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Chosen analyses for multi-circuit multi-voltage overhead lines capacitances

Abstract. *The paper discusses aspects related to modeling the capacitances of multi-circuit multi-voltage overhead power lines (HV, EHV). The problem of neutral point displacement under the influence of the capacitive asymmetry of such lines was considered. The results of analyses were presented for selected real multi-circuit multi-voltage overhead line constructions with varying degree of geometrical asymmetry.*

Streszczenie. *W artykule omówiono aspekty dotyczące modelowania pojemności wielotorowych wielonapięciowych linii napowietrznych wysokich i najwyższych napięć (WWLN). Rozpatrzono problem przesunięcia punktu neutralnego pod wpływem niesymetrii pojemnościowej takich linii. Wyniki analiz zaprezentowano dla wybranych rzeczywistych konstrukcji WWLN o różnym stopniu niesymetrii geometrycznej. (**Wybrane analizy dla pojemności wielotorowych wielonapięciowych linii napowietrznych**).*

Keywords: multi-circuit overhead lines, capacitance of overhead line, network's neutral point displacement.
Słowa kluczowe: wielotorowe linie napowietrzne, pojemność linii napowietrznej, przesunięcie punktu neutralnego sieci.

Introduction

In power systems' structures, as well in Poland as in the world, a significant increase of multi-circuit multi-voltage overhead lines is observed. In multi-circuit multi-voltage overhead lines, at least two circuits placed on the common structure have a different voltage rating. An appearance of such lines in the subtransmission networks carries with the necessity of their appropriate description using a mathematical model. In [1], the authors presented a mathematical model of multi-circuit multi-voltage overhead lines for series parameters. This paper extends the impedance model with capacitive parameters.

Mathematical modeling of multi-circuit multi-voltage overhead lines capacitances

Transmission overhead lines consist of three or more isolated parallel conductors. The capacitances that occur between each pair of conductors have an impact on a line operation. Overhead line capacitance compound from N conductors (N = 3n, n – number of circuits of the considered line), shown in Figure 1, are determined based on the charges on its conductors and the potentials of these conductors.

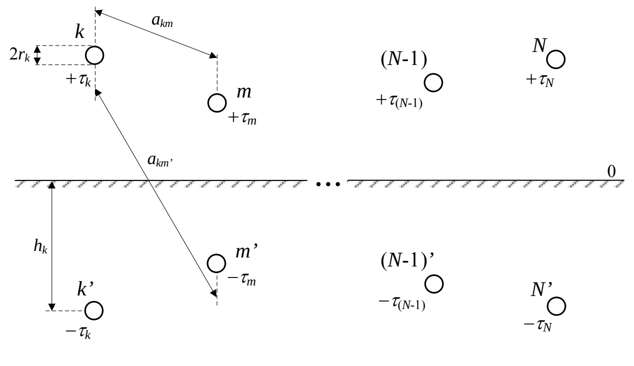

Fig.1. A sectional view of n-circuit line compound from N conductors with they mirror images

Overhead line conductors are considered as infinitely long parallel to each other and the earth's surface (which is treated as a conductive plane) cylinders of radius r_k, where k – conductor of overhead line $k \in \{1, 2, \ldots, N\}$, with linear charge density τ. It is assumed that distance between any conductors k and m, as well as between conductor k and the earth's surface, is much bigger than the radius of the conductor, then respectively $a_{km} \gg r_k$ and $h_k \gg r_k$. In the course of consideration, the earth is replaced by fictitious equivalent conductors which are mirror images of the real overhead line conductors with linear charge density $-\tau$.

A dependence between potentials V and charges Q of multi-circuit multi-voltage overhead line is given by the relation (1):

$$\mathbf{V}=\mathbf{P}\,\mathbf{Q} \Leftrightarrow \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1N} \\ P_{21} & P_{22} & \cdots & P_{2N} \\ \vdots & & \ddots & \vdots \\ P_{N1} & P_{N2} & \cdots & P_{NN} \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_N \end{bmatrix}. \tag{1}$$

The values of Maxwell potential coefficients P [m/F] are made dependent on point-insulating plate electrode system (conductor-earth's surface) and point-point electrode system (conductor-conductor) determined from geometry and material constants of conductors [3], then:

$$P_{kk}=\frac{1}{2\pi\varepsilon_0 l}\ln\frac{2h_k}{r_k}, \tag{2}$$

$$P_{km}=\frac{1}{2\pi\varepsilon_0 l}\ln\frac{a_{km'}}{a_{km}}, \tag{3}$$

where ε_0 – electric constant permittivity of vacuum [F/m], l – length of conductor [m], r_k – radius of conductor k [m], h_k – suspension height of conductor k above the earth's surface [m], a_{km} – distance between conductors k and m, $a_{km'}$ – distance of the conductor k from the mirror image of the conductor m. The potential coefficient P_{kk} applies to the given conductor k, while coefficient P_{km} to the pair of conductors k and m, where $k, m \in \{1, 2, \ldots, N\}$ and $m \neq k$.

The equation (1) for an n-circuit overhead line takes the form (4):

$$\mathbf{V}=\mathbf{P}\,\mathbf{Q} \Leftrightarrow \begin{bmatrix} \mathbf{V}_{\mathrm{I}} \\ \mathbf{V}_{\mathrm{II}} \\ \vdots \\ \mathbf{V}_{n} \end{bmatrix} = \begin{bmatrix} \mathbf{P}_{\mathrm{I}} & \mathbf{P}_{\mathrm{I.II}} & \cdots & \mathbf{P}_{\mathrm{I}.n} \\ \mathbf{P}_{\mathrm{II.I}} & \mathbf{P}_{\mathrm{II}} & & \mathbf{P}_{\mathrm{II}.n} \\ \vdots & & \ddots & \vdots \\ \mathbf{P}_{n.\mathrm{I}} & \mathbf{P}_{n.\mathrm{II}} & \cdots & \mathbf{P}_{n} \end{bmatrix} \begin{bmatrix} \mathbf{Q}_{\mathrm{I}} \\ \mathbf{Q}_{\mathrm{II}} \\ \vdots \\ \mathbf{Q}_{n} \end{bmatrix}, \tag{4}$$

where potentials and charges of an overhead line correspond to their values in individual phases of the given circuit i of n-circuit line, $i \in \{\mathrm{I}, \mathrm{II}, \ldots, n\}$:

$$\mathbf{V}_i=\begin{bmatrix} V_{\mathrm{L1}\,i} & V_{\mathrm{L2}\,i} & V_{\mathrm{L3}\,i} \end{bmatrix}^{\mathrm{T}}, \quad \mathbf{Q}_i=\begin{bmatrix} Q_{\mathrm{L1}\,i} & Q_{\mathrm{L2}\,i} & Q_{\mathrm{L3}\,i} \end{bmatrix}^{\mathrm{T}}. \tag{5}$$

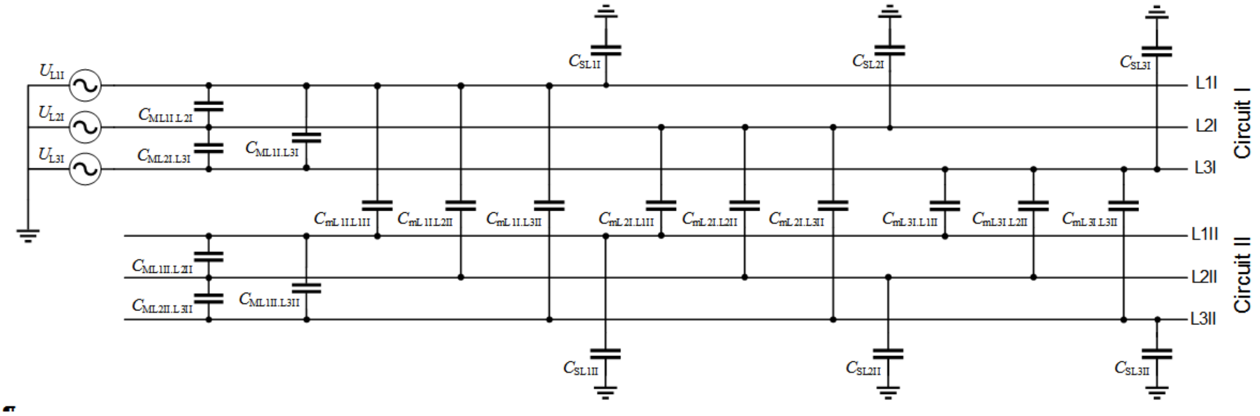

Fig. 2. Self and mutual capacitances of two-circuit two-voltage overhead line, $U_{nI} > U_{nII}$

Lightning conductors may also be modeled in equations (1) and (4). The influence of the lightning conductors is similarly taken into account as the series parameters [1]. In the further part of the article, only phase conductors of the line are considered, while the corresponding to them Maxwell's potential coefficients are already adjusted for corrections coming from the lightning conductors. The appearance of the bundle conductors was also taken into consideration by their aggregation to one equivalent conductor.

By transforming equation (4), where the earth potential is equal to zero:

$$\frac{1}{\sqrt{2}}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{Q} = \mathbf{P}^{-1}\cdot\frac{1}{\sqrt{2}}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{U}\,, \tag{6}$$

the result is the relation (7) which describes dependence between currents and nodal voltages of the multi-circuit line:

$$\mathbf{I} = \mathrm{j}\omega\mathbf{P}^{-1}\mathbf{U} = \mathrm{j}\omega\mathbf{C}\mathbf{U}\,, \tag{7}$$

where: $\mathbf{U}$ – matrix of phase voltages, $\mathbf{C}$ – matrix of partial capacitances of n-circuit overhead line. An example of all partial capacitances for a two-circuit line is shown in Figure 2.

Network's neutral point displacement

The real lines are usually not symmetrized by transposition of phase conductors, which causes i.a. capacitive asymmetry. It turns out that it is particularly important in the case of multi-circuit multi-voltage lines, where phase asymmetry (mainly asymmetry of capacitances between the phases of different circuits) causes an unacceptably high voltage of neutral point displacement in lower voltage network [2]. This, in turn, can affect the incorrect operation of earth-fault protection and the appearance of zero-sequence component currents with significant values in normal network operating states.

The influence of the capacitive asymmetry of the analyzed multi-voltage lines was determined by calculating the value of the zero-sequence component of the voltage appearing in the lower voltage circuit when a higher voltage circuit is supplied (Fig. 2). In the system shown in Figure 2, a symmetrical supply of circuit I, with disconnected circuit II, causes the appearance of non-zero asymmetrical potentials on the conductors of circuit II. Adding up the potentials of these conductors gives a triple zero-sequence component of voltage U_0.

By writing equation (7) for two circuits and using the fact of zero nodal currents in circuit II (8), it is possible to determine the voltage in the phases of circuit II.

$$\mathrm{j}\omega\begin{bmatrix}\mathbf{C}_{\mathrm{I}} & \mathbf{C}_{\mathrm{I,II}}\\ \mathbf{C}_{\mathrm{II,I}} & \mathbf{C}_{\mathrm{II}}\end{bmatrix}\begin{bmatrix}\mathbf{U}_{\mathrm{I}}\\ \mathbf{U}_{\mathrm{II}}\end{bmatrix} = \begin{bmatrix}\mathbf{I}_{\mathrm{I}}\\ 0\end{bmatrix}. \tag{8}$$

The solution of the second equation of relation (8) with reference to $\mathbf{U}_{\mathrm{II}}$ is relation (9):

$$\mathbf{U}_{\mathrm{II}} = -\mathbf{C}_{\mathrm{II}}^{-1}\mathbf{C}_{\mathrm{II,I}}\mathbf{U}_{\mathrm{I}}\,. \tag{9}$$

where the zero-sequence component of voltage U_0 can be determined directly:

$$U_0 = \frac{1}{3}\left|U_{\mathrm{L1II}} + U_{\mathrm{L2II}} + U_{\mathrm{L3II}}\right|. \tag{10}$$

Impact of multi-circuit multi-voltage overhead lines on the value of the network's neutral point displacement voltage - polemics

Several considerations were made to determine the effect of geometric asymmetry of multi-circuit multi-voltage overhead lines on the value of appearing zero-sequence component of voltage U_0, so the degree of network's neutral point displacement.

Table 1. Phase configurations of considered multi-circuit two-voltage overhead lines

	Location coordinates of phase conductors [m]				Location coordinates of lightning conductors [m]		
		L1	L2	L3		E1	E2
Case 1	Circuit I (400 kV)						
	x	-9.0	0.0	9.0	x	-7.5	7.5
	y	21.8	21.8	21.8			
	Circuit II (110 kV)						
	x	-4.0	0.0	4.0	y	32.6	32.6
	y	15.9	15.9	15.9			
Case 2	Circuit I (400 kV)						
	x	-9.0	0.0	9.0	x	-7.5	7.5
	y	30.4	30.4	30.4			
	Circuit II (110 kV)						
	x	4.0	4.0	4.0	y	41.2	41.2
	y	24.5	20.2	15.9			
Case 3	Circuit I (400 kV)						
	x	6.75	6.87	6.99	x	-1.1	4.1
	y	44.8	34.3	23.8			
	Circuit II (110 kV)						
	x	-3.34	-3.40	-3.46			
	y	47.0	42.1	37.2			
	Circuit III (110 kV)				y	53.1	53.1
	x	-3.51	-3.57	-3.63			
	y	32.3	27.4	22.5			

Table 1 includes the location coordinates of the conductors for three sample lines. The horizontal coordinates (x) are calculated from the axis of the tower, while the vertical coordinates (y) from the earth's surface. All conductor heights are equal to the average conductor height above the earth's surface, including insulator chain length and sagging curve.

A silhouette of two-circuit two-voltage overhead line, for case 1 (Tab. 1), is presented in Figure 3.

To analyze the values of possible zero-sequence component voltages in circuit II (110 kV), the values of these voltages were determined as a function of the distance of the extreme phase conductors of the 110 kV circuit from the tower axis dx. Calculations were made both with and without lightning conductors. In case 1 the differences are unnoticeable. The purpose of a significant range of changes in the considered case was to show the variability of voltage U_0. It should be noticed that the real minimum distance dx for 110 kV lines is about 3.5 m, which results from the voltage requirements and regulations. According the graph shown in Figure 4, for distance dx = 3.5 m voltage U_0 reaches 18.5 kV, which is far too high concerning acceptable values (Polish regulations [4] allow the value of the zero-sequence component of voltage in 110 kV networks at the level of 2% of the rated voltage which is 2.2 kV – this value is achieved at dx = 9.9 m).

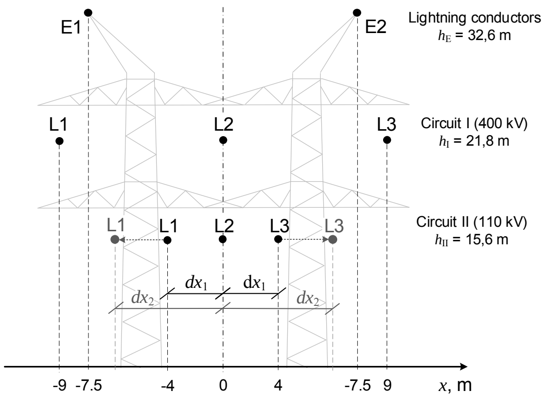

Fig.3. Horizontal phase conductor configuration of two-circuit two-voltage line 400+110 kV; dx_1, dx_2 – examples of two positions of the extreme phase conductors of circuit II; h_i - suspension height of circuit i above the earth's surface

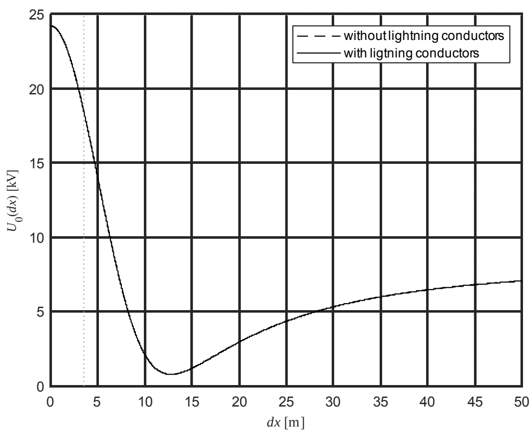

Fig.4. The zero-sequence component of voltage U_0 as a function of the location of extreme phases in a horizontal configuration (Fig.3) relative to the tower axis dx

The presented curve has a clearly noticeable minimum, which can be called natural, at dx = 12.5 m voltage U_0 reaches 0.8 kV. As the extreme phase conductors are moved further away from the tower axis, the voltage U_0 tends to 7 kV and it is caused only by the voltage appearing in the middle phase (with the horizontal coordinate x = 0 m).

The second considered case was a two-circuit two-voltage line 400+110 kV. The 400 kV circuit of this line has a horizontal phase conductor configuration (identical to the first case) and the 110 kV circuit has vertical phase conductor configuration (Tab. 1, case 2). This case is a fragment of a three-circuit line with two 110 kV circuits placed symmetrically on both sides of the tower. As in the first case, the voltage U_0 was determined on the 110 kV circuit as a function of the horizontal distance of the 110 kV circuit suspension from the tower axis.

The results are presented graphically in Figure 5. In this case, the influence of the lightning conductors on the value of voltage U_0 can be observed. This effect is advantageous, however, the voltage U_0 is only about 0.6 kV lower than if the lightning conductors had not been taken into account. For the vertical phase conductor configuration of circuit II, the maximum value of voltage U_0 is clearly observed. The voltage U_0 reaches a peak of 28.5 kV for distance dx = 11.8 m. Then, along with the increase of distance, the voltage U_0 decreases to zero (for dx = 100 m the value of voltage U_0 is about 1 kV and for dx = 200 m U_0 = 0.2 kV). Within the entire range of real dx values, the values of the zero-sequence component of voltage are significantly too high.

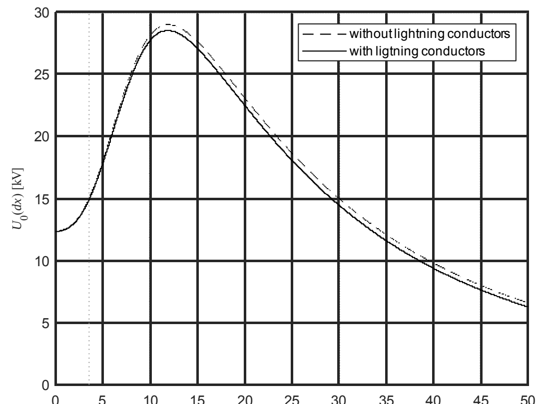

Fig.5. The zero-sequence component of voltage U_0 as a function of the location of extreme phases in the vertical configuration of circuit II relative to the tower axis dx

The third analyzed line configuration was a three-circuit two-voltage line with a vertical phase conductor configuration (Tab. 1, case 3).

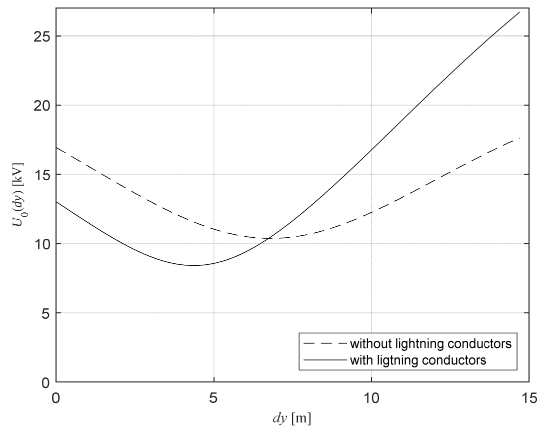

Fig.7. The zero-sequence component of voltage U_0 as a function of the 110 kV circuit mounting location dy from the lower (dy = 0 m) to the upper (dy = 14.7 m) position

In this case, the analysis of the appearance of voltage U_0 on one of the 110 kV circuit was performed. The two-circuit line of rated voltage 110 kV was analyzed by changing the positions of one of the 110 kV circuits so that in extreme locations the 110 kV circuit was the lower and upper circuit of the actual three-circuit line. The results of the analysis are presented in Figure 7. The variable dy = 0 m means the lower position of the 110 kV circuit (like circuit III in Tab. 1, case 3), while dy = 14.7 m means the exact transition to the upper position (like circuit II in Tab. 1, case 3). It can be observed that the location of the 110 kV circuit in the middle part of the considered range causes a reduction of voltage U_0 value on this circuit. Moreover, the positive impact of lightning conductors for range (0 ÷ 6.74) meters of dy is observed. The lightning conductors cause a reduction of voltage U_0 in the 110 kV circuit, but the minimum value still exceeds 8 kV.

Elimination methods of voltage U_0

To eliminate the appearing zero-sequence component of voltage U_0 in multi-voltage line circuits, the transposition of phase conductors should be done. In practice, two types of transposition are used: full transposition consisting of changing all three phases of the circuit (Fig.8a) or simplified transposition consisting of changing the position of only two phases (Fig.8b). The analysis of appearing the voltage U_0 shows that only transposition performed in a higher voltage circuit allows eliminating this phenomenon. For this purpose, two full transpositions should be done at 1/3 and 2/3 of the line length. In all considered cases this method eliminated the appearing voltage U_0 in the 110 kV circuit. In the case 1 (two-circuit line with a horizontal phase conductor configuration – Fig.3) elimination of the voltage U_0 was possible after applying two simplified transpositions – first for the phases L1 and L2, then second for phases L1 and L3. The obtained conclusions are consistent with those presented in [2].

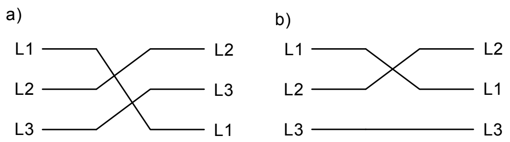

Fig. 8. Types of line transpositions [5]

Another way of full or partial elimination of the appearing voltage U_0 is the change the phase configuration in individual circuits. This solution only applies to at least three-circuit lines and is effective if there are at least two higher voltage circuits.

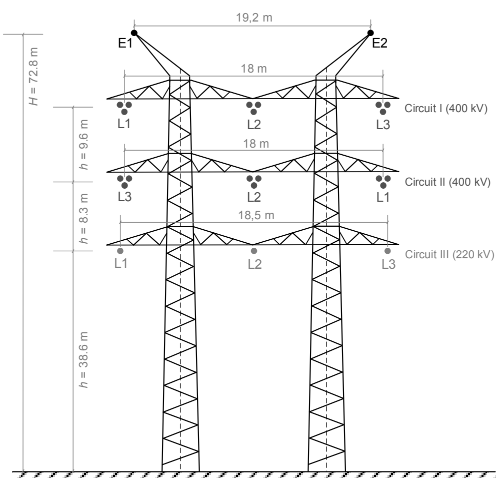

Fig. 9. A scheme of the silhouette of the tower of the two-voltage three-circuit line

An example of such a line is real three-circuit two-voltage line 2x400+220 kV (Fig.9) operating in the Polish system, which was the subject of analysis for series parameters in [1].

Figure 10 presents the analysis of the value U_0 in the 220 kV circuit depending on the divergence of the extreme phases of this circuit relative to the axis of the line (analogous case as for the first example). At a distance of about 9 m from the tower axis, which is the actual place of suspension of 220 kV circuit conductors, the zero-sequence component of voltage U_0 is very close to zero.

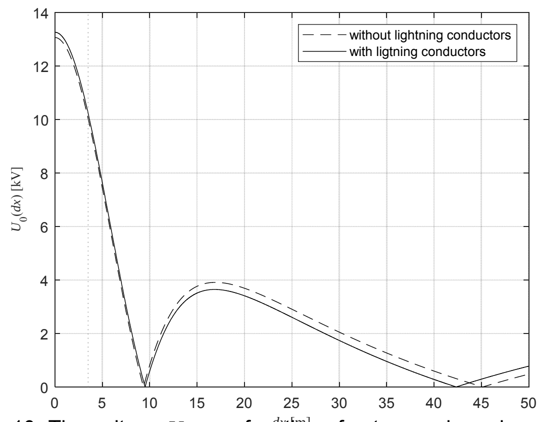

Fig.10. The voltage U_0 as a function of extreme phase location in a horizontal phase conductor configuration of the three-circuit two-voltage line located nearby the Łagisza station

Summary

The analysis of the cases of various multi-voltage overhead line configurations indicates a real problem which is the appearance of the zero-sequence component of voltage U_0 with considerable values in lower voltage circuits. It causes the need to perform transposition of a higher voltage circuit (this is an important conclusion because transposition of lower voltage circuit does not result in a decrease in the voltage U_0), which is not a simple technical procedure in every line configuration. In the case of the vertical configuration of phases, such transposition is possible by making a tower with a triangular configuration of this circuit and then returning to the vertical configuration.

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