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Effect of solar radiation on power losses and capacity of insulated and non-insulated wires of overhead power LINES

***Abstract**. The influence of solar radiation on the temperature regimes of power lines implemented with classical and new types of wires is considered. The maximum permissible temperatures limit the capacity of the lines, and the current temperature regime affects the loss of power and energy due to changes in the ohmic resistance. The paper presents the heat balance equations for insulated and non-insulated wires, formulas for calculating the heat transfer coef-ficient and solar radiation intensity, and an expression for the permissible current. Typical values of direct and diffused radiation are compared, provided that the wire is perpendicular to the sunlight. It is shown that solar radiation leads to an increase in the temperature of the wires by 5 and up to 7 degrees Celsius with a weak dependence on the type of wires and current load. The corresponding increase in real-power losses does not exceed 3%. The results obtained with the proposed technique for non-isolated wires show good convergence with previous studies. One of the advantages of the developed method is its versatility, which is manifested in the possibility of its application not only for non-insulated wires, but also for wires with insulation.*

Streszczenie.** Analizowany jest wpływ promieniowania słonecznego na warunki temperaturowe linii energetycznych z klasycznymi i nowymi typami drutów. Maksymalne dopuszczalne temperatury ograniczają możliwości linii, a warunki temperaturowe wpływa na utratę mocy i energii z powodu zmian rezystancji. W pracy przedstawiono równania bilansu cieplnego dla drutów izolowanych i nieizolowanych, wzory do obliczania współczynnika przenikania ciepła i natężenia promieniowania słonecznego oraz wyrażenie na dopuszczalny prąd. Porównywane są typowe wartości promieniowania bezpośredniego i rozproszonego, pod warunkiem, że drut jest prostopadły do światła słonecznego. **Analizą efektu promieniowania słonecznego na możliwości i straty mocy napowietrznych linii energetycznych

Keywords: heat balance equation, overhead power lines, temperature regime, real-power losses.
Słowa kluczowe: równanie bilansu cieplnego, napowietrzne linie energetyczne, straty mocy rzeczywistej.

Introduction

One of the conditions for the optimum operation of electric power networks is to minimize the loss of electric energy [1-4]. An assessment of the loss reduction effectiveness requires accuracy in loss determination, this being of particular importance [5]. It is necessary to consider temperature dependence of the ohmic resistance in improving the accuracy of loss calculation [6-10]. The wire temperature depends on the wind pattern, air temperature, current load, atmospheric pressure, and solar radiation [11-13]. The influence of solar radiation on the wire temperature is presented in detail in the paper [14, 15]. It is indicated that solar radiation significantly affects unloaded wires. The temperature in this case may increase by 10 to 12 °C. For current density of 2 A/mm^2 the heat caused by solar radiation does not exceed 3 to 5 °C. It is noted that in temperate latitudes the solar energy can increase the temperature of the wire operated in the range of permissible temperatures by 2 to 3 °C. In southern latitudes with an ambient temperature of 45 °C in clear weather, heating of the wire by solar radiation can reach 15 or 16 ° C. A more significant increase in the wire temperature in clear weather from exposure to solar radiation (up to 22.5 °C) is noted in the research of OAO Nauchno-Issledovatelsky Institut Electroenergetiki (VNIIE), a publicly held company under the laws of the Russian Federation [16]. The paper [16] indicates that solar radiation heating of the wire can be ignored in winter. Nevertheless, as modern research shows, the solar radiation power at the receiving platform at different angles and in the winter months can be of the same order as the radiation in the summer months.

Heat balance equations used

The above results were obtained in studies of traditional AS wires. This paper presents studies of modern high-temperature and self-supporting insulated wires of overhead power lines. The temperature of an insulated wire in a steady-state regime can be found based on the heat balance equation per unit length of the power line [17].

(1)
$$\Delta P = d_{\mathrm{wr}} \cdot \Big[\pi\alpha_{\mathrm{frc}} \left(\Theta_{\mathrm{out}} - \Theta_{\mathrm{amb}} \right) + \\ + \pi\varepsilon_{\mathrm{sur}} C_0 \left(T_{\mathrm{out}}^4 - T_{\mathrm{amb}}^4 \right) - A_s q_{\mathrm{sol}} \Big],$$

where ΔP are the real-power losses in the wire per unit length at a temperature of Θ_{wr}; d_{wr} is the wire diameter; α_{frc} is the forced convection heat transfer coefficient; Θ_{out} and Θ_{amb} respectively are the temperature of the wire outer surface and ambient temperature, °C; $\varepsilon_{\mathrm{sur}}$ is the emissivity factor of the wire surface for infrared radiation; C_0 = 5,67·10^{-8} W/(m^2·K^4) is the black body radiation constant; T_{out} and T_{amb} are respectively the absolute wire surface temperature and ambient temperature; A_s is the absorptivity of the wire surface to solar radiation; and q_{sol} is the solar radiation flux density to the wire.

The formulas [17, 18] are used to determine α_{frc}, S_{ins}, q_{sol}:

(2)
$$\alpha_{\mathrm{frc}} = 0,044 \frac{k_V \left(P_{\mathrm{atm}} V \right)^{0,6}}{\left(T_{\mathrm{amb}} d_{\mathrm{wr}} \right)^{0,4}};$$

(3)
$$S_{\mathrm{ins}} = \frac{1}{2\pi\lambda_{\mathrm{ins}}} \ln\left(\frac{d_{\mathrm{wr}}}{d_{\mathrm{c}}} \right);$$

(4)
$$q_{\mathrm{sol}} = k_{\mathrm{sh}} q_{swr} \sin\varphi_s + \pi q_{sdiff},$$

where k_{V} is the wind attack angle coefficient; P_{atm} is the atmospheric pressure; V is the wind speed; S_{ins} is the thermal resistance of insulation; λ_{ins} is the coefficient of insulation thermal conductivity; d_{c} is the diameter of conductor wire; k_{sh} is the coefficient of line section shading; $q_{s\mathrm{wr}}$ is the flux density of direct solar radiation on the surface perpendicular to sunlight; φ_s is the angle between the wire axis and the direction of sunlight; $q_{s\mathrm{diff}}$ is the flux density of diffused solar radiation.

Direct solar radiation varies throughout the year and during the day, so half the value of solar radiation on the earth's surface was used to account for the effects of solar radiation. The maximum value of direct solar radiation is estimated at 1000 W / m^2 . The annual and daily change also occurs for diffused radiation. An average value of 100 W / m^2 based on the obtained data is used for calculations. The shading factor k_{sh} is taken to account for the length of the line that is on average illuminated by the sun during the daytime. Since, as a rule, most electric power lines are operated far from high structures, the k_{sh} value is assumed to be 1. For 10 kV lines, the k_{sh} can be less due to the proximity of utility systems. For 110 kV lines with high supports, it is permissible to increase the k_{sh}.

In actual use, the angle φ_s is determined by the average azimuth of the wire and the latitude. In this paper, the maximum value of φ_s = 90° is assumed, which is observed at noon when the wire is positioned from West to East.

The value ΔP is determined by the relations:

(5)
$$\Delta P = \frac{\Delta P_0\left(1+\alpha\Theta_{out}\right)}{1-\alpha\Delta P_0 S_{ins}} = \Delta P_0'\left(1+\alpha\Theta_{out}\right) = \Delta P_0\left(1+\alpha\Theta_{wr}\right),$$

where $\Delta P_0 = I^2 r_0$ is the real-power losses in the wire per unit length at the temperature of 0°C; I is the current in the wire; r_0 is the in -length ohmic resistance at the temperature of 0 °C; α is the temperature coefficient of resistance; Θ_{wr} is the wire temperature.

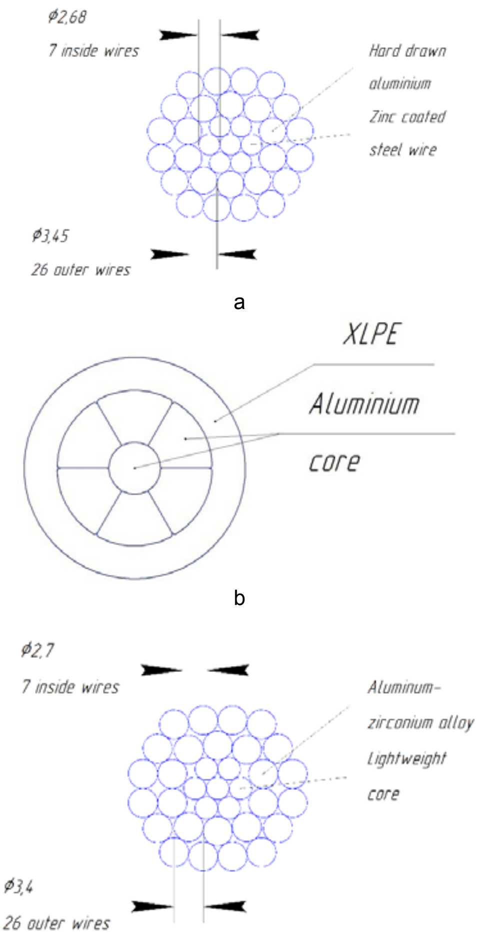


Fig.1. Arrangements of the selected wires:
a – ACSR-240/40 (DIN 48.204); b – PAS-W 1×95; c – ACCR-470-T16

Equation (1) is obtained assuming that the temperature gradient inside the wire core is equal to zero, i.e. grad $\Theta_{wr} = 0$. From this condition we write

(6)
$$\Theta_{wr} = \Theta_{out} + \Delta P \cdot S_{ins} = \frac{\Theta_{out} + \Delta P_0 S_{ins}}{1-\alpha\Delta P_0 S_{ins}}.$$

The temperature of the non-insulated wire and the real-power losses can be conducted on the basis of 1 at $S_{ins} = 0$. In this case we obtain

(7)
$$\Delta P_0\left(1+\alpha\Theta_{wr}\right) = d_{wr}\left[\pi\alpha_{frc}\left(\Theta_{wr}-\Theta_{amb}\right) + \pi\varepsilon_{sur}C_0\left(T_{wr}^4 - T_{amb}^4\right) - A_s q_{sol}\right].$$

Study of the influence of solar radiation on wires

Relations (1) – (7) were used to study the behavior of three types of wires:

– non-insulated wires ACSR-240/40;
– self-supporting insulated wires PAS-W 1×95;
– high-temperature non-insulated wires ACCR-470-T16.

The arrangements of the wires selected for the numerical experiment (table 1) are shown in fig. 1.

Table 1. Conditions of the numerical experiment

Name and designation of the parameter	Numerical value		
	ACCR-470-T16 [20]	PAS-W 1×95	ACSR-240/40 DIN 48.204
Ambient temperature Θ_{amb}, °C	-20	-20	-20
Permissible temperature Θ_{prm}, °C	210	90	80
Thermal conductivity coefficient of insulation λ_{ins}, W/(m·°C)	–	0.4	–
Reference linear ohmic resistance at 20 °C r_{20} or at 25 °C (for the wire ACCR) r_{25}, Ohm / km	0.1181	0.363	0.1188
Atmospheric pressure P_{atm}, Pa	100000		
Wind speed V, m / s	1		
Coefficient of the wind attack angle k_V	1		
Temperature coefficient of resistance α, °C^{-1}	0.0043		
Wire diameter d_{wr}, m	0.0216	0.0161	0.0219
Diameter of the conducting wire core d_c, m	0.0216	0.0113	0.0219
Density of direct solar radiation flow to the surface perpendicular to the sunlight q_{swr}, W/m^2	500		
Diffused solar radiation flux density q_{sdiff}, W / m^2	100		
Shading factor k_{sh} of line sections	1		
Angle between the wire axis and the direction of the sunlight φ_s	π/2		
Emissivity coefficient for the surface of the wire ε_{sur}	0.6	0.8	0.6
Absorption capacity of the wire surface for solar radiation A_s	0.6	0.9	0.6

Tables 2, 3, 4 and fig.s 2, 3, 4 represent various aspects of studying real-power losses and temperature losses for the specified types of overhead line wires, with or without solar radiation.

The ambient temperature is assumed to be -20 °C (tables 2, 3, and 4).

The notation shown in tables 2, 3, and 4 correspond to the following formulas

(8)
$$\Delta\Theta_{wr} = \Theta_{wr.s} - \Theta_{wr};$$

(9)
$$\Delta\Theta = \Theta_{out.s} - \Theta_{wr.s};$$

(10) $$\varepsilon_{\Delta P}=\frac{\Delta P_{\rm dif}}{\Delta P}\cdot 100\ \%;$$

(11) $$\Delta P_{\rm dif}=\Delta P_{\rm s}-\Delta P;$$

(12) $$\Delta\Theta_{\rm out}=\Theta_{\rm out.s}-\Theta_{\rm out},$$

where $\Delta\Theta_{wr}$, $\Delta\Theta$, $\Delta\Theta_{out}$ are temperature differences corresponding to the formulas (8), (9), and (12); ΔP_p and $\varepsilon_{\Delta P}$ are the absolute and relative differences in real power.

The "s" index in the formulas indicates solar radiation taken into account.

The nature of the graphs in fig. 2 indicates, on the one hand, the excess of the real power and temperature for the wire ACSR-240/40 in the case of solar radiation. When the current density J changes, the ranges of excess real power and temperature are from 0.442 to 13.366 kW/km and from 6.354 to 7.763 °C, respectively (table 2). On the other hand, this excess is not very large. The maximum relative excess of $\varepsilon_{\Delta P}$ is 2.98 %. The maximum core temperature excess is 7.763 °C.

A special feature of the graph is the increase in the difference between the losses of the ΔP_{dif} and the temperature difference $\Delta\Theta_{wr}$ of the wire with an increase in the current density (fig. 2). This feature can be explained as follows.

Table 2. Results of the numerical experiment for the wire ACSR-240/40 at $I_{calc\ prm}$ = 1104.6 A

I, p.u.	I, A	Current density J, A/mm^2	Excluding solar radiation		Including solar radiation		$\Delta\Theta_{wr.}$, °C	ΔP_{dif}, kW/km	$\varepsilon_{\Delta P}$, %
			Θ_{wr}, °C	ΔP, kW/km	$\Theta_{wr.s}$, °C	ΔP_s, kW/km			
0	0.0	0.00	-20.000	0.000	-13.646	0.000	6.354	0.000	0
0.2	220.9	0.92	-17.056	14.841	-10.635	15.284	6.421	0.442	2.98
0.4	441.8	1.84	-7.780	61.921	-1.159	63.745	6.621	1.824	2.95
0.6	662.7	2.76	9.285	149.900	16.240	154.211	6.955	4.311	2.88
0.8	883.7	3.68	36.993	297.019	44.381	305.160	7.388	8.141	2.74
1	1104.6	4.60	80.000	538.140	87.763	551.505	7.763	13.366	2.48

Table 3. Numerical experiment results of the wire PAS-W 1×95 with $I_{calc\ prm}$ = 544.81 A

I, p.u.	I, A	Current density, J, A/mm^2	Excluding solar radiation			Including solar radiation			$\Delta\Theta_{wr}$, °C	ΔP_{dif}, kW/km	$\varepsilon_{\Delta P}$, %
			Θ_{out}, °C	$\Theta_{wr.t}$, °C	ΔP, kW/km	$\Theta_{out.s}$, °C	$\Theta_{wr.s}$, °C	ΔP_s, kW/km			
0	0.00	0.00	-20	-20.00	0.000	-11.72	-11.72	0.000	8.279	0.000	0
0.2	108.96	1.15	-17.41	-16.89	11.041	-9.057	-8.519	11.469	8.371	0.429	3.88
0.4	217.92	2.29	-9.22	-7.047	46.179	-0.647	1.604	47.951	8.651	1.772	3.84
0.6	326.89	3.44	5.96	11.239	112.328	14.895	20.367	116.533	9.128	4.206	3.74
0.8	435.85	4.59	30.94	41.479	224.464	40.340	51.255	232.471	9.776	8.008	3.57
1	544.81	5.73	70.64	90.024	412.855	80.439	100.450	426.198	10.425	13.343	3.23

Table 4. Numerical experiment results for the wire ACCR-470-T16 with $I_{calc\ prm}$ = 1512.7 A

I, p.u.	I, A	Current density J, J, A/mm^2	Excluding solar radiation		Including solar radiation		$\Delta\Theta_{wr.}$, °C	ΔP_{dif}, kW/km	$\varepsilon_{\Delta P}$, %
			Θ_{wr}, °C	ΔP, kW/km	$\Theta_{wr.s}$, °C	ΔP_s, kW/km			
0	0.0	0.00	-20.000	0.000	-13.677	0.000	6.323	0.000	0
0.2	302.5	1.09	-14.514	27.455	-8.068	28.267	6.445	0.812	2.96
0.4	605.1	2.18	3.517	118.902	10.332	122.334	6.815	3.432	2.89
0.6	907.6	3.28	39.606	308.426	46.994	316.798	7.388	8.372	2.71
0.8	1210.2	4.37	104.850	679.757	112.631	695.432	7.781	15.675	2.31
1	1512.7	5.46	210.000	1393.118	216.905	1414.855	6.905	21.737	1.56

Any increase in the temperature of the wire, regardless of its cause, leads to an increase in real-power losses (heat generation) due to an increase in resistance. As a result, there is even greater increase in temperature. Thus, there is a positive feedback, which is stronger when the current density is higher (as the losses increase by 1 degree). In other words, at high currents any heating enhances itself to a greater extent than at low currents. In this case, heating caused by solar radiation plays the role of additional heating.

For the wire PAS-W in general we have a similar picture (fig. 3a, b). The changes relate to a slight quantitative increase in $\Delta\Theta_{wr}$, ΔP_{dif}, $\varepsilon_{\Delta P}$. The maximum value for $\Delta\Theta_{wr}$ is 10.425 °C and for ΔP_p it is 13.343 kW/km, and for $\varepsilon_{\Delta P}$ it is 3.88 % (table 3).

The value $\varepsilon_{\Delta P}$ for all the wires under consideration is close to 4 %. The fact is shown in the graph in fig. 4b. At the same time, differences in the values of permissible currents and ambient temperatures cause certain differences in the quantitative changes in the values ΔP_s. The permissible current I_{prm} for the non-insulated wire ACSR in the case of forced convection, based on equation (7), is proposed to be determined by the formula:

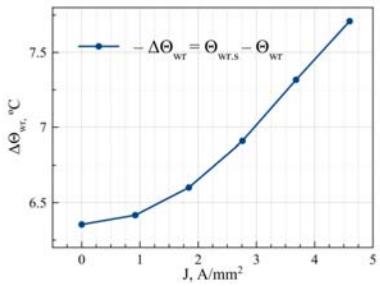
(13) $$I_{ad}=\sqrt{\frac{d_{\rm wr}\left[\pi\alpha_{\rm frc}\left(\Theta_{\rm ad}-\Theta_{\rm amb}\right)+\pi\varepsilon_{sur}C_0\left(T_{\rm ad}^4-T_{\rm amb}^4\right)\right]}{r_0\left(1+\alpha\Theta_{\rm wr}\right)}}.$$

Insulation in the wire PAS-W makes it possible to increase the number of parameters under study. Various aspects of the study are shown in fig. 3. All the dependencies have a corresponding physical interpretation.

In particular, in fig. 3b, the discrepancy increase of $\Theta_{wr\ s}$ and $\Theta_{out\ s}$ with increasing current density corresponds to equation (6).

Table 4 and fig.s 4a and 4b show the change trends of $\Delta\Theta_{wr}$ and ΔP_{dif} for the wires ACSR-470-T16 and ACSR-240/40 corresponding to the change trends for the wire PAS-W (I_{prm} = 544.81 A). The calculations with the AC wires (the analog of ACSR) and СИП-3 (the analog of PAS-W) manufactured in Russia showed almost complete identity of the graphs in fig.s 2, 3 and 4 in terms of the form and parameter values.

a



b

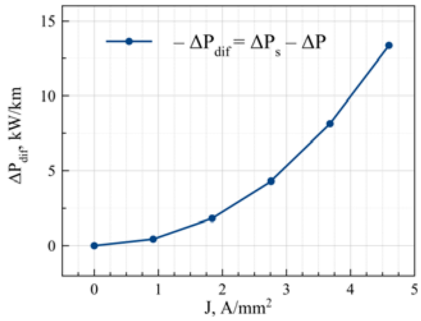
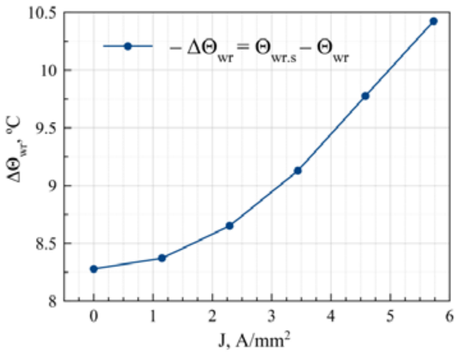


Fig.2. Research results of the wire ACSR-240/40 at $I_{calc\ prm}$ = 1104.6 A, depending on the current density: a is the temperature difference between $\Delta\Theta_{wr}$; b is the difference of real-power losses ΔP_{dif}

a



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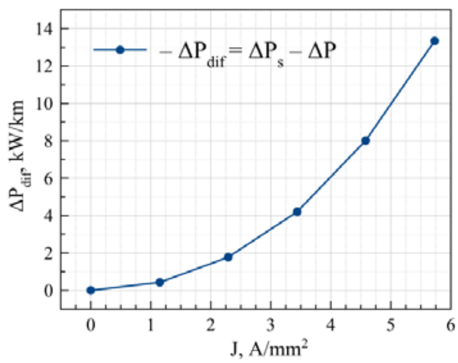

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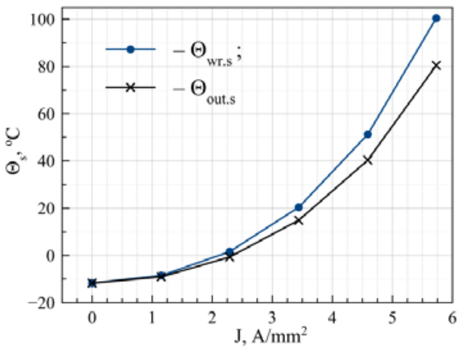


d

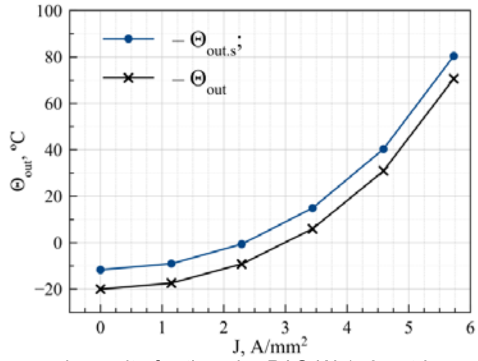
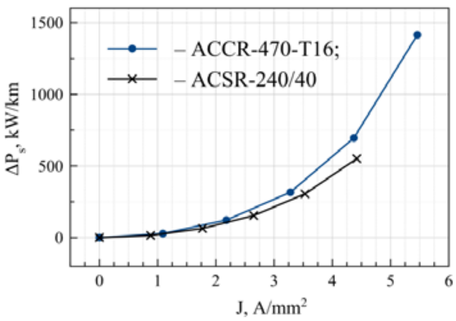


Fig.3. Research results for the wire PAS-W 1×95 at $I_{calc\ prm}$= 544.81 A, depending on the current density: a is the temperature difference between $\Delta\Theta_{wr}$; b is the difference of real-power losses ΔP_{dif}; c is the core temperatures $\Theta_{wr.s}$ and wire surface $\Theta_{out.s}$; d is the wire surface temperatures Θ_{out} and $\Theta_{out.s}$

a



b

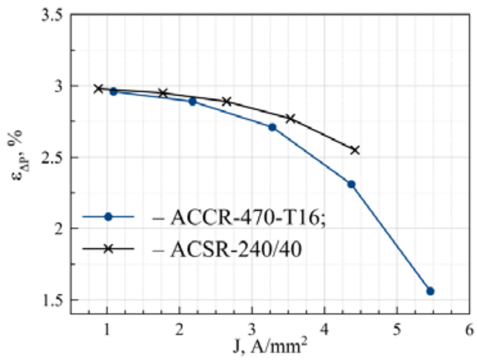


Fig.4. Research results for the wire ACCR-470-T16 and ACSR-240/40 (I_{prm}=1104.6 A) depending on the current density: a is the real-power losses taking into account solar radiation ΔP_s; b is the relative differences of real power $\varepsilon_{\Delta P}$

The comparison for the ambient temperature of +35 °C is given in table 5. The relative error is insignificant and it is 5.052 %.

Table 5. Comparison of the calculated values of the permissible current for the wire ACSR-240/40 with the permissible current calculated according to the catalog [19] at the ambient temperature Θ_{amb} = +35 °C and the wire temperature Θ_{amb} = +80 °C, the wind speed: V = 0.6 m / s, including solar radiation

Ambient temperature Θ_{amb}, °C	Permissible current, A		Relative error
	Catalogue, I_{prm2}	Proposed method, I_{ad3}	$\varepsilon_1 = \left\lvert \frac{I_{prm2} - I_{ad3}}{I_{prm2}} \right\rvert \cdot 100\,\%$
+35	645	612.413	5.052

Conclusion

The following conclusions can be drawn from the research.

1. For the types of wires and ambient temperature values considered in this paper, solar radiation taken into account leads to an increase in real-power losses by up to 3.88%. The maximum increase corresponds to the wire PAS-W 1×95 at a current of 32% of the permissible one. The relative differences in the real-power losses calculated with or without solar radiation are slightly reduced when the current load increases. However, the same differences in kW/km, conversely, increase.

2. As the current density increases, the difference in wire temperatures calculated with or without solar radiation generally increase. The maximum increase in the temperature difference is 10.425 °C and corresponds to the wire PAS-W.

3. For the standard ACSR-240/40 wire, a high coincidence of permissible current calculation data according to the proposed method with the value of the permissible current from the catalogue [19] was determined. The relative error does not exceed 5.052 %.

4. The developed method is applicable not only for standard non-insulated ACSR wires, but also for expanded capacity wires and self-supporting insulated wires.

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