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MAGNETIC FIELDS IN THE VICINITY OF HIGH-VOLTAGE POWER LINES, AND OPTIMISATION OF CONDUCTOR ARRANGEMENT

Roman Kostyszyn[1]*, Dominik Miśków[2]

[1] Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland,
Faculty of Electrical Engineering, e-mail: r.kostyszyn@we.umg.edu.pl,
ORCID 0000-0003-4132-2359

[2] Elfeko S.A., Hutnicza 20 a, 81-061 Gdynia, e-mail: dominik.piotr.miskow@gmail.com,
ORCID 0000-0002-1869-0375

*Corresponding author

Abstract: This paper presents calculations of the distribution of the magnetic fields generated by the current in phase conductors of overhead high-voltage power lines. The calculations are made for the area between the line paths and the terrain, with a particular focus on the area near the ground, important from the standpoint of humans present there, temporarily or permanently. Magnetic field distribution is determined for different arrangements of the phase conductors and line circuits, which are related to tower design. Minimum magnetic field value expressed in A/m and cost of building the power line are the optimisation criteria.

Keywords: HV line, magnetic field, field distribution calculation, development near HV lines, hazards to humans near HV lines.

1. INTRODUCTION

Transmitting electric power over long distances requires building high voltage (HV) electric power lines working at specific frequencies and current load capacity values. In Poland, most of the lines used are overhead designs. In a common (synchronised) electric power system, the voltage and current frequency is a stabilised value, characteristic for the entire system (in Poland and Europe it is 50 Hz).

The voltage value is standardised for individual grids in national systems and arises out of either currently used solutions or historical circumstances. In Poland, for HV transmission systems, the most common nominal voltages are: 110 kV, 220 kV and 400 kV.

The current value depends on the momentary power demand in the system and on the power transmission routes used. Power lines have a specific energy transmission capacity value, i.e. the maximum current that can occur without the risk of changing the parameters of the line, e.g. minimum conductor distance from the ground. In practice, the line current load is much lower, usually below 30% maximum.

An electric current flow generates a magnetic field, whose intensity depends, directly proportionally, on the value of current in the conductors, and on the spatial arrangement of the current circuits. Depending on the magnetic properties of the materials located within the magnetic field (relative magnetic permeability), it could be a source of magnetic flux density, otherwise known as magnetic flux density.

A magnetic field accompanies all equipment where an electric current flows. Usually, depending on the characteristics of the current, it is an alternating field with a 50 Hz frequency. This field couples with various elements, generating an electromotive force in them and, if they are conductive elements, it generates an electric current. This field interaction leads to interference in electrotechnical and other facilities, and for living organisms it may be hazardous to life and health.

2. CALCULATION METHOD

The PLS-CADD professional line design software from Power Line Systems Inc. Co. was used to determine the intensity of the magnetic field in the electric power line vicinity. The software was used to calculate magnetic field at a specific height above ground in a cross-section lateral to the line axis.

The following assumptions were made for the calculations:

- line conductors are infinitely long, straight and parallel to each other;
- the earth is a very poor conductor of magnetic field;
- the magnetic field is treated as quasi-static.

The presence of the ground can be simulated using an image of the conductor placed under the surface of the ground, at a distance of $1.31 \cdot \delta$. Where δ is the distance after crossing an electromagnetic wave which reduces its amplitude 1/e times. The depth of the conductor underground is many times greater than at the height at which the conductor is suspended above ground, its contribution to generating the magnetic field is therefore minor and is neglected in the calculations.

Magnetic flux density caused by the current flow, with the current being a complex value, is also expressed by a complex number. The induction caused by the current flowing through the conductor can be split into two components: horizontal and vertical. The horizontal component of induction at a specific point can be calculated using equation (1), while the vertical component from equation (2).

$$B_{kx} = \frac{2 \cdot 10^{-7} \cdot (I_{rk} + jI_{ik}) \cdot (X_M - X_k)}{(X_M - X_k)^2 + (H_M - H_k)^2} \tag{1}$$

$$B_{ky} = \frac{2 \cdot 10^{-7} \cdot (I_{rk} + jI_{ik}) \cdot (H_M - H_k)}{(X_M - X_k)^2 + (H_M - H_k)^2} \tag{2}$$

where:

B_{kx} – horizontal complex component of magnetic flux density,
B_{ky} – vertical complex component of magnetic flux density,
I_{rk} – real component of current in conductor k,
I_{ik} – imaginary component of current in conductor k,
X_M – abscissa of point M, where induction is calculated (centre of the coordinate system is located on the line axis),
X_k – abscissa of the centre of conductor k,
H_M – ordinate of point M relative to ground level,
H_k – ordinate of the centre of conductor k relative to ground level.

For a system of multiple conductors (as in a three-phase system), magnetic flux density from each individual conductor is calculated, then the results are totalled using equations (3) and (4)

$$B_x = \sum_k B_{kx} \tag{3}$$

$$B_y = \sum_k B_{ky} \tag{4}$$

where:

B_x – horizontal complex component of magnetic flux density,
B_y – vertical complex component of magnetic flux density.

The effective magnetic flux density value at the analysed point is calculated using equation (5).

$$B_{rms} = \sqrt{B_{rx}^2 + B_{ix}^2 + B_{ry}^2 + B_{iy}^2} \tag{5}$$

where:

B_{rms} – effective magnetic flux density value,
B_{rx} – real part of the induction horizontal component,
B_{ix} – imaginary part of the induction horizontal component,
B_{ry} – real part of the induction vertical component,
B_{iy} – imaginary part of the induction vertical component.

Final magnetic field value is calculated using equation (6).

$$\mathrm{H} = \frac{\mathrm{B}}{\mu} \tag{6}$$

where:

H – magnetic field,
B – magnetic flux density,
μ – magnetic permeability of the medium, for air $\mu = 1.257 \cdot 10^{-6}$[V·s/A·m].

Below is an example illustrating the calculation method. The calculations were performed for a line with a flat conductor arrangement, the distance between conductors being 10.5 m. The line was symmetrically loaded, conductor current was 2000 A. Conductor centre line height above the ground was 10 m. Magnetic flux density was calculated for a point 20 m away from the line axis and located 2 m above the ground.

The calculations began by determining the currents in individual conductors. The currents were phase-shifted by 120°, the middle phase was assumed as the reference.

$I_{ra} = -\sin(30°) \cdot 2000 = -1000$ [A] $I_{ia} = \cos(30°) \cdot 2000 = 1732.1$ [A]

$I_{rb} = 2000$ [A] $I_{ra} = 0$ [A]

$I_{rc} = -\sin(30°) \cdot 2000 = -1000$ [A] $I_{ra} = -\cos(30°) \cdot 2000 = -1732.1$ [A]

Next, using equations (1) and (2), the vertical components and levels of induction caused by the current flowing through the individual conductors (conductors designated a, b and c) were calculated.

$$B_{ax} = \frac{2 \cdot 10^{-7} \cdot (-1000 + j \cdot 1732.1) \cdot \big(20 - (-10.5)\big)}{\big(20 - (-10.5)\big)^2 + (2 - 10)^2} = -6.14 + j \cdot 10.6 \text{ [μT]}$$

$$B_{ay} = \frac{2 \cdot 10^{-7} \cdot (-1000 + j \cdot 1732.1) \cdot (2 - 10)}{\big(20 - (-10.5)\big)^2 + (2 - 10)^2} = 1.61 - j \cdot 2.79 \text{ [μT]}$$

$$B_{bx} = \frac{2 \cdot 10^{-7} \cdot (2000 + j \cdot 0) \cdot (20 - 0)}{(20 - 0)^2 + (2 - 10)^2} = 17.2 + j \cdot 0 \text{ [μT]}$$

$$B_{by} = \frac{2 \cdot 10^{-7} \cdot (2000 + j \cdot 0) \cdot (2 - 10)}{(20 - 0)^2 + (2 - 10)^2} = -6.90 - j \cdot 0 \text{ [μT]}$$

$$B_{cx} = \frac{2 \cdot 10^{-7} \cdot (-1000 - j \cdot 1732.1) \cdot (20 - 10.5)}{(20 - 10.5)^2 + (2 - 10)^2} = -12.3 - j \cdot 21.3 \text{ [μT]}$$

$$B_{ay} = \frac{2 \cdot 10^{-7} \cdot (-1000 - j \cdot 1732.1) \cdot (2 - 10)}{(20 - 10.5)^2 + (2 - 10)^2} = 10.4 + j \cdot 18.0 \; [\mu\mathrm{T}]$$

In the following step, the magnetic flux density values generated by current flowing in individual conductors were totalled using equations (3) and (4).

$$B_x = -6.14 + j \cdot 10.6 + 17.2 + j \cdot 0 - 12.3 - j \cdot 21.3 = -1.21 - j \cdot 10.7 \; [\mu\mathrm{T}]$$

$$B_y = 1.61 - j \cdot 2.79 - 6.90 - j \cdot 0 + 10.4 + j \cdot 18.0 = 5.09 + j \cdot 15.2 \; [\mu\mathrm{T}]$$

The effective magnetic flux density value was calculated using equation (5), and magnetic field was calculated using equation (6).

$$B_{rms} = \sqrt{(-1.21)^2 + (-10.7)^2 + 5.09^2 + 15.2^2} = 19.3 \; [\mu\mathrm{T}]$$

$$H = \frac{19.3}{1.257} = 15.4 \; [\mathrm{A/m}]$$

2.1. Additional assumptions

Due to the required insulation distances, electric power line conductors may not be located closer to the ground than: 5.85 m for 110 kV lines, 6.70 m for 220 kV lines and 7.80 m for 400 kV lines [PN-EN 50341-1:2013-03; PN-EN 50341-2-22: 2016-04]. The field intensity level calculations took the conductor-ground distances listed above into account.

Maximum current load capacity for high-voltage lines was designed with a large margin. This took into account emergency situations, where the line would have to take over another in the event of a sudden failure, during the highest demand for electric energy.

In practice, lines are normally loaded much less, as typically average values for the currents flowing in HV electric power line conductors are within 10–30% of the maximum load capacity [Jaworski and Szuba 2015]. For this reason, the calculations took into account a line load of 30%.

In accordance with the regulation concerning methods of verifying permissible electromagnetic field levels in the environment, measurements of grid frequency magnetic fields (50 Hz) should be performed at heights between 0.3 to 2 m [Regulation of the Minister of Health 2020]. As a result, magnetic field was calculated for a height of 2 m above ground.

3. CALCULATION RESULTS

3.1. Magnetic field and phase conductor arrangement

The research began by comparing the intensity of the magnetic fields generated by 110 kV electric power lines with different conductor configurations. Series of towers were analysed with a triangular (E111, B2 type P and S120), vertical (B2 type PL) and flat (A12) conductor arrangements. While the above tower series were designed for conductors of different cross-sections (different current load capacities), the calculations were performed assuming the same load current for each line (220 A, which was 30% of the load capacity of the typical AFL-6 240 conductor). Performing the calculations for different currents would make it impossible to compare the conductor configurations due to the relation between load current and magnetic flux density generated by a line. The maximum magnetic flux density level for each configuration is shown in Figure 1. Significant differences were observed in the magnetic flux density levels generated by lines of different conductor configurations at the same load.

The weakest field was generated by lines with a vertical conductor arrangement, but this configuration entailed a major increase in its weight. For example, a B2 PL tower would be 40% heavier than a B2 P tower [Polskie Towarzystwo Przesyłu i Rozdziału Energii Elektrycznej 1998].

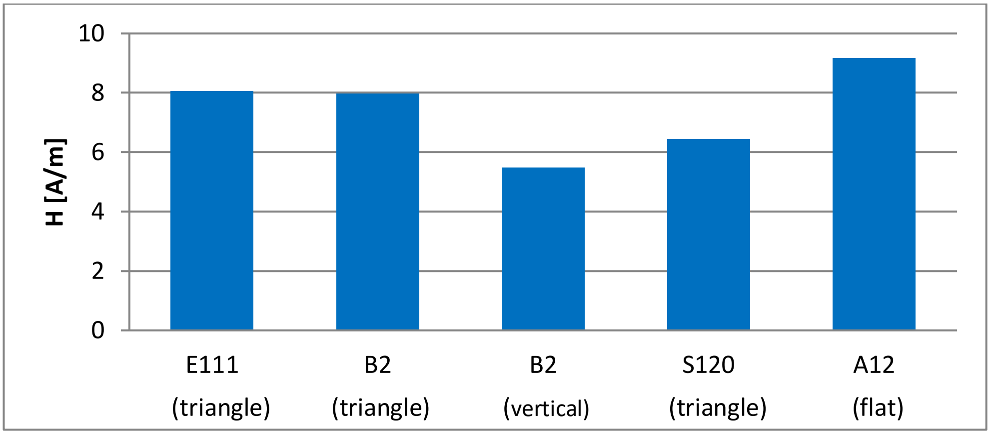

Fig. 1. Magnetic flux density for different designs of single circuit 110 kV lines, phase current 220 A

3.2. Effects of phase system in a double circuit line on the magnetic field

Next, the effects were investigated of a double circuit electric power line phase system on the magnetic field it generates. The analysis was performed for the Dc240 series with a twin-triangular conductor arrangement.

This design was designed for operation with AFL6 240 mm^2 conductors, with a load capacity of 733 A. The calculations were performed for a 30% line load (220 A), with the results given in Figure 2.

For a line with a twin-triangle conductor arrangement, the most beneficial was arranging the phases in the L1 L2 L3 / L3 L1 L2 order – proper phasing allowed a major reduction in the magnetic field near the line, which was achievable for a minor cost.

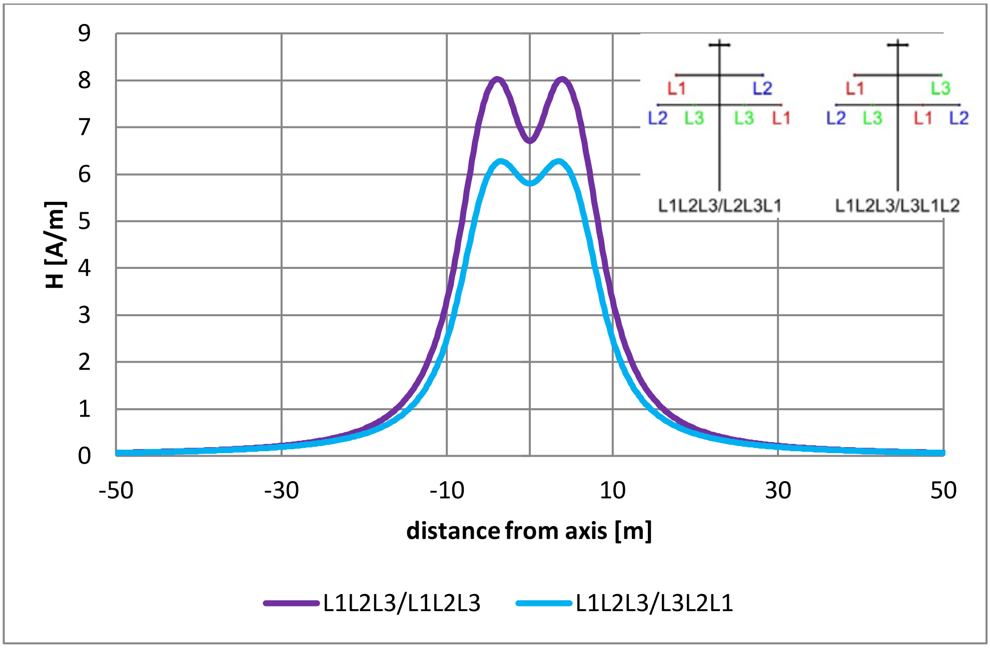

Fig. 2. Magnetic field distribution in a cross-section lateral to the line for the most advantageous and least advantageous phase system on a Dc240 series tower (twin-triangular conductor arrangement); phase current 220 A

3.3. Magnetic field in the vicinity of 110 kV double circuit lines

In the next stage of the study, magnetic fields were compared, generated by 110 kV nominal voltage double circuit lines with different support structure designs. Calculations were performed for the following tower series: E211, OS24 (barrel-type design), OL 24 (vertical conductor arrangement) and Dc240 (twin-triangular conductor arrangement). A load current of 220 A was assumed, see Figure 3 for the results. For each conductor configuration, magnetic field for the best and least advantageous phasing was provided. For comparison purposes, the magnetic field results obtained for a typical single circuit line were added to Figure 3.

Double circuit lines generate magnetic fields with maximum intensity comparable to single circuit lines, or with even lower intensity if the right phasing was used. Furthermore, the cost of building a double circuit line was much lower than the expenditure required for two single circuit lines. For example, a line based on E211 series towers would be 20% lighter than two lines with E111 series towers [Elfeko S.A. 2018]. Of course, building double circuit lines instead of single circuit lines would only be possible with the right grid topology.

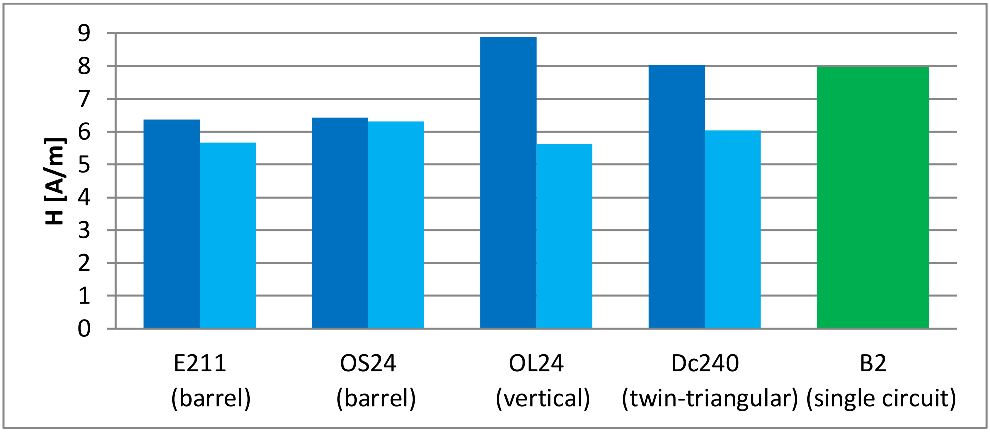

Fig. 3. Maximum magnetic field for different 110 kV electric power double circuit line tower designs (dark blue bar – disadvantageous phase system, blue bar – advantageous), compared with single circuit lines (in green); phase current 220 A

3.4. Conductor suspension height and the magnetic field

To determine the relation between the phase conductor distance from the ground and magnetic field under the power line, calculations were performed for a 400 kV double circuit line (E33 series towers), for the following conductor suspension heights: minimum required by the standard 7.8 m [PN-EN 50341-2-22:2016-04], extended by 2.5 m, 5 m and 10 m. E33 series towers have been designed to work with phase conductors in the form of a bundle of three AFL-8 350 conductors – the calculations take into account a phase current of 868 A (30% of conductor bundle current load capacity).

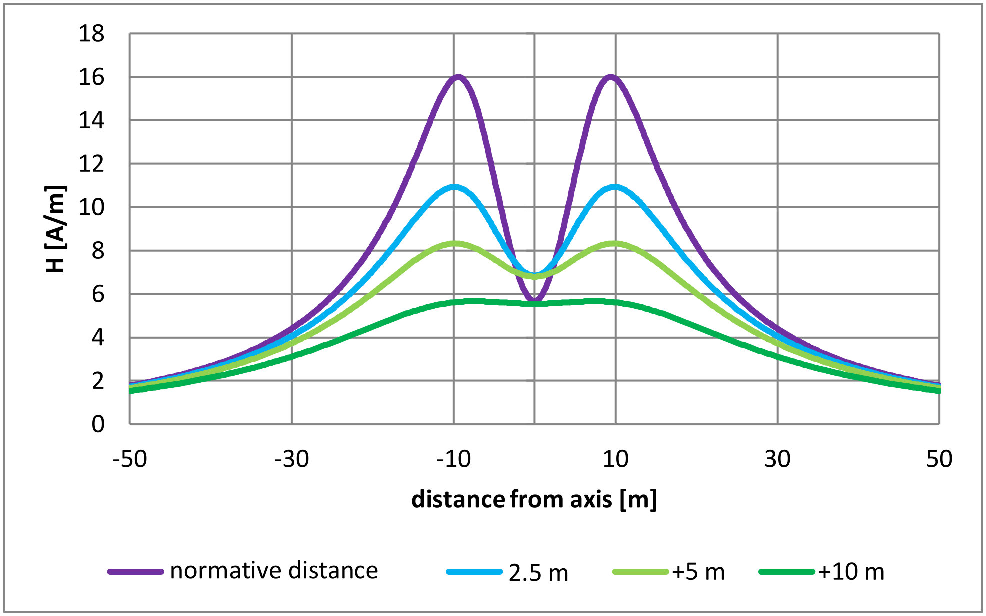

Fig. 4. Magnetic field in a cross-section perpendicular to the 400 kV line at different distances of phase conductors from the ground; phase current 868 A

The results shown in Figure 4 indicate that increasing the height at which conductors are suspended enables greatly reducing the magnetic field in the vicinity of the line, but has little effect on its levels at greater distances (above 40 m). The presented method of field reduction requires major expenditure, as increasing the height at 5 m which conductors are suspended for the E33 series involves increasing the tower weight by about 15%.

3.5. Magnetic field under lines of various voltages

To summarise the studies on the magnetic field generated by high-voltage power lines, field levels generated by lines with different nominal voltages were compared. To show the actual scale of magnetic effects, calculations were performed for 110, 220 and 400 kV lines loaded at 30%. The results were compared for single circuit lines with a flat conductor arrangement (series A12, H52, Y52) and double circuit lines with a vertical conductor arrangement (series OS24, ML52, E33).

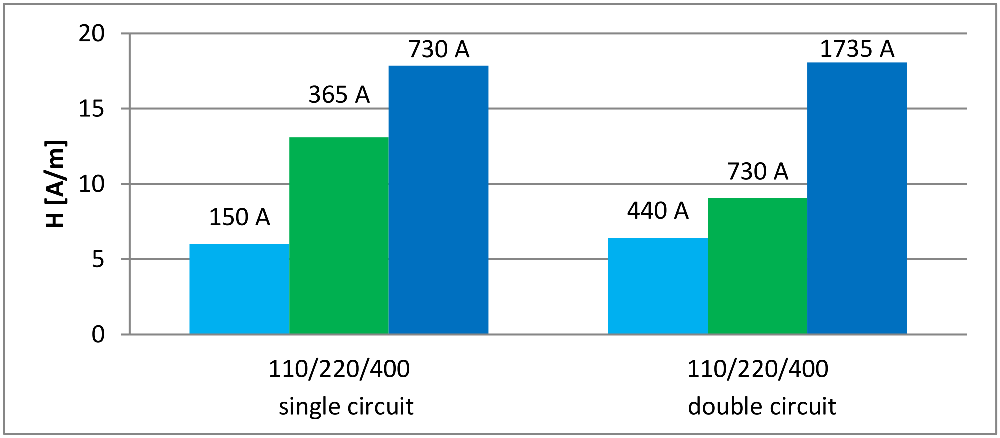

Fig. 5. Maximum magnetic flux density under electric power lines of different voltages under an average load; phase current equal to 30% maximum current

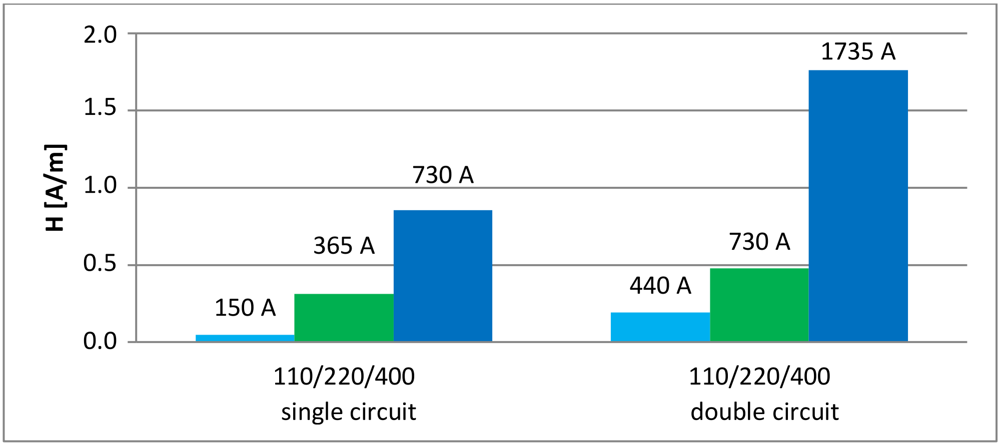

Fig. 6. Maximum magnetic flux density 50 m away from the axis of electric power lines of different voltages under an average load; phase current equal to 30% maximum current

Figure 5 shows the maximum magnetic field directly under the lines, while Figure 6 presents field intensity at a distance of 50 m from the line axis (a distance where residential buildings may be expected).

Magnetic field around the line grows with the line's nominal voltage, but the cause of this increase was not line voltage, but a greater current load capacity in the higher-voltage lines.

3.6. Magnetic field near electric equipment

The calculated magnetic field values generated by electric power lines were compared to values measured near functioning household appliances (Fig. 7). The measurements were performed at a distance from human chest/head that the proposed equipment may be located during their operation. The field intensity for a 110 kV line is provided directly under the line (in special cases, building lines with this voltage is permitted above residential buildings [PN-EN 50341-2-22:2016-04]), while for 220 kV and 400 kV lines it is stated as at a distance of 50 m from the axis (such lines may not cross residential development areas).

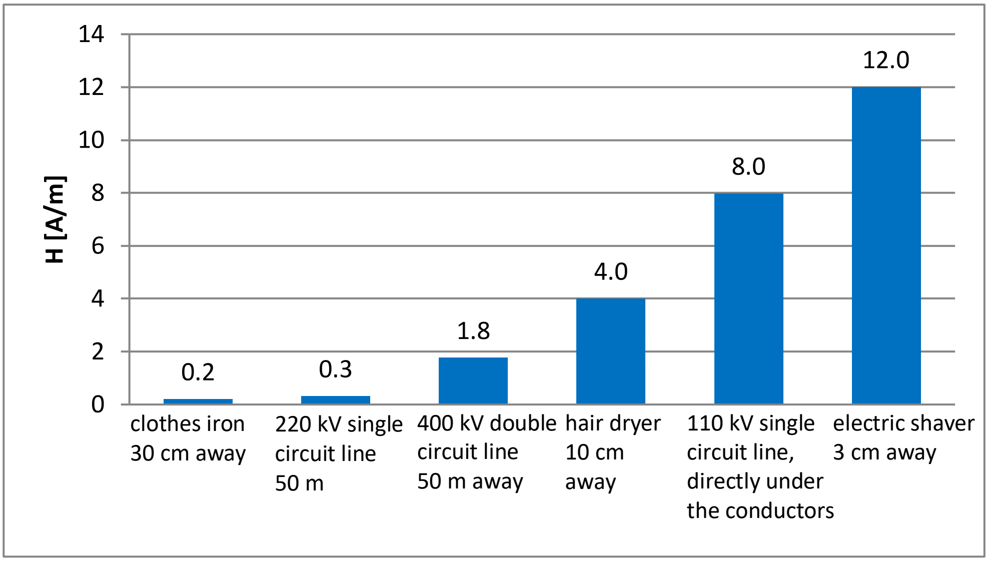

Fig. 7. Comparison of magnetic field generated by high-voltage lines and household electric equipment; source: unpublished materials of Elfeko S.A.

The comparison shown in Figure 7 indicates that magnetic field intensities generated by some electric equipment of everyday use greatly exceed the intensity values generated by electric power lines.

4. EFFECTS OF MAGNETIC FIELDS ON THE HUMAN BODY

The effects of magnetic fields on human health can be very difficult to determine and requires many years of experimental research. The occurrence of effects of long-term exposure to the magnetic fields generated by electric power lines continues to be a subject of scientific research.

The International Agency for Research on Cancer has qualified magnetic field as a potentially carcinogenic agent for humans and has assigned it the 2B category [World Health Organization International Agency for Research on Cancer 2002; International Agency for Research on Cancer 2022]. This category is used for exposure agents, mixtures and circumstances, for which there is limited evidence of carcinogenicity in humans, as well as less than sufficient evidence of carcinogenicity in experimental animals. Despite a large number of reports, no consistent connection between local exposure to magnetic fields and increased risk of neoplasms has been determined [World Health Organization International Agency for Research on Cancer 2002]. At present no study unambiguously confirming the harmful effect of magnetic fields with parameters not exceeding levels specified in the law on human or animal health has been published.

Magnetic fields generated by power lines have intensities lower than magnetic field generated by some household appliances. Therefore a power line running near a residential area does not introduce an agent that is not already present there as it does not increase health risks connected to magnetic interactions. In accordance with the Regulation of the Minister of Health dated 17 December 2019 concerning permissible electromagnetic field levels in the environment, magnetic field in any area accessible to humans may not exceed 60 A/m.

5. CONCLUSIONS

The most important methods of reducing the magnetic field generated by a HV line include:

- selecting the correct tower design;
- increasing the height at which conductors are suspended;
- building double circuit lines instead of single circuit lines;
- proper phasing on a double circuit line.

The simplest way to reduce magnetic field under a high-voltage line is to increase the distance between the phase conductors and the ground. It is an effective but expensive method, requiring the use of taller or more densely spaced support structures.

Another method of limiting the effects under the line is to use support structures with a conductor arrangement that provides a reduction of field intensity under the line. Among the solutions for single circuit lines, the most advantageous is a vertical conductor arrangement, which however requires more expensive design solutions. Towers with a flat conductor arrangement are the cheapest, but they create higher magnetic field values. Towers with a triangular conductor arrangement constitute a compromise between cost and field levels generated. For double circuit lines, the best results are achieved with a barrel-type design, while the least advantageous is the twin-triangular conductor arrangement.

For double circuit lines, another method of reducing the magnetic field is available – the choice of the right phase system in the line circuits. When two conductors next to each other have their currents in the same phase, the magnetic field they generate adds up instead of weakening. Using the right phasing, therefore, enables reducing the maximum magnetic field under the line by 10–20%. The cost of changing line phasing is low, compared to the costs necessary to achieve a similar reduction of magnetic effects by other means. A significant reduction in the magnetic field generated (especially when optimal phasing is used) can be achieved by building one double circuit line instead of two single circuit ones. Due to the effect of interactions from conductors in different line circuits nullifying each other, field intensity under a double circuit line is lower than under a single circuit line. Furthermore, the cost of building a double circuit line is lower than for two single circuit lines with the same load capacity. To summarise: the magnetic field generated must be taken into account when designing any high-voltage power line. There are solutions allowing it to be substantially reduced.

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