_b = q_b'' r_b / k_b T_o$,

$\phi_c = q_c'' r_c (r_a + r_c)/2d_c k_c T_o$, and q'' represents the heat flux density in the surface (W/m^2). The dimensionless heat flux is expressed in terms of the derivative of the dimensionless temperature by $\phi_a(\varphi,\tau) = \frac{\partial\theta_a}{\partial\eta}(1,\varphi,\tau)$, where $\eta = r/r_a$ and $\phi_b(\varphi,\tau) = \frac{\partial\theta_b}{\partial\eta}(1,\varphi,\tau)$, where $\eta = r/r_b$.

The Joule heating source term of equation (1) can be obtained by assuming parallel association of tube (i), wires (a) and (b), and the aluminum cover (c). Since the Joule effect is assumed to be uniformly distributed over the volume of the conductors, it can be assumed that the electric resistance of each conductor is evaluated at its average temperature over the cross section according to the equation $R = R_{20} f(\overline{\theta})$, where f is the temperature depended electric resistivity function. This assumption is justified by experimental results [3]. In terms of the physical variables, the dimensionless equation for p_i can be written as follows [6],

$$p_i = q_i f_i(\theta_i) f_a(\overline{\theta}_a)^2 f_b(\overline{\theta}_b)^2 f_c(\overline{\theta}_c)^2 / q^2 \quad (2)$$

where

$$q = \lambda_a \lambda_b \lambda_c f_a f_b f_c + f_i(N_a \lambda_b \lambda_c f_b f_c + N_a \lambda_a \lambda_b f_a f_b + N_b \lambda_a \lambda_c f_a f_c) \quad (3)$$

$q_i = (I^2 \Delta t_{sc}) R_{20i} \lambda_a^2 \lambda_b^2 \lambda_c^2 / \rho_i c_i \pi (R_o^2 - R_1^2) L T_o$,

$\lambda_a = R_{20a}/R_{20i} = \rho_{20a}\pi(R_o^2 - R_1^2)\sqrt{1+\kappa_a^2} / \rho_{20i}\pi r_a^2$,

$\lambda_b = R_{20b}/R_{20i} = \rho_{20b}\pi(R_o^2 - R_1^2)\sqrt{1+\kappa_b^2} / \rho_{20i}\pi r_b^2$,

$\lambda_c = R_{20c}/R_{20i} = \rho_{20c}\pi(R_o^2 - R_1^2)\sqrt{1+\kappa_c^2} / \rho_{20i}\pi(r_c^2 - r_a^2)$, L is the length of tube (i) corresponding to one turn of the wires around the tube N_a, N_b, and $N_c = N_a$ are the numbers of wires (a) and (b) and cover layer (c), respectively, ρ represents the specific mass, c represents the specific heat, R_{20} represents the electrical resistance at 20^{o}C, ρ_{20} represents the electrical resistivity at 20^{o}C, and k represents the thermal conductivity.

2.2 Covered wire (a)

The energy balance in wire (a) is governed by a differential equation which can be written in dimensionless form as follows [3, 6],

$$\frac{1}{\eta}\frac{\partial}{\partial\eta}\left(\eta \frac{\partial\theta_a}{\partial\eta}\right) + \frac{p_a}{F_{oa}} = \frac{1}{F_{oa}}\frac{\partial\theta_a}{\partial\tau} \quad (4)$$

where $\eta = r/r_a$, $F_{oa} = k_a \Delta t_{sc} / \rho_a c_a r_a^2$ is the Fourier number respective to wire core (a),

$p_a = q_a f_i(\theta_i)^2 f_a(\overline{\theta}_a) f_b(\overline{\theta}_b)^2 f_c(\overline{\theta}_c)^2 / q^2$,

$q_a = (I^2 \Delta t_{sc}) R_{20i} \lambda_a \lambda_b^2 \lambda_c^2 / \rho_a c_a \pi r_a^2 L_a T_o$, and

$L_a = L\sqrt{1+\kappa_a^2}$ is the length of the effective thermal contact surface strip of width $e_a = 2 r_a \varphi_o$.

The initial conditions for θ_i and θ_a are given by,

$$\theta_i(0) = \theta_a(\eta,\varphi,0) = 0 \quad (5)$$

From the overall energy balance in wire (a) it can be shown that the average temperature over the cross section of the wire can be expressed as

$$\frac{d\overline{\theta}_a}{d\tau} = p_a\left(\theta_i, \overline{\theta}_a, \overline{\theta}_b, \overline{\theta}_c\right) + \frac{2F_{oa}}{\pi}\phi_{oa}(\tau) \quad (6)$$

From equation (5) it follows that the initial condition for equation (6) is $\overline{\theta}_a(0) = 0$.

2.3 Uncovered wire (b)

Similarly to equation (4), for wire (b) the following equation holds,

$$\frac{1}{\eta}\frac{\partial}{\partial\eta}\left(\eta \frac{\partial\theta_b}{\partial\eta}\right) + \frac{p_b}{F_{ob}} = \frac{1}{F_{ob}}\frac{\partial\theta_b}{\partial\tau} \quad (7)$$

where $\eta = r/r_b$,

$p_b = q_b f_i(\theta_i)^2 f_a(\overline{\theta}_a)^2 f_b(\overline{\theta}_b) f_c(\overline{\theta}_c)^2 / q^2$,

$q_b = (I^2 \Delta t_{sc}) R_{20i} \lambda_a^2 \lambda_b \lambda_c^2 / \rho_b c_b \pi r_b^2 L_b T_o$, and

$L_b = L\sqrt{1+\kappa_b^2}$ is the length of the effective thermal contact surface strip of width $e_b = 2 r_b \varphi_o$.

The initial condition for θ_b is given by,

$$\theta_b(\eta, \varphi, 0) = 0 \tag{8}$$

From the overall energy balance for wire (b) it can be shown that the average temperature over the cross section of the wire can be expressed as

$$\frac{d\overline{\theta}_b}{d\tau} = p_b\left(\theta_i, \overline{\theta}_a, \overline{\theta}_b, \overline{\theta}_c\right) + \frac{2F_{ob}}{\pi}\phi_{ob}(\tau) \tag{9}$$

From equation (8) it follows that the initial condition for equation (9) is $\overline{\theta}_b(0) = 0$.

The heat flux at the thermal contact interface between the wire (b) and the tube (i) is related to a Biot number by the following equation [7],

$$\phi_b(\varphi, \tau) = -B_{ib}\left(\theta_b(1, \varphi, \tau) - \theta_i(\tau)\right) \tag{10}$$

for $0 \le \varphi \le \varphi_o$.

2.4 Covering layer (c)

Since the material of the layer (c) has high thermal conductivity it can be assumed that there is no thermal resistance in the radial direction. Therefore the diffusion equation reduces to a one-dimensional equations in terms of the circumferential variable $\overline{s} = (r_c + r_a)\varphi / 2$. The details of the derivation of the mentioned equation, accounting for the heat flux respective to wire (a), and the heat flux at the interface of thermal contact between the layer (c) and the tube (i) is reported in [6]. The following equation is obtained

$$\frac{\partial^2 \theta_c}{\partial \varphi^2} + \frac{p_c}{F_{oc}} + (\phi_c - \gamma \phi_a) = \frac{1}{F_{oc}} \frac{\partial \theta_c}{\partial \tau} \tag{11}$$

where $\gamma = k_a (r_a + r_c) / 2k_c d_c$,

$p_c = q_c f_i(\theta_i)^2 f_a(\overline{\theta}_a)^2 f_b(\overline{\theta}_b)^2 f_c(\overline{\theta}_c) / q^2$,

$q_c = (I^2 \Delta t_{sc}) R_{20i} \lambda_a^2 \lambda_b^2 \lambda_c / \rho_c c_c \pi (r_c^2 - r_a^2) L_c T_o$, and L_c , which is equal to L_a , is the length of the effective thermal contact surface strip of width $e_c = 2 r_c \varphi_o$.

The initial condition associated to equation (11) is given by

$$\theta_c(\varphi, 0) = 0 \tag{12}$$

Because of the symmetry of temperature distribution over layer (c) respective to angle φ it follows,

$$\frac{\partial \theta_c(0, \tau)}{\partial \varphi} = \frac{\partial \theta_c(\pi, \tau)}{\partial \varphi} = 0 \tag{13}$$

By assuming perfect thermal contact between the wire core (a) and the covering layer (c), no temperature discontinuity exists at the contact interface. Therefore

$$\theta_a(1, \varphi, \tau) = \theta_c(\varphi, \tau) \tag{14}$$

for $0 \le \varphi \le \pi$.

The heat flux at the interface of thermal contact between layer (c) and tube (i) is related to the Biot number by the following equation [6],

$$\phi_c(\varphi, \tau) = -B_{ic}\left(\theta_c(1, \varphi, \tau) - \theta_i(\tau)\right) \tag{15}$$

for $0 \le \varphi \le \varphi_o$.

The overall energy balance in layer (c), leads to the following differential equation [6],

$$\frac{d\overline{\theta}_c}{d\tau} = p_c\left(\theta_i, \overline{\theta}_a, \overline{\theta}_b, \overline{\theta}_c\right) + \frac{F_{oc}}{\pi}\left(\phi_{oc}(\tau) - \gamma \phi_{oa}(\tau)\right) \tag{16}$$

The initial condition for the above equation, according to equation (12) is given by $\overline{\theta}_c(0) = 0$.

The above equations are numerically solved for given values of the following dimensionless parameters

$$\Lambda_b = 2B_{ib} F_{ob} \varphi_o / \pi = h_b e_b \Delta t_{sc} / \rho_b c_b \pi r_b^2 \tag{17}$$

where $B_{ib} = h_b r_b / k_b$ is the Biot number, h_b is the effective heat transfer coefficient related to the heat transfer contact area between the wire and the tube.

$$\Lambda_c = 2B_{ic} F_{oc} \varphi_o / \pi = 2h_c e_c \Delta t_{sc} / \rho_c c_c \pi d_c (r_a + r_c) \tag{18}$$

where $B_{ic} = h_c r_c (r_a + r_c) / 2d_c k_c$ is the Biot number, h_c is the effective heat transfer coefficient related to the heat transfer contact area between the wire and the tube. The heat flux is assumed to vanish for $\varphi_o < \varphi \le \pi$ in both wires (b) and (c).

3. Discussion of Results

A cable ACSW-AAW was tested in a short-circuit mode. The electrical and thermophysical proprieties of the materials of the OPGW were supplied by Prysmian.

Figures 2, 3, 4, and 5 are reproduced from [4] in order to illustrate the effect of the design parameters on the cable performance during short-circuit test. Figure 2 shows that the increase of the aluminum cover thickness lead to a reduction of the maximum temperature achieved by the tube, for all values of the thermal resistance parameter Λ_b . In these figures Λ_c , respective to the aluminum cover layer is expressed in terms of Λ_b according to equations (17) and (18) as $\Lambda_c = 2\Lambda_b \rho_a c_a \pi r_a^2 / \rho_c c_c \pi d_c (r_a + r_c)$. Figure 3 shows that the effect of the increase of the aluminum cover thickness is to decrease the temperature of the aluminum alloy wires, for all values of Λ_b . This Figure 4 illustrates the effect of the aluminum cover thickness on the temperature distribution of the wires and the tube with time. Figure 5 gives a comparison of the maximum temperature achieved in the tube for the case of full aluminum covered steel wires and the case of ACSW-AAW five aluminum covered steel wires. It is seen from this figure that the effect of the cover thickness increase is to substantially reduce the maximum temperature achieved by the tube. The present analytical solution is presented in detail in [4]. In order to check the validation of the present solution, wires (a) and (b) were replaced by steel wires with the same diameter as reported in [3]. The thickness of the aluminum cover was reduced to a arbitrarily small value. The predicted value for the wire and the tube temperatures smoothly converges to the predicted values found in [3]. Its worth to mention that the predicted values found in [3] are in agreement with the experimental data obtained from several short-circuit tests for cable OPGW – SM 13,4 6 FO.

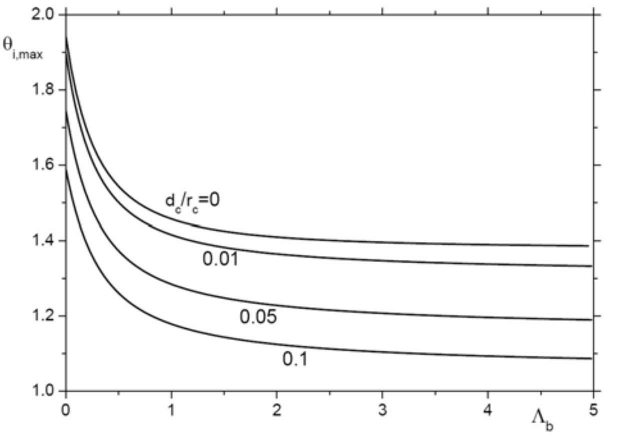

Figure 2. Maximum temperature achieved in the tube for the case of five aluminum covered steel wires and five aluminum alloy wires, for various ratios of d_c / r_c

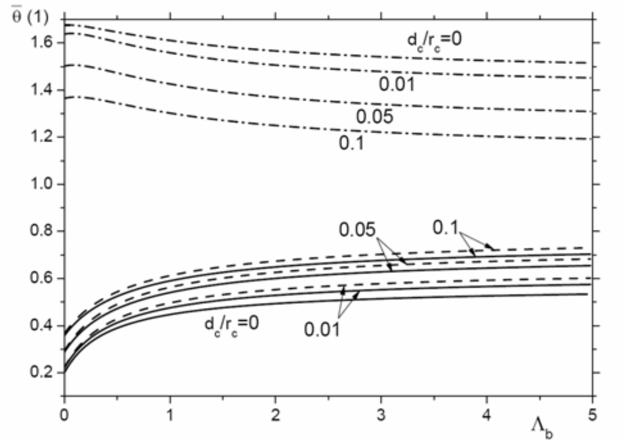

Figure 3. Temperature rise of the wires at the end time of the short-circuit for the case of five aluminum covered steel wires and five aluminum alloy wires (- - -) aluminum cover (c); (——) steel core (a); (-·-·) aluminum alloy (b)

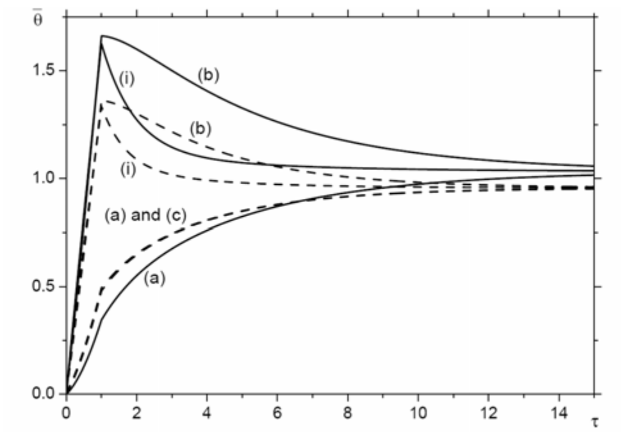

Figure 4. Temperature variation with dimensionless time for the case of five aluminum covered steel wires (a) and five aluminum alloy wires (b), for $d_c / r_c = 0$ (——), $d_c / r_c = 0.1$ (- - -), and $\Lambda_b = 0.3$

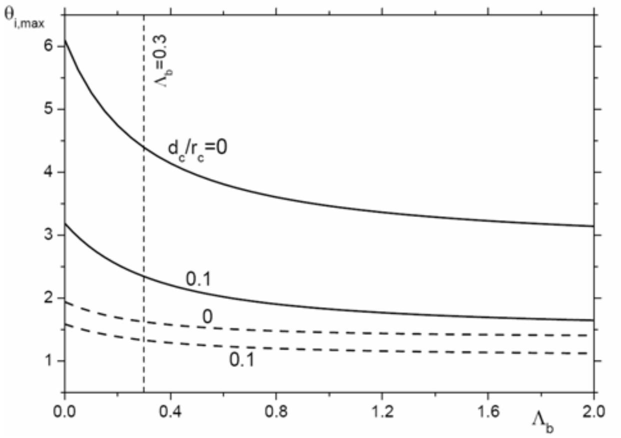

Figure 5. Comparison of the maximum temperature achieved in the tube for the case of ten aluminum covered steel wires (——) and the case of five aluminum covered steel wires and five aluminum alloy wires (- - -)

The predicted and the experimental temperatures for the cable analyzed here are plotted as a function of time in Figure 6. The thermal resistance Λ_b is determined by fitting the theoretical results with the experimental results. It is seen that Λ_b is not constant with time. The same conclusion was found in [3] for the case of galvanize steel wires.

The predicted results are compared with the experimental results obtained from a short circuit test of cable OPGW-SM-12,4 48FO of Prysmian. The cable is manufactured with four aluminum wires and seven aluminum covered steel wires with diameter equal 2.67mm. The outer diameter of the extruded tube is equal to 7.1mm and its inner diameter is equal to 5.1mm. The aluminum cover layer thickness of the steel wire is equal to 10% of the wire outer diameter. The cable was submitted to ten short circuit test of tests with effective electric current 9.7 kA ± 0.1kA, at the laboratory of CEPEL [8]. The temperature of the tube and the wires were measured by appropriate thermocouples fixed on the surface of each cable components. The thermocouples were fixed in the surface of the wires at points located at $\varphi = \pi$. The average of the measured temperature are obtained from qualified data of eight tests. The thermophysical proprieties of the cable materials as well as the electric resistivity are supplied by Prysmian [9]. It should be pointed out here that the predicted results plotted in Figure 6 are in agreement in terms of the steady-state equilibrium temperature limit only for an electric current intensity around 8.9kA. It means that there is no agreement between the predicted and experimental data in terms of the energy stored in the cable. Therefore, more tests are required in order to identify the source of disagreement.

The thermal contact resistance parameters Λ_b (AAW) and Λ_c (ACSW) are fitted against the respective measured temperature data. The numerical values of these parameters are shown in Figure 6. It should be pointed out here that these parameters are not the same as reported in [3] and [4]. However they are directly related to. The confidence interval respective to these parameters are not yet determined. More tests should be carried out for $\Delta t_{sc} = 0.5s$ and even larger values of time as reported in [3], in order to characterize the thermal contact resistance parameters. It is remarkable that parameters Λ_b and Λ_c are proved to be fairly independent of the cable steady – state equilibrium temperature, as well as the short circuit time interval Δt_{sc} , as reported in [3].

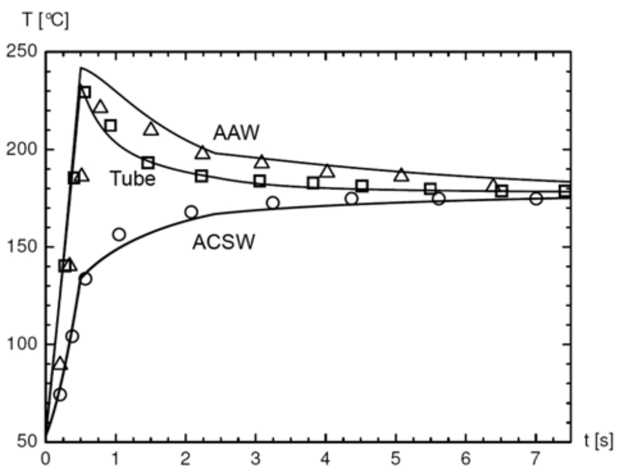

Figure 6. Comparison of the predicted results with the experimental results of short-circuit tests. For AAW, $\Lambda_b = 5.39$ for $t \le 0.5$; $\Lambda_b = 0.616$ for $0.5 \le t \le 2.4$; $\Lambda_b = 0.154$ for $t > 2.4s$ **, and for ACSW,** $\Lambda_b = 6.6165$ for $t \le 0.5$; $\Lambda_b = 3.3083$ for $0.5 \le t \le 2.4$; $\Lambda_b = 1.6541$ for $t > 2.4s$

Its worth noting that the predicted temperature of the tube agrees fairly well with the experimental data for the fitted values of Λ_b and Λ_c. As found in [3] for the case of an OPGW made of galvanized steel wires, the thermal contact resistance parameters are shown to be not constant with time. This is due to the fact that the wires keep stiffly in mechanical contact with the aluminum tube during the short circuit time interval. After the electric current stops, the cable vibrates and at the same time the wires length varies according to its thermal expansion coefficient. These thermal and mechanical effects contribute to impair the thermal contact resistance in the interface of the cable components.

4. Conclusions

In this paper, the heat transfer effects due to the heating caused by short-circuit of an OPGW composed of armored aluminum covered steel wires and aluminum alloy wires is analyzed. The thermal effect caused by the aluminum covering layer as well as the aluminum alloy on the maximum temperature achieved in the extruded tube is investigated. The predicted results are compared with experimental results obtained from short circuit tests, for the particular case of cable OPGW-SM-12,4 48FO manufactured by Prysmian. The thermal contact resistance parameters associate to the mechanical contact between both, the aluminum covered steel wires and the aluminum alloy wires with the extruded tube are determined. As shown in a previews paper, the aluminum alloy wires are much more effective in reducing the maximum temperature achieved in the aluminum tube than the aluminum covered steel wires. The experimental results presented here are far from be sufficient in order to determine the uncertainty related to the thermal contact resistance parameters. However, the results reported here enables one to concluded that the present analytical approach can be useful as a tool to experimentally determine the thermal contact resistance associate a to the heat transfer during the short circuit.

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