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ASSESSMENT OF HUMAN EXPOSURE TO ELECTRIC AND MAGNETIC FIELDS NEAR TRANSMISSION LINES USING FEMM

OCENA IZPOSTAVLJENOSTI ČLOVEKA ELEKTRIČNIM IN MAGNETNIM POLJEM V BLIŽINI DALJNOVODOV Z UPORABO FEMM

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Abstract

The intensity of ELF electric and magnetic fields near transmission lines is of particular interest in environmental and equipment protection studies. The use of numerical tools is the most efficient method for their assessment. In this paper, we numerically compute the electric and magnetic fields near different configurations of high-voltage transmission lines using the open- source software FEMM 4.2. Computed fields are compared with reference levels related to human exposure to electromagnetic fields. The accuracy of the applied method is validated with published, numerically computed and measured results.

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Povzetek

Intenzivnost električnih in magnetnih polj ELF v bližini daljnovodov je še posebej zanimiva za študije, ki so povezane z zaščito okolja in opreme. Uporabo numeričnih orodij lahko štejemo kot najučinkovitejšo metodo za njihovo ocenjevanje. V članku podamo prikaz numerično izračunanega električnega in magnetnega polja v bližini različnih konfiguracij visokonapetostnih daljnovodov z uporabo odprtokodne programske opreme FEMM 4.2. Izračunana elektromagnetna polja nato primerjamo z referenčnimi ravnmi, ki so povezane z izpostavljenostjo človeka elektromagnetnim poljem. Na koncu potrdimo natančnost uporabljene metode s podanimi numerično izračunanimi in merilnimi rezultati.

1 INTRODUCTION

Overhead transmission lines (OTL) generate extremely low frequency (ELF) electric and magnetic fields that may interact with technical or biological systems and produce possible harmful effects in case of excessive exposure [1], [2]. Therefore, the intensity and distribution of electric and magnetic fields near OTL are of particular interest in studies related to their possible adverse effects on the environment, human health, sensitive electronic equipment and critical infrastructures. To address the variety of problems that can occur, numerous standards and protocols have been introduced that define methods for assessment and protection from the effects of electromagnetic fields [3]-[5]. The use of electromagnetic simulation tools can be considered the most efficient method, especially when dealing with large and complex systems where measuring procedures can be time-consuming, expensive or impractical. Another advantage of the simulation tools is in the possibility of analysing systems in the initial phase of their planning and construction, and the ability to test the effectiveness of different protection techniques.

In this paper, we perform numerical analysis of the intensity and distribution of ELF electric and magnetic fields in the vicinity of OTL using the open-source software for analysing electromagnetic problems, FEMM 4.2, which is based on the finite element method (FEM) [6]-[8]. The modelling procedure is briefly described and validated using a full-wave electromagnetic model based on the method of moments (MoM) and by comparison of published and measured results. The analysis should provide general information for the expected field levels near 110 kV and 400 kV OTL. Therefore, different configurations of OTL and effectiveness of phase sequence transposition in double-circuit OTL are considered. Computed electric and magnetic field levels are compared with reference levels for human exposure to electromagnetic fields, established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [9].

2 PROCEDURES FOR MODELLING THE ELECTROMAGNETIC PROBLEM IN FEMM

Modelling electromagnetic problems in open space using the FEMM 4.2 software requires specifying a solution domain with suitable shape and size for the analysed problem and appropriate boundary conditions at its borders. The solution domain, in which the electromagnetic problem is solved, should have a circular shape. Since the height of the analysed OTL is nearly 40 m, to reduce the boundary's influence, the domain's radius is set to 300 m, which is more than seven times larger than the height of the analysed OTL. The domain is divided into two sections. The bottom section is ground, with specific conductivity σ, and the top section is air. The horizontal position of the OTL is at the centre of the domain (corresponding to distance of 0 m in the figures). Because the field computation is a time-consuming process and because we focus on the fields above the ground in the vicinity of the conductors, the discretization of the solution domain is done separately in sections, as shown in Fig. 1. The ground has the lowest degree of discretization. The air is divided into two half circles with 150 m and 300 m radius, where the inner circle has the highest degree of discretization to obtain more accurate results. The solution domain is discretized with about 340,000 nodes or 685,000 elements.

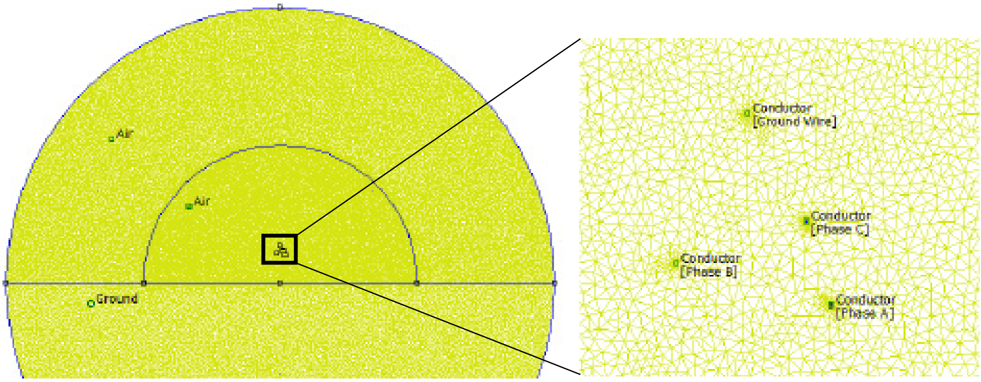

Figure 1: *Different degrees of discretization for the 110 kV single-circuit transmission line*

The FEMM 4.2 software provides instantaneous values of computed fields (electric or magnetic), while RMS values are further required to estimate human exposure to electromagnetic fields *[9].* To obtain the RMS values, we compute multiple samples of the instantaneous field values over one period of 20 ms. We have observed that 40 equally spaced samples over one period can provide a good estimate of the RMS values of the 50 Hz fields. To automate this process for all considered cases, we have used the Lua scripting language which is incorporated in the FEMM 4.2 software. The electric and magnetic fields are computed at multiple points at a height of 1 m above ground level, along a profile perpendicular to the centre of the transmission line, as required by the standard [3]. The above-mentioned procedures are general for calculating electric and magnetic fields. In the following subsections, we describe some specific procedures for computing the electric magnetic fields.

2.1 Procedures for obtaining the RMS electric field

The electric field and scalar potential are computed using the “Current Flow” module of FEMM 4.2. For this module, fixed voltages are required. The boundary condition for potentials at the domain’s borders is set to 0 V. The same condition is applied for the ground wires. The phase conductors are set to instantaneous phase voltages that correspond to the appropriate time points within one period of 20 ms using a Lua script. Two cases are observed for the double-circuit power line: in the first case the phase conductors are untransposed, and in the second case they are transposed. The relative dielectric permittivity of the whole domain is $\varepsilon_1 = 1$.

2.2 Procedures for obtaining the RMS magnetic field

The magnetic field and magnetic vector potential are computed using FEMM 4.2's "Magnetics" module. A fixed current strength and magnetic vector potential are required for this module. The boundary condition for the magnetic vector potential at the domain's borders is set to 0 Wb/m. The current strength in the ground wire is forced at 0 A. The maximum load current of the TL is considered for the current strength in the phase conductors. The instantaneous values for the current strength of each phase are set based on the time points using a Lua script. For the double-circuit power line, the untransposed and transposed cases are considered as well. The relative magnetic permeability of the whole domain is $\mu_r = 1$.

3 VALIDATION OF THE APPLIED METHOD

In this section, we validate the accuracy of the applied method by comparison with published and numerically computed results.

3.1 Validation with published results

Validation of the procedures presented in Section 2 is performed by comparing the simulated results and the results provided in the European standard IEC 62110:2009 [3] for the geometries and conditions provided in the standard. For the OTL, a 77 kV transposed double-circuit is considered. The current strength is assumed to be 200 A. The same geometry provided in Table 2 and Fig. 6 for the transposed double-circuit OTL without the ground wire is used (as specified in the standard [3]). The ground clearance is h_g = 11 m. The results are shown in Fig. 2. The differences in the simulated and provided electric and magnetic field levels at 1 m above ground level are observed to be less than 5%.

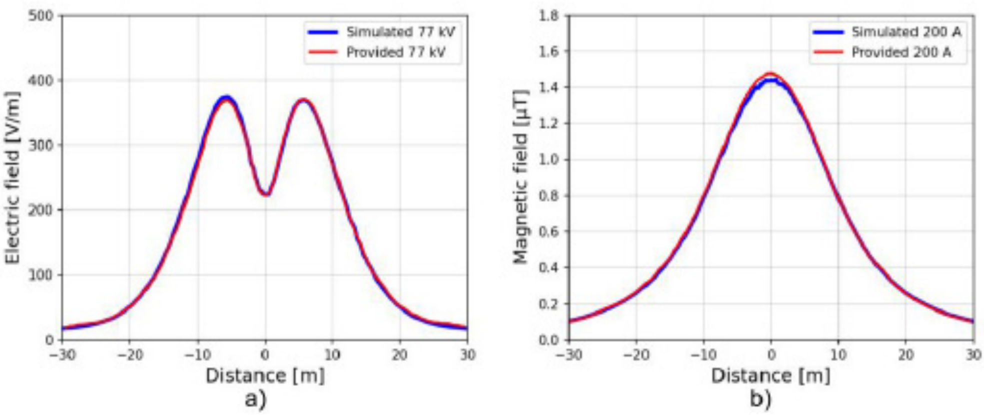

Figure 2: *Comparison between simulated and published results (in [3], Fig. A.5 and Fig. B.3) for a) RMS electric field and b) RMS magnetic field for double-circuit OTL*

The simulated magnetic field is also validated for underground transmission lines (UTL). A similar approach, as described in Section 2.2, is used with different discretization levels around the phase conductors. Double-circuit configuration with balanced 200 A current strength is considered. The phase conductors are placed vertically on the same axis with 0.35 m separation, while the horizontal separation between the two circuits is 1 m (as specified in the standard [3]). The magnetic field levels at 1 m above ground level were calculated for two different distances between the UTL and ground level: h_g = 1.85 m and h_g = 0.6 m. The results of this simulation are shown in Fig. 3, where less than 5% error is observed.

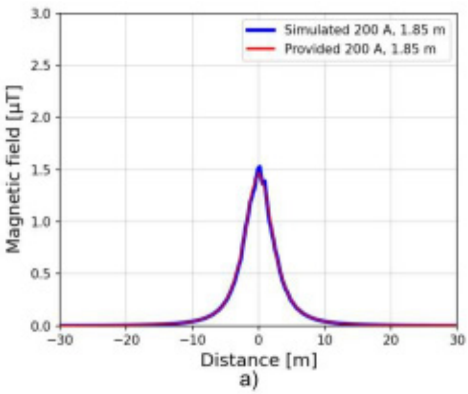

Figure 3: *Comparison between simulated and published results (in [3], Fig B.10) for RMS magnetic field near double-circuit UTL at a depth of a) 1.85 m and b) 0.6 m*

3.2 Validation with simulated results

Additional validation has been performed for the 110 kV single-circuit OTL with h_g = 15 m (see Fig. 6 and Table 2) for the electric and magnetic field levels (the latter are expressed in terms of the magnetic vector potentials). The same problem has also been simulated using a full-wave electromagnetic model based on the method of moments [10]. The results provided in Fig. 4 show excellent agreement, with less than 3% difference in the calculated electric and magnetic field levels.

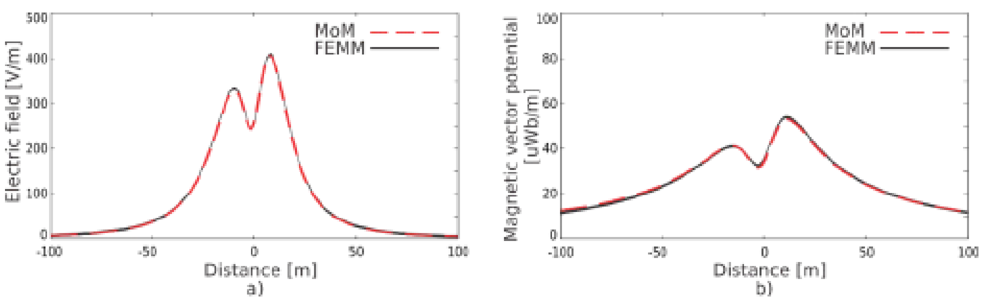

Figure 4: *Verification of the calculated RMS values of a) electric field and b) magnetic vector potential for 110 kV single-circuit transmission line with an independent MoM approach*

3.3 Validation with measurement results

The numerical results obtained in FEMM are also validated with measured values for the electric and magnetic field near OTL. The OTL in question is a 110 kV single-circuit tower with the position of the conductors provided in Table 1 (*x* values with respect to the centre of the OTL and *y* values with respect to ground level). The measurements were performed with a NARDA EFA-300 field analyser with suitable probes for electric and magnetic field measurement, and the positions provided in Table 1 were obtained by laser distance meter. When the measurements were taking place, the current strength of the conductors was nearly 100 A.

Table 1: *Position of the phase conductors and ground wire for the 110 kV single-circuit OTL*

Conductor	110 kV single-circuit	
	x [m]	*y* [m]
Phase A	3.53	7.75
Phase B	-3.07	9.55
Phase C	2.58	11.8
GW	0	17.5

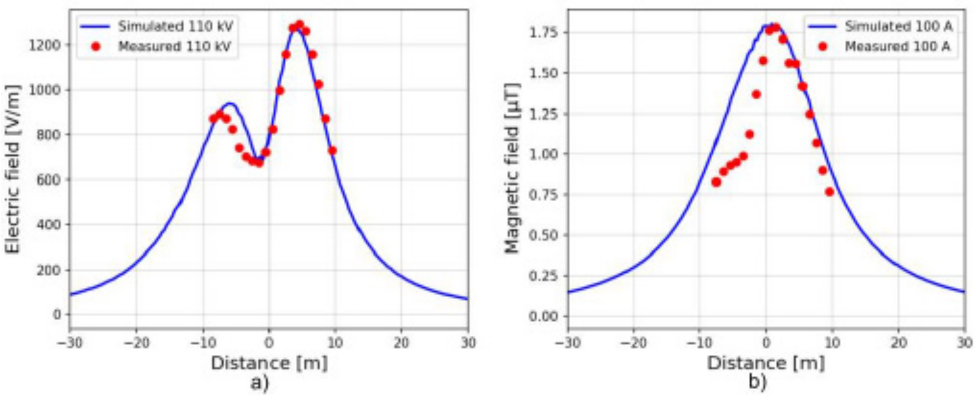

Figure 5: *Comparison between simulated and measured results for a) RMS electric field and b) RMS magnetic field for a single-circuit tower*

Fig. 5 shows the comparison between simulation and measurement results for the electric and magnetic fields at a height of 1 m from ground level, along a path perpendicular to the OTL, as required by the standard [3]. A good agreement with a 5% difference in values is mostly observed for the electric and magnetic fields, while at some points there is up to 20% difference. The error may be explained by the influence of a nearby parallel 110 kV single-circuit OTL at a distance of nearly 40 m from the analysed OTL. A better agreement of results could be expected if the contribution of the second OTL was considered.

4 PARAMETRIC ANALYSIS: RESULTS AND DISCUSSION

The subject of analysis are 110 kV single-circuit, 110 kV double-circuit, and 400 kV single-circuit overhead transmission lines. Details for the positions of the phase conductors and ground wire (GW) are provided in Fig. 6 and Table 2. The cross-sectional area of each conductor of the 110 kV OTL is 104 mm^2 (11.5 mm diameter). For the 400 kV OTL, the cross-sectional area of the phase conductors is 2 x 245 mm^2 (17.66 mm diameter each) with a mutual separation of 30 cm; for the ground wire, it is 120 mm^2 (12.36 mm diameter). Based on each conductor's previously mentioned surface area, the maximum load current for each phase conductor is 800 A and 1,920 A for the 110 kV and 400 kV towers, respectively. The parameter h_g represents the shortest distance between the conductors and the ground level. In our analysis, we consider two values of h_g: 30 m and 15 m. We assume earth with specific conductivity σ = 0.01 S/m. The electromagnetic problems have been analysed following similar procedures described in *[11]*.

Table 2: *Position of the phase conductors and ground wires for the 110 kV single-circuit, 110 kV double-circuit and 400 kV overhead transmission lines*

Conductor	110 kV single-circuit		110 kV double-circuit		400 kV single-circuit	
	x [m]	y [m]	x_1 / x_2 [m]	y [m]	x [m]	y [m]
Phase A	4.8	h_g	-3.2 / 3.2	h_g +6	-8.47	h_g
Phase B	-4.1	h_g +2.4	-3.5 / 3.5	h_g +3	0	h_g
Phase C	3.4	h_g +4.8	-3.8 / 3.8	h_g	8.47	h_g
GW	0	h_g +11	0	h_g +9	-5.07 / 5.07	h_g +4.45

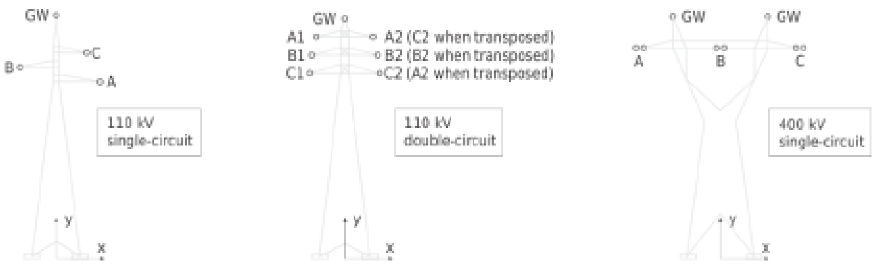

Figure 6: *Configuration of the analysed 110 kV and 400 kV overhead transmission lines*

Here we provide the simulation results for electric and magnetic fields for the different OTL configurations described in Fig. 6 and Table 2, and we compare the results with the reference levels for human exposure to electromagnetic fields provided by ICNIRP [9]. The electric and magnetic fields are computed at multiple points at a height of 1 m above ground level, along a profile perpendicular to the centre of the transmission line, as required by the standard [3]. The reference levels for general public exposure to the electric field at 50 Hz are set to 5 kV/m, and the magnetic field at the same frequency is set to 200 µT. For ground clearance of the transmission lines equal to h_g = 30 m, the results are represented by dashed lines; for h_g = 15 m, the results are represented by solid lines.

In Fig. 7, the results of the electric and magnetic fields for the single-circuit OTL are shown. It is observed that the maximum value of the electric field for the 400 kV OTL is 1.68 times lower than the reference levels, and for the 110 kV OTL, it is 12.2 times lower for the h_g = 15 m case.

In comparison, the values are further reduced by a factor of 3.54 for the h_g = 30 m case. The maximum values of the electric field appear close to the origin at x = 0 m, directly below the OTL's central axis. The 400 kV tower is an exception, where at x = 0 a sharp drop of the RMS electric field is observed mainly due to the annulment of the fields of each phase in one period. However, the range between 10 m and 20 m distance on the x-axis is of concern where the highest values of the electric field appear. Considering the system's geometry described in Table 2, this is close to the shortest distance between the ground level and the nearest phase conductor. In reality, the height of the conductors may be lower along the power line. If we consider a lower value for h_g, which is not constant along the length of the OTL, the 400 kV OTL can represent a potential risk to human health.

The maximum magnetic field value for the 400 kV OTL is 9.4 times lower, and for the 110 kV OTL it is 68 times lower than the reference levels for the h_g = 15 m case. For the h_g = 30 m case, there is a further decrease by a factor of 3.6.

Fig. 8 provides the results of the electric and magnetic fields for the double-circuit towers. The maximum values for electric and magnetic fields appear when the phases are untransposed. In the untransposed case the maximum electric field is 7.5 times lower, and in the transposed case it is 21.2 times lower than the reference levels for h_g = 15 m. In the untransposed case the maximum magnetic field is 40 times lower, and in the transposed case it is 72.9 times lower than the reference levels for h_g = 15 m. For h_g = 30 m, more than three times lower values are observed.

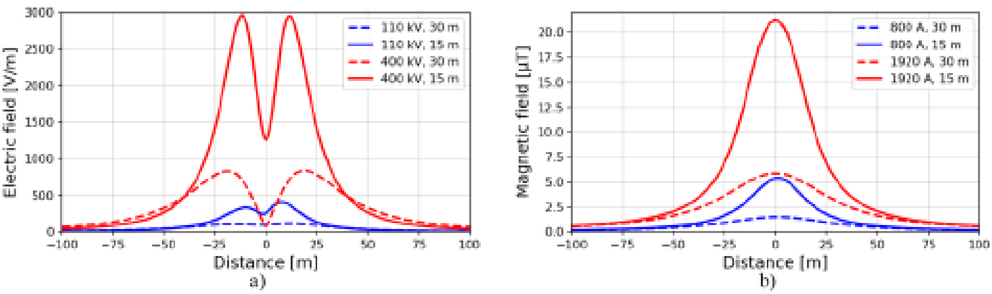

Figure 7: *a) RMS electric field and b) RMS magnetic field for single-circuit OTL*

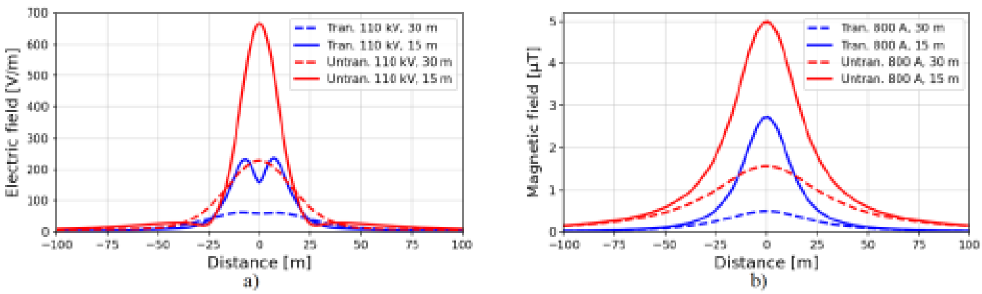

Figure 8: *a) RMS electric field and b) RMS magnetic field for double-circuit towers*

5 CONCLUSION

In this paper, we have numerically computed the RMS values of ELF electric and magnetic fields near 110 kV and 400 kV overhead transmission lines. Simulations were performed using the open-source software FEMM 4.2, using an automated procedure that has been briefly described. The electric and magnetic field levels for different OTL configurations were compared with the reference levels for human exposure to electromagnetic fields established by the ICNIRP. Additional computation and validation were done for different OTL and UTL configurations. It was observed that an error of less than 5% occurred between the computed and the reference values for validation. A comparison with measured values near an OTL was also provided, where good agreement with the computed values was observed. Therefore, in safety-related studies, the presented approach can be considered a decent substitute and an efficient method for assessing human exposure to ELF electric and magnetic fields.

Acknowledgments

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