IMPACT OF THE PHASE POSITIONS ON THE ELECTRIC AND MAGNETIC FIELD OF HIGH-VOLTAGE OVERHEAD LINES

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ABSTRACT

The magnetic and the electric field of a three phase double circuit high-voltage overhead power line depend on the geometrical arrangement of the conductors and on the allocation of the phases. This paper shows the resulting magnetic and electric fields for three different conductor arrangements (i.e. given tower geometries) often found in Europe - for all possible phase allocations respectively. In addition, a method is derived to identify exemplarily the best phase allocation for specific immission of a 3-level-tower, as well as an evaluation method of the highest field value without knowing the actual phase allocation.

INTRODUCTION

Approval processes for the construction and/or modification of high-voltage overhead lines have led to an increasing demand for detailed investigation of magnetic and electric fields. For this paper three common European tower designs for double circuit 400 kV overhead lines were chosen to demonstrate the influence of the positions of the phases on the magnetic and electric field. The positions of the conductors for a assumed 3-level, 2-level and 1-level-tower are given in Fig.1. The distance from the ground to the lowest conductors has been set to 10 m (i.e. the minimum distance considering wire-sag), in order to enable comparison of the results for different tower-geometries.

A double circuit line offers 36 (6 times 6) different possibilities of allocating the phases (L1, L2, L3, L1’, L2’, L3’) for a given geometrical conductor arrangement (P1, P2, P3, P1’, P2’, P3’) as shown in Tab. 1. These combinations result in 12 different field configurations – Var. 1, 2 and 3 all share the same electric and magnetic field and can be obtained by cyclically exchanging the phases. In Tab. 1 these 12 different cases are shown (No.1 to No.12) as well as the 3 variations obtained by cyclical exchanges (Var. 1-Var. 3). Cases No.1 to No.6 differ with cases No.7 to No.12 only in the fact that L2 and L3 are switched.

Calculation

Calculation of the Magnetic Field

The calculation of the magnetic flux density follows the theory of Biot and Savart using a two-dimensional vertical model. For an infinite straight thin conductor carrying a current I the magnetic flux density can be calculated applying the following expression (1).

\[
\mathbf{B}(t) = \frac{\mu_0}{4\pi} \frac{I(t)}{r} \mathbf{e}_n
\]

\( \mathbf{B}(t) \) time-dependent magnetic flux density in Vs/m² (T)
\( \mu_0 \) permeability of vacuum in Vs/Am
\( I(t) \) time-dependent current, a sinusoidal current with a frequency of 50 Hz in A
\( \mathbf{e}_n \) unit vector in circumferential direction

The magnetic flux density in a space free of magnetic materials obeys the principle of superposition. Therefore the resulting magnetic flux density of a given geometrical
arrangement can be calculated by vectorially adding the contribution of each line conductor respectively. For sinusoidal currents \( I(t) \), the magnetic flux density and the components in \( x \)- and \( y \)-direction \( B_x \) and \( B_y \) are also sinusoidal. If there is more than one conductor and the currents in the conductors have different phasing, a rotating field occurs. The RMS of the magnetic flux density (i.e. the equivalent magnetic flux density) can be calculated with the root mean square of the RMS values of the sinusoidal components \( B_x \) and \( B_y \):

\[
B_{\text{rms}} = \sqrt{B_{x\text{rms}}^2 + B_{y\text{rms}}^2}
\]

(2)

\( B_{\text{rms}} \) RMS of the rotating magnetic flux density

\( B_{x\text{rms}}, B_{y\text{rms}} \) RMS of the components in \( x \)- and \( y \)-direction

In the following always the equivalent flux density \( B_{\text{rms}} \) is applied.

### Calculation of the Electric Field

The electric field is calculated using the method of mirror charges (or image charges), using a mirror-plane - the conducting soil. The line charges \( \tau \) of the conductors are calculated by using the potential coefficient matrix of the power line. Afterwards the electrical field strength can be calculated with following expression derived from Coulomb’s law (3):

\[
E = \frac{\tau}{4\pi \varepsilon_0 r} \cdot \hat{c}_r
\]

(3)

\( E \) electric field strength in V/m

\( \tau \) line charge in As/m

\( \varepsilon_0 \) permittivity of vacuum in As/Vm

\( r \) distance from line conductor in m

\( \hat{c}_r \) unit vector in radial direction

The electric field also obeys the superposition principle and the equivalent electric field strength \( E_{\text{rms}} \) can be calculated analogously to \( B_{\text{rms}} \).

### Calculation of the Current in the Earth Wire

The current in the overhead earth wire \( I_e \) is calculated with the impedance-formulae by Cason and Pollaczek [1, 2] as shown in [3] using equation (4):

\[
\begin{bmatrix}
U_p \\
0
\end{bmatrix} = Z_{pp} Z_{pe} \begin{bmatrix}
I_p \\
I_e
\end{bmatrix}
\]

(4)

\( U_p \) voltage of active phase conductors

\( U_e = 0 \) voltage of earth conductor(s)

\( Z_{pp}, Z_{pe} \) impedance matrix of system \( p \), \( e \) (phases) and \( e \) (earth wires)

The resulting currents \( I_e \) of the earth wires can be calculated as follows (5):

\[
I_e = -Z_{pe}^{-1} \cdot Z_{pp} \cdot I_p
\]

(5)

The currents in the earth wire(s) cause an alternating magnetic field which has to be vectorially added to the rotary magnetic field of the currents in the phase conductors. The direction and amplitude of the current in the earth wire strongly depends on phase allocation and conductor arrangement. Therefore the current in the earth wire must be calculated for each case of phase arrangement of Tab. 1.

### RESULTS

In the following the calculation results for electric and magnetic fields are presented for tower designs according to Fig. 1. Phase currents of 2300 A and a maximum voltage of 420 kV (phase-to-phase) were assumed, together with a distance of 10 m from the ground to the lowest conductors. The following figures show the resulting fields in a height of 1 m above ground.

#### 3-Level-Tower

In the following Fig. 2 the magnetic flux density in 1 m above ground of a 3-level-tower for all 12 cases of allocating the phases are shown. As can be seen, it is not possible to point out a clearly best or worst case. Cases No.3 and No.9 provide the maximum values of the magnetic field in a region with a distance less than approx. 10 m from the line axis. On the other hand, these cases are the ones with the lowest values at a distance more than 18 m from the line axis. Cases No.4 and No.10 contribute the lowest maximum value but cause higher magnetic flux densities in more distant points. This means that by choosing a phase allocation with low magnetic flux density values directly under the wires, higher values in an outer area will occur. In Fig. 3 a zoomed area of Fig. 2 is presented to show that there are 12 different characteristics. Two characteristics are always very similar. The small deviation is due to the contribution of the field caused by the current in the earth wire to the field caused by the currents in the phase conductors.
For the electrical field the maximum field strength directly under the high-voltage-line (inner section) is interesting, because e.g. trees and buildings may mitigate the electric field. The highest maximum values under the high-voltage line are caused by case No.1 and No.7, the lowest maximum values by No.3 and No.9.

Contrary to the magnetic field there are only 6 different electric field patterns for the 12 phase allocation cases. This is because the earth wire doesn’t have the same effect it has on the magnetic flux density.

For example for a point 10 m above ground, in a distance of 40 m from the line axis, case No.7 provides the highest values of magnetic flux density. For each point in a cross section the maximum values can be calculated and visualized in one graph, as done in Fig.6. By means of this figure the highest value of the flux density can be evaluated without knowing the exact position of the phases.

For choosing an optimal phase position, the phase allocating cases which are providing the lowest flux densities are of more interest, thus a similar chart to Fig. 5 for the lowest values is provided in Fig. 7. These results can be a useful basis for designing overhead power lines to choose the positions of the phases for a specific immission point.

**2-Level-Tower**

For the assumed 2-level-tower the phase allocation No.3 and No.9 causes the lowest maximum magnetic flux density as well the lowest values in a distant area (distance to the line axis larger than approx. 20 m) as shown in Fig. 8. Also for the electrical field, phase allocating No.3 and No.9 are the best choices (Fig. 9). No.2 and No.8 provide the highest maximum values of magnetic flux density and electrical field strength in the inner area.
SUMMARY AND CONCLUSION

In Tab. 2 a summary of the calculation results is provided. For each tower design in Fig. 1 the
- maximum value
- and the value in 50 m distance from the line axis for the best and the worst case of phase allocation (lowest and highest immission value) for the magnetic flux density and the electric field strength in a height 1 m above ground are presented.

<table>
<thead>
<tr>
<th>No.</th>
<th>Brms (µT)</th>
<th>Brms (µT)</th>
<th>Erms (kV/m)</th>
<th>Erms (kV/m)</th>
<th>difference</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>best case</td>
<td>4/10</td>
<td>31.3</td>
<td>3/9</td>
<td>1.9</td>
<td>+18%</td>
<td>+178%</td>
</tr>
<tr>
<td>worst case</td>
<td>3/9</td>
<td>36.9</td>
<td>1/7</td>
<td>5.3</td>
<td>+15%</td>
<td>+161%</td>
</tr>
<tr>
<td>difference</td>
<td>+18%</td>
<td>+178%</td>
<td>+15%</td>
<td>+161%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>best case</td>
<td>2/8</td>
<td>41.0</td>
<td>4/10</td>
<td>4.0</td>
<td>+33%</td>
<td>+77%</td>
</tr>
<tr>
<td>worst case</td>
<td>2/8</td>
<td>41.0</td>
<td>4/10</td>
<td>4.0</td>
<td>+33%</td>
<td>+77%</td>
</tr>
<tr>
<td>difference</td>
<td>+33%</td>
<td>+77%</td>
<td>+27%</td>
<td>+101%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>best case</td>
<td>1/7</td>
<td>51.8</td>
<td>5/11</td>
<td>5.4</td>
<td>+20%</td>
<td>+84%</td>
</tr>
<tr>
<td>worst case</td>
<td>1/7</td>
<td>51.8</td>
<td>5/11</td>
<td>5.4</td>
<td>+20%</td>
<td>+84%</td>
</tr>
<tr>
<td>difference</td>
<td>+20%</td>
<td>+84%</td>
<td>+27%</td>
<td>+101%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in Tab. 2 there are great differences due to different allocation of the phases – e.g. the maximum $B_{rms}$ caused by the worst cases of phase allocation (No.2 and No.8) of the 2-level-tower is 33% higher than the maximum $B_{rms}$ caused by the best cases of phase allocation (No.3 and No.9) of this tower.

Furthermore one fact should be pointed out: The phase allocation cases No.3 or No.9 for the 3-level-tower have the highest maximum values of the magnetic flux density and the lowest one in 50 m distance. That means if the phase allocation is optimized for a distant point, stronger fields have to be taken into account directly under the power lines.

REFERENCES