Klemen DEŽELAK[1], **Gorazd ŠTUMBERGER**[1], **Franc JAKL**[1]

University of Maribor, Slovenia (1)

Optimization based reduction of the electromagnetic field emissions caused by the overhead lines

***Abstract**. This paper deals with the reduction of electric and magnetic field emissions caused by the single-circuit 400 kV overhead power line. These emissions are especially important on the border of the overhead power line right of way, where electromagnetic field emissions should be under prescribed limits. This paper deals with the two solutions. Firstly the usage of higher towers is investigated, while secondly the new conductor arrangements is defined in the optimization process.*

***Streszczenie.** W artykule poruszono problem ograniczenia emisji pola elektromagnetycznego wywołanego linią elektroenergetyczną 400 kV. Emisja ta jest szczególnie istotna na obszarze dostępnym (right-of-way) gdzie emisja pola elektromagnetycznego podlega szczególnym restrykcjom. Artykuł pokazuje dwa rozwiązania: użycie wyższych słupów energetycznych lub/i zastosowanie nowych ustawień przewodów energetycznych. (**Optymalna redukcja emisji pola elektromagnetycznego wywołanego liniami napowietrznymi**)*

Keywords: optimization, electric fields, magnetic fields, overhead power lines.
Słowa kluczowe: optymalizacja, pole elektryczne, pole magnetyczne, linie napowietrzne

Introduction

This work deals with the reduction of the electric and magnetic fields emissions caused by the overhead power lines. The sources of the magnetic and electric fields in the vicinity of the overhead lines are the electrical currents flowing through conductors and charges existing on it. Generally, these fields can be summed with fields induced in the earth or in nearby objects, neglected in this work. In the last decades the increasing public concern about exposure to electric and magnetic fields has been an important issue in most countries around the world. In that sense the relation between the electromagnetic field emissions and the possible induced body currents is often taken as basic restrictions by the international organization like IEEE (Institute of Electrical and Electronic Engineers), ICNIRP (International Commission on Non-Ionizing Radiation Protection), WHO (World Health Organization), Council of the European Union, which deal with the regulation and recommendation of limits related to acceptable emissions of electromagnetic fields [1]. The recent research findings lead to the restriction for the currents induced in human body. The acceptable values are set to the 10 mA at the occupational and 2 mA at the public area [1]. The aforementioned internationally accepted limits for allowed emissions of magnetic and electric fields are 100 and 500 µT, and 5 and 10 kV/m, respectively. However, the limits accepted by Slovenian government are ten times lower than those given in European Union recommendations [2]. In that sense the limit value of electromagnetic field emissions at public area in Slovenia are 10 µT and 0.5 kV/m [2]. Because of very strict limits set for emissions of electromagnetic fields on the border of overhead power line right of way (± 25m), some modification should be applied in newly constructed overhead power lines. This paper proposed two solutions for reduction of electromagnetic field emissions caused by overhead power lines. The first solution is the usage of higher towers, while the second solution proposes conductor rearrangements obtained by an optimization process. In the second case the position of each conductor is defined in the optimization procedure. The conditions that must be fulfiled are the values of the magnetic and electric fields on the border of the overhead power line right of way, the clearances between conductors, the clearances between conductor and the shield wire and the distance between the lowest conductor and ground at the point of maximal conductor sagging. The optimization goal is to find that conductor arrangements where magnetic and electric fields are under prescribed limits and the tower height is minimal.

Calculation of electric and magnetic field emissions

The overhead power line generates the magnetic and electric fields in their neighborhood. The electric field strength **E** [1] is caused by the charge on conductors and can be calculated by known charge distribution *q* on the overhead line (1). In (1) the vector **a**, with the length *a*, stands for the vector orthogonal to the conductor element *d***l**, with the length *dl*. Angles α_1 and α_2 are the angles between the beginning and the ending point of the conductor element and the observed point (point where the electric field is calculated – Fig. 1) [3].On the other hand the source of magnetic field density **B** [4] is the current *i* flowing in the individual overhead power line conductor (2). In equations (1) and (2) ε_0 and μ_0 are the physical constants valid for the free space. The permittivity of the free space is $\varepsilon_0 = 8.85 \cdot 10^{-12}$, while the magnetic permeability is $\mu_0 = 4\pi \cdot 10^{-7}$. In case of electric field calculation the mark *d***N** in Fig. 1 stands for the differential of electric field strength *d***E**, while for magnetic field calculation *d***N** stands for the differential of magnetic field density *d***B**.

$$d\mathbf{E} = \frac{q}{4\pi\varepsilon_0 a}\left(\begin{gathered} \left(\sin\alpha_2 - \sin\alpha_1\right)\frac{d\mathbf{l}}{dl} + \\ + \left(\cos\alpha_1 - \cos\alpha_2\right)\frac{\mathbf{a}}{a} \end{gathered} \right) \tag{1}$$

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

The charge *q* in (1) must be calculated for each time instant *t* and for the conductor section *d***l** by (3), where **C** is the matrix of the overhead line capacity, **q** is the matrix of charges for all conductors elements, while $\mathbf{u} = [u_1, u_2, u_3]^T$ is the matrix of the voltages defined in (4), where U_m is the voltage amplitude and ω is the angular frequency ($\omega = 2\pi f$). In case of overhead lines the magnetic field is caused by three time delayed line currents i_1, i_2 and i_3 changing with frequency f = 50 Hz (5), where I_m is the current amplitude and ω is the angular frequency ($\omega = 2\pi f$).

$$\mathbf{q} = \mathbf{C}\mathbf{u} \tag{3}$$

$$\begin{aligned} u_1 &= U_m \cos(\omega t) \\ u_2 &= U_m \cos\left(\omega t - \frac{2\pi}{3}\right) \\ u_3 &= U_m \cos\left(\omega t - \frac{4\pi}{3}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} i_1 &= I_m \cos(\omega t) \\ i_2 &= I_m \cos\left(\omega t - \frac{2\pi}{3}\right) \\ i_3 &= I_m \cos\left(\omega t - \frac{4\pi}{3}\right) \end{aligned} \tag{5}$$

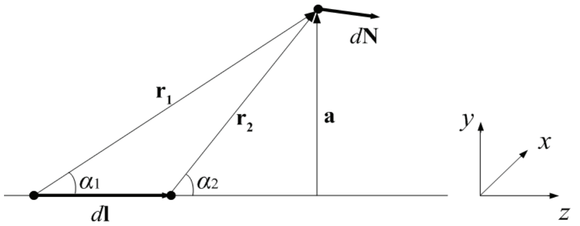

Fig.1. Calculation of magnetic field density and electric field strength caused by a straight conductor element d**l**

Expressions (3) to (5) are required for the electric field strength and magnetic field density calculations by (1) and (2). The results consist of three components in *x*-, *y*- and *z*-axis. After summing up all contributions, the lengths of the electric field strength and magnetic field density vectors *E* and *B* can be determined [5]. Using them, the Root Mean Square (RMS) values of the electric field strenght E_{RMS} and the magnetic field density B_{RMS} can be calculated by (6) and (7).

$$E_{\mathrm{RMS}}^2 = \frac{1}{T} \int_{t-T}^{t} E^2(\tau)\, d\tau \tag{6}$$

$$B_{\mathrm{RMS}}^2 = \frac{1}{T} \int_{t-T}^{t} B^2(\tau)\, d\tau \tag{7}$$

In (6) and (7) *E* and *B* stand for the length of the electric field strenght and magnetic field density vectors, *T* = 0.02 is the cycle of fundamental frequency, *t* is the time, while *τ* is the auxiliary integration variable. Fig. 2 shows the three dimensional view of overhead power line and human body standing under it at the point where the conductor sagging is maximal. The central point of Cartesian system of coordinates is on the earth at the midspan. The *x*-axis is directed toward the corridor border, the *y*-axis represents the height while the *z*-axis is directed along the overhead line axis. The Slovenian decree [2] deals with the two types of radiation sources. The first type represents existing radiation sources, while the new and reconstructed radiation sources represent the second type. It is very important that the limit values of the electromagnetic field emissions of the second type are quite strict (10 μT, 0.5 kV/m) in comparison to the first type. Calculations of the electromagnetic field emissions (Fig. 3) on the border of typical Slovenian overhead power line right of way (*x* ± 25m) show that electromagnetic field emissions can reach higher values as allowed in [2]. The results shown in Fig. 3 are obtained for the typical single-circuit Slovenian 400 kV overhead line (Fig. 4), where all conductors are represent as straight conductors, placed at the point of maximal conductor sagging (3/3 of sagging), between the two towers.

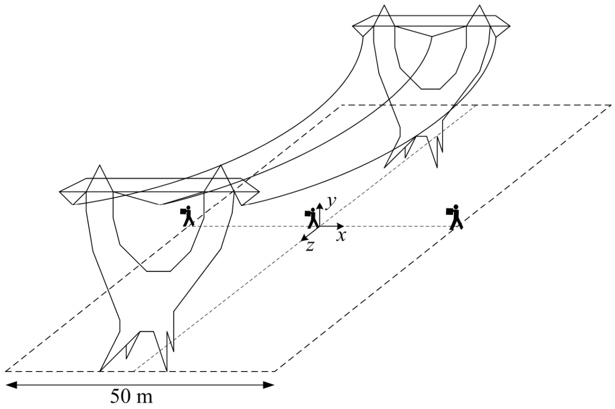

Fig.2. Overhead power line right of way (*x* = ± 25m) and human body standing beneath the overhead line

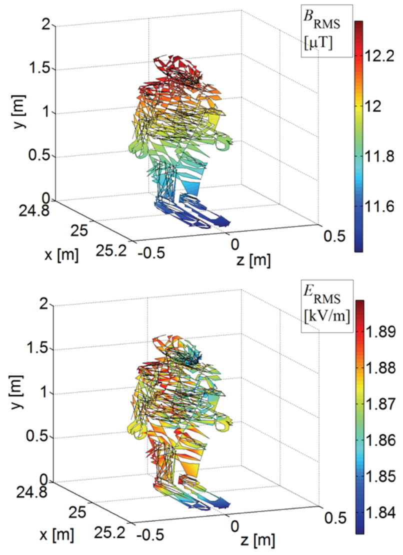

Fig.3. Electric and magnetic field outside of the human body on the *x* = ± 25m before optimization

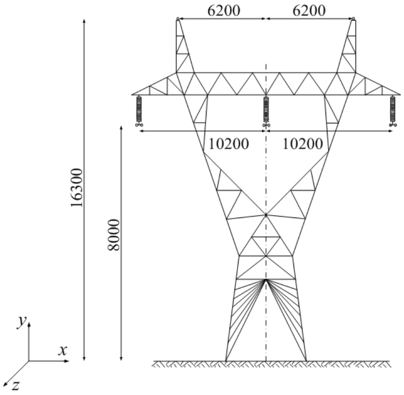

Fig.4. Typical Slovenian single-circuit overhead power line

It was shown that the agreement between calculated fields for the sagged conductor and for the straight conductor placed at 3/3 of sagging is excellent, while for the straight conductors placed at 2/3 of sagging, the calculated values of electric and magnetic fields are too small [5].

Reduction of electric and magnetic field emissions

Because of too high emissions of electromagnetic field, the newly constructed and even the reconstructed overhead power lines require some modification to fit the prescribed emissions limits. This paper deals with the two possible solutions. The first one proposes the use higher towers (Fig. 5) while the second one proposes new arrangement of conductors determined in an optimization procedure [5] – Fig. 6. In order to minimize computational effort and time required for optimization, the sagged conductors are approximated by the straight conductors placed at 3/3 of sagging in all calculations performed inside this paper [5]. The first solution is reducing of the magnetic and electric field emissions, caused by overhead power lines, by the usage of the higher towers. This means that the distance from the point of field emissions observation to the overhead lines is increased for additional height in *y*-axis Δh (Fig. 5). The additional height Δh = 0 m means that the distances shown in Fig. 4 are valid, while the additional height Δh = 25 m means that all distances in Fig. 4 are increased for 25 m. As it is shown in Fig. 5, the RMS values of the magnetic field are decreasing for higher towers, while the electric fields are increasing up to 3m tower height increase, while afterwards they are slowly decreasing. Aforementioned solution shows that, with the higher towers, the magnetic and electric fields decrease. However, due to the substantial increase of the costs this solution is not really suitable. For that reason the second solution to reduce B_{RMS} and E_{RMS}, on the basis of conductor arrangements obtained by an optimization, was applied. Fig. 6 shows basic idea of overhead power line conductors optimization. The position of conductor before the first iteration of optimization proces is defined in *x*-axis by x_{B} and in *y*-axis by y_{B}. During the optimization procedure, the optimization parameters in the form of local polar coorinates given by the distance *R* and the angle φ change, which leads to a new conductor position denotes by x_{E} and y_{E} (8), (9).

$$x_{\text{E}} = x_{\text{B}} + R\cos\varphi \tag{8}$$

$$y_{\text{E}} = y_{\text{B}} + R\sin\varphi \tag{9}$$

The number of parameters defined by optimization D_{opt} is defined by (10), where N_{con} stands for the number of overhead power line conductors and N_{ogw} is the number of overhead line ground wires. The position of overhead line ground wire changes only in the *y* direction, while the positions of all line conductors change in the *x* and *y* directions.

$$D_{\text{opt}} = 2N_{\text{con}} + N_{\text{ogw}} \tag{10}$$

The aforementioned optimization problem could be solved by the different optimization algorithms as a genetic algorithm, a differential evolution, a particle swarm optimization, etc, while in this work the differential evolution was applied. The differential evolution algorithm was introduced in 1995 by Storn and Price [6]. Nowadays it has become one of the most frequently used evolutionary algorithms solving the global optimization problems, even those dealing with technique [7], [8]. Basically the differential evolution works with the beginning population *pop*$_{\text{B}}$ and the crossover population *pop*$_{\text{CROSS}}$, which are of the same size [7]. The population *pop*$_{\text{B}}$ is chose completely randomly, while *pop*$_{\text{CROSS}}$ is obtained from *pop*$_{\text{B}}$ in two steps. Firstly the mutant point is generated by means of the scaling factor *F* [8], while finally the *pop*$_{\text{CROSS}}$ population could be obtained from mutant point, population *pop*$_{\text{B}}$ and crossover parameter *CR* [8]. During the selection all members of crossover population *pop*$_{\text{CROSS}}$ are compared with the members of the beginning population *pop*$_{\text{B}}$. Members with better objective function value are chosen for composing the new population, which replaces beginning population *pop*$_{\text{B}}$. The search continues as long as stopping conditions are not fulfilled [7].

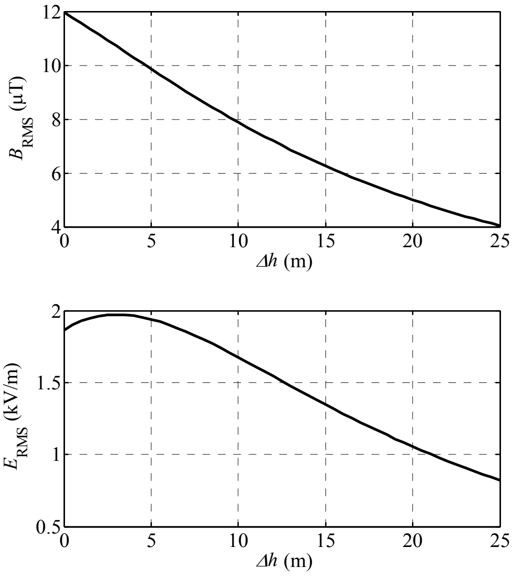

Fig.5. Calculated emissions of magnetic and electric field at the right of way border given as functions of tower height increase

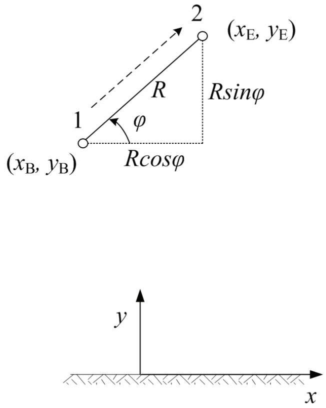

Fig.6. Description of conductor position used in optimization procedure to find optimal arrangement of conductors

The main criteria of the objective function are the electromagnetic emissions on the overhead power line right of way border and the height of the overhead line towers. Apart from that the additional parameters like clearances between phase conductors D_{pp} [9], [10], clearances between conductor and shielding wire D_{el} [9], [10], minimum distance between conductor and ground H_{min} = 8 m and shielding angle 30° must be considered in the objective function. Only those conductor arrangements, that fulfil the requirements of insulation coordination $D_{\text{pp}} \geq 3.68$ m, $D_{\text{el}} \geq 3.02$ m [11], [12], are considered as possible solutions of optimization problem.The goal of optimization procedure is to find the tower with the minimal height where the RMS values of the magnetic and electric field emissions on the border of the overhead power line right of way are under prescribed limits. The optimization in this paper tries to find the arrangement of single-circuit overhead line conductors, with two-conductor bundles, for the tower with one overhead ground wire. The conditions of symmetrical arrangements are considered as well. Afterwards all results presented in this paper are obtained without considering individual parts of tower. Fig. 7 shows overhead power line conductor arrangements (after and also before optimization) of two-conductor bundles for a single-circuit configuration with the one overhead ground wire.

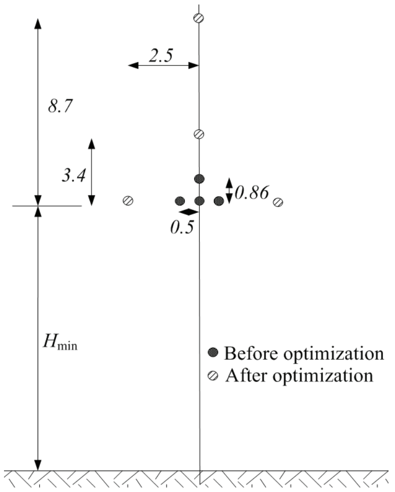

Fig.7. Conductor arrangements obtained from the optimization process

The arrangement of conductors is determined in the optimization process based on the differential evolution. All distances marked in Fig. 7 are valid for the midspan clearances. The calculated electric and magnetic fields for the arrangements of conductors presented in Fig. 7 (after optimization) are shown in Fig. 8.

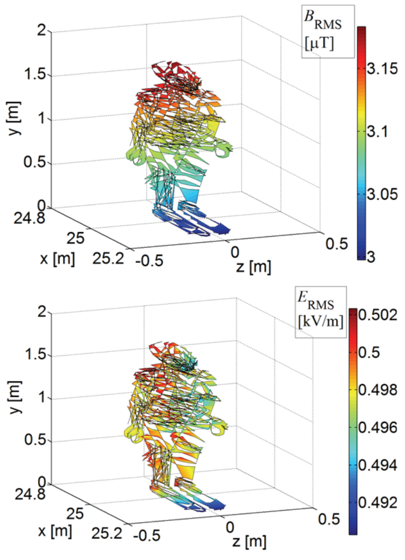

Fig.8. Electric and magnetic field outside of the human body on the $x = \pm 25$m after optimization

Fig. 8 shows electric and magnetic fields calculated for the arrangement of conductors determined in the optimization procedure. The calculations are performed for the overhead power lines at rated voltage 400 kV and maximal conductor currents 960 A. Fig. 8 clearly shows that the values of magnetic and electric fields on the right of way border, obtained for the optimization determined arrangements of conductors, are under allowed values [2] (B = 10 µT, E = 0.5 kV/m).

Conclusion

Magnetic field density and electric field strength calculations performed for existing 400 kV, single-circuit, overhead power lines in Slovenia show that field emissions on the border of the overhead power line right of way could be too high. For that reason, this work represents an attempt to decrease emissions of magnetic and electric fields by two solutions. Firstly the usage of higher towers and secondly an appropriate arrangement of conductors obtained in an optimization procedure. The goal of optimization is to find the tower with minimal height which fits all technical requirements while the RMS values of the magnetic flux density and electric field strength on the overhead power line right of way border are under prescribed limits.

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Authors

Klemen Deželak, univ. dipl. Inž. el., mail: klemen.dezelak@uni-mb.si; Prof. dr. Gorazd Štumberger, univ. dipl. Inž. el., E-mail: gorazd.stumberger@uni-mb.si; Prof. dr. Franc Jakl, univ. dipl. Inž. el., E-mail: franc.jakl@siol.si
Faculty of electrical engineering and computer science, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia,;