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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

COMPUTER MODELLING OF SWITCHING OVERVOLTAGES IN INTERSYSTEM ELECTRIC POWER TRANSMISSION

Specialty: 3341.01- Power plants (electrical part) and power systems.

Field of science: Technical sciences

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The thesis research took place at the High Voltage Physics and Technology laboratory of the Institute of Physics of the Ministry of Science and Education of the Republic of Azerbaijan.

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CHARACTERISTICS OF THE WORK

Relevance of the topic and the degree of elaboration.

It is a well-known fact that the economic conditions of any country are influenced by the state of its electric power industry. As evidenced by modern development, the rapid rise in demand for electricity leads to a significant increase in energy capacity and the construction of digital substations that are aligned with new modern technologies. Similarly, it results in boosting the transmission capacity of overhead power lines (OHL)and fulfilling their needs.

The country is transforming from an energy importer to an energy exporter thanks to the fast development of electric power industry, which is also resulting in dynamic economic growth.

The appropriate energy exchange strategy must be pursued in parallel with the increase in electricity production. Establishing interconnections between countries in energy exchange, improving transit options, and synchronizing energy systems are all vital elements in the electricity market of those countries. To accomplish this objective, it is important to implement high-level requirements for power production, transmission, and uninterrupted management of the power system.

Maintaining the stability and reliability of inter-system power transmission lines at higher voltage remains a significant challenge for the electric power industry. The development of electricity exchange between countries necessitates the solution of this problem in an economically viable manner that improves over time. Inter-system power transmission lines play a vital role in the exchange of energy between countries. In today's world, there is a close collaboration between the energy systems of developed and developing countries.

Close coordination is necessary to reduce the economic costs of lines for transmitting electricity over long distances, address environmental problems, and ensure their reliable operation.

Increasing the transmission capacity of long-distance power transmission lines, ensuring reliable operation of interconnectors, protecting the system and ensuring its transient stability are the main concerns from this point of view.

Long-distance power transmission, including inter-system transmission, has a problem with the limitation of switching overvoltages.

Methods for limiting atmospheric and switching overvoltages have been studied since 1921, when the International Council on Large Electric Systems (CIGRE), a global commercial entity focused on high-voltage electrical power, was founded in Paris, France. The organization's activities have led to the discovery of new problems that are currently awaiting solutions, in addition to the existing issues with massive, powerful power transmission lines that span 1,000-2,000 km annually on a regional and global scale.

In order to develop Azerbaijan's electrical energy policy, it remains a priority to conduct research in compliance with modern requirements for long-distance double-circuit overhead lines with a voltage class of 500 kV that extend over 500 km and more than 1000 km.

Academician Chuvarly C.M. and his school, along with Tikhodeyev N.N. and Kostenko M.V., who created prominent schools in the former USSR, are examples of scientists who studied the overvoltages and their limitation in long-distance power transmission lines.

In our country, Dmitriyev E.V., Shidlovski A.K., Antipov K.M., Lazymov T.M., Gadimov Y.B. and other scientists and specialists from the High Voltage Physics and Technology Laboratory of the Institute of Physics of the Ministry of Science and Education and the Azerbaijan Scientific Research and Design Institute of Energy of the Republic of Azerbaijan have played an important role in developing mathematical methods and models to calculate transient electromagnetic wave processes in power grids, while considering protection devices against switching overvoltages.

According to experiments, the majority of frequent switching overvoltages during electricity transmission over long distances are accidents caused by the length of the lines. Increasing the length of the line and voltage class also leads to an increase in the voltage in the grid elements.

In backbone long-distance transmission lines, inductive and capacitive reactive powers have an impact on load carrying capacity and cause losses. Besides, system and chain failures can occur as a result of insulation damage, equipment failure, the effects of overvoltages resulting from radial and non-radial load switching, lines and transformer tripping, etc, which is considered a critical situation for systems and equipment.

It has been proven by studies that shunt reactors (SR) that are unregulated and do not change parameters in 500 kV long-distance power transmission are exposed to several overvoltage effects[1]. The operating conditions of the insulation are aggravated by this situation. Because the voltage may go beyond the maximum permissible operating voltage. It has been noted that for OHL that have a voltage class of 500 kV and a length exceeding 380 km without shunt compensation, if the feeding current of the arc exceeds the critical limit when the damaged phase is opened, the arc cannot be successfully extinguished on its own. This results in a complication when operating auto-reclosing (AR) in single-phase short circuits. During switching events, such situations cause the operation of the AR to fail. Besides, the power system's stability level is reduced when the automatic recloser's current-free interval is longer than the recommended 1-2-second interval[2].

It has been discovered that the reactive power generated by self-excitation on the line side can be more than what is required during extreme voltages caused by load switching.

Higher reactive power output results in overloading, whereas lower output results in low current. Line tripping can occur in both mutual limits. Managing the overvoltages that occur during planned and emergency modes in long-distance power transmission is a significant concern.

Thus, in addition to these situations, it is necessary to examine electromagnetic wave processes in long-distance transmission lines,

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[1] Hamza, A.H, Samy, M.G, Ahmed, M.E, Ahmed S.Sh. Statistical analysis of switching overvoltages and insulation coordination for a 500 kV transmission line // IEEE-MEPSON Eighteenth International Middle East Power Systems Conference. Cairo, Egypt, - 2016, p. 683-686.

[2] Panasetsky, D.A, Alexey, B.O. On the problem of shunt reactor tripping during single-and three-phase-phase auto-reclosing // IEEE Eindhoven Power Tech. Eindhoven, Netherlands, - 2015, - p. 1-6.

which indicates the importance of a comprehensive approach and research to the matter.

To achieve this, digital technologies must be utilized to limit overvoltages in line with modern-day requirements, using mathematical models and computer technology. Further development and improvement of methods for managing intellectual and integrative activities is also required.

The research object and subject. Ensuring stability by limiting switching processes in complex electrical systems. Neutral ungrounded reactors (UR) connected in parallel to SRs are used in this research to address the limitation of overvoltages that can arise during switching in single- and double-circuit long-distance power transmission lines. Full-phase and non-full phase modes are used, with or without a star-connected parallel neutral UR at the start and end of the lines.

The purpose and objectives of the research. Development of methods for mathematical modelling of non-linear electrical circuits with distributed parameters. Improving the reliability of long-distance power transmission, including inter-system power transmission by applying neutral URs. The primary objective of the thesis is to reduce switching overvoltages in long-distance power transmission, enhance the transient stability of the system, and develop plans for optimal operation conditions.

Research methods. Mathematical modelling methods for linear and non-linear electrical circuits were used. During the research, various methods and techniques were used to simulate real systems and switching modes, including the Matlab and Matlab Simulink programs for bulk parameter circuits, and the programs and subprograms developed at the Institute of Physics of the Ministry of Education and Science of the Republic of Azerbaijan for distributed-parameter circuits (dissipative factors - skin effect on the ground and wires, corona effects on phase wires).

The main provisions presented for the thesis defense:

1. Examining and describing ways to reduce switching overvoltages, taking into account the neutral UR in long-distance power transmission;

2. Formulas for calculating electromagnetic wave processes in single- and double-circuit power transmission lines, and their detailed

numerical calculations;

3. Calculation equations of the analysis scheme and the method of solving the problem, incorporating the SR and neutral UR at the start and end of the lines in full-phase and non-full phase modes for long-distance power transmission by choosing different lengths;

4. Methods to develop an algorithm for calculating electromagnetic wave processes in multi-circuit inter-system power transmission lines;

Scientific innovations in the research. The research involved examining the influence of steady-state modes of transition processes in power transmission over long distances, taking into account the SR and neutral UR, and developing algorithms for mathematical modelling.

The **main scientific findings** in the thesis are outlined below:

1. A number of measures have been put forward to reduce switching overvoltages by incorporating a neutral UR in long-distance power transmission [1, 3, 5].

2. Comprehensive numerical calculations have been developed for switching overvoltages, which considers non-traditional compensation in single- and double-circuit power transmission lines.

3. The general mathematical model's structure and capabilities were enhanced by utilizing the bivariate cubic spline interpolation function method, which took into account dissipative factors.

4. An algorithm for calculating electromagnetic wave processes in multi-circuit inter-system power transmission lines was developed [12].

5. Curves for maximum phase voltage variation were created and analyzed by including a SR and neutral UR at the start and end of selected length lines.

The theoretical and practical significance of the research. In the case of long-distance power transmission lines, when combined shunt compensation was applied, the analysis scheme's calculation equations were set up, and a mathematical model of the system was generated. The developed method, mathematical modelling, algorithm, and software package make it possible to conduct accurate numerical and comparative analyses of electromagnetic wave processes under laboratory conditions.

The practical significance of the research is that it is a project with a scientific content that requires financial resources and will be addressed in the near future. Proposals have been submitted to the Azerbaijan Scientific Research and Design Institute of Energy and other relevant design bureaus. The research results will be utilized and referenced in the creation of justification documents.

Approval and implementation. The main provisions of the thesis were presented and discussed at the meetings of the Scientific Council of the Institute of Physics of the Ministry of Science and Education of the Republic of Azerbaijan, and at the scientific and technical conferences and forums listed below: "The 10th International Conference on Technical and Physical Problems of Electrical Engineering" (Azerbaijan), "The 11th International Conference on Technical and Physical Problems of Electrical Engineering (Romania-2015), "The 12th International Conference on Technical and Physical Problems of Electrical Engineering" (Spain-2016), "The 13th International Conference on Technical and Physical Problems of Electrical Engineering" (Turkey-2017), ICTPE, The 16th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2020) Istanbul, Turkey and International Conference on Electronics, Computing, Communication & Control technology (ICECCC-2024), Bangalore, India.

Name of the organization where the research was conducted. The thesis research took place at the High Voltage Physics and Technology laboratory of the Institute of Physics of the Ministry of Science and Education of the Republic of Azerbaijan.

The total volume of the thesis expressed in characters, with each section being indicated individually. The thesis consists of an introduction, four chapters, a conclusion, a list of references, and appendices. The main content of the research is conveyed through 163 pages, 52 images, and 11 tables. 108 sources and 11 websites are included in the references. The thesis, in terms of characters and sections, is roughly distributed as follows:

Overall: 171213 characters; Introduction – 21,224 characters, Chapter 1 – 48,367 characters; Chapter 2 – 52,837 characters; Chapter 3 – 24,062 characters; Chapter 4 – 25,345 characters; Conclusion – 1,696 characters.

SCOPE

The **Introduction** covers the relevance of the topic, the scientific purpose of the thesis, its scientific and practical significance, the scientific innovations achieved, the main provisions presented for defense, the approval, structure, and brief summary of the research work.

In the **first chapter**, the focus is on the main measures to ensure stability by limiting transient processes in complex electrical systems, sources of reference for modelling and controlling transient electromagnetic processes, and in particular, compensating devices to minimize switching overvoltages during long-distance power transmission. By analyzing the references, a comparison was made between the current state of the developed research methods and the results, including the limitation of switching overvoltages, their role during various fault modes, and the factors that affect them. Comparative results revealed that one of the most significant areas of interest is the protection of long-distance power transmission lines from overvoltages during planned and emergency modes. Events such as reactive power generated on the line side during overvoltages caused by load switching, switching processes at load nodes during large and small excitations, lines operating unloaded, single- and three-phase short circuits, excess reactive power caused by charging powers, interphase capacitance compensation, etc. are inevitable. It has been established that since a line with a length exceeding 300-350 km that operates without load acts as a reactive power source, the passage of capacitive current through the generators is deemed to be an undesirable mode for the grid. Converting generators into reactive power operators has a negative impact on their operation, causing instability. Moreover, when the voltage on the transmission lines is high, the capacitance of the line leads to displacement currents, which causes the line to be unstable and the permanently connected equipment to fail.

The chapter continues by exploring the duration of the primary protection activation equipment on the long line and how the protection operates during switching events. It has been proven that in order to guarantee reliable operation of networks with a voltage of 500 kV or higher, the main protective switching equipment of the line must not exceed permitted limits. The experiments conducted have shown that in single-phase short circuits with an average length of 100-300 km when SRs are connected at the start of the line, the feeding arc current during the automatic recloser operation is not higher than 30A, the current-free break does not exceed 0.5 seconds and, as a result, a decrease in the feeding arc current is achieved by using compensating reactors connected to the neutral of SRs during the current-free break. However, in the presence of high powers and voltages, and when the line has a geometry that is excessively long, the main protection switching equipment of the line may not respond quickly enough during switching processes, causing delays. Such flaws are viewed as critical for the power transmission system.

In order to fix these shortcomings, it has been suggested to have a neutral UR installed in parallel with the SR at the start and end of the power transmission line in accordance with the scheme selected in Figure 1, which provides interphase capacitance compensation and optimizes the transient stability of the system on long-distance transmission lines with higher voltages. The objective of combined shunt compensation is to reduce overvoltages in power transmission that has higher voltage and long distances, compensate for interphase capacitance in lines, and enhance reliability.

The primary concept of combined shunt compensation is that compensating reactors are used in the neutral of SRs in traditional shunt compensation, but this is not the case in combined shunt compensation. Here, special ungrounded reactors are employed with

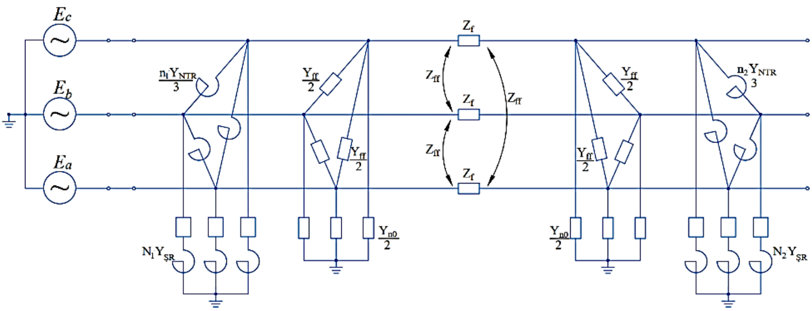

Figure 1. Replacement scheme for SRs and neutral URs in three-phase power transmission line

the neutral connected in an ungrounded star scheme, which allows the connection of only one phase of the SRs, which is similar to the phase where the short circuit took place. This results in an increase in the reliability of the power transmission line during the AR break due to the reduction in the number of devices switched during the AR and the increase in the level of transient stability of the system.

The implementation of AR on higher voltage lines is made easier by using combined shunt compensation[3].

Firstly, traditional compensation no longer requires compensating reactors connected to the neutral of SRs, and secondly, to reduce the feeding arc current, it is sufficient to connect only one phase of the SR same as the phase where the fault occurred, which prevents the existing fault from deteriorating during the protection's instant operation.

The chapter continues with a focus on the effectiveness of single-phase AR in high-overvoltage power transmission lines equipped with combined shunt compensation , the role of compensation devices during switching overvoltages in long-distance power transmission, and the analysis of flexible alternating current transmission systems (FACTS), as well as the analysis of corridor requirements and measures to reduce harmful effects and protect the environment as part of the design of overhead power transmission lines.

Thus, the following aspects should be given attention in light of the conclusions derived from the analysis of scientific and technical references:

- The capabilities of reliability models for switching process control systems in long-distance power transmission should be expanded.
- In order to increase the combined shunt compensation rate in single- and double-circuit long-distance power transmission lines, and on the other hand, to eliminate the shortcomings that are inherent in shunt compensation, it is necessary to revisit line protection issues.

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[3] Krasilnikov, E.N., Samorodov, G.I, Zilberman, S.M, Krasilnikova, T.G. The combined shunt compensation of EHV lines // IEEE EPEC Electrical Power and Energy Conference Advanced Technologies for Emerging Power Systems. Winnipeg, Canada: -2011, - p. 20-24.

➢ Real distributed-parameter nonlinear electrical circuits require a thorough analysis using mathematical modelling methods.

➢ Developing a calculation algorithm for electromagnetic wave processes in multi-circuit inter-system power transmission lines is a promising prospect.

The chapter concludes with a discussion of the Azerbaijan's role in energy exchange with neighboring countries, the stages of development of regional cooperation and commercial relations, the new energy corridor projects, as well as the activities to be carried out in the near future to ensure its integration into the Energy Regulatory System of the Black Sea and Mediterranean countries, as well as the global electricity market of Central Asia and Europe. It was acknowledged that smart projects are crucial for Azerbaijan from both a political and economic perspective.

The primary conclusions of Chapter 1 are reflected in the author's publications [1, 3].

The second chapter is focused on mathematically modelling electromagnetic wave processes in complex multi-wire power transmission lines.

The equations for electromagnetic wave processes in distributed-parameter multi-wire power transmission lines are presented below, taking into account dissipative factors[4].

$$\begin{aligned} -\frac{\partial u}{\partial x} &= L_0 \frac{\partial i}{\partial t} + f\left(\frac{\partial i}{\partial t}, i\right); \\ -\frac{\partial i}{\partial x} &= C_0 \frac{\partial u}{\partial t} + \varphi\left(\frac{\partial u}{\partial t}, u\right) \end{aligned} \qquad (1)$$

Here L_0, C_0) are the inductive and capacitive matrices of the power transmission line according to geometric dimensions, *u*,*i*- are the column matrices of voltages and currents,$f\left(\frac{\partial i}{\partial t}, i\right)$-is a function that considers the impact of skin effects on the ground and wires, $\varphi\left(\frac{\partial u}{\partial t}, u\right)$-is a

4 Problems of mathematical modeling in the problem of increase of reliability of high-voltage electric networks / Ch.M. Juvarly, E.V. Dmitriev, A.M. Gashimov //Izv., Academy of Sciences of Azerbaijan, series Phys.-Techn. and mat. Sciences, - Baku: - 1999. No. 6, - p. 128-133.

function that takes into account the effect of the corona phenomenon on wires. The selection and application of reactors in multi-wire conductors is a concern that must be addressed, which means that the issue of losses in conductors is also pertinent. Electromagnetic compatibility is greatly impacted by double circuit lines, which is why it's crucial to consider transition and quasi-stable modes when choosing reactors. In the two-circuit long-distance power transmission line according to the scheme selected in Figure 2, taking into account a neutral UR connected in parallel to the SRs at the start and end of the line, these expressions determine the equations of the nodal points at the start and end of the line:

$$
\begin{array}{cc}
\text{I} & \text{III} \\
e(t) = L_T \dfrac{di}{dt} + u_1; & e'(t)' = L_T \dfrac{di}{dt} + u'_1; \\
u_1 = L_1 \frac{di_{r1}}{dt};\ u_1 = L_2 \frac{di_{r2}}{dt}; & u'_1 = L'_1 \frac{di_{r1}}{dt}; u'_1 = L'_2 \frac{di_{r2}}{dt}; \\
u_1 = L_{wi} \dfrac{di_{w1}}{dt} + u_{w1} & u'_1 = L'_{w2} \frac{di_{w2}}{dt} + u'_{w2} \\
u_1 = L_{w2} \frac{di_{w2}}{dt} + u_{w2} & u'_1 = L'_{w2} \frac{di_{w2}}{dt} + u'_{w2}
\end{array}
\qquad (2)
$$

the column matrix for voltage and current can be expressed in the following way:

$$
u = \begin{vmatrix} u_{a1} \\ u_{b1} \\ u_{c1} \end{vmatrix}, i = \begin{vmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{vmatrix}, L = \begin{vmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{vmatrix}, C = \begin{vmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{vmatrix}
$$

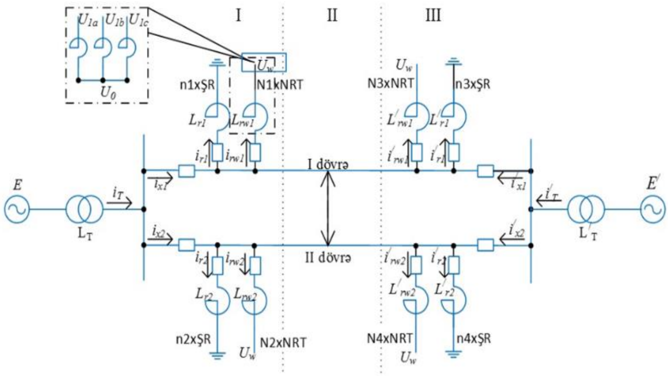


Figure 2. When n a two-circuit power transmission line, the SR and the neutral UR are at the start and end of the line

When considering the chosen calculation scheme, the calculations for the intermediate points at the beginning (I) and at the end (III) of the circuit can be expressed using the following formula:

Side I	Side III	
$-u_1 + (Z + Z_n)i_{x1} = v_{q1};$	$u'_1 + (Z + Z_n)i'_{x1} = v'_{p1};$	(3)
$-u_1 + (Z + Z_n)i_{x2} = v_{q2};$	$u'_1 + (Z + Z_n)i'_{x2} = v'_{p2}.$	

$$v_p = Z_n\left(i_d - \sum_{k=1}^{n} \varkappa_k i_{fk}\right) + hZ\mathrm{g}_0 U_d$$

$$v_q = Z_n\left(i_d - \sum_{k=1}^{n} \varkappa_k i_{fk}\right) - hZ\mathrm{g}_0 U_d$$

Where: v_q, v_q- energy loss when an electromagnetic wave travels along a line, g_0-conductivity per unit length of line, Z_n-is the wave resistance that accounts for the skin effect.

The expressions for SRs and neutral URs can be described like this:

$$Y_{SR} = -j \cdot B_{SR},\, B_{SR} = \frac{Q_{SR}}{U^2},$$

$$Y_{UR} = -j \cdot B_{UR},\, B_{UR} = \frac{Q_{UR}}{{U_{ig}}^2}$$

Here, Q_{SR} is the power of the SR, Q_{UR} is the power of the neutral UR, and U_{ig} is the operating voltage of the line.

The voltage at the neutral of the neutral UR can be measured in the following manner:

$$u_0 = \frac{u_{1a} + u_{1b} + u_{1c}}{3};$$

According to the specified mathematical model, calculation were made by selecting different lengths in a single-circuit long-distance power transmission line with a voltage class of 500 kV, with and without SRs and neutral URs in full-phase and non-full phase modes, the values of the maximum phase voltages at the start and end of the line were obtained, and the variation curves of each were provided separately[5]. The calculations were conducted in the following order:

- 380 km - with SRs and neutral URs in full-phase and non-full phase switching of line modes;
- 560 km - with SRs and neutral URs in full-phase and non-full phase switching of line modes;
- 740 km - with SRs and neutral URs in full-phase and non-full phase switching of line modes;
- 740 km - with only SRs in full-phase mode;
- 740 km - with only SRs in non-full phase switching of line modes;

The corresponding results for each phase are shown in Table 1 when the SRs and neutral URs are included at the start and end of the 380, 560, 740 km long distance transmission line, and also when only SRs are included in a 740 km long line.

The primary conclusions of Chapter 2 are reflected in the author's publications [2,5,8].

The third chapter focuses on the calculation algorithm for electromagnetic switching processes, taking into account neutral URs, based on the mathematical model established for a multi-circuit power transmission line. The characteristics of electromagnetic switching processes in multi-circuit long-distance power transmission lines were studied by developing a calculation algorithm, selecting schemes for the analysis of switching overvoltages, and using the proposed mathematical model.

Creating and analysing the calculation algorithm.

The most accurate and practical method for generating overvoltages in higher voltage power transmission lines is computer programs capable of jointly solving transient processes and modelling multi-wire power transmission lines.

[5] A. M. Hashimov, R.N. Huseyn. Non-traditional compensation in intersystem power transmission lines excessive switching voltage. The 11th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2015), Bucharest, Romania, 10-12 September 2015, Pp. 102-105

Table 1
Results of maximum phase voltage values.

Line mode	Line length l=km	Start of the line			End of the line			Reac Neut
		I Phase $\frac{u_1}{Ufm}$	II Phase $\frac{u_1}{Ufmax}$	III Phase $\frac{u_1}{Ufmax}$	I Phase $\frac{u_1}{Ufmax}$	II Phase $\frac{u_1}{Ufmax}$	III Phase $\frac{u_1}{Ufmax}$	$\frac{U_N}{Un}$
Full phase	380	1,06	1,04	1,16	1,23	1,15	1,22	0
Non-full phase	380	0,95	1,1	1,19	1,26	1,13	1,18	0
Full phase	560	1,1	0,93	1,08	1,13	1,02	1,16	0
Non-full phase	560	0,99	0,98	1,19	1,18	1,96	1,37	0
Full phase	740	1,19	1,11	0,99	1,35	1,47	1,11	0
Non-full phase	740	1,14	1,13	0,71	1,53	1,27	0,29	0
Full phase only with SRs	740	1,27	1,25	0,24	1,85	1,87	0,46	0
Non-full phase only with SRs	740	1,21	1,22	1,60	1,79	1,73	1,63	0

It is very complicated to design three-phase protection devices that fit every combination of parameters and circuits in shunting reactors and reactors with ungrounded neutrals and analyze their variances. Repetitive impulse overvoltages between the contacts of the circuit breakers causing dangerous overvoltages and high-frequency currents in the secondary circuit is an important issue.

By addressing such issues in two stages, it is possible to significantly improve the effectiveness of research and analysis processes. The initial stage involves selecting a calculation scheme and then analysing the qualitative effects of scheme parameters and protection devices on the characteristics of switching processes. In particular, the voltage level and changes in circuit characteristics, parameters, and protective devices during SR opening and closing are determined over a wider range, which allows for testing optimization with the help of a mathematical model.

The operations performed in the equipment are based on established algorithms when examining overvoltage protection methods. The algorithm utilizes the volt-ampere characteristics of linear and nonlinear protection devices, which, taking into account the skin effect, specifies the parameters of specific resistances and inductances, as well as mutual resistances and inductances between the ground and the wires, and between the wires themselves.

The algorithm that has been developed focuses on saving machine time and simplifying the analysis process for analyzing switching overvoltages in complex multiphase circuits.

In the thesis, a system of equations describing electromagnetic wave processes is formulated according to the scheme developed, and then using an analytical joint solution of the system of algebraic equations, the formulated schemes are applied. Based on these equations, a program is written to numerically experiment and calculate switching processes through switches during switching overvoltages. The programming language of the algorithm is used to implement the compiled program. The first step in writing a program involves creating a block diagram of the problem-solving algorithm and then designing the program accordingly.

The algorithm is defined by the following stages in the initial data sequence:

- ➢ parameters of specific resistances and inductances, mutual resistances and inductances between ground and wires and between wires,
- ➢ The parameters of the model, considering the connection of contacts based on the value of the maximum phase voltage in the power transmission line,

- calculation of voltage and current at the start and end of the line,
- establishing basic coefficients for power transmission line calculation formulas,
- calculation of currents and voltages at intermediate points between the power transmission line and the reactor, taking into account the connection moment,
- calculation of voltage and current at the nodal points of the presented scheme.

One or more logic problems can be solved using branching algorithms through the method described by the algorithm.

Cubic spline interpolation method.

Polynomials can be utilized to solve complex solvable differential equations and approximated descriptions of nonlinear resistances to obtain the required solution. It is common knowledge that the accuracy of the spline in the calculations conducted is determined by the number of points provided. In programming the algorithm of a model based on mathematical equations, one of the important requirements for the algorithm is to obtain more accurate approximations, increase the smoothness of the obtained curves, speed up the reporting process, and not make it complex. To approximate the values of the curves obtained from the switching process at other points, a method for numerically computing differential equations on a two-dimensional grid has been developed (linear and quadratic interpolation, smooth completion of the grid function) and used. Cubic spline interpolation is advantageous over other methods because it allows for more accurate results and smoother curves by calculating the coefficients of the interpolation polynomial. This mathematical method has the advantage of creating a smooth and accurate interpolation curve based on discrete known points.

In order to calculate wave processes for the research, we'll first take into account a difference scheme that approximates the power transmission line equations (Finite difference method), as shown in

Figure 3. Figure 4 shows a new three-dimensional computational grid that has been developed.

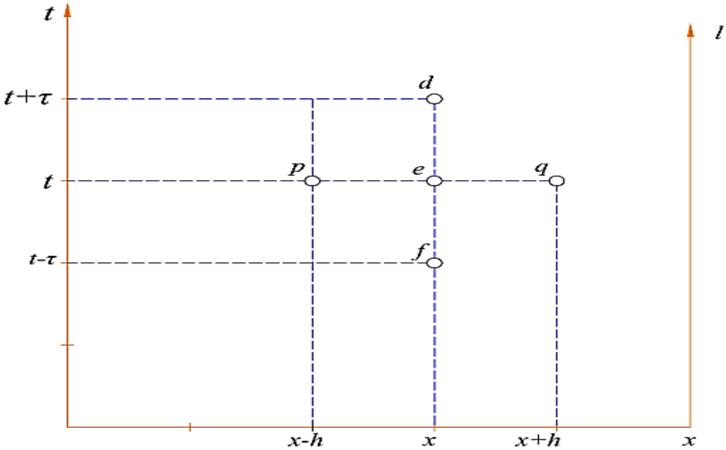


Figure 3. Difference scheme for approximating power transmission line equations.

To figure out the currents and voltages at the points within the computational grid, the cubic spline interpolation function method is employed, and the bivariate cubic spline polynomial in the segment g(x, y) is defined as follows[6]:

$$g(x,y) = g_{k,l}(x,y) = \sum_{i,j=0}^{3} a_{i,j}^{k,l}(x_k - x)^i (y_l - y)^j, \qquad (4)$$

where, *k=1,2,3,...,(0,t),(2h,t),(4h,t),...,(2nh,t). n-* is the number of coordinate support points.

[6] Marchuk, G.I, Numerical Methods and Applications. – Boca Raton: CRC press, - 1994. – 282 p.

$$g(x_{i-1},y) = H_{i-1,j-1}\frac{(y_i - y)^3}{6\tau_i} + H_{i-1,j}\frac{\left(y - y_{j-1}\right)^3}{6\tau_i} + \left(f_{i-1,j-1} - \frac{H_{i-1,j-1}\tau_j^2}{6}\right)\frac{y_i - y}{\tau_i} + + \left(f_{i-1,j} - \frac{H_{i-1,j}\tau_j^2}{6}\right)\frac{y - y_{j-1}}{\tau_i} \qquad (5)$$

where, $H_{ij} = g_{yy}\left(x_{i,}y_i\right), h_i = x_i - x_{i-1}, M_{ij} = g_{xx}\left(x_{i,}y_i\right), \tau_i = y_i - y_{j-1}$.

In the second chapter, the voltage and current at the coordinate points *(x, t)* of the double-circuit power transmission lines were calculated using formulas (4) and (5) based on the differential equation model describing electromagnetic wave processes according to the scheme depicted in Figure 2.

$$u_d = 0{,}5(1+\sigma)^{-1}\left[u_p + u_q + Z\left(i_p - i_q\right) - 2\sigma(\pm u_3)\right] + 2\theta_2$$

$$i_d = 0{,}5(Z+Z_n)^{-1}\left[u_p - u_q + Z\left(i_p - i_q\right) + 2\sigma(\pm u_3)\right] + 2\theta_1$$

$$\begin{aligned}
&u_{d_I} + (Z+Z_n)_I i_{d_I} + (Z+Z_n)_{I-II} i_{d_{II}} + (Z+Z_n)_{I-T} i_T = v_{p_I} + v_{p_{I-II}} + v_{p_{I-T,}} \\
&u_{d_{II}} + (Z+Z_n)_{I-II} i_{d_I} + (Z+Z_n)_{II} i_{d_{II}} + (Z+Z_n)_{II-T} i_T = v_{p_{II}} + v_{p_{I-II}} + v_{p_{II-T,}} \\
&-u_{d_I} + (Z+Z_n)_I i_{d_I} + (Z+Z_n)_{I-II} i_{d_{II}} + (Z+Z_n)_{I-T} i_T = v_{q_I} - v_{q_{I-II}} - v_{q_{I-T,}} \\
&-u_{d_{II}} + (Z+Z_n)_{I-II} i_{d_I} + (Z+Z_n)_{II} i_{d_{II}} + (Z+Z_n)_{II-T} i_T = v_{q_{II}} + v_{q_{I-II}} + v_{q_{II-T.}}
\end{aligned} \qquad (6)$$

Here, $u_p, u_{q,} i_p, i_q$ $p(x-h, t-\tau), q(x+h, t-\tau)$are the known values of the voltage and current column matrices at the points p and q of the multi-conductor power transmission line with the given coordinates.

Smoothing out the overvoltage curves obtained from the switching process requires a slight increase in the calculation period.

The method for reducing the calculation step.

In accordance with the three-dimensional computational grid proposed in Figure 4, after calculating the currents and voltages at the start and end of the line, the currents and voltages for the points *2h*, *4h*, *6h* , etc are also calculated from the computational grid *(t+τ)* moment. To enhance the precision of the curves obtained from the switching process and the speed of computation, the step is reduced during the calculation and the grid scheme is chosen to ensure that the coefficients of the expressions remain unchanged. The method of reducing the calculation step involves selecting the maximum possible calculation step between the initial discrete points of the data. The coefficients of arithmetic expressions are determined according to this step. At a specific point in the calculation, the step is lowered, and extra points are artificially inserted between the known discrete points in the computational grid.

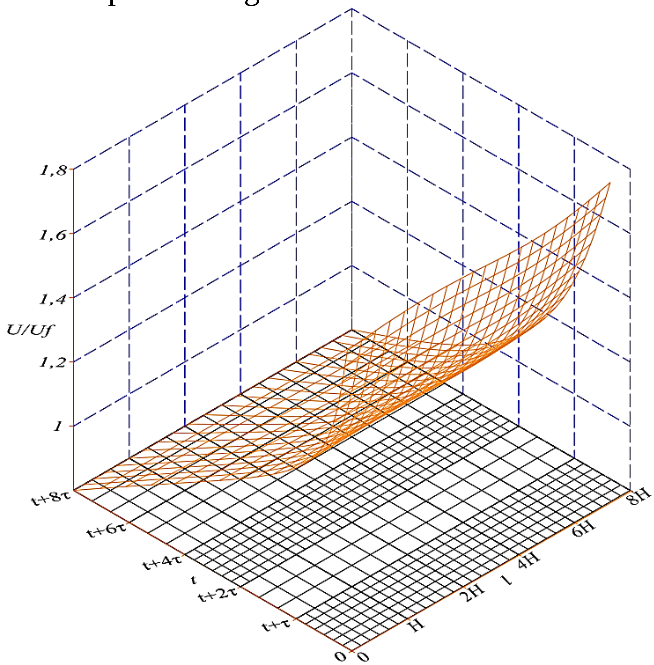
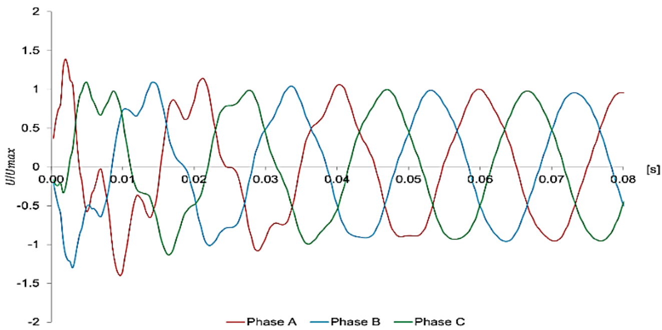
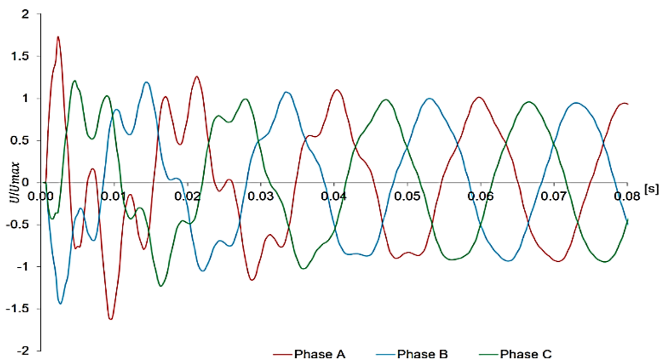


Figure 4. Three-dimensional computational grid

Using the voltage and current at the main fixed points of the grid, the voltage and current at the additional points are calculated. This reduced step is used to run the calculation for a specific period of time, and at some point, during the calculation, the previous value of the step is brought back, and the calculation continues with the initial step. The new values of voltages and currents at points $(0,t+nt)$, $(2h,t+nt)$,...$(1,t+nt)$ are calculated using spline polynomials based on their known values. Also, these values make it possible, with a smaller step in the direction of the moment $(0, 2t)$ at point x,



a)



b)

Figure 5. Calculation results: a) - with SRs and neutral URs at the start and end of the line, b) with SRs at the start and end of the line (without neutral URs)

The curves of the results that were derived from the calculations done using the method and algorithm developed in Chapter 3 are displayed in Figure 5. The calculation includes options a) with SRs and neutral URs at the start and end of the line, and b) with only SRs on the line (without neutral URs).

The research results reveal that the jumps in the change of the overvoltage occur at intervals of releasable limit during the periods 1, 2, and when there are no neutral URs on the line, the overvoltage curves become more prominent. The calculation is based on the assumption that that all three phases will close simultaneously when the line is connected.

The primary conclusions of this chapter are reflected in the author's publications [6,7,12].

The **fourth chapter** deals with the protection issues related to overvoltages arising from emergency switching modes in single-phase multi-circuit long-distance power transmission with one-way feeding. A mathematical model has been developed to analyze the feasibility and use of nonlinear overvoltage limiters (OVL) and neutral URs during single-phase short circuits.

The moment when single-phase short circuits open and close in combined shunt compensation in a long-distance power transmission line powered by a unilateral source was considered as per the developed scheme. It has been shown that single-phase short circuits up to $80 - 90\ \%$ have an unstable nature on higher voltage lines, so they must be eliminated during short-term power-off periods. When an accident occurs, the line is opened and reclosed as follows:

after an accident occurs, the load on the line is first switched off, and then the same-named SR is connected to the line in the phase where the fault occurred, while allowing the arc current to decrease and the arc to successfully extinguish itself during the operation of the single-phase automatic recloser. After a certain period of time, which is known as a “break without current”, it automatically reconnects. During the break without current, the residual arc in the separated part should extinguish and the separated part should deionize. After the arc is extinguished, the system goes back to normal, and the SR is unattached from the line.

First of all, to enhance the accuracy of the mathematical model of these processes, a mathematical model of the expressions below was developed using the matrix approach, taking into account neutral URs and non-linear overvoltage limiters in the research work.

The expressions are described as follows when there are non-linear overvoltage limiters on the line:

$$\frac{di_{\mathrm{OVL}}}{dt} = L_{\mathrm{OVL}}{}^{-1}(u_1 - u_{\mathrm{OVL}}),$$

$$i_{OVL_I} = \begin{vmatrix} u_{OVL_a} \\ u_{OVL_b} \\ u_{OVL_c} \end{vmatrix},$$

$$i_1 \begin{vmatrix} i_A \\ i_B \\ i_C \end{vmatrix}, i_{\c{s}r1} \begin{vmatrix} i_{\mathrm{sr}A} \\ i_{srB} \\ i_{srC} \end{vmatrix}, i_e \begin{vmatrix} i_A \\ i_B \\ i_C \end{vmatrix}, i_{ntr1} \begin{vmatrix} i_{UR1A} \\ i_{UR1B} \\ i_{UR1C} \end{vmatrix}, u_e \begin{vmatrix} u_A \\ u_B \\ u_C \end{vmatrix}, U_n \begin{vmatrix} N_{n1} \\ N_{n2} \\ N_{n3} \end{vmatrix},$$

where u_A, u_B, u_C- are the phase voltages of the neutral UR.

In the event of a single-phase short circuit, the voltage value for a line being fed from a single-sided source is expressed in the following way:

$$U_{bqq} = K_{bqq} U_{yxg} \tag{7}$$

where U_{bqq} is the single-phase short circuit, K_{bqq} is the asymmetry coefficient in the short circuit mode, and U_{yxg}- is the voltage at the end of the unloaded line.

The voltage and asymmetry coefficient in no-load operation are determined as follows:

$$K_{bqq} = \left| e^{j\frac{2\pi}{3}} + \frac{1-m}{2+m} \right|, \tag{8}$$

where $m = \frac{Z_{d0}}{Z_d}, Z_d = \frac{B}{A}, Z_{d0} = \frac{B_0}{A_0}$ is the direct and zero-sequence input resistance relative to the short-circuit point, A, B, A_0, B_0, is the coefficient of the corresponding 4 polarity according to the direct and zero-sequence scheme, $e^{j\frac{2\pi}{3}}$ is the complex numerical phase multiplier. Where, the expression for the single-phase short-circuit mode can be written as follows when we take into account the dependence in expression (8):

$$K_{bqq} = \left| \frac{1-m}{(1+2m)U_{y.i.r}} + \frac{3m}{1+2m} e^{j\delta} \right| \tag{9}$$

where δ is the displacement angle between the e.m.f.'s.
The matrix form of expressions (8) and (9) is as follows:

$$K_{bqq} = \begin{vmatrix} \frac{1-m}{(1+2m)U_{y.i.r}} + \frac{3m}{1+2m} e^{j\delta} & -\frac{1}{3} L_1 L_2^{-1} & -\frac{1}{3} L_1 L_2^{-1} \\ -\frac{1}{3} L_1 L_2^{-1} & \frac{1-m}{(1+2m)U_{y.i.r}} + \frac{3m}{1+2m} e^{j\delta} & -\frac{1}{3} L_1 L_2^{-1} \\ -\frac{1}{3} L_1 L_2^{-1} & -\frac{1}{3} L_1 L_2^{-1} & \frac{1-m}{(1+2m)U_{y.i.r}} + \frac{3m}{1+2m} e^{j\delta} \end{vmatrix}$$

The corridor requirements for replacing single-circuit power transmission lines with double-and multi-circuit power transmission lines, as well as environmental issues, are also examined in this chapter.

It proposes utilizing a double-circuit pylon to transmit power over a long distance with a voltage class of 500 kV. Taking into account the geometry and skin effects of the proposed two-circuit pylon, the values for specific resistances and inductances between the ground and the wires, and between the wires themselves, as well as the values for mutual resistances and inductances were calculated within the $50 - 1000$ Hz interval. Their curves were shown and the way they changed was analyzed. Figure 6 shows the characteristics of the changes in the curves. The curves 1 and 2 represent mutual resistance and inductance, while curves 3 and 4 represent specific resistance and inductance. Table 2 shows the outcomes obtained from the research that was carried out.

In the conclusion, the results of the research conducted are summarized.

The primary conclusions of chapter 4 are reflected in the author's publications [3,9,10].

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Table 2.

Values of interphase mutual resistance and inductance in the range of 50-1000Hz

	1 − 2		1 − 3		1 − 4		1 − 5		1 − 6		1 − 7		1 − 8	
	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km	r, Om/km	$L \cdot 10^{-2}$ Hn/km
50	0.06738	0.65371	0.06738	0.65371	0.04042	0.61530	0.04712	0.61492	0.04733	0.63745	0.04630	0.56266	0.04628	0.56278
100	0.11417	0.58704	0.11417	0.58704	0.09234	0.54946	0.09255	0.54889	0.09312	0.57110	0.09037	0.49815	0.09032	0.49831
150	0.16045	0.54820	0.16045	0.54820	0.13659	0.51161	0.13696	0.51090	0.13797	0.53285	0.13312	0.46135	0.13303	0.46155
200	0.20614	0.52072	0.20614	0.52072	0.18002	0.48514	0.18056	0.48430	0.18208	0.50604	0.17485	0.43579	0.17472	0.43603
250	0.25119	0.49949	0.25119	0.49949	0.22278	0.46487	0.22349	0.46392	0.22559	0.48546	0.21575	0.41634	0.21558	0.41662
300	0.29559	0.48229	0.29559	0.48229	0.26494	0.44850	0.26585	0.44744	0.26855	0.46881	0.25593	0.40072	0.25572	0.40103
350	0.33938	0.46787	0.33938	0.46787	0.30658	0.43481	0.30768	0.43366	0.31104	0.45485	0.29548	0.38774	0.29523	0.38808
400	0.38263	0.45552	0.38263	0.45552	0.34775	0.42307	0.34905	0.42182	0.35310	0.44287	0.33446	0.37667	0.33416	0.37704
450	0.42541	0.44474	0.42541	0.44474	0.38849	0.41282	0.38999	0.41148	0.39476	0.43238	0.37392	0.36705	0.37258	0.36746
500	0.46776	0.43520	0.46776	0.43520	0.42882	0.40374	0.43053	0.40231	0.43605	0.42307	0.41090	0.35857	0.41052	0.35900
550	0.50974	0.42666	0.50974	0.42666	0.46878	0.39560	0.47070	0.39409	0.47700	0.41471	0.44844	0.35102	0.44801	0.35147
600	0.55140	0.41893	0.55140	0.41893	0.50840	0.38824	0.51052	0.38664	0.51763	0.40714	0.48557	0.34422	0.48510	0.34469
650	0.59276	0.41189	0.59276	0.41189	0.54768	0.38152	0.55002	0.37985	0.55796	0.40022	0.52231	0.33804	0.52180	0.33854
700	0.63385	0.40542	0.63385	0.40542	0.58665	0.37535	0.58920	0.37360	0.59799	0.39358	0.55869	0.33241	0.55813	0.33293
750	0.67469	0.39945	0.67469	0.39945	0.62533	0.36966	0.62809	0.36783	0.63776	0.38796	0.59472	0.32723	0.59412	0.32778
800	0.71529	0.39389	0.71529	0.39389	0.66372	0.36437	0.66670	0.36248	0.67726	0.38249	0.63042	0.32245	0.62978	0.32302
850	0.75566	0.38871	0.75566	0.38871	0.70185	0.35945	0.70504	0.35748	0.71651	0.37739	0.66581	0.31802	0.66513	0.31861
900	0.79580	0.38386	0.79580	0.38386	0.73971	0.35485	0.74313	0.35281	0.75552	0.37260	0.70090	0.31390	0.70018	0.31451
950	0.83572	0.37929	0.83572	0.37929	0.77733	0.35053	0.78096	0.34841	0.79430	0.36811	0.73571	0.31005	0.73494	0.31068
1000	0.87542	0.37498	0.87542	0.37498	0.81471	0.34646	0.81856	0.34428	0.83285	0.36387	0.77024	0.30644	0.76943	0.30710

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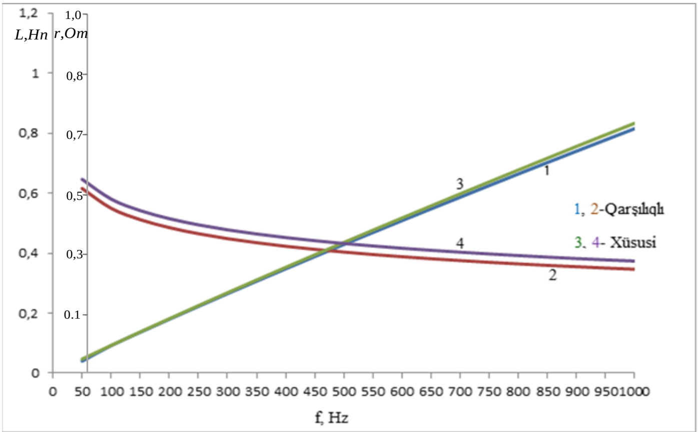

Figure 6. Curves of specific interphase mutual resistances and inductances in the frequency range of 50-1000 Hz.
Curves 1-2 are for mutual, curves 3-4 are for specific

RESULTS

1. Analyses were conducted to limit switching overvoltages in long-distance power transmission lines, and the relevance of developing and improving mathematical modelling in the transient and steady states of electromagnetic wave processes was demonstrated.

2. The use of neutral URs along with SRs at the start and end of single- and double-circuit long-distance power transmission lines has undergone extensive research by selecting various modes.

3. An algorithm for calculating electromagnetic wave processes in multi-circuit inter-system power transmission lines with neutral URs was developed.

4. Curves for maximum phase voltage variation were produced by including a SR and neutral UR reactor at the start and end of selected length lines.

5. Comprehensive calculations and comparative analyses of switching overvoltages with or without a star-connected parallel neutral URs in combination with SRs at the start and end of the single-

and double-circuit long-distance power transmission lines were conducted.

6. A mathematical model was produced using a matrix approach, taking into account neutral URs and overvoltage limiters in the multi-circuit intersystem power transmission lines.

7. Taking into account the geometry and skin effects of the selected two-circuit pylon, the values for specific resistances and inductances, as well as the values for mutual resistances and inductances in long-distance power transmission lines were calculated within the $50 - 1000$ Hz interval. Their curves were provided and the way they changed was analyzed.

8. Neutral URs are recommended to have a power of approximately $20 - 25$ % of SRs, which is considered important to ensure reliable operation of neutral URs in $500\,kV$ power transmission lines.

LIST OF PUBLICATIONS RELATED TO THE THESIS SUBJECT MATTER

1. R. N. Huseynov. "Application of unconventional compensation in inter-system power transmission". Power Industry Problems, No. 1, Baku, 2014, pp. 93-100.
2. R. N. Huseynov. “Mathematical modelling of wave processes in power transmission lines given short circuit reactors with ungrounded neutral”. The 10th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2014), Baku, Azerbaijan, 7-8 September 2014, Pp. 398-400.
3. A. M. Hashimov, R. N. Huseyn. "Limiting internal overvoltages in long-distance power transmission". Power Industry Problems, No. 3, Baku, 2015, pp. 38-51.
4. A. M. Hashimov, R.N. Huseyn. Non-traditional compensation in intersystem power transmission lines excessive switching voltage. The 11th International Conference on Technical and Physical

Problems of Electrical Engineering (ICTPE-2015), Bucharest, Romania, 10-12 September 2015, Pp. 102-105.

5. A. M. Hashimov, R. N. Huseyn. The use of neutral ungrounded reactors for double-circuit higher-voltage power transmission lines. Power Industry Problems, No. 2, Baku, 2016, pp. 3-19.
6. R. N. Huseyn. Calculation algorithm with consideration of ungrounded reactors on extra-high voltage double-loop power transmission lines. The 12th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2016), Bilbao, Spain, 10-12 September 2016, Pp. 102-104.
7. R. N. Huseyn. “Calculation algorithm of electromagnetic transients in multi-wired systems considering ungrounded reactors”, 13th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2017), Van, Turkey, 21-23 September 2017, pp. 342-346.
8. A. M. Hashimov, R. N Huseyn. “Implementation of reactors with ungrounded neutrals under excess voltages in long-distance power transmission”. International Educational Applied Scientific Research Journal (IEASRJ), vol: 3, Issue :12 Dec. 2018, e-ISSSN: 2456-5040.
9. A. M. Hashimov, R. N Huseyn. “Modelling of Electromagnetic Wave Processes Taking into Account Reactors with Ungrounded Neutrals and OVLs in Double-Circuit Long-Distance ETL”. International Journal on Technical and Physical Problems of Engineering (IJTPE) Published by International Organization of IOTPE, Vol: 11, Issue: 41, dec 2019, Serial No: 0041-1104-1219.
10. A. M. Hashimov, R. N Huseyn. “Mathematical modelling of electromagnetic wave processes in inter-system linked power interchange”. 16th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2020) Istanbul, Turkey, 12-13 October 2020, pp. 37-40.
11. S. L. Kurkute, R. N. Huseyn, S.N. Bora, S. Annappa “An Innovative Metod for short term electrical load forecasting Based on Adaptive CNN MRMR Model”. International conference on Electronics, Computing, Communication & Control technology, ICECCC-2024), 02-03 May 2024, IEEE Xplore,

DOI:10.1109/ICECCC61767.2024.10593853

12. R. N. Huseyn, A. M. Hashimov, A. Shokri, H. Mukalazi "Calculation algorithm for electromagnetic wave processes in multi-wire intersystem ETL", Discover Electronics Journal, Vol.I, №5, 2024, doi.org/10.1007/s44291-024-00005-2.

The candidate's personal activities as part of joint research with co-authors:

[3]-Application of mathematical modelling in limiting internal overvoltages in long-distance power transmission;

[4]- Planning the selection of a scheme for limiting switching overvoltages, taking into account unconventional compensation in inter-system power transmission;

[5]- Development of a software module for the use of neutral URs for double-circuit higher-voltage power transmission lines;

[8]- Mathematical modelling method and analysis of the accuracy of maximum phase voltages when applying neutral URs for overvoltages on long-distance power transmission lines;

[9]- Modelling of electromagnetic wave processes taking into account neutral URs and single-phase overvoltage limiters in double-circuit long-distance power transmission;

[10]- Application of electromagnetic wave processes to a mathematical model for interconnected energy exchange between systems;

[11]- An algorithm for calculating electromagnetic wave processes in multi-circuit inter-system power transmission lines.

The thesis defense is scheduled for on 16 May 2025 at_____ at the meeting of the Dissertation Council ED 2.04 operating under the Azerbaijan Technical University.

Address: 25 H. Javid Avenue, City of Baku, AZ1073.

The thesis is accessible at the library of the Azerbaijan Technical University, Ministry of Science and Education of the Republic of Azerbaijan.

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