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REDUCTION OF ELECTRIC AND MAGNETIC FIELD OF DOUBLE-CIRCUIT OVERHEAD LINES

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Abstract: The paper describes an algorithm for optimal design of the phase conductors in double-circuit three-phase overhead lines that are characterised by balanced voltage and current systems. A suitable transposition of individual conductors enables to reduce the electric and magnetic fields in its vicinity. The procedure is illustrated on several examples whose results lead to particular recommendations for designers.

Keywords: double-circuit transmission line, reduction of the electric and magnetic field of overhead lines

1 Introduction

Transmission lines (vhv, hv) for transferring very high power are usually designed as double-circuit three-phase overhead lines with earth wires. Due to the proximity of both circuits their mutual effects have to be considered. To reduce the mutual linkage the overhead lines are usually transposed. With respect to the position of the phase conductors the transposition is not always equally efficient. Beside positive effects on the impedance of the line the optimised arrangement of the conductors can reduce the electric and magnetic field strengths in their vicinity [1] and, consequently, their negative impact on environment. The maximum allowed values of both the electric and magnetic field strengths with respect to their effects on human bodies are given by the safety rules. The optimised transposition enables to better satisfy these recommendations.

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2 Matrices for expression of phase currents, voltages and charges

2.1 Current and voltage matrices

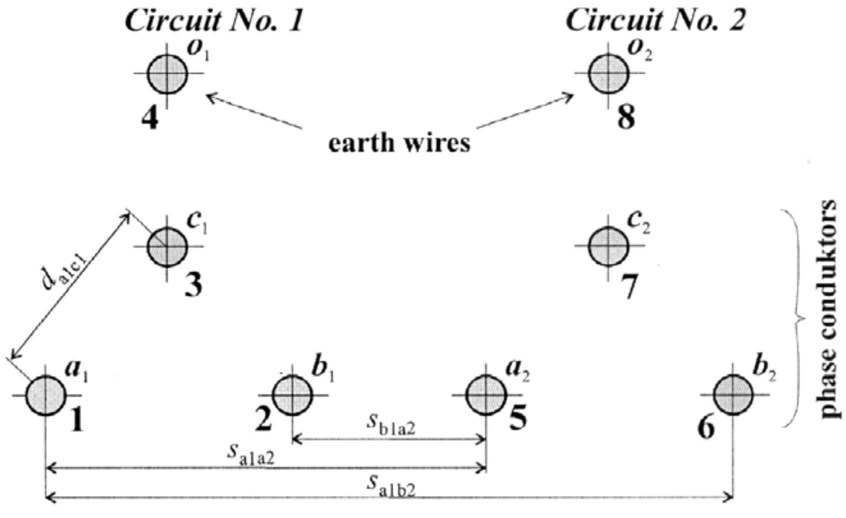

Fig. 1 Conductors of double-circuit overhead line

Let us consider a double-circuit overhead line with two earth wires according to Fig. 1. On the conditions of balanced voltage and current systems the currents in the earth wires are negligible and voltages earth- wire-to-earth are equal to zero. Supposing sinusoidal steady state the complex representation of time varying functions can be used. If the phases a_1, b_1, c_1 in the circuit No. 1 are placed on conductors 1, 2, 3 and the phases a_2, b_2, c_2 in the circuit No. 2 are placed on conductors 5, 6, 7 then the voltage and current phasors can be expressed in matrix forms

$$(1) \qquad \mathbf{U}_1 = U_1 \begin{bmatrix} 1 \\ \boldsymbol{a}^2 \\ \boldsymbol{a} \end{bmatrix} \qquad \mathbf{I}_1 = I_1 \begin{bmatrix} 1 \\ \boldsymbol{a}^2 \\ \boldsymbol{a} \end{bmatrix}$$

where U_1 and I_1 are the amplitudes of phase voltage and current in the circuit No. 1. There are thirty-six possible arrangements of phases in the layout but only six of them being basic. The other provide the same results. These six basic arrangements of phases can be defined in terms of columns $\boldsymbol{p}_i$ of matrix $\mathbf{P}$

$$(2) \qquad \mathbf{P} = \{p_1, p_2, p_3, p_4, p_5, p_6\} = \begin{bmatrix} 1 & 1 & \boldsymbol{a} & \boldsymbol{a}^2 & \boldsymbol{a}^2 & \boldsymbol{a} \\ \boldsymbol{a}^2 & \boldsymbol{a} & 1 & 1 & \boldsymbol{a} & \boldsymbol{a}^2 \\ \boldsymbol{a} & \boldsymbol{a}^2 & \boldsymbol{a}^2 & \boldsymbol{a} & 1 & 1 \end{bmatrix}$$

If the arrangement of phases in the circuit No.1 is given by the column $\boldsymbol{p}_i$ and in the circuit No.2 by column $\boldsymbol{p}_j$, respectively, the matrices of voltage and current phasors are

$$(3) \qquad \mathbf{I}_{ij} = \begin{bmatrix} I_1 \boldsymbol{p}_i \\ I_2 \boldsymbol{p}_j \end{bmatrix} \qquad\qquad (4) \qquad \mathbf{U}_{ij} = \begin{bmatrix} U_1 \boldsymbol{p}_i \\ U_2 \boldsymbol{p}_j \end{bmatrix}$$

2.2 Matrix of charges

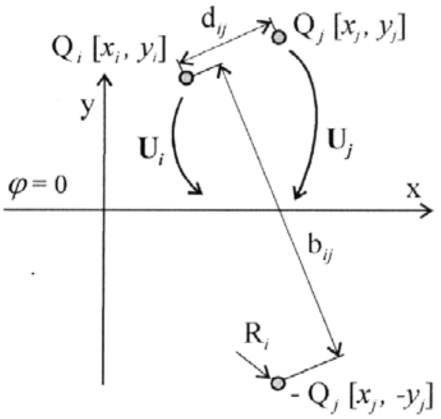

Fig. 2 Calculation of capacitance coefficients

The charges of conductors for known phase voltage can be determined by means of the method of partial capacitances. After expressing the matrix of potential coefficients **A** we find the inverse matrix **B**

$$(5)\qquad \mathbf{A} = \{\ \alpha_{ij}\},\qquad\qquad \mathbf{B} = \mathbf{A}^{-1} = \{\ \beta_{ij}\},$$

$$i, j = 1, 2, \ldots 8$$

where $\alpha_{ii} = k \ln \dfrac{2y_i}{R_i},\ \alpha_{ij} = k \ln \dfrac{b_{ij}}{d_{ij}},\qquad k = \dfrac{1}{2\pi\varepsilon_0 l} = 1{,}8 \cdot 10^{10},\quad l = 1\,\mathrm{m}$

$$b_{ij} = \sqrt{(x_i - x_j)^2 + (y_i + y_j)^2}\,,\qquad d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

Now, we formulate a submatrix $\mathbf{B}_{11}$ respecting the mutual capacitance effects in circuit No.1 and $\mathbf{B}_{12}$ expressing the impact of the circuit No. 2 on the circuit No.1

$$\mathbf{B}_{11} = \{\ \beta_{ij}\},\qquad i = 1, 2, 3, 4\qquad j = 1, 2, 3$$

$$(6)\qquad \mathbf{B}_{12} = \{\ \beta_{ij}\},\qquad i = 1, 2, 3, 4\qquad j = 5, 6, 7$$

Similarly, we form submatrices $\mathbf{B}_{21}$ and $\mathbf{B}_{22}$

$$\mathbf{B}_{21} = \{\ \beta_{ij}\},\qquad i = 5, 6, 7, 8\qquad j = 1, 2, 3$$

$$(7)\qquad \mathbf{B}_{22} = \{\ \beta_{ij}\},\qquad i = 5, 6, 7, 8\qquad j = 5, 6, 7$$

The charges on each conductor of double-circuit line for any arrangement of phases (the circuit No.1 according to the column $\boldsymbol{p}_i$ and the circuit No.2 according to the column $\boldsymbol{p}_j$) are given by elements of matrix $\mathbf{Q}_{ij}$

$$(8)\qquad \mathbf{Q}_{ij}(8,1) = \begin{bmatrix} U_1 \mathbf{B}_{11}\, \boldsymbol{p}_i & + U_2 \mathbf{B}_{12}\, \boldsymbol{p}_j \\ U_1 \mathbf{B}_{21}\, \boldsymbol{p}_i & + U_2 \mathbf{B}_{22}\, \boldsymbol{p}_j \end{bmatrix}$$

3 Distribution of electric and magnetic field in the vicinity of overhead lines

Supposing straight and parallel conductors placed above the perfectly conducting earth we determine the distribution of the electric and magnetic field strength at the height *h*. The calculation is carried out for two possibilities – the distance of the conductors above the earth given by the size of towers and the minimal distance between the conductors and the surface of the earth.

3.1 Distribution of electric field

It is known that the electric field strength of one conductor above the perfectly conducting earth – Fig. 3 - is proportional to the magnitude of its charge (that is given by eq. (8)) and to the distances r_{ij}, r'_{ij} (given by the layout of the conductor and its image and by the position of the point M at which the electric field strength is calculated). For the x and y components of the phasor of the electric field strength we obtain

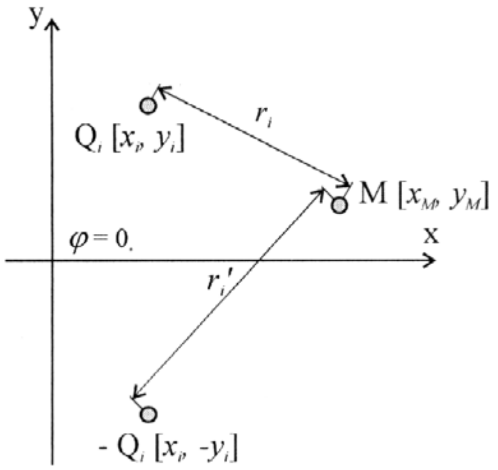

Fig. 3 Calculation of electric strength at point M

(9) $$\boldsymbol{E}_{xi}(M) = k\boldsymbol{Q}_i D_{xi}\,, \qquad \boldsymbol{E}_{yi}(M) = k\,\boldsymbol{Q}_i D_{yi}\,, \qquad i, j = 1, 2, \ldots 8$$

where $$D_{xi} = (x_M - x_i)\left(\frac{1}{r_i^2} - \frac{1}{r_i'^2}\right), \qquad D_{yi} = \frac{y_i - y_M}{r_i^2} + \frac{y_i + y_M}{r_i'^2}$$

$$r_i = \sqrt{(x_M - x_i)^2 + (y_M - y_i)^2}\,, \qquad r_i' = \sqrt{(x_M - x_i)^2 + (y_M + y_i)^2}$$

After superposition we receive the magnitude of the resultant electric field strength at point M

(10) $$\boldsymbol{E}_{xM} = \sum_i \boldsymbol{E}_{xi}(M), \quad \boldsymbol{E}_{yM} = \sum_i \boldsymbol{E}_{yi}(M), \quad \boldsymbol{E}_M = \sqrt{|\boldsymbol{E}_{xM}|^2 + |\boldsymbol{E}_{yM}|^2}$$

3.2 Distribution of magnetic field

The x and y components of the phasor of the magnetic field strength at the point M which are produced by the current of the i-th conductor (see eq. (3)) are given by following formulae

(11) $$\boldsymbol{H}_{xi}(M) = \frac{\boldsymbol{I}_i}{2\pi}\,\frac{y_i - y_M}{r_i^2}\,, \qquad \boldsymbol{H}_{yi}(M) = \frac{\boldsymbol{I}_i}{2\pi}\,\frac{x_M - x_i}{r_i^2}$$

where $$r_i = \sqrt{(x_M - x_i)^2 + (y_M - y_i)^2} \qquad i, j = 1, 2, \ldots 8$$

After superposition the magnitude of results magnetic field can be expressed in the form

(12) $$\boldsymbol{H}_{xM} = \sum_i \boldsymbol{H}_{xi}(M), \quad \boldsymbol{H}_{yM} = \sum_i \boldsymbol{H}_{yi}(M), \quad \boldsymbol{H}_M = \sqrt{|\boldsymbol{H}_{xM}|^2 + |\boldsymbol{H}_{yM}|^2}$$

4 The examples

The analysis of the electric and magnetic field was performed for two types of double-circuit towers: “Soudek” and “Donau”. The distribution of the field at the height 1,2 m above the earth was calculated for six basic arrangements (given by the matrix **P** – eq. (2)), and for two heights of conductors above the earth (for the distance given by the size of towers and for the minimal allowed distance between conductors and the earth). Provided that the surge impedance ends the overhead line, then the real power and the rated voltage give the magnitude of the current.

variant 1: $I_1 = I_2 = 790\text{A}$ $U_1 = U_2 = 400\text{kV}$ (tower "Donau")
variant 2: $I_1 = I_2 = 341{,}5\text{A}$ $U_1 = U_2 = 110\text{kV}$ (tower "Soudek")

TOWER DONAU	TOWER DISTANCE			MINIMAL DISTANCE 8 m		
PHASE ARRAGEMENT	E[kV/m]	H [A/m]	B [μT]	E[kV/m]	H [A/m]	B [μT]
× ○ 1 ● ○ × ●	1,2	13,1	16,5	8,9	145,5	182,9
× ● 2a ● ○ × ○	1,9	28,1	35,3	9,4	159,7	200,7
× ○ 2b ● ○ ● ×						
× × 3 ● ○ ● ○	2,1	29,3	36,8	9,1	138,5	174,0
× × 4 ● ○ ○ ●	2,5	30,5	38,3	10,0	156,9	197,1
× ● 5 ● ○ ○ ×	2,3	38,9	48,9	10,2	175,6	220,6

Tab. 1

TOWER SOUDEK	TOWER DISTANCE			MINIMAL DISTANCE 6 m		
PHASE ARRAGEMENT	E[kV/m]	H [A/m]	B [μT]	E[kV/m]	H [A/m]	B [μT]
× ● 1 ○ ○ ● ×	0,4	7,1	8,9	2,5	60,6	76,2
× ● 2a ○ × ● ○	0,7	13,5	17,0	3,0	66,4	83,4
× ○ 2b ○ ● ● ×						
× × 3 ○ ● ● ○	1,0	18,7	23,5	3,5	68,6	86,2
× ○ 4 ○ × ● ●	1,4	23,6	29,7	5,3	90,7	114,0
× × 5 ○ ○ ● ●	1,5	24,4	30,7	5,3	89,9	112,9

Tab. 2

The results of the first variant (tower "Donau") are shown in Tab. 1. The arrangement of the phases is expressed in the general form by symbols „•“, „o“ and „×“, the results of the variant 2 (tower "Soudek") are summarised in Tab. 2. Distribution of E [kV/m] and H [A/m] for both variants is depicted in Fig. 4. The curve 1 belongs to the best case (the first rows in Tabs. 1, 2) and the curve 5 belongs to the worst case (the last rows in Tabs. 1, 2). These examples show that for both types of towers the optimum arrangement occurs when the conductors of the same phases are separated as much as possible from each other and the distance between the different phases is kept as small as possible. The unsuitable arrangement occurs if the phases are placed symmetrically, enantiomorphly or the conductors of the same phase are closed. In those cases the magnetic field is two-times or three-times higher then in the optimum case. Moreover, beside this phenomenon a suitable transposition in double-circuits has a positive effect on the line inductance, which was shown in [2]. The allowed value of the electric field strength is 5 kV/m and the allowed value of magnetic flux density is 100 μT. It is seen that in case of minimal distance of the conductors above earth for tower Donau the allowed values were exceeded.

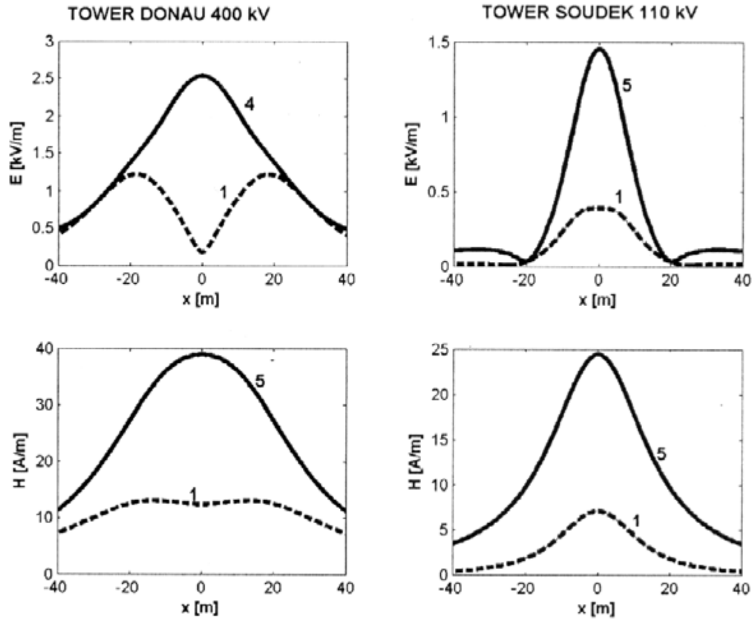

Fig. 4 Distribution of E [kV/m] and H [A/m] for tower Donau and Soudek

5 Conclusion

The algorithm for the evaluation of the optimum transposition in double-circuit three-phase overhead lines was developed and illustrated on two examples. The results proved that the suitable arrangement of phases of particular conductors leads to reduction of the magnetic field, namely in the space where the magnetic field can negatively affect the human body. The suggested algorithm can be used for double-circuit overhead lines with the same voltage level or for parallel lines with different voltage levels.

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