

CURRENT AMPACITY OF BUS-BAR WITH NECK FOR APPLICATION IN CURRENT TRANSDUCERS

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Abstract

This paper describes the Analysis of the current ampacity of the bus-bar with neck for application in current transducers. Primarily, the theoretical calculation was performed for bus-bar with different cross-section. Then, verification of obtained results is performed by thermovision research of temperature field distribution at different currents carrying through the bus-bar. The experimental results show possibility of the applied theoretical approach for determining optimal current ampacity.

Keywords: Busbar, ampacity, overtemperature, thermovision.

INTRODUCTION

The basic principle applied in the contactless current transducers is to indirectly measure the magnetic field around the conductor carrying the measured current. Ampere's law states that the magnetic field (in Gauss) around a round conductor that carries the current of intensity I (in Amps) is:

$$B = \frac{0.2I}{R} \quad (1)$$

where R is the distance between the centre of the conductor and the measured point.

The magnetic field can be measured by using Hall sensors, magnetoresistance sensors, coils, etc. In order to increase sensitivity of the whole current transducer it is need to increase the magnetic field B . The increasing of the magnetic field could be obtained by the decreasing of the distance R .

To this goal the busbar should be nacked, as shown in fig. 1:

Despite the fact that sensitivity increases, the narrowing conductors also eliminates the influence of the lateral skin effect in the case of busbars. It must be said that, in the case of the busbar carrying the current, the magnetic field in around area depends on the frequency of the measured current, among the other. In addition, the narrowing conductors and magnetic sensors approaching achieve a better immunity to the external (parasitic) magnetic fields.

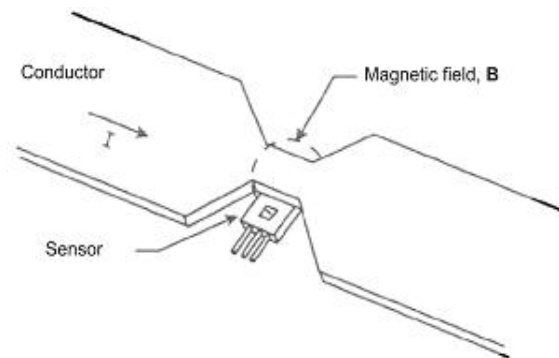


Fig 1. The magnetic sensor close to the nacked busbar

However, the narrowing has some negative consequences, such as increased heating and lower mechanical strength of the material on the narrowing side. This paper describes the problem of increased conductor heating at the narrowing place.

THE COMPUTATION OF THE AMPACITY FOR A BUSBAR

An approximately method to estimate the ampacity of a copper busbar in the air (without air convection) assumes the current density of $2A/mm^2$ (i.e. $1250A/in^2$). This method could be used only to a roughly estimate the possible size of a bus bar; however, the finally dimension will be determined by using the method described in the following section, according to the experimental results [3].

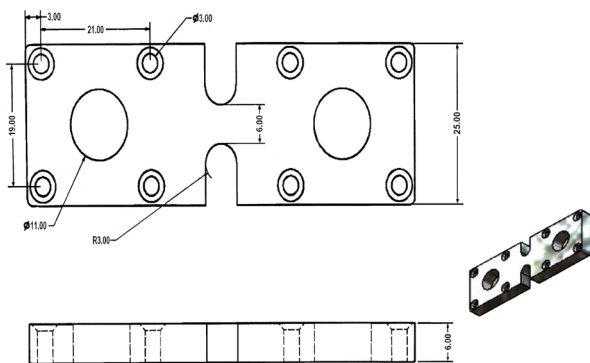


Fig 2. The drawing of a flat busbar with neck

THE HEAT GENERATED BY THE CURRENT THROUGH THE BUSBAR

Product $I^2 R$ [W] is measure for generated heat per unit of lenght of a conductor that carries DC (I is the current through the conductor, and R is resistance per length). The value of resistance in case of a DC busbar system could be directly calculated according specific resistance of copper or copper alloys.

In the case of an ac busbar system, resistance increases due to skin effect, i.e., the current carries near the surface of the conductor. The ratio of the resistance for AC and the corresponding resistance for DC current is called the coefficient of skin effect. This value equals to one for DC, but it increases with the frequency and the physical dimensions of the conductor carries AC current.

The dissipated power per unit of length of a conductor is:

$$P_0 = I^2 R_0 S \text{ [W/mm]} \quad (2)$$

where is: I [A]- the intensity of the current in the conductor, R_0 [Ω/mm]- resistance per length for DC, and S_S - the coefficient of skin effect:

Despite the fact that sensitivity increases, the narrowing conductors also eliminates the influence of the lateral skin effect in the case of busbars. It must be said that, in the case of the busbar carrying the current, the magnetic field in around area depends on the frequency of the measured current, among the other. In addition, the narrowing conductors and magnetic sensors approaching achieve a better immunity to the external (parasitic) magnetic fields.

$$S_s = \frac{R_f}{R_0} \quad (3)$$

where R_f [Ω] is resistance of the conductor for AC.

HEATING OF BUSBAR WITH VARIABLE CROSS-SECTION

Heating of current-conductive elements with variable cross-section in steady state is characterized by different temperature along the conductor [1], [2]. Thereupon, heat is transferred along the element from the point with the higher temperature to the point with the lower temperature. Due to different cross-sections, the temperature along the elements changes according to different principles.

Since the specific electrical resistance ρ , the coefficient of thermal conductivity λ and the coefficient of heat dissipation k_t depend on the temperature, consequently they have different values both on the parts with different cross-sections and on the parts along the homogeneous section. Therefore, the mean values for expected temperatures are being used in computation.

One part of such conductor, which is positioned at the distance x from the appropriate coordinate center (fig. 3), is observed. Since steady state of heating is considered, therefore all energetic processes could be considered in the unit of time.

The quantity of heat that comes into the elementary part positioned at x in unit of time is:

$$Q'_1 = -\lambda s_p \frac{\partial \tau}{\partial x} \quad (4)$$

while quantity of heat that dissipates at $x dx$ is:

$$Q'_2 = -\lambda s_p \frac{\partial}{\partial x} \left(\tau + \frac{\partial \tau}{\partial x} dx \right) \quad (5)$$

where S_p is the cross-section surface.

Due to existence of the current with the intesity I in observed elementary part the generated quantity of heat in unit of time is:

$$Q'_3 = q s_p dx \quad (6)$$

where is q power of dissipation per unit of conductor volume:

$$q = \frac{\rho I^2}{s_p^2} \quad (7)$$

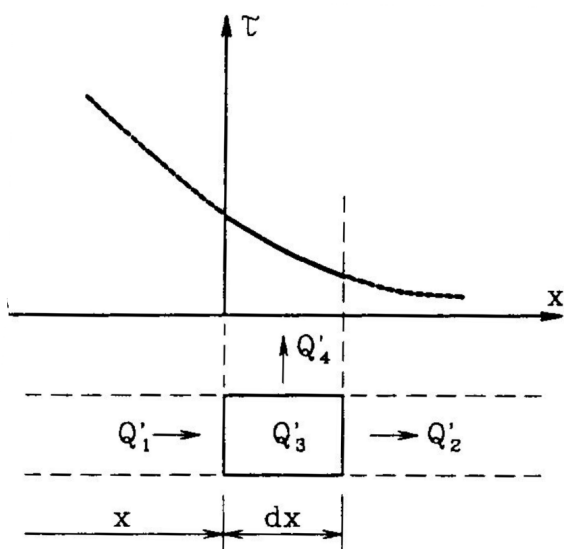


Fig. 3. The elementary part of a current-conductive element

The quantity of heat that dissipates from outside surface in environment is:

$$Q'_4 = k_i O dx \quad (8)$$

The follow equation is given based on condition that the total rise of quantity of heat for observed element in steady state is equal to zero:

$$Q'_1 + Q'_3 = Q'_2 + Q'_4 \quad (9)$$

By replace corresponding terms for quantity of heat in expression (9), and after arrangement, the differential equation of the temperature change is given as follows:

$$\frac{\partial^2 \tau}{\partial x^2} - \frac{k_i O}{\lambda s_p} \tau = -\frac{q}{\lambda} \quad (10)$$

The general solution of the differential equation (10) is:

$$\tau = \tau_p + K_1 e^{ax} + K_2 e^{-ax} \quad (11)$$

where:

$$\tau_p = \frac{qs_p}{k_i O} \quad \text{and} \quad a = \sqrt{\frac{k_i O}{\lambda s_p}} \quad (12)$$

The general solution of the differential equation represents the temperature change along the homogeneous section of the conductor. The first component on right side of relation (11) represents steady temperature of the conductor without the temperature change along the conductor. The constants K_1 and K_2 are determined according to the appropriate initial conditions for each concrete case.

The case which is considered here is shown in fig. 4.

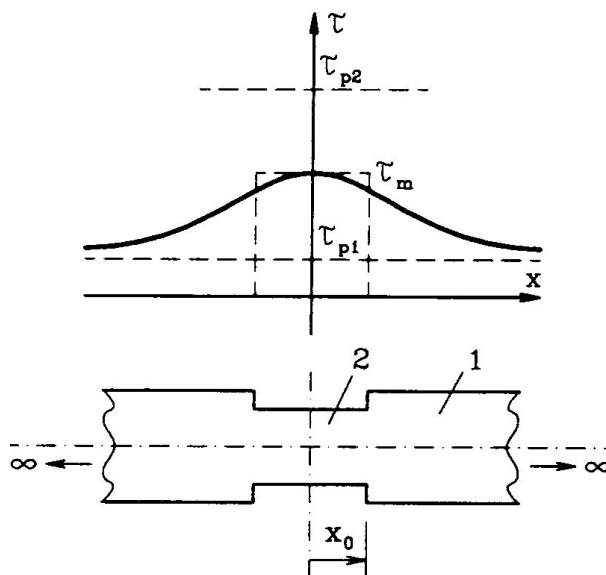


Fig. 4. Heating of conductor with variable cross-section

In the case of a infinite long conductor, the general expressions for of the temperature distribution along the parts 1 and 2 are:

$$\tau_1 = \tau_{p1} + K_5 e^{a_1 x} + K_6 e^{-a_1 x} \quad (13)$$

$$\tau_2 = \tau_{p2} + K_7 e^{a_2 x} + K_8 e^{-a_2 x} \quad (14)$$

According to relation (13) it is clearly that the temperature rises up to infinite if the distance refer to the place of discontinuity increases ($x \rightarrow \infty$). Whereas this is an absurd, it is obviously that must be $K_5 = 0$. Based on condition that for $x=0$ follows:

$$\left. \frac{\partial \tau_2}{\partial x} \right|_{x=0} = 0 \quad (15)$$

It is the place with the highest temperature. From the previously follows that the constants K_7 and K_8 are equal ($K_7 = K_8 = K$). Also, for $x = x_0$:

$$\left. \begin{aligned} \tau_{1(x=x_0)} &= \tau_{2(x=x_0)} \\ \frac{\partial \tau_1}{\partial x} \Big|_{x=x_0} &= \frac{\partial \tau_2}{\partial x} \Big|_{x=x_0} \end{aligned} \right\} \quad (16)$$

Based on these conditions, the constants K_6 , K_7 and K_8 are given as:

$$K_6 = -2 \frac{a_2}{a_1} K e^{a_1 x_0} sh(a_2 x_0) \quad (17)$$

$$K_7 = K_8 = K = \frac{1}{2} \frac{\tau_{p2} - \tau_{p1}}{ch(a_2 x_0) + \frac{a_2}{a_1} sh(a_2 x_0)} \quad (18)$$

The temperature distribution along parts 1 and 2 (fig. 4) for an infinite long conductor with a neck section in the middle part is:

$$\tau_1 = \tau_{p_1} + \frac{a_2}{a_1} \frac{\tau_{p_2} - \tau_{p_1}}{ch(a_2 x_0) + \frac{a_2}{a_1} sh(a_2 x_0)} e^{-a_1(x-x_0)} sh(a_2 x_0) \quad (19)$$

$$\tau_2 = \tau_{p_2} - \frac{\tau_{p_2} - \tau_{p_1}}{ch(a_2 x_0) + \frac{a_2}{a_1} sh(a_2 x_0)} ch(a_2 x) \quad (20)$$

where:

$$\tau_p = \frac{q s_p}{k_t O}, \quad a = \sqrt{\frac{k_t O}{\lambda s_p}} \quad \text{and} \quad q = \frac{\rho I^2}{s_p^2} \quad (21)$$

The maximal temperature is in the middle of neck ($x=0$), and it is equal to:

$$\tau_2 = \tau_{p_2} - \frac{\tau_{p_2} - \tau_{p_1}}{ch(a_2 x_0) + \frac{a_2}{a_1} sh(a_2 x_0)} \quad (22)$$

In the cases where the length l of the neck section is small ($l=2x_0$), it can be assumed that there is no temperature change along it. With such approximation, the temperature distribution (i.e. overtemperature) along the rest part of the conductor can be determined on a relatively simple way. If the overtemperature of the neck is τ_m , then the overtemperature of the rest part of the conductor (for coordinate system positioned like in fig. 4) is:

$$\tau = \tau_p + (\tau_m - \tau_p) e^{-a(x-x_0)} \quad (23)$$

The overtemperature τ_m is determined according the condition that heat from the neck propagates symmetrically on both sides. Therefore:

$$0.5(q_2 l s_{p_2} - k_{t2} S_2 l \tau_m) = -\lambda s_p \left. \frac{\partial \tau}{\partial x} \right|_{x=x_0} \quad (24)$$

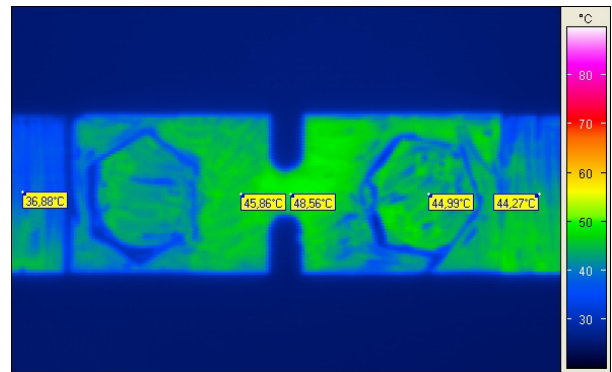
From last two relations for overtemperature τ_m , we obtain:

$$\tau_m = \frac{q_2 l s_{p_2} + 2 \lambda a s_p \tau_p}{k_{t2} S_2 l + 2 \lambda a s_p} \quad (25)$$

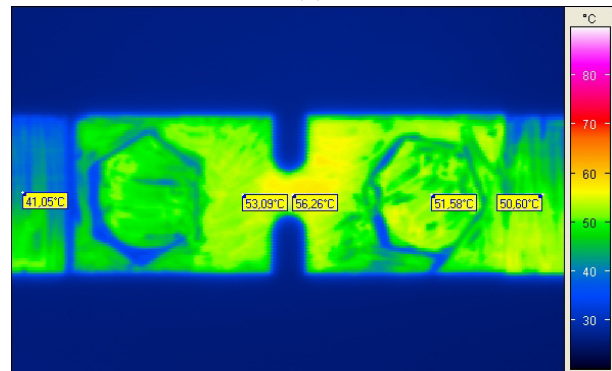
THE THERMOVISION EXAMINATION

The busbar (whose dimensions are given in fig. 2) was carried by the currents of certain effective values and the frequency of 50Hz. The imaging was done after the establishment of steady state. The checking of the busbar heating was done by the thermovision camera. To obtain more precise thermal measurement,

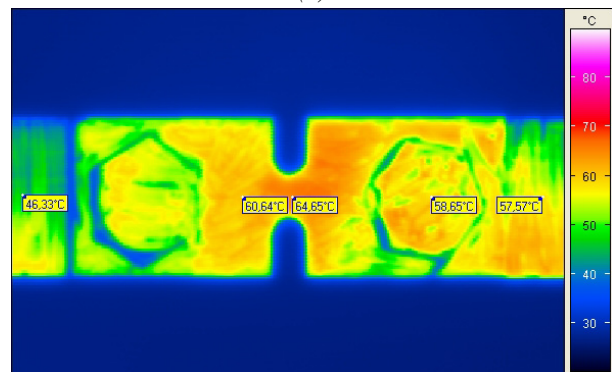
the busbar is painted in black color (due to possible problems with the determination of the emissivity coefficient of copper). The thermograms are given in fig. 5. The overtemperature of the neck section is calculated based on the analysis given in section 4 and formula (25). Thereby the following constants were used: $\lambda=401\text{W/mK}$, $\rho_{\text{Cu}}=1.7 \cdot 10^{-8}\Omega\text{m}$, $k_t=k_{t1}=k_{t2}=13\text{W/m}^2\text{K}$, and the ambience temperature without air convection $t_a=25^\circ\text{C}$. For an effective current of 450A calculated overtemperature was approx 45°C . Since the ambience temperature was about 25°C , therefore the predicted temperature of the neck part was 70°C . Based on recorded thermograms shown in fig. 5, the one can note that the measured temperature in this case is 78°C . The measured temperature is about 8°C higher than predicted one.



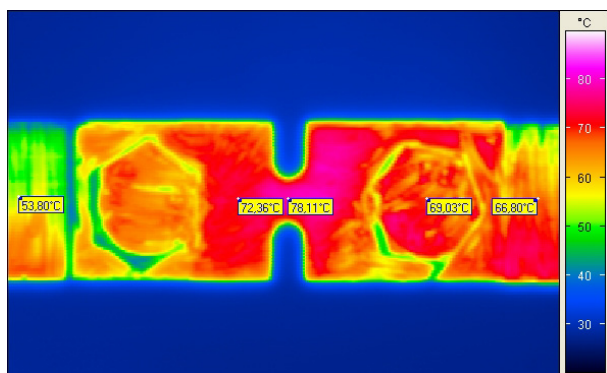
(a)



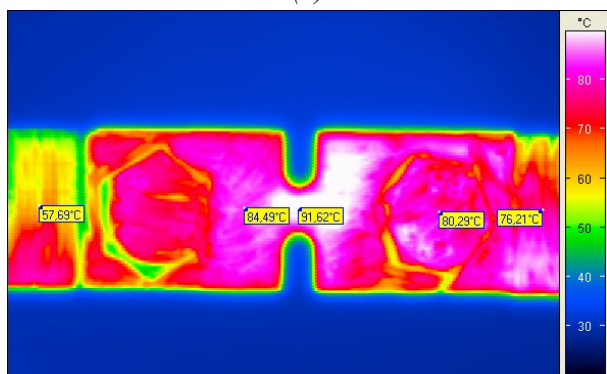
(b)



(c)



(d)



(e)

Fig. 5. The thermograms of busbar for different currents: (a)300A; (b)350A; (c)400A; (d)450A; (e)500A

CONCLUSION

Problem of increased conductor heating at the narrowing place was theoretically described, the first. Then the theoretically and the experimentally obtained results were compared. The experimentally results were obtained by the thermov-

ision recording the copper busbar with the neck. As already said, the measured temperature is about 8°C higher than predicted one. This temperature increasing can be explained by the fact that the real busbar is not infinitely long, in opposite to the assumption in the theoretical model. In addition, the contacting was performed by using screws which contribute an additional heating. Therefore, thermovision method has proved useful. The busbar designed for 300A may also submit the same current after the narrowing. In other words, the overtemperature of the narrowed part is not too large, so that standard electronic components can work in its vicinity, even at the currents over 400A.

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