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# Emissions of electromagnetic fields caused by sagged overhead power lines

***Abstract**. Nowadays people became aware of the overhead lines and their emissions of electromagnetic fields. This work presents a method for calculation of the electric field strength and magnetic field density caused by the overhead power lines at the ground level. The method considers the conductor sagging. It is shown that the sagged conductors can be replaced with the properly placed straight conductors without substantial decrease in accuracy of calculated results.*

***Streszczenie.** Obecnie daje się zauważyć wzrost świadomości społecznej istnienia linii elektroenergetycznych napowietrznych i emitowania przez nie pola elektromagnetycznego. Artykuł prezentuje metodę obliczeń natężenia pola elektrycznego i strumienia magnetycznego od linii elektroenergetycznej na poziomie ziemi. Metoda uwzględnia obniżenie (zwis) przewodu. Pokazano, że zwis przewodów może zostać zastąpiony przez właściwie umieszczone proste przewody bez istotnej utraty dokładności. **(Emisja pola elektromagnetycznego przez linie elektroenergetyczne przy uwzględnieniu ich zwisu)***

**Keywords:** overhead power line, magnetic fields, electric fields, conductor sagging.
**Słowa kluczowe:** linie napowietrzne, pole magnetyczne, pole elektryczne, zwis przewodu

## Introduction

In nowadays, the people become increasingly aware of the overhead power lines presence [1]. One of the reasons for that are the electromagnetic field emissions caused by the overhead power lines which could influence their health. This concern leads to the different objections related to the construction of the new overhead power lines. Additionally, the re-constructions of the existing overhead power lines and even different spatial plans could be under the influence of the people's objections [1]. Moreover, in the case of overhead power lines not only emissions of electromagnetic fields but also the audible noise emissions are present, which could be a significant parameter.

This paper only focuses on emissions of magnetic and electric fields caused by overhead power lines. The discussion related to the biological effects of the power frequency magnetic fields started in the late 1970's, while in the recent years the relationship between the electromagnetic field emissions and the health is being increasingly investigated [1–3]. The most important fact in aforementioned investigations is the relation between the electromagnetic field emissions and currents induced in the human body. The possible induced body currents are often taken as the basic restrictions by the international organization like International Commission on Non-Ionizing Radiation Protection - ICNIRP, Institute of Electrical and Electronic Engineers, Council of the European Union, World Health Organization, etc. The recent research findings led to the limits for induced human body current, which are set to 2 mA at the public and 10 mA at the occupational area [4]. That limits are related to the magnetic field density limits of 100 μT and 500 μT, and the electric field strength limits of 5 kV/m and 10 kV/m [4]. In the past, the Council of the European Union recommends its member states to apply the reference values of the ICNIRP, especially to limit the biological and health effects to the general public. In that sense Slovenia adopted the legislation regarding to the electromagnetic fields in the natural and living environment [5]. The adopted limit values for emissions of electromagnetic field for the reconstructed and the newly constructed overhead power lines are set to the 10 μT and 0.5 kV/m [3], [5]. It is important to mention that these limit values are valid in the areas of a more sensitive use, like the living areas, hospitals, schools, etc. They must be fulfilled everywhere outside the overhead power line right of way whereas inside the overhead power line right of way 10 times higher values are allowed. Since the limit values for allowed emissions of electric and magnetic fields are extremely strict, the correct calculation of these emissions caused by the newly constructed and re-constructed overhead power lines is highly important.

This paper proposes a method for calculation of the magnetic and electric field emissions caused by the overhead power line considering conductor sagging. The method is tested for the Slovenian double-circuit 400 kV overhead power line, with the two-conductor bundle.

## Magnetic field density and electric field strength calculations

Generally, the electric and magnetic fields are coupled, and it is necessary to solve Maxwell's equations to determine them. But in the case of overhead power lines, at the supplied voltage frequency 50 Hz, where electromagnetic field has a wavelength of 6000 km, the quasistatic methods could be used [2]. These methods use the static Maxwell's equations (1) – (6), where the static electric and magnetic fields could be calculated separately. In (1) – (6) $\mathbf{B}$ is the magnetic field density vector, $\mathbf{E}$ is the electric field strength vector, $\mathbf{D}$ is the electric field density vector, $\rho$ is the charge density, $\mathbf{H}$ is the magnetic field strength vector and $\mathbf{J}$ is the current density vector. The permittivity $\varepsilon$ and the permeability $\mu$ are composed from the relative $\varepsilon_r$, $\mu_r$ and vacuum $\varepsilon_0$, $\mu_0$ values.

(1) $$\nabla \times \mathbf{E} = 0$$

(2) $$\nabla \cdot \mathbf{D} = \rho$$

(3) $$\nabla \times \mathbf{H} = \mathbf{J}$$

(4) $$\nabla \cdot \mathbf{B} = 0$$

(5) $$\mathbf{B} = \mu \mathbf{H} = \mu_0 \mu_r \mathbf{H}$$

(6) $$\mathbf{D} = \varepsilon \mathbf{E} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

The electric field emissions are caused by the charge $q$ placed on the conductor element $d\mathbf{l}$. The electric field strength vector $d\mathbf{E}$ in any point in vicinity of the overhead power line, can be calculated by the equation (7) [6]. In (7) $dl$ is the length of the conductor element $d\mathbf{l}$, $\varepsilon_0$ is the permittivity of the free space while $\mathbf{R}$ is the vector pointing from the conductor element $d\mathbf{l}$ to an arbitrary point of observation. Its length is denoted by $R$.

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

The magnetic field density vector $d\mathbf{B}$ caused by the current $i$ flowing through the straight conductor element $d\mathbf{l}$, with the length $dl$, can be calculated by the Biot-Savart's law (8) [7], where $\mu_0$ 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 of observation.

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

**Conductor sagging consideration**

With derivation proposed in [8] the equation for the electric field strength vector $d\mathbf{E}$ and magnetic field density vector $d\mathbf{B}$ caused by the charge $q$ and current $i$ of the straight conductor element $d\mathbf{l}$ are obtained. The calculated $d\mathbf{E}$ and $d\mathbf{B}$ are composed of components in the axes $x$, $y$ and $z$ (9), (10). The axes are defined with the unity vectors $\hat{\mathbf{a}}_x$, $\hat{\mathbf{a}}_y$ in $\hat{\mathbf{a}}_z$ shown in Figs. 1 and 4, while $dB_x$, $dE_x$, $dB_y$, $dE_y$, $dB_z$, $dE_z$ are the contributions of the magnetic field density and electric field strength in all three axes.

(9) $$d\mathbf{E} = dE_x\hat{\mathbf{a}}_x + dE_y\hat{\mathbf{a}}_y + dE_z\hat{\mathbf{a}}_z$$

(10) $$d\mathbf{B} = dB_x\hat{\mathbf{a}}_x + dB_y\hat{\mathbf{a}}_y + dB_z\hat{\mathbf{a}}_z$$

On the other hand the conductor of overhead power line inside the span is not straight. In fact, the shape of the conductor between the two towers can be described by the catenary curve, which depends on the environmental conditions and characteristics of the conductor. To obtain even more exact results of the electric and magnetic field emissions, the conductor sagging should be included in the calculations [9], [10]. Fig. 1 shows the section $d\mathbf{l}$ of the overhead power line conductor with length $dl$. In Fig. 1 the $dy$ and $dz$ are the components of $dl$ in the axes $z$ and $y$, $p$ is the conductor weight, while $\sigma$' and $\sigma$' + $d\sigma$' are the conductor tensile stress components in the vertical $\sigma$'', $\sigma$'' + $d\sigma$'' and horizontal $\sigma$, $\sigma$ + $d\sigma$' directions.

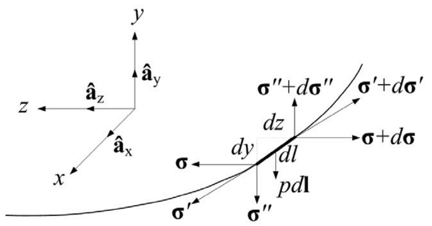


Fig.1. The section $d\mathbf{l}$ of the overhead power line inside the span

Since the conductor cross section $A$ is considered as constant, the balance of tensile forces can be expressed with tensile stress. Thus the force balance in the horizontal and vertical direction yields (11) and (12). Considering (13) in (12), leads to (14), (15) and (16).

(11) $$\hat{\mathbf{a}}_z A d\sigma = 0 \;\Rightarrow\; \hat{\mathbf{a}}_z A\sigma = konst$$

(12) $$\hat{\mathbf{a}}_y A d\sigma" = \hat{\mathbf{a}}_y Apdl$$

(13) $$dl = \sqrt{dz^2 + dy^2} = dz\sqrt{1+\left(\frac{dy}{dz}\right)^2}$$

(14) $$\frac{d\sigma"}{dz} = p\sqrt{1+\left(\frac{dy}{dz}\right)^2}$$

(15) $$\frac{\sigma"}{\sigma} = \frac{dy}{dz} \;\Rightarrow\; \sigma" = \sigma\frac{dy}{dz}$$

(16) $$\sigma\frac{d^2y}{dz^2} = p\sqrt{1+\left(\frac{dy}{dz}\right)^2}$$

Considering the initial conditions and the integration constant – $\sigma/p$ the solution of (16) can be given by (17) [11] describing the conductor sagging in the form of catenary curve.

(17) $$y = \frac{\sigma}{p}\left(\mathrm{ch}\frac{zp}{\sigma} - 1\right)$$

In this paper the function, which describe the sagging curve $y(z)$, is given in the position discrete points. With position discrete points the sagged conductor is represented by a finite number of short, but straight sections of conductor. The length of the all straight conductor sections is equal. In case of the magnetic field density calculations the position discrete points are shown in Fig. 2, while Fig. 3 shows the position discrete points in the case of electric field strength calculation.

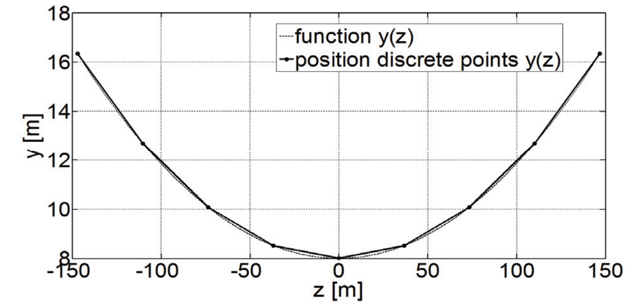


Fig.2. Shape of the sagging curve given in the position discrete points appropriate for magnetic field density calculation

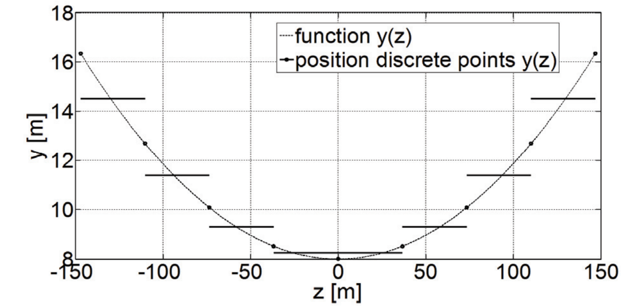


Fig.3. Shape of the sagging curve given in the position discrete points appropriate for electric field strength calculation

In order to determine the line charges $q$ required in (7), the conductors between two discrete points are approximated with the straight conductors, parallel to the ground, as shown in Fig. 3. Since the matrix of the transmission line capacities $\mathbf{C}$ depends only on the line geometry between the two discrete points, the matrix of charges $\mathbf{q}$ on individual conductor elements can be determined from known matrix of line voltages $\mathbf{u}$ (18) [11]. The elements of $\mathbf{u}=[u_1,u_2,u_3]^{\mathrm{T}}$ are given in (27)-(29).

(18) $$\mathbf{q} = \mathbf{C}\mathbf{u}$$

Until now only the position discretization for one conductor was discussed. In case of the overhead power line there exist several conductors. Their number depends on the numbers of overhead power line circuits, number of conductors in the bundle, manner of energy transmission and the number of the overhead earth wires. In the case of the electromagnetic fields calculations, each conductor, contributing to the electromagnetic field emissions, is composed of straight conductor elements defined with the position discrete points. Let us suppose that after the position discretization of all conductors over the whole span, the number total of all straight conductor sections equals $N$. The contribution of the $i$-th conductor element $d\mathbf{l}$ to the electric filed strength $d\mathbf{E}$ and magnetic field density $d\mathbf{B}$ is described by (9) and (10), respectively.

Using the described procedure, the contributions $dB_x$, $dE_x$, $dB_y$, $dE_y$, $dB_z$, $dE_z$ of all $N$ straight conductor sections are summed as it is described with (19) to (24). In this way the components of the magnetic field density vector $B_x$, $E_x$, $B_y$ and the components of the electric field strength vector $E_y$, $B_z$, $E_z$, are determined in an arbitrary point of observation.

(19) $$E_x = \sum_{i=1}^{N} dE_{x,i}$$

(20) $$E_y = \sum_{i=1}^{N} dE_{y,i}$$

(21) $$E_z = \sum_{i=1}^{N} dE_{z,i}$$

(22) $$B_x = \sum_{i=1}^{N} dB_{x,i}$$

(23) $$B_y = \sum_{i=1}^{N} dB_{y,i}$$

(24) $$B_z = \sum_{i=1}^{N} dB_{z,i}$$

After that the lengths of the electric field strength vector $E$ and magnetic field density vector $B$ are calculated by (25) and (26).

(25) $$E = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

(26) $$B = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

In case of the overhead power line, the current and voltage, respectively charge, change periodically. In order to determine the root mean square (rms) values of $E$ and $B$, the time discretization is introduced. Thus, (19) to (26) are calculated for each discrete time instant $t$ considering the instantaneous values of the voltages and currents.

The three-phase overhead power line is normally fed by the three phase sinusoidal voltages $u_1$, $u_2$ and $u_3$ (27)-(29). They are displaced for $2\pi/3$, $U_m$ is the amplitude and $f$ = 50 Hz is the frequency.

(27) $$u_1 = U_m \cos(2\pi ft)$$

(28) $$u_2 = U_m \cos\left(2\pi ft - \frac{2\pi}{3}\right)$$

(29) $$u_3 = U_m \cos\left(2\pi ft - \frac{4\pi}{3}\right)$$

Similarly, in the case of symmetrically loaded overhead power line, the line currents $i_1$, $i_2$ and $i_3$ are described by (30) – (32), where $I_m$ is the amplitude.

(30) $$i_1 = I_m \cos(2\pi ft)$$

(31) $$i_2 = I_m \cos\left(2\pi ft - \frac{2\pi}{3}\right)$$

(32) $$i_3 = I_m \cos\left(2\pi ft - \frac{4\pi}{3}\right)$$

In this way, the instantaneous values of the currents (30)-(32), voltages (27)-(29), conductor element charges $q$ (18) as well as $E$ (25) and $B$ (26), are determined in each time discrete point. The rms values of the electric field strength $E_{rms}$ and magnetic field density $B_{rms}$ are defined by (33) and (34), where $L$ is the number of samples per one cycle of fundamental frequency, while $j$ denotes sample.

(33) $$E_{rms} = \sqrt{\frac{1}{L}\sum_{j=1}^{L} E^2(j)}$$

(34) $$B_{rms} = \sqrt{\frac{1}{L}\sum_{j=1}^{L} B^2(j)}$$

**Results of magnetic field density and electric field strength calculations**

Fig. 4 shows the conductor arrangements of a double circuit transmission line in Slovenia, where the above conductors represent the first phase and the below conductors represent the third phase. All distances marked in Fig. 4 are given for the mid-span clearances. The calculated electric fields strength, produced by the electric charges, and the magnetic field density, produced by the moving charges, for two conductors bundle, are shown in Figs. 5 and 6. The results are given for the overhead power line with rms voltage 400 kV, rms line current 960 A, span 293.9 m, and conductor sagging 8.86 m.

Figs. 5 and 6 show the differences among the results calculated for the sagged conductor and the ones obtained for the approximations of the sagged conductors with the straight ones placed in the points of maximal conductor sagging and 2/3 of maximal conductor sagging. The agreement among the results is evaluated by (35) to (38).

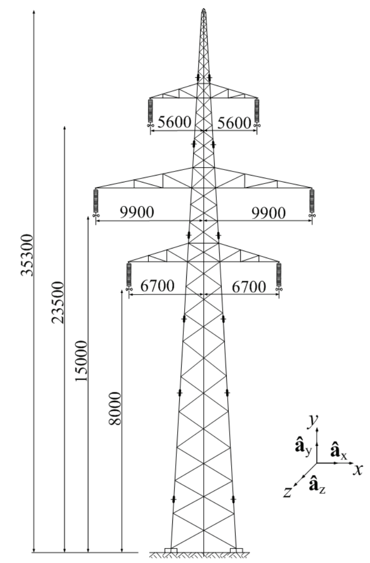


Fig.4. The arrangements of overhead power line conductors for double circuit line

In (35) – (38) $M$ is the number of observed points beneath the overhead power line along the $x$ axis, where the rms values of magnetic field density and electric field strength is calculated. The indices 2/3 and 3/3 mean the results obtained for approximation with the straight placed at 2/3 and 3/3 of the conductor sagging, respectively. $E_{\mathrm{rms,k}}$ and $B_{\mathrm{rms,k}}$ are the values calculated by (33) and (34) in the point $k$.

$$B_{\mathrm{agr},3/3} = 100 - \frac{\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(B_{\mathrm{rms}(3/3),\,\mathrm{k}} - B_{\mathrm{rms,\,k}}\right)^2}}{\frac{1}{100}\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(B_{\mathrm{rms,\,k}}\right)^2}} \tag{35}$$

$$E_{\mathrm{agr},3/3} = 100 - \frac{\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(E_{\mathrm{rms}(3/3),\,\mathrm{k}} - E_{\mathrm{rms,\,k}}\right)^2}}{\frac{1}{100}\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(E_{\mathrm{rms,\,k}}\right)^2}} \tag{36}$$

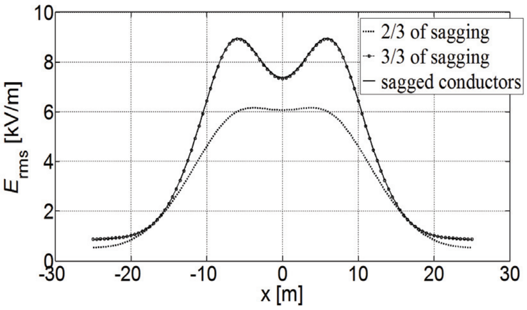


Fig.5. Calculated electric field strength of overhead power line: straight conductors at 2/3 and 3/3 of sagging and sagged conductors

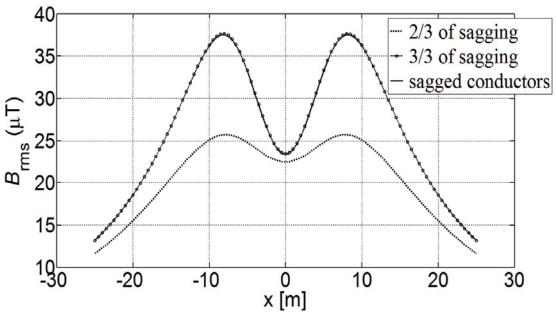


Fig.6. Calculated magnetic field density of overhead power line: straight conductors at 2/3 and 3/3 of sagging and sagged conductors

$$B_{\mathrm{agr},2/3} = 100 - \frac{\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(B_{\mathrm{rms}(2/3),\,\mathrm{k}} - B_{\mathrm{rms,\,k}}\right)^2}}{\frac{1}{100}\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(B_{\mathrm{rms,\,k}}\right)^2}} \tag{37}$$

$$E_{\mathrm{agr},2/3} = 100 - \frac{\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(E_{\mathrm{rms}(2/3),\,\mathrm{k}} - E_{\mathrm{rms,\,k}}\right)^2}}{\frac{1}{100}\sqrt{\frac{1}{M}\sum_{\mathrm{k}=1}^{M}\left(E_{\mathrm{rms,\,k}}\right)^2}} \tag{38}$$

The results presented in Figs. 5 and 6 as well as results obtained by (35) to (38) show a very good agreement between the results obtained for the sagged conductors and those obtained for their approximation with the straight conductors placed at 3/3 of sagging $B_{\mathrm{agr},3/3}$ = 99.66 % (35) and $E_{\mathrm{agr},3/3}$ = 99.48 % (36). However, when the straight conductors are placed at 2/3 of the sagging, the agreements calculated by (37) and (38) are poor $B_{\mathrm{agr},2/3}$ = 74.87 % and $E_{\mathrm{agr},2/3}$ = 72.19 %.

## Conclusion

This paper deals with the calculation of the magnetic field density and electric field strength with the use of equations for static electric and magnetic fields. The proposed method considers the sagging of conductors. It is shown that acceptable results can be obtained even when the sagged conductors are approximated with appropriately placed straight conductors. The differences between the maximal root mean square values of the fields calculated with straight conductors, placed in the points of the highest conductor sags and those calculated considering the conductor sagging, do not exceed 1%.

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