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CALCULATIONS OF MAGNETIC FLUX DENSITY IN THE VICINITY OF THE 10/0.4 KV SUBSTATIONS WITH 0.4 KV BUSBARS

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Abstract. *The paper addresses a very important topic of the assessment of the general public exposure to magnetic fields in the vicinity of 10/0.4 kV substations. Previous testing results have shown that 10/0.4 kV substations located inside buildings can be a significant source of magnetic field in the rooms located next to them. The levels of magnetic flux density in these cases primarily depend on the transformer type and its rated power as well as on the equipment disposition in the substation. In the cases of substations with oil transformers, the dominant source of magnetic flux density in the environment are usually the 0.4 kV busbars, which connect the transformer and 0.4 kV switchboard. For that reason, the paper focuses on this type of 10/0.4 kV substations. The magnetic flux density levels are determined by calculations which are based on the model of 0.4 kV busbars. The busbars are modeled as straight-line conductors. The calculations are carried out for substations with 400 kVA, 630 kVA and 1000 kVA transformers, which are most commonly used in residential and other buildings. The calculations are repeated for different distances from the busbars and between them and for different values of the transformer rated load. The objective of the performed analysis is to reach general conclusions on the levels of magnetic flux density that may occur in the vicinity of the abovementioned substations, as well as the assessment of compliance with the regulations on the protection of the general public from electromagnetic fields. The obtained results have shown that in some cases the magnetic field levels can significantly exceed the prescribed reference levels. For that reason, the distances from the busbars at which the reference levels will not be exceeded were calculated in the paper for different rated powers of the transformers. The distances calculated in this paper can be used during the design of new substations inside buildings, in order to avoid the appearance of high magnetic field values.*

Keywords*: calculation, magnetic field, magnetic flux density, non-ionizing radiation, substation.*

1. INTRODUCTION

Protection of the general public from non-ionizing radiation is regulated by national and international [1–3] recommendations and rulebooks. Recommendation 1999/519/EC [2] establishes a framework for harmonized protection of the general public from non-ionizing radiation to which all the European Union countries should adhere in adopting local regulations. The reference level of exposure of the general public to power frequency (50 Hz) magnetic field, prescribed by [2], is set to 100 μT. This reference level is equal to the reference level given by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in the ICNIRP guidelines from 1998 [1]. In the ICNIRP guidelines from 2010 [3] the reference level for power frequency magnetic field is 200 μT.

The Republic of Serbia fulfilled the requirements of [2] in 2009 by adopting national legislation on the protection of the general public from non-ionizing radiation, i.e. the Law on Protection from Non-Ionizing Radiation [4] and six rulebooks. Rulebook on Limits of Exposure to Non-Ionizing Radiation [5] established a reference level of exposure, which is 40 μT for power frequency magnetic flux density (50 Hz) in increased sensitivity areas. According to the definition given in rulebooks [5] and [6], increased sensitivity areas are "residential areas where people can stay 24 hours a day; schools, homes, preschool institutions, maternity wards, hospitals, tourist facilities, and children's playgrounds; areas of undeveloped plots intended, according to the urban development plan, for the specified purposes, in accordance with the recommendations of the World Health Organization". Rulebook on Sources of Non-Ionizing Radiation of Special Interest, Types of Sources, Methods and Frequentness of their Testing [6] defines the concept of non-ionizing radiation source of special interest. According to this rulebook, sources of special interest are those whose electromagnetic field in an increased sensitivity area amounts to at least 10% of the reference level prescribed for that frequency. In the case of power frequency field (50 Hz), 10% of the reference level for magnetic flux density is 4 μT. Owners of the sources of special interest have the obligation to provide field testing once every four years. However, in the same rulebook, sources of special interest are defined as those with voltage levels higher than 35 kV, which means that the 10/0.4 kV substations are not considered an important electromagnetic field source according to Rulebook [6]. For that reason, it is important to analyze the levels of magnetic field in the vicinity of these substations and demonstrate that these levels in some cases can be very high. The conclusions about the levels of magnetic field in the vicinity of 10/0.4 kV substations

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could be the basis for the improvement of the Serbian legislation on the protection of the general public from non-ionizing radiation.

The Italian legislative framework introduced the issue of the impact of electromagnetic fields generated by electrical infrastructures and the need to assess their impact and define protectionist criteria for human exposure starting from 1988. In particular, after a period characterized by multiple regional laws that were also heterogeneous among themselves, the Italian legislator decided to rationalize and unify the approach to the issue with Law no. 36 of 22/2/2001 [7] and the related Prime Ministerial Decree of 8 July 2003 [8]. The spirit of the Italian legislator was driven by the desire to adopt a criterion of prudence in assessing human exposure by distinguishing professional exposure from that of the population. For the former, the legislative framework derives from international guidelines (e.g. ICNIRP) also contained in the recommendation and subsequent European directive, which base the limits of electromagnetic fields on short-term acute effects on health. For the population, the legislator has instead adopted a criterion of caution in order to protect people from the so-called "long-term effects" linked to prolonged exposure to electromagnetic fields even of low intensity. On the basis of these principles, the provision indicates several reference levels for exposure:

- exposure limits (art.3. c.1 letter b): the value of electric, magnetic and electromagnetic field, considered as an emission value, defined for the purposes of protecting health from acute effects (for example at 50 Hz for the population: 100 μT and 5 kV/m), which must not be exceeded in any condition of exposure of the population and workers to ensure health protection pursuant to and in compliance with article 32 of the Italian Constitution;
- attention value (art.3 c.1 letter c): is the value of electric, magnetic and electromagnetic field, considered as an emission value, which must not be exceeded in residential environments, schools and in places used for prolonged stays (more than 4 hours). It constitutes a precautionary measure for the purpose of protection from possible long-term effects and must be achieved within the time and manner established by law; for the magnetic field the limit is 10 μT;
- quality objectives (art.3 c.1 letter d): the values of electric, magnetic and electromagnetic fields, defined by the State for the purpose of progressive mitigation of exposure to the same fields; for the magnetic field the limit is 3 μT.

In practice, the attention value is applied to everything that was created before 2003 and after that year the quality objective must be adopted.

Table 1. Reference levels for power frequency (50 Hz) magnetic flux density according to Serbian, Italian and international regulations

ICNIRP 1998	Recommendation 1999/519/EC	ICNIRP 2010	Serbian legislation	Italian legislation
100 μT	100 μT	200 μT	40 μT / 4 μT	10 μT / 3 μT

The aforementioned reference levels for power frequency (50 Hz) magnetic flux density according to Serbian, Italian and international regulations are summarized in Table 1.

Recent studies about the health effects of magnetic field [9, 10] confirm the relevance of the topic of human exposure to electromagnetic fields.

Previous research has shown that 10/0.4 kV substations are a significant source of power frequency magnetic field in the environment [11–18]. The most unfavorable situation from the aspect of exposure of people to magnetic field is when the substation is located inside the building, and immediately next to or above it there is an increased sensitivity area. An unfavorable circumstance in this case is the proximity of the substation to the increased sensitivity area. Since the magnetic field decreases significantly with increasing the distance from the source, in the areas located only a few meters away from the substation, magnetic flux density levels are significantly lower. This case occurs when the substations are constructed as individual objects and are located several meters away from the closest building. In the case when a 10/0.4 kV substation is located in the building, and immediately next to or above it there is an increased sensitivity area, the levels of magnetic flux density in this area may exceed the reference levels prescribed by the aforementioned national and international legislation. The levels of magnetic flux density near the substation primarily depend on the layout of the equipment, the type of transformer, as well as the rated power of the transformer, i.e. its rated current. According to the results of previous testings [16], substations where the 0.4 kV busbars, which connect the transformer and the 0.4 kV switchboard, are located directly next to the ceiling or the wall of the substation, are the most unfavorable configuration from the aspect of exposure to magnetic field, when there is an increased sensitivity area on the other side of the wall or the ceiling. For that reason, the topic of this paper is focused on the analysis of the magnetic field levels in such cases. The analysis is based on the results of magnetic flux density calculations for different values of the currents, distances from the busbars and distances between the busbars. The results have shown that in some cases the magnetic field levels can significantly exceed the prescribed reference levels. It should be pointed out that the analysis in the paper is simplified and takes into account only the 50 Hz component of magnetic field, while harmonics are not taken into account. In some cases, the influence of the harmonics is not negligible and therefore this topic will be the subject of the future research.

2. Testing of magnetic field in the vicinity of substations with 0.4 kV busbars near the ceiling

Magnetic field testings in increased sensitivity areas are carried out in accordance with the requirements of standards [19–22]. In practice, the testings are based on magnetic flux density measurements. Depending on the specific situation, measurements can be performed at different heights. If it is necessary to assess the exposure of a person in a standing position, the measurements are carried out at a height of 1 m from the ground or the floor of the room. If there is substantial inhomogeneity of the field, i.e. if the value of the field changes significantly

Figure 1 shows the 10/0.4 kV substation with busbars located near the ceiling.

Figure 1. Substation in the basement of a school (10/0.4 kV, 1 × 1000 kVA)

depending on height, the three-point measurement method, which is described in standard [22], is applied. The three-point measurements are carried out at the heights of 0.5 m, 1 m and 1.5 m from the ground or the floor of the room, and the mean value of the obtained results is calculated. Five-point measurements are carried out at the height of 0.2 m from the floor of the room under which the source of the magnetic field is located and are performed in cases where it is necessary to assess the exposure of a person in a lying position. After the measurements, the three highest values are selected from the five measured ones and their mean value is calculated, according to the method described in standard [22].

During the measurement period, the transformer load is usually significantly lower than the rated load. Therefore, it is necessary to determine the level of magnetic flux density that would occur in the increased sensitivity area when the current of the transformer is equal to the rated current. The highest value of magnetic flux density for the case of the transformer rated load can be determined by calculations or extrapolation of measurement results. In this paper, the highest values of magnetic flux density are determined by calculations based on the model of 0.4 kV busbars.

3. Magnetic flux density calculations

3.1. Calculation procedure

The calculations of the magnetic flux density, B, are based on modeling of the busbars that connect the transformer and the 0.4 kV switchboard. This model is applicable in all situations when the 0.4 kV busbars are the dominant source of magnetic field in the increased sensitivity area, which is the most common case with substations with oil transformers located inside buildings.

The model of busbars used for calculations is shown in Figures 2 and 3. The marks in Figures 2 and 3 have the following meaning:

A, B, C – busbar markings corresponding to phases A, B and C,

P – profile along which the magnetic flux density is calculated,

l – busbar length,

d – distance between busbars,

r – distance between the line passing through the middle of the busbars and the profile P.

The calculation was first carried out for different busbar lengths of 7.5 m, 10 m, 20 m and 30 m, where the currents in all three conductors were 910 A, while the distance r was 0.5 m and the distance d was 0.2 m. In all cases, the profile P along which the calculations are performed was in the middle of the busbars, as shown in Figure 2. The highest value of magnetic flux density is obtained at the point x = 0 m (e.g. 225.22 µT @ 7.5 m and 223.26 µT @ 30 m) [23].

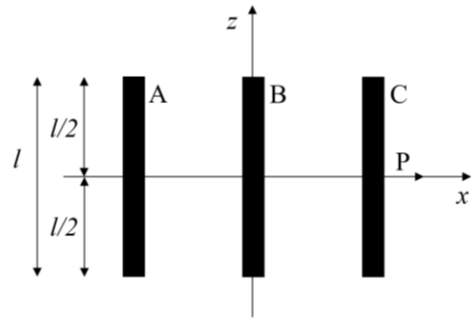

Figure 2. Longitudinal section of the 0.4 kV busbars

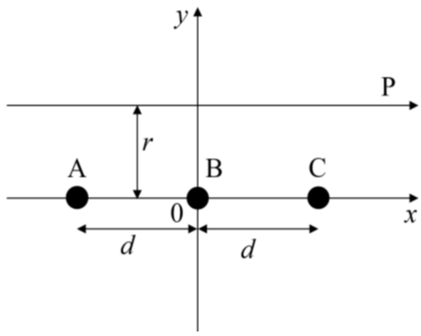

Figure 3. Cross section of the 0.4 kV busbars

The calculation was then repeated using a model based on modeling of busbars with infinitely long straight conductors. The magnetic field in the vicinity of a rectilinear conductor with a circular cross section is calculated by using the equation:

$$B = \frac{\mu_o \cdot I}{2\pi R} \tag{1}$$

where marks denote the following:

B – magnetic flux density,

I – current intensity,

R – distance from the center of the conductor,

μ_0 – magnetic permeability of the vacuum.

The resultant field of three parallel conductors is the resultant of vector summation of the component fields $\vec{B}_i$, which is given by the following equation:

$$\vec{B} = \sum \vec{B}_i \tag{2}$$

In the case when the busbars were modeled with infinitely long straight conductors, the highest magnetic flux density value of 223.12 µT was obtained. Since the relative deviation between the obtained results is lower than 1%, further calculations were carried out using a simpler model based on modeling of busbars with infinitely long straight conductors. The calculations were carried out for a balanced three-phase system, i.e. with the assumption that the currents in all three phase conductors are equal and that the phase shift is 120° ($I = I_A = I_B = I_C$, $\theta_A = 0°$, $\theta_B = 120°$, $\theta_C = 240°$).

3.2. Analysis of the influence of the distance between the busbars and the distance from the busbars on the values of magnetic flux density

In the first case, the influence of the distance between the busbars on the values of magnetic flux density was analyzed. The calculation of magnetic flux density was carried out at the distance from the busbars r = 0.5 m and for the current I = 1000 A. The distance between the busbars, d, was varied in range from 15 cm to 50 cm. The obtained results are shown in Figure 4. On the basis of the results given in Figure 4, it can be concluded that the values of the magnetic flux density increase with increasing the distance between the busbars. Additionally, the width of the zone in which certain reference level is exceeded also increases with the increase of distance between the busbars.

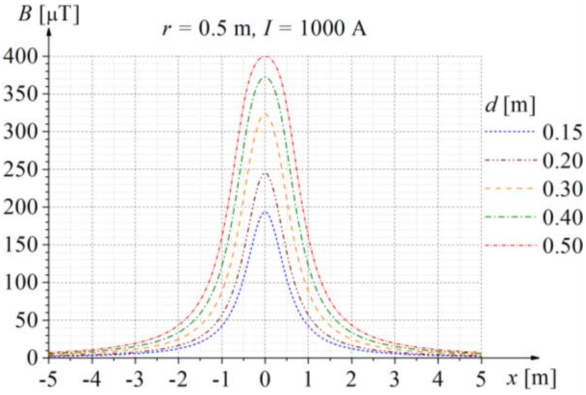

Figure 4. Calculated values of magnetic flux density for different distances between busbars (d)

In the second case, the influence of the distance from the busbars on the values of magnetic flux density was analyzed. The calculations were carried out for the distance between the busbars d = 0.3 m and the current I = 1000 A. The distance from the busbars, r, was varied in range from 0.5 m to 1 m. In the case r = 0.5 m the highest value of magnetic flux density along the profile P was 323.5 μT while in the case r = 1 m it was 96.8 μT. These results show that the values of magnetic flux density decrease significantly with the increase of distance from the busbars.

3.3. Calculations for a 400 kVA transformer

The calculations were carried out for the substation with a 400 kVA transformer. The rated current of the transformer on the low voltage side is 577 A. The calculations were carried out for the case when the transformer load is equal to its rated load and when the distance between the busbars, d, is 0.5 m. The calculations were carried out for different values of the distance from the busbars. The minimum distance is 0.5 m, which corresponds to the case when the busbars are in the immediate vicinity of the substation ceiling, and the calculations are carried out in the increased sensitivity area located directly above the substation, at a height of 0.2 m above the floor of the room. The values of the distance, r, were gradually increased with a 0.1 m step until the distance at which magnetic flux density values do not exceed the reference level of 100 μT prescribed by [1, 2] was reached. The results of the magnetic flux density calculations are shown in Figure 5.

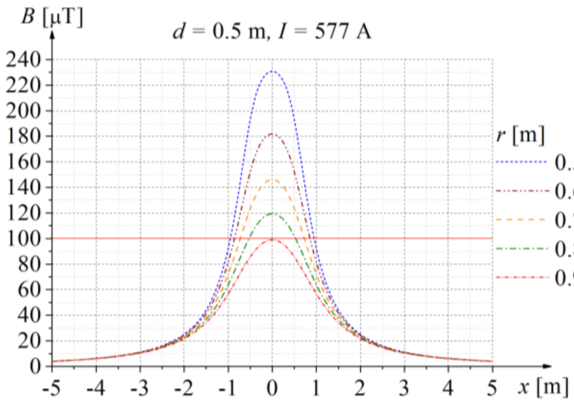

Figure 5. Calculated values of magnetic flux density for a 400 kVA transformer (d = 0.5 m)

The magnetic flux density values at the rated current of the transformer decrease below the reference level of 100 μT at a distance of 0.9 m from the busbars.

3.4. Calculations for a 630 kVA transformer

The previous analysis was repeated for the substation with a 630 kVA transformer. The rated current of the transformer on the low voltage side is 910 A. The calculations were carried out for the case when the transformer load is equal to its rated load and when the distance between the busbars, d, is 0.5 m. The distance from the busbars was gradually increased from 0.5 m to the distance at which magnetic flux density values do not exceed the reference level of 100 μT. The results of the magnetic flux density calculations are shown in Figure 6. The magnetic flux density values at the rated current of the transformer decrease below the reference level of 100 μT at a distance of 1.2 m from the busbars.

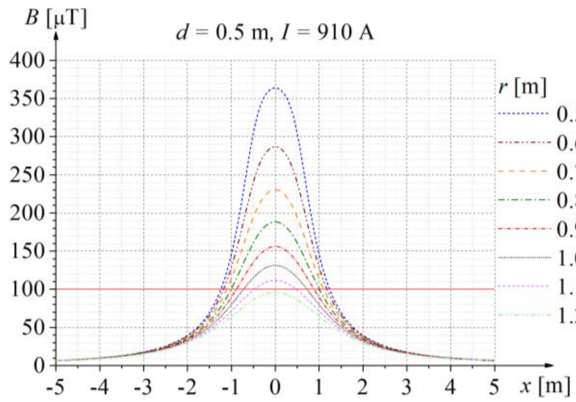

Figure 6. Calculated values of magnetic flux density for a 630 kVA transformer (d = 0.5 m)

3.5. Calculations for a 1000 kVA transformer

The analysis was also carried out for the substation with a 1000 kVA transformer, whose rated current on the low voltage side is 1443 A. The calculations were carried out for the case when the transformer load is equal to its rated load, for the distance between the busbars of 0.5 m and for different distances from the busbars. The obtained results are shown in Figure 7. The magnetic flux density values at the rated current of the transformer drop below the reference level of 100 μT at a distance of 1.6 m from the busbars.

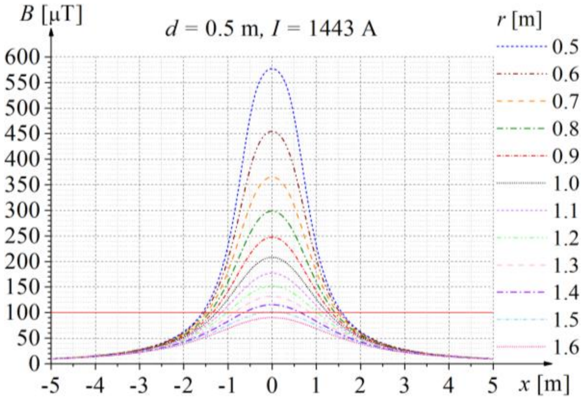

Figure 7. Calculated values of magnetic flux density for a 1000 kVA transformer (d = 0.5 m)

3.6. Calculations for different reference levels

The previous analysis was repeated for the reference levels given in Table 1. The limits of 4 μT and 40 μT refer to Serbian legislation, while the limits of 3 μT and 10 μT refer to Italian legislation. The reference level of 100 μT is prescribed by ICNIRP guidelines [1] and Recommendation 1999/519/EC [2], while the reference level of 200 μT is prescribed by ICNIRP guidelines [3].

A summary of the obtained results is given in Tables 2 and 3. Table 2 refers to the distance of 0.25 m between the busbars, while Table 3 corresponds to the distance of 0.5 m. These tables show the values of the distances from the low voltage busbars at which the calculated values of magnetic flux density will not exceed the prescribed reference level for different values of the transformer rated power (400 kVA, 630 kVA and 1000 kVA).

Table 2. Distances from the 0.4 kV busbars at which the calculated values of magnetic flux density will not exceed the prescribed limit (*d* = 0.25 m)

Rated power	Magnetic flux density limit					
	3 μT	4 μT	10 μT	40 μT	100 μT	200 μT
400 kVA	4.1 m	3.6 m	2.3 m	1.1 m	0.7 m	0.5 m
630 kVA	5.2 m	4.5 m	2.8 m	1.4 m	0.9 m	0.6 m
1000 kVA	6.5 m	5.6 m	3.6 m	1.8 m	1.1 m	0.8 m

The values of the distance *r* for which the magnetic flux density values do not exceed certain reference level are higher at greater distances between the busbars, as well as at higher rated currents of the transformer.

Table 3. Distances from the 0.4 kV busbars at which the calculated values of magnetic flux density will not exceed the prescribed limit (*d* = 0.5 m)

Rated power	Magnetic flux density limit					
	3 μT	4 μT	10 μT	40 μT	100 μT	200 μT
400 kVA	5.8 m	5.0 m	3.2 m	1.6 m	0.9 m	0.6 m
630 kVA	7.3 m	6.3 m	4.0 m	2.0 m	1.2 m	0.8 m
1000 kVA	9.2 m	7.9 m	5.0 m	2.5 m	1.6 m	1.1 m

4. Conclusion

The paper analyzed the levels of magnetic flux density in the increased sensitivity areas located above or next to 10/0.4 kV substations where the busbars connecting the transformer and 0.4 kV switchboard are dominant magnetic field source in the increased sensitivity area. It has been shown that the most unfavorable situations from the aspect of exposure to magnetic field are when the 10/0.4 kV substations are located in residential buildings, schools and other facilities that are categorized as increased sensitivity areas. For the above reasons, conducting testings in the increased sensitivity areas that are located directly next to or above 10/0.4 kV substations in buildings is of great importance. In cases when it is determined that there is a possibility of exceeding the reference level, it is necessary to apply measures to reduce the levels of magnetic field. In this paper, calculations of magnetic flux density were carried out for substations with 400 kVA, 630 kVA and 1000 kVA transformers, which are most commonly used in residential and other buildings. In order to obtain the highest possible levels of magnetic field, the calculations were carried out for the case when the transformer load is equal to its rated load. Calculations were carried out for different distances between busbars, as well as for different distances from the busbars. The obtained results show that the levels of magnetic flux density in the increased sensitivity areas are mostly influenced by the load current of the transformer, the distance between the busbars and the increased sensitivity area, as well as the mutual distance between the busbars. It has been shown that the magnetic flux density values in the increased sensitivity areas located directly above or next to the substation can significantly exceed the reference level prescribed by national and international legislation if the busbars are located near the ceiling or the wall. In certain situations, values that are several times higher than the reference level have been obtained by calculations for the case of the rated load of the transformer. The distances from the busbars at which the reference levels will not be exceeded were calculated in the paper for different rated powers of the transformers. It should be emphasized that the calculated values are the minimum distances that are necessary in order to achieve that the magnetic field levels are lower than certain prescribed limits. However, ensuring even greater distances between the substation and the increased sensitivity area would contribute to the additional reduction of exposure of people to magnetic field and should be considered whenever possible. During the design and the construction of new substations inside buildings, it is necessary to take care of the layout of the equipment in the substation and adhere to the specified distances calculated in this paper, so as to avoid the appearance of high magnetic field values in increased sensitivity areas. The results obtained in the paper could be used for the improvement of the Serbian legislation, considering the fact that according to the current rulebook, the 10/0.4 kV substations are not considered a source of special interest.

It should be emphasized that the analysis carried out in the paper takes into account only the 50 Hz component of magnetic field, while the influence of harmonics is not considered. In some cases, the influence of harmonics is not negligible and therefore this topic will be the subject of future research.

Further research will be focused on the analysis of measurement results obtained near 10/0.4 kV substations and their comparison with calculation results as well as on magnetic field calculations for more complex substation configurations and the analysis of the influence of harmonics on assessment of compliance.

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