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Magnetic field emissions caused by overhead power line: analytical calculations, numerical calculations and measurements

***Abstract**. In the paper an analytical method for calculation of magnetic field emissions, caused by overhead power line, is dealt with. The obtained results are verified with measurements performed on a 400 kV double-system overhead power line and with numerical calculations using finite elements method. The results obtained by the proposed analytical method are compared with results of calculation where conductor sagging is considered. The proposed method is suitable to be used in optimization procedures where the computational time could have an important role.*

***Streszczenie.** W artykule opisano analityczną metodę obliczania emisji pola magnetycznego przez napowietrzną linię elektroenergetyczną. Wyniki porównano z pomiarami przeprowadzonymi na linii napowietrznej dwutorowej 400kV z wykorzystaniem metody elementów skończonych. Proponowana metoda pozwala na dużą oszczędność czasową i optymalizację tego rodzaju obliczeń. (**Emisja pola magnetycznego napowietrznych linii elektroenergetycznych – obliczenia analityczne i numeryczne oraz pomiary**).*

Keywords: overhead power line, measurements, magnetic fields, FEM.
Słowa kluczowe: napowietrzna linia elektroenergetyczna, pomiary, pole magnetyczne, FEM.

Introduction

People become increasingly aware of the overhead power lines presence which might influence their health. This concern leads to the different objections related to the construction of the new and the re-constructions of the existing overhead power lines [1], [2]. In that sense the increased public concern about exposure to magnetic field emissions presents an important technical issue. Especially relations between the magnetic field emissions and the induced body currents are often taken as a basic restriction criteria of different international organizations like WHO, ICNIRP, etc [1]. The recent research findings led to the limitation of allowed currents induced in a human body, which are set to 10 mA/m^2 at the occupational area and to 2 mA/m^2 at the public area [3]. The Slovenian limit values for emissions of magnetic field for the reconstructed and newly constructed overhead power lines are set to the 10 μT [4], [5]. That limit values are valid in the areas of a more sensitive use, like the living areas, schools, hospitals, 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 value is allowed. To reduce the aforementioned magnetic field emissions, different solutions, like changing the sequences of phase conductor placements, the usage of higher towers or optimal arrangements of phase conductor determined within an optimization process, has been applied so far [6] - [9]. When magnetic field calculation is used in an optimization procedure, the computational effort required for the magnetic field calculation has an extremely important role. Overhead power line conductor sagging inside the span can be described by the catenary curve [2], which could cause even higher computational effort required for accurate magnetic field calculation. For that reason it is necessary to apply methods for calculation of magnetic field emissions, where the computational effort is as low as possible and the accuracy of calculated results is acceptable. One of such methods is proposed in this paper. It is confirmed by the comparison of calculated results with the measured and FEM calculated ones.

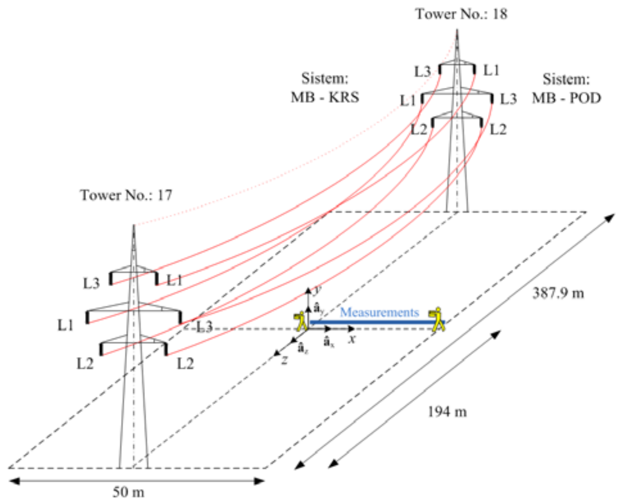

Fig.1. The arrangement of overhead power line conductors and positions of measurements

Discussed system and description of measurements

Measurements, as well as all calculations, of magnetic field emissions were performed for the span in the length of 387.9 m shown in Fig. 1. It is located between the towers 17 and 18 of the 400 kV Slovenian double-system overhead power line (system I: MB-KRS, system II: MB-POD). The magnetic field emissions were measured at the middle of the span (194 m from the tower 17), where the conductor sagging is maximal. At the time of measurements the system MB-KRS was switched off (no currents), while the system MB-POD was switched on. In case of magnetic field calculation, as a part of an optimization procedure, the obtained values are especially important at the overhead power line right of way border. These values should be lower than values prescribed by the national regulations. In our case the aforementioned overhead power line right of way is equal to ± 25 m.

Magnetic field measurement performance

In calculation and measurement of magnetic field emissions caused by and overhead power line, the clearances between conductors, clearances between conductors and observation point and values of currents in the conductors have an important role. In that sense all the distances at the tower are shown on Fig. 2, while Fig. 3 shows the values of the measured phase current RMS values. The distance between the lower conductor and the ground at the point of maximal conductor sagging at the measurement point was 9.087 m means. Afterwards, using Fig. 2, it is clear that the conductor sagging value equals (22.03 - 9.087) m = 12.943 m.

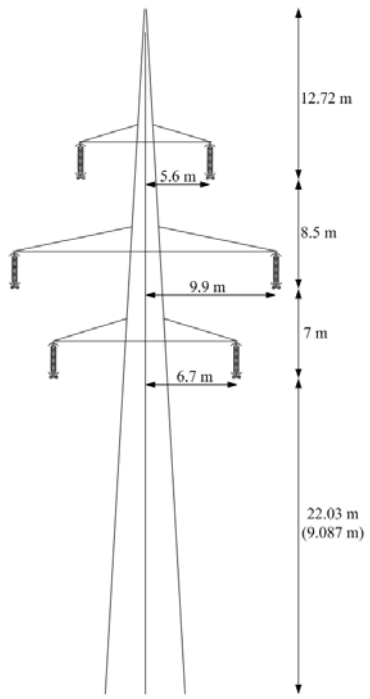

Fig.2. Distances between the individual conductors

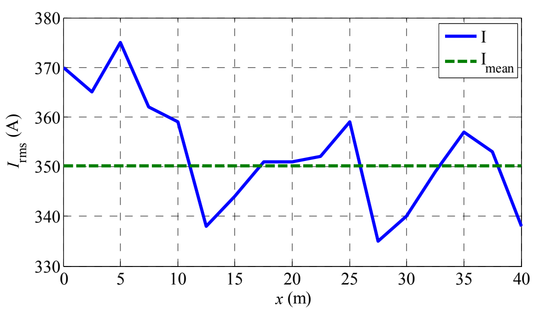

Fig.3. Measured rms values of line current during magnetic field measurements

FEM calculations

Generally, electromagnetic fields are described by Maxwell equations, where electric and magnetic fields are defined by the curl and divergence operation. In differential form the Maxwell equations in air are given by (1) – (6), where $\mathbf{B}$ is the magnetic field density vector, $\mathbf{E}$ is the electric field strength vector, $\mathbf{D}$ is the electric field density vector, ρ is the charge density, $\mathbf{H}$ is the magnetic field strength vector and $\mathbf{J}$ is the current density vector. The permittivity ε and the permeability μ are composed from the relative ε_r, μ_r and vacuum ε_0, μ_0 values.

(1) $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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

(3) $$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

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

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

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

Generally, the electric and magnetic fields are coupled, but in the case of overhead power lines, where the supplied voltage frequency is 50 Hz, the quasistatic methods could be used [10]. These methods use the static Maxwell's equations, where the static magnetic field could be calculated separately by (4), (5) and (7).

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

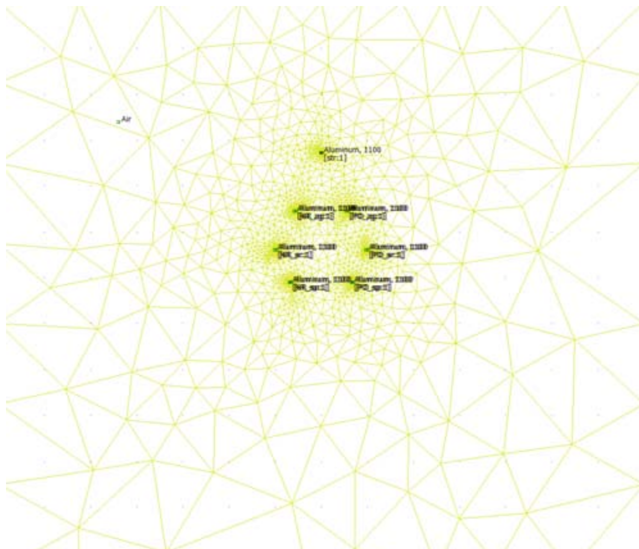

Fig.4. 2D mesh in applied FEM solution – pre-processing

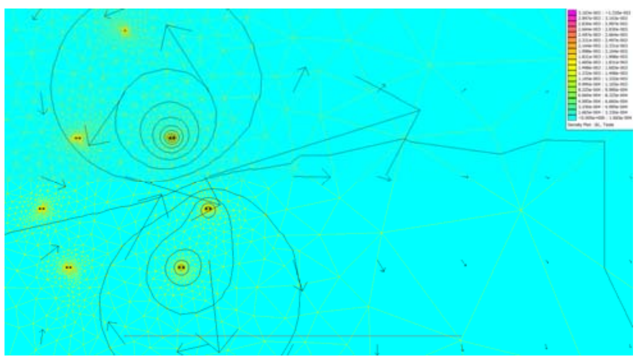

Fig.5. FEM calculations (time t = 0 s) – post-processing

Figs. 4 and 5 show 2D mesh in applied FEM solution – pre- and post-processing. Results shown in Figs. 5 and 6 are obtained for time *t* = 0 s, where the values of currents in the individual phases are equal to i_{L1} = 247 A, i_{L3} = -123 A and i_{L2} = -123 A. The FEM calculated results of magnetic field density for other times are shown in Fig. 7.

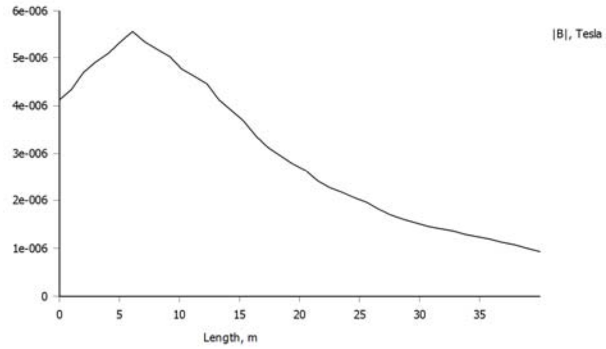

Fig.6. FEM calculations of magnetic field density at time *t* = 0 s

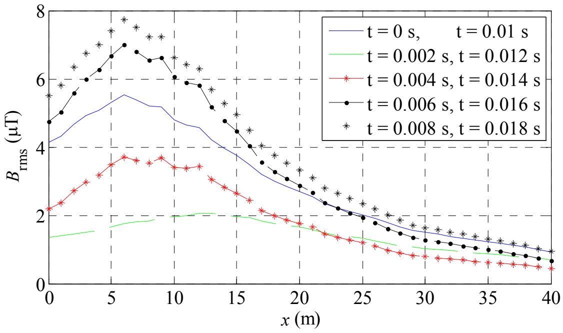

Fig.7. FEM calculations of magnetic field density in times *t* = 0 s - *t* = 0.018 s

Analytical calculations

The magnetic field density *d***B** caused by the current *i* through the straight conductor element *d***l**, with the length *dl*, can be obtained by (8), where μ_0 stands for the permeability of the free space and **a** stands for the vector orthogonal to the *d***l**, which points from the direction of *d***l** to an arbitrary point of observation. Its length is denoted with *a*, while α_1 and α_2 are the two angles between beginning and ending point of the conductor element *d***l** and the observation point [8].

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

Equation (8) were applied for the analytical calculation of magnetic field emissions firstly for the sagged conductor consideration (Fig. 8, [2]) and secondly for the sagged conductor approximated with the straight one. In that case the straight conductors are placed at the point of the maximal conductors sagging [2].

By equation (8) calculated $d\mathbf{B}$ contains three components in the axes x, y and z (9). These axes are defined with the unity vectors $\hat{\mathbf{a}}_x$, $\hat{\mathbf{a}}_y$ in $\hat{\mathbf{a}}_z$ shown in Fig. 1, while dB_x, dB_y, dB_z are the contributions of the magnetic field density in all three axes.

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

In case of the overhead power line the current changes periodically with frequency *f* = 50 Hz. In order to determine the root mean square (rms) values of B, the time discretization is introduced. Thus *d***B** is calculated for each discrete time instant t considering the instantaneous values of the currents. In the case of symmetrically loaded overhead power line, the line currents i_1, i_2 and i_3 are described by (11) – (13), where I_m is the current amplitude.

(11) $$i_1 = I_m \cos(2\pi f t)$$

(12) $$i_2 = I_m \cos\left(2\pi f t - \frac{2\pi}{3}\right)$$

(13) $$i_3 = I_m \cos\left(2\pi f t - \frac{4\pi}{3}\right)$$

Finally, the root mean square values of the magnetic field density B_{rms} is defined by (14), where L is the number of samples per one cycle of fundamental frequency, *B* is a function of B_x, B_y and B_z, while j denotes the sample [2].

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

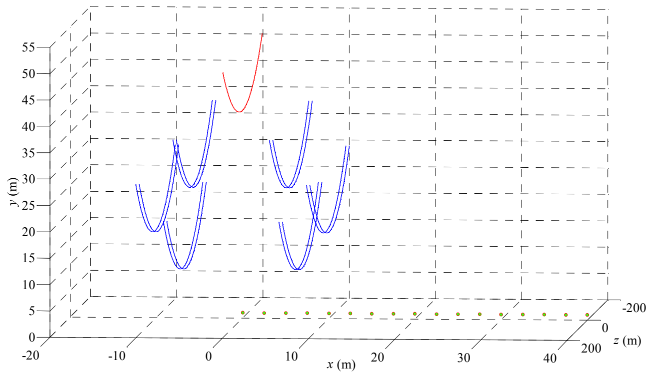

Fig.8. The sagged conductor consideration - analytical calculations

Comparison of results

The magnetic field emissions calculated by the described analytical method for the straight and sagged conductors are shown in Fig. 9 together with the measured and FEM-calculated ones.

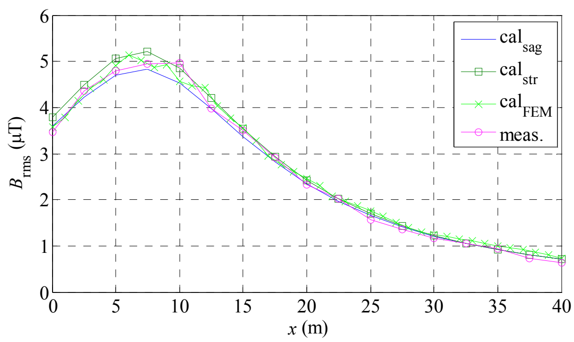

Fig.9. Comparison of results - magnetic field density

Presented results show a very good agreement between the measured and calculated results obtained for the sagged conductors. However, when the straight conductors are placed at the point of maximal conductor sagging, the agreement between measured and calculated results is still acceptable, which can be stated also for the FEM calculated values. However, at the overhead power line right of way border the results are practically identical, which means that the analytical method with straight conductors can be used in the cases, where emissions at the overhead power line right of way have to be evaluated.

Conclusion

This paper deals with the analytical calculation, FEM calculation and measurements of the magnetic field density caused by an overhead power line. The proposed analytical method considers the sagging of conductors as well as their approximation with the straight conductors placed at the points of maximal conductor sagging. The calculated results are compared with the measured one. It is shown that acceptable results can be obtained even when the sagged conductors are approximated with the appropriately placed straight conductors, which gives excellent agreement with the measured results at the overhead power line right of way border. The proposed method is suitable for calculation of magnetic field emissions within optimization procedures, where sufficiently accurate and fast calculation can substantially improve optimization procedure performances.

REFERENCES

[1] I. Tannemaat, M. Beerleage, C. Stuutman, C. Engelbrecht, Public concern after upgrading an overhead line from 150 kV to 380 kV, *International Colloquium Power Frequency Electromagnetic Fields*, Sarajevo, 2009, No. 34

[2] K. Deželak, G. Štumberger, F. Jakl, Emissions of Electromagnetic Fields caused by Sagged Overhead Power Lines, *Przeglad Elektrotechniczny,* 2011, vol. 87, no. 3, pp. 29-33

[3] R. Cruz, L. A. Dominques, A. M. Neto, C. R. Barbosa, T. Dovan, Analysis of electromagnetic fields exposure limits from International standards – application of compotutional modelling to assess human exposure to EMF, *International Colloquium Power Frequency Electromagnetic Fields*, Sarajevo, 2009, No. 5

[4] B. Cestnik, K. Grabner, N. Ljubijankic, Electromagnetic field calculation and measurement of electric power facilities according to Slovenian legislation, *International Colloquium Power Frequency Electromagnetic Fields*, Sarajevo, 2009, No. 39

[5] Official Gazette of the Republic of Slovenia No. 70/96, The decree on electromagnetic radiation in the natural and living environment, *Slovenia, 1996*

[6] M. S. H. Al Salameh, M. A. S. Hassouna, Arranging Overhead Power Transmission Line Conductors using Swarm Intelligence Technique to Minimize Electromagnetic Fields, *Progress in electromagnetics research B,* 2010, vol. 26, pp. 213-236

[7] A. S. Farag, J. M. Bakhashwain, A. Al-Shehri, T. C. Cheng, Bundled Conductor Configuration Optimization for Compact Transmission Lines Incorporating Electromagnetic Field Management, *Electric power system research,* 1998, vol. 44, pp. 189-202

[8] K. Deželak, F. Jakl, G. Štumberger, Arrangements of Overhead Power Line Phase Conductors Obtained by Differential Evolution, *Electric power system research,* 2011, vol. 81, pp. 2164-2170

[9] K. Deželak, G. Štumberger, F. Jakl, Optimization Based Reduction of the Electromagnetic Field Emissions caused by the Overhead Lines, *Przeglad Elektrotechniczny,* 2011, vol. 87, no. 3, pp. 33-36

[10] B. J. Maddock, Overhead line design in relation to electric and magnetic field limits, *Power Engineering Journal*, 1992, vol. 6, no. 5, pp. 217-224

[11] A. V. Mamishev, R. D. Nevels, B. D. Russell, Effects of conductor sag on spatial distribution of power line magnetic fields, *IEEE Transactions on Power Delivery,* 1996, vol. 11, no. 3, pp. 1571-1576

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