



OPTIMAL COMBINATION OF BUSBARS FOR ELECTRIC SMELTING FURNACES

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Abstract: In order to achieve minimal heating losses in conductors supplying electric smelting furnaces, working on higher frequencies, different combinations of aluminium and copper conductors with standardized rectangular cross-sections are investigating. Considering skin effect and proximity effect in all conductors, minimal heating losses are obtained when conductors' resistance per kilometre is minimal. The optimization was carried out on a model of five different combinations of busbars, five standardized busbars' dimensions and 13 frequencies. All results are given in the forms of standard diagrams.

Key Words: Skin and proximity effects/Minimal losses/Conductors with rectangular cross-sections

1. INTRODUCTION

In order to improve the efficiency of electric smelting furnaces, they are supplying with higher frequencies. Consequently, in all supplying conductors, skin effect and proximity effects are emphasized. Those two effects increase heating losses in supplying busbars.

The goal of this research is to find out the optimal combination of busbars providing minimal resistance per kilometre of conductors' length, i.e. minimal losses.

The behaviour of a single conductor of rectangular cross-section was investigating and presented in [1] and it can be expected that the combination of multiple busbars may give better results.

For that reason, five different combinations of aluminium and copper, shown in Fig. 1, are investigated. All combinations are calculated for 13 different frequencies and for five different standardized busbars [2], given in Table 1.

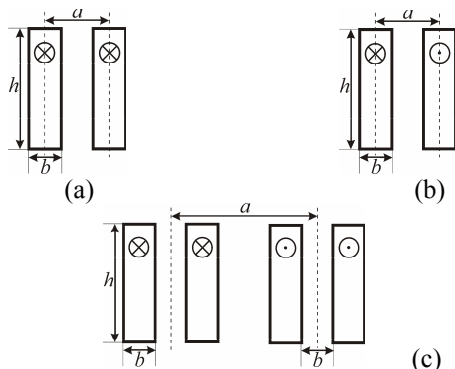


Fig. 1. Different arrangements of conductors with rectangular cross-section.

Table 1. Dimensions of standardized conductors of rectangular cross-section

| Busbar | h [mm] | b [mm] | S [mm ²] |
|--------|----------|----------|------------------------|
| 60x10 | 60 | 10 | 600 |
| 100x10 | 100 | 10 | 1000 |
| 120x10 | 120 | 10 | 1200 |
| 160x10 | 160 | 10 | 1600 |
| 200x10 | 200 | 10 | 2000 |

The problem was also carried out for different distances between the conductors (value a in Fig. 1) witch depend on furnaces' supplying voltages, as shown in Table 2.

Table 2. Minimal distances between conductors for different nominal voltages

| Nominal voltage [kV] | a [mm] |
|----------------------|----------|
| 1 | 40 |
| 3 | 60 |
| 6 | 90 |

The entire calculation was performed applying COMSOL Multiphysics computer program package, based on Finite Element Method (FEM).

However, in this paper, only two different arrangements of conductors (Fig. 1.a and Fig. 1.d) are presented.

2. THEORETICAL APPROACH

In order to determine the conductors' resistance, total current distribution, induced electric field, Joule's losses power and AC resistance must be carried out.

Having a linear situation, the problem can be solved in complex domain.

The geometry of the conductors suggests that the orthogonal Cartesian coordinate system, shown in Fig. 2 should be applied, with the z -axis parallel to the conductors' longitudinal axis.

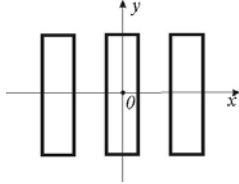


Fig. 2. Busbars in chosen Cartesian coordinate system.

In that case the complex current density vector has just z component, which depend on x and y coordinates. Complex magnetic vector potential has also only z -component and is a function of x and y coordinates,

$$\vec{A}(x, y) = \vec{i}_z A_z(x, y). \quad (1)$$

Starting from well known partial differential equation in complex domain [3], [4],

$$\Delta \vec{A} - j\omega\mu\sigma \vec{A} = -\mu \vec{J}, \quad (2)$$

with, in chosen Cartesian coordinate system, for imposed current density vector having just z component, can be written as,

$$\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} - j\omega\mu\sigma A_z = -\mu J_z, \quad (3)$$

complex magnetic vector potential was determined.

In order to solve the above partial differential equation, boundary condition must be defined. Although electromagnetic field extends toward infinity, its influence at the far end of the domain becomes negligible. In accordance with it, we chose that magnetic vector potential is fixed to zero at the exterior boundary of the air domain.

The determined magnetic vector potential defines z component of induced electric field strength vector,

$$\vec{E}_{indz}(x, y) = -j\omega \vec{A}_z(x, y), \quad (4)$$

and induced z component of current density vector,

$$\vec{J}_z(x, y) = \sigma \vec{E}_{indz}(x, y). \quad (5)$$

Heating power losses (Joule's losses) per kilometer are calculated as,

$$P'_J = \int_{spp} \frac{J_z^2}{\sigma} dS, \quad (6)$$

and the resistance per kilometre of entire conductor's system is,

$$R' = \frac{P'_J}{|I|^2}. \quad (7)$$

In order to calculate the above mentioned expression, COMSOL MULTYPHISICS 3.5a computer program [6] based on Finite Elements Method for 2D and 3D problems was applied.

3. MODEL

The entire calculation was carried out applying AC/DC modul of COMSOL Multiphysics 3.5a computer program package. A 2D model, representing a cross section of busbar system in surrounding air domain, is set up. The mode "Quasi-static, Magnetic/ Perpendicular Induction Currents/Vector Potential" is chosen, together with "Time-harmonic analysis".

In the calculating model, rms value of current is chosen to be the same in every conductor, equal 1A, in the same direction. Conductivity for all busbars, made of aluminium and copper is set to $\sigma_{Al}=3.774 \cdot 10^7$ S/m and $\sigma_{Cu}=5.618 \cdot 10^7$ S/m, respectively.

In the model, conductors are surrounded by air, with defined electromagnetic characteristics, $\epsilon_r=1$, $\mu_r=1$, $\sigma=0$. On exterior boundary, the surface current density

$$J_s = \frac{-\sum I_i}{2\pi R_b} \quad (8)$$

was supposed, providing total current density to be zero. The radius of modeling domain is chosen to be $R_b=1m$.

Magnetic vector potential is continuous across all interior boundaries between aluminum (copper) busbars and surrounding air.

In order to determine the current distribution properly in all conductive parts of observed busbar system, a very fine mesh is initialized (Fig. 3).

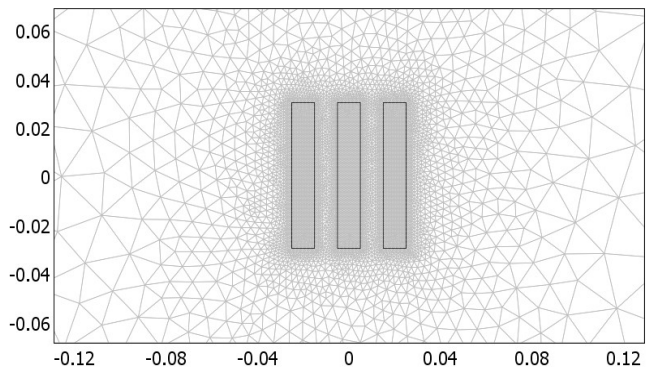


Fig. 3. Part of analyzed domain, with generated mesh.

Thanks to the facts, that applied software offers flexible postprocessing capabilities, the skin effect ratio has been calculated easily and has been presented as a function of frequency and as a function of term $\sqrt{f/R_c}$

$$\frac{R_{\approx}}{R_{=}} = f(f) \quad \text{and} \quad \frac{R_{\approx}}{R_{=}} = f\left(\sqrt{\frac{f}{R_{=}}}\right). \quad (9)$$

4. OBTAINED RESULTS

Having a linear problem, independent on chosen imposed current, for all calculations it was assumed the rms value of current to be, $I=1A$.

In all calculations aluminum and copper conductors, arranged as two and three busbars (Fig. 1a and Fig. 1d) are considered, and the frequency values were 50/3Hz, 50Hz, 100Hz, 150Hz, 250Hz, 350Hz, 450Hz, 500Hz, 750Hz, 1000Hz, 1500Hz, 2000Hz and 2500Hz.

As an example of calculated values, typical diagram of frequency dependent resistance coefficient, $R_{\approx}/R_{=}$, for the combination in Fig. 1d (three coupled busbars), for all busbar types (Table 1.), made of aluminium is shown in Fig. 4.

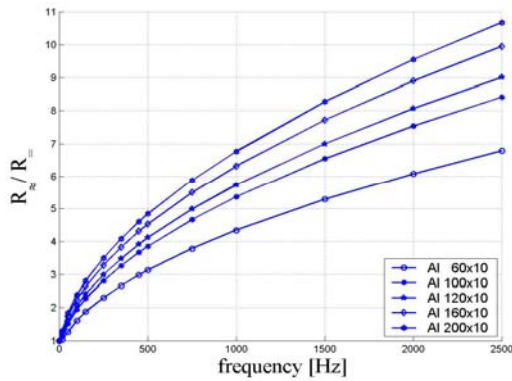


Fig. 4. Frequency diagram of the resistance coefficient for three aluminium busbars.

In order to compare the resistance coefficients for busbars made of differential materials, curves for both aluminium and copper are presented on the same graph, as shown in Fig. 5.

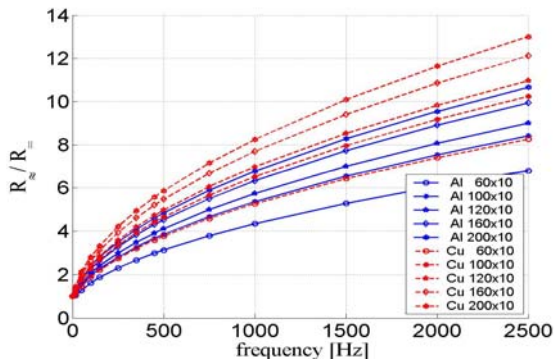


Fig. 5. Frequency diagram of the resistance coefficient for both aluminium and copper busbars (three conductors).

Both figures, Fig. 4 and Fig. 5 show, that resistance coefficient increases with frequency and with increasing dimensions of busbars. The tendency on resistance coefficient increasing with increasing dimensions of busbars is the same for both busbar materials. That means that skin and proximity effects are increasing total

Joule's heating in both, aluminium and copper conductors.

As it can be concluded from Fig. 5 system made of aluminium has lower resistance coefficient than the one made of copper.

Also, as it could be expected, due to its higher conductivity, both skin effect and proximity effect are more emphasized in copper system than in aluminium one. Therefore, in Fig. 5, all copper curves are above aluminium curves for the same busbars dimensions.

However, the price per kilo and the much lower density of aluminium could become the determining factors witch metal to choose in praxis [5].

Another typical diagram of resistance coefficient, $R_{\approx}/R_{=}$, as a function of coefficient $\sqrt{f/R_{=}}$, for the fourth combination in Fig. 1 (three coupled busbars), for all busbar types, made from aluminium is shown in Fig. 6.

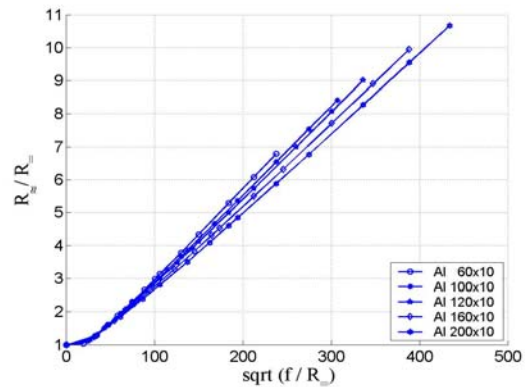


Fig. 6. Resistance coefficient as a function of $\sqrt{f/R_{=}}$ for three aluminium busbars.

Comparing the same diagram for both materials, the plot in Fig. 7 demonstrates a good match of resistant coefficient dependence on term $\sqrt{f/R_{=}}$.

The shape of curves in Fig. 6 and even more in Fig. 7, demands an additional explanation.

A case of emphasized skin effect is considered when skin depth,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (10)$$

is much smaller than linear dimensions of the conductor's cross-section. In this case, AC resistance of a circular cross-section conductor, with radius a , can be expressed as [3],

$$R_{\approx} = \frac{\sqrt{\omega\mu}}{2\pi a} \sqrt{\frac{2\sigma}{\sigma}}. \quad (11)$$

From the above expression it can easily be derived that, for a conductor of circular cross-section, resistance coefficient can be expressed as

$$\frac{R_{\approx}}{R_{=}} = \sqrt{\frac{\mu}{4}} \sqrt{\frac{f}{R_{=}}}. \quad (12)$$

This means that the resistance coefficient is linearly proportional to the coefficient $\sqrt{f/R_0}$, which is obvious in both Fig. 6 and Fig. 7. The starting nonlinearity occurs because the supposed condition,

$$\delta \ll a, \quad (13)$$

is not satisfied for lower frequencies.

Expression (12) also suggests that the resistance coefficient does not depend on conductor's cross-section size, or on conductor's conductivity. Dispersed curves for different conductor's cross-sections, in Fig. 6 and Fig. 7, are the consequence of rectangular, not circular cross-section, while the independence on conductor's conductivity is clearly shown in Fig. 7.

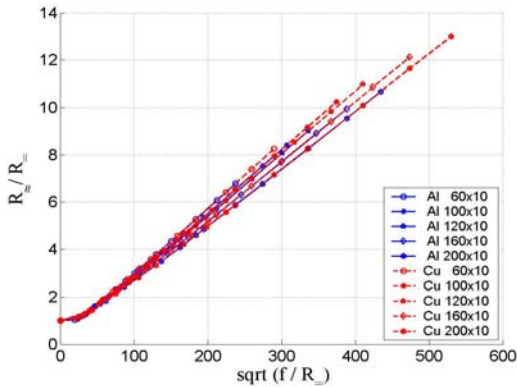


Fig. 7. Resistance coefficient as a function of $\sqrt{f/R_0}$ for both aluminium and copper busbars (three conductors).

From Fig. 8, where a system of two aluminium and two copper busbars is considered, it could be observed that the resistance coefficient follows the same increasing trend as in Fig. 5, for system composed of three busbars. Generally, system of two busbars have a lower rate of AC to DC resistance, than that consists of three busbars.

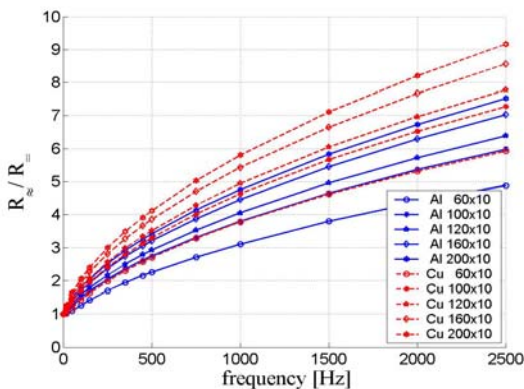


Fig. 8. Frequency diagram of the resistance coefficient for both aluminium and copper busbars (two conductors).

Fig. 9 illustrates the frequency diagram of resistance coefficient for two copper busbars of different cross sections (60mm×10mm and 200mm×10mm) on three different distances (d=40, 60, 90mm).

As it was expected, the results show that increasing distance between busbars, decreases resistance coefficient for both observed cross-sections.

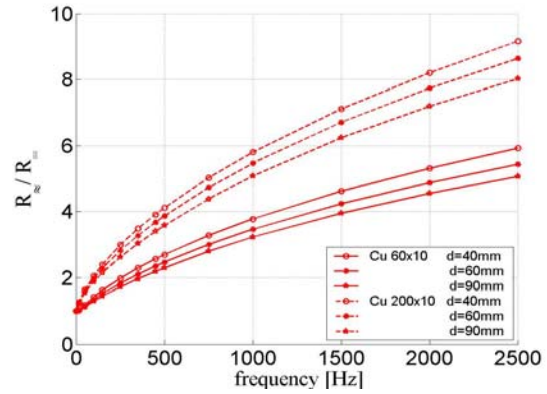


Fig. 9. Frequency diagram of resistance coefficient for copper busbars of different cross section and on different distances d .

Decreased resistance coefficients in this case are direct consequence of decreasing proximity effect.

Fig. 10 is a similar example, when systems of equal cross sections (200mm×10mm), on same distances as above, but made of different materials were compared.

Also expected, copper system, due to its higher conductor's conductivity, has higher resistance coefficients.

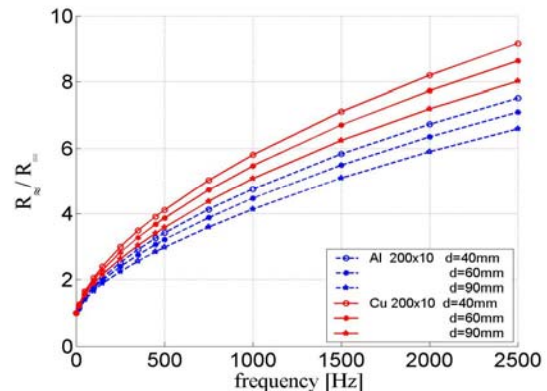


Fig.10. Frequency diagram of resistance coefficient for aluminium and copper busbars of same cross section on different distances d .

5. CONCLUSION

This paper has presented the investigation to find out the best choice of supplying conductors used in electric smelting furnaces. As an optimisation criterion, the system's resistance coefficient was adopted.

As it can be concluded and as it could be expected, minimal resistance, i.e. minimal losses occurred in a system of multiple busbars with smaller cross-sections.

Hence, depending on available space for the busbars mounting, the optimal solution can be chosen.

On the other hand, the applied program package, COMSOL Multiphysics, is shown to be an appropriate tool for reaching an optimal solution of the problem.

In spite of all our efforts, the applied program package could not give us correct results for two phase shifted currents (180° , meaning the currents in opposite directions, or 90° shifted currents). This is the reason why in this paper we did not present all conductor's arrangements shown in Fig. 1, but only the cases of same current directions in two or three conductors systems.

Solving this problem will be the challenge for our future research.

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6. REFERENCES

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