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ELECTROMAGNETIC FIELD UNDERNEATH OVERHEAD HIGH VOLTAGE POWER LINE

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Abstract: *An increasing number of power line systems presented in our neighbourhood, in order to satisfy need for electric power, cause public concern about adverse health effect. Therefore, determination of human exposure to power frequency electromagnetic fields is very important. In order to get the thorough acquaintance with electric and magnetic fields in vicinity of overhead power lines, it is necessary to determine both, the magnitude of electric and magnetic field strength, as well as their polarization. In this paper the double circuit 400 kV three-phase overhead power lines are examined..*
Key Words: electric field strength, magnetic flux density, polarization, power lines

1 INTRODUCTION

Computation of the fields produced by overhead power lines is important for studying possible health effects of extremely low frequency electric and magnetic field produced by transmission and distribution lines. The magnitudes of the fields are the highest under the power lines and decrease rapidly with the distance from the lines. From the point of view of human exposure, the most critical points are those within or close to the right of way of the lines.

Electrical activity of electric field penetrated to the human body, compared to the tiny signals associated with cellular activity, is quite small. Some researchers believe that power lines electric field adds a stress factor to nervous system activity. Human Radiation Effects Group [1] describes how electric field affects airborne particles: "Aerosols in the proximity of power line electric fields become polarized. The polarity of the particles reverses in concert with the alternating current, setting up an oscillatory movement. The particles become stickier and they are more likely to adhere to skin or to lung tissue."

Electric fields in presence of conducting objects, including the vegetation, most building materials and people could be easily perturbed. For example, the building materials could screen the electric fields decreasing it by factors typically ranging from 10 to 1000 times [2]. On the other hand, magnetic field is difficult to shield and easy penetrate most materials including vegetation, building materials and people. The exceptions are ferromagnetic materials and highly conductive materials, such as aluminum and copper. One of the mechanisms of interaction between alternating magnetic fields and the human body is inducing currents in tissue.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established a continuous electric field exposure limit of 5 kV/m and a continuous magnetic field exposure limit of 100 μT for general public at 50 Hz frequency [3]. These limit values are sometimes approached in close proximity to large transmission lines, although typical exposure is much lower. Away from the power lines, field levels are much lower than proposed limits. As we can see, none of regulations is dealing with polarization of electric and magnetic field vectors. Therefore, if low levels of fields have no influence on a human body, could we say the same for polarization of electric and/or magnetic fields?

2 ELECTRIC AND MAGNETIC FIELDS

Configuration of power lines (PLs) depend on service demand and varies from single-circuit line, flat configuration double circuit line [4], double circuit line (DCL), optimized DCL (ODCL) to independent power lines. ODCL is a type of DCL, which is characterized by a particular disposition of the phases in order to minimize the magnetic and electric field generated [5]. This paper examines the route of DCL and ODCL 400 kV AC three-phase overhead power line, by calculating the electric field strength, E, magnetic flux density, B, and polarization of these fields. Frequency of the system is 50 Hz. The phase conductors and ground wires are assumed parallel to a large flat conducting ground plane. The sag is taken into account by using an average height of conductors.

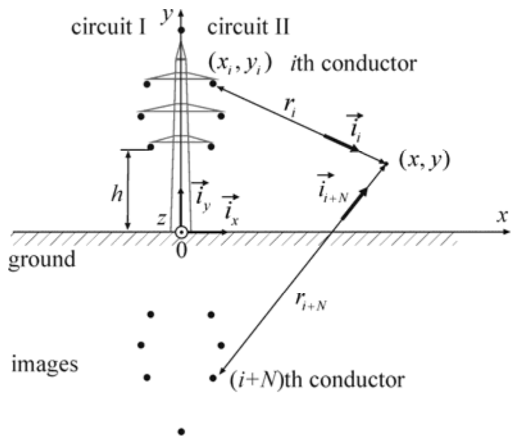

Fig. 1. Cross section of overhead double circuit power line.

Fig. 1 shows the cross section of the power lines and images, as well. The earth occupies the lower half space ($y < 0$), whereas the air occupies the upper half space ($y > 0$). The power lines have one conductor per phase of 13.28 mm radius. Horizontal separations of circuit's conductors are 11.1 m for two lower conductors, 14.1 m for two middle conductors and 9.5 m for two upper conductors. Conductor's vertical separations of both circuits are 8 m between low and middle conductors, and 9.2 m between middle and up conductors, and assumed constant. By PL height, h, is meant the height of lower conductors, and it is 17 m, except if stated otherwise. Ground wire of 6.34 mm radius, centred horizontally, is 8 m above the upper phase conductors. A coordinate vector (x, y) identifies the field point.

Due to low frequency, electric and magnetic fields could be determined separately using the quasi-static methods [6], [7]. The time variation of the fields is harmonic, therefore a phasor notation can be used.

Electric Field

Calculation of the electric field strength is made according to image and superposition theorems. The permittivity of vacuum, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m, is assumed everywhere and the earth is considered as a perfect conductor. The root-mean-square (rms) line voltages are assumed constant.

Two circuits mounted on a single tower are located close to each other, and therefore coupled. This coupling needs to be included in the calculation of the electric field strength [8]. The conductors and ground wires are represented by the line charges. The influence of an unknown surface charge density on the earth is replaced by the images [9], as depicted in Fig. 1.

The electric field at observed point can be calculated as a vector sum

$$\underline{\vec{E}}\,(x,y) = \sum_{i=1}^{N} \frac{\underline{q}_i'}{2\pi\varepsilon_0}\left(\frac{\vec{i}_i}{r_i} - \frac{\vec{i}_{i+N}}{r_{i+N}}\right), \qquad (1)$$

where r_i is the distance from ith line charge $\underline{q}_i'$ and r_{i+N} is the distance from $(i+N)$th image. Vectors $\vec{i}_i$ and $\vec{i}_{i+N}$ are unit vectors depicted in Fig. 1.

Fig. 2 illustrates lateral distribution of the rms value of electric field strength at 1 m above the ground level in vicinity of DCL with the same phase arrangement.

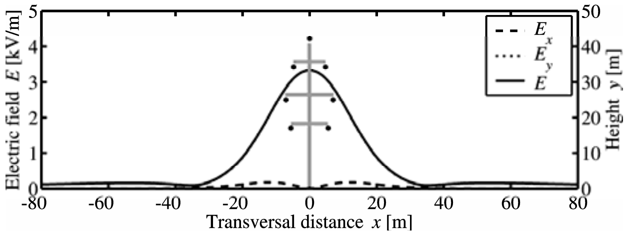

Fig. 2. Lateral distribution of the electric field strength at 1 m above the ground in vicinity of 400 kV DCL. Same phase arrangement.

Lateral distribution of the electric field strength depends on the phase arrangement in power lines. Underneath the power line, the same phase arrangement produces the highest electric field strength (Fig. 2), whereas mirror phase arrangement (ODCL) produces the lowest electric field strength (Fig. 3).

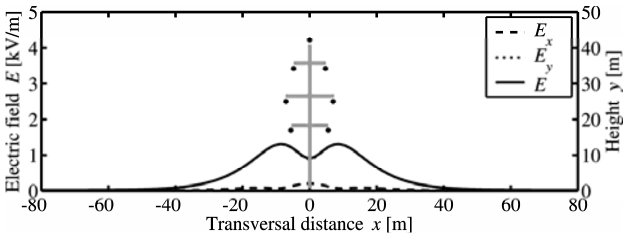

Fig. 3. Lateral distribution of the electric field strength at 1 m above the ground in vicinity of 400 kV ODCL.

In comparison to the intensity of electric field strength under single power line, the DCL with same phase arrangement produces significantly higher field, whereas the ODCL produces lower electric field, as illustrated in Fig. 4.

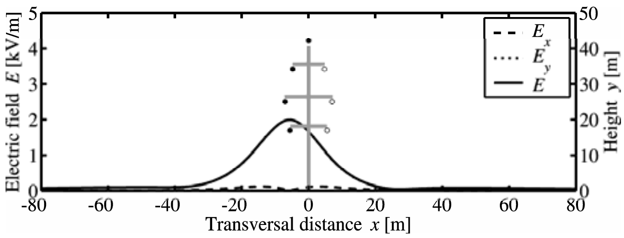

Fig. 4. Lateral distribution of the electric field strength at 1 m above the ground in vicinity of single circuit 400 kV power line.

Fig. 5 shows that the lower conductors cause higher electric field intensity under the lines. If the conductors are higher than 13 m, the electric field intensity does not exceed the public reference level of 5 kV/m, proposed by the ICNIRP [3]. Further, away from the DCL the electric field strength decreases rapidly.

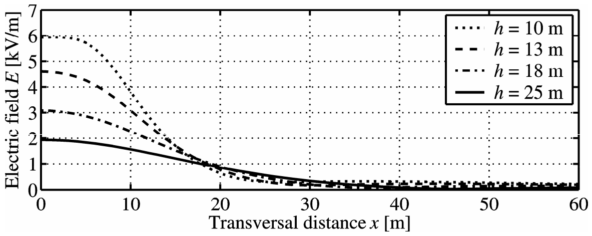

Fig. 5. Electric field strength at 1m above ground for various DCL height. Same phase arrangement.

Magnetic Field

Magnetic flux density is evaluated using image and superposition theorems. The earth is assumed as nonmagnetic conductive medium. The magnetic permeability of the whole space is taken to be the free space value, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m. The magnetic field strength is given by $\vec{\underline{H}} = \vec{\underline{B}}/\mu_0$.

The quasi-static magnetic field of a line source in free-space above earth is equivalent to the magnetic field of the line source plus a "complex image" in free-space [10], [11]. The image currents are negative of the line currents. If the line source is located at height y_i, the complex image is a line source at a "complex depth" equal to $y_i + \delta(1-\mathrm{j})$, where $\delta = \sqrt{1/(\mu_0 \pi f \sigma)}$ is the earth skin depth, $\mathrm{j} = \sqrt{-1}$, σ is the conductivity of earth, and f is the frequency of the source current. Since the typical values for the conductivity of the earth is in range from 0.001 to 0.1 S/m, the image currents are located at hundreds of meters below the ground. This image expression is valid under two conditions: if the frequency is low and if the ground is nonmagnetic.

The magnetic flux density produced by transmission lines at observed point (x, y) can be calculated as

$$\vec{\underline{B}}(x,y) = -\sum_{i=1}^{N} \frac{\mu_0 \underline{I}_i}{2\pi}\left(\frac{y-y_i}{r_i^2} - \frac{y+y_i+\delta(1-\mathrm{j})}{\underline{r}_{i+N}^2}\right)\vec{i}_x + \sum_{i=1}^{N} \frac{\mu_0 \underline{I}_i (x-x_i)}{2\pi}\left(\frac{1}{r_i^2} - \frac{1}{\underline{r}_{i+N}^2}\right)\vec{i}_y, \tag{2}$$

where ith conductor, located at height y_i with respect to a coordinate system depicted in Fig. 1, carries a rms current I_i in the positive z-direction, r_i is the distance from ith conductor, $\underline{r}_{i+N}$ is the "complex" distance from $(i+N)$th image and N is the number of the conductors.

The magnetic field highly depends on the power line load, which varies during the day and year. For calculations, a 1000 A rms phase currents has been selected; the values that correspond to the maximum load. The effect of transmission line current unbalance is not considered, because it is usually low.

The lateral distribution of magnetic flux density depends on the phase arrangement in power lines. Underneath power lines, same phase arrangement produces the highest magnetic flux density, whereas mirror phase arrangement (ODCL) produces the lowest magnetic flux density. Fig. 6 shows the highest magnetic flux density for DCL, whereas Fig. 7 shows magnetic flux density for ODCL that ensures the lowest magnetic flux density.

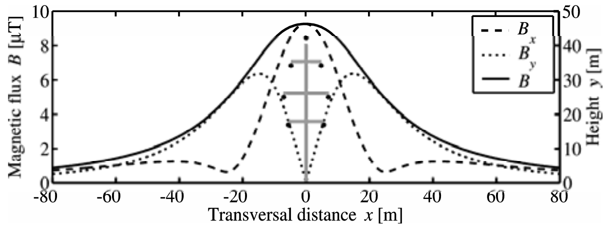

Fig. 6. Lateral distribution of the magnetic flux density at 1 m above the ground in vicinity of 400 kV DCL. Same phase arrangement.

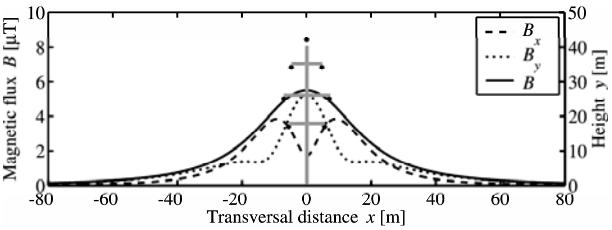

Fig. 7. Lateral distribution of the magnetic flux density at 1 m above the ground in vicinity of 400 kV ODCL.

The lower conductors cause greater magnetic flux density underneath the lines. Fig. 8 shows that the magnetic flux density at height of 1 m above ground underneath DCL with rms phase currents of 1000 A does not exceed 20 µT, which is five times lower than public reference value proposed by the ICNIRP [3].

In close proximity to the power lines the magnetic field primarily depends on the currents in the conductors and ground return currents can be neglected. Far from the power lines the magnetic field strongly depends on ground return currents, hence far from the lines the magnetic field does not depend on conductors' heights.

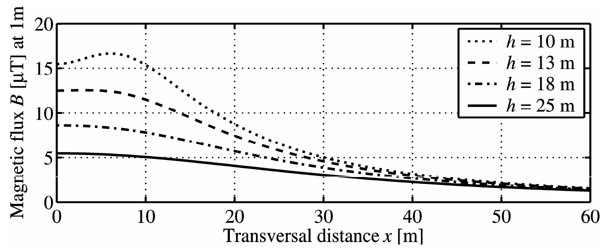

Fig. 8. Magnetic flux density at 1m above ground for various DCL height. Same phase arrangement.

3 POLARIZATION

The field vectors, due to a three phase power lines, are usually taken into account by reporting the rms values of the field vectors and vector components, as shown in Figs. 2-8. The rms value of the field vector is independent of the phases of field components. The power lines electric and magnetic fields have elliptical polarization. Precise characterization of the fields does not allow neglecting the phase difference between components. Therefore, to investigate power line fields, it is necessary to determine both; the magnitude and phase of two orthogonal components. The polarization pattern is useful additional information for interpretation of measured results.

The IEEE Standard 644-1994 [12] explains that the resultant field is given by the expression

$$A_R = \sqrt{A_x^2 + A_y^2}, \tag{3}$$

where A_x and A_y are the rms values of two orthogonal field components. The resultant field is also given by

$$A_R = \sqrt{A_{\max}^2 + A_{\min}^2}, \tag{4}$$

where $A_{\max}$ and $A_{\min}$ are the rms values of the semimajor and semiminor axes of field ellipse, respectively, shown in Fig. 9.

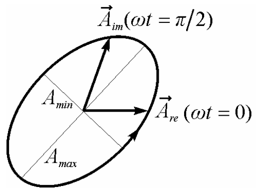

Fig. 9. Components of elliptically polarized fields.

The resultant field A_R is always greather or equal to $A_{\max}$. If the field is linearly polarized, $A_{\min} = 0$ and $A_R = A_{\max}$. If the field is circularly polarized, $A_{\max} = A_{\min}$ and $A_R = 1{,}41\ A_{\max}$.

The electric field strength and magnetic flux density can be represented as rotating vectors which trace an ellipse in a plane perpendicular to the conductors. Fig. 10 and Fig. 11 illustrate the electric field and magnetic field polarization at 1 m above ground level in vicinity of 400 kV DCL. The electric field at the height of 1 m above ground level is nearly vertically polarized, except in some points, as shown in Fig. 10. Numbers beside each ellipse are semiminor ($E_{\min}$) versus semimajor ($E_{\max}$) axes ratio $m_E = E_{\min}/E_{\max}$.

At ground level, the magnetic flux density is nearly linearly polarized vector underneath power lines with same phase arrangement, as shown in Fig. 11. Numbers beside each ellipse are semiminor ($B_{\min}$) versus semimajor ($B_{\max}$) axes ratio defined as $m_B = B_{\min}/B_{\max}$.

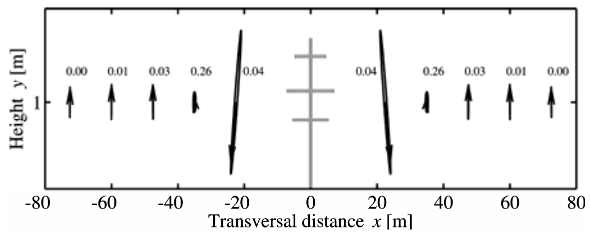

Fig. 10. Electric field polarization at 1 m above ground level. Same phase arrangement. Numbers beside each ellipse are electric field polarization ratio m_E.

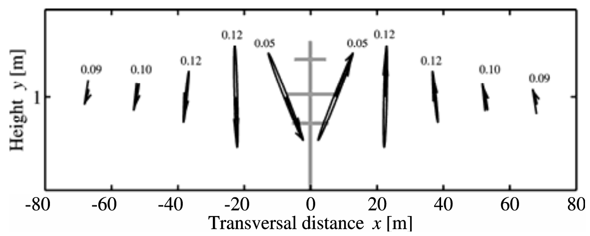

Fig. 11. Magnetic field polarization at 1 m above ground level. Same phase arrangement. Numbers beside each ellipse are electric field polarization ratio m_B.

From the point of view of human exposure it is important to know how far from the lines the elliptic polarization can be considered as linear. The IEEE Standard 644-1994 proposes that polarization can be considered as linear if the semiminor versus semimajor axes ratio $m = A_{\min}/A_{\max}$ is less than 0.1 [12].

For DCL with the same phase arrangement, electric and magnetic field polarization ratio m_E and m_B are depicted in Fig. 12 and Fig. 13, respectively. At the distances of more than 40 m from power lines the electric field polarization can be considered as linear. At the distances of more than 50 m from power lines the magnetic field polarization can be considered as linear.

For the same phase arrangement, increasing conductors heights, the distances at which the polarization of the electric field can be considered as linear slightly increase, too. For same phase arrangement, increasing conductors heights, the distances at which the polarization of the magnetic field can be considered as linear slightly decrease.

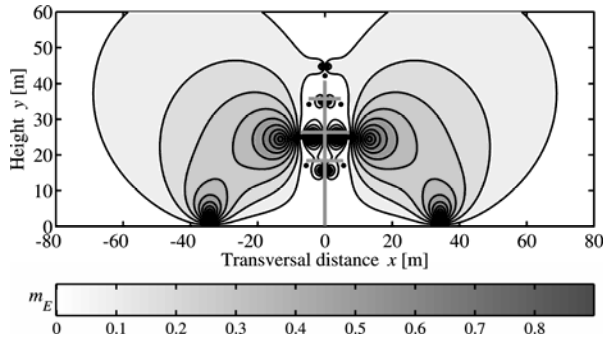

Fig. 12. Electric field polarization ratio m_E in vicinity of 400 kV DCL. Same phase arrangement.

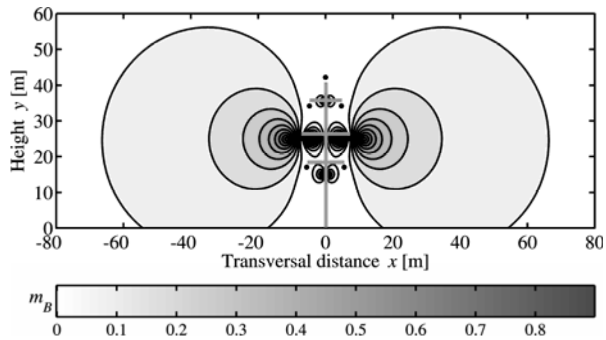

Fig. 13. Magnetic field polarization ratio m_B in vicinity of 400 kV DCL. Same phase arrangement.

For ODCL, electric and magnetic field polarization ratio m_E and m_B are depicted in Fig 14. and Fig. 15, respectively. At ground level, at the distances of more than 70 m from power lines the electric field polarization can be considered as linear. At the distances of more than 150 m from power lines the magnetic field polarization can be considered as linear.

For ODCL, increasing conductors heights, the distances where the polarization of the electric field can be considered as linear slightly increase, too. For ODCL, changing conductors heights, the magnetic field polarisation pattern remains almost the same.

The electric and magnetic field polarization tends to be linear by increasing the distance. The distance at which the polarization of electric and magnetic fields can be considered as linear highly depends on phase arrangement in DCL.

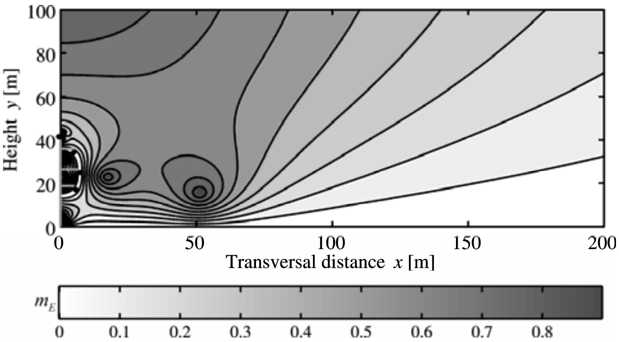

Fig. 14. Electric field polarization ratio m_E in vicinity of 400 kV ODCL.

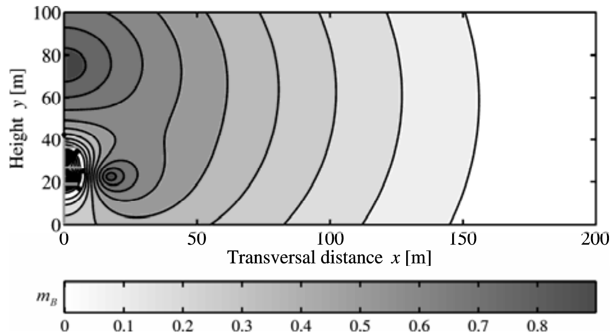

Fig. 15. Magnetic field polarization ratio m_B in vicinity of 400 kV ODCL.

4 CONCLUSION

This paper presents the calculation of the electric field strength and magnetic flux density caused by the 400 kV DCL and ODCL. The traditional two-dimensional quasi-static method is applied to determine the power lines fields. The terrain variations have influence on the line height and therefore a better accuracy requires knowing the exact geometry variations along the line path, which is usually not available.

The lateral distribution of magnetic and electric field depends on the phase arrangement in power lines. It is possible to find the optimal phase arrangement which give the lowest magnetic and electric field at the same time.

However, the magnetic flux density at height of 1 m above ground level underneath 400 kV DCL with rms phase currents of 1000 A does not exceed 20 μT, which is five times lower than public reference value proposed by the ICNIRP [3]. If the conductors' heights are lower than 13 m, the electric field intensity at 1 m above ground level may exceed the public reference level, proposed by the ICNIRP [3].

The distance at which the polarization of electric and magnetic fields can be considered as linear highly depends on phase arrangement in DCL. Phase arrangement that gives the lowest field pattern, doesn't give the most appropriate polarization pattern. However, at the distances of more then 150 m from DCL the electric and magnetic fields polarization can be considered as linear.

5 REFERENCES

[1] T. Penick, "Possible health effects of power line electric fields," for EE368 Electrical Power Transmission and Distribution, April 1999.

[2] J. Swanson, "Residential power–frequency electric and magnetic fields: sources and exposures," *Radiat. Prot. Dosim*., vol. 83, no. 1–2, pp. 9-14, 1999.

[3] International Commission on Non-ionizing Radiation Protection: "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (Up to 300 GHz)," *Health Physics*, vol. 74, pp. 494-522, April 1998.

[4] M. Milutinov, A. Juhas and M. Prša, "Electric and magnetic field in vicinity of overhead multi-line power system", *Acta Electrotehnica, Proceedings of the 2nd International Conference on Modern Power Systems MPS 2008*, Cluj-Napoca, Romania, 12-14 November 2008, pp. 313-316.

[5] M. Benes, M. Comelli and R. Villalta, Regional Environment Protection Agency of Friuli Venezia Giulia (ARPA FVG) - Environmental Physics, Udine, Italy, "ELF field in the proximity of complex power line configuration measurement procedures", Radiation Protection Dosimetry 2006 118(3):290-295; doi:10.1093/rpd/nci348.

[6] D. W. Deno, "Transmission line fields," *IEEE Trans. Power App. Syst*., vol. 95, pp. 1600-1611, Sep/Oct. 1976.

[7] R. G. Olsen, and P. S. Wong, "Characteristics of low frequency electric and magnetic fields in the vicinity of electric power lines," *IEEE Trans. Power Del*., vol. 7, pp. 2046-2053, Oct. 1992.

[8] M. Milutinov, A. Juhas, and M. Prša, "Electric field strength and polarization of multi three-phase power lines," in *Proc. PES 2007*, Niš, Serbia, paper 01-8, Sept. 2007.

[9] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*, ser., Electrical and Electronic Engineering. New York, USA: McGraw-Hill, 1961.

[10] P. R. Bannister, "Extension of quasi-static range finitely conducting earth-image Theory Techniques to Other Ranges," *IEEE Trans. Antennas Propag.*, vol. 26, pp. 507-508, May 1978.

[11] I. V. Lindell, J. J. Hänninen, and R. Pirjola, "Wait's complex-image principle generalized to arbitrary sources," *IEEE Trans. Antennas Propag.*, vol. 48, pp. 1618-1624, Oct. 2000.

[12] IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields From AC Power Lines, IEEE Std. 644-1994.