FACTA UNIVERSITATIS (NIŠ)
SER.: ELEC. ENERG. vol. 22, no.3, December 2009, 293-303

Proximity Effect Against Skin Effect in Two Coupled U-shaped Busbars

Karolina Kasaš - Lažetić, Miroslav Prša, and Nikola Ðurić

Abstract: U-shaped busbars are frequently applied in distribution systems. In order to increase busbars ampacity it is important to be well acquainted with all busbar's characteristics, for optimal construction of the system.

In this article, an analysis of induction effects on two coupled U-shaped busbars' ampacity is presented, together with an attempt to achieve better performances of busbars.

The combination of skin and proximity effect significantly increases the AC conductor's resistance, compared to its resistance in a DC current case. An additional resistance lead to extra losses of energy through Joule heating, which is not negligible, not only from economy aspects, but from ecological aspects too.

This paper continues our investigations to find the best combination of two coupled U-shaped conductors in order to confront skin and proximity effects, making an improvement of their characteristics, decreasing losses in them. For that reason an analysis of different positions and different distances between them has been accomplished.

Keywords: U-shaped busbars, skin effect, proximity effect.

1 Introduction

IN a conductor with alternating current, the intensity of current density vector will increase toward the conductor's surface. This phenomenon is called skin effect. On the other side, influence of alternating current in an adjacent conductor is known

Manuscript received on November 15, 2009. This paper is a combination of two earlier papers presented at the 9th International Conference on Applied Electromagnetics PES 2009, August 31-September 02, 2009, Nis, Serbia and at Simpozijum INFOTEH Jahorina, March, 18-20, 2009, Jahorina, BiH.

The authors are with Faculty of Technical Sciences, Trg D. Obradovića 6, 21000 Novi Sad, Serbia (e-mails: [kkasas, prsa, ndjuric]@uns.ac.rs).

as proximity effect. These induction effects result in non-uniform current distribution over a cross section - consequently making busbars to have higher losses and to operate on higher temperature.

The apparent conductor's resistance is always higher for AC than for DC current. The ratio of AC to DC watt loss is known as $R_{\approx}/R_{=}$ ratio and is usually given graphically as a function of frequency.

Applying Comsol multiphysics computer program package, based on Finite Element Method, current distribution in the cross section of two conductors and the total resistance per kilometre of conductors were calculated.

2 Attributes

Theoretically, having a two-dimensional problem, with imposed AC current perpendicular to paper, time varying magnetic filed is in a paper plane. Hence, two induced currents, due to skin and proximity effects, having also just z-component, could confront each other, decreasing resistance and Joule's losses in the system.

After the investigation made and presented in [1–3], in this paper all five busbars arrangements and all eight standardised busbar types were taken into consideration.

The cross-section of a U-shaped busbar is given in Fig. 1, while the dimensions of standardised aluminium or copper busbars are in Table 1 [4].

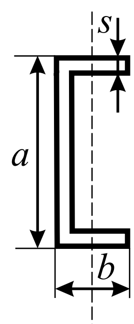

Fig. 1. Cross-section of a U-shaped busbar.

The mutual positions of busbars are shown in Fig. 2.

3 Theoretical Approach

The goal of this paper is to find the possibility that proximity effect decrease consequences of skin effect. To achieve the goal, the system of different positions and

Table 1. Dimensions of standardised U-shaped conductors.

Busbar type	a (mm)	b (mm)	s (mm)	d (mm)	d_1 (mm)	S (mm^2)
U6	60	30.0	4	25	85	448
U8	80	37.5	6	25	105	858
U10	100	37.5	8	25	125	1272
U12	120	45.0	10	30	150	1900
U14	140	52.5	11	35	175	2453
U16	160	60.0	12	40	200	3072
U18	180	67.5	13	45	225	3757
U20	200	75.0	14	50	250	4508

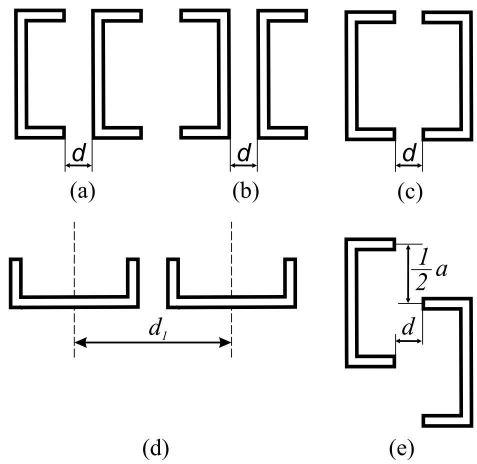

Fig. 2. Different positions of two U-shaped busbars.

different mutual distances (d, d_1) were investigating. The optimisation criterion is chosen to be minimal AC resistance per kilometer, or minimal $R_{\approx}/R_{=}$ ratio.

In order to estimate if skin effect and proximity effect (induced currents) act in the same direction, or in opposite directions, the distance between two coupled busbars was increased. Increasing distances always decrease proximity effect. Hence, if, for increasing distances, $R_{\approx}/R_{=}$ ratio decreases, that means that skin and proximity effects act in the same direction. On the other hand, if, for increasing distances, $R_{\approx}/R_{=}$ ratio increases, that would present a successful attempt to oppose those two effects.

Hence, the entire calculation, total current distribution, induced electric field, Joule's losses power and AC resistance must be carried out for all different parameters of two coupled conductors.

Busbar's cross-section suggests that Cartesian coordinate system is the most suitable choice. The coordinates of this coordinate system are positioned so that current has just z component, as shown in Fig. 3, for the ultimate position of conductors, presented in Fig. 2.

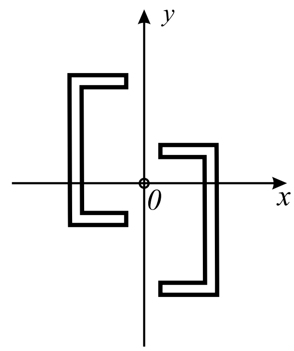

Fig. 3. Conductor's positions in Cartesian coordinate system.

Having a linear problem, complex values can be involved.

The most convenient way to resolve the problem is to apply complex magnetic vector potential, which has the same component as imposed current density vector, z-component, changing across x-y plane,

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

Magnetic vector potential is a solution of partial differential equation [5, 6],

$$\Delta\vec{\underline{A}} - j\omega\mu\sigma\vec{\underline{A}} = -\mu\vec{\underline{J}}, \tag{2}$$

where ω is circular frequency, μ is permeability and σ is conductivity of observed conductors. $\vec{\underline{A}}$ and $\vec{\underline{J}}$ are complex magnetic vector potential and complex current density vector respectively. In Cartesian coordinate system equation (2) has the following form:

$$\frac{\partial^2 \underline{A}_z}{\partial x^2} + \frac{\partial^2 \underline{A}_z}{\partial y^2} - j\omega\mu\sigma\underline{A}_z = -\mu\underline{J}_z, \tag{3}$$

In order to solve the above partial differential equation, boundary conditions must be defined. Having an unlimited problem, knowing that electromagnetic field can be neglected far away from the conductors, we chose that there is a surface current on radius R_b, much bigger than linear dimensions of conductor's cross-sections. The surface current must give the total imposed current in opposite direction, so electromagnetic field disappears outside of this radius.

Complex induced electric field strength vector is,

$$\vec{\underline{E}}_{ind} = -j\omega\vec{\underline{A}}. \tag{4}$$

This complex vector has also just z-component, depending on x- and y- components only,

$$\underline{E}_{indz}(x,y) = -j\omega\underline{A}_z(x,y). \tag{5}$$

Total complex current density vector can now be expressed as,

$$\underline{J}_z(x,y) = \sigma\underline{E}_{indz}(x,y). \tag{6}$$

Verification of calculated complex current density vector values is very simple. Integration over the each conductor's cross-section,

$$\underline{I} = \int_{S_{pp}} \underline{J}_z dS, \tag{7}$$

must give the imposed complex current in each conductor.

Heating power losses (Joule's losses) per unit conductor's length are,

$$P_J^{'} = \int_{S_{pp}} \frac{J_z^2}{\sigma} dS. \tag{8}$$

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

$$R_{\approx}^{'} = \frac{P_J^{'}}{|\underline{I}^2|}. \tag{9}$$

In this paper all above calculations were performed applying COMSOL Multiphisics 3.5a computer package. Calculations of current distribution across the conductors cross section under the influence of skin effect and proximity effect is based on solution of partial differential equations applying final element method. All other values were determined with direct expressions or with post processing integrations.

Applied program has also different possibilities of graphical presentations of obtained results.

In the next chapter a short description of applied Comsol package module is presented.

4 Applied Program and Input Data

As said above the entire calculation was carried out applying AC/DC module of COMSOL Multiphysics 3.5a computer program package [7], based on Finite Elements Method (FEM) for 2D or 3D problems. From this program package the 2D

"Quasi-static, Magnetic-Perpendicular Induction Currents, Vector Potential" mode is chosen, together with "Time-harmonic analysis". As it can be seen in Fig. 3, problem can be treated as two-dimensional.

In the calculated model, current in both conductors is chosen to be the same, I_1=I_2=1A, in the same direction. Conductor's conductivity was taken from the program's materials library (for aluminum this value is, σ_{Al}=3.774$\cdot 10^{-7}$S/m).

Conductors are surrounded by air, with defined electromagnetic characteristics, ε_r=1, μ_r=1, σ=0.

For the radius R_b, outside of witch electromagnetic field can be neglected was chosen the value of, R_b=1m. On this boundary a surface current density,

$$J_s = \frac{-(I_1 + I_2)}{2\pi R_b}, \tag{10}$$

was supposed, providing total current to be zero.

Generated mesh is adaptive, with smaller elements inside the conductors and in its vicinity.

The applied program support several possibilities of calculated results presentations. In this paper a common way to presentation is chosen. The resistance coefficient, also known as coefficient of resistance, skin effect ratio and extra loss coefficient, has been presented as a function of frequency and as a function of term, $\sqrt{f/R_{=}}$,

$$\frac{R_{\approx}}{R_{=}} = f(f) \quad \text{and} \quad \frac{R_{\approx}}{R_{=}} = f(\sqrt{\frac{f}{R_{=}}}). \tag{11}$$

The most common way to present DC and AC resistance is to express them in Ω/km.

5 Numerical Results

In order to achieve the best conductor's arrangement, meaning the most uniform current distribution across the conductor's cross section, all positions shown in Fig. 2 were examined. As an example in Fig. 4 a current distribution in two busbars of type U14, on a frequency of 150Hz, is presented.

The reason of this choice of frequency lies in the fact that both effects are more emphasized than on basic frequency 50Hz and in the same time this is the third harmonic, the mostly present in electrical networks.

Comparing all five positions, arrangement shown in Fig. 4 was confirmed as the best solution, with the most uniform current distribution and the least significant skin effect and proximity effect.

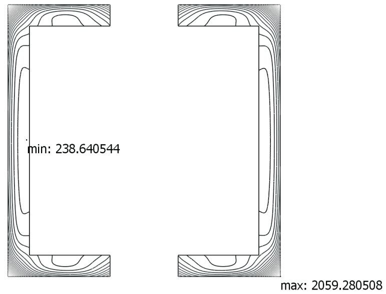

Fig. 4. Current distribution in U14 busbar type, f=150Hz.

In order to determine resistance coefficient $R_{\approx}/R_{=}$, a DC resistance per unit length had to be calculated first,

$$R'_{=} = \rho \frac{l}{S}. \tag{12}$$

After that, applying (9), AC resistance, $R_{\approx}$, for different frequencies, was calculated. Both, average heating losses defined in (8) and AC resistance (9) were determined with postprocessing integration in COMSOL package.

As an example, calculated values of resistance coeffcient, $R_{\approx}/R_{=}$, for four standardized dimensions and different frequencies, are graphically presented in Figs. 5 and 6. All results are for conductor's arrangement shown in Fig. 2d.

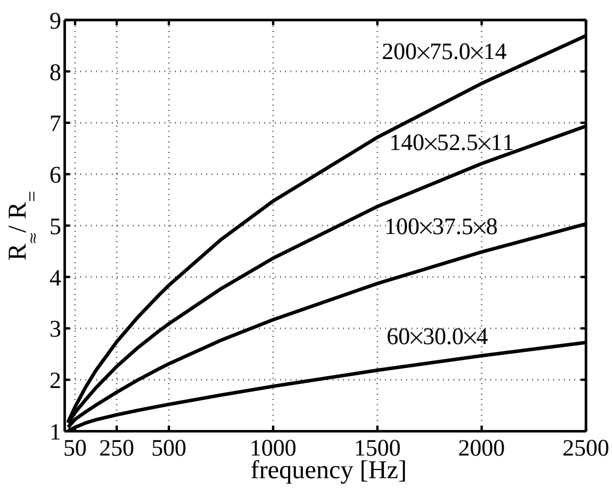

Fig. 5. Frequency diagram of resistance coefficient.

Another tipical diagram of resistance coefficient, $R_{\approx}/R_{=}$, as a function of term

$\sqrt{f/R_{=}}$ is commonly used in conductor's caracteristic presentations. This funcionally dependance is very convinient because it bearly depends on conductors cross section area.

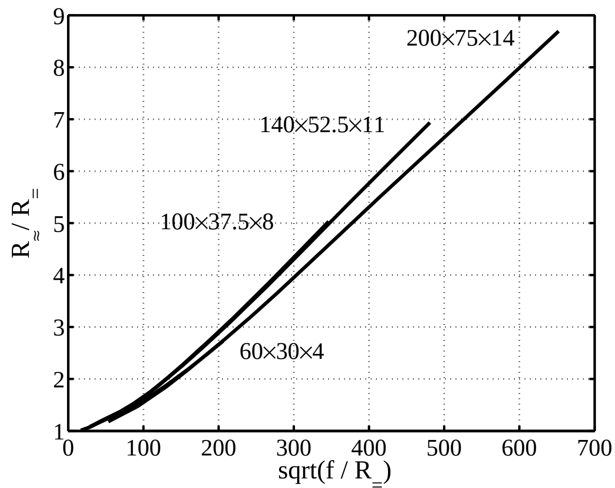

Fig. 6. Resistance coefficient as a function of $\sqrt{f/R_{=}}$.

As expected, all those results show clearly, that resistance coefficient increase with increasing busbars cross section area and increasing frequency.

Results for five different positions and six different distances of two aluminium U14 busbars are given in Table 2. In all cases, the complex current in both coupled busbars was chosen to be $\underline{I}$ = (1+j0)A, in the same direction, on frequency of 150Hz.

Table 2. Resistance coefficient of standardized U-shaped conductors.

	⊏⊏ (a)	⊐⊏ (b)	⊏⊐ (c)	⊔⊔ (d)	⊏⊐ (e)
d(mm)	$R_{\approx}/R_{=}$				
0	-	-	-	-	1.89
25	2.12	2.56	1.71	1.87	1.77
35	2.06	2.48	1.68	1.84	1.73
50	2.00	2.38	1.65	1.81	1.69
100	1.85	2.13	1.59	1.73	1.60
200	1.72	1.90	1.55	1.67	1.55

As it could be concluded, the best results (minimal resistance coefficient), are obtained for the third position and maximal distance between the conductors.

In the next diagram, shown in Fig. 7, the obtained values of resistance coefficient from Table 2 are presented.

This diagram is of crucial importance for our goal.

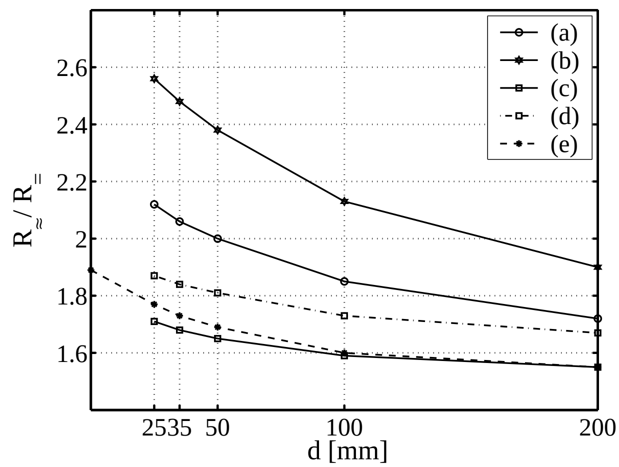

Fig. 7. Resistance coefficient for different busbars arrangement and distances.

Namely, on the diagram is shown resistance coefficient depending on conductor's arrangement and conductor's distances and we expected that, for some of busbars position, resistance coefficient should increase with increasing distance between two coupled conductors. In that case, we could conclude that our attempt was successful and that we achieved desired result, i.e. that the induced currents as a source of proximity effect are in opposite direction to the induced currents provoking skin effect, decreasing total Joule's losses in coupled conductors.

But, as it can be seen in Fig. 7, the resistance coefficient is decreasing with increasing distances, meaning that both effects are increasing total Joule's losses.

However, another interesting result appears in our calculations.

As shown in Fig. 8, frequency dependence of resistance coefficient does not depend much on busbars arrangements, for different distances between conductors.

As it also can be seen in Fig. 8, frequency dependence of resistance coefficient barely depends on busbars positions. The resistance coefficient decreases with increasing distances. This decreasing of resistance coefficient is obviously the consequence of decreasing proximity effect.

6 Conclusion

The influence of mutual position and distances of two coupled busbars, for some standardized dimension of a U-shaped time varying current carrying conductor, for different frequencies are analysed.

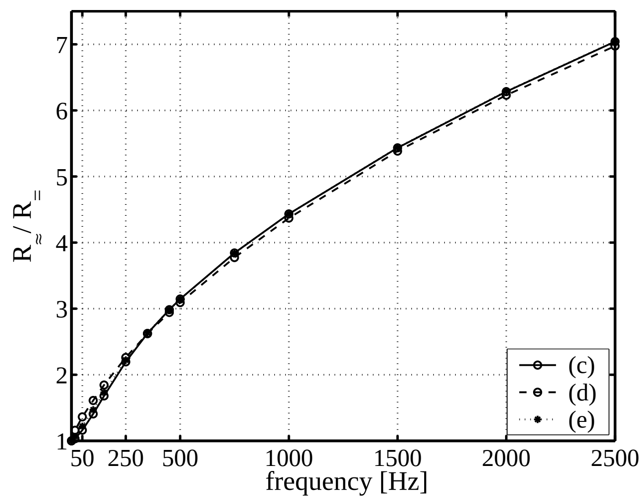

Fig. 8. Frequency diagram of resistance coefficient for $d = 35mm$.

In order to achive confrontation of skin and proximity effects, different distances, out of standardized ones, were taken into consideration, as well.

The optimization criterion was the total resistance per kilometer. Considering all aspects of reducing energy loss and achieving high performances of busbars, all the efforts we made are presented in this paper.

However, we still did not succeed to persuade proximity effect to decrease additional losses due to skin effect. In the paper is shown also that the software package COMSOL Multphisics 3.5a can successfully determine all parameters of any conductor system, so it can be applied for power system construction optimization.

Acknowledgment

This work was partially supported by the Serbian Ministry of Sciences and Technology as a part of the Project No. 18043, 2008-2010.

References

[1] K. Kasaš-Lažetić and M. Prša, "Proximity effect against skin effect in two coupled U-shaped busbars," in *Simpozijum INFOTEH Jahorina*, Jahorina, BiH, Mar. 18–20, 2009.

[2] ——, "Proximity effect against skin effect in two coupled U-shaped busbars - attempt II," in *9th International Conference on Applied Electromagnetics PES 2009*, Niš, Serbia, Aug. 31–Sept. 02, 2009.

[3] M. Prša and K.Kasaš-Lažetić, "Frequency dependent current distribution and impedance in a U-shaped busbar," in *Acta Electrotehnica, Proceedings of the 2nd International Conference on modern Power Systems MPS 2008*, Nov. 12–14, 2008, pp. 404–407.

[4] L. Gerić, *Razvodna postrojenja*. Novi Sad, Serbia: Univerzitet u Novom Sadu, Fakultet tehničkih nauka Novi Sad, 2006, (in Serbian).

[5] B. D. Popović, *Elektromagnetika*. Beograd, Serbia: Građevinska knjiga, 2000, (in Serbian).

[6] M. Stojaković, *Matematička analiza 2 - drugi deo*. Novi Sad: Fakultet tehničkih nauka Novi Sad, 2001, (in Serbian).

[7] *COMSOL MULTIPHYSICS, CLS 3.5 documentation*, 2008.