NUMERICAL METHODS TO EVALUATE THE ELECTROMAGNETIC FIELDS BELOW OVERHEAD TRANSMISSION LINES AND THEIR MEASUREMENT

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Abstract—**An increasing sensibility to ecological problems is seen. In the phase of planning high-voltage lines, the magnetic and electric field quantities have to be examined in order to avoid EMC problems with the surroundings of the power line. This request even gets more important with the trend towards higher transmission line voltages.**

In this paper, the computation of the electric and magnetic field distribution below ac high-voltage lines is demonstrated. Advantages and disadvantages of two different methods able to evaluate the field quantities are described. The first discussed method, a semi numerical method using the laws of electrostatic techniques to simulate the three dimensional field distribution below the overhead line and second, the finite element method using specific boundary conditions to compute the two dimesional field distribution in an efficient way are under considerations. Results from both techniques are compared to measured data to verify the computed field values.

I. INTRODUCTION

High-voltage lines generate electric and magnetic fields in their neighbourhood. The source of the magnetic fields are the currents in the phase conductors. The electric field is caused by the high potential of the conductors. Due to the geometry of electrical energy transmission lines a wide expansion of the field is obvious.

An injurious influence to the health of human beings caused by the direct effect of technical low frequency electromagnetic fields (50/60 Hz) is scientifically not proven yet. Since ca. 25 years research efforts to find a correlation mechanism between the field quantities and their effect to the human beings are going on but without significant success. In this situation, the electric and magnetic field quantities of high-voltage lines have to be examined in order to avoid EMC problems with the environment close to the power transmission line while planning high voltage lines.

To evaluate the influence of the energy line, it is not sufficient to calculate the coupling impedances or capacitances of the line. It is necessary to analyse the generated fields itself. The IRPA[2] and CENELEC[3] standards supply maximum values for the duration of the stay of human beings exposed to electromagnetic fields of frequencies below 10 kHz. There, for the general public the permanently allowed effective value of field strength with 50/60 Hz is 10 kV/m for the electric- and 0.1 mT for the magnetic field. For short exposition times increasing limits are admissible. Distinguishing between laboring and public individuals, in table I. the limits for the magnetic fields are collected. The simulation of the line during planning has the advantage to know about possible risks and disturbing influences.

Table I.
Maximal exposure values for the magnetic field strength.

	workers	general public
	mT	
2 hours a week	5.0	-
a whole day	0.5	0.1
for limbs	25.0	-
a few hours a week	-	1.0

II. NUMERICAL FIELD COMPUTATION

Mathematical techniques to calculate the electromagnetic field quantities necessarily require a model of the technical device to reflect the physical behaviour of the high-voltage transmission line. The problem specifies a small diameter conducting conductors above a large flat conducting ground plane. The phase conductors are at a time depending specified electrical potential and are carrying a time depending current as well. Due to the slack of the phase conductors the field problem turn's out to be three dimensional.

Using the finite element method (FEM) the interesting field area has to be discretised into geometrically small and simple shaped regions. Mainly non-overlapping triangle or squares shaped finite elements are used. It is assumend, that the elements have homogenious material properties. In each of the elements a function, mainly linear, is choosen to approximate the field equations. The conductors itself and their surrounding air have to be discretised. Therefore, this procedure results in a very large system of equations that has to be solved. Considering the geometrical arrangement of an overhead line, the numerical analysis using the finite element method is very costly and computer time consuming. Due to

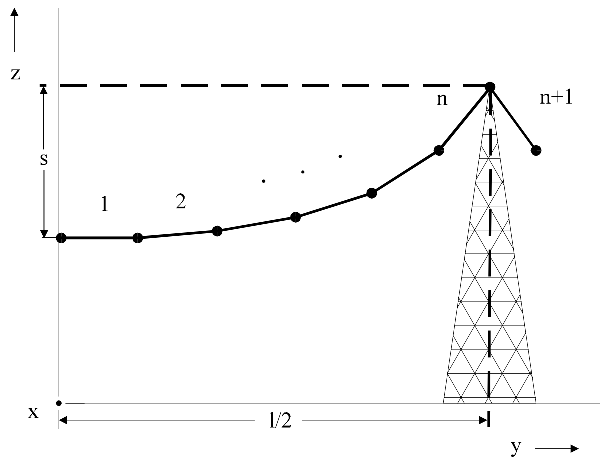


Fig. 1. Geometric modelling of a conductor by 2n infinitesimally-thin filament segments per span field length.

this reason two dimensional field calculations can be considered only.

Because of the very large wavelength the electric- and magnetic field problem of the transmission line may be considered to be quasi static. Therefore, the solutions can be determined by static field techniques as well. With respect to the slack of the phase conductors the geometry of the single conductor is approximated by infinitesimally-thin segmented filaments. In contrast to the FEM using this field computation technique the conductors itself have to be discretised only. The geometrically discretisation is shown in fig. 1. Due to symmetry between two high-voltage poles half of the span field is drawn only. The value of s indicates the slack and l denotes the span field length.

III. SEMI NUMERICAL METHODS

Solving the electric field problem each segment of the line model represents a constant line charge. In the case of evaluating the magnetic field distribution each segment of this polygon represents a current. Using this mathematical model the point matching method can be applied to solve the electric field problem and the BIOT' SAVART law determines the quantities of the magnetic field, respectively. Due to linearity, the superposition of the partial field values of the single conductors or segmented filaments respectively, results in the overall three dimensional field distribution below the high-voltage line.

It is assumend that only symmetric rotary voltage and current systems are taken into consideration. The ground below the transmission line is considered to being an even plane. To consider the slack of the conductors a quadratic approximation is used [1]. Bundle conductors are taken into account with an equivalent radius [1].

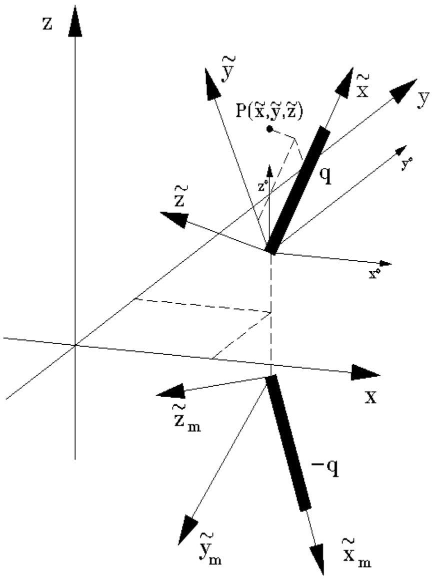


Fig. 2. Co-ordinate transformation of the infinitesimally-thin filament

A. Three Dimensional Electric Field

A constant line-charge at any position in the original co-ordinate system (x, y, z) is drawn in fig. 2. To evaluate the field quantities of the line-charge, this co-ordinate system has to be transformed into a system $(\tilde{x},\tilde{y},\tilde{z})$. This transformation is performed in two steps. The first step consists of a parallel shift of the origin into the starting point of the line-charge. In a second step a rotation of this temporary co-ordinate system (x°, y°,z°) around the x°-axis is carried out in the way that the line charge lies in the x°-y° plane. The last rotation in this step is around the z°-axis so that the line-charge lies in the x°-axis. In this co-ordinate system the potential φ of the line charge in the point $P(\tilde{x},\tilde{y},\tilde{z})$ is given by

$$\varphi(\tilde{x},\tilde{y},\tilde{z}) = \frac{q}{4\pi l\varepsilon}\ln\left[\frac{l-\tilde{x}+\sqrt{\tilde{y}^2+\tilde{z}^2+(l-\tilde{x})^2}}{-\tilde{x}+\sqrt{\tilde{x}^2+\tilde{y}^2+\tilde{z}^2}}\right] \; . \tag{1}$$

It is assumed, that the ground potential below the voltage line is set to φ = 0. To evaluate the field quantities with respect to this boundary condition, the line-charge has to be mirrored at the plane x-y. The superposition of line-charge *q* and mirror-charge -*q*, indicated in fig. 2, gives the potential φ in the point $P(x,y,z)$ inside the global co-ordinate system.

With the known complex potentials $\underline{\varphi}_i$ of the *i* conductors and transformed (1) to compute the coefficient matrix **A**, a linear set of equations can be formulated.

$$\mathbf{A}\cdot\underline{\mathbf{q}} = \underline{\varphi} \tag{2}$$

The solution determines the charge $\underline{q_i}$ of each element of the conductors. With this value the components of the electro static field strength $\boldsymbol{E}$ in the point $\mathrm{P}(x, y, z)$ can be computed.

$$\mathbf{E} = -grad\varphi \tag{3}$$

B. Three Dimensional Magnetic Field

Due to the linearity, the field quantities can be computed and superposed by the BIOT' SAVART law. In this case each segment of the infinitesimally-thin filament carries a current *i(t)*. The generated flux density of this part of the conductor is given by

$$|d\mathbf{B}| = \frac{\mu_0}{4\pi r^2}\cdot i(t)\cdot dl\cdot\sin\alpha \quad . \tag{4}$$

After integrating (4), the flux density in a point inside the system $(\tilde{x}, \tilde{y}, \tilde{z})$ is calculated with

$$\left|\mathbf{B}_j\right| = \frac{\mu_0}{4\pi r}\cdot i(t)\cdot\left(\frac{l-\tilde{x}}{\sqrt{(l-\tilde{x})^2 + r^2}} + \frac{\tilde{x}}{\sqrt{\tilde{x}^2 + r^2}}\right) \quad . \tag{5}$$

If n is the number of current leading conductors, the superposition of the partial flux densities results in the overall flux density.

$$\mathbf{B} = \sum_{j=1}^{n}\mathbf{B}_j \tag{6}$$

IV. FINITE ELEMENT METHOD

Because maximum values for the field quantities are supplied, a cross-section of the transmission line is made at the place where the wires are closest to the ground level. A 2 dimensional finite element model lateral to the line at this place is build. The region of the cross-section is subdivided in triangular finite elements. The potential distribution over each element is approximated by a polynomial. Instead of solving the field equations directly, the principle of minimum potential energy is used to obtain the potential distribution over the whole model. The calculation time of one transmission line on a PC-486 platform is about 30 minutes.

A. Two Dimensional Meshgeneration

The ratio of the largest size of a finite element to the smallest size in a finite element model of a transmission line is about 10,000. The circular boundary of the model has a radius of about 100 m, while the radius of the conductors is a few centimeters. Therefore special attention must be paid to obtain a regular mesh with good shaped elements. This ensures an accurate solution of the field problem. Figure 3 shows a part of the finite element model around one of the phase conductors. The change in the size of the elements in the direction away from the conductor can be seen in fig. 3..

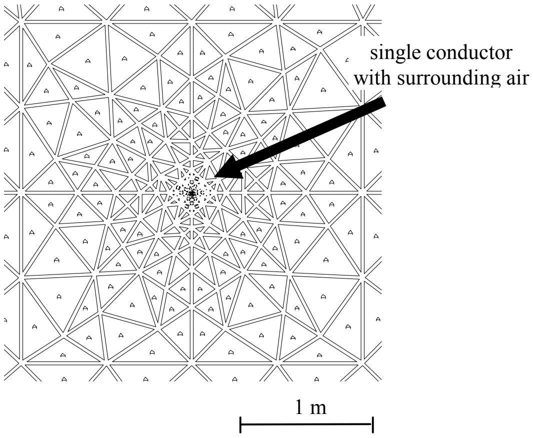


Fig. 3. Part of the finite element model arround a single phase conductor.

Computing the electric field strength it is assumed that the ground plane below the transmission line is considered being an equipotential surface. Therefore it is not necessary to discretise the ground as indicated in fig. 4. Contrary to this, in the model for the magnetic field caculation the ground posses the same magnetic properties as the surrounding air and therefore it has to be modelled as shown in fig. 5.

B. Open Boundary Conditions

Applying fixed potentials to the circular boundary contour, the DIRICHLET conditions, means that the field is forced to be zero at a certain distance. To avoid a high number of elements to discretise the outer domain of the interesting field area open boundaries are applied by using a second model and

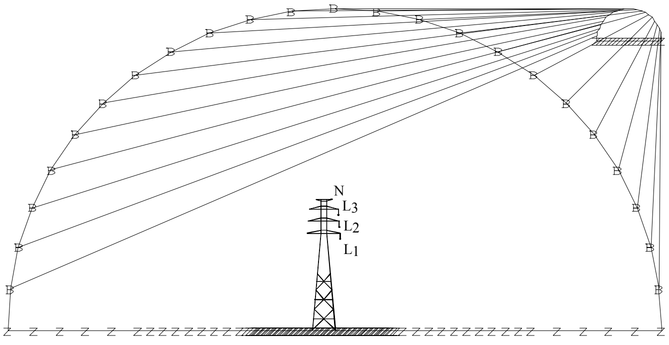


Fig. 4. Open boundary model to compute the electric field.
(the triangulation of the domain is invisible)

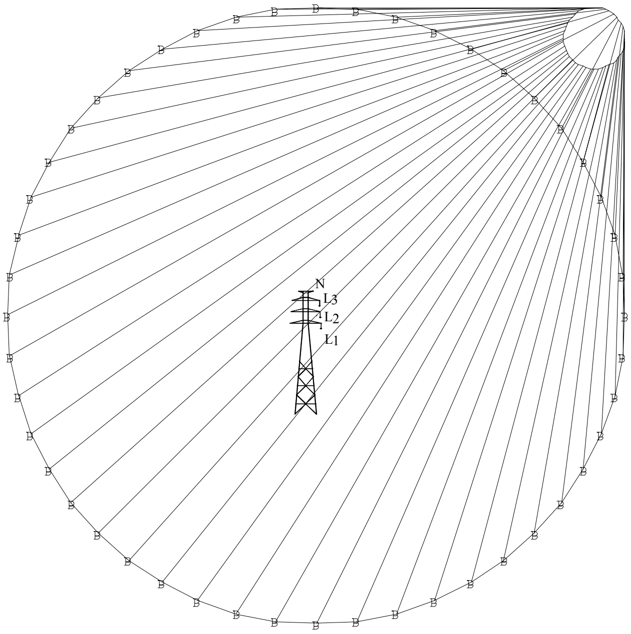


Fig. 5. Open boundary model to compute the magnetic field.
(the triangulation of the domain is invisible)

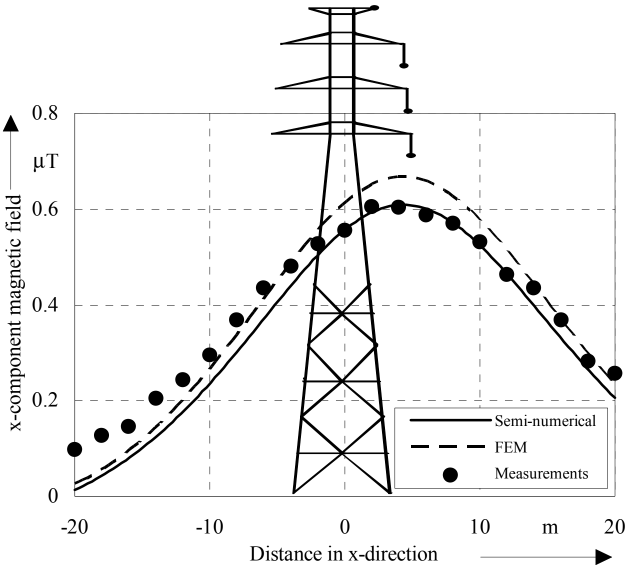
connecting it with the first model by binary constraints. The potential is forced to be equal between a node of the boundary of the first model and the corresponding node at the boundary of the second model. This ensures that the potential in infinite distance from the domain is zero. Figure 4 shows the open boundary model of the power line for the electrostatic and fig. 5 for the magnetic computation respectively.

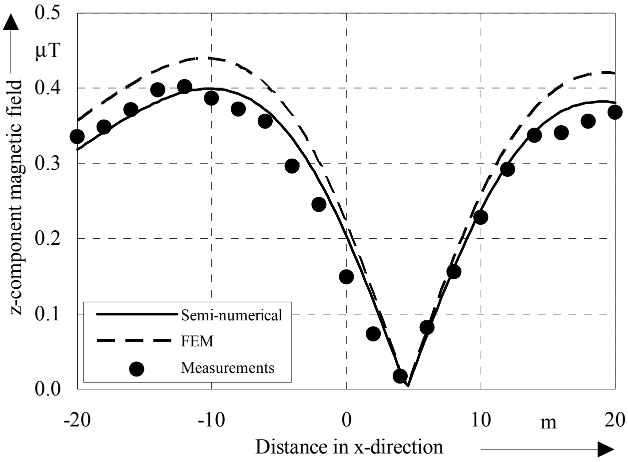
MEASUREMENT OF THE FIELD QUANTITIES

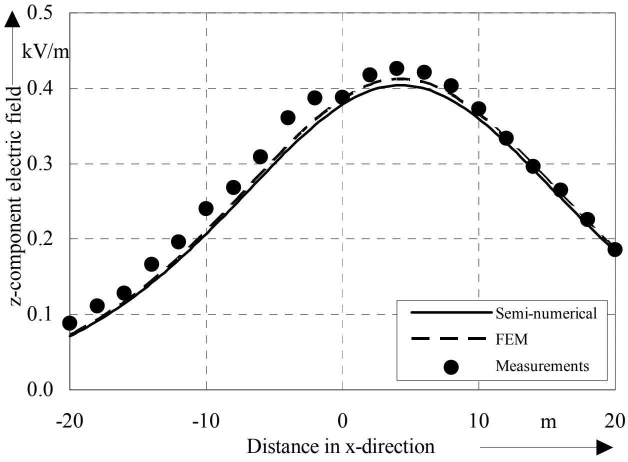
The measurements of the electric field strength excited by the transmission line is based on the induced current of the charge oscillations between two halves of an isolated conductive body. The measurements of the magnetic field strength is based on the electromotive force induced in a coil. Therefore the probe of the field meter, HOLADAY INDUSTRIES model HI-3604, consists both of two circular isolated parallel plates and of a circular coil. To avoid perturbations of the electric field, a fiber optic receiver and a non-conductive tripod to support the field meter are used. Only the effective value of the space component perpendicular to the plane of the probe is measured. The field quantities below the overhead transmission lines are measured at a height of 1 m above the ground level.

VI. COMPUTED RESULTS AND COMPARISON

All computations and measurements are performed at the place of the highest slack and at 1 m above the ground level. Because the transmission line is situated in a non-hilly area in Belgium, the assumption of the ground level to be even holds. To obtain a reasonable accurracy of the local field values a third order finite element solution is neccessary, which explains the long computation time. Figure 6a and b show the x- and z-component of the effective value of the magnetic field. Figure 7 shows the effective value of the z-component of the electric field. The calculations and the measurement show good agreement.







VIII. CONCLUSIONS

Efficient methods to compute the electric and magnetic field below high-voltage lines have been demonstrated. In the semi numerical model the slack of the transmission line is approximated by infinitesimally-thin segmented filaments of constant charge or current to solve the electrostatic and magnetic fields, respectively. With reasonable accuracy a three dimensional field distribution can be computed.

With the methods introduced, it is possible to predict by the simulation of planned or existing high-voltage lines if the European standards on limits of exposure to 50/60 Hz electric and magnetic fields are violated. Example calculations of power lines with different types of high-voltage poles carrying multiple voltage systems have been demonstrated. Good agreement between measured data of a Belgian 115 kV line and calculated field distribution can be asserted.

From the engineering point of view a two dimensional solution of the field problem below high-tension lines is sufficient. With respect to the field values the 2 dimensional approximation, assuming an infinite length of the phase conductors, represents the *worst case*. However, energy supplier are forced to support a 3 dimensional view of the electric and magnetic fields below transmission lines to the public. The methods introduced are representing a useful tool to generate quick and visual response to this request.

ACKNOWLEDGMENTS

The authors express their gratitude to the Belgian Ministry of Scientific Research for granting the IUAP No. 51 on Magnetic Fields and the Council of the Belgian National Fond of Scientific Research.

REFERENCES

[1] Hameyer, K., Hanitsch, R. and Belmans, R.: "Optimisation of the electro static field below high-tension lines", *Proc. 6th International IGTE Symposium on Numerical Field Calculation in Electrical Engineering*, Graz, Austria, pp. 264-269, September 1994.

[2] International Non-ionizing Radiation Committee of the International Radiation Protection Association IRPA: "Interim guidelines on limits of exposure to 50/60 Hz electric and magnetic fields", *Health Physics*, Vol. 58, No. 1, January 1990, pp. 113-122.

[3] Draft European Prestandard: "Human exposure to electromagnetic fields of low frequency", *prENV 50 166, part 1* (0-10 kHz) and *part 2* (10 kHz - 300 GHz), November 1994.

[4] DIN VDE: "Gefährdung durch elektromagnetische Felder, Schutz von Personen im Frequenzbereich von 0 Hz bis 300 GHz", *DIN 0848 part 2*, 1986.

[5] ANSI / IEEE Std. 644-1987: "IEEE standard procedures for measurement of power frequency electric and magnetic fields from ac power lines", *The Institute of Electrical and Electronics Engineers*, Inc. 345 East 47th Street, New York, NY 10017, USA, November 1987.