Arrangements of Overhead Power Line Conductors Related to the Electromagnetic Field Limits

Klemen Deželak, Gorazd Štumberger, Franc Jakl
University of Maribor
Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, 2000 Maribor
Maribor, Slovenia
klemen.dezelak@uni-mb.si, gorazd.stumberger@uni-mb.si, franc.jakl@siol.net

Abstract—**This paper deals with a few solutions for reduction of electric and magnetic field emissions caused by the overhead power lines. Calculations carried out for existing high voltage 400 kV overhead lines in Slovenia show that the emissions of electric and magnetic field at the border of overhead line right of way could be too high. For that very reason, the proposed paper, was attempted to minimize the emissions of electric and magnetic fields caused by the overhead line based on rearrangement of its line conductors. The first proposed solution is to change the sequences of conductor placements between both systems of the double-circuit overhead line. The second solution is the usage of higher overhead lines tower, while the third solution is electromagnetic field reduction based on conductor arrangements obtained in an optimization process. In the given case, optimization goal is to find that arrangement of the conductors, where the height of the tower is minimal and while the values of the magnetic and electric fields on the border of the overhead line right of way are under prescribed limits. All calculated results in this work are made for double-circuit overhead power line in the Electric Power Network of Slovenia.**

Keywords-overhead power line; electric field; magnetic field; optimization; sagged conductor

I. Introduction

In this paper, emissions of electric and magnetic field caused by high voltage transmission line are studied. It is well known that all of the electromagnetic phenomena defining by the general properties can be threated by a few equations called the Maxwell equations, which describes the nature of electric and magnetic fields and the creation of magnetic and electric fields due to electric and magnetic fields changing. Generally, the magnetic and electric field are coupled, and it is necessary to solve Maxwell's equations to obtained them [1]. But in the case of overhead lines, at the supplied voltage frequency 50 Hz, where electromagnetic field has a wavelength of 6000 km, some simplifications can be assumed and electric and magnetic fields can be calculated in an independent way [1], [2]. In the high wavelength range, where the wavelength is very large in comparison to the size of the voltage source, the quasistatic methods can be used [1]. This methods use the static Maxwell's equations, where the static electric and magnetic fields can be easily calculated.

Biological effects of power frequency electric and magnetic fields have been discussed by hundreds of studies and papers. In the 1975 and earlier the electric field performed the limit only in the overhead line design to the view of safety point, while the biological and health effect had not had important impact. For example the main criteria, related to the human, was that the short circuit current flowing through a person body standing below the overhead line and touching a high conducting object should not exceed 5 mA [3], [4]. But in the last decades the increasing public concern about exposure to electric (and also magnetic) fields has been an important issue in most countries around the world [5]. At the ground level the electric field lines are vertical to the ground plane and in case of human body beneath of line can induce body currents, which may exceed the safe limits [6], [7].

In the same way the discussion of biological effects of power frequency magnetic fields started in the late 1970's [8], while in the recent years the relationship between magnetic fields and the health is increasingly being investigated [1]. From many studies can be established that the aforementioned induced body currents can appear even in presence of magnetic fields [1]. The relation between the electromagnetic field levels and the possible induced body currents is often taken as basic restrictions by the international organization like ICNIRP (International Commission on Non-Ionizing Radiation Protection), IEEE (Institute of Electrical and Electronic Engineers), Council of the European Union, WHO (World Health Organization), deals by regulation and recommendation of limits connected to the electromagnetic fields [9]. The recent research findings are leading to the induced human body current restricted to the 2 mA at the public and 10 mA at the occupational area [4], [5] and [9]. This limits are connected to the the magnetic (100 and 500 μT) and electric field (5 and 10 kV/m) limits [4], [5].

On the other hand the magnetic and electric field limit values accepted by Slovenian government are ten times lower than European Union recommendations [10]. In the same sense the limit magnetic field, at public area in Slovenia, is 10 μT and limit electric field is 0.5 kV/m [10]. Because of very strict electromagnetic field limit values on the border of overhead right of way some modification should be applied for newly constructed overhead power lines. This paper proposed three solutions for the electromagnetic field reduction based on rearrangement of the overhead power line conductors. All solutions and their results, proposed in this work, are valid for Slovenian double-circuit 400 kV overhead power line, with two conductor bundle. The first solution is to change the sequences of conductor placements between two circuits. The second solution is the usage of higher overhead lines tower, while the third solution is electromagnetic field reduction based on conductor arrangements obtained in an optimization process. The first and second solutions have been studied and published in many works so far, while the third proposed solution is relatively new.

II. MAGNETIC AND ELECTRIC FIELD EMISSIONS

A. Magnetic Field Density

The magnetic field density $d\mathbf{B}$ caused by the current i flowing through the straight section of a conductor with the length $d\mathbf{l}$, can be calculated by using the Biot-Savart's law (1) [11], where μ_0 stands for the permeability of the free space, and $\mathbf{R}$ denotes the vector from the element $d\mathbf{l}$ pointed to an arbitrary point. The length of vector $\mathbf{R}$ is characterized by the R.

$$d\mathbf{B} = \frac{\mu_0 i}{4\pi R^3}\left(d\mathbf{l}\times\mathbf{R}\right) \tag{1}$$

Biot-Savart law (1) can be easily converted to another form (2). This form (2) can be easily applied for the calculation of the magnetic field caused by the overhead power lines, where $\mathbf{a}$ is the vector orthogonal to the $d\mathbf{l}$, and it is pointing from $d\mathbf{l}$ to the any observation point. Its length is designated as a. Additional the marks α_1 and α_2 are two angles between the start and end points of the conductor element $d\mathbf{l}$ and the point of observation (Figure 1).

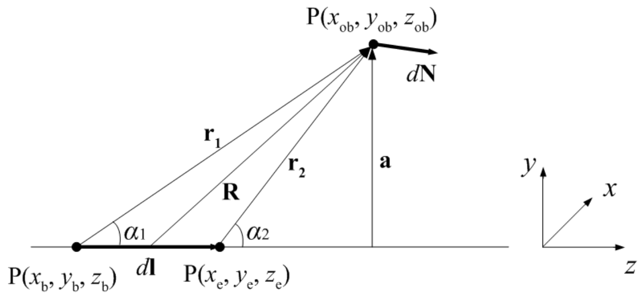

Figure 1. Magnetic and electric field calculation.

As Figure 1 shows the begging ("b") point of the conductor element $d\mathbf{l}$ is characterized by $P(x_b, y_b, z_b)$, while the ending ("e") point is marked by $P(x_e, y_e, z_e)$. Marks x_b, y_b, z_b, x_e, y_e and z_e are stand for the coordinates in three direction x, y and z. The point $P(x_{ob}, y_{ob}, z_{ob})$ is an arbitrary point where the magnetic field is observed ("ob"). In the case of the magnetic field calculations $d\mathbf{N}$ in Figure 1 is considered as $d\mathbf{B}$.

$$d\mathbf{B} = \frac{\mu_0 i}{4\pi a}(\cos\alpha_1 - \cos\alpha_2)\left(\frac{d\mathbf{l}}{dl}\times\frac{\mathbf{a}}{a}\right) \tag{2}$$

Magnetic field density calculated by equation (2) consists of three components dB_x, dB_y and dB_z in three axes x, y and z (3).

$$d\mathbf{B} = \left(dB_x, dB_y, dB_{xz}\right) \tag{3}$$

If there exists several straight conductor sections, individual components must be summed in x, y and z directions (4), (5), (6), which finally results in three magnetic field density components in all three axes B_{sx}, B_{sy} and B_{sz}. All three magnetic field components can be valid at the same time denoted by t.

$$B_{sx}(t) = \sum dB_x(t) \tag{4}$$

$$B_{sy}(t) = \sum dB_y(t) \tag{5}$$

$$B_{sz}(t) = \sum dB_z(t) \tag{6}$$

The length of the magnetic field density vector B at the time t can be calculated by (7).

$$B(t) = \sqrt{B_{sx}(t)^2 + B_{sy}(t)^2 + B_{sz}(t)^2} \tag{7}$$

In the case of the overhead power line, there are three phases with three time delayed ($2\pi/3$ = 120°) currents i_1, i_2, i_3 (8), (9), (10) where I_m is the current amplitude and ω is the angular frequency ($2\pi f = 2\pi 50$).

$$i_1 = I_m \cos(\omega t) \tag{8}$$

$$i_2 = I_m \cos\left(\omega t - \frac{2\pi}{3}\right) \tag{9}$$

$$i_3 = I_m \cos\left(\omega t - \frac{4\pi}{3}\right) \tag{10}$$

The Root Mean Square (RMS) value of the magnetic field density B_{RMS} can be calculated by (11), where magnetic field density B is defined by (7), T = 0.02 means a cycle of fundamental frequency, while τ is the integration of auxiliary variable.

$$B_{\mathrm{RMS}}{}^2 = \frac{1}{T}\int_{t-T}^{t} B^2(\tau)\,d\tau \quad (11)$$

B. Electric Field Strength

The electric field emissions are caused by the charge q placed on the conductor element $d\mathbf{l}$, with length dl. In that way, the electric field strength $d\mathbf{E}$ in the any observation point, may be calculated by the equation (12) [12]. In (12) $\mathbf{R}$ is the vector pointing from the conductor element $d\mathbf{l}$ to the any point of observation. Its length is denoted by R, while ε_0 is the permittivity of the free space. In the case of the electric field calculations $d\mathbf{N}$ in Figure 1 could be considered as $d\mathbf{E}$.

$$d\mathbf{E} = \frac{q\,dl}{4\pi\varepsilon_0 R^3}\mathbf{R} \quad (12)$$

After the short derivation the electric field equation (12) could be transformed in another form (13), where $d\mathbf{E}$ is consisted by its components in tangential ("t") and radial ("r") axis (14), (15). Those expressions could be easily used for electric field calculation caused by overhead power lines. In (14) and (15) $\mathbf{a}$ is the vector orthogonal to the $d\mathbf{l}$, which is pointing to the direction of any point of observation (Figure 1). Its length is designated as a, while α_1 and α_2 are the two angles between the beginning and ending of the conductor element $d\mathbf{l}$ and the point of observation.

$$d\mathbf{E} = d\mathbf{E}_{\mathrm{t}} + d\mathbf{E}_{\mathrm{r}} \quad (13)$$

$$d\mathbf{E}_{\mathrm{t}} = \frac{q}{4\pi\varepsilon_0 a}\left(\sin\alpha_2 - \sin\alpha_1\right)\frac{d\mathbf{l}}{dl} \quad (14)$$

$$d\mathbf{E}_{\mathrm{r}} = \frac{q}{4\pi\varepsilon_0 a}\left(\cos\alpha_1 - \cos\alpha_2\right)\frac{\mathbf{a}}{a} \quad (15)$$

Electric field strength calculated by (13) consists of three components dE_{x}, dE_{y} and dE_{z} in three axes x, y and z (16).

$$d\mathbf{E} = \left(dE_{\mathrm{x}}, dE_{\mathrm{y}}, dE_{\mathrm{z}}\right) \quad (16)$$

If there exists several straight conductor sections, individual components must be summed in x, y and z directions (17), (18), (19), which finally results in three electric field strength components in all three axes E_{sx}, E_{sy} and E_{sz}. All three electric field components can be valid at the same time denoted by t.

$$E_{\mathrm{sx}}(t) = \sum dE_{\mathrm{x}}(t) \quad (17)$$

$$E_{\mathrm{sy}}(t) = \sum dE_{\mathrm{y}}(t) \quad (18)$$

$$E_{\mathrm{sz}}(t) = \sum dE_{\mathrm{z}}(t) \quad (19)$$

The length of the electric field strength vector E at the time t can be calculated by (20).

$$E(t) = \sqrt{E_{sx}(t)^2 + E_{sy}(t)^2 + E_{sz}(t)^2} \quad (20)$$

In the case of the overhead power line, there are three phases with three time delayed ($2\pi/3$ = 120°) line-to-ground voltages u_1, u_2, u_3 (21), (22), (23) where U_{m} is the voltage amplitude and ω is the angular frequency ($2\pi f = 2\pi 50$).

$$u_1 = U_{\mathrm{m}}\cos(\omega t) \quad (21)$$

$$u_2 = U_{\mathrm{m}}\cos\left(\omega t - \frac{2\pi}{3}\right) \quad (22)$$

$$u_3 = U_{\mathrm{m}}\cos\left(\omega t - \frac{4\pi}{3}\right) \quad (23)$$

The Root Mean Square (RMS) value of the electric field strength E_{RMS} can be calculated by (24), where electric field strength E is defined by (20), T = 0.02 means a cycle of fundamental frequency, while τ is the integration of auxiliary variable.

$$E_{\mathrm{RMS}}{}^2 = \frac{1}{T}\int_{t-T}^{t} E^2(\tau)\,d\tau \quad (24)$$

The charge q required in (12), (14) and (15) could be calculated for each conductor element $d\mathbf{l}$ at time t by equation (25), where $\mathbf{C}$ is the matrix of transmission line capacities, $\mathbf{q}$ is the matrix of charges on all conductor elements and $\mathbf{u}$ is the matrix of voltages (26).

$$\mathbf{q} = \mathbf{C}\,\mathbf{u} \quad (25)$$

$$\mathbf{u} = \left[u_1 \;\; u_2 \;\; u_3\right]^{\mathrm{T}} \quad (26)$$

III. THE CONDUCTOR SAGGING CONSIDERATION

Equations (2), (14) and (15) can be used for the calculation of the magnetic and electric field caused by current and charge of a straight conductor. The magnetic and electric fields, in any point of observation in the vicinity of the overhead lines with multiple conductors, can be obtained by summing up contributions of all conductors. Because the magnetic field density and electric field strength are time-dependent vectors the field components in the axes x, y and z must be defined first and then summed up for all conductors. With the proposed method, the conductor sagging can be easily considered into the account [13]. In that sense the individual conductor between two towers is divided into short and straight section, while summing up, the contributions of all sections to the magnetic and electric field in the given point of observation, gives total values of electric and magnetic fields emissions. Finally, the RMS values are calculated by integrating the magnetic flux density and electric field strength vectors over one cycle of the fundamental frequency (11) and (24).

IV. Reduction of Magnetic and Electric Fields Emissions

Figure 2 shows typical 400 kV overhead power line located in Slovenia. This is a double-circuit overhead line with two conductor bundle. All distances [mm] marked in Figure 2 are valid at the mid-span, where the conductor sagging is maximal.

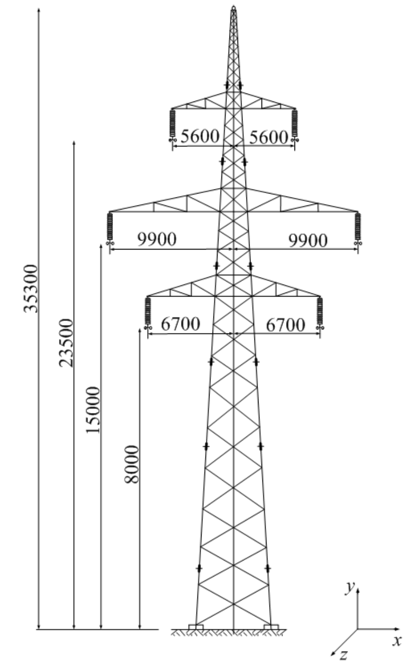

Figure 2. Typical Slovenian double-circuit 400 kV overhead power line.

Figures 3 and 4 show the electric and magnetic field calculated for the sagged conductor as well as for the straight conductor located at 2/3 and 3/3 of the conductor sagging. All calculations are carried out for two conductors bundle, 400 kV phase-to-phase voltage, line current 960 A per conductor, overhead line span 293.9 m and conductor sagging 8.86 m. The RMS value of the magnetic and electric fields on the border of the overhead line right of way ($x = \pm$ 25m, y = 1m) are highly important. For newly built power lines the RMS values of the magnetic and electric fields on the border of overhead power line should not exceed the values 10 μT and 0.5 kV [10].

As Figures 3 and 4 show the magnetic field density and electric field strength along the x direction could exceed the prescribed limit values [10]. This means that for the newly built overhead lines new conductor arrangements must be found.

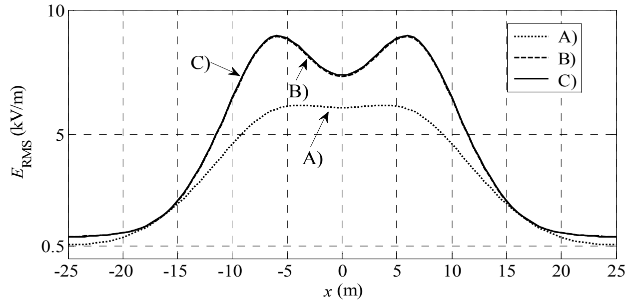

Figure 3. Calculated electric field (y = 1m) of double-circuit overhead power line with two conducor bundle: straight conductor at 2/3 (A) and at 3/3 of sagging (B) and sagged conductor (C).

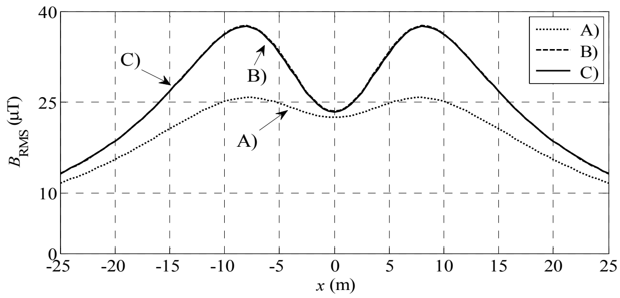

Figure 4. Calculated magnetic field(y = 1m) of double-circuit overhead power line with two conducor bundle: straight conductor at 2/3 (A) and at 3/3 of sagging (B) and sagged conductor (C).

This work deals with three possible solutions, which can be applied in the process of the new overhead line construction, to reduce electric and magnetic fields emissions.

A. *Changing the Sequences of conductor placements*

Firstly, the reduction of electric and magnetic field, with changing the sequences of the conductor placements between both systems, is threated (Figures 5 - 7).

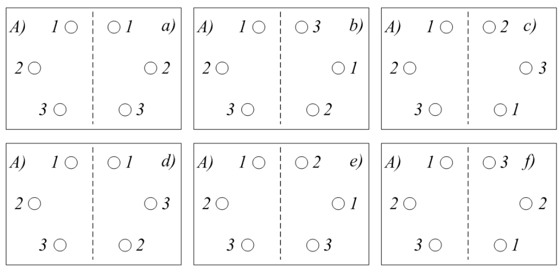

Figure 5. Different conductor sequences of right circuit applied on the double-circuit overhead line.

For the left circuit the conductors sequence A was used, while for the right circuit the six different conductors sequences (a, b, c, d, e and f) were applied. In Figure 5 the number 1 stands for the first phase, the number 2 represents the second phase and the number 3 represents the third phase. Results of E_{RMS} and B_{RMS} on the border of overhead power line right of way for all different combinations are shown on Figures 6 (+ 25 m) and 7 (-25 m).

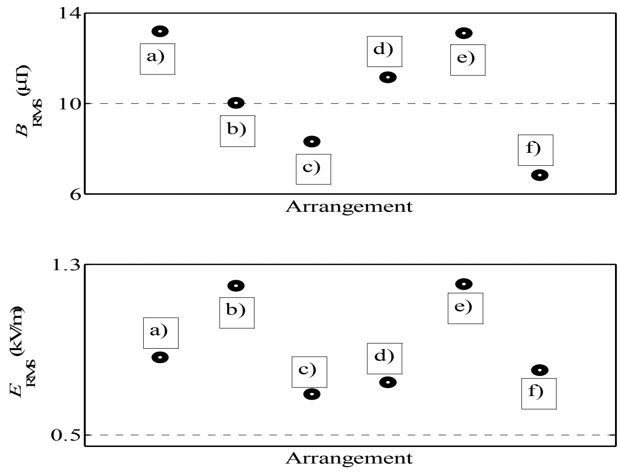

Figure 6. Electric field strength and magnetic field density calculations (y = 1m, x = + 25m).

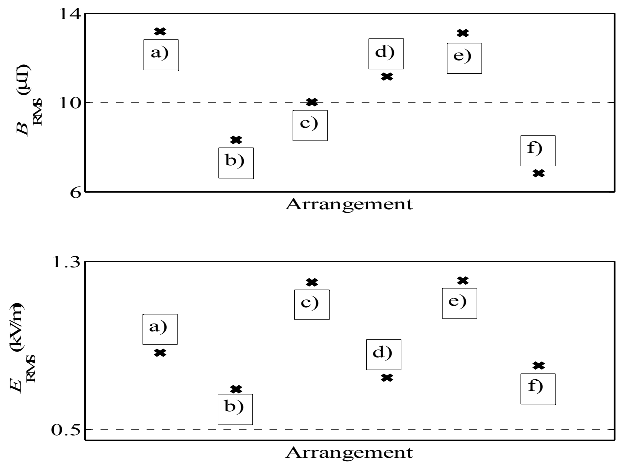

Figure 7. Electric field strength and magnetic field density calculations (y = 1m, x = - 25m).

B. *Usage of the Higher Overhead Power Lines Towers*

The second solution is to reduce the electric and magnetic field, caused by overhead lines, by the usage of the higher towers. This means that the distance from the point of interest to the overhead lines is increased (Figure 8). The height of 0 m means that the level of Figure 2 is valid, while the height 25 m means that all distances in Figure 2 are higher for 25 m. The RMS values of the magnetic field are lower for higher altitudes, while the electric fields are decreasing to 7m high and afterwards slowly increasing to approximately 20m.

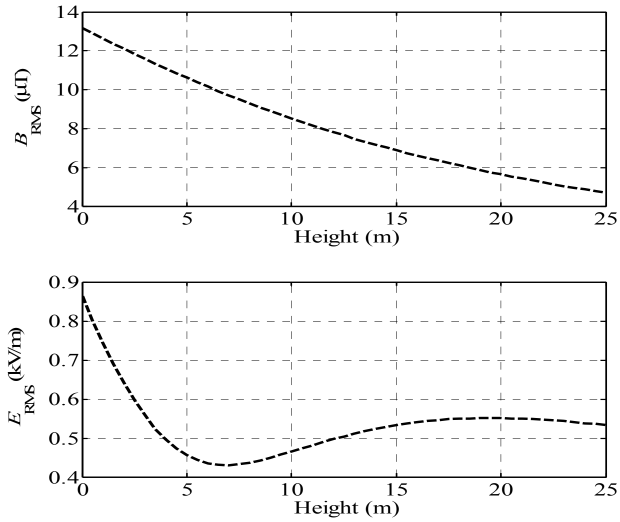

Figure 8. Electric field strength and magnetic field density calculations (y = 1m) for the double-circuit Slovenian overhead power lines dependent on the increased height.

C. *Optimization of Overhead Power Line Conductor Arrangements*

The first solution to reduce the magnetic and electric field emissions, presented in this work (A), shows that both can be reduced but their values are still higher than prescribed. The second solution (B) shows that, with the higher towers, the magnetic and electric field decrease, but because of the substantial increase of the cost this solution is not really suitable. For that reason the third solution (C) to reduce B and E, on the basis of conductor arrangements obtained by an optimization, was applied [13]. The optimization goal is to find such conductors arrangement where the tower height is minimal and the RMS values of the magnetic flux density and electric field strength at the border of the overhead line right of way are below of the prescribed limits. Further optimization conditions are minimum air clearances required to prevent a distruptive discharge between phase conductors (3.68 m) and between conductors and objects at ground potential (3.02 m) during slow-front overvoltages [14]. It follows that clearances between the conductors and the spacing between conductors and overhead ground wire are selected to fulfill the requirements related to the insulation coordination [15], [16]. Minimal value of distance between the conductors and the ground is H_{min} = 8 m, while the shielding angle is set to the 30° [13]. The optimization procedure tries to find the symmetrical arrangements of the overhead line conductors with double-circuit and one overhead ground wire. All results of the presented work are obtained with straight conductor and without consideration of the individual tower parts. As we can see from Figures 3 and 4 the results can be acceptable even when the sagged conductors are approximated with the straight conductor placed in the point of maximal sagging. Figure 9 shows the overhead power line arrangements, of two conductor bundle, determined during the optimization process. All distances in Figure 9 [m] are valid at the midspan.

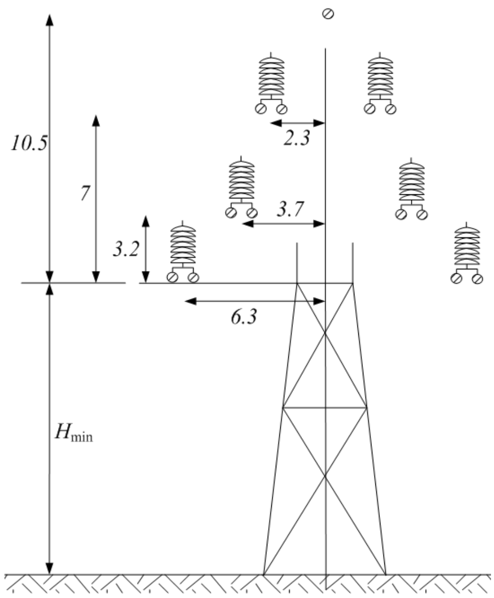

Figure 9. Overhead power line arrangements of two conductor bundle of double tower configuration obtained from optimization process.

Figures 3 and 4 shows electric and magnetic fields calculated for the initial conductor arrangement (Figure 2), where those values are higher than prescribed limits. On the other hand the calculations of B_{RMS} and E_{RMS} on the border of overhead power line right of way obtained for arrangements defined by an optimization are under prescribed limits (Figure 10).

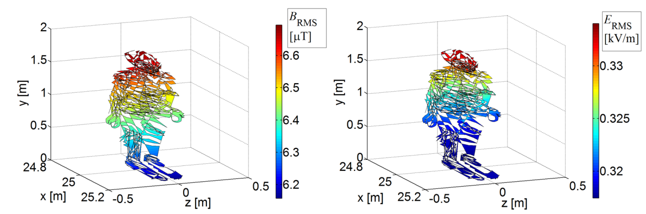

Figure 10. Calculated magnetic and electric fields on the border of overhead line (± 25 m) for conductor arrangement obtained by an optimization.

V. CONCLUSION

Magnetic and electric field calculations carried out for existing 400 kV transmission lines in Slovenia show that field emissions at the border of overhead power lines could be too high. For this reason, this paper represents an attempt to decrease the emissions of electrical and magnetic fields, by a three different solutions. While the first and second solutions, based on the exchange of conductor sequences and the usage of higher towers, are not quite appropriate, the third solution based on conductor re-arrangements obtained in an optimization process could be satisfied. In the given case optimization goal is to find conductors arrangement where the height of the tower is minimal, whereas the values of the magnetic and electric fields on the border of the overhead line right of way are under prescribed limits.

ACKNOWLEDGMENT

This work was partly supported by ELEKTRO – SLOVENIJA, d.o.o., Project No. 6576.

REFERENCES

[1] C. Garrido, A. F. Otero, J. Cidras, “Low-frequency magnetic fields from electrical appliances and power lines,” IEEE Tran. Pow. Delivery, vol. 18, No. 4, pp. 1310–1319, October 2003.

[2] V. C. Motrescu, U. V. Rienen, “Computation of Currents Induced by ELF Electric Fields in Anisotropic Human Tissues Using the Finite Integration Technique (FIT),” Adv. In Radio Science, No. 3, pp. 227–231, 2005.

[3] EPRI, “Transmission Line Reference Book, 345 kV and Above,” EPRI Report, Second Edition, 1982.

[4] J. Mokoena, P. H. Pretorius, P. T. Bhulose, A. A. Burger, D. Muftic, “Electric and Magnetic Field Limits Applied to Overhead Power Line Design in South Africa,” Inter. Coll. – Pow. Freq. Electro. Fields ELF EMF, Paper 11, Sarajevo, 2009.

[5] R. Cruz, L. A. Dominques, A. M. Neto, C. R. Barbosa, T. Dovan, “Analysis of Electromagnetic Fields Exposure Limits from International Standards – Application of Computational Modelling to Assess Human Exposure to EMF,” Inter. Coll. – Pow. Freq. Electro. Fields ELF EMF, Paper 5, Sarajevo, 2009.

[6] C. Polk, “Bioligical Effects of Low-Level Frequency Electric and Magnetic Fields,” IEEE Transl. Ed., vol. 34, No. 3, pp. 243–249, 1991.

[7] H. Yildrim, O. Kalanderli, “Calculation of Electric Field Induced Currents on Human Body Standing Under a high Voltage Transmission Line by Using Charge Simulation Method,” Inter. Conf. Bio. Eng, pp. 75-77, Istanbul, 1998.

[8] E. A. Sebo, S. A. Sebo, “Public Reaction to Power Frequency Electric and Magnetic Field (EMF) Effects,” Inter. Syp. Tech. Soc., pp. 103 – 109, 1996.

[9] CIGRE C4.205, “Characterisation of ELF Magnetic Fields,” CIGRE Tech. Brochure, No. 21, 1980.

[10] Official Gazette of the Republic of Slovenia No. 70/96, “The Decree on Electromagnetic Radiation in the Natural and Living Environment,” Slovenia, 1996.

[11] W. T. Kaune, L. E. Zaffanella, “Analysis of Magnetic Fields Produced Far from Electric Power Lines,” IEEE Tran. Pow. Delivery, vol. 7, No. 4, pp. 2082–2091, 1992.

[12] A. R. Panicali, “Calculation of Electric Fields due to Lines of Charge,” IEEE Tran. Electro. Comp, vol. 33, pp. 67–68, 1991.

[13] K. Deželak, G. Štumberger, F. Jakl, “Arrangements of overhead power line conductors determined by differential evolution,” HRO CIGRE, Cavtat, 2009.

[14] EN 50341-1, “Overhead Electrical Lines Exceeding AC 45 kV - Part 1: General Requirements - Common Specifications,” CENELEC, Brussels, 2001.

[15] EN 60071-1, “Insulation Coordination - Part 1: Definitions, Principles and Rules,” CENELEC, Brussels, 1995.

[16] EN 60071-2, “Insulation Coordination - Part 2: Application Guide,” CENELEC, Brussels, 1995.