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CURRENT-TEMPERATURE ANALYSIS OF THE AMPACITY OF OVERHEAD CONDUCTORS DEPENDING ON APPLIED STANDARDS

ANALIZA TOKOVNO-TEMPERATURNE PREOBREMENLJIVOSTI VODNIKOV DALJNOVODOV GLEDE NA UPORABLJENE STANDARDE

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Abstract

The opening of the electricity market is accompanied by new market participants whose requirements need to be fulfilled in order for the electricity market to function. To do so, transmission capacity is of significant importance. As the building of new overhead lines is an expensive and long-term investment, increasing the transmission capacities of existing lines is an unavoidable necessity. The transmission capacity of overhead power lines is commonly determined by limitations on the conductor's temperature, characterized by its ampacity. The conductor's temperature, and therefore the ampacity, is dependent on weather conditions. This fact enables increasing the transmission capacity according to calculations based on current weather conditions and forecasts, as opposed to static and conservative values.

This paper discusses the application of different standards and comparison of results for transmission capacity value, with particular reference to Croatian legislation on transmission overhead power lines. Calculation of sensitivity on input parameters is also examined because of the changes in the weather that change transmission capacity. As an extreme case of unfavourable weather

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conditions, an example is given of transmission capacity value trends during the hottest recorded day Croatia. The conclusion is that increases of the transmission capacity on particular power lines is possible but, for the safe and secure operation of the transmission grid, a seasonal regime of operation or ampacity zones depending on the time of the year could be made.

Povzetek

Odpiranje trga z električno energijo spremlja vstop novih udeležencev na trg, kateri morajo izpolniti določene zahteve, da trg z električno energijo lahko nemoteno deluje ob upoštevanju prenosne zmogljivosti prenosnega omrežja. Gradnja novih daljnovodov je finančno zahtevna ter predstavlja dolgoročne naložbe in je žal neizogibna zaradi želenega povečanja prenosnih zmogljivosti obstoječih daljnovodov. Maksimalna tokovna zmogljivost in temperatura vodnikov omejuje zmogljivost prenosa daljnovodov. To dejstvo omogoča povečati prenosno zmogljivost v skladu z izračuni, ki temeljijo na trenutnih vremenskih razmerah in napovedih, v nasprotju s statičnimi in klasičnimi vrednostmi.

Ta članek obravnava uporabo različnih standardov in primerja rezultate vrednosti prenosnih zmogljivosti prenosnih daljnovodov z upoštevanjem hrvaške zakonodaje. Analiziran je vremenski vpliv na vhodne parametre, kar vpliva na prenosne zmogljivosti in posledično na občutljivost izračuna. Kot ekstremni primer neugodnega vremenskega vpliva je v analizi zajet tudi najbolj vroč dan na območju hrvaškega prenosnega sistema. V zaključku dela je predstavljeno, da je možno povečati zmogljivosti prenosnega omrežja oziroma posameznih daljnovodov, vendar za varno in zanesljivo obratovanje omrežja je potrebno upoštevati sezonski režim delovanja.

1 INTRODUCTION

The transmission capacity of electric grid elements is significantly defined by deterministic safety criteria. Therefore, certain categories of failures or breakdowns are of great importance for the assessment of an electric grid and electric power system safety. If a physical quantity (allowed current, voltage, etc.) exceeds the defined and allowed range of values in the case of failure, the situation before the fault is considered to be unsafe. According to the safety criteria, the grid configuration must be designed in such a manner that it is able to ensure, in all operating conditions, that the failure of any power line does not lead to operational restrictions of its own and/or neighboring regulation areas. For the same reason, regulations for power lines treat and determine the highest ampacity of overhead conductors in individual systems.

From that, the timely determination of the available transmission capacity must follow, as is the most urgent task to be perform in order to increase both the safety and efficiency of the electricity system. Due to a significant number of cases in which the transmission capacity is determined by the highest allowed conductor temperature, such determination or calculation of the conductor temperature during operation is becoming increasingly important. Therefore, the conductor temperature values are calculated with regard to regulations and all factors that affect heating and cooling. Specific research is conducted on the mathematical impact of each factor on the determination of the conductor temperature calculation.

2 VALID STANDARDS IN CROATIA FOR CALCULATION OF AMPACITY IN OVERHEAD CONDUCTOR

Designing overhead power lines in Croatia is subjected to the Ordinance of technical standards for the construction of overhead power lines of nominal voltage from 1 kV to 400 kV (Croatian Official Gazette (COG) 53/91, 24/97). The valid ordinance is taken from the Official Journal of SFRY 65/88 in which the conductors and protecting wires are calculated for a range of temperatures from -20°C minimum to +40°C maximum, and for the temperature at which there is an additional load, i.e. -5°C. Article 16 states that the cross section of the conductor lines must be large enough that the overall temperature of the conductor due to the heating from the current does not exceed +80°C, whereby the calculation is conducted with an ambient temperature of +40°C. The article remains unchanged, apart the amendment in 1997 for classic conductor ropes, while for special conductors it allows exceeding the earlier specified conductor temperature if there is proven mechanical stability for a specific conductor. The final result of the maximum conductor temperature corresponds to the most adverse weather conditions, i.e. a small or negligible influence of wind (up to 0.6 m/s) and continuous ambient temperature of +40°C. The value of ampacity determined by this method, in most cases, even in the summer under maximum temperatures, remains below the possible ampacity limit with regard to the temperature limit and regulated safety heights, COG No. 24/97, [1].

3 CALCULATION OF TEMPERATURE ACCORDING TO THE IEEE STD 738-2006

Calculation of the temperature of bare, non-insulated overhead power lines is made with various methods that serve for the calculation of heat transfer and allowed current load of transmission power lines. The mathematical basis of the calculation used is the House and Tuttle method altered and adjusted according to the ECAR (East Central Area Reliability). The method takes into account all the relevant weather factors (influence of the sun and wind) without simplifications, which are made in some other calculations, IEEE [2].

The conductor temperature at a specific location is a function of more variables that have different impacts on the calculation. In the first place, there are weather conditions and their variability in space and time. Other important factors are solar flux, power line orientation in relation to the position of the sun and the direction of the wind motion, the type of the terrain (hilly, forested, etc.), cross-section and the percentage of aluminum in the cross-section, characteristics of materials including steel core, conductor geometry and 'air pockets', current, connected equipment, the density and viscosity of air, surface and external conditions (coefficient of emission and absorption) and corrosion, IEEE [3].

Potentially the greatest mistake possible in the temperature calculation involves a variable that takes into account direction and wind motion. This is because the wind motion is subjected to frequent changes. In the upper atmosphere, wind motion is relatively laminar, but closer to the surface, due to the influence of the terrain and the thermal effects, the motion of the wind becomes turbulent. Therefore, it is necessary to distinguish the still air flow from the turbulent air flow. The House and Tuttle method uses two different equations for forced convection or heat transfer with large air flow. Since the turbulence begins at a certain wind speeds and reaches its peak at higher speeds, the transition from one curve to another is a curve, not a discontinuity. A single value is selected as a suitable value for the calculation of permissible conductor loads; the individual value of transfer results in a discontinuity of current, when this value is reached. Therefore, to avoid this discontinuity, which occurs in House and Tuttle method, ECAR makes a change from still air motion into forced, turbulent air flow at the point or place where the curves are the result from the crossing of two equations (4.1 and 4.2).

This method is primarily intended for calculating thermal values at a fixed state and transient occurrences, and conductor temperatures at fixed, constant weather conditions. In the given circumstances of widely available computers, the method for calculation bypasses certain simplifications, which can be recommended when speed or complexity of calculation, is of great importance. Weather conditions often vary along power lines; therefore, the temperature of the conductor varies from one section to another of the same power line. The proper evaluation and calculation of the conductor temperature via IEE Std 738-2006 should take into account local weather conditions along the sections of the power line.

3.1 Calculation at fixed (constant) state

If there is data available for the maximum temperature of a non-insulated, intertwined conductor (T_c) and weather parameters for constant (unchanging) conditions ($V_{w,}$ $T_{a,}$ etc.), it is possible to calculate heat losses due to convection and radiation (q_c and q_t), gain of heat by insolation (q_s) and conductor resistance $R(T_c)$ using the equations in the third chapter.

Corresponding conductor current (I), which produced this temperature under these weather conditions can be found from the heat balance equation of an unchanging state, according to Equation 3.1. While this calculation can be done for each conductor temperature and under all weather conditions, the maximum allowed temperature of the conductor (e.g. 75°C to 150°C) and moderate weather conditions (e.g. 0.6 m/s to 1.2 m/s wind speed, 30°C to 45°C in summer weather conditions) are often used to calculate the thermal values of conductors at a constant state.

$$q_c + q_r = q_s + I^2 \cdot R(T_c) \tag{3.1}$$

$$I = \sqrt{\frac{q_c+q_r+q_s}{R(T_c)}} \tag{3.2}$$

Since heat losses by radiation and convection are not linearly dependent on the conductor temperature, the heat balance equation (3.2) yields conductor temperature expressions for current and weather variables by iteration, i.e. by taking into account electrical current of the conductor:

a) Conductor temperature is assumed,

b) Corresponding heat losses are calculated,

c) Conductor current that generates this temperature is calculated according to Equation 3.2,

d) Calculated current is compared with given conductor current,

e) Conductor temperature is then increased or decreased, until the calculated current does not reach the set current.

3.2 Calculation at transient state

Thermal evaluation of a transient state is regularly calculated by repeating the previous calculations $T_c(t)$ in the range of I_f values, and then selecting I_f value, which causes the conductor temperature to reach its maximum value in a given time. The temperature of the overhead power line is constantly changing, in accordance with changes of the current and the weather conditions. It is assumed that the weather parameters (speed and direction of wind, ambient temperature, etc.) are not changed and that every change of current is limited by a gradual step change, from the initial current Ii to the final current If, as shown in Figure 3.1. Shortly before the step or gradual change of current ($t=0^-$), it is assumed that the conductor is in thermal equilibrium, i.e. that the sum of the heat produced by ohmic losses and heat of the sun is equal to the heat loss by convection and radiation, [10].

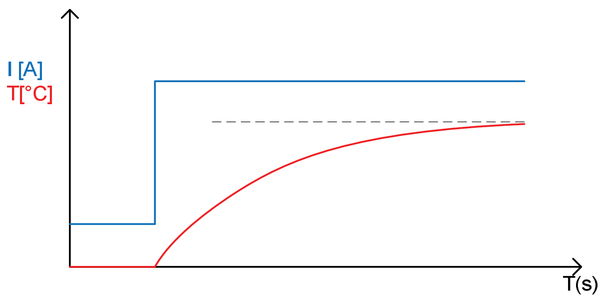

Figure 1: *Gradual, step change of the current from the initial to final current*

Immediately after the gradual, step change of the current ($t=0^+$), the conductor temperature is unchanged (as conductor resistance and heat losses due to convection and radiation), but there is an increase in heat generation due to ohmic losses. Therefore, at moment $t=0^+$ the conductor temperature begins to increase, the increase is given in the heat balance equation for transient state (3.3), as follows:

$$\frac{dT_c}{dt} = \frac{1}{mC_p}\left[R(T_c)\cdot I^2 + q_s - q_c - q_r\right] \tag{3.3}$$

that is

$$q_c + q_r + mC_p\frac{dT_c}{dt} = q_s + I^2\cdot R(T_c) \tag{3.4}$$

After a period of time, Δt, the conductor temperature increases with temperature change, ΔT_c. Increased conductor temperature leads to greater heat losses due to convection and radiation, and a greater ohmic resistance of the conductor due to increased heat generation. The conductor temperature continues to rise from Δt to $2\Delta t$, but with a smaller increase. After a large number of such time intervals, the conductor temperature approaches its final temperature of constant state, T_f.

The accuracy of the iterative calculation of the transient state requires that the set time of the step or gradual change is sufficiently short compared to the thermal time constant. It is always prudent to repeat the calculation with a shorter interval of change, in order to check the change of the calculated values.

4 EQUATIONS FOR CALCULATION OF THERMAL VALUES (STATES) AND RESISTANCE OF THE CONDUCTOR

Previously, equations for the thermal equilibrium of the fixed state and transient state from 3.1 to 3.4 have been given. Heat losses due to forced convection is described in Equation 4.1, which is used for weak winds, while Equation 4.2 is used for high-speed winds [9].

$$q_{c1} = \left[1{,}01 + 0{,}0372 \cdot \left(\frac{D \cdot \rho_f \cdot V_w}{\mu_f}\right)^{0.52}\right] \cdot k_f \cdot K_{angle} \cdot (T_c - T_a) \tag{4.1}$$

$$q_{c2} = \left[0{,}0119 \cdot \left(\frac{D \cdot \rho_f \cdot V_w}{\mu_f}\right)^{0.6} \cdot k_f \cdot K_{angle} \cdot (T_c - T_a)\right] \tag{4.2}$$

At any wind speed, the higher value of the two calculated heat losses due to convection is taken. The loss of heat due to transmission by the wind is multiplied by the wind movement factor, where φ is the angle between the wind direction and axis of the conductor (see Equation 3.3).

$$K_{angle} = 1.194 - cos\varphi + 0{,}194 \cdot \cos(2\varphi) + 0{,}368 \cdot \sin(2\varphi) \tag{4.3}$$

As an alternative, wind direction factor can be expressed as a function of the angle β between the wind direction and perpendicular to the conductor axis. This angle is the complement to φ; the wind direction factor then changes according to equation 4.4.

$$K_{angle} = 1 - 1.194 - sin\beta - 0{,}194 \cdot \cos(2\beta) + 0{,}368 \cdot \sin(2\beta) \tag{4.4}$$

When there is no air flow and the wind speed is 0 m/s, heat losses are the result of natural convection and are shown in equation 4.5.

$$q_{cn} = 0{,}0205 \cdot \rho_f^{0.5} \cdot D^{0.75}(T_c - T_a)^{1.25} \tag{4.5}$$

The aim is to prove that at low wind speeds cooling due to the convection should be calculated using the vector sum of the wind speed and the 'natural' wind speed. However, using only the higher heat losses is recommended due to forced and natural convection at low wind speed instead of their vector sum, because it is moderate, IEEE [2].

For forced and natural convection, density, ρ_f, viscosity, μ_f, and the thermal conductivity coefficient, k_f, of the air are taken from Table 2, or their values are calculated according to Equations 5.2 to 5.4, at T_{film}:

$$T_{film} = \frac{T_c + T_a}{2} \tag{4.6}$$

Heat losses due to radiation are given in Equation 4.7:

$$q_r = 0{,}0178 \cdot D \cdot \varepsilon \cdot \left[\left(\frac{T_c+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right] \quad (4.7)$$

Gain of heat due to insolation is calculated with Equation 4.8, for which the data is used from Tables 3, 4 and 5:

$$q_s = \alpha \cdot Q_s \cdot \sin(\theta) \cdot A' \quad (4.8)$$

where θ is:

$$\theta = arccos[\cos(H_c) \cdot \cos(Z_c - Z_l)] \quad (4.9)$$

The electrical resistance of a bare, intertwined conductor changes with frequency, average current density and temperature. The calculated values of resistance for most of the standard aluminium conductors are given for frequencies of 60 Hz, from 25°C to 75°C. These calculated values include a skin effect dependent on frequency, for all types of intertwined conductors, but for others, except for the ACSR (Aluminium Conductor Steel Reinforced); they do not include the correction of the effects of the magnetic core dependent on current density, which is significant for the ACSR conductors that have odd numbers of intertwined aluminium conductor layers, IEEE [2].

Accordingly, electrical resistance is calculated only as a function of conductor temperature; however, the entered values for resistance can be a function of frequency and current density. For example, the value of conductor temperature at high temperature, T_{high}, and low temperature, T_{low}, can be taken from table values, see IEEE [2]. Conductor resistance at any other temperature, T_c, is calculated via linear interpolation according to the equation (4.10).

$$R(T_c) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right] \cdot (T_c - T_{low}) + R(T_{low}) \quad (4.10)$$

Since, the specific resistance of most common metals used in intertwined conductors increases with temperature much faster than in a linear fashion, specific resistance calculated according to Equation 4.10 will be somewhat higher (it should be taken into account in the calculation) until the conductor temperature is between T_{low} and T_{high}. However, if the conductor temperature exceeds T_{high}, the calculated specific resistance will be somewhat lower. The conclusion is that the use of data for temperatures from 25°C to 75°C, the Alcan Cable Catalogue, [7], is appropriate for the rough calculation of thermal values for temperatures up to 175°C under constant and changing weather conditions, the approximate fault calculations could be made to the melting point of standard materials for conductors.

The heat capacity of the conductor is defined as a product of specific heat and mass per length unit. If the electrical conductor consists of more materials (e.g. ACSR line), then the heat capacities of the core and every external, surrounding intertwined waist are defined this way.

For the calculation of temperature, under transient state in time intervals from 5 to 30 minutes, the temperature of the conductor components remains approximately equal after the step increase of the current. The heat capacity of the conductor can be calculated as the sum of heat capacities of the components, according to the equation (4.11):

$$mC_p = \sum m_i C_{pi} \quad (4.11)$$

The heat capacity of the conductor is the sum of the products of the specific heat and mass per length unit of the component parts or components of the conductor. The mass per length unit of a conductor and the component parts or components of the conductor of all the usual aluminium and composite power lines is given in IEEE [2].

For example, with the 26/7 Drake ACSR conductor type, the weights of the steel core and external aluminium are 1.116 kg/m and 0.5119 kg/m, the total heat capacity at 25°C is as follows:

$$mC_p(Al) = 1.116\ kg/m \cdot 955 J/kg°C = 1066 J/m°C \quad (4.12)$$

$$mC_p(Steel) = 0.5519\ kg/m \cdot 476\ J/kg°C = 262.7 J/m°C \quad (4.13)$$

Specific heat levels of the materials for electrical conductors is given in Table 1.

Table 1: *Specific heat of wire materials for conductors*

Material	J/(kg°C)
Aluminum	955
Copper	423
Steel	476
Aluminum clad steel	534

5 EQUATIONS FOR PROPERTIES OF AIR, ANGLES AND ENERGY FLUX OF THE SUN

Equations are given for viscosity (5.1), solar altitude (5.4), and azimuth (5.6). Tables of typical values are given for illustrative purposes.

Dynamic viscosity is determined as follows:

$$\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4} \quad (5.1)$$

Density of air can be determined from Table 2 or it can be calculated as follows:

$$\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.0036 \cdot T_{film}} \quad (5.2)$$

Thermal conductivity can also be determined from the table or by equation:

$$k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2 \quad (5.3)$$

Table 2: *Viscosity, density and thermal conductivity of air*

Temperature T_{film}	Dynamic viscosity μ_f	Density of air – ρ_f (kg/m^3)				Thermal conductivity of air, k_f
°C	x10^6(Pas)	0 m	1000 m	2000 m	4000 m	W/(m°C)
0	17.2	1.293	1.147	1.014	0.785	0.0242
5	17.4	1.270	1.126	0.995	0.771	0.0246
10	17.6	1.247	1.106	0.978	0.757	0.0250
15	17.9	1.226	1.087	0.961	0.744	0.0254
20	18.1	1.205	1.068	0.944	0.731	0.0257
25	18.4	1.184	1.051	0.928	0.719	0.0261
30	18.6	1.165	1.033	0.913	0.707	0.0265
35	18.8	1.146	1.016	0.898	0.696	0.0269
40	19.1	1.127	1.000	0.884	0.685	0.0272
45	19.3	1.110	0.984	0.870	0.674	0.0276
50	19.5	1.093	0.969	0.856	0.663	0.0280
55	19.8	1.076	0.954	0.843	0.653	0.0283
60	20	1.060	0.940	0.831	0.643	0.0287
65	20.2	1.044	0.926	0.818	0.634	0.0291
70	20.4	1.029	0.912	0.806	0.625	0.0295
75	20.7	1.014	0.899	0.795	0.616	0.0298
80	20.9	1.000	0.887	0.783	0.607	0.0302
85	21.1	0.986	0.874	0.773	0.598	0.0306
90	21.3	0.972	0.862	0.762	0.590	0.0309
95	21.5	0.959	0.850	0.752	0.582	0.0313
100	21.7	0.946	0.839	0.741	0.574	0.0317

The altitude of the sun H_c in degrees (or radians) is given in Equation (5.4), in which independent variables are inverse trigonometric functions in degrees (or radians).

$$H_c = arcsin[\cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta)] \qquad (5.4)$$

The hour angle, ω, is the number of hours from the noon multiplied by 15° (e.g. 11 hours am is -15°, 2 hours pm is +30°). Solar declination δ, is as follows:

$$\delta = 23{,}458 \cdot sin\left[\frac{284+N}{365} \cdot 360\right] \qquad (5.5)$$

where the independent variable *sin* is given in degrees.

The equation is valid for all latitudes, both positive, and negative, i.e. the northern and southern hemispheres.

The solar azimuth Z_c (in degrees) is shown in Equation (5.6):

$$Z_c = C + \arctan(x) \tag{5.6}$$

where x is:

$$x = sin\left[\frac{\sin(\omega)}{\sin(Lat)\cdot\cos(\omega)-\cos(Lat)\cdot\tan(\delta)}\right] \tag{5.7}$$

The constant of the solar azimuth C (in degrees), is the function of hour angle ω, and the solar azimuth variable x, as shown in Table 3.

Table 3: *Constant of the solar azimuth C, as a function of hour angle, and the solar azimuth variable x*

Hour angle ω [°]	C if x>0°	C if x<0°
-180<ω<0	0	180
0<ω<180	180	360

Table 4: *Solar altitude H_c, and azimuth Z_c, at different latitudes for an annual peak, solar thermal input*

	Local sunny weather						
Latitude	10:00 h		noon		14:00 h		
(Degrees-North)	Hc	Zc	Hc	Zc	Hc	Zc	N
-80	32	33	33	180	32	327	350
-70	40	37	43	180	40	323	350
-60	48	43	53	180	48	317	350
-50	55	52	63	180	55	308	350
-40	60	66	73	180	60	294	350
-30	62	83	83	180	62	277	350
-20	62	96	90	180	62	264	20
-10	61	97	88	180	61	263	50
0	60	91	90	180	60	269	80
10	61	85	89	180	61	275	110
20	62	85	90	180	62	275	140
30	62	97	83	180	62	263	170
40	60	114	73	180	60	245	170
50	55	128	63	180	55	232	170
60	48	137	53	180	48	223	170
70	40	143	43	180	40	217	170
80	32	147	33	180	32	213	170

Table 5: *Total thermal flux, received by the surface at sea level*

Solar altitude degrees	Clear atmosphere	Industrial atmosphere
H_c (°)	Q_s (W/m²)	Q_s (W/m²)
5	234	136
10	433	240
15	583	328
20	693	422
25	770	502
30	829	571
35	877	619
40	913	662
45	941	694
50	969	727
60	1000	771
70	1020	809
80	1030	833
90	1040	849

6 COMPARATIVE ANALYSIS OF AMPACITY BY VALID CROATIAN STANDARDS AND IEEE STD 738-2006

Construction data for several typical types of ACSR conductors according to the ASTM (American Society for Testing and Materials) B232 standard are given in Table 6. Figure 2 displays compared ampacities of the table-listed ACSR types of conductors according to COG No. 24/97, [1], and IEEE, [2], for meteorological conditions on 7 May 2013 at 20:00.

Table 6: *Catalogue data for typical ACSR conductors for overhead power lines according to* Alcan Cable Catalogue [6]

Code name	Area and ratio of the cross section		Resistance		
	Nominal cross section [mm²]	Section ratio Al/Cu	DC resistance [Ω/km] at 20°C	AC resistance at 60 Hz [Ω/km]	
				at 25°C	at 75°C
Waxving	135.18	18/1	0.2113	0.2150	0.2580
Chickadee	201.41	18/1	0.1417	0.1450	0.1730
Hawk	241.69	26/7	0.1171	0.1200	0.1440
Swift	322.26	36/1	0.0876	0.0920	0.1130
Starling	362.54	26/7	0.0781	0.0800	0.0958
Drake	402.82	26/7	0.0702	0.0728	0.0793

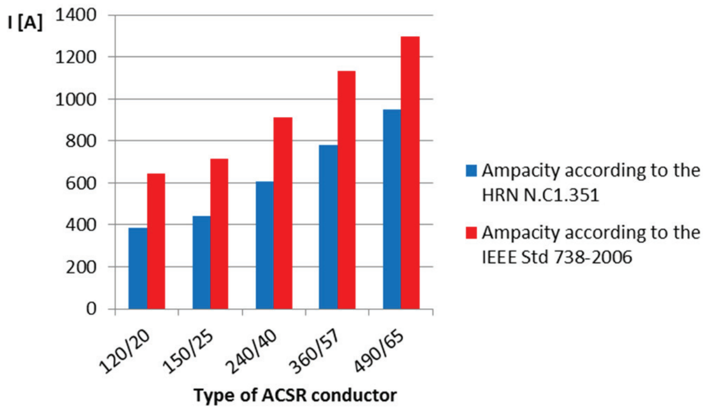

Figure 2: *Comparison of ampacities by applied standard on 7.5.2013 at 20:00 h*

Figure 2 displays the compared, calculated ampacities of the applied standard, COG No. 24/97, [1], (blue bars) and IEEE, [2] (red bars). The calculation is done for the relation between Zagreb and Osijek on 7 May 2013 at 20:00 when the ambient temperature was between 15°C and 20°C, wind speed around 2 m/s, the result of which was 30% higher ampacity of the ACSR line.

Table 7 gives the catalogue list of ACSR conductors' typical construction according to the HRN N.C1.351 standard with allowed continuous current, which is the result of a calculation with a temperature of 40°C and a wind speed of 0.6 m/s.

Table 7: *ACSR conductors, typical construction according to the* HRN N.C1.351, Technical Manual Končar, [7]

Nominal cross section [mm²]	Section ratio Al/Steel	Longitudinal resistance at 20°C [Ω/km]	Resistance at 80°C [Ω/km]	Allowed permanent current [A]
120/20	26/7	0.23740	0.2948	385
150/25	26/7	0.19390	0.2410	442
240/40	26/7	0.11880	0.1475	605
360/57	26/19	0.08014	0.0995	780
490/65	30/19	0.05924	0.0733	951

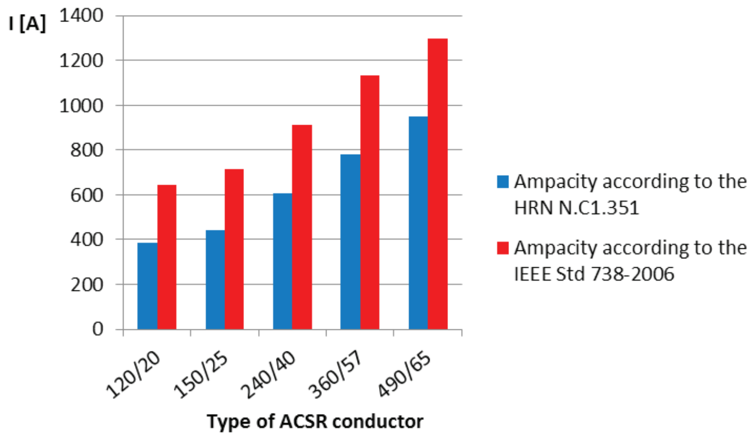

Figure 3: *Comparison of ampacities by applied standard on 7.5.2013 at 20 h*

Figure 3 shows the compared results of allowed ampacity depending on the applied standard, for typical constructions of ACSR conductors according to the HRN N.C1.351 standard. It can be seen that the ampacity in the case of IEEE Std 738 is 25% to 40% higher than the results according to the COG No. 24/97, [1].

In conclusion, it can be said that ACSR conductors are loaded under the limit most of the time. The ampacity that is considered as a standard is valid for a very short time period of the year. The most unfavourable day in 2012 was 6 August, on which the temperature reached 40°C throughout Croatia, but only between 10:00 and 17:00. This fact is significant because of the possibility for a particular power line to become overloaded for a definite time interval beyond the limits set by legislation, in order to meet the requirements of demanding market participants.

7 CALCULATION SENSITIVITY ON INPUT PARAMETERS

According to IEEE Std 738-2006, described in previous chapters, calculation of ampacity considering input parameters is (beside ambient temperature and the time of the day) is most sensitive when the speed and direction of the wind are taken into account. The accuracy of the method according to the applied standard has been the subject of discussion, but there were determined minimum deviations in regard to the actual situation, Strobach, Straumann, Franck, [4], and Lindberg, [5]. For example, the ACSR conductor, type 490/65 on the relation between Zagreb and Osijek is taken. In this account, the initial data of conductor characteristics, the location of the power line and the weather conditions of the meteorological stations are taken for 12 May 2013 at 13:00. The most unfavourable factor in the calculation is the analysis of wind motion. Fluctuations in air motions are continuous and constantly changing. Figure 4 shows the impact of the incident angle between the wind flow and power line direction on the final result of the maximum allowed current. An error that can be entered in the calculation is not significant if it is an angle between 70° and 90°. However, for angles up to 30°, errors can amount to 20% of the total allowed current value. The differences are more pronounced as the wind speed increases.

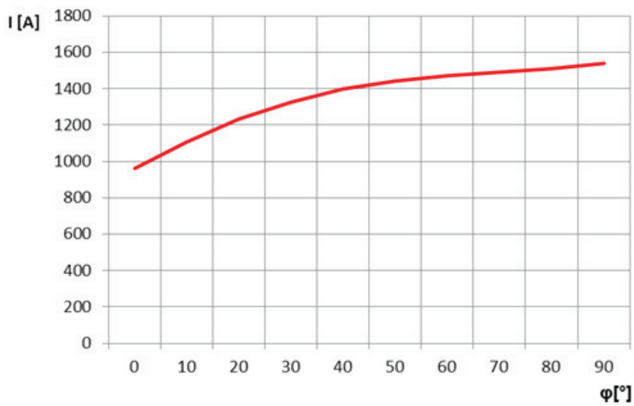

Figure 4*: The interdependence of the angle between the direction of the wind and the power line with ampacity*

It is practically impossible on the longer sections of the power line to define for every moment the angle between the direction of the wind in relation to the direction of the power line, except in the case of the network of meteorological stations along the route of the power line. In that case, the calculation must take into account the most unfavourable data, especially for long relations like the one between Zagreb and Osijek. While the weather conditions on individual sections can be ideal, there is only one section needed where conditions are such that the heat gain by insolation is maximum, and the wind flow is not present.

8 BORDERLINE CASE

The requirement that the maximum conductor temperature not exceed +80°C under constant ambient temperature of +40°C is set so that even in the summer the power line is not found to be at risk of excessive thermal stress causing deformation of material and illicit sag. As a reference example of such a case, a calculation on 6 August 2012 (according to the state hydro meteorological office the hottest day since systematic measurements began) can serve. Figure 5 shows compared ampacities according to the catalogue data from Table 8 for ACSR conductor type 490/65 and those according to calculation in the IEEE Std 738-2006. For the weather conditions that caused different results, especially significant is the impact of the wind and the time of the day. At the time of the highest temperature of 40.5°C at 17:00, ampacity was above catalogue value of 951 A, due to the time of the day when the solar radiation is not as intense as it is during the middle of the day. Moreover, regarding the data for 13:00, when the ampacity is above the catalogue value although it is at a time of intense solar radiation, such a result is a consequence of the wind speed and direction during that hour. Figure 5 gives data for the thermally most unfavourable time of the day, i.e. between 10:00 and 17:00. From Figure 5, it is also visible that during the engagement of the particular power line it is not safe to perform transmission, taking into consideration data acquired for each hour, because such result is subjected to frequent changes due to the changes of the input parameters. However, the operation regime can be scheduled on the principle of summer and winter periods, as well as the ampacity zones depending on the time of the year.

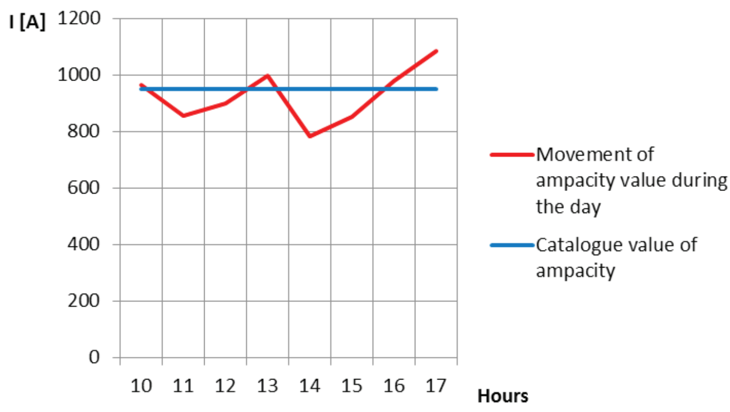

***Figure 5**: Value of ampacity during 6.8.2012.*

9 CONCLUSION

The purpose and the objective of the IEEE Std 738-2006 method is to show the impact on the method for the calculation of the relation between the current and the temperature in bare, non-insulated, overhead power lines. The temperature on the surface of the conductor is a function of current weather conditions, surface conditions of the conductor, the diameter of the conductor and the properties of conductor materials. This paper shows the calculation method for the current and the temperature relation of bare, overhead power lines under given weather conditions. In addition to the mathematical part, the sources of values that are needed to use when calculating are indicated. The method does not generate the list of actual relations between the current and allowed ampacity of a large number of conductors, but primarily provides a standard method for performing such calculations.

For the purpose of the method, it is assumed that the current is unchangeable and continuous for the entire time, or that it is gradually changing from the initial to the final value. It is also assumed that the weather conditions are continuous during the time interval used for the calculation.

An overview of the ampacity calculation for typical weather conditions according to the IEEE Std. 738-2006 and according to the valid legal regulations is given in Chapter 6. The compared figures give the sense of a set limit for ampacity that cannot be reached most of the year. The borderline case is when the values of ampacities approach each other are the hottest days, i.e. only in the limited period of time during the middle of the day in the hottest summer months.

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Nomenclature

A' [m²/m]	Projected area of conductor per unit length
C [degrees]	Solar azimuth constant
C_{pi} [J/kg oC]	Specific heat of i^{th} conductor material
D [mm]	Conductor diametar
H_c [degrees]	Altitude of sun
H_e [m]	Elevation of conductor above sea level
I [A]	Conductor current
I_i [A]	Initial current before step change

I_f [A]	Final current after step change
K_{angle}	Wind direction factor
K_{solar}	Solar altitude correction factor
k_f [W/m°C]	Thermal conductivity of air at temperatureT_{am}
Lat [degrees]	Degrees of latitude
mC_p [J/m°C]	Total heat capacity of conductor
m_i [kg/m]	Mass per unit length of i^{th} conductor material
N	Day of the year (21. january = 21, 12. february = 43, etc.)
q_{cn}, q_{c1}, q_{c2} [W/m]	Convected heat loss rate per unit length
q_r [W/m]	Radiated heat loss rate per unit length
q_s [W/m]	Heat gain rate from sun
Q_s [W/m²]	Total solar and sky radiated heat flux rate
$R(T_c)$ [Ω/m]	AC resistance of conductor at temperature T_c
T_a [°C]	Ambient air temperature
T_c [°C]	Conductor temperature
T_f [°C]	Conductor temperature many time constants after step increase
T_i [°C]	Conductor temperature before the step increase
T_{am} [°C]	$(T_c + T_a)/2$
T_{low} [°C]	Minimum conductor temperature for which ac resistance is specified
T_{high} [°C]	Maximum conductor temperature for which ac resistance is specified
V_w [m/s]	Speed of air stream at conductor
Z_c [degrees]	Azimuth of sun
Z_l [degrees]	Azimuth of power line
Δt [s]	Time step used in transient calculation
ΔT_C [°C]	Conductor temperature increment corresponding to time step
α	Solar absorptivity (0,23 do 0,91)
Δ [degrees]	Solar declination (od 0 do 90)
ε	Emissivity (0,23 do 0,91)
φ [degrees]	Angle between wind and axis of conductor
β [degrees]	Angle between wind and perpendicular to conductor axis
ρ_f [kg/m³]	Density of air
Θ [degrees]	Effective angle of incidence of the sun's rays
μ_f [Pas]	Dynamic viscosity of air
ω [degrees]	Hours from local sun noon times 15
χ	Solar azimuth variable