

## **Using the EMTP/ATP program for calculation of electric and magnetic field distribution under overhead line**

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This paper presents the method of calculation of the electric and magnetic fields under overhead transmission line with any number of circuits, phase positions, voltages and current loads. Calculations of this type usually require specialized and costly programs. The program EMTP/ATP is a royalty free tool to calculate the electric transient and steady states in complex power systems. You can use this program and through appropriate modeling the multi-phase wire system representing the line and measurement device calculate the strength of the electric and magnetic fields. The results of calculations are characterized by a very small error compared to the results obtained by using the specialized commercial program. This method can be used with other popular engineering tools like Matlab/Simulink or PSCad.

### **1. National regulation requirements**

For the Polish conditions, the regulation [1] specifies the permissible levels of electromagnetic fields strength in the vicinity of the equipment producing these fields, depending on the field frequency and the nature and purpose of the environment. In the case of overhead power lines permissible rms electric field strength of 50 Hz frequency is 1 kV/m in the areas allocated for housing and 10 kV/m for the remaining places available for the population. The rms value of the magnetic field strength with a frequency of 50 Hz in places accessible to the public should not exceed 60 A/m.

Measurement of the electric field takes place at height of 2 m and of a magnetic field at height from 0.3 m to 2 m above the ground or other surfaces on which people can stay.

In the standards [2, 3], the methods of measuring the strength of electric and magnetic fields of industrial frequency are discussed. In [2], the constructions of the electric field meters with a dipole probe or a grounded flat dipole and using Pockels effect are described. In [3], the structure of the magnetic field meters equipped with an antenna framework probe or a Hall-effect sensor are described. The factors affecting the measurement errors, such as proximity to humans or other

objects, weathering, the presence of other fields, harmonic content, or position of the meter are presented. It is assumed that the error of the electric field and the magnetic measurements using a commercially available meters is the order of 10% [3].

## 2. Calculation of electric and magnetic field in the vicinity of overhead line

Calculations of electromagnetic field strengths in the vicinity of the HV devices are performed using specialized, often expensive programs. This paper presents a technique for calculating the distribution of electric and magnetic fields in the vicinity of overhead line using the program which does not have a function of the electromagnetic field calculation but in which the measurement process can be simulated. Engineers often have such a tool like Matlab/Simulink, PSCAD, or royalty free EMTP/ATP [4, 5] in their computers.

For the calculation of steady states and slow transient states the Pi model of the overhead power line is fast and sufficiently accurate.

For fixed frequency voltages and currents in the series and shunt elements of the line equivalent scheme are related to the following formulas (1):

$$-\frac{d}{dx}[\mathbf{u}] = [\mathbf{Z}] \cdot [\mathbf{i}_x] \quad -\frac{d}{dx}[\mathbf{i}_y] = [\mathbf{Y}] \cdot [\mathbf{u}] \quad (1)$$

where  $[\mathbf{u}]$  - vector of phase voltages,  $[\mathbf{i}_x]$ ,  $[\mathbf{i}_y]$  - vectors of currents in the series and shunt branches,  $[\mathbf{Z}]$ ,  $[\mathbf{Y}]$  - complex matrix of series impedances and shunt admittances.

Formulas for calculating  $[\mathbf{Z}]$  have been developed by Carson [4] for telecommunication lines. They assume a single-layer earth model. Carson's formulas are usually sufficiently accurate for the calculation of network phenomena.

Elements of matrix  $[\mathbf{Z}]$  are calculated from the formula (2):

$$Z_{ii} = (R_{i-int} + \Delta R_{ii}) + j(\omega \cdot \frac{\mu_0}{2 \cdot \pi} \cdot \ln \frac{2 \cdot h_i}{r_i} + X_{i-int} + \Delta X_{ii})$$

$$Z_{ik} = Z_{ki} = \Delta R_{ik} + j(\omega \cdot \frac{\mu_0}{2 \cdot \pi} \cdot \ln \frac{D_{ik}}{d_{ik}} + \Delta X_{ik}) \quad (2)$$

where:  $R_{i-int}$ ,  $X_{i-int}$  - internal impedance of wire depending on its construction,  $\Delta R_{ik}$ ,  $\Delta X_{ik}$  - Carson correction terms for earth return effects,  $h_i$ ,  $D_{ik}$ ,  $d_{ik}$ ,  $r_i$  - geometrical parameters of the line:  $h_i$  - the height of wire above the ground,  $D_{ik}$  - distance between conductor  $i$  and image of conductor  $k$ ,  $d_{ik}$  - distance between conductors  $i$  and  $k$ ,  $r_i$  - radius of the conductor  $i$ .

The matrix  $[\mathbf{Y}] = \omega \cdot [\mathbf{P}]^{-1}$  is calculated from the Maxwell potential coefficient matrix, whose elements describe (3):

$$P_{ii} = \frac{1}{2 \cdot \pi \cdot \epsilon_0} \cdot \ln \frac{2 \cdot h_i}{r_i} \quad P_{ik} = P_{ki} = \frac{1}{2 \cdot \pi \cdot \epsilon_0} \cdot \ln \frac{D_{ik}}{d_{ik}} \quad (3)$$

Presented formulas are the basis for calculations of phase or modal overhead transmission line parameters.

### 2.1. Calculation of electric field strength - a basic method

In the case of computing electric field under the overhead line in the middle of the span where the field is the greatest, assuming that the wire runs parallel to the ground and there are no objects distorting the field distribution the classic method of superposition can be used [6].

In general, the overhead line can be built as multi-phase, multi-circuit, multi-voltage with single or bundle conductors. Using the method of mirror reflection, the components of the electric field at the measuring point P can be shown in Figure 1, where  $q$  - linear charge on the wire,  $r$ ,  $r'$  - the distance between the wire and the measuring point P and between its mirror image and the point P.

In the multi-conductor system, the relation between the linear charge, its potential and the geometry of the line is presented by the formula (4):

$$[\mathbf{u}] = [\mathbf{P}] \cdot [\mathbf{q}] \quad (4)$$

where:  $[\mathbf{q}]$  - matrix of linear charge on the wire,  $[\mathbf{P}]$  -Maxwell potential coefficients matrix.

The components of the electric field strength ( $E$ ,  $E'$ ) produced by the conductor with a charge  $q$  and its mirror image with charge  $-q$  are shown in the equation (5):

$$E = \frac{q}{2 \cdot \pi \cdot \epsilon_0 \cdot r}, \quad E' = \frac{-q}{2 \cdot \pi \cdot \epsilon_0 \cdot r'} \quad (5)$$

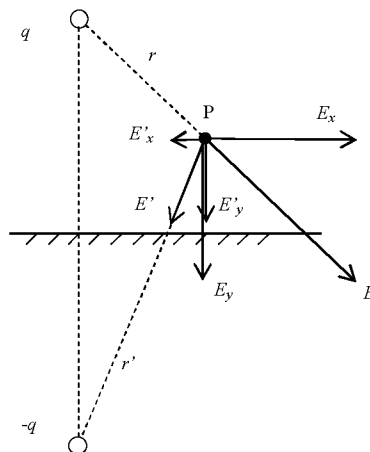


Fig. 1. The components of the electric field strength at point P, whose source is a charged wire

## 2.2. Calculation of electric field strength using the EMTP/ATP

The EMTP/ATP program allows to model the multi-phase, multi-circuit, multi-voltage overhead line with single or bundle conductors as well as calculation current and voltage waveforms in steady and transient states. The components of the electric field strength in the environment of the line can be calculated by modeling the measuring technique. The wires of overhead line are completed by two wires placed vertically or horizontally above the ground, Figure 2.

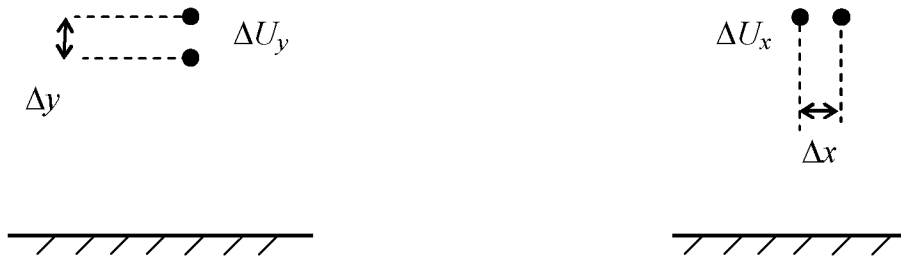


Fig. 2. Location of the wires for measuring the vertical and horizontal component of the electric field strength

The voltage between these wires is proportional to the vertical or horizontal component of the electric field strength. Instantaneous values of the vertical  $E_y(t)$  and horizontal  $E_x(t)$  components of the electric field strength  $E$  can be calculated from the formulas (6):

$$E_y(t) = \frac{\Delta U_y(t)}{\Delta y} \quad E_x(t) = \frac{\Delta U_x(t)}{\Delta x} \quad (6)$$

where:  $\Delta U_y(t)$  and  $\Delta U_x(t)$  - instantaneous values of voltages between conductors placed vertically or horizontally at the height of measurement,  $\Delta y$  and  $\Delta x$  - distances between conductors.

## 2.3. Calculation of the magnetic field strength - a basic method

The value of magnetic field strength  $H$  and its components  $H_x$  and  $H_y$  from one wire of the overhead line with a current value  $i$ , for configuration presented in Figure 3 is given by (7).

$$H = \frac{i}{2 \cdot \pi \cdot r} \quad (7)$$

where:  $r$  - distance from the wire to the measuring point P.

The total magnetic field strength in the vicinity of the power line loaded with current is calculated by the superposition method.

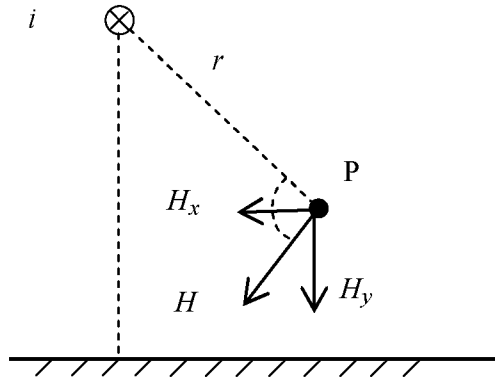


Fig. 3. The components of the magnetic field strength at point P, whose source is the current  $i$  in the wire

## 2.4. Calculation of the magnetic field strength using EMTP/ATP

The components of the magnetic field strength in the vicinity of the power line can be calculated by modeling the measuring technique, Figure 4. Two wires in close proximity to each other are stretched under the power line at the height of the measuring point. Wires are shorted together at one end and the voltage induced in the loop is measured at the other end. The value of this voltage is proportional to the horizontal or vertical component of the magnetic field strength.

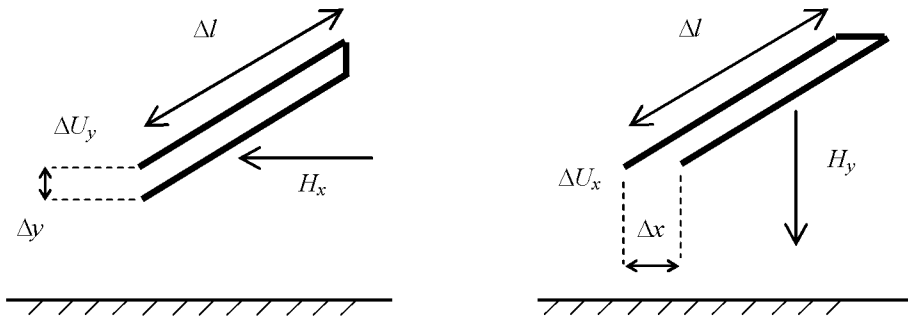


Fig. 4. Location of test wires for measuring horizontal and vertical components of the magnetic field strength

Electromotive force  $e(t) = \Delta U$  induced in the loop of test wires is given by (8) and the amplitude of the horizontal  $H_{x\_max}$  and vertical  $H_{y\_max}$  components of magnetic field strength are presented by (9):

$$e(t) = -z \cdot \frac{d\phi(t)}{dt} = -z \cdot \frac{d(B(t) \cdot S)}{dt} = -z \cdot \frac{d(\mu_0 \cdot H(t) \cdot S)}{dt} = -z \cdot S \cdot \mu_0 \cdot \frac{dH(t)}{dt} \quad (8)$$

$$H_{\max} = \frac{\Delta U_{\max}}{z \cdot S \cdot \mu_0 \cdot \omega} \quad (9)$$

where:  $\Delta U_{\max}$  - amplitude of the measured voltage in the loop,  $S$  - area of the loop (coil),  $z$  - number of coils,  $z = 1$ .

### 3. Results of calculation

Calculations of the electric and magnetic field strength distribution using the earlier described method with the EMTP/ATP program were performed. The obtained results were compared with those calculated with the specialized program for calculation of the electromagnetic field strength distribution under the power line using the superposition method described in point 2.

Calculations were performed for the single-circuit 110 kV power line carried on towers of S12 series and for the multi-circuit 2x400 kV+2x 220 kV power line on LHP towers. Geometry of towers is shown in Figure 5.

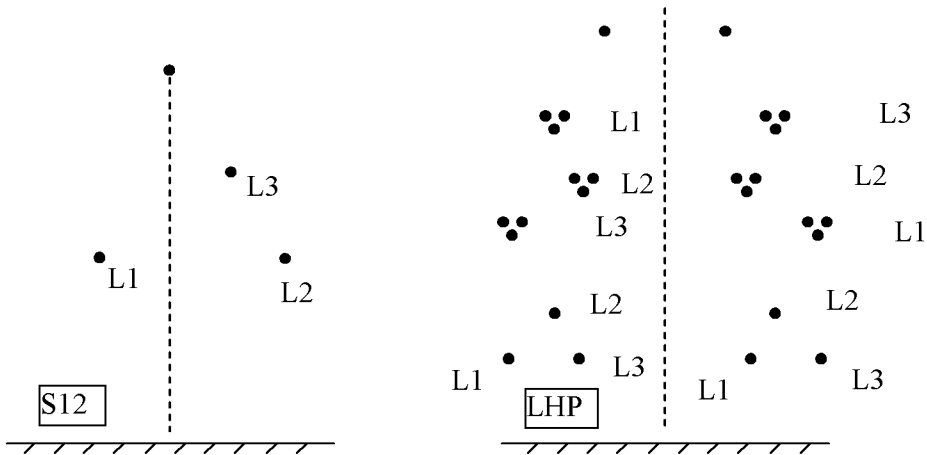


Fig. 5. Geometry of S12 and LHP towers taken for the calculation of the distribution of electric and magnetic field strength

The data of power lines are as follows: a line of 110 kV - 400 A load current, line 2x 220 kV+2x 400 kV - 2500 A load current in circuits of 400 kV and 1000 A at 220 kV circuits.

Figure 6 and 7 shows the distribution of the electric field strength  $E$  and its components and the magnetic field strength  $H$  under the 110 kV power line on S12 towers at a height of 1.8 m.

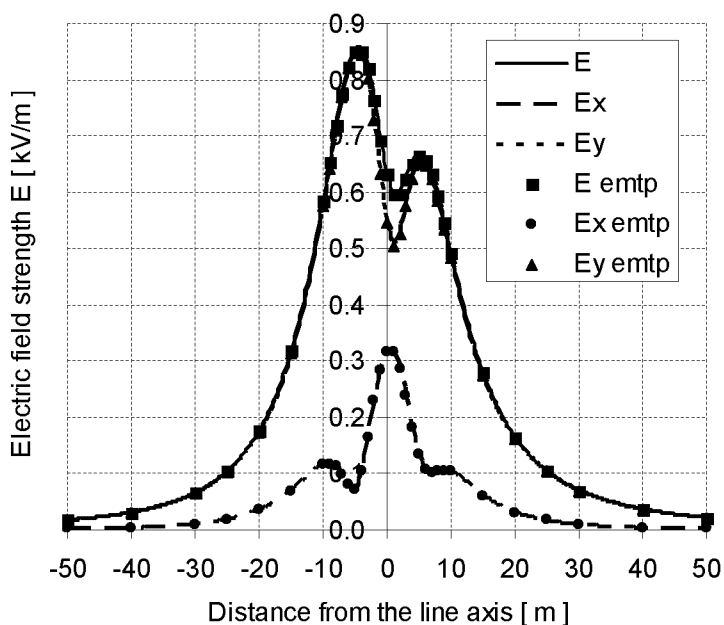


Fig. 6. Distribution of electric field strength  $E$  and its components under the 110 kV power line on S12 towers at a height of 1.8 m above ground

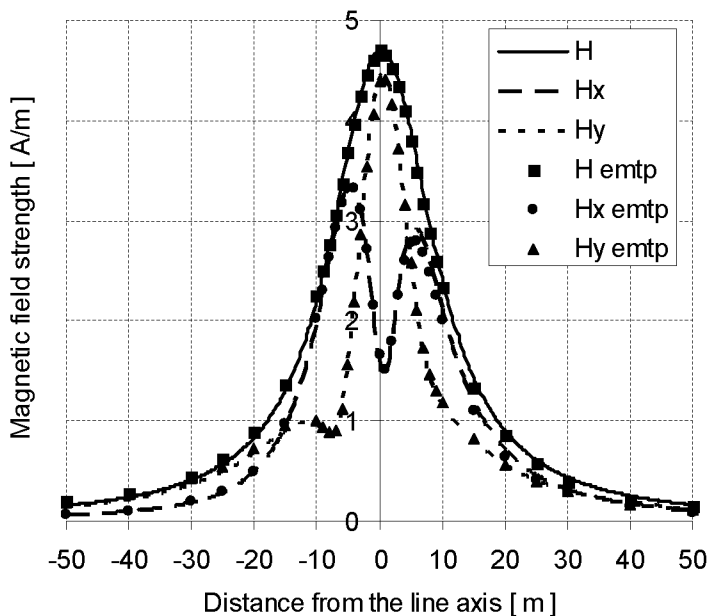


Fig. 7. Distribution of magnetic field  $H$  (b) under the 110 kV power line on S12 towers at a height of 1.8 m above ground

The continuous lines show the results of the calculations using the commercial program and the points show the results of calculations using the EMTP/ATP and the presented in the paper method. The error of calculation for the electric field does not exceed 0.02 kV/m (at maximum value 0.86 kV/m) and in the case of the magnetic field 0.17 A/m (at maximum value 4.7 A/m). It can be stated that the described method is satisfactory.

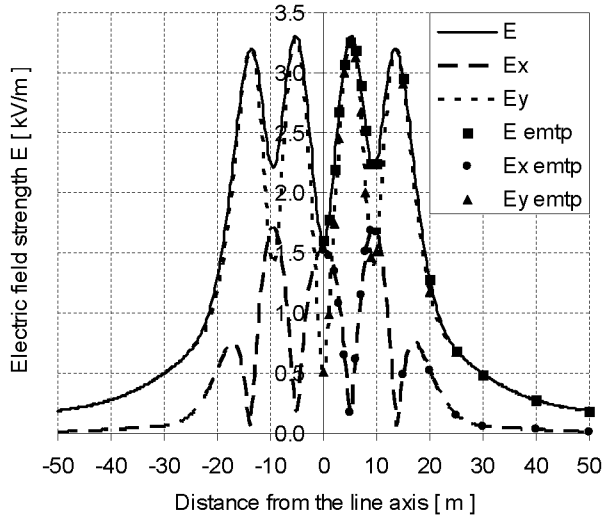


Fig. 8. Distribution of electric field strength  $E$  and its components under the power line  $2 \times 400 \text{ kV} + 2 \times 220 \text{ kV}$  on LHP towers at a height of 2 m above ground

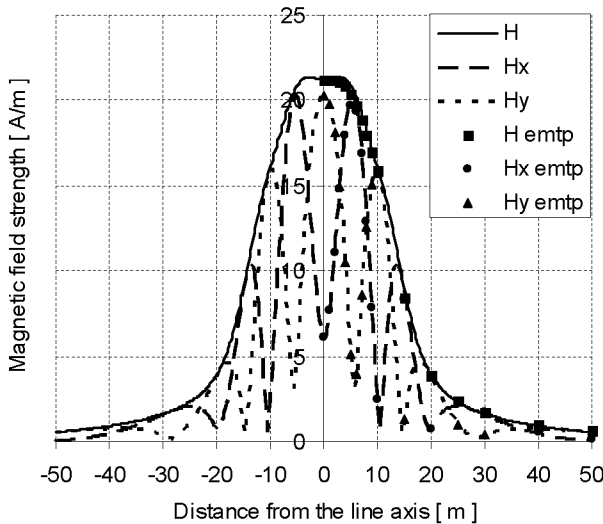


Fig. 9. Distribution of magnetic field  $H$  and its components under the power line  $2 \times 400 \text{ kV} + 2 \times 220 \text{ kV}$  on LHP towers at a height of 2 m above ground



Figure 7 and 8 shows the distribution of electric field strength  $E$ , its components and magnetic field  $H$  under the four-circuit, two-voltage power line  $2 \times 400 \text{ kV} + 2 \times 220 \text{ kV}$ . The error of calculation for the electric field strength does not exceed  $0.09 \text{ kV/m}$  (at maximum value  $3.3 \text{ kV/m}$ ) and in the case of the magnetic field  $0.67 \text{ A/m}$  (at the maximum value  $21.4 \text{ A/m}$ ). The calculation error does not exceed  $10\%$ .

#### **4. Conclusions**

- The presented method allows to calculate the distribution of electric and magnetic field strength in the vicinity of a multi-circuit and multi-voltage power line with any phase configuration. For this calculation commercial and costly program is not indispensable. You can use a royalty free tool, like EMTP/ATP program which directly does not have necessary function. The calculation consists in modeling of meter devices. The calculation error does not exceed the value achieved by the measurement method.
- The application the EMTP/ATP program enables to calculate the value of electric and magnetic field strengths during the fault conditions, short circuits, atmospheric lightning, wire falling etc. Typical commercial programs do not have such options.
- It is possible to perform calculations for different phase configurations. It is very important at designing a multi-circuit and multi-voltage power line to minimize the width of the buffer zone under the line.

#### **References**

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