COMPUTATION AND MEASUREMENT OF ELECTROMAGNETIC FIELDS OF AC-HIGH-VOLTAGE TRANSMISSION LINES

K Hameyer, R Mertens and R Belmans

Katholieke Universiteit Leuven, Belgium

ABSTRACT

Overhead transmission lines generate in their vicinity electric and magnetic fields. The source of the magnetic fields are the currents in the phase conductors. The electric fields are caused by the high potential of the phase conductors.

Nowadays an increasing sensitivity to ecological problems can be stated. An injurious influence to the health of human beings caused by the direct effect of low frequency electromagnetic fields (50/60 Hz) is scientifically not proved yet. Since ca. 25 years research efforts to find a correlation mechanism between the field quantities and their effect on the human being 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.

In the paper two different numerical methods to compute the generated electric and magnetic field quantities will be introduced and compared.

INTRODUCTION

To evaluate the influence of the transmission line, it is not sufficient to calculate the coupling impedances or capacitances of the line. It is necessary to analyse the actually generated fields in the neighbourhood of the transmission line during the planning phase and to check if given standards for maximum field values are matched. The IRPA (2) and CENELEC (3) standards supply those maximum values for the duration of the stay of human beings exposed to electromagnetic fields of frequencies below 10 kHz.

EFFECTS OF FIELDS WITH LOW FREQUENCY

The interaction of electromagnetic fields with living organisms can be separated into two mechanisms, thermal and non-thermal interactions. The thermal interaction means the mechanism of the absorption of electromagnetic energy resulting in an increasing temperature. Non-thermal means these interactions where the absorbed energy is not large enough to cause a significant temperature rise. In fields of low frequency the wave energy is not or negligibly absorbed by the body. This implies, that biological effects cause by electric or magnetic fields of low frequency are non-thermal. Observed non-thermal effects on human beings can be the stimulation of nerves, upright standing skin hair, visual disturbances, ... Possible results of those effects may depend on the field characteristics as there are the intensity and frequency. To judge the mentioned effects, existing technical standards supply the quantities of the electric, magnetic and electromagnetic fields as a function of the frequency (2, 3). This is important because the interaction of electromagnetic fields and matter is strongly dependent on the wave length of the considered field.

A number of standards like those in preparation by the European Committee for Electrotechnical Standardisation (CENELEC) are based on the known effects for short exposure times. Long term effects are not considered. In IRPA (2) is stated that no long term effects were detected. Hence, to consider possibly not yet discovered effects the values for technical fields are reduced by a factor. In table 1 the maximum exposure values for the electric and magnetic field are summarised. The values are distinguished according to the general public and professional working individuals.

TABLE 1 -Maximum exposure values for the electric and magnetic field.

exposure	electric field strength E kV/m (rms)	magnetic flux density B mT (rms)
professionals:		
8 hours	10	0,5
short time	30[(a)]	5[(b)]
only limbs	-	25
general public:		
≤ 24 hours per day[(c)]	5	0,1
some hours per day[(d)]	10	1

a) the exposure time t in $[h]$ from fields E in $[kV/m]$ in the range from 10-30 kV/m can be calculated with $t \leq 80 / E$
b) maximum 2 hours per workday
c) exposure in open air like recreation areas, meeting places
d) the limits may be broken for a few minutes per day if no indirect coupling is guaranteed

FIELD COMPUTATION

Mathematical techniques to calculate the electro-magnetic field quantities necessarily require a model of the technical device to reflect the physical behaviour of the high-voltage transmission line. The problem specifies small diameter conductors above a large flat conducting ground plane. The phase conductors are at a time dependent specified electrical potential and are also carrying a time dependent current. Due to the catenary of the phase conductors the field problem turns out to be three dimensional. It is assumed that only symmetric three phase voltage and current systems are considered. The ground below the transmission line is considered being an uniform plane.

Semi Numerical Method

A first possible method is a semi numerical approximation allowing three dimensional calculations of both types, electric and magnetic field. Due to the large wavelength of the field problem has to be considered as quasi static. Therefore, the solution can be determined by static techniques. With respect to the catenary of the phase conductors the geometry of the single conductor is approximated by infinitesimally-thin segmented filaments. Due to the symmetry between two poles one half of the arrangement is drawn in fig. 1 only. The value of *s* indicates the catenary and *l* is the distance between the two high voltage poles, the span field length.

The electric field. The electric field is computed by mirroring single line charges at the assumed to be ideal conducting ground plane below the phase conductors. Each infinitesimally-thin filament segment represents in this case a line-charge. 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 $(\tilde{x}, \tilde{y}, \tilde{z})$. The 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

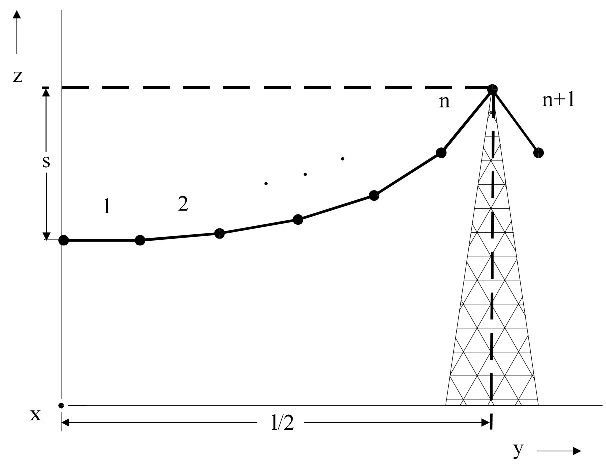

Figure 1: Geometric modelling of a conductor.

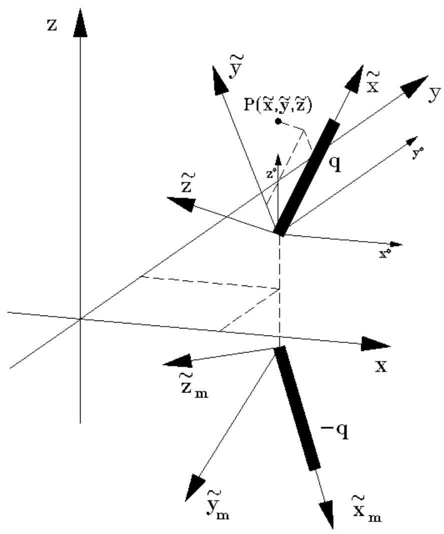

Figure 2: Co-ordinate transformation of a infinitesimally-thin filament segment.

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

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.

To consider the above mentioned catenary of the conductors a quadratic approximation is used. Referring to fig. 1, it can be written as

$$f(y) = s \cdot \left(1 - \frac{4}{l^2} y^2\right) \quad . \quad (2)$$

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

$$\mathbf{A} \cdot \underline{\mathbf{q}} = \underline{\varphi} \quad (3)$$

The solution determines the charge $\underline{q}_i$ of each element of the conductors. With this value the components of the

Figure 3: Convergence behaviour of the simulation with respect to the slag of the high-tension line.

electro- static field strength in the point $P(x, y, z)$ can be computed.

$$\mathbf{E} = -grad\varphi = -\left(\frac{\partial\varphi}{\partial x}\mathbf{a}_x + \frac{\partial\varphi}{\partial y}\mathbf{a}_y + \frac{\partial\varphi}{\partial z}\mathbf{a}_z \right) \quad (4)$$

To illustrate the convergence behaviour of the method, attention should be paid to fig. 3. With an increasing number of infinitesimally-thin filament segments for one half of the span field, the electro-static field strength converges to a certain value. Calculations with 5…7 polygon elements deliver results with a reasonable accuracy and acceptable computational costs. The values plotted in fig. 3 are taken from a calculation at the point of the maximum slag and $1m$ above ground plane.

The magnetic field. The magnetic field problem is considered to be linear. Hence, the superposition of partial fields, calculated with the BIOT-SAVART law are resulting in the overall three dimensional field distribution below the energy line.

In this case each segment of the infinitesimally-thin filament (fig. 1) carries a current *i(t)*. The generated flux density of this part of the conductor is given by

$$|d\mathbf{B}| = \frac{\mu_0}{4\pi r^2} \cdot i(t) \cdot dl \cdot \sin\alpha \quad . \quad (5)$$

The point where the flux density has to be calculated has to be transformed into the co-ordinate system $(\tilde{x}, \tilde{y}, \tilde{z})$. After integrating eq. (5), the flux density is calculated with

$$\left|\mathbf{B}_j\right| = \frac{\mu_0}{4\pi r} \cdot i(t) \cdot \left(\frac{l-\tilde{x}}{\sqrt{(l-\tilde{x})^2 + r^2}} + \frac{\tilde{x}}{\sqrt{\tilde{x}^2 + r^2}} \right) \quad . \quad (6)$$

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

$$\mathbf{B} = \sum_{j=1}^{n} \mathbf{B}_j \quad . \quad (7)$$

Finite Element Method

The second numerical field computation method able to compute solutions in this problem class is the well known finite element method. Special boundary conditions applied to the field problem result in an effective use of this method. The application of *open boundary* conditions gives the opportunity to discretise the field problem in regions of interest only. This results in less computational costs. With respect to the computational efforts only two-dimensional computations are performed with this numerical method.

A cross-section of the transmission line is made at the place where the wires are closest to the ground level. There it is expected to obtain the highest field values. A 2 dimensional finite element model lateral to the line at this place is built. The region of the cross-section is subdivided in triangular finite elements (fig. 4). 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 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 centimetres. Therefore special attention must be paid to obtain a regular mesh with good shaped elements. This ensures an accurate solution of the field problem. Therefore, a high degree of discretisation resulting in a large system of equations must be applied. Figure 5 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 a conductor can be seen in fig. 5.
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 calculation the ground posses the same magnetic properties as the surrounding air and therefore the

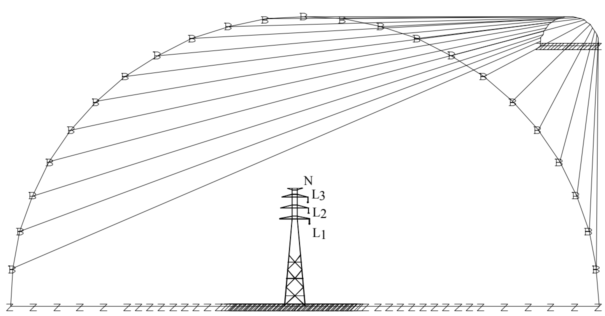

Figure 4: Open boundary model to compute the electric field of a 150 kVac single system transmission line. (the triangulation of the domain is invisible)

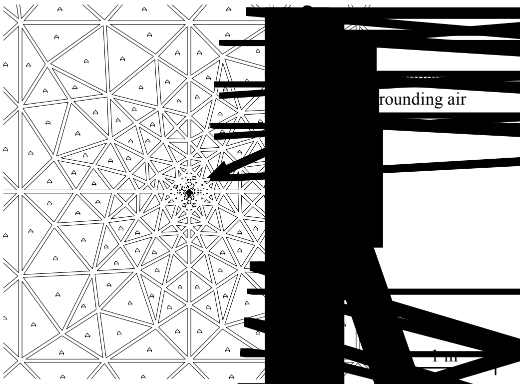

Figure 5: Part of the finite [illegible] around a single phase [illegible]or.

ground has to be discretised [illegible]. This r[illegible]ts in an increased number of finite el[illegible] and thus [illegible] higher computational costs.

In contrast to the semi-num[illegible] method, wh[illegible] the phase conductors are modelle[illegible] and that take[illegible]ew seconds to compute the field quantities, the calcu[illegible]n time of one transmission line on a PC-486 plat[illegible] using the finite element method is about 30 minutes.

MEASUREMENTS

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 fibre optic receiver and a non-conductive tripod t[illegible] support the field meter are used. Only the effective val[illegible] of the space component perpendicular to the plane of [illegible] probe is measured. The field quantities below [illegible] overhead transmission lines are measured at a heig[illegible]f 1 *m* above the ground level.

NUMERICAL AND EXPERIMENTAL RES[illegible]TS

All computations and measurements of [illegible]elgian 150 kVac single three phase system transm[illegible]on line are performed at the place of the maximu[illegible]catenary. Because the transmission line is situated i[illegible] non-hilly area in Belgium, the assumption of the g[illegible]nd level to be even holds here.

To obtain a reasonable accuracy of the [illegible]al field values a third order finite element solution [illegible]necessary. The use of shape functions of third orde[illegible]plains the long computation time for this field evalu[illegible]n. Figure 6a and 6b show the x- and z-component [illegible]he effective value of the magnetic field. Good ag[illegible]ment between the

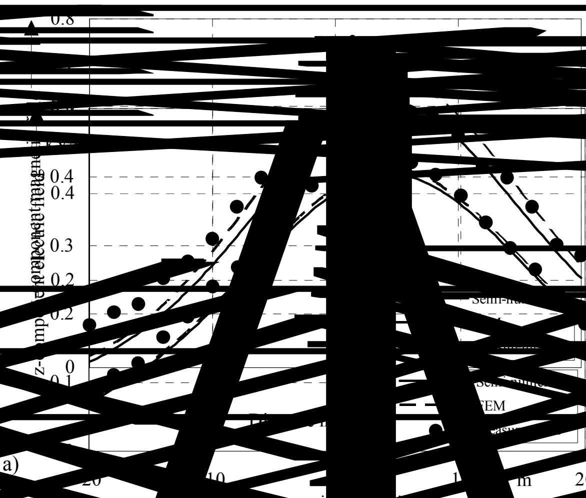

Figure 7[illegible]ompa[illegible] of c[illegible]d electri[illegible] distributio[illegible]th measured da[illegible]ove g[illegible]l.

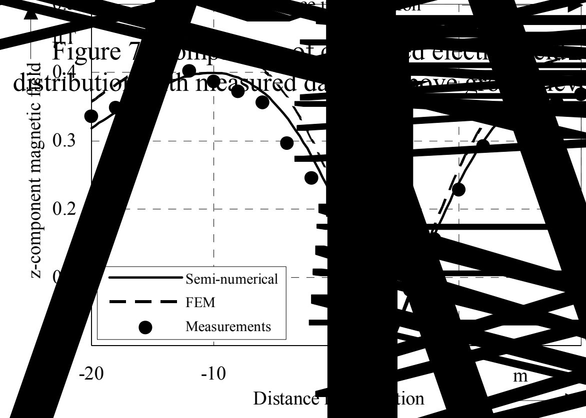

Figure 6: Comparison of co[illegible]d magn[illegible]eld [illegible]istribution with measured da[illegible] above gr[illegible]d level [illegible]) x-component and b) z-com[illegible]t in the g[illegible]l co-ordinate system de[illegible]n fig. 1.

m[illegible]rements and computed [illegible]n be stated. T[illegible]wo di[illegible]onal approach overestimates both x- a[illegible] com[illegible]nt of the magnetic field. The reason for this lies [illegible]e type of approximating the geometry of [illegible] transm[illegible]on line. In the two dimensional model a ph[illegible] condu[illegible]f infinite length with constant height a[illegible] ground [illegible]nsidered. Therefore, the two dimen[illegible]al approach [illegible]resents the worst case respective[illegible] the highest va[illegible]of field strength.

Figure 7 sh[illegible] the effective value of the z-c[illegible]ponent of the ele[illegible] field. The calculations [illegible]d the measurement [illegible] good agreement.

In fig. 8 the thr[illegible]mensional electric fie[illegible]istribution below the 150 k[illegible] transmission line o[illegible]ned by the semi-numerical m[illegible]d is plotted. T[illegible] geometrical model of the sing[illegible]hase conducto[illegible]consists of [illegible] polygon elements p[illegible]lf of the over[illegible]pan field. T[illegible] high-voltage pole is [illegible]ted at the [illegible]al co-ordina[illegible] x=0 *m* and y=220 *m*.

As expected, the maximum field values are found in the middle of the span field at the co-ordinates y= 0 *m*. Here, the values of the electric field strength are in the range of 4 kV/m, thus below the maximal allowed exposure values for the general public given by the standards in table 1. Referring to fig. 6 the magnetic flux density of the x- respectively z-component generated by the current carrying conductors are in the range of 0.4-0.6 µT. Accordingly to table 1 those values of the magnetic flux density are far below the allowed limits as well.

Due to the linearity of the problem formulation, calculations of power lines with different types of ac-high-voltage poles carrying multiple three phase voltage and current systems can be computed. In this case the field components generated by the single systems have to be superposed according to the relative phase angle between the systems and the considered instant of time. Figure 9 shows the results, computed by the semi-numerical technique, of a high-voltage transmission line consisting of six three phase systems with different voltage level (2x380 kV, 2x220 kV, 2x110 kV). For the magnetic flux density it is assumed that each system carries a current of 1000 A. The system with the largest transmission voltage is fixed on the top of the pole, respectively the system with the lowest voltage is located at the lowest height.

The computed field values for electric and magnetic field quantities show that the limits given in table 1 are not broken by this configuration.

If the allowed field limits are violated, in Hameyer (5) the numerical optimisation of the electric field below ac-high-voltage line is reported. There, the position of the ground conductors is varied to minimise the generated field in 1*m* above ground level.

CONCLUSIONS

Two efficient methods to compute the electric and magnetic field below ac-high-voltage lines have been introduced and demonstrated at an example of a 150 kVac three phase single system transmission line. Both methods are compared with respect to accuracy and the necessary computational efforts. Advantages and disadvantages of both methods are discussed. To verify the results of the field simulations, measurements of a power line have been carried out. A good agreement between computed and measured data can be stated and a comparison between practical measurement and theoretically predictions is given.

In the semi numerical model the catenary 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. Relatively low computation times are necessary to compute the three dimensional field distribution below the power line. Using a standard PC-486/66, the calculation time lies in the range of some seconds.

With the finite element method, the distribution of both, electric and magnetic field quantities is computed. With respect to the high computational costs, when compared to the semi-numerical method, a 2-dimensional approach in the middle of the span field is chosen. Due to the necessary high discretisation of the problem the computational costs are in the range of 30 minutes using a PC-486/66.

Good agreement between measured data of a Belgian 150 kV line and calculated field distribution by both methods can be stated.

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. The maximal allowed data are given in table 1.

ACKNOWLEDGEMENTS

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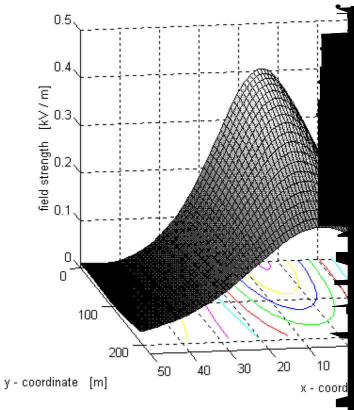

Figure 8: Electric field distributi[redacted] kVac high-tension line computed b[redacted] semi n[redacted] method.

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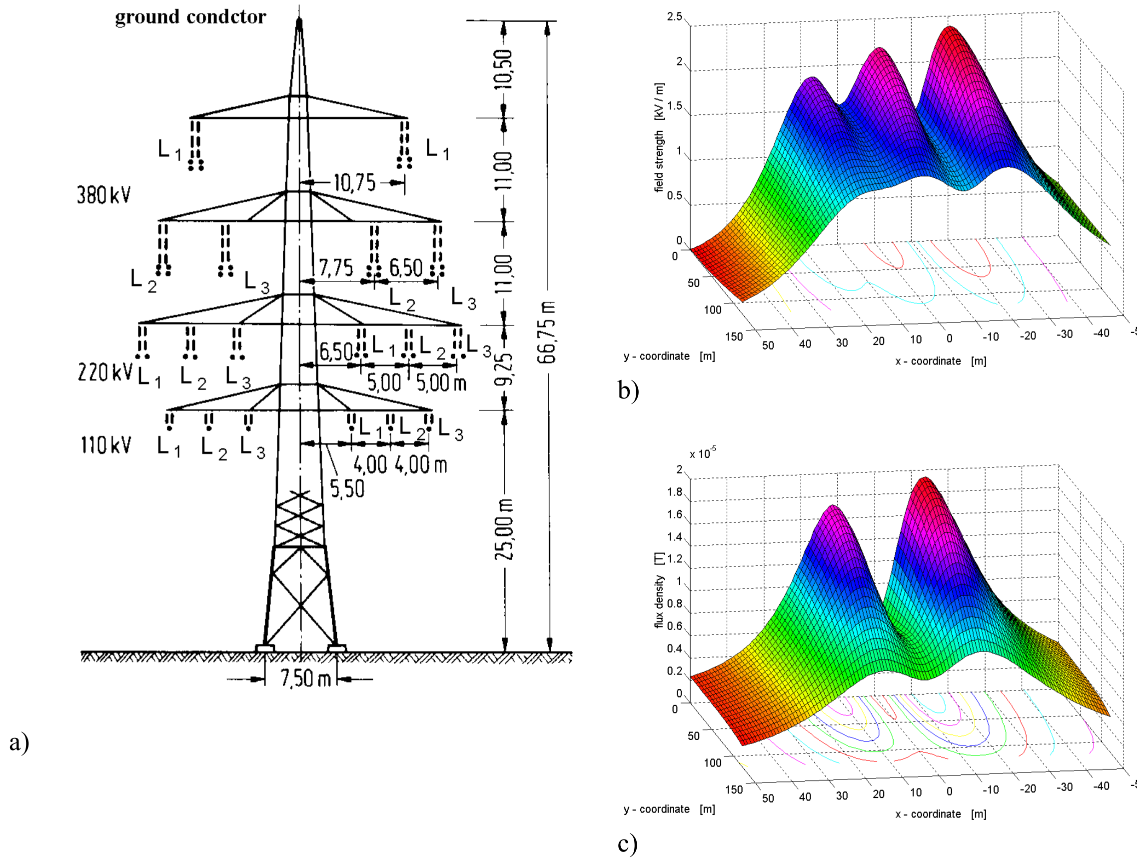

Figure 9: High-voltage pole construction carrying 6 systems (2x380 kV, 2x220 kV, 2x110 kV) and b) the resulting electric field distribution. (All the rotary current systems leading an effective current of 1000 A, the pole is located at the co-ordinate x=0 m, y=160 m)