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INFLUENCE OF THE THERMAL CONVECTION CALCULATION ON THE AMPACITY TEMPERATURE OF OVERHEAD CONDUCTOR SUBJECT TO LOW SPEED WIND

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Abstract. *In this work, the stationary ampacity and surface temperature of a commercial electric cable ACSR Grosbeak are evaluated using three approaches, IEEE, CIGRE and Morgan, in the range of wind speeds 0-1 m / s. The objective is to verify the influence of thermal convection evaluation on the surface temperature and ampacity of the conductor. For this, the three methods were implemented in a EES program, meteorological parameters were fixed and the influences of speed and angle of attack of the wind and slope of the conductor were analyzed. The results show that the methods CIGRE, IEEE and Morgan are practically equivalent for wind speeds above 0.5 m / s and normal to the axis of the conductor. However, the maximum deviations between the calculated ampacities reach 16-19% for wind speeds below 0.5 m / s with an angle of attack of 10 degrees. Whereas most conservative average deviations of 7 and 9%, differences in the surface temperature of the conductor between 7 and 8.5 ° C were evaluated with respect to previously established design temperature. The results show also little influence of the conductor inclination on the ampacity calculation and a reduction between 25 and 30% in the cooling efficiency of the conductor for angle of attack of 10 degrees. Finally, this work points to the need of searching for more accurate and efficient methods of ampacity calculation for wind speeds between 0 and 0.5 m / s, where the mixed convection prevails, and also for more thermally efficient electric conductors.*

***Key words:* ampacity, thermal convection, electric conductor, surface temperature.**

1. INTRODUCTION

The ampacity expresses the ability to transport electrical current of a transmission line as a function of energy generated and dissipated by the conductor under the influence of certain meteorological parameters. Among these parameters, the wind speed is one of the most important for the dissipation of the generated energy. The power generated by the passage of current should be properly dissipated to prevent overheating of the conductor and guarantee the projected electrical current. Regions with low wind speed are unfavorable for transmission lines due to poor heat dissipation of the conductor by thermal convection to the environment. The ampacity of the project is determined, in Brazil, following the procedures of CIGRE WG 22-12 [1] published in the Journal Electra number 144 of October 1992 or the IEEE standard [2], based on the method of House and Tuttle modified by ECAR [3]. Schmidt [4] compare the two methods and concludes that the main differences are calculated in ampacities due to magnetic heating (0 to 3%) and the wind speed with an angle of incidence less than 10 degrees (about 10. Apart from that, states that two methods can be considered equivalent to determining the ampacity design of most transmission lines. However, these two standards require distinct criteria for calculating ampacities for low wind speeds, for which the natural convection or mixed prevails. IEEE states that the calculation of the power dissipation by convection to the environment is made considering the higher coefficient evaluated for natural and forced convection calculated by two equations, one for low speed and one for higher speeds, without establishing limits for each equation. On the other hand, CIGRE states that the calculation of heat loss by convection to wind speeds from 0 to 0.5 m / s is done considering the greater of the Nusselt numbers calculated a) considering forced convection with angle of incidence of the wind of 45% b) 55% of the value of the Nusselt for forced convection and angle of incidence of 90 ° c) Nusselt for natural convection. Low wind speeds generally occur at night and in regions of unfavorable topography and a possible overestimation of losses by convection in the project phase may cause an underestimation of the surface temperature of the conductor, and vice versa**.** Thus, conductors in transmission lines passing through regions of virtually stagnant air could be subject to greater demands thermomechanical [5]. Best practices recommend that the average temperature of a conductor does not exceed more than 10°C to the project temperature and the local maximum temperature does not exceed the design in over 20°C, in operations with nominal current [6]. The studies by Morgan [7, 8.9] emphasize the importance of natural convection

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and the mixed convection over the temperature of the conductors and establish a more detailed method for calculating the coefficients of natural and mixed convection including, for example, the influence of the angle between the cable and the horizontal**.** For calculating the mixed convection, Morgan [7] creates a fictitious effective Reynolds number, equaling the Nusselt number of the natural convection to the Nusselt number of forced convection. Corrections to the Nusselt number to take into account the wind direction relative to the axis of the conductor are also different in the three methods. In this work, the influence of these three methods of calculating the thermal convection is evaluated over an estimated ampacity and the steady surface temperature of a commercial electrical cable type ACSR, aluminum conductor steel reinforced, in the range of wind speeds from 0 to 1 m / s.

2. METHOD

The conductor used in this work is the Grosbeak, which has a core with outer diameter D = 25.16 mm and the diameter of the aluminum wires d = 3.97 mm. The other parameters used in the calculations were taken from Schmidt [4]:
Ambient temperature: 40 ° C
Latitude: 30
Azimuth of the Conductor: 90 th
Atmosphere: Clean
Solar heating: present
Diffuse solar radiation: ignored
Emissivity: 0.5
Absorptivity: 0.5
Elevation above sea level: 0 m
Type of ground surface: urban
Time: 11:00
Day of the year: June, 10
Conductor temperature: 100°C.

A preliminary analysis, considering the conductor Grosbeak with superficial temperature of 100°C in an environment at 40°C and 100 kPa, allows the following conclusions:

For wind speeds between 0 and 0.06 m/s or, in other words, the ambient air is nearly stagnant, the ratio Gr/Re^2, with Gr and Re being the Reynolds and Grashoff numbers, respectively, is greater than 10 so that the natural convection prevails [10].

a) For wind speeds between 0.02 and 0.6 m/s results the range $0.1 < Gr/Re^2 < 10$ and the mixed convection predominates.
b) For wind speeds above 0.6 m / s implies $Gr/Re2 < 0.1$ and therefore the forced convection predominates.

It is apparent, therefore, that especially for wind speeds between 0 and 0.6 m/s it is needed most rigorous calculation of heat loss by convection of the conductor**.** Importantly, each of the three methods analyzed here adopts a distinct approach to establish limits of influence of natural and forced convection, but none specifically uses the criterion Gr/Re^2.

An energy balance per meter of conductor, neglecting ferromagnetic ionization effects (corona) and evaporation results in [5, 11]:

$$P_j + P_s = P_c + P_r$$

Where:
$P_j = RI^2$ the thermal power generated in the conductor by Joule effect in W/m.
P_s the solar power incident on the surface of conductor W/m.
P_c the convective thermal power dissipated by the conductor in W/m.
P_r the radiative thermal power dissipated by the conductor in W/m.
R the electrical resistance of the conductor in ohms/m.
I the intensity of the current (ampacity) conductor in amperes.
The radiative power dissipated by the conductor has been established for all three methods as:

$$P_r = 5{,}67x10^{-8}\varepsilon\pi D(T_p^4 - T_\infty^4)$$

Where:
T_p the surface temperature of the cable in K.
T_∞ the considered temperature of the sky in K.

The IEEE standard considers smooth conductor in the calculation of heat dissipation by convection. In the methods of CIGRE and Morgan the conductor roughness will be considered and it is given by [7]:

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$$RR = \frac{d}{2 \cdot (D - d)}$$

The convection is considered as mixed at a range of speeds between 0 and 0.5 m/s for methods CIGRÉ and Morgan. The Power dissipated by convection and thermal radiation and received by solar irradiation were then evaluated for various wind conditions, applying the procedures described in GIGRÉ [1] IEEE [2] and Morgan [7,8,9].

To make easier the calculations, a program was developed in the software EES - Engineering Equation Solver applying the three methods. Thus, the ampacity can be determined given the surface temperature of the conductor. Alternatively, the surface temperature of the conductor can also be calculated given its ampacity. The other conditions were previously established.

Figure 1 shows a screen with the default program inputs, the cable temperature, the thermal powers and the ampacities calculated.

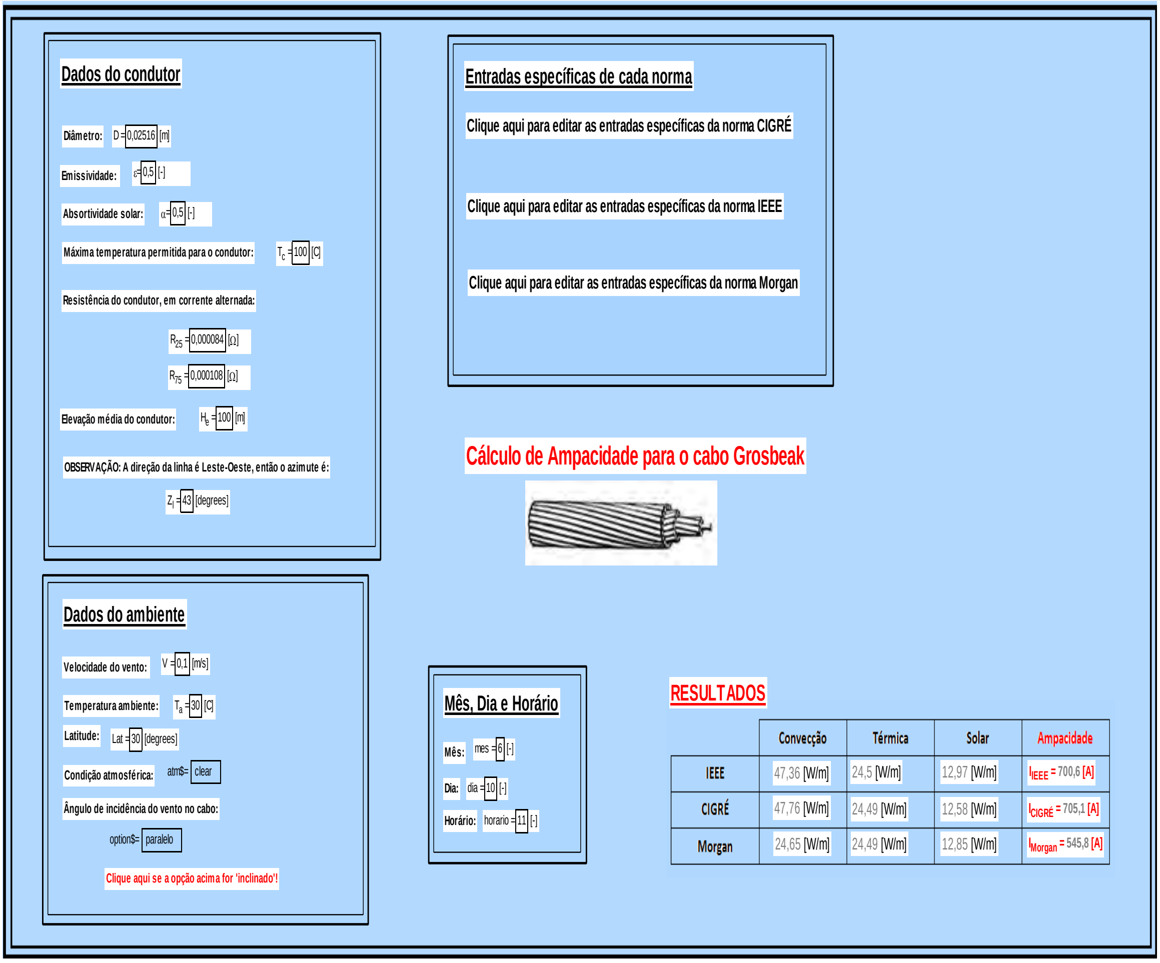

Figure 1. Screen reproduction of the program developed in EES to calculate ampacity.

3. RESULTS

Figure 2 shows the results of the ampacities calculated by the three methods for a wind speed normal to the axis of the conductor that has zero angles to the horizontal. The largest variances occur at speeds ranging from 0 to 0.5 m / s for methods Morgan and CIGRÉ**.** The maximum percentage deviation in this range is 52 amperes or 7.4%, taking as reference the values obtained with the Morgan standard**.** The method IEEE presents the average behavior between CIGRÉ and Morgan in this range and almost coincides with the Morgan method for speeds between 0.5 and 1 m/s. The maximum deviation between CIGRÉ and IEEE is 35 amperes or 4.8% and 29.1 amperes or 4.1% between Morgan and IEEE.

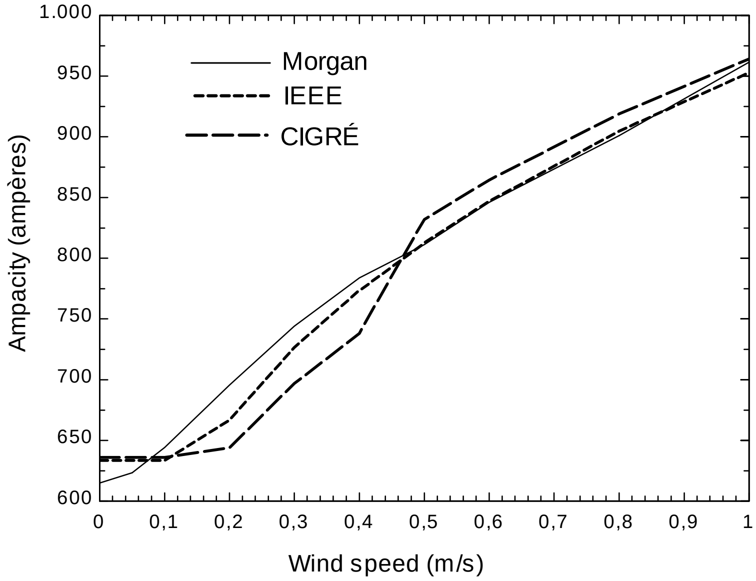

Figure 2. Ampacities calculated by the 3 methods versus wind speed normal to the conductor with surface temperature of 100°C.

The maximum deviation of 52 amperes was found for wind speed of 0.2 m/s and the reduction in the temperature of the conductor that would equate the Morgan ampacity to the CIGRE, operating at 100°C, would be 7°C.For wind normal to the conductor, the conductor's inclination to the horizontal has no influence on ampacities calculated in IEEE and CIGRÉ, but changes the values calculated by the Morgan method**.** In this case, the solar radiation incident on the conductor is a function of this inclination, and in addition, Morgan [7] proposes to replace D by D/cos (ζ), in which ζ is the angle between the conductor and the horizontal in the calculation of the Nusselt and Grashoff numbers in the thermal convection. For angles up to 20° between the conductor axis and the horizontal, the maximum deviation was 4% in wind speed equal to 0 m/s.

Figure 3 shows the results of the ampacities calculated by the three methods versus wind speed with an angle of 10 ° relative to the axis of the conductor that has zero angles to the horizontal. It is noticed that in this case, the methods CIGRÉ and Morgan overestimate the mixed convection for speeds up to 0.5 m/s relative to the method IEEE, recovering nearest values above this speed. This occurs because of two basic aspects: a) the IEEE method does not establish a transition speed between the mixed convection and forced convection as the methods CIGRÉ and Morgan and b) the IEEE method considers smooth conductor while CIGRÉ and Morgan methods include coefficients in the equations for calculation of forced and mixed convection defined by ranges of roughness, the angle of attack of the wind and of the Reynolds number. Schmidt [4] found deviations up to 10% between CIGRE and IEEE for angles of attack up to 10°, while the results of this study point to maximum deviation of 16%. Between Morgan and IEEE the maximum deviation was 19%. Above 0.5 m/s, the maximum deviations dropped to 2.3% and 11%, respectively.

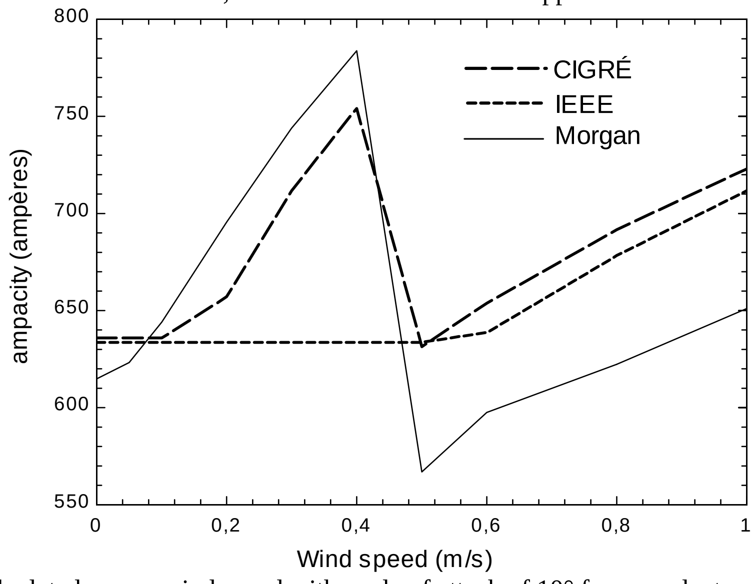

Figure 3. Ampacities calculated versus wind speed with angle of attack of 10° for a conductor with surface temperature of 100°C.

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Figure 4 shows the results of the ampacities calculated by the three methods for wind speed with an angle of 45° to the axis of the conductor that has zero angles to the horizontal. Note, in this case a large attenuation of the deviations from the previous case with angle of attack of 10 °. There is a good agreement between IEEE and CIGRE throughout the range of speeds with maximum deviation of 2.4%. The ampacities obtained from Morgan outweigh up to 52 amperes or 7.4% those calculated in CIGRÉ and up to 62 amperes or 8.9% those calculated in IEEE in the range of speeds from 0 to 0.4 m/s. Above this speed the results of the three methods converge with maximum deviation of about 2%. The maximum deviation of 62 amperes was found for wind speed of 0.2 m/s and the reduction in the temperature of the conductor that would match the Morgan ampacity to the IEEE ampacity with the conductor at 100°C was 8.5°C, to this wind speed.

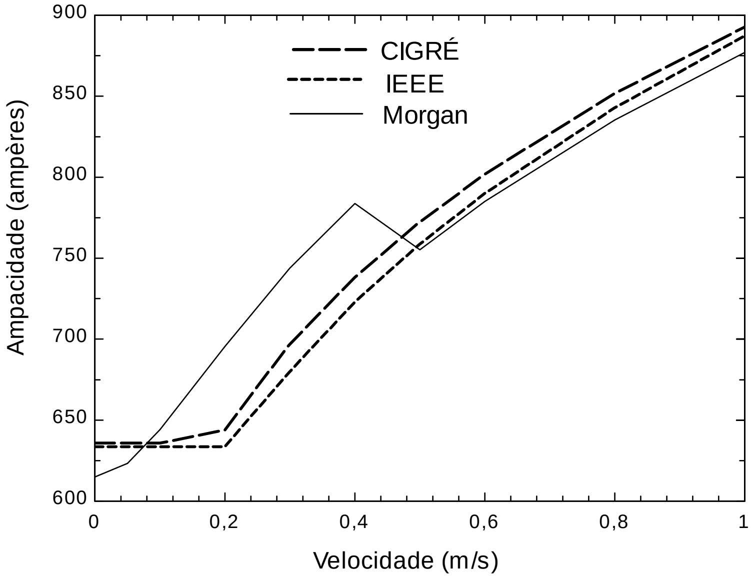

Figure 4. Ampacities calculated versus wind speed with angle of attack of 45° for a conductor with surface temperature of 100°C.

Considering only speeds above 0.5 m/s, the results of the ampacity for the IEEE method as a reference and defining a cooling efficiency percentage of the conductor given by $\eta_c = \left(1 - \frac{\Delta A}{A_n}\right) 100$, being A_n the ampacity for wind direction normal to the conductor and ΔA the difference between this ampacity and that calculated for wind oblique to the conductor, it is concluded η_c is between 70 and 75% for angle of attack equal to 10° and the order of 93% for 45° angle of attack. These results are in perfect agreement with the experimental results obtained in wind tunnel by Hall et al. [12].

Finally, it should be emphasized that the thermal solar radiation calculated with IEEE and CIGRÉ are almost equal with deviation of 0.14 W/m, with a greater difference between Morgan and IEEE of 1.8 W/m. However, these differences have little influence on the results obtained considering that the magnitude of the total thermal power dissipated by convection and radiation is 60 W/m.

4. CONCLUSIONS

A program developed in EES allowed the simultaneous calculation of ampacities in a ACSR Grosbeak conductor by three different methods: CIGRE, IEEE and Morgan**.** Meteorological parameters were fixed and the influences of speed, angle of attack of the wind and inclination of the conductor were analyzed. For wind speeds between 0 and 1 m/s and angles of attack of 10°, 45° and 90° the main conclusions are:

- For wind normal to the conductor axis, angle of attack of 90° the maximum deviation between the ampacities CIGRÉ and IEEE or IEEE and Morgan was 5%. Between Morgan and CIGRÉ a maximum deviation of 7.4% occurred at a speed of 0.2 m/s.
- To wind with angle of attack of 10°, the ampacities CIGRÉ and Morgan showed large fluctuations between 0 and 0.5 m/s. In this range, the maximum deviation between IEEE and CIGRÉ was 16% and 19% between Morgan and IEEE and also occurred at the speed of 0.2 m/s. Above 0.5 m/s, the maximum deviations fell respectively to 2.3% and 11%.
- To wind with angle of attack of 45°, the ampacities CIGRÉ and IEEE showed good agreement with maximum deviation of 2.4%. For speeds between 0 and 0.4 m/s, the maximum deviation between Morgan and CIGRE was 7.4% and 8.9% between Morgan and IEEE. Above 0.4 m/s, the maximum deviation between the ampacities of the three methods was approximately 2%.

- For inclinations of the cable up to 20° relative to the horizontal, the maximum deviation of the ampacities calculated by the Morgan method was 4% and occurred at wind speed condition equal to zero.
- The results indicate that differences in ampacity project of the transmission line in the range from 7% to 9% could cause differences in the surface temperature of the cable between 7°C to 8.5°C relative the surface temperature expected in the project.
- For speeds greater than or equal to 0.5 m/s, the cooling efficiency of the conductor is 70% to 75% for the angle of attack of 10 and 93% for the angle angle of attack of 45°.

Finally, the results of the study point to the need to continue researching methods more accurate and efficient for the calculation of ampacity for wind speeds between 0 and m 0.5 m/s, where the mixed convection prevails. Nevertheless, it is interesting to develop new solutions of thermally efficient conductors for transmission lines.

5. ACKNOWLEDGEMENTS

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