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POWER LINE MAGNETIC FIELD DEVIATIONS FOR THREE DIFFERENT DEFINITIONS OF CURRENT UNBALANCE

ODSTOPANJE MAGNETNEGA POLJA DALJNOVODA ZA TRI RAZLIČNE DEFINICIJE TOKOVNEGA NERAVNOVESJA

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Abstract

An estimation procedure of the public's exposure to the low-frequency magnetic field generated by overhead power lines, according to the international standards, implies measurement and an extrapolation. It is necessary to measure both the magnetic field around the lines and the current in the lines simultaneously. The extrapolation procedure implies the calculation of the maximum magnetic field that will occur when the line current achieves its maximum. The calculation relies on a proportion between the current in the power line and the magnetic field around the power line, which is valid only when the currents are balanced. Unfortunately, the standards do not cover the unbalanced cases. The relation between the current unbalance and magnetic field could improve the estimation procedure. In the literature, several different definitions of the current unbalance could be found. In this paper, a comparison of three different definitions of current unbalance and their relation to the deviation of a magnetic field are considered. The magnetic field is calculated in the vicinity of the bus bar. The same procedure could also be applied around overhead power lines. The definitions for the current unbalance used in this paper are derived from the existing definitions of the voltage unbalance. Only one of these three definitions considers phase unbalance. The relationships between current unbalance and the maximum deviation of the magnetic field are found to be proportional.

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Povzetek

Po mednarodnih standardih se za izpostavljenost nizkofrekvenčnemu magnetnemu polju, ki ga ustvarjajo nadzemni daljnovodi opravljajo meritve, katere je potrebno ekstrapolirati. Meritve magnetnega polja okoli vodnika in toka v vodniku je potrebno opravljati v enakem časovnem intervalu. Postopek ekstrapolacije pomeni izračun največjega magnetnega polja, ki se pojavi pri največjem linijskem toku. Izračun temelji na razmerju med tokom v daljnovodu in magnetnim poljem okoli daljnovoda, kar velja le, če so tokovi v ravnovesju. Razmerje med tokovnim neravnovesjem in magnetnim poljem bi lahko izboljšalo postopek ocenjevanja, vendar standardi tega ne upoštevajo. V literaturi je moč zaslediti več različnih definicij tokovnega neravnovesja. V tem prispevku je predstavljena primerjava med tremi različnimi definicijami tokovnega neravnovesja in njihovega razmerja do odstopanja magnetnega polja. Magnetno polje se izračuna v bližini zbiralke, pri čemer se lahko enak postopek uporabi pri nadzemnih daljnovodih. Definicija tokovnega neravnovesja je v tem prispevku izpeljana iz napetostnega neravnovesja, pri čemer je ena od treh definicij izpeljana iz faznega neravnovesja. Ugotovitve so pokazale, da je razmerje med tokovnim neravnovesjem in največjim odstopanjem magnetnega polja sorazmerno.

1 INTRODUCTION

As reported in Bio-Initiative, *[1]*, electromagnetic pollution and its effects on various biological systems, both by short and continuous exposure, have been the subject of extensive research for several decades. The magnetic fields generated at 50/60 Hz by overhead power lines or bus bars inside the building are categorized as being extremely low frequency (ELF). The reference levels for general public exposure at the frequency of 50 Hz of the magnetic field and the magnetic flux density prescribed by ICNIRP, *[2]*, are 160 A/m and 200 µT, respectively. Reference levels for the occupational and public exposure to EMF, proposed by ICNIRP, *[2]*, became the basis for national legislation worldwide. Many countries have been adopted these levels without any changes. Serbia's national legislation, *[3]*, prescribes five times lower values; 32 A/m and 40 µT. The reference levels in the legislation are considerably lower and ensure additional safety for the general public.

Measurements of the magnetic field generated by overhead power line and estimation of the maximal exposure are covered by standards such as IEEE 644-1994 [4] and IEC 62110:2009, *[5].* According to *[5]*, the values obtained by measurements are for the load conditions occurring at the time of measurement; therefore, these values need to be extrapolated to consider the maximum load of the circuits. This extrapolation procedure assumes that the power line currents are balanced, and equation (1) in *[5]* should be applied. The current unbalance causes the magnetic field deviation and thus introduces additional uncertainty in the adopted procedures, as authors have discussed in *[6]-[10].* Multiple different definitions of the voltage unbalance could be found in the literature. As opposed to the previously published papers, *[6]-[10]*, in which only one of the definitions is used, in this research the authors utilized three definitions of current unbalance and consider the correlations of current unbalance with the deviation of the magnetic field for all three definitions.

2 CURRENT UNBALANCE

A three-phase circuit is considered balanced if the phase voltages and the phase currents are of the same amplitude and its phases are shifted by 2π/3 from each other. If either or both of these conditions are not met, the circuit is considered unbalanced (see e.g., *[11]*). Fig. 1 illustrated the phasor diagram of phase currents in balanced and unbalanced cases. Based on *[12]*, we adjusted three definitions of voltage unbalance for current unbalance. The first two definitions considered only amplitude unbalance, and the last one both amplitude and phase unbalance.

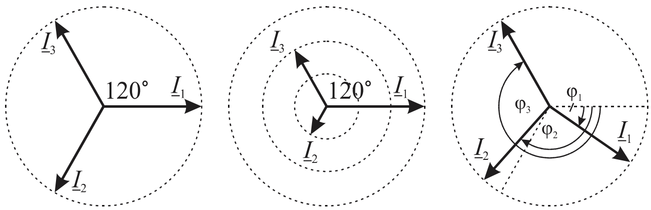

Figure 1: *Phasor diagrams of a) the balanced phase currents, b) magnitude unbalanced phase currents and c) phase unbalanced phase currents*

The first definition considers the maximum deviation of currents from the average value. It is defined by

$$u_{I1} = \frac{\max(|I_1 - I_{avg}|, |I_2 - I_{avg}|, |I_3 - I_{avg}|)}{I_{avg}} \cdot 100\ \%, \tag{2.1}$$

where I_1, I_2 and I_3, represent root-mean-square (RMS) values of the phase currents, while $I_{avg} = (I_1 + I_2 + I_3)/3$.

The second definition uses the difference of the maximum and the minimum RMS values as the measure for the unbalance. It is described by

$$u_{I2} = \frac{\max(I_1, I_2, I_3) - \min(I_1, I_2, I_3)}{I_{avg}} \cdot 100\ \%. \tag{2.2}$$

The third definition is the so-called " true definition of unbalance" because it accounts for both amplitude and phase unbalance. For $a = e^{j2\pi/3}$, it is given by:

$$u_{I3} = \frac{\left|\underline{I}_1 + a^2 \underline{I}_2 + a \underline{I}_3\right|}{\left|\underline{I}_1 + a \underline{I}_2 + a^2 \underline{I}_3\right|} \cdot 100\ \%. \tag{2.3}$$

All three current unbalances u_{I1}, u_{I2}, and u_{I3} are expressed in percentages.

3 CALCULATION METHOD

In this paper, the magnetic field is calculated near horizontally aligned bus bars illustrated in Fig. 2. The system consists of three phase conductors and a neutral one. The phase currents are denoted by $\underline{I}_1$, $\underline{I}_2$, and $\underline{I}_3$. The current in the neutral conductor is denoted by $\underline{I}_N$, where $\underline{I}_N = -\left(\underline{I}_1 + \underline{I}_2 + \underline{I}_3\right)$. Reference directions of the phase currents are out of the *xy* plane, and they are the same as the reference direction of the current in the neutral conductor. Conductors are assumed to be straight and parallel. Instead of the rectangular cross-section of the conductor, a current filament in the centre of the conductors are considered. The centre of the conductors is separated by $d = 15\,cm$. Applying the Biot-Savart law, the magnetic flux density is calculated in the cross-section of the bars (*xy* plane).

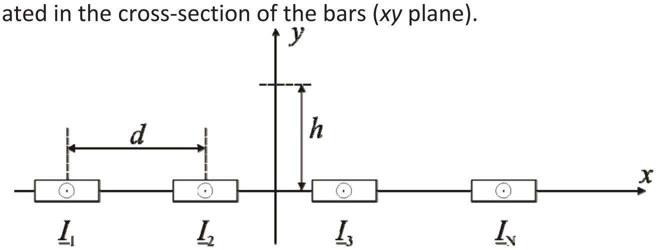

Figure 2: *Cross-section of the analysed system. Bus bars consisted of three phase and one neutral conductor horizontally aligned*

The deviation of magnetic flux density is defined as

$$\delta B = \frac{(B - B_0)}{B_0} \times 100\%, \tag{3.1}$$

where $B_0 = \left|\underline{B}_0\right|$ and $B = \left|\underline{B}\right|$ denote the magnetic flux density in balanced and unbalanced cases, respectively. B_0 is calculated assuming that the RMS values of all three phase currents $\underline{I}_1$, $\underline{I}_2$, and $\underline{I}_3$ are the same and equal to the I_{avg}; and phases of the phase currents are 0, -120°, and 120°, respectively. Current unbalance is achieved either by changing the RMS value or the phase of the phase current. In what follows, the four cases of unbalance, listed in Table 1, are considered. The bold text is used to denote a quantity that sweeps its values through a defined range. The remain quantities keep their value unchanged.

Table 1: *List of four analysed cases. The bolded quantity sweeps its values through a defined range*

Case	RMS (A)	Angle (°)
1	a) $\boldsymbol{I_1}, I_2, I_3$ b) $I_1, \boldsymbol{I_2}, I_3$ c) $I_1, \boldsymbol{I_2}, \boldsymbol{I_3}$	a), b), c) $\varphi_1, \varphi_2, \varphi_3$
2	a) $\boldsymbol{I_1}, \boldsymbol{I_2}, I_3$ b) $I_1, \boldsymbol{I_2}, \boldsymbol{I_3}$ c) $\boldsymbol{I_1}, I_2, \boldsymbol{I_3}$	a), b), c) $\varphi_1, \varphi_2, \varphi_3$
3	a), b), c) I_1, I_2, I_3	a) $\boldsymbol{\varphi_1}, \varphi_2, \varphi_3$ b) $\varphi_1, \boldsymbol{\varphi_2}, \varphi_3$ c) $\varphi_1, \varphi_2, \boldsymbol{\varphi_3}$
4	a), b), c) I_1, I_2, I_3	a) $\boldsymbol{\varphi_1}, \boldsymbol{\varphi_2}, \varphi_3$ b) $\boldsymbol{\varphi_1}, \varphi_2, \boldsymbol{\varphi_3}$ c) $\varphi_1, \boldsymbol{\varphi_2}, \boldsymbol{\varphi_3}$

For example, in the first case, the amplitude unbalance is obtained by sweeping the RMS of only one phase current in the range of 100 A ± 20 %. The currents in the other two phases are kept unchanged to the value of 100 A. In the second case, the amplitude unbalance is obtained by sweeping the RMS of two phase currents in the range of 100 A ± 20 %, while the value of the third phase current remains unchanged. In the third case, only the phase unbalance is allowed. The phase of only one phase current is changed in the range of $\varphi \pm 15°$. In the fourth case, the phases of two currents in the range of $\varphi \pm 15°$ being swept. In all considered cases, the RMS values of the currents take the values from 80 A to 120 A with the step size of 2 A, while the phases take the values from $\varphi - 15°$ to $\varphi + 15°$ with the step of $1°$.

Combinations of cases (1,3), (1,4), (2,3), and (2,4), in which both the amplitude and phase could be changed, are possible in practice, but they are not considered in this paper.

4 RESULTS

A deviation of magnetic flux density and current unbalance is calculated for all four cases at several points located on the *y*-axis at height h above the bus bar. Figures 3, 4, 5, and 6 show magnetic flux density relative deviation versus current unbalances at $h = 1\,m$. Each figure is related to one case, and each graph is related to one subcase. On all graphs, each set of dots is related to one of the definitions of current unbalance explained before. For the balanced currents $u_I = 0$, and the corresponding deviation is $\delta B = 0$. When the unbalance increases, the deviation also increases. The goals of this research are to determine the relation between these two quantities and to compare this relation for all three definitions.

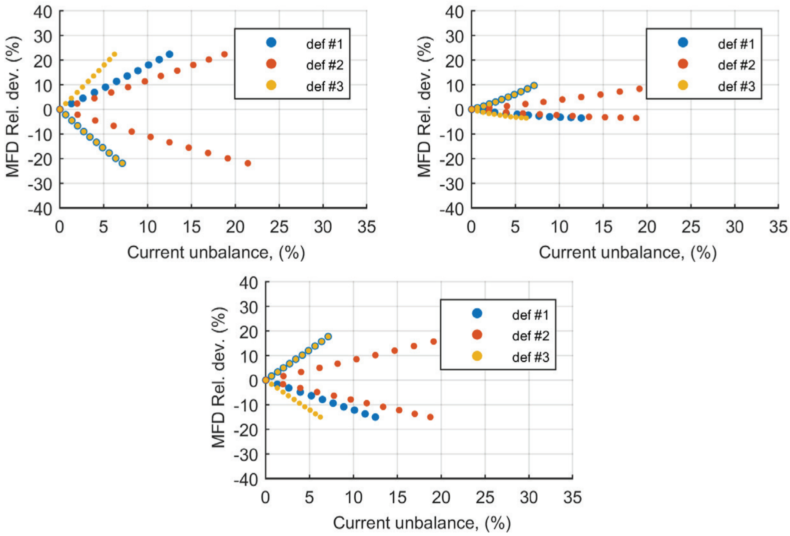

Figure 3: *Relation between current unbalance and deviation of the magnetic flux density for case 1, and subcase a, b and c, calculated at h=1m*

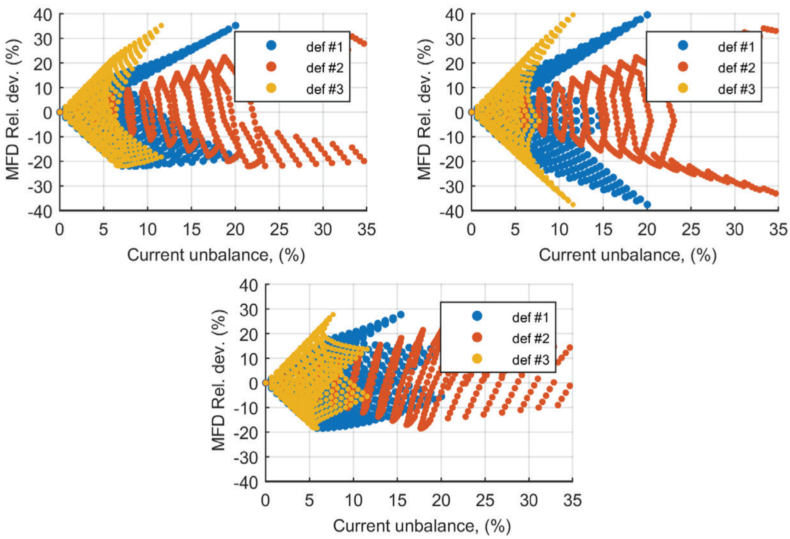

Figure 4: *Relation between current unbalance and deviation of the magnetic flux density for Case 2, and Subcases a, b and c, calculated at h=1m*

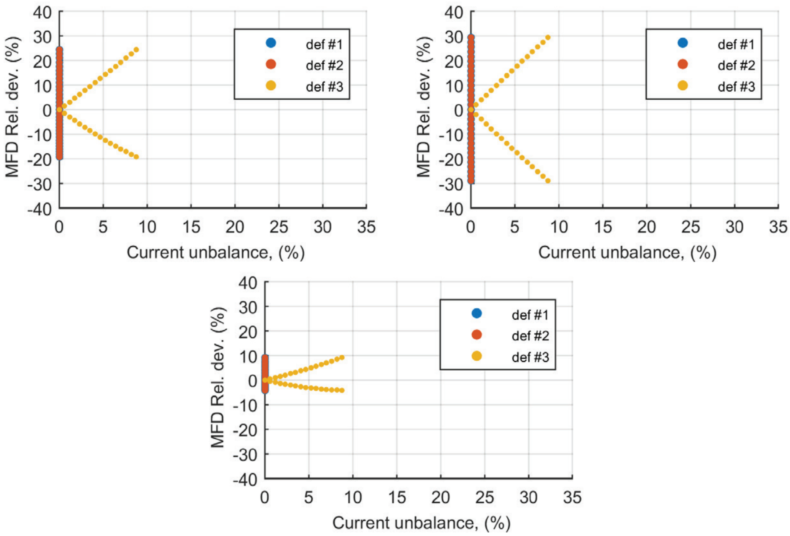

Figure 5: *Relation between current unbalance and deviation of the magnetic flux density for Case 3, and Subcases a, b and c, calculated at h=1m*

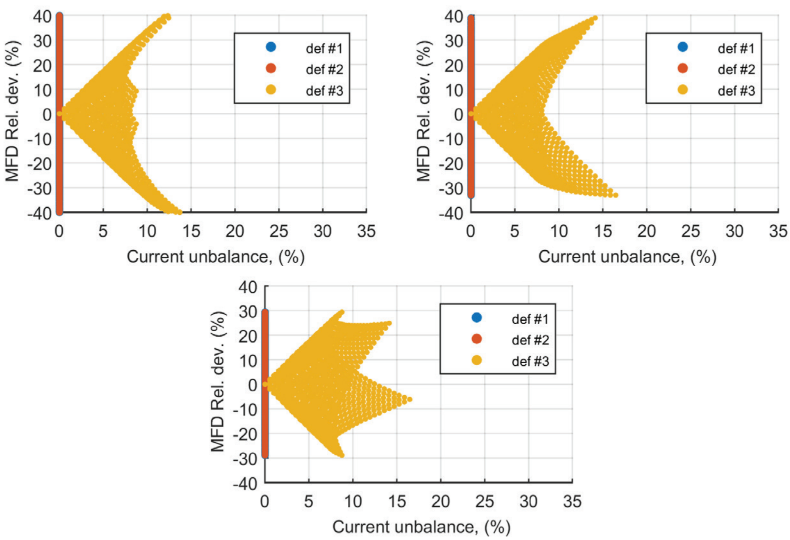

Figure 6: *Relation between current unbalance and deviation of the magnetic flux density for Case 4, and Subcases a, b and c, calculated at h=1m*

In Cases 1 and 2, an increase of the current unbalance results in an almost linear spreading of the range of magnetic field deviation, for all three definitions. In all graphs, δB populates the area bounded with a positive and a negative slope. This means that the relationship between current unbalance and the maximum magnetic field deviation can be described by:

$$\delta B = k u_I , \tag{4.1}$$

where k denotes the slope coefficient. Definition 3 experiences the fastest spreading and has the steepest slope. Recall that Definitions 1 and 2, do not consider the phase unbalance. Hence, in Cases 3 and 4, the current unbalance is nonzero only for Definition 3. In both cases, for Definition 3, a linear dependency between the current unbalance and the range of deviation can be observed.

In each case, subcase with the steepest slope, either positive or negative, can be determined. The slope coefficients for all previous graphs are listed in Table 2. The steepest slope achieved using Definition 1 has a coefficient $k=-3.38$, for Definition 2 the steepest slope has $k=1.21$, while for Definition 3 $k=3.63$. All these values are obtained in Case 2, Subcase c. By observing all three definitions, the steepest slope $k=3.63$ is obtained by using Definition 3.

For example, the value of $k=3.63$ shows that at 1 m above bus bars, the magnetic field generated by currents with 10% of unbalance is up to 36.3% higher than the magnetic field generated by balanced currents.

Table 2: Positive/negative slope coefficients for the point located on the y-axis at h=1m above bus bars.

Case	Subcase	Definition 1	Definition 2	Definition 3
1	a	1.79 / -3.38	1.19 / -1.13	3.57 / -3.38
	b	1.34 / -0.46	0.45 / -0.31	1.34 / -0.93
	c	2.47 / -1.22	0.82 / -0.81	2.47 / -2.44
2	a	2.47 / -3.38	1.19 / -1.13	3.61 / -3.48
	b	2.47 / -3.38	1.19 / -1.13	3.63 / -3.48
	c	2.47 / -3. 38	1.21 / -1.13	3.63 / -3.48
3	a	inf / inf	inf / inf	2.78 / -2.57
	b	inf / inf	inf / inf	3.38 / -3.38
	c	inf / inf	inf / inf	1.05 / -0.77
4	a	inf / inf	inf / inf	3.52 / -3.55
	b	inf / inf	inf / inf	3.52 / -3.55
	c	inf / inf	inf / inf	3.52 / -3.55

Increasing the distance from the bus bars from *h*=1m to *h*=2m another set of 12 graphs could be obtained. The steepest slope once again is obtained in Case 2 Subcase c, for Definition 3, with the correlation coefficient $k=3.70$. Furthermore, at *h*=3m the correlation coefficient is $k=3.71$. Hence, the correlation coefficient increases very slowly with the increasing the distance from the bus bars.

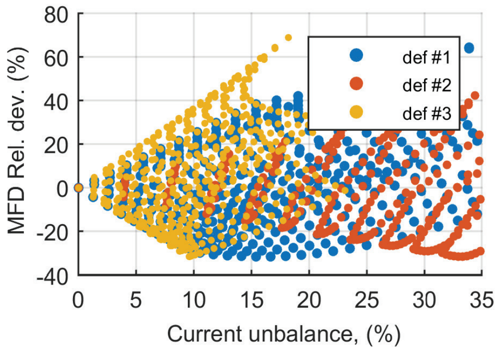

Figure 7: *Relation between current unbalance and deviation of the magnetic flux density for Case 2, and Subcase c, calculated at h=1m. I1=100A, while I2 and I3 are in a range from 60A to 140A*

Further increase of the current unbalance can be simulated by increasing the range of RMS values. Fig 7 shows the deviation of the magnetic flux density versus current unbalances in Case 2 Subcase c. RMS of the phase current I_2 and I_3 is in the range from 60 A to 140 A. The RMS value of the current I_1 remains 100 A. For Definition 3, the slope coefficient slightly increases from 3.63 to 3.78, implying that the upper boundary has a nearly constant slope.

5 CONCLUSIONS

The range of the magnetic field deviation considerably depends on the current unbalance. Moreover, the choice of the definition of the current unbalance significantly alters the corresponding range of magnetic field deviation. The widest range is obtained using the third definition, named “true definition of unbalance”. For the analyzed configuration, the boundary of the range of the deviation for this definition has a slope of about 3.7, and a slight increase with increasing the distance from the bus bars. Also, the slope slightly increases with increasing the deviation of amplitudes of currents. It can be concluded that the relationship between current unbalance and the maximum deviation of the magnetic field is linear.

Acknowledgment

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