E3S Web of Conferences **384**, 01021 (2023)
RSES 2022
https://doi.org/10.1051/e3sconf/202338401021

The innovative EHV line and its main indicators

Krasilnikova Tatyana[1], *Makhmudov* Karomatullo[1], *Samorodov* German[2] and *Novikov* Nikolay[3*]

[1]NSTU, Department of Automated Electric Power Systems, 630073 Karl Marx Avenue 20, Novosibirsk, Russia
[2]Branch of JSC «STC FGC UES» – Siberian Research Institute of Energy, 630126 Klenovaya str 10/1, Novosibirsk, Russia
[3]JSP «STC FGC UES», NRU MPEI, JIHT RAS, 115201 Kashirskoe highway 22, вuilding 3, Moscow, Russia

Abstract. Single-circuit EHV lines widely used all over the world have a significant drawback, consisting in the fact that with the most probable single-phase stable failures, the line is completely taken out of operation. In this paper, a single-circuit EHV line is considered, one phase of which is made in the form of two parallel semi-phases, any of which is used as a backup phase in emergency modes. To symmetrize the conditions in the middle of the line, the Series Capasitor (SC) are included in the two usual phases. The article presents an algorithm for calculating normal modes, the main indicators of an innovative 500 kV line, consisting in its increased capacity, reliability and economic efficiency. The main provisions are illustrated by the example of a 500 kV line with a length of 500 km.

Introduction

Single-circuit EHV lines are widely used all over the world [1-6], which have the disadvantage that with the most probable single-phase stable failures, the line fails completely. This fact gives superiority to DC lines that can operate with single-pole stable damage at one pole with a transmission of 50% of the maximum power [7]. There are a number of ways to increase the capacity of single-circuit AC lines (the use of compact lines of increased natural power [8], the use of SC [9]), in which the issue of reliability only worsens.

The reliability of a single-circuit line can be improved by using the reserve phase of the line [10], which is switched on instead of the emergency operating phase (Fig.1). The reserve phase is used only in short-term emergency modes, and the rest of the time remains disabled, which is its significant disadvantage.

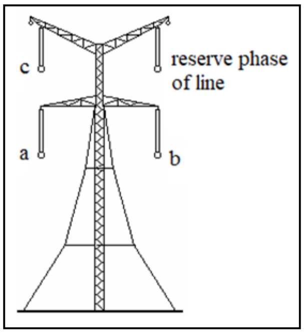


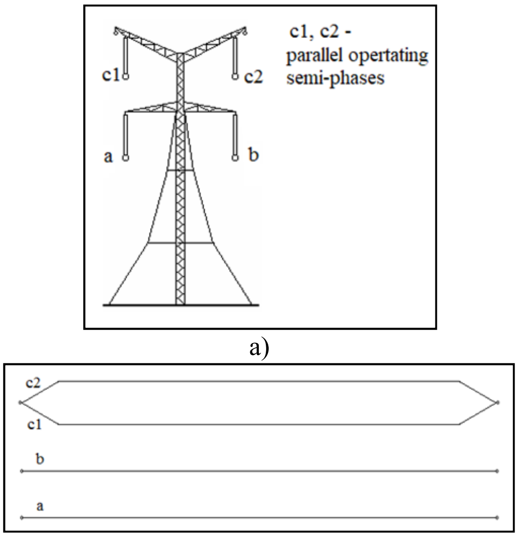
Fig. 1. A line with a reserve phase.

The purpose of this work is to develop a line that provides increased capacity with high reliability of operation, while being characterized by favorable economic indicators.

General characteristics of the innovative line

In the innovative line [11], one phase is performed in the form of two parallel operating semi-phases, one of which is used as a reserve phase in emergency modes.

Figure 2a shows the layout of the phases and semi-phases of the innovation line on the support, and Figure 2b shows its scheme.



a)

b)

Fig. 2. A line with parallel operating semi-phases: a - the location of the phases on the support; b - the scheme of the innovative line.

Structurally, the total cross-section of the semi-phases is equal to or close to the cross-section of the individual phase. Fig.3 shows the possible designs of phases and semi-phases of the 500 kV line, with respect to which calculations are carried out in the future. The proposed phase and semi-phase designs

---

*Corresponding author: novikov@ntc-power.ru differ in geometric dimensions and the number of wires in the phase: these are traditional (option A) and compact (option B) designs.

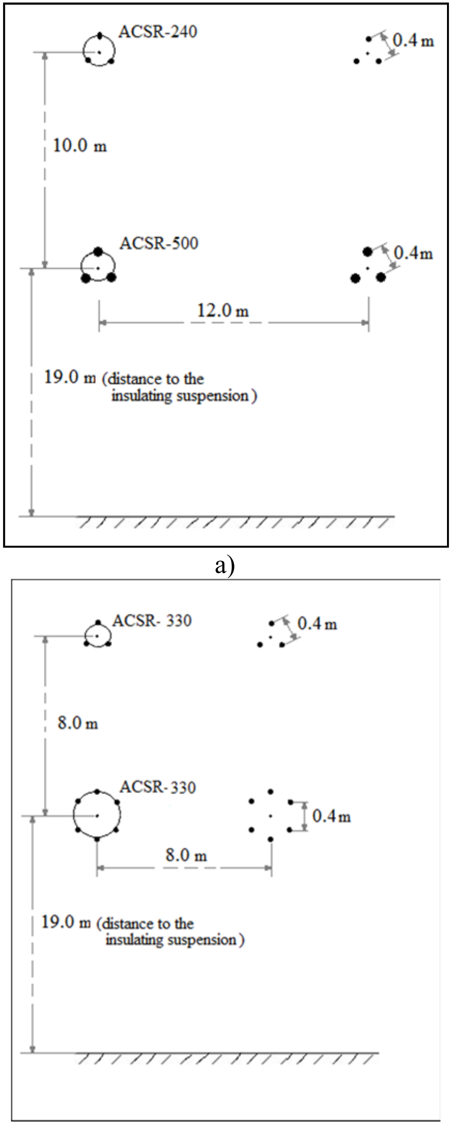


Fig. 3. Designs of phases and semi-phases of the innovative line: a – traditional design (option A); b – compact design (option B).

Mathematical model of an innovative line for calculating normal conditions

The innovative line has a phase-by-phase longitudinal and transverse asymmetry, and for the symmetry of normal conditions, it is necessary to install SC in the middle part of the normal phases, and at the ends of one of the semi-phases, shunt reactors are connected, as shown in Fig.4. Since the innovative overhead line is characterized by phase asymmetry, the universal method for calculating steady-state conditions is the matrix method, when the line and other installations are described in phase coordinates.

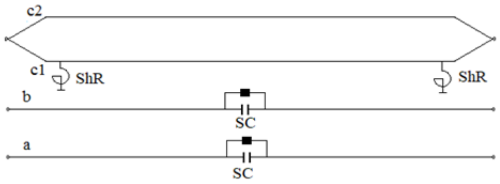


Fig. 4. Scheme of innovative overhead line with semi-phases for calculating normal conditions.

The complete phase matrix of the circuit is formed according to the above figure

$$\boldsymbol{M}_{12} = \boldsymbol{M}_{ShR} \cdot \boldsymbol{M}_{l/2} \cdot \boldsymbol{M}_{SC} \cdot \boldsymbol{M}_{l/2} \cdot \boldsymbol{M}_{ShR} \tag{1}$$

The corresponding matrices in formula (1) are defined as follows. The complete matrix of the untransposed half section of the line has the form

$$\boldsymbol{M}_{l/2} = \begin{vmatrix} \boldsymbol{A}_{l/2} & \boldsymbol{B}_{l/2} \\ \boldsymbol{C}_{l/2} & \boldsymbol{D}_{l/2} \end{vmatrix} \tag{2}$$

where

$$\boldsymbol{A}_{l/2} = \begin{vmatrix} A_{aa} & A_{ab} & A_{ac1} & A_{ac2} \\ A_{ba} & A_{bb} & A_{bc1} & A_{bc2} \\ A_{c1a} & A_{c1b} & A_{c1c1} & A_{c1c2} \\ A_{c2a} & A_{c2b} & A_{c2c1} & A_{c2c2} \end{vmatrix},$$

$$\boldsymbol{B}_{l/2} = \begin{vmatrix} B_{aa} & B_{ab} & B_{ac1} & B_{ac2} \\ B_{ba} & B_{bb} & B_{bc1} & B_{bc2} \\ B_{c1a} & B_{c1b} & B_{c1c1} & B_{c1c2} \\ B_{c2a} & B_{c2b} & B_{c2c1} & B_{c2c2} \end{vmatrix},$$

$$\boldsymbol{C}_{l/2} = \begin{vmatrix} C_{aa} & C_{ab} & C_{ac1} & C_{ac2} \\ C_{ba} & C_{bb} & C_{bc1} & C_{bc2} \\ C_{c1a} & C_{c1b} & C_{c1c1} & C_{c1c2} \\ C_{c2a} & C_{c2b} & C_{c2c1} & C_{c2c2} \end{vmatrix},$$

$$\boldsymbol{D}_{l/2} = \begin{vmatrix} D_{aa} & D_{ab} & D_{ac1} & D_{ac2} \\ D_{ba} & D_{bb} & D_{bc1} & D_{bc2} \\ D_{c1a} & D_{c1b} & D_{c1c1} & D_{c1c2} \\ D_{c2a} & D_{c2b} & D_{c2c1} & D_{c2c2} \end{vmatrix}.$$

$$\boldsymbol{M}_{SC} = \begin{vmatrix} \boldsymbol{1}_4 & \boldsymbol{Z}_{SC} \\ \boldsymbol{O}_4 & \boldsymbol{1}_4 \end{vmatrix} \tag{3}$$

where $\boldsymbol{Z}_{SC} = \begin{vmatrix} Z_{SC} & 0 & 0 & 0 \\ 0 & Z_{SC} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}$, $Z_{\text{sc}} = i \cdot X_{\text{sc}}$ –phase reactance of the SC.

The zero and unit matrices of the 4th order are respectively determined by

$$\boldsymbol{0}_4 = \begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \qquad \boldsymbol{1}_4 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}.$$

The other main element of the four-wire circuit includes shunt reactors (ShR) located at the ends of the line. In general, unvariable ShR (UShR) and variable ShR (VShR) can be used. (The ShRs at the ends of the line are not shown in Fig.4, since it is assumed that the conditions of transmission of natural power is being considered when the reactors are switched off.)

So, in particular, the complete VShR matrix for the line under consideration will be written

$$\boldsymbol{M}_{VShR} = \begin{vmatrix} \boldsymbol{1}_4 & \boldsymbol{0}_4 \\ \boldsymbol{Y}_{VShR} & \boldsymbol{1}_4 \end{vmatrix} \qquad (4)$$

where $\boldsymbol{Y}_{VShRi} = \boldsymbol{Z}_{VShRi}^{-1}$.

In turn $\boldsymbol{Z}_{VShR} = \begin{vmatrix} Z_{VShRa} & 0 & 0 & 0 \\ 0 & Z_{VShRb} & 0 & 0 \\ 0 & 0 & Z_{VShRc1} & 0 \\ 0 & 0 & 0 & Z_{VShRc2} \end{vmatrix}$,

where $\boldsymbol{Z}_{VShRi} = \frac{1}{\boldsymbol{Y}_{VShRi}}$ –reactance of the i-th phase, i=a,b,c1,c2.

Vector-columns of specified voltages at the ends of the line are accepted

$$\boldsymbol{U}_1 = \frac{U_{nom}}{\sqrt{3}} e^{i\delta} |1 \quad h^2 \quad h \quad h|^t,$$

$$\boldsymbol{U}_2 = \frac{U_{nom}}{\sqrt{3}} e^{i\delta} |1 \quad h^2 \quad h \quad h|^t, \qquad (5)$$

where $\boldsymbol{U}_1 -$ rated line voltage; δ –angular shift between voltage att the ends of the line; $h = e^{i2\pi/3}$ –phase operator.

Next, we find the vector column of currents at the end of the line

$$\boldsymbol{I}_2 = |I_{2a} \quad I_{2b} \quad I_{2c1} \quad I_{2c2}|^t = \boldsymbol{B}_{12}^{-1}(\boldsymbol{E}_1 - \boldsymbol{A}_{12}\boldsymbol{E}_2) \qquad (6)$$

Given that the current in phase "c" consists of the currents of the semi-phases "c1" and "c2", we find the current at the end of the line

$$I_{2c} = I_{2c1} + I_{2c2}$$

And accordingly, the column vector of the three-phase current will be

$$I_{2abc} = |I_{2a} \quad I_{2b} \quad I_{2c}|^t.$$

To assess the level of asymmetry that occurs in the circuit, we define a vector column of symmetrical components of currents at the beginning of the line

$$\boldsymbol{I}_{1sym} = |I_{11} \quad I_{12} \quad I_{10}|^t = \boldsymbol{H}_{sym} \cdot \boldsymbol{I}_{1abc} \qquad (7)$$

where $\boldsymbol{H}_{sym} = \begin{bmatrix} 1 & h & h^2 \\ 1 & h^2 & h \\ 1 & 1 & 1 \end{bmatrix}$ –transformation matrix from phase components to symmetric components; I_{11}, I_{12}, I_{10} –respectively, the currents of the positive, negative and zero sequences.

The coefficient of asymmetry in the current of the negative sequence will be determined accordingly

$$K_{12} = I_{12}/I_{11} \qquad (8)$$

An important characteristic of the circuit that determines its capacity is the angular characteristic, which represents the dependence of the active power transmitted along the line on the angular shift between the voltages at the ends of the line. Thus, the total power at the end of the line is defined as the scalar product of the corresponding column vectors of voltage and current

$$S_2(\delta) = \boldsymbol{U}_{2abc}(\delta) \cdot \boldsymbol{I}_{2abc}(\delta)$$

where $\boldsymbol{U}_{2abc} = \frac{U_{nom}}{\sqrt{3}} e^{i\delta} |1 \quad h^2 \quad h \quad h|^t$ –vector is a column of voltages at the end of the line.

Accordingly, the angular characteristic of the scheme is found as

$$P_2(\delta) = ReS_2(\delta) \qquad (9)$$

The maximum of the angular characteristic at $\delta = 90^0$determines the maximum transmitted power of the circuit

$$P_{2\max} = P_2(90^0)$$

Accordingly, capacity of the circuit is reduced taking into account the margin coefficient for static stability

$$P_{2\text{cap}} = \frac{P_{2\max}}{K_{mc}} \qquad (10)$$

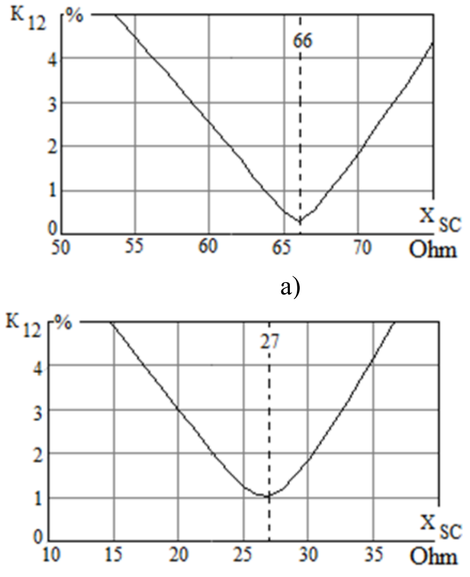
where $K_{mc} = 1{,}2$ –the margin coefficient for static stability.

Reduction of asymmetry in normal conditions

Based on the proposed algorithm, we will analyze the normal conditions of the 500 kV innovation line with a length of 500 km, bearing in mind the level of asymmetry that occurs in it.

In the absence of a two-phase SC in the middle of the line and a ShR at the ends of one of the semi-phases, the asymmetry coefficient reaches 14%, which significantly exceeds the permissible value for synchronous generators of no more than 6%. The decrease in the asymmetry coefficient in the negative sequence occurs not only due to the SC, but also as a result of the use of ShR.

As follows from the calculations, in the case of using UShRs, the suseptance of which is 0.65 mSm, the optimal reactance of the SC for a traditional design (option A) is 66 Ohm, and for a compact design (option B) - 27 Ohm; the corresponding asymmetry coefficients are equal for option A - 0.3%, for option B - 1.0% (Fig. 5).



a)

b)

Fig. 5. Dependence of the asymmetry coefficient in the negative sequence on the reactance of the SC: a – traditional design; b – compact design.

Thus, it can be concluded that with the combined use of a two-phase SC and a single-phase ShR, relatively small asymmetry coefficients are provided.

The main indicators of the innovative line

Doubled capacity

The main indicator of the innovative line, first of all, is its doubled capacity compared to the traditional single-circuit line. Table 1 shows a comparison of the capacities of traditional and innovative lines calculated according to (10). The innovative line provides an almost two-fold increase in capacity compared to a single-circuit traditional line.

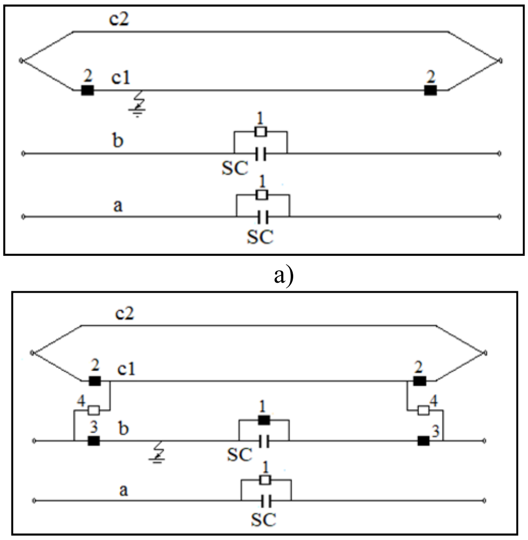
Table 1. Comparison of capacities of traditional and innovative 500 kV lines (500 km)

Line type	Traditional (single-circuit) line	Innovative line	
		Traditional design	Compact design
Capacity, MW	1460	2900	2880
Capacity ratio		1,99	1,97

Increased reliability

In the EHV lines, the overwhelming number of failures is single-phase. In case of unstable failures in the innovation line, as in the traditional line, the Single-Phase Automatic Reclosing is used.

A noticeable proportion of failures are sustained. The proposed scheme, in the event of sustained failures, allows you to switch to operation in post-emergency mode with the possibility of transmitting at least 50% of the power of the initial maximum conditions. So, if one of the semi-phases is permanently damaged, it is switched off by switches 2 (Fig. 6a), and the line switches to operation in emergency mode. At the same time, in order to ensure an acceptable level of asymmetry, it is necessary to shunt the SC with switches 1. In case of sustained damage to one of the phases, for example, phase "b", it is switched off by switches 3, and the corresponding semi-phase, disconnected by switches 2 from the other semi-phase, is switched on by switches 4 instead. In order to ensure an acceptable level of asymmetry, it is necessary in this case to shunt the SC with switch 1 in phase "a", as shown in Fig. 6b.



a)

b)

Fig. 6. Schemes of post-emergency mode with sustained damage: a – damage on the semi-phase «c1»; b – damage on the phase «b».

Increased economic efficiency

The optimal conditions of a traditional overhead line is the transmission of natural power, which for a 500 kV overhead line is rounded 900 MW and, respectively, for two circuits 1800 MW. According to the condition of heating losses, the total cross-section of phases and semi-phases in the single-chain version is assumed to be equal to the total cross-section of phases of the double-chain line.

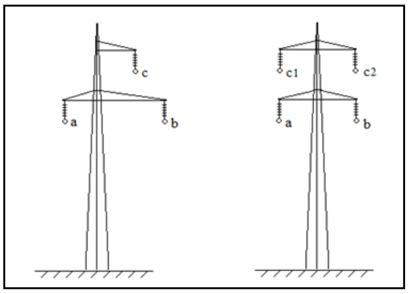
Reliable technical and economic information is available at the level of 2000 [12], and therefore a comparative analysis is made in the prices of this period, which is quite acceptable with comparative estimates.

The cost of a single-circuit three-phase line on steel supports in the range of HV and EHV is quite accurately extrapolated by the dependence

$$K_{3ph}(U_n) = a \cdot e^{bU_n} \qquad (11)$$

where the coefficients a, b are determined based on the cost of 220 and 330 kV voltage lines.

Figure 7 shows the free-standing supports of the traditional single-circuit line [13] and the innovative single-circuit line, which shows that an additional wire is added to the innovative line and its cost increases by the suspension of this wire.



a) b)

Fig.7. Intermediate supports: a - traditional three-phase line; b - innovative line

According to [14], the cost of wires and insulation is approximately 40% of the cost of the line. Then the capital investment in the innovative line, taking into account the suspension of the additional wire, will be

$$K_{in}(500) = (1 + \tfrac{0,4}{3}) K_{3ph}(500) \qquad (12)$$

The unit cost of the line depends significantly on the cross-section, and it can be estimated using the linear dependence of the cost on the total cross-section of all phases

$$K_{in} = 2,72 + 0,45 \cdot 10^{-3} S, \text{ million·rubles/km} \qquad (13)$$

As a result, we obtain the unit cost of an innovative line with free-standing supports, which with its total cross-section 3*6*330 mm^2 will amount to 5.4 million rubles/km.

The unit cost of two circuits on different free-standing supports according to [12] is 8.0 million rubles/km.

For the above data, Table 2 presents a technical and economic comparison of a two-circuit traditional line with a single-circuit innovation line, which shows a noticeable economic advantage of the innovative option.

Table 2 Technical and economic indicators of two-circuit traditional and single-circuit innovative lines

Line type / Parameters		Two cicuits of traditional overhead lines on different supports	Single-circuit innovative overhead line (compact design)
Transmitted power, MW		1800	1800
The cost of the line, million rubles		4000	2700
Installed capacity of the SC and its cost	Qsc, MVar	-	250
	Ksc, million rubles	-	150
Total capital investments	million rubles	4000	2850
	%	140	100

Conclusions

In this article, a new type of single-circuit EHV line is justified, the capacity of which exceeds that for a traditional line by two times. In addition, the proposed line has increased reliability, allowing, in case of sustained failures, to switch to operation in post-emergency mode with the possibility of transmitting at least 50% of the power of the initial maximum conditions.

A technical and economic comparison of two-circuit traditional and single-chain innovative lines with a voltage of 500 kV, a length of 500 km and a capacity of 1800 MW showed that the capital costs in the two-circuit version are 40% more than in the innovative version.

References

1. I.M. Bortnik, 1200 kV Transmission Line in the USSR. The First Result of Operation, CIGRE (1988)
2. H.K. Xie, K. Mu, EHV Transmission and its Insulation: Under Planning and Construction in China, IEEE Electrical Insulation Magazine, **15**, 2 (1999)
3. G. Trudel, S. Bernard, G. Scott, Hydro-Quebec's defense plan against. extreme contingencies, IEEE Trans. Power Systems, **14**, 3 (1999)
4. A.O. Silva, H.P. Chagar, A.O. Filho, H.A Magalhaes., D.C. Barros, O.P. Santos, J.B. Silva, R.P. Guimaras, Reliability and Upgrading Studies of The 765 kV Itaipu Transmission System, CIGRE, (2000)
5. H. Zhou, Y. Su, Y. Chen, Q. Ma and W. Mo, The China Southen Power Grid, IEEE power & energy magazine, (2016)
6. A.F. Dyakov, The electric networks of super- and ultra-high voltage UES of Russia: theoretical and practical issues, Moscow: Energoprogress Corporation EEEK Publ., 2012, 696 p.
7. J. Arrillaga, Y.H. Liu, N.R. Watson, Flexible Power Transmission, The HVDC Options, John Wiley &Sons, Ltd, (2007)
8. L. Yafang, Y. Yichao, W. Huiren and others. Study of 500 kV compact transmission technology, CIGRE, (1998)
9. J. Gingras, R. Mailhot, J. Lavergne, Review of The Hydro-Quebec System operation with Series Compensation, CIGRE, (2000)
10. G. I. Samorodov, T. G. Krasilnikova, V. P. Dikoy, S. M. Zilberman and R.A. Iatsenko, *Non-Conventional Reliable AC Transmission System for Power Delivery at Long and Very Long Distances*, in Proc. 2002 IEEE/PES Transmission and Distribution Conference, Vol.2, Yokohama, Japan, (2002)
11. G. I. Samorodov, T. G. Krasilnikova, Patent No. 2765656, Single-circuit power transmission line of high or extra high voltage, Date of state registration in the State Register of Inventions of the Russian Federation 01.02.22. Bull. No. 4.
12. Handbook on the design of electrical networks, Ed. D.L. Faibisovich. - 3rd ed., revised. and additional, ENAS, (2009)
13. Handbook of high voltage electrical installations. Ed. I.A. Baumstein and M.V. Khomyakov, Energy, (1974)
14. G.N. Aleksandrov et al. Designing ultrahigh voltage transmission lines, Ed. G.N. Alexandrov and L.L. Peterson, Energoatomizdat, (1983)