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IMPROVING THE OPERATION OF 6-35 kV DISTRIBUTION ELECTRIC NETWORKS BY CHOOSING THE NEUTRAL TREATMENT MODE

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CONCEPTUAL LANDMARKS OF RESEARCH

The relevance and importance of the addressed topic lie in the fact that electric power has become a vital element for the economic progress of any country. It constitutes a crucial factor in the development of industries, infrastructures, and services, ultimately contributing significantly to increasing labor productivity and improving quality of life. The significance of electric power in the evolution and formation of the current civilization is truly immeasurable.

Ensuring the demand for electrical energy at a national level is the primary task of the National Power System (NPS), which is divided into specialized segments - generation, transmission, distribution, and supply of electric power. Distribution electrical networks (DEN) of 6-35 kV and their associated technologies represent one of the most dynamic domains of development within the power sector. At the beginning of the 21st century, continuous improvements in equipment, technologies, and materials have allowed for a change in approaches to the construction of distribution networks, revisiting the principles of organizing consumer supply systems, and the necessity of implementing innovative solutions in their development and management. [1].

The main trends in the development of distribution electrical networks (DEN) that will influence their long-term evolution are as follows:

- increased demand for electrical energy and augmentation of existing DEN Capacity: meeting the growing demand for electrical energy and ensuring increased transport capacity of existing DEN.
- enhancing energy efficiency of distribution networks: this includes reducing technical and non-technical losses, improving management, and electrical security.
- implementation of innovative technologies: such as smart grids and advanced energy storage methods to optimize distribution.
- integration of renewable energy sources and distributed generation: connecting renewable energy sources to the distribution grid and facilitating distributed generation.

Of the technical measures used in distribution networks, the treatment of their neutrals is of particular practical importance which has a direct or indirect impact on: continuity and reliability of the electricity supply to consumers; the behaviour of medium voltage (MV) electricity networks in single-phase fault conditions and its impact on the quality of the electricity distribution service (duration and frequency of interruptions to the electricity supply); the electrical installations and their operation; the technical solutions adopted; the level of assurance of electrical safety, etc. Distribution networks play an important role in ensuring the continuity of electricity supply, increasing energy efficiency, ensuring the safety of electricity station staff and electricity consumers, and ensuring an adequate price of electricity to end users.

The choice of neutral treatment in medium voltage (6 - 35) kV electrical networks is a complex issue due to the multitude of parameters to be considered. There is currently no uniform solution to this problem in worldwide practice.

Studies and research carried out over the last 15 to 20 years [2-5] confirm that obtaining a technically or techno-economically determined criterion for the choice of an efficient neutral treatment solution in MV power networks is difficult. Thus, the choice of an efficient neutral treatment method has to be made in relation to a specific electricity network in the conditions of a specific country.

Description of the situation in the research area and identification of research problems.

Since 1 January 2003, the latest (7th) edition of the Rules for the Installation of Electrical Installations (NAIE) [6] has been implemented in the Republic of Moldova, which provides for the possibility of operating 3-35 kV electrical networks both with the neutral insulated and with the neutral earthed by means of a suppression coil or a resistor (p. 1.2.16).

At present, there are two ways of neutral treatment, regulated by NAIE [6], implemented over time in the REDs of the Republic of Moldova, as follows:

1. isolated neutral;
2. the neutral treated by the ASC arc suppression coil, this being manually or automatically adjustable.

These modes of treatment are applicable to certain configurations and network types and have advantages and disadvantages, which require continuous refinement. Most distribution networks at the voltages mentioned operate in the capacitive current compensation mode via a choke coil. There are also a small number of substations where the neutral is insulated, but only there, where the distribution networks are not extensive, basically made up of overhead lines, resulting in low values (below 10 A) of capacitive currents in the network.

Due to the difficulties in promoting investments in 6 - 35 kV networks in the country, the focus is now on improving the way of neutral treatment by identifying and implementing new ways of neutral treatment using special neutral resistors. Research in this direction has hardly been carried out, which shows that there is a great potential for improving the operation of 6-35 kV distribution networks.

At the same time, tests to determine the earthing current are practically excluded, because advanced wear of equipment in electrical networks will lead to failure situations with serious consequences. In this case, mathematical modelling of the regimes analysed and their simulation in specialised software is required.

The aim of the research: to analyse the potential of implementing neutral treatment by resistor only or combined (ASC and resistor) in the electricity distribution networks of the

Republic of Moldova and to identify a set of measures/actions to improve the existing treatment modes, as well as to carry out case studies by modelling the operating regimes of electricity networks with different neutral treatment modes.

Research objectives:

- to carry out a bibliographical study on the current situation of the problem worldwide and in the Republic of Moldova;
- comparative analysis of different ways of treating neutral;
- analysis of the single-phase fault regime in 6-35 kV distribution networks and identification of basic criteria for the choice of an efficient neutral treatment solution;
- Single-phase fault regime modelling for different neutral treatment modes;
- application of the results obtained for the elaboration of the set of measures/recommendations applicable in the conditions of the Republic of Moldova.

Research hypothesis: improving the existing ways of neutral treatment of distribution networks in the Republic of Moldova or implementing new solutions will contribute to reducing overvoltages in case of single-phase faults, excluding the evolution of single-phase faults into multi-phase short circuits, increasing the reliability of electricity supply to final consumers, reducing the number of disconnections and increasing the performance indicators of the distribution service.

Summary of research methodology and justification of research methods chosen

Various mathematical tools were used to achieve the objectives proposed in the work, such as: mathematical modelling of the steady-state and transient operation regimes of electrical networks caused by the earthing of a phase (metallic earthing and arcing); analytical calculations; simulations in the MatLab Simulink programming environment; experimental tests using the laboratory stand "Analysis of neutral treatment methods in 6 - 35 kV networks", developed within the research carried out in the PhD thesis.

The rationale for the research methods is driven by the complexity of the phenomena occurring in single-phase, metallic and arc faults. The transient regimes caused by these can lead to much higher values of voltages and currents than in steady state. Conducting experiments and measurements in highly worn electrical networks can cause failure regimes with serious consequences.

Scientific novelty. For the first time, the neutral treatment regime of 6-35 kV networks in the Republic of Moldova is addressed and the implementation of new neutral treatment methods is justified. Mathematical models for calculating the regime parameters for different ways of neutral treatment of 6-35 kV distribution networks are developed, which allows modelling and simulation of these regimes, identifying the rational one, avoiding experimental tests, limited by the advanced wear of the equipment within the electrical networks.

Theoretical significance. In the thesis, mathematical models of single-phase metallic and arc fault regimes for different ways of treating the neutral of 6-35 kV power grids were developed. The main influencing factors in the choice of the neutral treatment regime of distribution networks in the RM were identified.

Practical significance. In the paper mathematical models of four neutral treatment regimes were developed, analytical expressions of regime parameters were obtained. The analysed regimes were modelled and simulated, which demonstrated the correctness of the obtained models. The developed models can be further developed for concrete power grids.

Implementation of the scientific results and the application value of the work

The results of the research were implemented at the "Centrala" 110/10 kV, "Balti-330 kV" 330/110/10 kV and "CET-Nord" 110/10 kV power stations of RED-NORD: the calculation program of capacitive grounding currents for any network configuration; recommendations on efficient ways of neutral treatment in RED-NORD networks and corresponding equipment.

A modern laboratory stand "Analysis of neutral treatment methods in 6 - 35 kV networks" has been developed at the Department of Energetics of UTM. The stand allows modelling of neutral treatment regimes (insulated, compensated) for both single-phase metallic and arc faults.

The results obtained are used in the teaching process in the subjects of Transmission and Distribution of Electricity and Electrical Part of Power Plants and Stations.

Approval of the results obtained

The results of the PhD thesis have been published, presented and discussed in national and international seminars, symposia and conferences: Technical-Scientific Conferences of Collaborators, PhD Students and Students of UTM (years 2005, 2006, 2008, 2011, 2014, 2016); SIELMEN International Conferences (years 2007, 2013, 2017, 2019, 2023), International Conference and Exposition on Electrical And Power Engineering (EPE), Iași, 2022; II Международная научная конференция, Минск, 2022 г.; International Conference on Modern Power Systems (MPS), Cluj-Napoca , 2023; national proceedings Energy security and routed power lines. Institute of Energetics, 2022; journals: Annals of the University of Craiova (years 2019, 2020) and Journal Of Engineering Science UTM, 2023.

Publications on the thesis topic. The results of the scientific research obtained have been published in 22 papers, including 8 papers without co-authors, 4 methodological-didactic papers.

Structure and volume of the thesis: The paper contains introduction, four chapters, general conclusions and recommendations, bibliography of 108 titles and includes 4 appendices, 181 pages, 122 figures, 12 tables.

Key words: power system, electrical distribution networks, neutral treatment mode, single-phase fault, overvoltages, neutral displacement, mathematical modelling.

2. THESIS CONTENT

The introduction of the paper presents the current trends in the field of 6-35 kV distribution network efficiency improvement, argues the topicality, importance and necessity of the research carried out, the aim and objectives of the thesis, the scientific problem solved, the theoretical and practical importance of the paper.

Chapter 1 **"Analysis of neutral treatment methods in 6-35 kV electrical distribution networks"** is a summary of the current state of trends in the approach, development, implementation and operation of different neutral treatment modalities in 6-35 kV electrical distribution networks worldwide.

The foreign country classifier according to the standard [7], provides five ways of treating neutral. That is, in world practice in medium voltage networks (1 - 69 kV), as opposed to high voltage networks (110 kV and above), the following modes of neutral treatment are found [8-13]:

1. *Isolated neutral.* It is widely applied in the post-Soviet states of Russia, Belarus, Ukraine, as well as in Italy, Spain, China and parts of Germany, Romania, Finland (20 kV overhead networks). The essential disadvantages of this mode of neutral treatment led to its exclusion from application as early as the 1940s and 1950s in most countries of Europe, Australia, North and South America.
2. *Compensated neutral (earthed through arc suppression coil ASC),* method applied in most European countries, China and Russia.
3. *Neutral grounded by low or high resistance*. This solution can be found in France, parts of Germany, Bulgaria, Hungary and Russia. In recent years this treatment method is also implemented in Romania, Belarus, Ukraine.
4. *Combined neutral or mixed solution* (combination of options *2* and *3*). This solution is applied in Germany, Czech Republic, Russia.
5. *Neutral grounded directly.* Neutral treatment applied in UK networks and in networks in USA, Canada (Anglo-Saxon solution).

For each method of neutral treatment of distribution networks, different theoretical aspects related to the topic of the paper are analyzed, the main characteristics of the neutral treatment methods of MV networks, advantages and disadvantages are presented.

According to the literature [14, 15], it lists the technical requirements that must be met to ensure optimal management of medium-voltage electrical networks, i.e., to choose an appropriate neutral treatment solution for these networks:

- quality of supply to consumers and ensuring continuity of supply;

- the degree of reservation in supplying consumers;
- network and equipment characteristics:
    - the nature of the network concerned (aerial, cable or mixed network);
    - network structure (length, looping possibilities);
    - the degree of ageing of the insulation;
    - the permissible value of the fault currents;
- values of overvoltages and single-phase fault currents;
- the possibility of selective and rapid protection systems or appropriate automation;
- technologies that can be used to detect and separate defects;
- the possibility of achieving effective protection against injury to people and animals and protection against the spread of damage;
- regulations and rules on the safety of people and animals;
- values of the earth connection resistances;
- economics of the solution and the need for new types of equipment.

It is important to note that these requirements cannot be met in their entirety, as they are dependent on the voltage, structure and characteristics of the network, etc. An appropriate balance between these requirements is necessary to ensure the necessary continuity and reliability in the supply of electricity to consumers, the provision of the respective protections and earthing facilities, to guarantee the electrical safety of people and animals, and to reduce the number of disconnections and their associated costs.

The choice of a neutral treatment solution for MV networks is of significant importance for the reliability of network operation and determines the main network parameters: logic and relay protection schemes against single-phase faults, the level of overvoltages resulting from simple earthing, the value of the earthing current, as well as the level of electrical safety of personnel and the continuity of electricity supply to consumers.

Any treatment solution adopted involves a considerable investment effort and requires multilateral substantiation of the decision taken over a long period of time.

Worldwide, the problem of how to choose the most efficient way to treat the neutral of medium-voltage grids is solved differently. This in itself demonstrates that none of the known neutral treatment methods has an absolute advantage over the others. Each of them can be characterized by a number of advantages and disadvantages and it is necessary to decide which of them has priority for the specific power system under consideration.

Another important aspect analyzed - distributed generation (DG) in electricity grids with the connection of renewable energy sources (RES) which is a current trend to solve environmental problems as well as energy shortages [16-19]. In addition to the undeniable benefits of DG, the integration of renewables in the power system has an impact on electricity grids and creates new challenges for specialists in the field. The choice of the rational neutral treatment can directly or indirectly solve the problem of protections and their structure, since the character of single-phase faults depends directly on the neutral treatment.

Derived from the study conducted in the first chapter, conclusions have been formulated, highlighting the importance, relevance, and necessity of revising the existing methods for treating the neutral in 6-35 kV distribution electrical networks. Additionally, prioritizing the implementation of neutral treatment using neutral resistors or a combined approach has been emphasized.

Chapter 2 **"Methods of creating artificial neutrals"** deals with practical aspects of access to the neutral of medium voltage electrical networks. Neutral treatment, either by ASC or resistor, involves connecting them to the network neutral. The three-phase power transformers used in 6-35 kV electrical distribution networks have a delta secondary winding connection scheme, so the grid neutral is inaccessible (physically missing). This is why it is necessary to create an artificial neutral using special transformers.

In this case, it is important that the transformers used to create the artificial neutral are correctly sized. In normal operation they must have high resistance and minimum losses in the direct sequence scheme, and in single-phase fault operation - low resistance in the homopolar sequence scheme.

First, it is proposed to use a special power transformer with star-delta winding connection scheme, called an *artificial neutral transformer (ANT)* [20, 21].

The artificial neutral point is formed by connecting this transformer to the MV busbars of the transformer substation (fig.1). In the formed neutral point, the arc suppression coil ASC (fig.1, *a* and *c*), a special resistor (fig.1, *b* and *d*), or the arc suppression coil in parallel with a resistor (fig.1, *e*, *f* and *g*) are connected.

The use of ANT transformers offers the possibility to connect to their secondary and own service consumers, which has to be taken into account when sizing the ANT.

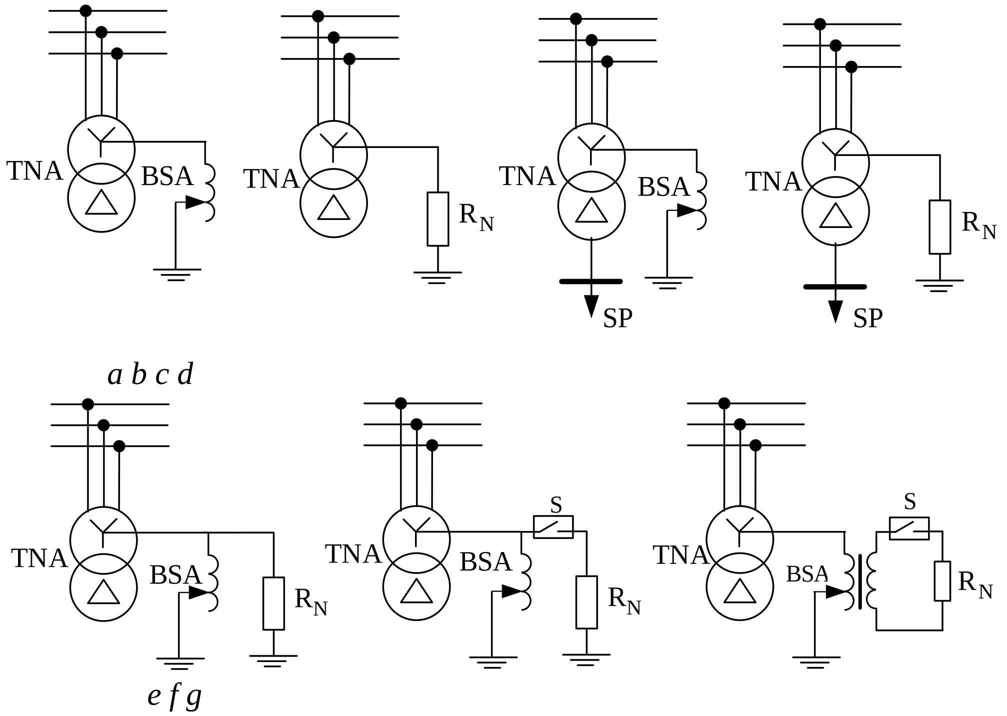

Fig. 1. Using ANT with star-delta scheme to create the artificial neutral point
where: TNA - artificial neutral transformer; BSA - arc suppression coil;
R_N - neutral resistor; S - key.

Another way to create the artificial neutral is to use a special transformer with zig-zag winding connection without secondary winding and accessible neutral point, called a *homopolar sequence filter* (FSH) [22, 23]. The FSH construction provides high values of winding reactances for forward and reverse sequence currents (X_1 and X_2) and very low values of homopolar sequence reactances (by reverse winding the half-windings on the columns, the magnetic fluxes phase shift 180° and, as a result, the resulting fluxes become theoretically zero (Fig. 2).

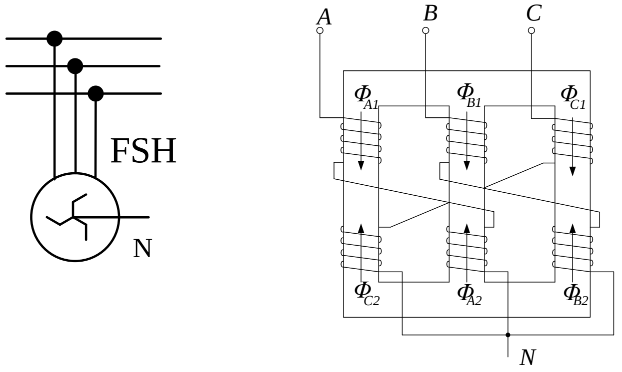

Fig. 2. Schematic diagram of the transformer with zigzag winding connection (FSH)

For the neutral connection of the low voltage resistor, it is proposed to use the ANT with open star-delta winding connection scheme (fig.3). The primary winding is connected in the star and the neutral point is connected directly to earth. In turn, the secondary winding is connected in the open delta, in the circuit of which the low voltage resistor and the protective devices are connected [22-24]. It should be noted that the ferromagnetic core of this transformer has a special construction, called *in mantle*. Transformers with a ferromagnetic core in the mantle are designed to withstand very high magnetic flux currents, and have a low magnetic resistance, which allows to reduce the no-load losses and avoid overheating when earthing a phase.

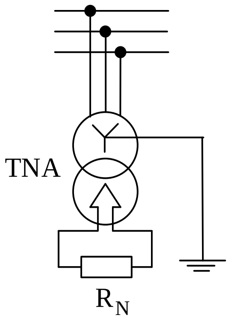

Fig. 3. Grid connection scheme of the open star-delta ANT

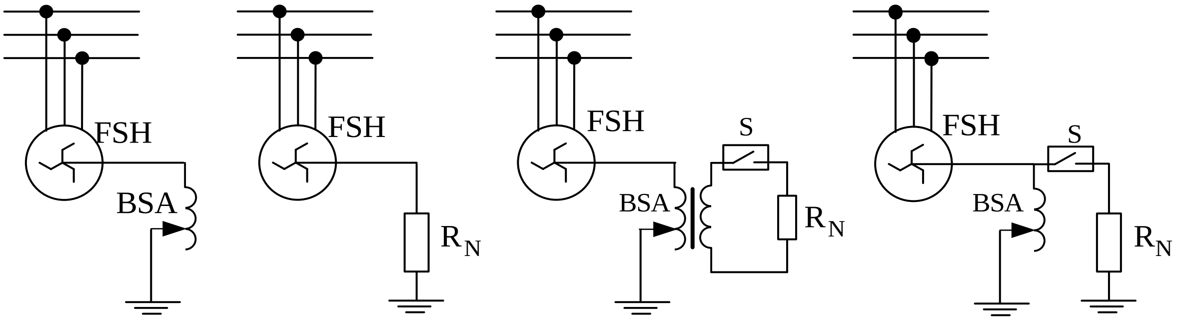

Fig. 4. Schematic of neutral creation using transformer with FSH zigzag winding connection

Subsequently, for each neutral treatment mode and type of transformer used (ANT, FSH), the methodology for choosing their rated power is presented, and the conditions for connecting the neutral equipment are analysed and determined.

In order to reduce the number of disconnections in case of single-phase transient faults in overhead electrical networks with a resistor-treated neutral with a high resistance value, it is proposed to implement the "shunt circuit breaker" solution. The solution allows the selection and elimination of about 75-80% of single-phase faults, as in the case of RAR (Automatic Reserve Reset), but without disconnecting consumers.

Chapter 3 **"Demand on electricity networks by mode neutral treatment"**

In 6-35 kV distribution networks, single-phase faults account for 75-80% of all faults. Of these, metallic grounding accounts for about 10-15%, the others being accompanied by arcing at the fault site [24]. The probability of self-starting arcing, the duration of burning, the intermittent nature of the arcing, the amount of grounding current cause overvoltages on the healthy phases, which can reach values of 3-3.5 of the phase voltage U_f, as well as the consequences of these overvoltages (piercing of the insulation at the weakest points of the power grid and transformation of the single-phase fault into polyphase short circuits). The thermal action of the current at the earthing point can cause fires. In order to avoid or reduce the consequences of single-phase faults and their accompanying overvoltages, it is necessary to create conditions in which the arc at the fault site will self-stress or burn out stably and the earthing current will be limited to non-hazardous values.

Solving these problems requires a thorough study of the processes that develop in distribution networks in the case of single-phase faults.

At the same time, carrying out tests to measure the regime parameters under these conditions is complicated and can cause failure situations with serious consequences, especially when the electrical network equipment has an advanced degree of wear. In this case, mathematical modelling of the grid regimes and their simulation in specialised software is required.

In this chapter, mathematical models are developed to calculate the regime parameters of 6-35 kV distribution power networks for different neutral treatment modes, which allowed mathematical modelling of different network operating regimes, identifying the optimal neutral treatment mode avoiding experimental tests.

Mathematical models of the operation of electrical distribution networks in steady-state and transient single-phase fault and normal operation for different neutral treatment modes are developed.

In order to obtain the analytical relationships of the state quantities in the stabilized single-phase fault regime, the equivalent calculation scheme has been used, whose structure is obtained on the basis of the relationships between the symmetrical components of voltage and current, respectively, considering the conditions specific to this fault and valid at the fault location (fig.5). In this scheme D, I and H represent the equivalent schemes of the network in relation to the fault location, valid for the three symmetrical components: direct, inverse and homopolar.

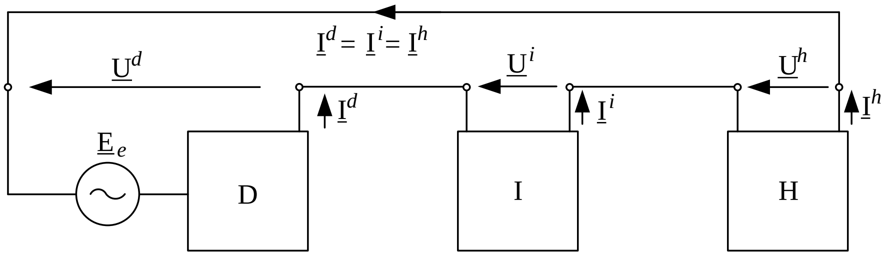

Fig. 5. Equivalent scheme for single-phase network fault

After a series of transformations, the voltages on the network phases were obtained in the stabilized single-phase fault regime:

$$\underline{U}_B = \underline{a}^2 \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \frac{\underline{E}_e}{2 \cdot \underline{Z}^d + \underline{Z}^h} = \underline{E}_e \cdot \left(\underline{a}^2 + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h} \right) = \underline{k}_B^{def} \cdot \underline{E}_e; \qquad (1)$$

$$\underline{U}_C = \underline{a} \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \frac{\underline{E}_e}{2 \cdot \underline{Z}^d + \underline{Z}^h} = \underline{E}_e \cdot \left(\underline{a} + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h} \right) = \underline{k}_C^{def} \cdot \underline{E}_e; \qquad (2)$$

$$\underline{k}_B^{def} = \underline{a}^2 + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h}; \; \underline{k}_C^{def} = \underline{a} + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h}, \qquad (3)$$

where: $\underline{k}_B^{def}$, $\underline{k}_C^{def}$ - voltage coefficients at a single-phase fault.

These coefficients are complex quantities, their modulus shows the multiple of the increase of the voltages on the healthy phases at a single-phase fault with respect to the phase e.m.t. corresponding to the section with the fault, but without the fault, i.e. the phase voltage of phase A.

Single-phase fault current (earthing):

$$\underline{I}_{PP} = \underline{I}^d + \underline{I}^i + \underline{I}^h. \qquad (4)$$

The voltage on the *electrical neutral* of the network (the physical neutral can be missing - when the secondary winding of the transformer is connected in a delta) will always be equal to the zero-sequence voltage, as the direct and reverse voltage sequence system respectively does not lead to the neutral shifting:

$$\underline{U}_N = \underline{U}^h. \qquad (5)$$

When the homopolar system emerges, the neutral changes its potential from 0 to $\underline{U}^h$.

In the following, the results obtained are applied to the calculation of state quantities during single-phase fault in a network with isolated neutral (relations 1-5 are valid) and neutral treated by an impedance. For the case of the impedance-treated neutral, it is necessary to calculate both the impedances of different sequences and to recalculate the e.m.t., introduced in the transfigured complex scheme. The calculation relations are obtained and presented in the paper. The earthing current, the voltages on the healthy phases and the neutral displacement voltage, as in the previous case, will be determined with relations (1-5).

Of particular interest are the transient processes when earthing an electric arc phase in medium voltage networks. The phenomena that occur in these cases lead to dangerous overvoltages. For the development of the mathematical model, the transient processes at first insulation penetration and arc quenching were analysed for different ways of treating the neutral, where the transient processes are more pronounced with higher values of overvoltages.

At the first phase *break* the voltage on the damaged phase becomes zero momentarily. The voltages of the healthy phases, going through an oscillating process with attenuation, will reach the values of the line voltages. Mathematically, these voltages can be expressed as the sum of two components, forced and free. The forced components are the voltages that settle on the healthy phases in a stabilised earthing regime:

$$\left.\begin{aligned} u_{Bfr}(t) &= \sqrt{3}\cdot E_m \cdot \sin(\omega \cdot t + 210°); \\ u_{Cfr}(t) &= \sqrt{3}\cdot E_m \cdot \sin(\omega \cdot t + 150°). \end{aligned}\right\} \qquad (6)$$

The free components are characterized by the amplitude U_{ml}, the attenuation coefficient δ_1 and the natural frequency of oscillation ω_1:

$$\left.\begin{aligned} u_{Blb}(t) &= U_{Bml} \cdot e^{-\delta_1 \cdot (t-t_1)} \cdot \cos \omega_1 \cdot (t-t_1); \\ u_{Clb}(t) &= U_{Cml} \cdot e^{-\delta_1 \cdot (t-t_1)} \cdot \cos \omega_1 \cdot (t-t_1). \end{aligned}\right\} \qquad (7)$$

Tensions on healthy phases will be:

$$\left.\begin{aligned} u_B(t) &= \sqrt{3}\cdot E_m \cdot \sin(\omega \cdot t + 210°) - E_m \cdot (1-k_C) \cdot e^{-\delta_1 \cdot (t-t_1)} \cdot \cos \omega_1 \cdot (t-t_1); \\ u_C(t) &= \sqrt{3}\cdot E_m \cdot \sin(\omega \cdot t + 150°) - E_m \cdot \cdot (1-k_C) e^{-\delta_1 \cdot (t-t_1)} \cdot \cos \omega_1 \cdot (t-t_1). \end{aligned}\right\} \qquad (8)$$

From the analysis of the relationships obtained, it appears that the overvoltage that can occur on the healthy phases at the first piercing depends on several factors: the piercing moment, the attenuation coefficient δ_1, the pulsation of the free component ω_1 and the ratio between the mutual and homopolar capacitances. Considering the worst-case conditions, the maximum overvoltage at the first piercing can be determined. This will occur when: the voltage on the faulted phase will reach the amplitude value E_m, neglecting the attenuation coefficient ($\delta_1 = 0$) and the mutual capacitances, and the maximum of the free component coincides with the moment, when the forced component reaches the amplitude value, i.e. $\sqrt{3}\cdot E_m$.

After analysing the variation of the forced and free components, the relationship for the neutral voltage was obtained:

$$u_N(t) = -E_m \cdot \sin \omega \cdot t - \frac{2}{3} E_m \cdot (1-k_C) \cdot e^{-\delta_1 \cdot (t-t_1)} \cdot \cos \omega_1 \cdot (t-t_1) \,. \qquad (9)$$

If the breakdown occurs when the voltage on the faulted phase reaches the amplitude value, attenuation, mutual capacitances are neglected and the frequency of the free component is assumed to be much higher than the industrial one, the maximum possible value of the overvoltage on the neutral results:

$$U_{N\max} \approx 1{,}67 \cdot E_m \,. \qquad (10)$$

To determine the parameters of the transient process, the operational method was used, which involves the composition of the equivalent scheme of the power grid. Passive elements, which have the ability to accumulate energy (in the magnetic or electric field), and which also cause the transient process, are introduced into the scheme as energy sources feeding the free components of the transient process. These sources are assigned values corresponding to the start of the transient process. By going from the origin function to the image function, a composite DC circuit is obtained, for which it is not a problem to determine the currents in the branches and the voltages on the elements. Finally, a transition from image to origin is performed and the actual parameters of the transient process are determined.

After the arc is extinguished, in general, a transient process will also occur. In the case, when the arc extinguishing takes place when the voltage on the grid neutral crosses zero, the transient process will practically not take place. To determine the possible overvoltages occurring at arc quenching, the voltage restoration character on the faulty phase was analyzed.

The nature of the transient process when the arc is extinguished depends strongly on the resistance in the grid neutral. The restoring voltage on the faulted phase is presented by the forced and the free component:

$$u_A(t) = u_{Afr}(t) + u_{Alb}(t) . \quad (11)$$

The forced component is determined by the e.m.t. of phase A and the voltage on the neutral:

$$u_{Afr}(t) = e_A(t) + u_N(t) \quad . \quad (12)$$

The free component is determined by the amplitude, attenuation coefficient and pulsation of the free component:

$$u_{Alb}(t) = U_{mAlb} \cdot e^{-\delta_2 \cdot (t-t_2)} \cdot \cos\omega_2 \cdot (t-t_2) \quad . \quad (13)$$

Finally, for the voltage on the faulted phase, the relation is obtained:

$$u_A(t) = e_A(t) + u_N(t) - \left[e_A(t_2) + u_N(t_2)\right] \cdot e^{-\delta_2 \cdot (t-t_2)} \cdot \cos\omega_2 \cdot (t-t_2) \quad . \quad (14)$$

In the case of the isolated neutral, the level of overvoltages on both the faulty and healthy phases will be determined by the forced component (by the voltage on the neutral at time t_2), and their maximum can reach the value $2E_m$.

In the case of the compensated neutral, after the arc has been suppression the ASC has a decisive influence on the transient process of voltage change on the neutral and on the faulted phase. The transient process of voltage change on the neutral and on the faulted phase was examined on the basis of the corresponding equivalent scheme, which allowed to obtain mathematical relationships. As a result of successive mathematical transformations, the calculation relations were obtained:

$$u_N(t) = U_{Nm} \cdot e^{-\frac{\partial}{2}\cdot \omega t} \cdot \sin(\omega_{st} t + \varphi_{N0}) \,, \tag{15}$$

$$\begin{aligned} u_A(t) &= e_A(t) + u_N(t) + U_{Am} \cdot e^{-\delta_2 \cdot (t - \frac{T_1}{2})} \cdot \cos \omega_2 (t - \frac{T_1}{2}) = \\ &= E_m \cdot \sin\left[\omega \cdot (t - \frac{T_1}{2}) + \frac{3 \cdot \pi}{2 \cdot \omega} \right] + U_{Nm} \cdot e^{-\frac{\partial}{2}\cdot \omega (t - \frac{T_1}{2})} \cdot \sin(\omega_{st} t + \varphi_{N0}) + \\ &+ U_{Am} \cdot e^{-\delta_2 \cdot (t - \frac{T_1}{2})} \cdot \cos \omega_2 (t - \frac{T_1}{2}). \end{aligned} \tag{16}$$

The course of the transient process depends to a large extent on the time of arc quenching: at the first zero crossing of the free component of the earthing current or at the zero crossing of its forced component, and on the parameters of the transient process: $\partial,\ \omega_1,\ \omega_2,\ \delta$ Based on the deduced relations, the variations of the current through neutral and the voltages for different values of the transient process parameters were obtained.

For the analysis of transient processes, which occur in resistor-treated networks, the equivalent scheme of the medium voltage network with the resistor-treated neutral was used. The mathematical modelling of the transient process shows that the value of the resistor has a small influence on the frequency of free oscillations and therefore on the transient process when the arc is ignited.

The conditions which ensure that the surplus electrical charges are fully discharged in a half period of the industrial frequency, after which the arc can again reignite, have been established on the basis of the equivalent network scheme with the resistor-treated neutral after the arc has been extinguished. Differential equations describing this process and demonstrating the positive effect of the resistor when the active current component created by it is approximately equal to or greater than the capacitive current component. The voltage on the neutral in an arc-on and arc-off cycle was determined based on Petersen theory:

$$U_{N\max}^{(n)} = u_{N0} \cdot e^{-\frac{t}{\tau_N}} = \frac{2}{3} U_{B\max}^{(n-1)} \cdot e^{-\frac{T/2}{\frac{1}{(G_{N*}+\delta)\omega}}} = \frac{2}{3} U_{B\max}^{(n-1)} \cdot e^{-\pi(\delta + G_{N*})} \,. \tag{17}$$

Maximum computing overvoltage for $k_C = 0,2\ \delta = 0,05\ k_{\delta_1} = 0,1\ G_{N*} = 1$:

$$\begin{aligned} U^{(n)}_{B\max} &= E_m \cdot \frac{1{,}5+(1-k_C)\cdot(1-k_{\delta_1})}{1-\frac{2}{3}\cdot(1-k_C)\cdot(1-k_{\delta_1})\cdot e^{-\pi(\delta+G_{N*})}} = \\ &= E_m \cdot \frac{1{,}5+(1-0{,}2)\cdot(1-0{,}1)}{1-\frac{2}{3}\cdot(1-0{,}2)\cdot(1-0{,}1)\cdot e^{-\pi(0{,}05+1)}} = 2{,}26\cdot E_m. \end{aligned} \tag{18}$$

According to the Peters-Slepian theory the influence of the resistor is not only the rapid attenuation of the voltage on the neutral, but also the change in the phase difference between the e.m.t. on the faulted phase and the forced component of the earthing current. The latter leads to a time lag between the moment of zero crossing of the forcing current component and the moment of reaching the maximum e.m.t. on the faulted phase, resulting in a decrease of the remaining voltage on the network neutral. At t_1 the arc is ignited and a transient process takes place. When the arc is extinguished (t_2), this process already attenuates. The voltage on the neutral at time t_2 results:

$$u_N(t_2) = -E_m \cdot \sin(2\pi-\beta) = E_m \cdot \sin(\beta)\,. \tag{19}$$

The magnitude β shows the phase angle between the voltage on the neutral and the forced component of the earthing current, its value will be determined by the ratio between the capacitive and active component of the earthing current:

$$\beta = arctg\,\frac{I_{C1}}{I_{a1}} = arctg\,\frac{3\omega C_0}{3G_0+G_N} = arctg\,\frac{1}{\partial+G_{N*}}\,, \tag{20}$$

here index 1 indicates the industrial frequency harmonic. Relation (20) demonstrates the dependence of the resistor conductance G_N on the angle β. As the value of the resistor resistance increases, the angle β decreases, which leads to a reduction of the remaining voltage on the neutral after arc extinction, i.e. to a reduction of the overvoltage on the healthy phases at the next arc ignition.

For the determination of the overvoltages according to the Beleacov theory, it was taken into account that the forced component of the voltage on the healthy phases at the time of arc restrike (t_3) constitutes $1.5E_m$, and the attenuation introduced by the resistor was taken into account when determining the free component:

$$U_{B\max} = 1{,}5E_m + \left[E_m + 1{,}2E_m \cdot e^{-\pi(\partial+G_{N*})}\right]\cdot(1-k_C)\cdot(1-k_{\delta_1})\,. \tag{21}$$

From the series of curves obtained, it was found that in the electrical network with the resistor-treated neutral, under the assumption of intermittent arcing, the overvoltages do not exceed $2E_m$, which is an advantage compared to other methods of treating the neutral. It is important to note that the probability of intermittent arcing is very low because the earthing current reaches considerable values and the arc burns stable. This regime can be considered stationary and not transient. The protection will be adjusted at disconnection, which considerably reduces the negative influence of long-standing surge action. At the same time, it reduces the risk of electrocution of humans and animals, as the fault is cleared within seconds, depending on the timing of the protection.

The processes that occur when earthing a phase in the ASC neutral treatment regime in parallel with a resistor are not principally different from the case of neutral treatment by ASC alone. This is explained by the fact, that the presence of the resistor only changes the conductance between neutral and earth, so that the relations deduced for the case of ASC treatment only are valid also in this case, adding the conductance of the resistor (G_R). This neutral treatment regime is actual in the case of overhead lines, where phase-to-ground capacitance non-symmetry occurs. As has been shown, pronounced non-symmetry causes the neutral displacement to exceed the allowable voltage of $0.15U_{f.nom}$ [26]. Connecting a resistor in parallel with the ASC allows to give the ASC in resonance with keeping the voltage on the neutral within the current standards. At the same time, the presence of the resistor in the situation where the phase asymmetry of the network is small, allows to reduce the overvoltages when earthing the phase by electric arc.

It should also be noted that the installation of the resistor is much more economically convenient than the installation of a ASC with automatic fine tuning.

Chapter 4 **"Choosing efficient neutral treatment in distribution networks. Case studies".**

The development in Chapter 3 of mathematical models of physical processes in electrical distribution networks for different neutral treatment modes led to the need for a verification of these models for a concrete distribution network.

The case study, carried out for this purpose, for 6-35 kV distribution networks in the Republic of Moldova, provides for the calculation of network regimes for different modes of neutral treatment, the modelling of these regimes in the Matlab Simulink program, the comparison of the results obtained and recommendations on the efficient way of neutral treatment under concrete conditions.

The case study was carried out for the power station "Power station 110/10 kV mun. Balti" of RED-NORD networks.

Two power transformers of type ТМПС-16000/110/11 with parameters ΔPsc=85 kW, Usc=10,5% and connection diagram Y0/Δ-11 are installed at the substation; one artificial neutral transformer of type ТМПС-630/10,5/0,23 with parameters is connected to each 10 kV busbar section: ΔPsc=8,63 kW, Usc=5,5%, ΔP0=0,997 kW, I0%=0,49%, I_{1n} =34,6 A and connection diagram Y0/Δ-11; in the neutral of each ANT are connected two ASC of type: РЗДСОМ-380/10 and РЗДПОМ-480/10.

The summed capacitances on each of the transformer substation distribution installation sections obtained by calculation are: for section 1 - C_{01} =13.34 μF; for section 2 - C_{02} =13 μF, earthing current I_{pp} =73 A.

The calculation was done for section 1, feeder no.2. The schematic of feeder no.2 and the earthing location are shown in Fig. 6.

For the option of treating the neutral by ASC combined with a high resistance resistor, determine its resistance and the impedance of the combined circuit, considering that ASC operates in overcompensation mode ($k=1.1$), it follows that the capacitive current will not exceed 8 A.

From the technical catalogue choose a resistor with a resistance value $R_n = 500\ \Omega$ so that the current through it does not exceed 10 *A*.

Combined circuit impedance:

$$\underline{Z}_N = \frac{\underline{Z}_{BSA} \cdot R_N}{\underline{Z}_{BSA} + R_N} = \frac{(1,033 + j76,426) \cdot 500}{(1,033 + j76,426) + 500} = 12,377 + j74,38\ \Omega.$$

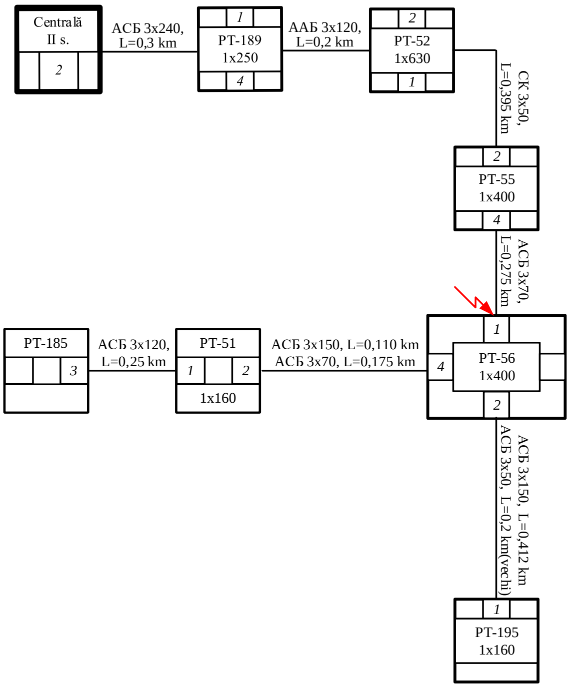

Fig. 6. Structural scheme of feeder no.2 of the ST "Power station 110/10kV mun. Balti"

The comparative study of the network regimes and the calculation of the state quantities for the neutral treatment variants: isolated, compensated, resistive and combined was carried out according to the algorithm: determination of the impedances of the elements of the electrical network for different sequences, according to the relations obtained in chapter 3, calculation of the earthing current, the voltages on the healthy phases and the voltage on the neutral, modelling of the respective regime in the Matlab Simulink program, construction of the phase diagrams and comparison of the results obtained. The results obtained by calculation and simulation are as follows (Table 1-5):

Table 1. Comparative data, isolated neutral

	I_{PP} , A	**U_A , V**	**U_B , kV**	**U_C , kV**	**U_N , kV**
Calculation	73,132-$e^{j89,86°}$	0	10,05-$e^{-j150,29°}$	10,07-$e^{j150,08°}$	5,817-$e^{j179,86°}$
Simulate	72,94-$e^{j89,64°}$	0	10,02-$e^{-j150,3°}$	10,04-$e^{j150°}$	-

Table 2. Comparative data, neutral treated by ASC

	I_{PP} , A	**U_A , V**	**U_B , kV**	**U_C , kV**	**U_{N2} , kV**
Calculation	2,424-$e^{j4,5°}$	0	9,998-$e^{-j150,01°}$	10-$e^{j149,99°}$	5,536-$e^{-j178,88°}$
Simulate	2,479-$e^{j4,488°}$	0	9,994-$e^{-j150°}$	9,996-$e^{j149,9°}$	5,535-$e^{-j178,7°}$

Table 3. Comparative data, low resistance resistor treated neutral

	I_{PP} , A	**U_A , V**	**U_B , kV**	**U_C , kV**	**U_{N2} , kV**
Calculation	104,184-$e^{j41,3°}$	0	9,989-$e^{-j150,55°}$	10,08-$e^{j149,67°}$	5,668-$e^{j176,93°}$
Simulate	103,2-$e^{j148,8°}$	0	9,979-$e^{-j150,4°}$	10,04-$e^{j149,7°}$	5,62-$e^{j176,8°}$

Table 4. Comparative data, ASC in parallel with a high resistance resistor

	I_{PP} , A	**U_A , V**	**U_B , kV**	**U_C , kV**	**U_{N2} , kV**
Calculation	13,04-$e^{j1,45°}$	0	9,991-$e^{-j150,05°}$	10-$e^{j149,93°}$	5,518-$e^{j179,3°}$
Simulate	12,84-$e^{j2,23°}$	0	9,989-$e^{-j150,1°}$	9,996-$e^{j149,9°}$	5,514-$e^{-j179,3°}$

Table 5. Power system state measurements at a single-phase fault for different neutral treatment modes obtained by calculation

Neutral regime	I_{PP} , A	U_A , kV	U_B , kV	U_C , kV	U_{N1} , kV
Isolated neutral	73,132-$e^{j89,86°}$	0	10,05-$e^{-j150,29°}$	10,07-$e^{j150,08°}$	5,817-$e^{j179,86°}$
Neutral treated by ASC	2,424-$e^{j4,5°}$	0	9,998-$e^{-j150,01°}$	10-$e^{j149,99°}$	5,536-$e^{-j178,88°}$
Low value resistor treated neutral	104,184-$e^{j41,3°}$	0	9,989-$e^{-j150,55°}$	10,08-$e^{j149,67°}$	5,668-$e^{j176,93°}$
ASC treated neutral and high value resistor	13,04-$e^{j1,45°}$	0	9,991-$e^{-j150,05°}$	10-$e^{j149,93°}$	5,771-$e^{j179,92°}$

According to the expressions, deduced in Chapter 3, the values of the neutral displacement voltage U_N and the current through the neutral I_N in normal operation of the network, in the case of treating the neutral through ASC and through ASC in parallel with a high value resistor, at a non-symmetry of the electrical network at 5% phase-to-earth capacitance inequality, were also determined. The results obtained are shown in Table 6.

The correspondence between the values obtained through calculations based on the developed mathematical model and the results obtained by simulating the neutral treatment regimes in Simulink are within the permissible error limits, practically identical. Furthermore, the simulation model can be further developed to achieve a broader correspondence with real physical processes in networks.

Table 6. Results of the calculation of regime parameters

Treatment mode	Neutral voltage in normal operation at 5% phase to earth capacitance non-symmetry, U_N , V	Voltage on neutral in single-phase fault mode, U_N , V	Earthing current, I_{PP} , A
Neutral treated by ASC	$U_N = 1846\ V\ (32\%\ din\ U_f)$	$5{,}536\text{-}e^{-j178{,}88°}$	$2{,}424\text{-}e^{j4{,}5°}$
ASC treated neutral and high value resistor	$U_N = 526{,}5\ V\ (9\%\ din\ U_f)$	$5{,}771\text{-}e^{j179{,}92°}$	$13.04\text{-}ej^{1{,}45°}$

The results of the study showed that the compensated neutral (ASC) network regime is rational for single-phase faults. At the same time, in normal operation ASC causes the neutral displacement voltage to increase and possibly exceed the regulated value.

At the same time, the combined neutral treatment (ASC in parallel with a 500 Ω resistor for the case under consideration) leads to a reduction of the voltage on the grid neutral (in normal operation) of about 3.5 times, which results in a more favorable grid operation regime and allows integration within the neutral displacement voltage values stipulated by the Standards in force [26], p.542 which is particularly important in case of grid phase non-symmetry.

A major influence on the state magnitudes at a single-phase fault in medium-voltage power networks is the capacitive reactance, which can change during the operation of power networks.

GENERAL CONCLUSIONS

1. Following an extensive bibliographical study in the field of neutral treatment of 6-35 kV electrical distribution networks, focusing on the advantages and disadvantages of each treatment method, by referring to regulations and solutions practiced worldwide, it was established: a) isolated neutral is an outdated and dangerous treatment method (overvoltages can reach the level of 4.27Em), currently excluded from operation in most developed countries; b) the lack of single technical and techno-economic criteria for choosing the treatment method for the neutral of electrical networks (Chapter 1 [Dobrea I., 2017; 2019]).
2. The research carried out highlights the need for access to the neutral point for connection to it of the ASC arc suppression coil and/or the neutral resistor, which has resulted in the systematization and submission of proposals on how to create the artificial neutral with the use of special transformers, as well as their sizing methodology (Chapter 2 [Dobrea I., 2014]).
3. The study shows that the solution chosen for the treatment of the medium-voltage network neutral, the single-phase fault regime and the phenomena that accompany it have a decisive influence on the continuity and quality of the electricity distributed to end consumers and on the demand on the electricity network. The chosen solution influences the network regime parameters in both transient and steady state mode depending on the conditions under which the fault occurs (Chapter 3 [Dobrea I. et. al., 2017; Dobrea I., 2019]).
4. The obtained result contributing to the solution of the important scientific problem confirms that the way of treating the neutral determines the conditions under which single-phase faults occur and the evolution of phenomena in which the electric arc at the fault site will self-stress or burn stable and the grounding current will be limited to non-hazardous values (Chapter 3 [Dobrea I., 2019]).
5. The obtained result that contributes to the solution of important scientific problems consists in the development of mathematical models of the operation of electrical distribution networks in stabilized and transient single-phase and normal fault operation for different neutral treatment modes, which allows to avoid experimental tests under conditions of advanced wear of the insulation of the networks in the MR (Chapter 3 [Dobrea I. et al., 2013, Dobrea I., 2019]).
6. An important conclusion obtained on the basis of the developed mathematical models - the presence of the resistor in the grid neutral reduces the value of transient overvoltages, damping them very quickly, while cancelling the conditions of occurrence of temporary resonance overvoltages on the fundamental harmonic (subsections 3.3, 3.4 [, Dobrea I., 2019; Dobrea I. et al., 2023]).
7. Numerical simulation analysis of the transient regime at a single-phase fault has allowed to determine how various quantities influence the time evolution of voltages and currents. In the case of single-phase net or arcing faults, the values of the overvoltages depend mainly

on the initial phase of the voltage and the value of the voltage at the time of fault occurrence. This significant increase in voltage creates the conditions for the transformation of a simple earth fault into a multiple fault, with serious consequences for the installations of distribution networks (subchapters 3.1- 3.3 [Dobrea I. 2006, 2007; Boșneaga V. et al. 2022, 2023]).

8. Numerical simulation in the Matlab Simulink environment has shown that ASC, connected to the power grid neutral with sharp phase non-symmetry causes the neutral to shift, exceeding the regulated values (subsections 3.3, 4.1 [Dobrea I. et al., 2023]).
9. The obtained results contributed to the development of a model for simulating the relevant test network using Matlab application, to perform a set of numerical simulations covering the investigated neutral treatment solutions (Chapter 4 [Dobrea I. et al., 2023; Boșneaga V. et al. 2022]).

RECOMMENDATIONS

Based on the research conducted and the results obtained, it is recommended:

1. If there is no need to switch the network with isolated neutral to another neutral treatment solution, it is necessary to find solutions to increase the sensitivity of the current homopolar voltage protections or to purchase modern protections for selective and fast fault detection and location.
2. From the analysis of the results obtained, the ASC neutral treatment solution is recommended for use in overhead electrical networks. ASC leads to a reduction of overvoltages and a fast extinguishing of the earthing arc or its stable burning. At the same time, prolonged operation of the network with earthed phase can lead to double earthing or polyphase short circuits, and not least to the danger of electrocution of humans and animals.
3. The use of high resistance resistor is recommended when capacitive currents do not exceed 10 A. The protection will act on signalling, so there will be no reduction in continuity of power supply to consumers.
4. In wired electrical networks where the capacitive currents exceed 10 A and where the consumers allow the power supply to be interrupted, it is recommended to use the resistor with a low resistance value. The resistor ensures selective, and relatively simple, operation of the protection which operates on disconnection. The duration of temporary overvoltages is maximum 2 s.
5. The solution of the combined neutral is indicated in the case of mixed networks whose earthing current is greater than 10 A. In this case, transient faults are separated from permanent faults and the possibility of selective detection of the faulty line and its disconnection in a very short time is ensured. The resistor causes a reduction in the neutral displacement in normal network operation caused by the ASC.

BIBLIOGRAPHY

1. САМОЙЛЕНКО, В., МУХЛЫНИН, Н., ПАЗДЕРИН, А., ЖУРАВЛЕВ, А. Перспективные тенденции развития распределительных сетей. В: журнал „Электроэнергия. Передача и распределение”. Учредители: ООО "Кабель" ISSN: 2218-3116 Номер: S1 (12) Год: 2019.
2. ГУСАРОВ, Л.А. Способы заземления нейтрали источников питания в сетях среднего напряжения, достоинства и недостатки, реальная практика применения в мире. В: *"Электрик Инфо"* онлайн журнал 2020 г. Disponibil: https://electrik.info/article/1692-sposoby-zazemleniya-neytrali-istochnikov-pitaniya-v-setyah-srednego-napryazheniya.html
3. НАЗАРЫЧЕВ, А., ТИТЕНКОВ, С., ПУГАЧЕВ, А. Комплексные инновационные решения по заземлению нейтрали в сетях 6-35 кВ В: *Электроэнергия. Передача и распределение*. №3 (36), 2016, с. 33-39.
4. ЦЕЛЕБРОВСКИЙ, Ю., ЧЕРНЕНКО, Н. Анахронизмы в электрических сетях напряжением 6...35 кВ. В: *Проблемы электроэнергетики и телекоммуникаций севера России: сб. ст. 2 Всерос. с междунар. участием науч.-практ. конф., Сургут, 22–23 апр. 2021 г.* Москва: Знание-М, 2021, С. 157-165. ISBN 978-5-00187-067-8.
5. SHIPP, David, ANGELINI, Frank. *Characteristics of different power systems neutral grounding techniques: Fact and fiction*. USA, Etalon 2018, pp.7-8.
6. *Правила устройства электроустановок*. 7-е изд. – М.: Изд-во НЦ ЭНАС, 2004.
7. EY Renewable Energy Country Attractiveness Index (RECAI 60).
   Disponibil: https://www.ey.com/en_gl/recai/
8. Definition of Criteria to Operate 20 kV Networks with Arc Suppression Coils According to *Standards EON aner AG - Germany*, (20th International Conlerence on Electricity Distribution, ClRED. Prague, 2009)
9. CALORIE, R., CERRETTI, A., GERI, A., LAURIA, S., MACCIONI, M., GATTA, FM. Abnormal Ground Fault Overvoltages in MV Networks, Analyses and Experimental Tests 21st International Conference on Electricity Distribution, Frankfurt, 6–9 June 2011.
10. HAND, Martin, MCDONAGH, Neil. *Esb's Adoption of Smart Neutral Treatments on Its 20 kV System.* CIRED Workshop, Lyon, 7–8 June 2010.
11. FOLLIOT, P., BOYER, J., BOLLE, S. *Neutral Grounding Reactor for Medium Voltage Networks*. Alstom report.
    Disponibil: http://www.cired.net/publications/cired2001/1_5.pdf
12. ZAMORA, I., MAZON, A. J., ANTEPARA, F., PUHRINGER, M., SAENZ, J.R. *Experiences of Neutral Resonant System Implantation in Gorliz Substation.* 17th International Conference on Electricity Distribution, Barcelona. 12–15 May 2003.
13. LOURO, M., CUNHA ABREU, J., DUARTE, F., MARTINS, M., FITEIRO, R., VALE, F. Effects on the Quality of Service of Changing the Neutral Grounding of MV Networks. 21st International Conference on Electricity Distribution, Frankfurt. 6–9 June 2011.
14. ВАЙНШТЕЙН, Р.А., КОЛОМИЕЦ, Н.В., ШЕСТАКОВА, В.В. *Режимы заземления*

нейтрали в электрических системах: учебное пособие. Томск: Изд-во ТПУ, 2006.– 118с.

15. НАЗАРОВ, В.В. Нейтраль распределительных сетей 6–35 кВ. Какое заземление необходимо? В: *Новости ЭлектроТехники*. 2013. № 5(83). Disponibil: http://www.news.elteh.ru/arh/2013/83/07.php
16. KULIKOV, A. L., OSOKIN, V. L., PAPKOV, B. V. The problems and peculiarities of distributed electricity. In: *Bulletin NGIEI*. 2018. № 11 (90), pp. 123–136. ISSN 2227-9407.
17. INAȚOC, ANDREEA-GEORGIANA. *Controlul și stabilitatea de tensiune în sistemele electroenergetice de distribuție active:* rezumatul tz. de doct. în științe inginerești. București, 2022. 15 p.
18. ВОРОПАЙ, Н.И. Распределенная генерация в электроэнергетических системах. В: *Международная научно-практическая конференция «Малая энергетика-2005»,* Сб. докладов, Иркутск, 2005, с. 30–42.
19. KLIMOV, P.L. The effect of wind power plant distributed generation on distribution networks. In*: Proceedings of Irkutsk State Technical University*. 2017, vol. 21, no 2, pp. 97–105. DOI: 10.21285/1814-3520-2017-2-97-105, vol. 21, no 2, pp. 97–105.
20. ГУСАРОВ, Л.А. Способы заземления нейтрали источников питания в сетях среднего напряжения, достоинства и недостатки, реальная практика применения в мире. В: *"Электрик Инфо"* онлайн журнал 2020 г. Disponibil: https://electrik.info/article/1692
21. EREMIA, Mircea. Electric Power Systems. Volume I. Electric Networks. București, 2006, pp.355-357.
22. SHIPP, David, ANGELINI, Frank. *Characteristics of different power systems neutral grounding techniques: Fact and fiction*. USA, Etalon 2018, pp.7-8.
23. KASSIM, Rasheed Hameed. Zig-zag grounding transformer modeling for zero-sequnce impedance calculation uising finite element method. In: Diyala Journal of Engineering Sciences. Vol. 08, No. 06, pp. 36-87, September 2015, pp.65-73.
24. МЛАДЗИЕВСКИЙ, Е. П., РЫЖКОВА, Е. Н. Сравнительный анализ аварийности распределительных сетей в условиях однофазного замыкания на землю. В: *Сборник трудов XVII международной научно-практической конференции.* Издательство: ОГУ имени И.С. Тургенева, 2019, pp. 55-61. Disponibil: https://www.elibrary.ru/download/elibrary_42256785_80779092.pdf
25. GUȘĂ, Mircea. *Tehnica Tensiunilor Înalte*. Iași, 2020, pp.2-18.
26. Hotărâre Nr. 393 din 01-11-2019 privind aprobarea documentului normativ-tehnic în domeniul energeticii NE1-01:2019 „Norme de exploatare a instalațiilor electrice ale consumatorilor noncasnici”. În: *Monitorul Oficial*, 31-01-2020, nr. 24-34, art. 90.

PUBLICATIONS ON THE RESEARCH TOPIC

Papers in in scientific journals

1. **DOBREA, I.** The influence of the treatment mode of the neutral in the 6-35 kV networks on the displacement voltage in the quasi-stationary regime. In: *Annals of the University of Craiova, Electrical Engineering ser.*, 2019, nr. 1(43), pp. 128-133. ISSN 1842-4805.
2. MURDID, E., JINGAN, B., **DOBREA, I.**. Influence of Synchronized Measurement Errors on the Results of Identification of the Transmission Line Parameters. In: *Annals of the University of Craiova, Electrical Engineering ser.,* 2020, N. 44, Iss. 1, pp. 14-19. ISSN 1842-4805.

Papers in the proceedings of conferences

3. STRATAN, I., PROȚUC, I., **DOBREA, I.** Contributions to the rational method of neutral earthing with MALLAB+SIMULINK. Analele universității din Craiova, Seria: inginerie electrică, nr.31, 2007, Vol. II, *6th International Conference of Electromecanical and Power Sistem* – SIELMEN 2007.
4. **DOBREA, I.**, POGORA, V., MACOVEI, I. Analiza supratensiunilor la punerea unei faze la pămînt în rețeaua 10 kV adiacentă stației electrice „Centrala” 110/10 kV, or. Bălți. Seria: inginerie electrică, anul 2013, *9th International Conference of Electromecanical and Power Sistem* – SIELMEN 2013.
5. **DOBREA, Ina,** CORNOVAN, Irina. Analysis of the Actual Situation Regarding the Methods of Processing the Neutral in the 6-35 kV Networks. In: SIELMEN 2017: Proceedings of the *11-th international conference on electromechanical and power systems*, 11-13 octombrie, 2017. Chișinău, 2017, pp. 619-622. ISBN 978-1-5386-1846-2.
6. **DOBREA, I**. The Opportunity to Treat the Neutral Through the Resistor or Combined Compensation Coil – Resistor. Proceedings of the *12th International Conference on Electromechanical and Energy Systems*. SIELMEN 2019, October 9-11, 2019, Craiova-Chișinău, Electronic ISBN: 978-1-7281-4011-7, USB ISBN: 978-1-7281-4010-0. DOI:10.1109/SIELMEN.2019.8905891.
7. БОШНЯГА, В., СУСЛОВ, В., СТРАТАН, И**, ДОБРЯ, И**. Особенности работы кабельной распределительной сети 6-35 кВ в установившемся режиме с изолированной и компенсированной нейтралью при однофазном замыкании на землю. In: *Устойчивое развитие энергетики Республики Беларусь: состояние и перспективы*: сб. докл. II Междунар. науч. конф. (Минск, 3–6 окт.2022 г.) / под ред. Т. Г. Зориной. – Минск : Беларус. наука, 2023. – 461 с. ISBN 978-985-08-2994-8.
8. BOSNEAGA, V., SUSLOV, V., STRATAN, I., **DOBREA I.** The peculiarities of the steady state modes of medium voltage cables grid at various neutral grounding and single-phase to ground failure. In: *2022 International Conference and Exposition on Electrical And Power Engineering (EPE)*. Iași, 20-22 October 2022. Electronic ISBN:978-1-6654-8994-2, USB ISBN:978-1-6654-8993-5. Electronic ISSN: 2644-223X.
9. BOSNEAGA, V., SUSLOV, V., STRATAN, I., **DOBREA I.** The Peculiarities of Steady State Condition of Medium Voltage Cable Line 10 kV in Partial Compensation Mode of Neutral Grounding at Single-phase to Ground Fault. *2023 10th International Conference on Modern*

Power Systems (MPS), Cluj-Napoca, Romania, 2023, pp. 1-5, doi: 10.1109/ MPS58874.2023.10187482. Electronic ISBN:979-8-3503-2682-6.

10. BOSNEAGA, V., SUSLOV, V., STRATAN, I., **DOBREA, I.** Steady State Condition of Cable Line 10 kV at Single-Phase to Ground Fault with Resistive Neutral Earthing. *2023 International Conference on Electromechanical and Energy Systems (SIELMEN),* Craiova, Romania, 2023, pp. 1-6, doi: 10.1109/SIELMEN59038.2023.10290827. Electronic ISBN:979-8-3503-1524-0, Print on Demand(PoD) ISBN:979-8-3503-1525-7.
11. **DOBREA, I.** Calculul curenților de punere la pămînt în rețeaua 10 kV a stației electrice "Horești". *Conferința Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților*, Chișinău 2005.
12. **DOBREA, I.** Studiul supratensiunilor în rețelele cu neutrul izolat cu utilizarea aplicației SIMULINK. *Conferința Jubiliară Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților consacrată celei de-a 40-a Aniversări a Doctoranturii U.T.M.*, 17-18 noiem. 2006, Chișinău. Vol. 1: Radioelectronică și Telecomunicații. Calculatoare, Informatică și Microelectronică. Energetică / Univ. Tehn. a Moldovei. – Chișinău: U.T.M., 2006. – 477 p. ISBN 978-9975-45-024-9. ISBN 978-9975-45-025-6 (vol. 1).
13. **DOBREA, I.** Utilizarea combinată a bobinei de stingere și a rezistorului de legare la pămînt pentru tratarea neutrului în rețelele de medie tensiune în sistemul electroenergetic al RM. *Conferința Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților,* 15-17 noiem. 2008, Chișinău. Vol. 1. Univ. Tehn. a Moldovei. Chișinău : U.T.M., 2008. 420 p. ISBN 978-9975-45-065-2. – ISBN 978-9975-45-114-7 (vol. 1).
14. **DOBREA, I.** Studiul metodelor de reglare automată a bobinelor de stingere. In: *Conferința Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților, Universitatea Tehnică a Moldovei,* 8 – 10 decembrie, 2011. Chișinău, 2012, vol. 1, pp. 238-239. ISBN 978-9975-45-208-3 (Vol.1).
15. **DOBREA, I.** Tratarea neutrului în rețelele de medie tensiune. Universitatea Tehnică a Moldovei, *Conferința Jubiliară Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților consacrată celei de-a 50-a Aniversări a U.T.M.,* 20 – 21 octombrie : Univ. Tehn. a Moldovei. Tehnica-UTM, 2014. ISBN 978-9975-45-249-6.
16. **DOBREA, I.** Analiza situației actuale privind modalitățile de tratare a neutrului în rețelele 6 – 35 kV. In: *Conferința Tehnico-Științifică a Colaboratorilor, Doctoranzilor și Studenților, Universitatea Tehnică a Moldovei,* 1-14 decembrie, 2016. Chișinău, 2017, vol. 1, pp. 379-382. ISBN 978-9975-45-500-8. ISBN 978-9975-45-501-5 (Vol.1).

Papers in national collections:

17. БОШНЯГА, В, СУСЛОВ, В., СТРАТАН, И, **ДОБРЯ, И**. Особенности работы кабельной распределительной сети 6-35 кВ в установившемся режиме однофазного замыкания на землю с перекомпенсацией тока повреждения. В: *Securitatea energetică și linii electrice dirijate. Volumul nr.13(28).* Institutul de Energetică. Chișinău: S.n. 2022. Culegere de lucrări. ISBN 978-9975-158-68-8.
18. **DOBREA, I.**, ROTARU, A., STRATAN, I. Opportunity of using a mixed neutral treatment solution in the distribution electrical networks of the Republic of Moldova. In: *Journal of Engineering Science 2023,* 30 (3), pp. 60-77. ISSN 2587-3474, eISSN 2587-3482.

ADNOTARE

Autor – *DOBREA Ina*. **Titlul** – *Îmbunătățirea regimului de funcționare a rețelelor electrice de distribuție 6-35 kV prin alegerea modului de tratare a neutrului*. Teză de doctor în vederea conferirii titlului științific de doctor în științe inginerești la specialitatea *221.01. Sisteme și tehnologii energetice*. Chișinău 2023.

Structura lucrării: Lucrarea conține o introducere, patru capitole, concluzii generale și recomandări, bibliografie din 106 titluri și include 4 anexe, 157 pagini, 122 figuri, 12 tabele. Rezultatele obținute sunt publicate în 18 lucrări științifice.

Cuvinte cheie: sistem electroenergetic, rețele electrice de distribuție, regimul de tratare a neutrului, defect monofazat, supratensiuni, deplasarea neutrului, model matematic.

Domeniul de studiu: științe inginerești.

Scopul tezei: analiza potențialului de implementare a tratării neutrului rezistiv și combinat în rețelele electrice de distribuție din Republica Moldova și identificarea unui set de măsuri/acțiuni în vederea îmbunătățirii modurilor existente de tratare, precum și realizarea unor studii de caz prin modelarea regimurilor de funcționare a rețelelor electrice cu diferite moduri de tratare a neutrului.

Obiectivele tezei: realizarea unui studiu bibliografic privind stadiul actual a problemei pe plan mondial și în Republica Moldova; analiza comparativă a diferitelor moduri de tratare a neutrului; analiza regimului de defect monofazat în rețelele electrice de medie tensiune și identificarea criteriilor de bază privind alegerea soluției optimale; modelarea și simularea regimurilor normale și de defect monofazat metalic sau prin arc electric; aplicarea rezultatelor obținute pentru elaborarea setului de măsuri/recomandări aplicabile în condițiile RM.

Noutatea și originalitatea științifică a tezei. Elaborarea modelelor matematice de calcul ai parametrilor de regim pentru diferite modalități de tratare a neutrului rețelelor electrice de distribuție 6-35 kV, ceea ce permite modelarea matematică a acestor regimuri, identificarea celui optimal evitând încercările experimentale, limitate de uzura avansată a echipamentelor din cadrul rețelelor electrice.

Rezultatul obținut în baza modelelor matematice obținute sunt elaborate recomandări/propuneri practice privind implementarea modalităților noi de tratare (prin rezistență și combinată) a neutrului rețelelor electrice de distribuție din Republica Moldova.

Semnificația teoretică. Teza aduce contribuții științifico-practice la calculul și analiza regimurilor de funcționare a rețelelor electrice de distribuție 6-35 kV cu diferite modalități de tratare a neutrului în scopul identificării modalității de tratare a neutrului ce asigură îmbunătățirea calității serviciului de distribuție a energiei electrice și fiabilității funcționării acestora.

Valoarea aplicativă a lucrării. În lucrare s-au elaborat modelele matematice a patru regimuri de tratare a neutrului, au fost obținute expresiile analitice ale parametrilor de regim. Regimurile analizate au fost modelate și simulate, ceea ce a demonstrat corectitudinea modelelor obținute.

Implementarea rezultatelor științifice. 1. Implementarea rezultatelor cercetărilor la stațiile electrice „Centrala” 110/10 kV, „Bălți-330 kV” 330/110/10 kV și „CET-Nord” 110/10 kV, RED-Nord. 2. La Departamentul Energetica a fost elaborat un stand modern de laborator „Analiza metodelor de tratare a neutrului în rețelele 6-35 kV”. 3. Rezultatele obținute sunt utilizate în cursurile Transportul și Distribuția Energiei Electrice (TDEE -titularul disciplinei prof. univ. dr., Ion SRTATAN) și Partea Electrică a Centralelor și Stațiilor (PECS -titularul disciplinei lect. univ. Ina Dobrea).

АННОТАЦИЯ

Автор – *Добря Ина*. **Название** – *Улучшение режимов работы распределительных электрических сетей 6-35 кВ посредством выбора метода заземления нейтрали.*
Диссертация о присвоение докторской степени в области технических наук,
специальность *221.01. Энергетические системы и технологии*. Кишинэу 2023.

Структура работы: работа состоит из введения, четырех глав, выводов и рекомендаций, библиографии из 106 наименований и включает 4 приложений, 157 страниц, 122 рисунков и 12 таблиц. Результаты исследования опубликованы в 18 научных работах.

Ключевые слова: электроэнергетическая система, распределительные электрические сети, режим заземления нейтрали, однофазное замыкание, перенапряжения, смещение нейтрали, математическая модель.

Область исследования: инженерная наука.

Цель диссертации анализ потенциала внедрения резистивного и комбинированного заземления нейтрали в распределительных электрических сетях Республики Молдова и выявление комплекса мероприятий/рекомендаций с целью улучшения существующих методов заземления нейтрали а также проведение исследований с моделированием режимов работы электросетей с различными способами заземления нейтрали.

Задачи диссертации: библиографическое исследование текущего состояния проблемы на мировом уровне и в Республике Молдова; сравнительный анализ различных способов заземления нейтрали; анализ однофазных замыканий на землю в сетях среднего напряжения и выявление основных критериев выбора оптимального решения; моделирование нормальных и однофазных замыканий на землю металлических или дуговых; применение полученных результатов для разработки мероприятий и рекомендаций, применимых в условиях Республики Молдова

Научная новизна работы: Разработка математических моделей расчета режимных параметров при различных способах заземления нейтрали в распределительных электрических сетях 6-35 кВ, позволяющие проводить математическое моделирование этих режимов, выявление оптимального режима не прибегая к экспериментальным испытаниям, ограниченных высоким износом оборудования в электрических сетях.

Решенная научная проблема: на основе полученных математических моделей разработаны практические рекомендации/предложения по внедрению новых способов заземления нейтрали (резистивное и комбинированное) в распределительных электрических сетях Республики Молдова.

Теоретическая значимость. Диссертация вносит научно-практический вклад в расчет и анализ режимов заземления нейтрали электрических сетей среднего напряжения с целью повышения эффективности распределительных электрических сетей, качества услуг по распределению электроэнергии и надежности их эксплуатации.

Прикладное значение работы: разработаны математические модели четырех режимов заземления нейтрали, получены аналитические выражения параметров режимов. Анализируемые режимы были смоделированы и симулированы, что доказало корректность полученных моделей.

Внедрение научных результатов: 1. Внедрение результатов исследований на электростанциях «Centrala» 110/10 кВ, «Bălți -330 кВ», 330/110/10 кВ и «CET-Nord» 110/10 кВ, RED-Nord. 2. В департаменте Энергетика разработан современный лабораторный стенд «Анализ методов заземления нейтрали в сетях 6-35 кВ». 3. Полученные результаты используются в курсах «Передача и распределение электрической энергии» (TDEE – проф., д.т.н. Ион СРТАТАН) и «Электрическая часть электростанций и подстанций» (PECS – лект. Ина Добря).

ANNOTATION

Author – *DOBREA Ina*. **Title** – *Improving the operation of 6-35 kV distribution electric networks by choosing the neutral treatment mode*. PhD thesis for the awarding of the scientific title of doctor of technical sciences, specialty *221.01. Energy systems and technologies*.
Chișinău 2023.

Structure: The paper consists of an introduction, four chapters, conclusions and recommendations, 106 bibliography titles, and includes 4 Annexes, 157 pages, 122 figures, 12 tables. The results are published in 18 scientific papers.

Keywords: electrical distribution networks, neutral treatment regime, single-phase fault, overvoltages, displacement of the neutral, mathematical model.

Field of study: engineering sciences.

The aim of the thesis: analyzing the potential for implementing resistive and combined neutral treatment in the distribution electrical networks in the Republic of Moldova and identifying a set of measures/actions to improve existing treatment methods, as well as conducting case studies by modeling the operating modes of electrical networks with different neutral treatment methods.

Paper Objectives: conducting a bibliographic study on the current status of the issue worldwide and in the Republic of Moldova; conducting a comparative analysis of various neutral treatment methods; analyzing the single-phase fault regime in medium-voltage electrical networks and identifying basic criteria for choosing the optimal solution; modeling and simulating normal and single-phase metallic or arc electrical fault regimes; applying the obtained results to develop a set of applicable measures/recommendations in the context of the Republic of Moldova.

Scientific novelty and originality of the work. Developing mathematical models for calculating the operating parameters for different methods of neutral treatment in 6-35 kV distribution electrical networks, allowing for mathematical modeling of these regimes, and identifying the optimal one while avoiding experimental trials limited by the advanced wear and tear of equipment within the electrical networks.

Important scientific problem solved based on the mathematical models obtained, practical recommendations/proposals have been developed for the implementation of new methods of neutral treatment (through resistance and combined) in the distribution electrical networks of the Republic of Moldova.

Theoretical importance. The thesis contributes scientific and practical insights to the calculation and analysis of operating modes in 6-35 kV distribution electrical networks with various neutral treatment methods to identify the method of neutral treatment that ensures improved quality of electric power distribution service and reliability of their operation.

The practical value of the work. In the paper, mathematical models for four neutral treatment regimes were developed, and analytical expressions for the operating parameters were obtained. The analyzed regimes were modeled and simulated, demonstrating the correctness of the obtained models.

Implementation of research results. Research results: 1. Implementation of the research results at the power stations "Centrala" 110/10 kV, "Bălți-330 kV" 330/110/10 kV and "CET-Nord" 110/10 kV, RED-Nord. 2. A modern laboratory stand "Analysis of neutral treatment methods in 6-35 kV networks" was developed at the Energy Department. 3. The obtained results are used in the courses Transport and Distribution of Electric Energy (TDEE - subject holder, university professor, Ion SRTATAN) and Electrical Part of Power Plants and Stations (PECS - subject holder, university lecturer Ina Dobrea).

DOBREA INA

IMPROVING THE OPERATION OF 6-35 kV DISTRIBUTION ELECTRIC NETWORKS BY CHOOSING THE NEUTRAL TREATMENT MODE

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