The Differences between IEEE and CIGRE Heat Balance Concepts for Line Ampacity Considerations

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Abstract — **Both IEEE and CIGRE have developed the line ampacity standards based on the same concept of the heat balance equation considering the balance between heat absorbed and dissipated. This document presents the differences in aspect of the heat balance equation, solution and application for ampacity calculation between the newest IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors – IEEE Std 738™-2006 which is the revised version of IEEE Std 738™-1993 and CIGRE Mathematical Model for Evaluation of Conductor Temperature in the Steady (or Quasi-Steady) State (Normal Operation).**

Keyword s- heat balance equation, ampacity standards, Joule, magnetic, solar, corona heating, convective, radiative, evaporative cooling

I. INTRODUCTION

The ambient weather and meteorological conditions are very important from the point of view of the ampacity ratings for the overhead conductors. The maximum allowable ampacity ratings can vary considerably depending on the external conditions. Many different approaches were found in literature for the possibility of expanding of the maximum load current of the overhead conductor in accordance to external weather conditions, all in range of 120% to 170% of the nominal current. This phenomenon can be explained based on the (1), where for the favorable conditions the right side of the equation is very big, therefore allowing to increase the left side and not to exceed the rated conductor temperature, because the additional heat caused by the load current over its designed limit is balanced by the heat dissipated due to very good ambient cooling conditions.

II. HEAT BALANCE EQUATION

Both IEEE and CIGRE methods are based on the steady state heat balance concept that heat gain is equal to heat loss. Also both of them take into account meteorological parameters influencing the thermal state of the conductor including the mean wind velocity, direction and turbulence, ambient temperature and solar radiation. However, both methods represent different ways of calculation of the heat balance equation. The version used by CIGRE has the following form:

$$P_J + P_M + P_S + P_i = P_C + P_r + P_w \tag{1}$$

where:

P_J	Joule heating (due to current flow),
P_M	magnetic heating,
P_S	solar heating,
P_i	corona heating,
P_C	convective cooling,
P_r	radiative cooling,
P_w	evaporative cooling.

while the heat balance equation according to the IEEE standard is presented by:

$$P_J + P_S = P_C + P_r \tag{2}$$

Comparing (1) and (2) it can be noticed that the IEEE method omits three elements: magnetic heating, corona heating and evaporative cooling, because of usually insignificant impact on the determination of ampacity ratings. However, the magnetic heating is considered by IEEE standard by entering the ac resistance (3) of the conductor at low and high value of conductor temperature [4], despite the fact that CIGRE standard contains the corona heating and evaporative cooling those are generally not used for ampacity calculations.

$$R(T_c) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right](T_c - T_{low}) + R(T_{low}) \tag{3}$$

This method of resistance calculation allows the user for calculating the high and low temperature resistance values, whichever is needed.

III. HEATING DUE TO THE JOULE AND MAGNETIC EFFECTS

Joule and magnetic heating refer to the conductor heating due to its resistance (Joule heating) and due to cyclic magnetic flux which causes heating by eddy currents, hysteresis and magnetic viscosity (magnetic heating).

The Joule heat gain for non-ferrous conductors is calculated by CIGRE method, in the same way as for IEEE method, as follows:

$$P_j = k_j I^2 R_{dc} \left[1 + \alpha\left(T_{av} - 20\right)\right] \qquad (4)$$

where:

I effective current,

R_{dc} dc resistance at 20ºC per unit length,

α temperature coefficient of resistance per degree Kelvin,

T_{av} mean temperature,

k_j factor taking into account the increase in resistance due to the skin effects.

The ac resistance can be calculated as follows:

$$R_{ac} = k_j R_{dc} \qquad (5)$$

For ferrous conductors the CIGRE standard adjusts the Joule heating term to account for magnetic heating and skin effect (the increase in the conductor resistance as a function of the frequency of the alternating current) [3].

The theory works on the basis that the power input must be the same for both ac and dc currents for the same average temperature of the conductor. The dc current that will result in a certain temperature being reached is calculated and the empirical formulae are then used to convert the dc to the ac current. Similarly, should the temperature be calculated for a given ac current, the empirical formulae are used to evaluate the equivalent dc current and hence the rise in temperature due to it [2]. Equation (4) is then reduced to:

$$P_j = I_{dc}^2 R_{dc} \left[1 + \alpha\left(T_{av} - 20\right)\right] \qquad (6)$$

The power input must be the same for ac and dc for the same average temperature of the conductor. Thus:

$$I_{ac}^2 R_{ac} = I_{dc}^2 R_{dc} \qquad (7)$$

IV. Heating Due to Solar Radiation

The most important thing in solar heating determination is the position of the sun in relation to the conductor. It comprises several elements: the solar declination, the hour angle of the sun and the latitude of the line. In case of the solar heating both methods present some differences. Up to Jan 2007 the IEEE standard (IEEE Std 738-1993) application was quite limited due to tabular method for the solar heat determination – it was based on specific days of a year (June 10 and July 3), only three hours a day (10 a.m., noon and 2 p.m.) and only at the Northern hemisphere. These limitations introduced the restriction of using IEEE standard only in terms specified above and causing this standard unusable for any other case. However, IEEE introduced in Jan 2007 (IEEE Std 738-2006 a revised version of the former). The new approach is as flexible in use as the CIGRE one, however based on different methods of calculations.

Currently the IEEE standard uses the altitude of the sun, its azimuth and the total heat flux received by a surface at sea level. The solar altitude of the sun, H_c, in degrees (or radians) is given by:

$$H_c = \arcsin\left[\cos\left(Lat\right)\cos\left(\delta\right)\cos\left(\omega\right) + \sin\left(Lat\right) + \sin\left(\delta\right)\right] \qquad (8)$$

where:

Lat degrees of latitude,

δ solar declination (0-90),

ω hour angle.

The hour angle, ω, is the number of hours from noon times 15º (for example 11 a.m. is -15º and 2 p.m. is +30º). The solar declination, δ, is equal:

$$\delta = 23.4583\left[\frac{284+N}{365}360\right] \qquad (9)$$

where N is a day number of the year (January 21=21, February 12=43, etc.). The above equation is valid for all latitudes, whether positive (northern hemisphere) or negative (southern hemisphere).

The solar azimuth, Z_c, (in degrees) is defined by:

$$Z_c = C + \arctan\left(\chi\right) \qquad (10)$$

where:

$$\chi = \frac{\sin\left(\omega\right)}{\sin\left(Lat\right) + \cos\left(\omega\right) - \cos\left(Lat\right)\tan\left(\delta\right)} \qquad (11)$$

The solar azimuth constant, C, is a function of the hour angle, ω, and the solar azimuth variable, χ. Its values can be found in Table 3 in [1].

The total heat flux received by a surface at sea level, Q_s [W/m^2], is dependent both on the solar altitude and atmospheric clarity and can be presented by the following equation:

$$Q_s = A + BH_c + CH_c^{\ 2} + DH_c^{\ 3} + EH_c^{\ 4} + FH_c^{\ 5} + GH_c^{\ 6} \qquad (12)$$

whereas, the A-G coefficients, depending on the atmosphere type, are listed in Table 5 in [1].

The CIGRE standard is more complex. It considers direct radiation, reflected radiation and defuse radiation, not as IEEE considering only the direct radiation. However, because of the costs of the direct solar radiation meters, there are two methods proposed: the simplified one and the one using all parameters.

The simplified method is based on the global radiation meters that are sufficiently accurate and reliable, and is represented by the equation below:

$$P_S = \alpha_S S D \tag{13}$$

where:

α_S absorptivity of conductor surface,
S global solar radiation,
D external diameter of conductor.

The value of α_S varies from 0.27 for bright stranded aluminum conductor to 0.95 for weathered conductor in industrial environment. For most purposes 0.5 value may be used.

The second method, taking into account isotropic diffuse radiation, is described by:

$$P_S = \alpha_S D\left[I_D\left(\sin\eta + \frac{\pi}{2}F\sin H_S\right) + B\right] \tag{14}$$

where:

$$I_D = 1280\frac{\sin H_S}{\sin H_S + 0.314}$$

$$B = I_d\frac{\pi}{2}(1+F)$$

I_D direct solar radiation,
η angle of the solar beam with respect to the axis of the conductor,
F reflectance of the ground,
H_S solar altitude,
I_d diffuse solar radiation,
Z hour angle of the sun,
N^* day of the year

whereas:

$$\eta = \arccos\left(\cos H_S \cos\left(\gamma_S - \gamma_C\right)\right)$$

$$H_S = \arcsin\left[\sin\Phi\sin\delta_S + \cos\Phi\cos\delta_S\cos Z\right]$$

$$\gamma_S = \arcsin\left[\frac{\cos\delta_S \sin Z}{\cos H_S}\right]$$

$$\delta_S \approx 23.4\sin\left[\frac{360^\circ\left(284+N^*\right)}{365}\right]$$

γ_S and γ_C are the azimuths of the sun and conductor respectively, Φ is the latitude and δ_S is the declination.

The different approaches of IEEE and CIGRE result with approximately 10-15% higher value of the CIGRE method than IEEE.

It is also worth mentioning that both methods increase the solar intensity for altitude above sea level. CIGRE standard considers the difference in solar intensity increase according to the part of the year (summer/winter months) while IEEE does not. In summer this results in higher rate intensity increase by CIGRE and lower rate intensity increase in winter in reference to IEEE method.

V. Cooling Due to Convection

Generally, both IEEE and CIGRE calculate separately the forced and the natural convective cooling. The natural convective cooling is the cooling without wind participation while the forced one is caused mainly by the wind. IEEE standard presents two equations for forced convection heat loss rate, the first one appropriate for low wind speeds (15a) and the second one for high wind speeds (15b):

$$q_{c1} = \left[1.01 + 0.0372\left(\frac{D\rho_f v_w}{\mu_f}\right)^{0.52}\right] k_f K_{angle}\left(T_c - T_a\right) \tag{15a}$$

$$q_{c2} = \left[1.0119\left(\frac{D\rho_f v_w}{\mu_f}\right)^{0.6} k_f K_{angle}\left(T_c - T_a\right)\right] \tag{15b}$$

where:

q_{c1}, q_{c2} convection heat loss rate,
ρ_f density of air,
v_w speed of air stream at conductor,
k_f thermal conductivity of air at temperature T_{film},
T_c conductor temperature,
T_a ambient air temperature.

The application of each of the above equations is dependent on the wind speed, inappropriate use could introduce large errors, so to make it universal for any wind speed the IEEE standard suggests to calculate both values and always choose the bigger one, standing for forced convection heat loss rate. Taking into consideration the wind influence, IEEE multiplies the convective heat loss rate by the wind direction factor, K_{angle}, being defined by:

$$K_{angle} = 1.194 - \cos\phi + 0.194\cos 2\phi + 0.368\sin 2\phi \tag{16}$$

where ϕ is the angle between the wind direction and the axis of the conductor

The alternative way for the wind direction factor calculation is based on the angle between the wind direction and a perpendicular to the conductor axis [1].

With zero wind speed the convection loss rate is called the natural convection, and is expressed by the equation:

$$q_{cn} = 0.0205\rho_f^{0.5} D^{0.75}\left(T_c - T_a\right)^{1.25} \tag{17}$$

Presented above IEEE approach has been changed in Jan 2007 (IEEE Std 738-2006), according to the old one where the most values were tabularised. The new approach is more universal and useful than the old one.

In case of convection heat loss rate the CIGRE standard, after the dimensional analysis that showed that certain non-dimensional groups of parameters are useful in calculation, a few coefficients are introduced:

- The Nusselt number, $Nu = \frac{h_c D}{\lambda_f}$, where h_c is the coefficient of convective heat transfer (W/m^{2}K), and λ_f is the thermal conductivity of air (W/mK);
- The Reynolds number, $\mathrm{Re} = \frac{\rho_r \mathrm{v} D}{v}$, where v is the wind velocity (m/s), v is the cinematic viscosity (m/s^2), and ρ_r is relative air density ($\rho_r = \frac{\rho}{\rho_0}$, where ρ is the air density at the altitude in question and ρ_0 is the air density at sea level);
- The Grashof number, $Gr = \frac{D^3 (T_s - T_a) g}{(T_f + 273) v^2}$;
- The Prandtl number, $\mathrm{Pr} = \frac{c\mu}{\lambda_f}$, where c is the specific heat of air at constant pressure (J/kgK) and μ is the dynamic viscosity of air (kg/ms), each corresponding to the respective part of convection heat loss rate equation.

For example, the Nusselt number corresponds and varies due to the wind direction in reference to the conductor axis, (more details can be found in [2]). As in IEEE standard also CIGRE one divided total convection heat loss rate into parts – forced and natural convective cooling, and in addition introducing the third part, corresponding only to low wind speeds.

VI. Cooling Due to Radiation

Both IEEE and CIGRE standards for radiative cooling are practically the same, so only the CIGRE point of view is presented in this work. Because the radiation loss is usually a small fraction of the total heat loss, especially with forced convection, the CIGRE method proposes to calculate it in accordance to the given equation:

$$P_r = \pi D \varepsilon \sigma_B \left[(T_s + 273)^4 - (T_a + 273)^4 \right] \tag{18}$$

where the emissivity ε is dependent on the conductor surface and varies from 0.27 for new stranded conductors to 0.95 for industrial weathered conductors (the suggested value is 0.5), σ_B is the Stefan-Boltzmann constant, T_a is the ambient temperature and T_s is the conductor surface temperature.

VII. Cooling Due to Evaporation

Only the CIGRE standard lists evaporative cooling in the heat balance equation, however, the evaporative cooling does not alter significantly with water vapour being present in the air or with water droplets being entrained in the flow around conductor. It does alter significantly as soon as the conductor is wetted. In general, the evaporative cooling effects are mostly ignored.

Summary

In general both IEEE and CIGRE standards are very useful and present sufficient accuracy – usually varying each other by no more than 5-15%. Before Jan 2007 IEEE standard was much less universal in use, because of tabularised methods of choosing parameters and tables restrictions (e.g. only one hemisphere available for solar intensity), but nowadays both can be used in the same range. It only depends on the user what concept he will follow and also what kind of data he has available to use and what are the purposes of use. CIGRE standard seems to be more complex and offers more details to be enlisted, however, not always it is necessary to spend time on detail calculations if the results obtained in easier way are also sufficient. There is no better or worse method, they are just different and used wisely offer a big array of application possibilities.

References

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