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ELECTRIC FIELDS IN THE VICINITY OF HIGH-VOLTAGE POWER LINES, OPTIMISATION OF POWER LINE DESIGN

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Abstract: This paper presents calculations in the distribution of the electrical fields generated by the potential of phase conductors in overhead high-voltage power lines. The calculations relate to the area between the line paths and the terrain, with particular focus on the area near the ground, which is important in terms of any humans present there, temporarily or permanently. Field intensity distribution is determined for different arrangements of phase conductors and line paths, and for different tower designs. The optimisation criterion is the width of the area excluded from residential development, defined as double the distance from the axis of the line where the electrical field strength exceeds the regulatory permitted 1 kV/m value.

Keywords: HV line, electrical field, field distribution calculation, development near HV lines, hazards for humans near HV lines

1. INTRODUCTION

To sustain and develop itself, modern civilization needs large amounts of concentrated energy, with electrical energy playing the most important role in the process. The current situation and available projections confirm its crucial importance and the possibility that it may take over roles previously fulfilled by other energy types.

The characteristic quality of electrical energy is its concentrated production, relatively simple transmission and easy, highly efficient conversion into other locally useful types of energy.

Currently, trends for the microproduction of electrical energy and its use on site or sharing among households have emerged, but for the time being, the importance of such an economy is minor.

The transmission of energy from systemic producers to its points of distribution near large concentrations of consumers, either residential or industrial, at present primarily uses overhead high-voltage lines. In Poland, at the transmission and general distribution levels, voltages of 400 kV, 220 kV and 110 kV are used. Annually, the power in the National Electric Power System ranges from 12.133 to 27.617 GW (PSE data for 2021, 15-minute average), depending on instantaneous consumer demand, while the energy generated in 2021 totalled 173.583 TWh.

System-wide distribution of power in varying volumes, while maintaining an uninterrupted power supply under various environmental and technical conditions, requires an extensive power line and distribution station system with sufficient redundancies. The current trend to saturate the system with unstable renewable sources necessitates an expansion in the transmission capacity, not only in Poland, but continent-wide.

Constructing a power line requires occupying a strip of terrain where human activity is limited, both during the construction and subsequent operation. Other than purely structural issues, there also exists a hazard to human health and life due to how the human body is affected by the electrical field, whose value depends on the design of the line and the properties of the voltage used.

The detail size and effects of the electrical field on human health remain debatable, as it is rather a cumulative effect than a momentary one. The effects of the magnetic field, which also depend on the line design and the conductor current, also need to be considered.

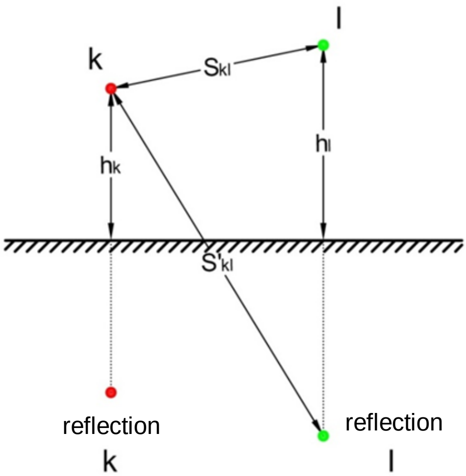
2. CALCULATION METHOD

The PLS-CADD professional line design software by Power Line Systems Inc. Co. was used to determine the intensity of the electrical field in the vicinity of the power line. The software calculated the electrical field strength at a specific height above ground in a cross-section lateral to the line axis.

The following assumptions were made for the calculations:

- no electrical charge is present in the space between the line and the ground;
- charges are located only on the surface of the conductors, on the earth and on grounded object;
- line conductors were modelled as infinitely long conductors with a circular cross-section, parallel to each other, suspended over level ground;
- the earth is a perfect conductor;
- air permittivity between the conductors and the ground equals $\varepsilon = 8{,}854 \cdot 10^{-12} F/m$;
- the field is treated as quasi-static.

Electric field strength is calculated using the charge simulation method (CSM). Charges on the surface of conductors are simulated by placing them in the geometric centre of the conductor, while charges on the ground are replaced by reflections of conductor charges placed underneath its surface (as if the ground surface was a mirror reflecting the conductors). These charges have identical values, but opposite polarisation to the conductor charges.



Based on these charges, it is possible to calculate the electrical field strength at a given point in space between the conductors and the ground. The field value at that point is equal to the superposition of the fields generated by the individual charges. The charge simulation method is illustrated in Figure 1.

Fig. 1. Charge simulation method

For electrical power lines, the values of charges on the conductors were not known, but they could be calculated from the voltage difference using equation (1).

$$[Q]=[P]^{-1}[V] \tag{1}$$

where:

$[Q]$ – linear charge matrix,
$[V]$ – conductor voltage matrix,
$[P]$ – potential coefficient matrix.

The potential coefficients for the system of parallel conductors were calculated using equations (2) and (3).

$$P_{kk}=\frac{1}{2\pi\varepsilon}\ln\left(\frac{4h_k}{d_k}\right) \tag{2}$$

$$P_{kl}=\frac{1}{2\pi\varepsilon}\ln\left(\frac{S'_{kl}}{S_{kl}}\right) \tag{3}$$

where:

P_{kk} – self potential coefficient of conductor k,
P_{kl} – mutual potential coefficient of conductors k and l,
d_k – diameter of conductor k,
h_k – height of conductor k above ground surface,
S_{kl} – distance between conductors k and l,
S'_{kl} – distance between conductor k and reflection of conductor l.
$\varepsilon = 8{,}854 \cdot 10^{-12} F/m$.

Knowing the charges gathered on the conductors, equations (4) and (5) could be used to calculate the vertical and horizontal components of the field, originating from individual conductors, at a particular point.

$$E_{kx} = \frac{(Q_{rk}+jQ_{ik})}{2\pi\varepsilon} \cdot \left[\frac{X_M}{X_M^2+(H_k-H_M)^2} - \frac{X_M}{X_M^2+(H_k+H_M)^2}\right] \tag{4}$$

$$E_{ky} = \frac{(Q_{rk}+jQ_{ik})}{2\pi\varepsilon} \cdot \left[\frac{H_M-H_k}{X_M^2+(H_k-H_M)^2} - \frac{H_M+H_k}{X_M^2+(H_k+H_M)^2}\right] \tag{5}$$

where:
E_{kx} – horizontal component of the electrical field generated by conductor k,
E_{ky} – vertical component of the electrical field generated by conductor k,
Q_{rk} – real part of the charge gathered on conductor k,
Q_{rk} – imaginary part of the charge gathered on conductor k,
X_M – horizontal distance between point M, for which the field is calculated, and conductor k,
H_M – height of point M above the terrain,
H_k – height of the conductor above the terrain.

The total vertical and horizontal field components were calculated by summing the interactions from individual conductors using equations (6) and (7).

$$E_x = \sum_k E_{kx} \tag{6}$$

$$E_y = \sum_k E_{ky} \tag{7}$$

where:
E_x – electrical field horizontal component,
E_y – electrical field vertical component.

The vertical and horizontal components of the electrical field are complex numbers. The final effective field intensity value at the analysed point was calculated using equation (8).

$$E_{rms} = \sqrt{E_{rx}^2 + E_{ix}^2 + E_{ry}^2 + E_{iy}^2} \tag{8}$$

where:
E_{rms} – electrical field strength effective value,
E_{rx} – real part of the field intensity horizontal component,

E_{ix} – imaginary part of the field intensity horizontal component,
E_{ry} – real part of the field intensity vertical component,
E_{iy} – imaginary part of the field intensity vertical component.

If the line were fitted with bundle conductors, each bundle was replaced with an equivalent conductor. An equivalent conductor was determined as one that gathered an identical charge to a bundle when affected by an identical voltage (it had the same capacitance relative to the ground as the bundle). The equivalent conductor diameter was calculated using equation (9).

$$d_{eq} = d_b \cdot \sqrt[n]{\frac{nd}{d_b}}$$
$$d_b = \frac{s}{\sin(\pi / n)} \tag{9}$$

where:
d_{eq} – equivalent conductor diameter,
d_b – bundle diameter,
n – number of bundle component conductors,
d – bundle component conductor diameter,
s – distance between bundle component conductors.

Calculations were then performed as for single conductors.

In the calculation example illustrating the method used, a line with a rated voltage of 400 kV was chosen (maximum voltage 420 kV), with a flat conductor arrangement. The distance between conductors was set at 10.5 m. Each phase conductor was a bundle of three conductors with a diameter of 26 mm, the distance between the conductors in a bundle was 0.4 m, and the bundle height above the terrain was 10 m. Field intensity was calculated for a point 20 m away from the line axis and located 2 m above ground.

Equation (9) was used to calculate the bundle diameter and equivalent conductor diameter.

$$d_b = \frac{0.4}{\sin(\pi/3)} = 0.46\ [\mathrm{m}] \qquad d_{eq} = 0.46\ \mathrm{m} \cdot \sqrt[3]{\frac{3 \cdot 0.026}{0.46}} = 0.26\ [\mathrm{m}]$$

Next, equations (2) and (3) were used to calculate the individual and mutual potential coefficients for phase conductors a, b and c.

$$P_{aa} = P_{bb} = P_{cc} = \frac{1}{2\pi\varepsilon} \cdot \ln\left(\frac{4 \cdot 10}{0.26}\right) = 9.09 \cdot 10^{10}\ [\mathrm{m/F}]$$

$$P_{ab} = P_{ba} = P_{bc} = P_{cb} = \frac{1}{2\pi\varepsilon} \cdot \ln\left(\frac{\sqrt{10.5^2 + (2 \cdot 10)^2}}{10.5}\right) = 1.38 \cdot 10^{10}\ [\mathrm{m/F}]$$

$$P_{ac} = P_{ca} = \frac{1}{2\pi\varepsilon} \cdot \ln\left(\frac{\sqrt{21^2 + (2 \cdot 10)^2}}{21}\right) = 5.80 \cdot 10^9 \text{ [m/F]}$$

Based on the calculation results, a potential coefficient matrix $[P]$ was composed, which was transformed into an invertible matrix $[P]^{-1}$.

$$[P] = \begin{bmatrix} 9.09 & 1.38 & 0.58 \\ 1.38 & 9.09 & 1.38 \\ 0.58 & 1.38 & 9.09 \end{bmatrix} \cdot 10^{10} \text{ [m/F]}$$

$$[P]^{-1} = \begin{bmatrix} 11.3 & -1.64 & -0.47 \\ -1.64 & 11.5 & -1.64 \\ -0.47 & -1.64 & 11.3 \end{bmatrix} \cdot 10^{-12} \text{ [F/m]}$$

The real and imaginary components of conductor voltages were now calculated. The voltages were phase-shifted by 120°, the middle phase being assumed as reference.

$$V_{ra} = -\sin(30°)\frac{420}{\sqrt{3}} = -121.24 \text{ [kV]} \qquad V_{ia} = \cos(30°)\frac{420}{\sqrt{3}} = 210 \text{ [kV]}$$

$$V_{rb} = \frac{420}{\sqrt{3}} = 242.49 \text{ [kV]} \qquad V_{ra} = 0 \text{ [kV]}$$

$$V_{rc} = -\sin(30°)\frac{420}{\sqrt{3}} = -121.24 \text{ [kV]} \qquad V_{ra} = -\cos(30°)\frac{420}{\sqrt{3}} = -210 \text{ [kV]}$$

The calculated voltage components were recorded in matrix [V].

$$[V] = \begin{bmatrix} -121.24 & 210 \\ 242.49 & 0 \\ -121.24 & -210 \end{bmatrix} \text{ [kV]}$$

Equation (1) was used to calculate the linear charge matrix.

$$[Q] = \begin{bmatrix} 11.3 & -1.64 & -0{,}47 \\ -1.64 & 11.5 & -1{,}64 \\ -0.47 & -1.64 & 11{,}3 \end{bmatrix} \begin{bmatrix} -121{,}24 & 210 \\ 242{,}49 & 0 \\ -121{,}24 & -210 \end{bmatrix} \cdot 10^{-9} = \begin{bmatrix} -1{,}71 & 2{,}47 \\ 3.19 & 0 \\ -1.71 & -2.47 \end{bmatrix} \cdot 10^{-6} \text{ [C/m]}$$

Subsequently, equations (4) and (5) were used to calculate the vertical and horizontal components of the electrical field generated by the charges on the individual conductors.

$$E_{ax} = \frac{(-1.71 + j \cdot 2.47) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{30.5}{30.5^2 + (10-2)^2} - \frac{30.5}{30.5^2 + (10+2)^2}\right] = -70.2 + j \cdot 101.4 \text{ [V/m]}$$

$$E_{ay} = \frac{(-1.71 + j \cdot 2.47) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{2-10}{30.5^2 + (10-2)^2} - \frac{2+10}{30.5^2 + (10+2)^2}\right]$$
$$= 590.2 - j \cdot 852.9 \text{ [V/m]}$$

$$E_{bx} = \frac{(3.19 + j \cdot 0) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{20}{20^2 + (10-2)^2} - \frac{20}{20^2 + (10+2)^2}\right]$$
$$= 363.1 + j \cdot 0 \text{ [V/m]}$$

$$E_{by} = \frac{(3.19 + j \cdot 0) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{2-10}{20^2 + (10-2)^2} - \frac{2+10}{20^2 + (10+2)^2}\right]$$
$$= -2251.4 + j \cdot 0 \text{ [V/m]}$$

$$E_{cx} = \frac{(-1.71 - j \cdot 2.47) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{9.5}{9.5^2 + (10-2)^2} - \frac{9.5}{9.5^2 + (10+2)^2}\right]$$
$$= -646.0 - j \cdot 933.6 \text{ [V/m]}$$

$$E_{cy} = \frac{(-1.71 - j \cdot 2.47) \cdot 10^{-6}}{2\pi\varepsilon} \cdot \left[\frac{2-10}{9.5^2 + (10-2)^2} - \frac{2+10}{9.5^2 + (10+2)^2}\right]$$
$$= -3166.0 + j \cdot 4575.6 \text{ [V/m]}$$

During the next step, the field intensities generated by individual conductors were totalled using equations (6) and (7).

$$E_x = -70.2 + j \cdot 101.4 + 363.1 - 646.0 - j \cdot 933.6$$
$$= -353.0 - j \cdot 832.2 \text{ [V/m]}$$

$$E_y = 590.2 - j \cdot 852.9 - 2251.4 - 3166.0 + j \cdot 4575.6$$
$$= 1504.8 - j \cdot 3722.7 \text{ [V/m]}$$

The effective electrical field strength value was calculated using equation (8).

$$E_{rms} = \sqrt{(-353.0)^2 + (-832.2)^2 + 1504.8^2 + (-3722.7)^2} = 4115.8 \text{ [V/m]}$$

2.1. Additional assumptions

Due to the required insulation distances, electrical power line conductors may not be located closer to the ground than: 5.85 m for 110 kV lines, 6.70 m for 220 kV lines, or 7.80 m for 400 kV lines [PN-EN 50341-1:2013-03; PN-EN 50341-2-22:2016-04]. The field intensity calculations were based on the conductor-ground distances listed above taken into account.

In accordance with regulation [Regulation of the Minister of Health 2020] concerning methods of verifying the observance of permissible electromagnetic field levels in the aspect of measuring the intensity of electrical fields with a grid frequency of 50 Hz, the electrical field strength was calculated at a height of 2 m above ground.

3. CALCULATION RESULTS

3.1. Electric field and tower design

The simulation calculations began by determining the electrical field under the 110 kV single circuit lines supported on series of towers of different designs. Series of towers with a triangular (E111, B2 type P and S120), vertical (B2 type PL) and flat (A12) conductor arrangements were analysed. The study concerned two aspects: maximum electrical field strength sity value under the line, and width of the terrain strip where residential development has been prohibited due to exceeded permissible field intensity for such buildings (1 kV/m).

The calculation results are shown in Figures 2 and 3. The lowest electrical field strength was found for lines with a triangular conductor arrangement (S120), while the land strip where intensity exceeded 1 kV/m was the most narrow for lines with a vertical conductor arrangement (B2 type PL).

Changing the tower design allowed a significant reduction in electrical field strength under the line, and a narrowing of the land strip excluded from development. However, it frequently entailed increased costs, as the design of a B2 PL tower, for example, was 40% heavier than a B2 P tower [Polskie Towarzystwo Przesyłu i Rozdziału Energii Elektrycznej 1998].

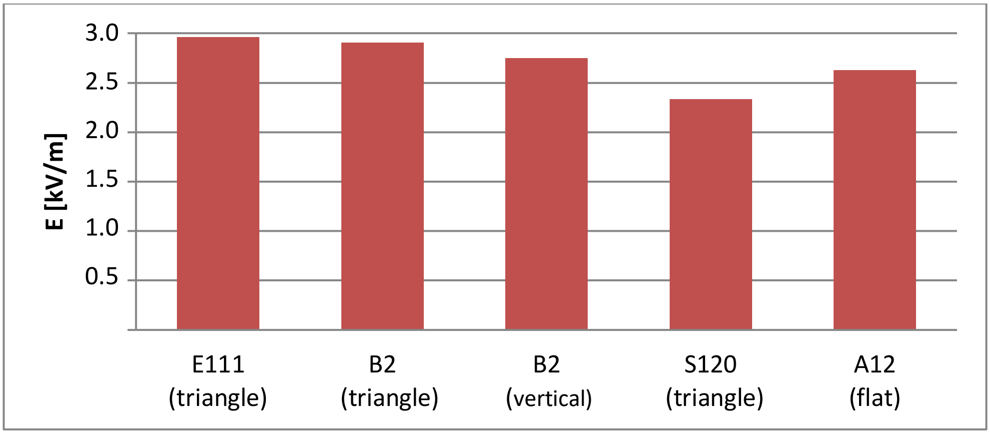


Fig. 2. Electric field strength in the middle of a span for different 110 kV single circuit line tower designs

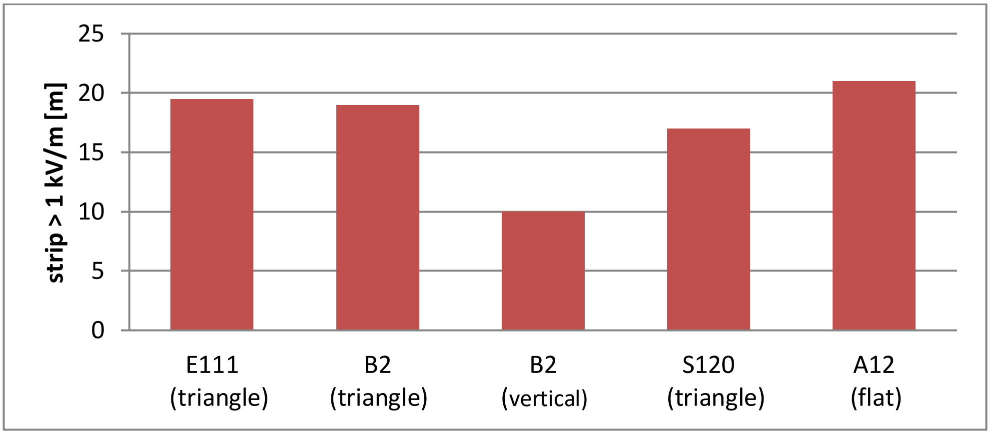


Fig. 3. Width of the land strip under the line where permissible electrical field strength level is exceeded for land intended for residential development (1 kV/m), for different 110 kV single circuit line tower designs

3.2. Effects of phase system in a double circuit line on electrical field distribution

Double-circuit electrical power lines differ from one another, not only in the support structure used but also the sequence of phases in individual circuits. To study the impact on electrical field strength under a double-circuit electrical power line, calculations were performed taking into account different phase sequences for a series of Dc240 towers with a twin-triangular conductor arrangement.

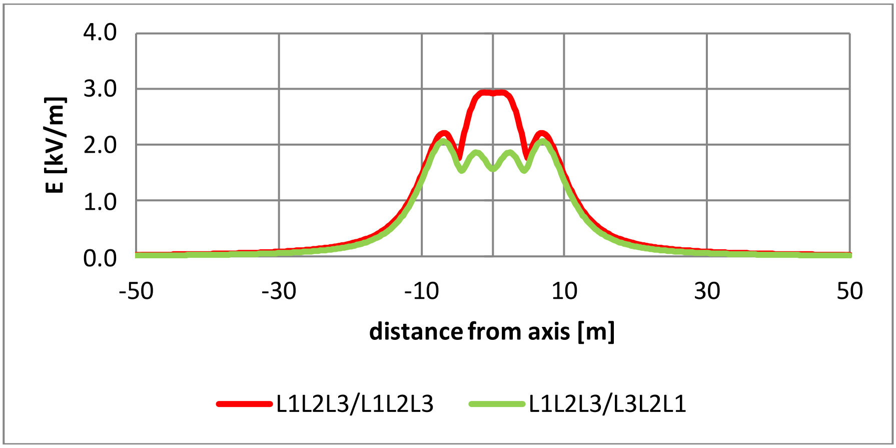


Fig. 4. Electric field strength distribution in a cross-section perpendicular to the line axis for the most advantageous and least advantageous phase system on a Dc240 series tower (twin-triangular conductor arrangement)

Electric field strength distribution in a cross-section perpendicular to the line, as shown in Figure 4, shows a significant reduction in electrical field strength for asymmetric phasing. Changing the phasing of a double circuit line involves certain costs, although they are minor compared to the entirety of the investment.

3.3. Electric field in the vicinity of double circuit lines

In the next stage of the study, electrical field strength levels for different 110 kV double circuit line tower designs were compared, as shown in Figures 5 and 6. The calculations were performed for series E211 and OS24 (barrel-type conductor arrangement), OL 24 (vertical conductor arrangement), and Dc240 (twin-triangular conductor arrangement). For each design, electrical field parameters and width of the strip with intensity exceeding 1 kV/m are shown for the optimum and least advantageous phase system. For comparison purposes, results for typical single circuit lines are provided with the figures.

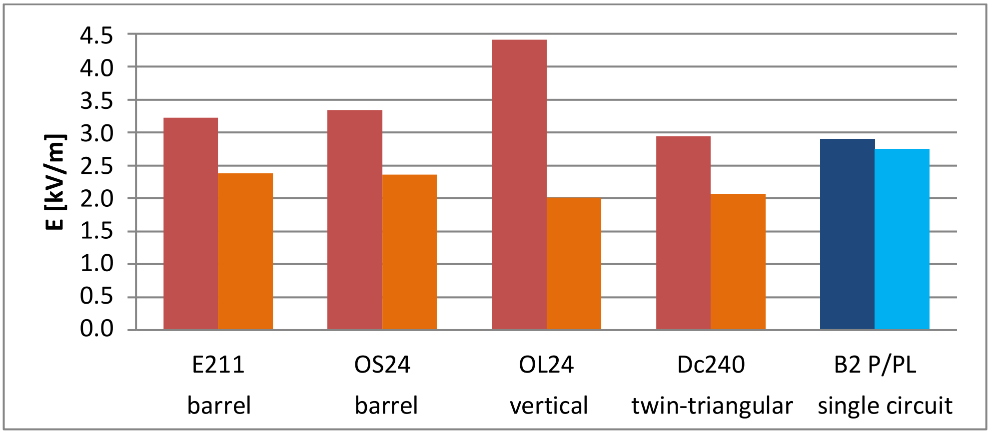


Fig. 5. Maximum electrical field strength for different 110 kV electrical power double circuit line tower designs (red bar – disadvantageous phase system, orange bar – advantageous), compared with single circuit lines (in blue)

When using the right phasing, double circuit lines generate a field with a lower maximum intensity than single circuit lines. Additionally, for most double circuit series (except Dc240 series), the width of the area excluded from residential development is comparable to typical single circuit lines. The land strip taken up by a double circuit line is much smaller than two single circuit lines, equivalent in terms of power transmitted. Furthermore, the cost of building a double circuit line is much lower than two single circuit lines – a line supported on E211 series towers is 20% lighter than two lines on E111 series towers [Elfeko S.A. 1995].

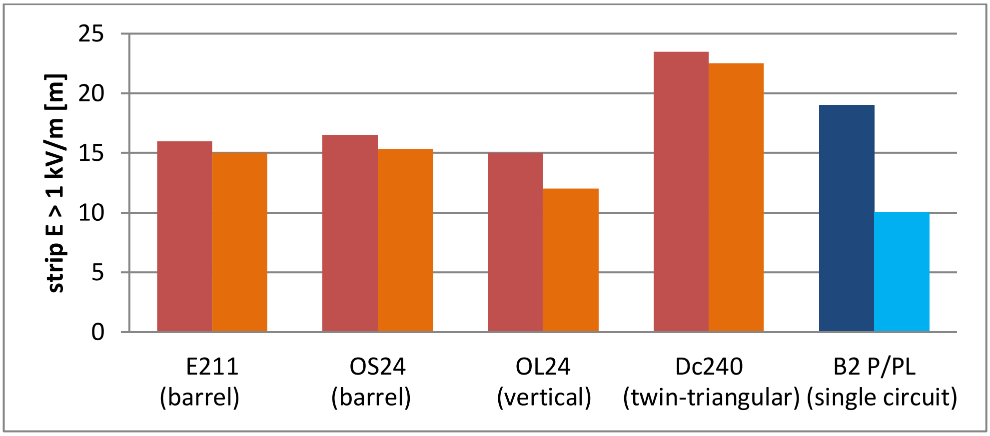


Fig. 6. Maximum width of the land strip where electrical field strength exceeds 1 kV/m for different designs of double circuit electrical power towers ((red bar – disadvantageous phase system, orange bar – advantageous), compared with single circuit lines (in blue)

3.4. Conductor suspension height and electrical field strength

The simplest method of reducing the electrical field under a line would be to increase the distance of the phase conductors from the ground. The effectiveness of this method was verified by calculating the electrical field strength distribution for a 400 kV line on E33 towers at different distances of phase conductors from the ground. The study was conducted for the following distances: minimum required by the standard 7.8 m [PN-EN 50341-2:2016-04], extended by 2.5 m, 5 m and 10 m (Fig. 7).

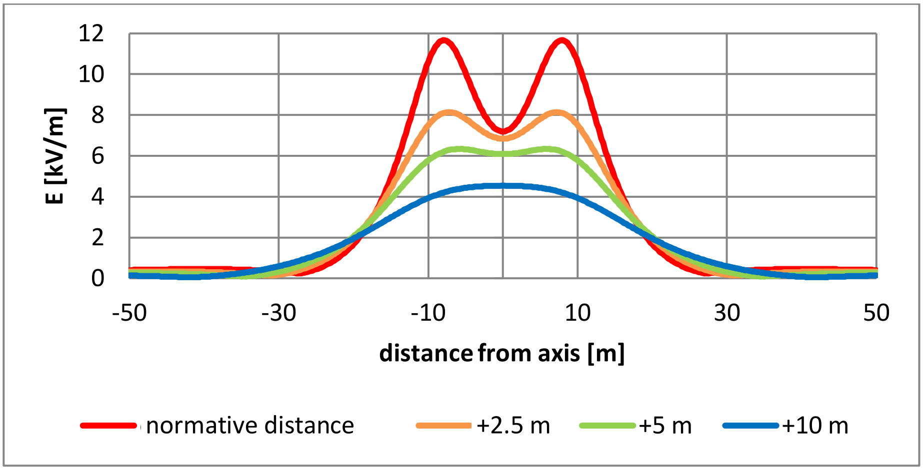


Fig. 7. Electric field strength in a cross-section perpendicular to the 400 kV line at different distances of phase conductors from the ground

Increasing the phase conductor distance from the ground allows a major reduction in the maximum electrical field strength value directly under the conductors, but has a reverse effect for terrain near the line (20–30 m from the axis). Increasing the conductor suspension height by 5 m for the E33 series results in about a 15% increased tower weight.

3.5. Electric fields in the vicinity of multi-voltage lines

Multi-voltage lines (with different voltages for different circuits) enable reduced electrical field strength in a similar manner to double circuit lines. To determine the effectiveness of reducing the electrical field levels, an analysis was performed for a multi-voltage line of 400/220/110 kV with its upper circuits in a vertical conductor arrangement with a 400 kV voltage and its lower circuits in a twin-triangular arrangement and with 220 kV and 110 kV voltages (Fig. 8). Activating the lower circuits (especially the 110 kV circuit) allows a major reduction in electrical field strength and narrowing of the land strip excluded from development. However multi-circuit lines entail numerous issues; both during the design stage and operation.

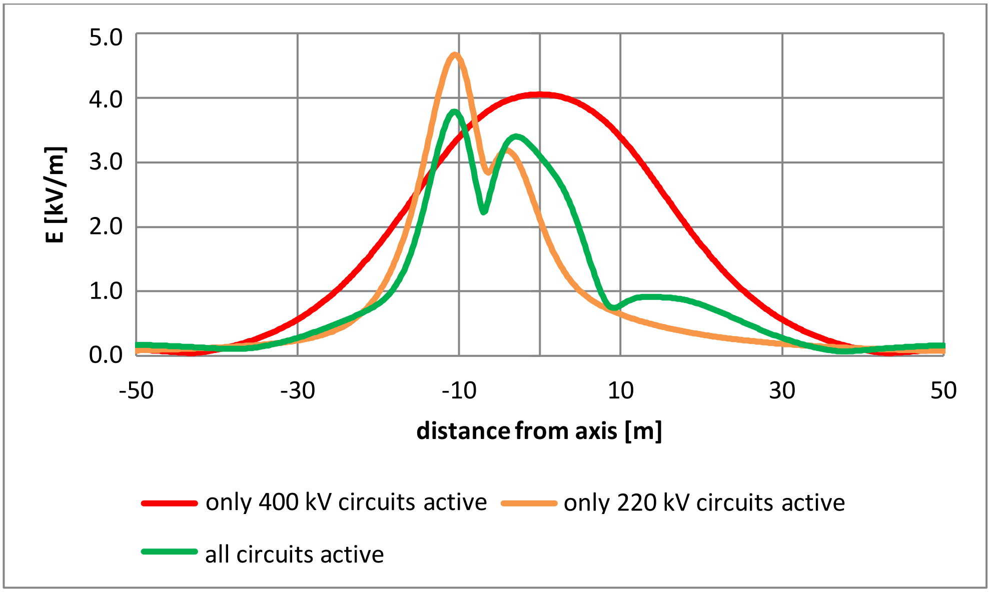


Fig. 8. Electric field under a multi-voltage line; upper circuits 400 kV, lower left circuit 220 kV and lower right circuit 110 kV

The fundamental technical problem is the induction of strong currents in the 220 kV and 110 kV conductors as a result of current flowing in the 400 kV line conductors. There are also operating issues related to the necessity of deactivating the entire line (or working on live conductors) if work is required on any of its lines. Building multi-voltage lines in Poland is additionally made difficult by the fact that transmission (400 kV, 220 kV) and distribution lines (110 kV) have different owners.

3.6. Electric fields generated by different voltage lines

To summarise the studies on the electric fields generated by high-voltage power lines, field levels generated by lines with different nominal voltages were compared.

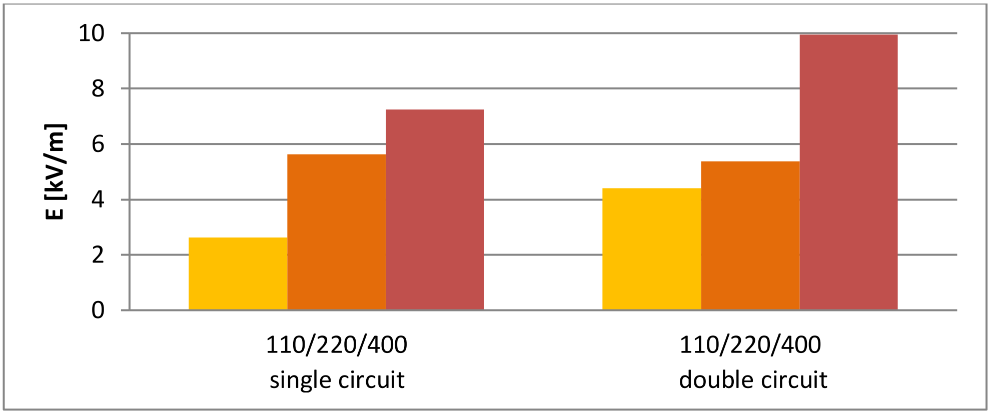


Fig. 9. Electric field strength for electrical power lines of different voltages, in the middle of a span

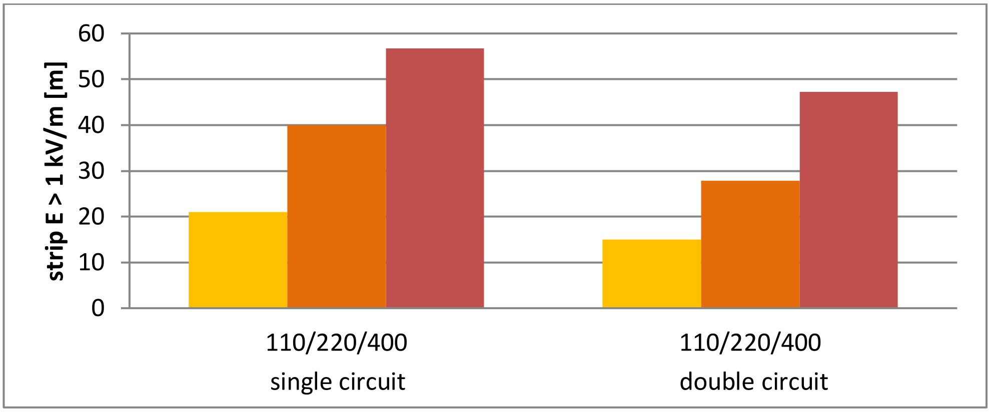


Fig. 10. Width of land strip where electrical field strength exceeds 1 kV/m, for electrical power lines of different voltages

Single circuit lines with a flat conductor arrangement (series A12, H52, Y52) and double circuit lines with a vertical arrangement (series OS24, ML52, E33) were selected for the comparison.

Figure 9 shows a comparison of the lines in terms of electrical field strength in the middle of the span, and Figure 10 shows the comparison in terms of the width of the land strip excluded from residential development due to an electrical field strength exceeding 1 kV/m.

Both electrical field strength in the vicinity of the line and the land strip excluded from residential development greatly increase with higher line voltages. However, if line transmission capacity is considered, this increase is not so significant. One 400 kV line enables transmitting energy equivalent to two 220 kV lines or eight 110 kV lines [Dołowy, Kraszewski and Różycki 2015]. The total land strip where electrical field strength exceeds 1 kV/m for eight 110 kV lines is over 160 m, while for a single 400 kV line, which is equivalent in its transmission capacity, it is less than 60 m.

4. CONCLUSIONS

Electric field strength generated by an electrical power line can be minimised by:

- selecting the right tower design;
- increasing the height at which the conductors are suspended;
- building double circuit lines instead of single circuit ones;
- proper phasing on a double circuit line;
- using active screening (multi-voltage line).

The simplest way to reduce electrical field strength under a high-voltage line is to increase the distance between the phase conductors and the ground. This can be achieved by using taller or more densely positioned support structures, which increases the cost of building the line. It must be remembered that this approach reduces the field intensity under the line, but may increase it in adjacent land.

Another method of limiting the electromagnetic effects under the line is to use support structures with a conductor arrangement that provides a reduction in field intensity under the line. For single circuit lines, the most advantageous vertical conductor arrangement allows the effect to be contained in a narrow strip near the line, although it is a more costly design solution. The flat conductor arrangement is the least expensive design, but it is the least effective in terms of the electrical field generated. Towers with a triangular conductor arrangement constitute a compromise between the cost and the field levels generated. In practice, in densely built-up areas (especially in cities), the vertical conductor arrangement is used, with the triangular conductor in other cases. For double circuit lines, the barrel-type design is optimal (a vertical arrangement with the middle phase slightly extended outwards), while the least advantageous is the twin-triangular conductor arrangement.

For double circuit lines, the order of phases in line circuits is important. When two conductors next to each other have their voltages in phase, the electrical field they generate adds up, otherwise it is weakened. Using the right phasing allows reducing maximum electrical field strength under the line by 20–30%, and narrowing the land strip where intensity exceeds 1 kV/m by 5–10%. In most cases, using an advantageous phasing does not entail a significant increase in investment costs. For some grid systems, it is necessary to use phase interleaving to achieve this, but these are standard solutions, only with 400 kV lines are they problematic due to the very large insulation distances required between conductors with different phases. The cost of changing phasing, even on 400 kV lines, is minuscule compared to the costs necessary to achieve a similar reduction in electrical effects by other means.

A significant reduction in the electrical field generated (especially when optimal phasing is used) can be achieved by building one double circuit line instead of two single circuit ones. Due to the effect of interactions from conductors in different line circuits nullifying each other, field intensity under a double circuit line is lower than under a single circuit line. The land strip taken up by a double circuit line is much smaller than that taken up two single circuit lines. Furthermore, the lower costs of building a double circuit line compared to erecting two single circuit lines also favour the use of multi-circuit systems, which additionally allow active screening – using live conductors. Conductors of the higher-voltage line (400 kV) are placed on the upper level of the support structure, while lower-voltage line conductors (e.g. 110 kV) are placed on the lower level. Phase order is selected so that total field intensity under the line is as low as possible. Multi-circuit and multi-voltage lines are problematic; however, both during the design stage and operation.

To summarise: the electrical field generated must be taken into account when designing any high-voltage power line. Two aspects are important for such projects – maximum field intensity and width of the strip of land excluded from residential development.

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