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THE INFLUENCE OF UNBALANCED CURRENT IN BUS BARS ON MAGNETIC FIELD DISTRIBUTION

VPLIV NEURAVNOTEŽENEGA TOKA V ELEKTRIČNIH ZBIRALKAH NA PORAZDELITEV MAGNETNEGA POLJA

Miodrag Milutinov [1ℜ], Karolina Kasaš Lažetić [1], Teodora Spasić [1], Miroslav Prša [2]

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Abstract

The analysis of magnetic field and current density distribution in the case of a three phase bus bar system with a current of 500 A is presented in this paper. The impact is investigated of the position of the neutral conductor on the magnetic field and current density distribution. The main goal of the calculations was to find the position of the neutral conductor which produces the lowest magnetic field and current density in the case of current unbalance. The numerical calculations were performed in the COMSOL Multiphysics program package on a simplified 2D model. The calculation results are presented graphically, as the diagrams of the magnetic flux and current density magnitude distribution in the three-phase bus bar system plane, are perpendicular to the system's axis. The obtained results show that, in both cases, (current balance and current unbalance), the position of the neutral conductor influences the magnetic flux density distribution.

Povzetek

V prispevku je predstavljena analiza porazdelitve magnetnega polja in gostote toka v primeru trifaznega zbiralnega sistema s tokom 500 A. Raziskuje se vpliv položaja nevtralnega vodnika na magnetno polje in porazdelitev gostote toka. Glavni cilj izračunov je bil najti položaj nevtralnega vodnika, ki proizvaja najmanjše magnetno polje in gostoto toka v primeru tokovne

1ℜ Corresponding author: Prof. Miodrag Milutinov, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, Tel.: +381 63 352 601, E-mail address: miodragm@uns.ac.rs

1 University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia

2 Retired from the University of Novi Sad, Faculty of Technical Sciences

neuravnoteženosti. Numerični izračuni so bili izvedeni v programskem paketu COMSOL Multiphysics na poenostavljenem 2D-modelu. Rezultati izračuna so predstavljeni grafično kot diagrami porazdelitve magnitude magnetnega pretoka in gostote toka v ravnini trifaznega sistema zbiralk, pravokotni na os sistema. Dobljeni rezultati kažejo, da v obeh primerih (tokovno ravnotežje in tokovno neuravnoteženost) položaj nevtralnega vodnika vpliva na porazdelitev gostote magnetnega pretoka.

1 INTRODUCTION

Parts of a power delivery system, such as distribution lines, generate a magnetic field at a frequency of 50/60 Hz, which belongs to the extremely low frequency range (ELF) from 3 Hz to 3 kHz. Depending on the intensity, this magnetic field could have influence on various biological systems, both by short and continuous exposure [1][2]. The level of the adverse effect depends on the magnetic field`s magnitude and frequency. Two common magnetic field quantities are the magnetic field strength and the magnetic flux density, denoted by H and B, respectively. Although the influence of magnetic fields on the human body and tissue is complex, these two quantities are used to estimate the potential adverse health effect. Based on extensive scientific literature, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) proposed the so-called referenced level for the occupational and general public exposure to electromagnetic fields (EMF) [3], which became the basis for national legislation worldwide, and it was adopted without any changes. The reference levels are used for easy and quick estimation of adverse health effects by comparing their value with the measured/calculated values. The reference levels of the magnetic field and the magnetic flux density for general public exposure at the frequency of 50/60 Hz are 160 A/m and 200 µT, respectively, as prescribed by ICNIRP. These reference levels for public exposure to EMF became the basis for national legislation worldwide. Many countries have adopted these levels without any changes. Serbia's national legislation [4], prescribes five times lower values; 32 A/m of magnetic field intensity and 40 µT of magnetic flux density vector magnitude, which are considerably lower, and ensure additional safety for the general public. Both physical quantities must be measured or calculated in free space (in air) around the current carrying conductors. In a vacuum the magnetic field strength and the magnetic flux density (MFD) are related trough the vacuum permeability expressed by the following equation

$$B = \mu_0 H \tag{1.1}$$

where the vacuum permeability is a constant, taking the value of $\mu_0 = 4\pi \cdot 10^{-7}$ H/m. The same relation could be used in the air around the conductor allowing measurement or calculation of only one of the quantities.

The magnitude of the MFD generated by distribution lines depends on the currents and geometry of the system, as shown in [5]-[7]. In a three-phase system, the currents in the phase conductors are expressed by

$$\begin{aligned} i_1 &= I_1\sqrt{2}\cos(\omega t + \psi_1), \\ i_2 &= I_2\sqrt{2}\cos(\omega t + \psi_2), \\ i_3 &= I_3\sqrt{2}\cos(\omega t + \psi_3). \end{aligned} \tag{1.2}$$

By aligning the conductors with the z direction of the Cartesian coordinate system an MFD has only x and y components, as depicted in Fig. 1. Pair $k-\text{th}$ present the coordinate of the centre line of the $k-\text{th}$ conductor, while pair (x,y) present the coordinate of the point in the plane.

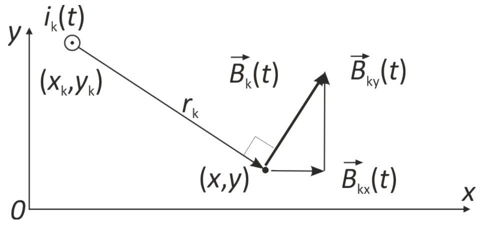

Figure 1: *MFD vector in the plane perpendicular to the conductors*

The net x and y component of MFD is equal to the following sums:

$$B_x(x,y,t) = -\frac{\mu_0}{2\pi}\sum_{k=1}^{3}\frac{i_k(t)}{r_k^2}(y-y_k), \tag{1.3}$$

$$B_y(x,y,t) = \frac{\mu_0}{2\pi}\sum_{k=1}^{3}\frac{i_k(t)}{r_k^2}(x-x_k). \tag{1.4}$$

The intensity and orientation of the MFD at any point in the xy plane besides the positions of the conductors and amplitudes of the currents, depends on the phase arrangement. In a three-phase circuit, the system could be balanced or unbalanced. A three-phase circuit is balanced if the phase currents are of the same amplitudes and the phase of each current is shifted 120° from each other. If either or both conditions are not met, the circuit is unbalanced [8].

The usual assumption is that currents are balanced, where an unbalanced current could affect the magnetic field distribution additionally [9]-[12]. In a power transmission subsystem with only three phase conductors the three-phase circuit is nearly balanced, where several ways to quantify the current unbalance existed in the literature. Some of them are used in the author's previous works [13]-[15], where it was presented how the current unbalance affects the magnetic field distribution in the vicinity of the power lines. In these papers the authors showed that a magnetic field generated by an unbalanced circuit drops more slowly with distance than in the balanced case. Also, they tried to find the correlation between current unbalance and MFD deviation.

The power delivery subsystem has an additional, so-called neutral conductor, with instantaneous current i_0 equal to the sum of the three phase currents, expressed by

$$i_0(t) = i_1(t) + i_2(t) + i_3(t). \tag{1.5}$$

The current in the neutral conductor is in the opposite direction, and generates an additional magnetic field, which reduces the net magnetic field. The influence of current unbalance in a 3+1 subsystem on the magnetic flux density magnitude and polarisation of the magnetic field is presented in the author's previous works [16]-[19]. In this paper, the influence is examined of the neutral conductor position that provides the lowest magnetic field outside the system. It is assumed that the currents are phase shifted by 120° from each other, and only amplitude unbalance is considered.

2 MODEL

A model of the energy bus bar system from the E-LINE-KX catalogue produced by EAE Corporate is analysed in this paper [20]. It was created with sheets of insulated copper conductors placed in a closed aluminium housing, as shown in Fig. 2. According to the manufacturer`s information, the rated current I_R of the analysed bus bar is 500 r.m.s. This rated current was used for the MFD calculation.

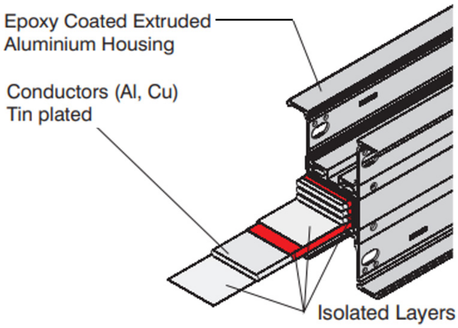

Figure 2: *Analysed bus taken from the catalogue [20]*

The cross-section of the model with dimensions expressed in (mm) is shown in Fig. 3. The cross-section of each copper conductor is $6 \times 25\,\mathrm{mm}^2$ coated with 1 mm epoxy as isolation between the conductors. The conductors are labelled with numbers 1, 2, 3, and 0, where the numbers from 1 to 3 correspond to phase currents, and 0 presents the neutral conductor.

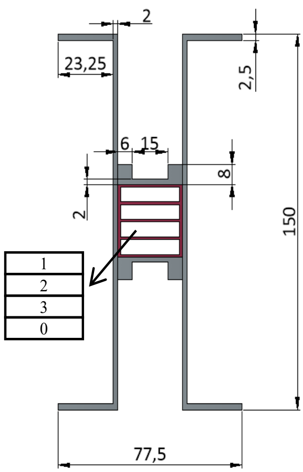

Figure 3: *The cross-section of the analysed bus bar*

Calculation of the current density distribution inside the conductors and the magnetic flux density in the air around the bus bar was done in the COMSOL Multiphysics software package, which solves partial differential equations using the Finite Element Method. For these calculations a 2D model of the system was created, and the following equations were applied

$$\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{J}_e, \qquad (2.1)$$

$$\vec{J} = -\sigma \frac{\partial \vec{A}}{\partial t} \qquad (2.2)$$

where σ and $\vec{J}_e$ are the conductivity and the permeability of the material applied in the model, $\vec{J}_e$ is the applied external current density, $\vec{A}$ is the induced current density, and $\vec{A}$ is the magnetic vector potential. The magnetic flux density was calculated by the following equation

$$\nabla \times \vec{B} = \frac{1}{\mu}\left(\vec{J} + \vec{J}_e\right) \qquad (2.3)$$

The influence of the position of the neutral conductor on the current density distribution and the magnetic flux density distribution was analysed in the balanced and the unbalanced cases.

In the balanced case, the rated current $= 500\text{A}$ was applied to all three phase conductors. In the unbalanced case the current in one of the phase conductors was assumed to be up to 20% lower. For example, the notation 1-1-0.8 means that $I_1 = I_R$, $I_2 = I_R$ and $I_3 = 0.8 I_R$. Additionally, the magnitude of the magnetic flux density vector was calculated along the *x*-axis outside the bus bar housing. Comparing the magnitudes of the magnetic flux density in both the balanced (denoted with B_0) and unbalanced cases (denoted with *B*), the relative deviation was calculated as

$$\delta B = \frac{B - B_0}{B_0} \cdot 100\% \qquad (2.4)$$

3 RESULTS

Fig. 4 shows the MFD distribution inside the bus bar in the balanced case at 50 Hz for all possible positions of the neutral conductor. In the balanced case there was no external current applied to the neutral conductor. The induced current in the neutral conductor is negligible at a frequency of 50 Hz, therefore, the position of the neutral conductor impacts the magnetic field only by increasing the spatial distance between the phase conductors.

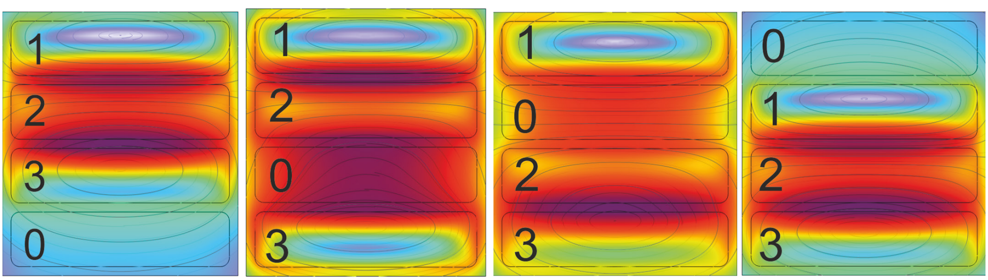

Figure 4: *MFD distribution inside the bus bar in the balanced case at 50 Hz*

The induced current in the neutral conductor increases by increasing the frequency of the external applied current. Repeating the calculations at a frequency of 450 Hz MFD distribution inside the bus bar are shown in Fig. 5. This frequency was chosen as the 9-th harmonic of the fundamental frequency. At this frequency skin effect and proximity effect affect the MFD distribution.

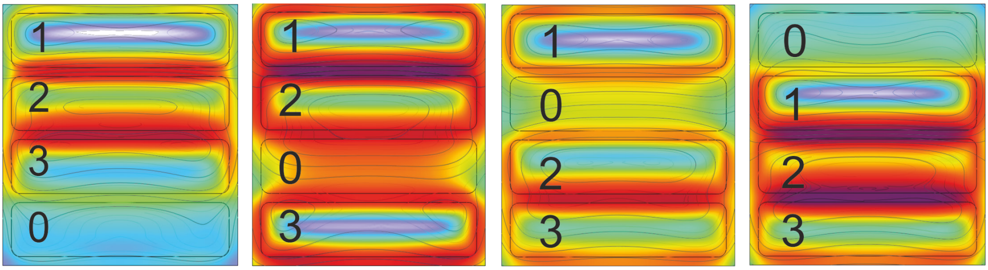

Figure 5: *MFD distribution inside the bus bar in the balanced case at 450 Hz*

Figs. 6 and 7 show the MFD distribution outside the bus bar at 50 Hz and 450 Hz in the balanced case, respectively. The position of the neutral conductor impacts the distribution of the MFD only near the bus bar. Increasing the distance from the bus bar this impact becomes negligible.

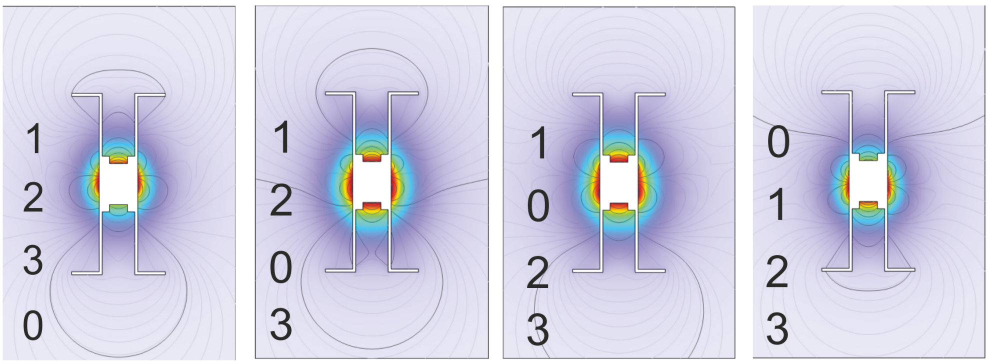

Figure 6: *MFD distribution outside the bus bar in the balanced case at 50 Hz*

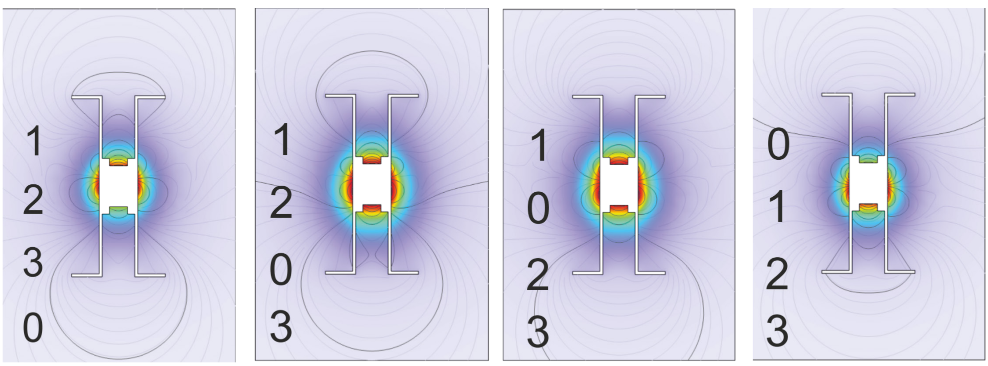

Figure 7: *MFD distribution outside the bus bar in the balanced case at 50 Hz*

In the case of an unbalanced current, the MFD had a different distribution, even further from the bus bar. Increasing the unbalance, the MFD becomes more dependent on the position of the neutral conductor. The MFD distribution in the unbalanced case, when the current in the third conductor was $I_3 = 0.8I_R$, is shown in Fig. 8.

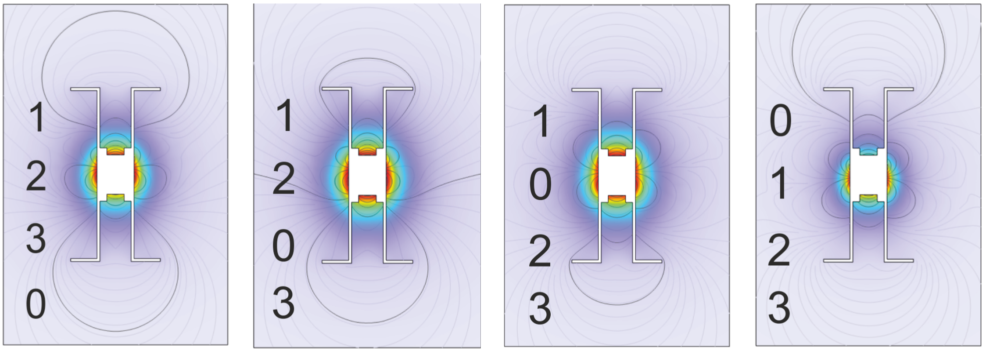

Figure 8: *MFD distribution outside the bus bar in the unbalanced case 1-1-0.8, at 50 Hz*

MFDs calculated only along the *x*-axis for all four positions of the neutral conductor in the balanced and unbalanced cases are shown in Fig. 9 and Fig. 10, respectively. The magnitude of the MFD was calculated outside of the bus bars, starting at x =20 mm from an origin located in the centre of the bus bar. It can be seen in more detail how the MFD magnitude depends on the position of the neutral conductor. In the balanced case (Fig. 9) the magnitude decreases faster if the neutral conductor is outside the deck, (see lines labelled 1230 and 0123). The reference levels of 200 uT and 40 uT were reached at about 65 mm and 140 mm outside of the bus bar, respectively. In the unbalanced case (Fig. 10) for the current combination 1-1-0.8, the lowest MFD occurred for the 0123 layout, when the neutral conductor was located furthest from the conductor with the lower current. Other combinations, for example, 1-0.8-1 or 0.9-1-1, give different positions of the neutral conductor that generated the lowest MFD.

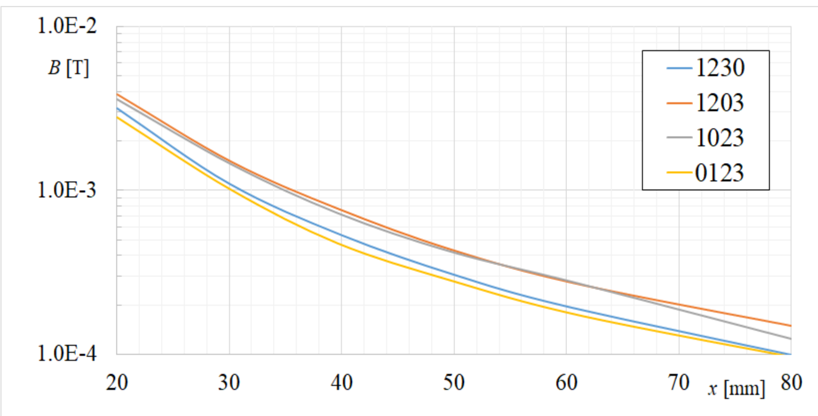

Figure 9: *MFD distribution outside the bus bar in the unbalanced case 1-1-0.8, at 50 Hz*

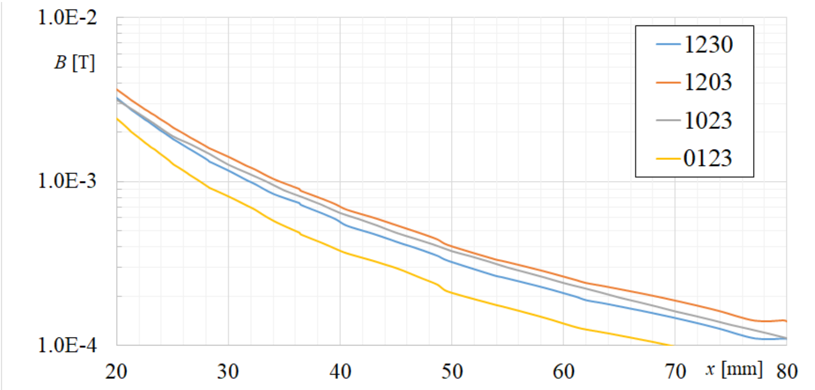

Figure 10: *MFD distribution outside the bus bar in the unbalanced case 1-1-0.8, at 50 Hz*

By analysing all the combinations of currents and positions of the neutral conductors and applying equation (2.4), the relative deviation of the magnitude of the MFD along the x-axis for all combinations is listed in the following Tables. Each column (except the first one) corresponds to one combination of current intensity in phase conductors 1, 2 and 3, respectively.

Table 1: *Relative deviation of MFD for a "1-2-3-0" layout*

x (mm)	*0.9-1-1*	*0.8-1-1*	*1-0.9-1*	*1-0.8-1*	*1-1-0.9*	*1-1-0.8*
20	-8%	**-14%**	-2%	-4%	1%	3%
30	-11%	**-20%**	-1%	-1%	3%	6%
40	-12%	**-23%**	0%	1%	4%	7%
50	-13%	**-24%**	0%	1%	4%	8%
60	-13%	**-25%**	0%	1%	4%	9%
80	-13%	**-26%**	0%	2%	4%	9%

Table 2: *Relative deviation of MFD for a "1-2-0-3" layout*

x (mm)	*0.9-1-1*	*0.8-1-1*	*1-0.9-1*	*1-0.8-1*	*1-1-0.9*	*1-1-0.8*
20	-5%	**-9%**	-2%	-4%	-3%	-5%
30	-5%	**-10%**	-1%	-2%	-3%	-6%
40	-5%	**-11%**	-1%	-2%	-3%	-7%
50	-6%	**-11%**	-1%	-2%	-3%	-7%
60	-6%	**-11%**	-1%	-2%	-3%	-7%
80	-6%	**-11%**	-1%	-1%	-3%	-7%

Table 3: *Relative deviation of MFD for a "1-0-2-3" layout*

x (mm)	*0.9-1-1*	*0.8-1-1*	*1-0.9-1*	*1-0.8-1*	*1-1-0.9*	*1-1-0.8*
20	-3%	-6%	-1%	-1%	-6%	**-11%**
30	-3%	-7%	0%	-1%	-6%	**-11%**
40	-4%	-7%	0%	-1%	-6%	**-11%**
50	-4%	-7%	0%	-1%	-6%	**-11%**
60	-4%	-7%	0%	-1%	-6%	**-11%**
80	-4%	-7%	0%	-1%	-6%	**-11%**

***Table 4:** Relative deviation of MFD for a "0-1-2-3" layout*

x (mm)	*0.9-1-1*	*0.8-1-1*	*1-0.9-1*	*1-0.8-1*	*1-1-0.9*	*1-1-0.8*
20	1%	3%	-3%	-5%	-7%	-12%
30	3%	7%	-1%	-1%	-11%	**-20%**
40	4%	8%	0%	1%	-12%	**-23%**
50	5%	9%	0%	2%	-13%	**-25%**
60	5%	9%	0%	2%	-14%	**-26%**
80	5%	10%	0%	2%	-14%	-26%

Positive values in each Table listed above mean that the MFD in the unbalanced case is higher than in the balanced case. If the MFD in the unbalanced case is less than the MFD in the balanced case, the values are negative. Searching for the columns with the most negative values, we could find the position of the neutral conductor that would provide the lowest MFD.

Table 1 has both positive and negative values, which means that the neutral conductor located at the bottom can both decrease or increase the net MFD, depending on the amplitudes of the phase currents. The same conclusion can be obtained observing Table 4. Tables 2 and 3 contained only negative values, leading us to the conclusion that the neutral conductor located in the middle of the bus bar decreased the net MFD for any combination of current amplitudes. Columns 2 and 3 in each Table listed above correspond to unbalance, due to an amplitude deviation in line L1. It can be noticed that increasing the amplitude deviation from 10% (0.9-1-1) to 20% (0.8-1-1) the MFD relative deviation nearly doubled. The same could be said by observing columns 4 and 5, and columns 6 and 7, corresponding with the amplitude deviation in lines L2 and L3, respectively. Increasing the current unbalance further increased the MFD deviation.

3 CONCLUSIONS

The presence of current unbalance in power distribution systems is inevitable, and for that reason the analysis of its impact on the magnetic flux density distribution in the vicinity of energy bus bar systems is always reasonable.

In the balanced case the current in the neutral conductor is zero, and the magnitude of the MFD decreases more rapidly if the phase conductors are closer to each other. Therefore, in the balanced case, the best position of the neutral conductor is at the top or at the bottom of the bus bar. In unbalanced cases the magnitude of the magnetic flux density vector depends on the position of the neutral conductor, and it could be lower or higher compared to the balanced case. The lowest magnetic flux density was obtained by relocating the neutral conductor from the outside (top or bottom) in the middle of the bus bar system, in between the phase conductors.

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