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OPPORTUNITY OF USING A MIXED NEUTRAL TREATMENT SOLUTION IN THE DISTRIBUTION ELECTRICAL NETWORKS OF THE REPUBLIC OF MOLDOVA

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Abstract. The optimal solution selection for the treatment of the neutral point in distribution networks (6-35 kV) holds significant practical importance as it directly or indirectly affects the continuity and reliability of supplying electrical energy to consumers, the behavior of medium-voltage electrical networks under single-phase fault conditions, and its impact on the quality of the power distribution service (duration and frequency of power interruptions). It also affects resulting overvoltages, adopted technical solutions, level of electrical security assurance, investments, and so forth. Developing a mathematical model for various methods of treating the neutral point in distribution networks allows for the calculation and analysis of these operating conditions, identifying the optimal one, thus avoiding experimental attempts that are limited by the advanced wear of equipment within the electrical networks of the Republic of Moldova. Based on the developed mathematical model, comparative calculations are performed regarding the feasibility of implementing the combined neutral regime.

Keywords: *combined (mixed) neutral, overvoltage, neutral voltage displacement, arc suppression coil (ASC), resistor.*

Rezumat. Alegerea soluției optimale de tratare a neutrului rețelelor de distribuție (6-35) kV are o importanță practică deosebită care se repercută, direct sau indirect, asupra continuității și fiabilității în alimentarea consumatorilor cu energie electrică, asupra comportării rețelelor electrice de medie tensiune în regim de defect monofazat și impactul acestuia asupra calității serviciului de distribuție a energiei electrice (durata și frecvența întreruperilor alimentării cu energie electrică), supratensiunilor rezultate, soluțiilor tehnice adoptate, nivelului de asigurare a securității electrice, investițiilor, etc. Elaborarea modelului matematic pentru diferite modalități de tratare a neutrului rețelelor electrice de distribuție permite calculul și analiza acestor regimuri, identificarea celui optimal evitând încercările experimentale, limitate de uzura avansată a echipamentelor din cadrul rețelelor electrice din Republica Moldova. În baza modelului matematic dezvoltat în lucrare sunt realizate calcule comparative privind oportunitatea implementării regimului neutrului combinat.

Cuvinte cheie: *neutru combinat (mixt), supratensiuni, deplasarea neutrului, bobină de stingere a arcului electric (BSA), rezistor.*

1. Introduction

Ensuring the electricity demand nationwide is the main task of the National Power System (NPS), which is divided into specialized segments - generation, transmission, distribution, and supply of electric energy. The 6-35 kV distribution electrical networks and their associated technologies represent one of the most dynamic development areas in the power sector. Until the end of the 20th century, the power system evolved towards expansion and centralization, benefiting from the quantitative advantages offered by the "economies of scale" in technical systems [1]. During this period, distribution electrical networks played a role in providing complete coverage to the served territories and in the "top-down" distribution of electric energy, using simple and reliable schemes. In the early 21st century, continuous improvements in equipment, technologies, and materials have allowed a change in the approach to constructing distribution networks, revising the principles of organizing the consumer power supply system, and necessitating major changes.

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

- Increasing electricity demand and ensuring the enhancement of the existing DENs' transport capacity. According to the International Energy Agency (IEA) Report [2], global electricity demand will rise from 2.6% in 2023 to an average of 3.2% in 2024-2025.
- Improving energy efficiency in distribution networks (including reducing technical and non-technical losses), enhancing management, and electrical security.
- Implementing innovative technologies, such as smart grids and advanced energy storage.
- Integrating renewable energy sources and distributed generation into the distribution electrical networks.
- Rising electrical load density, driven by the increased height of residential and utility buildings, as well as the growth in power ratios and the compactness of modern production systems.

Among the known technical measures, the treatment mode of the neutral point in distribution networks holds significant practical importance, which directly or indirectly impacts the continuity and reliability of supplying electric energy to consumers. It also affects the behavior of medium-voltage electrical networks under single-phase fault conditions and its impact on the quality of the power distribution service (duration and frequency of power interruptions), electrical installations, and their operation, adopted technical solutions, and the level of electrical security assurance, among others.

In accordance with the foreign country classification based on standard [3], there are five modes of neutral treatment. Specifically, in global practice, concerning medium-voltage networks (1 – 69 kV), unlike high-voltage networks (110 kV and above), the following neutral treatment solutions are observed in MT electrical networks [4-7]:

1. *Isolated Neutral:* Widely applied in post-Soviet countries such as Russia, Belarus, Ukraine, as well as in Italy, Spain, China, and some areas in Germany, Romania, and Finland (for 20 kV overhead networks). However, this method of neutral treatment in 1-69 kV networks possesses too many disadvantages, leading to its elimination from operation in the 1940s-1950s in most European, Australian, North and South American countries.

2. *Compensated Neutral (earthed through an arc suppression coil):* Applied in most European countries, China, and Russia.
3. *Neutral earthed through a low or high-value resistor:* Found in France, some areas in Germany, Bulgaria, Hungary, and Russia. In recent years, this neutral treatment method has been implemented in Romania, Belarus, and Ukraine.
4. *Combined Neutral or Mixed Solution (combining variants 2 and 3):* Applied in Germany, the Czech Republic, and Russia.
5. *Directly Earthed Neutral:* The method of neutral treatment used in the United Kingdom and the USA, Canada (the Anglo-Saxon Solution).

In the Republic of Moldova, the medium-voltage (MV) electrical networks, ranging from 6 to 35 kV, are managed by the companies ÎCS "Premier Energy Distribution" SA, RED Nord SA, and ÎS Moldelectrica. The 6-10 kV electrical networks, approximately 22 thousand km in length, are mostly overhead (88.6%), with 11.4% consisting of cable networks. The 35 kV electrical networks, approximately 1300 km in length, are exclusively overhead.

Currently, within the RM's Distribution Electrical Networks, there are two neutral treatment solutions regulated by the Rules of Electrical Installations Design (REID) [8], implemented over time as follows:

1. Isolated Neutral.
2. Neutral treated through an arc suppression coil (ASC), with manual or automatic adjustment.

These treatment systems are dedicated to specific network configurations and have advantages and disadvantages, which necessitate continuous improvement. Most of the distribution networks at the mentioned voltages operate in a mode of compensating capacitive current through the ASC. There is also a small number of stations where the neutral is isolated, but only in cases where the distribution networks are short, and the capacitive currents at the station have low values (below 10 A).

Studies and research conducted in the last 15 to 20 years [5, 6, 9] confirm the impossibility of obtaining a specific technical or techno-economic criterion for selecting the optimal neutral treatment solution in medium-voltage (MV) electrical networks. Thus, the choice of the optimal neutral treatment mode must be made in relation to a specific electrical network, under the conditions of a particular country.

Currently, in the Republic of Moldova, there are no studies and research for implementing resistive or combined neutral treatment. Additionally, there are no regulations or guidelines regarding the application of possible solutions or methods for compensating capacitive currents in earth connections. The purpose of this study is to analyze the potential for implementing combined neutral treatment in DENs of the Republic of Moldova, with the objectives being: analyzing the normal and single-phase fault conditions in MV electrical networks, identifying the fundamental criteria for choosing the appropriate solution, estimating the feasibility of implementing combined neutral treatment under the conditions of the Republic of Moldova.

The research hypothesis is focused on improving the existing modes of neutral treatment in RM's distribution networks or implementing new solutions that will contribute to the following: reducing overvoltages in the case of single-phase earth connections, reducing the number of disconnections and improving distribution service performance indicators [10], eliminating the evolution of single-phase faults into polyphase short circuits, enhancing the reliability of electricity supply to end consumers.

2. Materials and Methods

2.1. Expressions of network state variables during a single-phase fault

In distribution networks with voltage levels of 6-35 kV, single-phase faults constitute 75-80% of the total fault occurrences. Metallic ground connections account for approximately 10-15%, while the rest are accompanied by electric arcs at the fault location. The probability of arc self-extinction, burning duration, intermittent nature of the arc, and the value of the grounding current determine the overvoltages on the healthy phases, which can reach values of 3-3.5 times the phase voltage (U_f). Additionally, the consequences of these overvoltages include insulation breakdown in the weakest points of the electrical network and the transformation of single-phase faults into polyphase short circuits. The thermal action of the earth fault current may also cause fires.

To avoid or reduce the consequences of single-phase faults and the accompanying overvoltages, it is necessary to create conditions in which the electric arc at the fault location will self-extinguish or burn stably, and the grounding current will be limited to non-hazardous values.

The state of the electrical network in a steady-state single-phase fault condition is characterized by the values of certain quantities known as state variables, including:

- Phase voltages,
- Neutral-to-ground voltage,
- Fault current.

To obtain the analytical relationships of the state variables of the electrical network that characterize the steady-state condition of a single-phase fault, an equivalent calculation scheme will be used. The structure of this scheme is derived based on the relationships between the symmetrical components of voltage and current, considering the specific conditions of this fault and their validity at the fault location [11] (Figure 1).

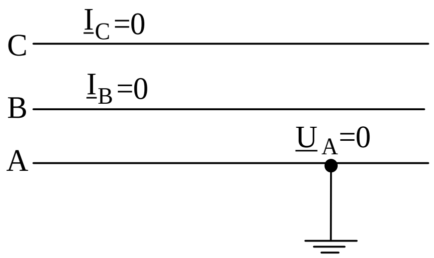

Figure 1. A single-phase fault.

If the currents due to consumers connected to the line are not taken into account, the presence of the fault can be expressed through the following relationships:

$$\left.\begin{aligned} \underline{I}_B = \underline{I}_C = 0; \\ \underline{U}_A = 0. \end{aligned}\right\}, \tag{1}$$

where: $\underline{I}_B$ is the current in phase B; $\underline{I}_C$ - the current in phase C; $\underline{U}_A$ - the voltage on phase A.

Taking into account the decomposition into symmetrical components of voltages and currents, assuming phase A as the reference, the following relationships can be written:

$$\left.\begin{aligned} \underline{I}^h + \underline{a}^2 \cdot \underline{I}^d + \underline{a} \cdot \underline{I}^i = 0; \\ \underline{I}^h + \underline{a} \cdot \underline{I}^d + \underline{a}^2 \cdot \underline{I}^i = 0, \end{aligned}\right\} \tag{2}$$

where $\underline{a} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$; $\underline{a}^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$.

From (2) it follows:

$$\underline{I}^h + \underline{a}^2 \cdot \underline{I}^d + \underline{a} \cdot \underline{I}^i = \underline{I}^h + \underline{a} \cdot \underline{I}^d + \underline{a}^2 \cdot \underline{I}^i, \quad (3)$$

or

$$(\underline{a}^2 - \underline{a}) \cdot \underline{I}^d = (\underline{a}^2 - \underline{a}) \cdot \underline{I}^i, \quad (4)$$

so:

$$\underline{I}^d = \underline{I}^i, \quad (5)$$

By substituting this result into one of the equations (2) for decomposing the current from the healthy phases, we obtain:

$$\underline{I}_B = \underline{I}^h + \underline{a}^2 \cdot \underline{I}^d + \underline{a} \cdot \underline{I}^i = \underline{I}^h + (\underline{a}^2 + \underline{a}) \cdot \underline{I}^d = \underline{I}^h - \underline{I}^d = 0,$$

as a consequence:

$$\underline{I}^h = \underline{I}^d = \underline{I}^i. \quad (6)$$

Conditions (1) and (6) allow the preparation of the equivalent calculation scheme (Figure 2). In this scheme, D, I, and H represent the equivalent networks of the system with respect to the fault location, valid for the three symmetrical components: positive sequence, negative sequence, and zero sequence [7].

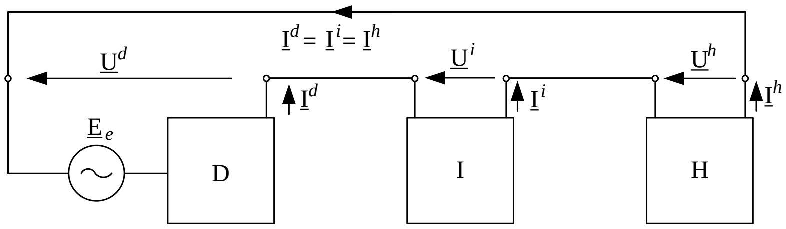

Figure 2. Schema echivalentă pentru defectul monofazat.

The three schemes are connected in series. In the positive sequence diagram, the considered source is included, assumed to provide a system of three voltages with equal magnitudes and 120° phase displacement, forming a positive sequence system of voltages. There are no electromotive forces (e.m.f) in the negative sequence and zero sequence components.

For the symmetrical components of voltage, the following can be written:

$$\left.\begin{aligned} \underline{U}^d &= \underline{E}_e - \underline{I}^d \cdot \underline{Z}^d; \\ \underline{U}^i &= -\underline{I}^i \cdot \underline{Z}^i; \\ \underline{U}^h &= -\underline{I}^h \cdot \underline{Z}^h. \end{aligned}\right\} \quad (7)$$

Similarly, for the symmetrical components of current, the relationship is valid:

$$\underline{I}^d = \underline{I}^i = \underline{I}^h = \frac{\underline{E}_e}{\underline{Z}^d + \underline{Z}^i + \underline{Z}^h}. \quad (8)$$

The single-phase to ground faults current is determined using the relationship:

$$\underline{I}_{PP} = \underline{I}^d + \underline{I}^i + \underline{I}^h. \quad (9)$$

The voltages on the phases of the network in the steady-state condition of a single-phase fault are determined as follows:

- for phase A (fault which occurs at A-Phase)

$$\underline{U}_A = \underline{U}_A^h + \underline{U}_A^d + \underline{U}_A^i = (-\underline{I}^h \cdot \underline{Z}^h) + (\underline{E}_e - \underline{I}^d \cdot \underline{Z}^d) + (-\underline{I}^i \cdot \underline{Z}^i) =$$
$$= \underline{E}_e - \underline{I}^d \cdot (\underline{Z}^h + \underline{Z}^d + \underline{Z}^i) = \underline{E}_e - \frac{\underline{E}_e}{\underline{Z}^h + \underline{Z}^d + \underline{Z}^i} \cdot (\underline{Z}^h + \underline{Z}^d + \underline{Z}^i) = 0;$$

- for phase B:

$$\underline{U}_B = \underline{U}^h + \underline{a}^2 \cdot \underline{U}^d + \underline{a} \cdot \underline{U}^i = -\underline{I}^h \cdot \underline{Z}^h + \underline{a}^2 \cdot (\underline{E}_e - \underline{I}^d \cdot \underline{Z}^d) + \underline{a} \cdot (-\underline{I}^i \cdot \underline{Z}^i);$$

- for phase C:

$$\underline{U}_C = \underline{U}^h + \underline{a} \cdot \underline{U}^d + \underline{a}^2 \cdot \underline{U}^i = -\underline{I}^h \cdot \underline{Z}^h + \underline{a} \cdot (\underline{E}_e - \underline{I}^d \cdot \underline{Z}^d) + \underline{a}^2 \cdot (-\underline{I}^i \cdot \underline{Z}^i).$$

For electric power transmission and distribution networks composed only of passive elements (without generators), it can be considered that:

$$\underline{Z}^d = \underline{Z}^i.$$

Thus:

$$\underline{U}_B = -\underline{I}^d \cdot \underline{Z}^h + \underline{a}^2 \cdot \underline{E}_e - (\underline{a}^2 + \underline{a}) \cdot \underline{I}^d \cdot \underline{Z}^d = \underline{a}^2 \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \underline{I}^d;$$
$$\underline{U}_C = -\underline{I}^d \cdot \underline{Z}^h + \underline{a} \cdot \underline{E}_e - (\underline{a}^2 + \underline{a}) \cdot \underline{I}^d \cdot \underline{Z}^d = \underline{a} \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \underline{I}^d.$$

By introducing, in the obtained expressions, the relationship (8) of the current in the positive sequence, we obtain:

$$\underline{U}_B = \underline{a}^2 \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \frac{\underline{E}_e}{2 \cdot \underline{Z}^d + \underline{Z}^h} = \underline{E}_e \cdot \left(\underline{a}^2 + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h} \right) = \underline{k}_B^{def} \cdot \underline{E}_e; \quad (10)$$

$$\underline{U}_C = \underline{a} \cdot \underline{E}_e + (\underline{Z}^d - \underline{Z}^h) \cdot \frac{\underline{E}_e}{2 \cdot \underline{Z}^d + \underline{Z}^h} = \underline{E}_e \cdot \left(\underline{a} + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h} \right) = \underline{k}_C^{def} \cdot \underline{E}_e; \quad (11)$$

$$\underline{k}_B^{def} = \underline{a}^2 + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h}; \qquad \underline{k}_C^{def} = \underline{a} + \frac{\underline{Z}^d - \underline{Z}^h}{2 \cdot \underline{Z}^d + \underline{Z}^h}, \quad (12)$$

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

These coefficients are complex numbers, and their modulus represents the multiple of increase in voltages on the healthy phases during a single-phase fault compared to the phase voltage at the corresponding section without a fault. In other words, this is the phase voltage of phase A.

The voltage on the *electrical neutral* of the network (physical neutral may be absent – when the secondary winding of the transformer is connected in a delta configuration) will always be equal to the homopolar voltage, as the positive and negative sequence systems do not result in neutral displacement:

$$\underline{U}_N = \underline{U}^h. \quad (13)$$

At the appearance of the homopolar system, the neutral undergoes a potential change from 0 to $\underline{U}^h$.

2.2. Transient processes at single phase-to-ground faults in medium-voltage networks with the neutral treated by ASC

In addition to reducing the industrial frequency component of the earth fault current and extinguishing the electric arc, the ASC also plays a significant role during the transient process. It reduces the rate of change of voltage on the network neutral and, consequently, on the phases, leading to a considerable reduction in the amplitudes of the free components and, thus, to a decrease in overvoltages in the network.

To analyze the transient processes during the ignition and extinction of the electric arc when the neutral is treated by the ASC, the following scheme will be used (Figure 4).

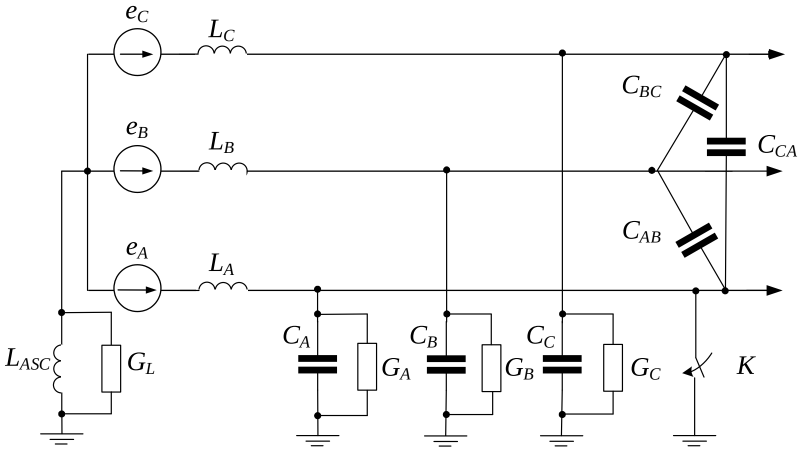

Figure 4. The equivalent schematic of the electrical network with the neutral treated through the arc suppression coil.

It is worth mentioning that the resistances of the phases were not included in the schematic since they are contained within the equivalent resistance, which includes the current return path resistance and the resistance of the fault arc grounding.

This resistance can vary within wide limits and can be different for different stages of the transient process. For instance, for the free components with higher frequencies than the industrial frequency, the skin effect is more pronounced, resulting in a higher resistance. Due to these considerations, the attenuation coefficient, denoted as k_δ, is used in practice, which is obtained from practical experience gained during the operation of medium-voltage networks [12].

Just like in the case of isolated neutral, during the ignition of the fault arc, the non-fault phases' capacitances are charged up to the line voltage. This process exhibits oscillatory behavior with attenuation. The ASC practically does not influence the amplitude or frequency of the free component, as it is shunted by the inductance of the faulty phase, which is much smaller than the inductance of the ASC. Therefore, during the initial breakthrough, the ASC does not affect the transient process parameters, and it behaves analogously to an isolated neutral [13].

From Figure 5, it can be observed that when phase A is grounded, the ASC is connected to the e.m.f. of phase A, which triggers a transient process of current modification in the ASC. Considering that $L_f \ll L_{ASC}$, the inductance of the faulty phase can be neglected, as it does not affect the transient process occurring in the ASC. The schematic representation of this transient process will look like this:

For the Figure 5 circuit, three equations can be formulated according to Kirchhoff's laws:

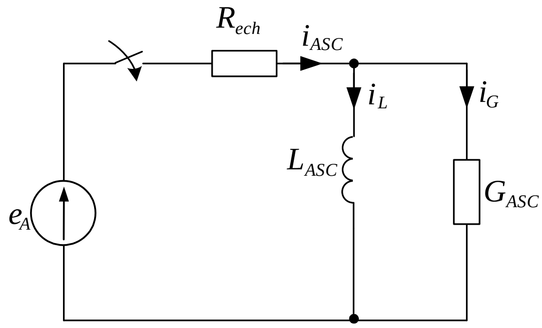

Figure 5. The equivalent circuit for analyzing the transient process in ASC during the first insulation breakdown.

$$\begin{cases} i_{ASC} = i_L + i_G; \\ R_{ech} \cdot i_{ASC} + L_{ASC} \cdot \dfrac{di_L}{dt} = e_A; \\ \dfrac{i_G}{G_{ASC}} - L_{ASC} \cdot \dfrac{di_L}{dt} = 0. \end{cases} \tag{14}$$

If this system is solved for the current i_L, the differential equation of the transient process is obtained:

$$(R_{ech} \cdot G_{ASC} + 1) \cdot L_{ASC} \cdot \frac{di_L}{dt} + R_{ech} \cdot i_L = e_A. \tag{15}$$

The solution of this differential equation will be:

$$i_L = i_{Lfr} + i_{Llb}. \tag{16}$$

The forced component will be expressed as follows:

$$i_{Lfr} = I_m \cdot \sin(\omega t + \psi_{st} - \varphi), \tag{17}$$

where: $I_m = \dfrac{E_m}{\sqrt{R_{ech}^2 + \omega^2 \cdot L_{ASC}^2}}$ (if the ASC conductance is neglected); $\psi_{st} \approx 90°$ – it is the phase of the voltage at which the insulation breakdown occurs (assuming that the breakdown occurs when the voltage on the non-fault phase reaches its peak value), which is why the initial phase of the current corresponds to the phase of the voltage at the time of breakdown); φ – the phase difference between the voltage across the coil and the forced component of the current.

The free component will be:

$$i_{Llb} = A \cdot e^{-\frac{t}{\tau}}, \tag{18}$$

where: A is the integration constant, determined from the initial conditions, i.e. $i_L=0$, or $I_m \cdot \sin(\psi_{st} - \varphi) + A = 0$, which yields: $A = -I_m \cdot \sin(\psi_{st} - \varphi)$; τ – the time constant. The time constant can be determined from the equation (15):

$$\tau = L_{ASC} \cdot \left(G_{ASC} + \frac{1}{R_{ech}} \right). \tag{19}$$

From the above-explained details, the relationship for the current in ASC during arc ignition can be obtained:

$$i_L = I_m \cdot \sin(\omega t + \psi_{st} - \varphi) - I_m \cdot \sin(\psi_{st} - \varphi) \cdot e^{-\frac{t}{\tau}}. \tag{20}$$

Angle $\varphi \approx 90°$, since $R_{ASC} >> L_{ASC}$, implies $\psi_{st} - \varphi \approx 0$, which means that the free component is negligibly small. Therefore, the conclusion can be drawn that in the compensated network, the transient process during the first insulation breakdown does not differ from the transient process that occurs in the network with an isolated neutral.

After arc extinction, the ASC decisively influences the transient process. This is due to the fact that the ASC significantly alters the network's admittance to ground, facilitating the discharge of electric charges to the ground. Moreover, the considerable inductance of the ASC prevents sudden voltage rise on the network's neutral and phases, thereby limiting the level of overvoltage.

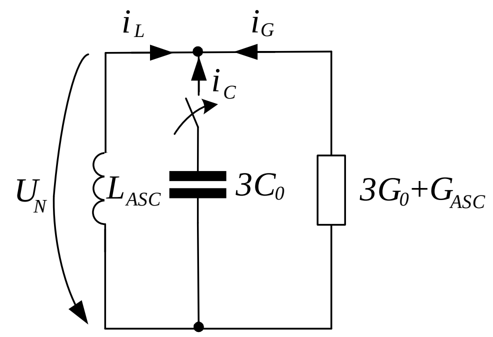

Figure 6. The equivalent circuit for the transient process that occurs after arc extinction.

In Figure 6 the phase-to-ground conductance is denoted by G_0.

The diagram (Figure 6) represents an oscillating circuit in which the transient process can be described by the following relationships:

$$i_L = \frac{1}{L_{ASC}} \cdot \int U_L \cdot dt; \tag{21}$$

$$i_C = 3C_0 \cdot \frac{dU_C}{dt}; \tag{22}$$

$$i_G = (3 \cdot G_0 + G_{ASC}) \cdot U_G; \tag{23}$$

$$i_C + i_G + i_L = 0. \tag{24}$$

If we substitute equations (21), (22), and (23) into equation (24), considering the equality $U_N=U_C=U_G=U_L$, we obtain:

$$3C_0 \cdot \frac{dU_N}{dt} + (3 \cdot G_0 + G_{ASC}) \cdot U_N + \frac{1}{L_{ASC}} \int U_N \cdot dt = 0. \tag{25}$$

If equation (25) is divided by $3C_0$ and then differentiated with respect to time, the resulting differential equation describes the neutral voltage during the transient process when the electric arc is extinguished.:

$$\frac{dU_N^2}{dt^2} + \frac{(3 \cdot G_0 + G_{ASC})}{3C_0} \cdot \frac{dU_N}{dt} + \frac{1}{3C_0 \cdot L_{ASC}} \cdot U_N = 0. \tag{26}$$

For a more simplified and clear analysis of this relationship, the following coefficients are introduced:

- Coefficient of deviation from complete compensation:

$$\upsilon = 1 - \frac{I_{L1}}{I_{C1}} = 1 - \frac{E_f \cdot \frac{1}{\omega L_{ASC}}}{E_f \cdot 3\omega C_0} = 1 - \frac{1}{3\omega^2 C_0 L_{ASC}} = 1 - \frac{\omega_0^2}{\omega^2}, \tag{27}$$

where: I_{L1}, I_{C1} represent the inductive currents through the ASC and the corresponding capacitive ground-fault current at the industrial frequency; $\omega_0 = \frac{1}{\sqrt{3C_0 L_{ASC}}}$ – frequency of resonance of the oscillating circuit of the ASC; C_0 – the phase capacitances; ω – the angular frequency corresponding to the industrial frequency.

When compensation is complete, then $I_{L1} = I_{C1}$ and $\upsilon = 0$; when $I_{L1} < I_{C1}$ subcompensation occurs and $\upsilon > 0$, when $I_{L1} > I_{C1}$ overcompensation occurs and $\upsilon < 0$.

- The attenuation coefficient that characterizes the active component of the ground-fault current:

$$\partial = \frac{I_{a1}}{I_{C1}} = \frac{E_f \cdot (3G_0 + G_{ASC})}{E_f \cdot 3\omega C_0} = \frac{3G_0 + G_{ASC}}{3\omega C_0}, \tag{28}$$

where I_{a1} is composed of two components, the first one is determined by current leakage on the insulator surfaces and constitutes 2 - 3% of the capacitive current of the network, but the second component is determined by losses in the ASC and constitutes approximately 2% of the inductive component of the current in the ASC, For the given data, the attenuation coefficient has the value of 0,05 [12-14]; I_{C1} – the capacitive ground-fault current at the industrial frequency.

Taking into consideration equations (27) and (28), equation (26) becomes:

$$\frac{dU_N^2}{dt^2} + \partial\omega \cdot \frac{dU_N}{dt} + \omega^2 \cdot (1-\upsilon) \cdot U_N = 0. \tag{29}$$

The roots of this equation are expressed as follows:

$$p_{1,2} = \left[-\frac{\partial}{2} \pm \sqrt{\left(\frac{\partial}{2}\right)^2 - (1-\upsilon)} \right] \cdot \omega. \tag{30}$$

Since $\left(\frac{\partial}{2}\right)^2$ << $1-\upsilon$ the roots of the equation will be complex conjugates, indicating that the discharge will exhibit an oscillatory character.

The solution of equation (25) will have the following form:

$$u_N(t) = U_{Nm} \cdot e^{-\frac{\partial}{2}\cdot\omega t} \cdot \sin(\omega_{st} t + \varphi_{N0}), \tag{31}$$

where $\omega_{st} = \omega \cdot \left| \sqrt{\left(\frac{\partial}{2}\right)^2 - (1-\upsilon)} \right|$ – is the angular frequency of the free oscillations of the transient process of neutral voltage modification; U_{Nm}, φ_{N0} – are the initial amplitude and initial phase of the free component of the neutral voltage. These quantities are determined from the initial conditions, i.e., they depend on the values taken by $u_N(0)=u_C(0)$ și $i_L(0)$, , thus, on the moment of arc extinction.

After the electric arc is broken, the free component of the voltage u_N overlaps with the phase voltages. In this case, the voltage on the faulty phase can be expressed as follows:

$$\begin{aligned} u_A(t) &= e_A(t) + u_N(t) + U_{Am} \cdot e^{-\delta_2 \cdot (t - \frac{T_1}{2})} \cdot \cos\omega_2 (t - \frac{T_1}{2}) = E_m \cdot \sin\left[\omega \cdot (t - \frac{T_1}{2}) + \frac{3\cdot\pi}{2\cdot\omega}\right] + \\ &+ U_{Nm} \cdot e^{-\frac{\partial}{2}\cdot\omega(t - \frac{T_1}{2})} \cdot \sin(\omega_{st} t + \varphi_{N0}) + U_{Am} \cdot e^{-\delta_2 \cdot (t - \frac{T_1}{2})} \cdot \cos\omega_2 (t - \frac{T_1}{2}). \end{aligned} \quad (32)$$

In equation (32), the free component resulting from the process of restoring the voltage on the faulty phase is included. This process is characterized by the amplitude U_{Am}, attenuation coefficient δ_2 and angular frequency ω_2, while T_1 is the period of the free component for the transient process that occurs after arc ignition. It is assumed that the arc extinguishes at the first passage through zero of the free component of the current, which happens after a time equal to $\frac{T_1}{2}$. Time $t=0$ is considered at the moment of breakthrough, when the voltage on the faulty phase reaches the value of E_m.

For capacitive current, the relationship is valid:

$$i_C(t) = 3C_0 \cdot \frac{du_C}{dt} = 3C_0 \cdot \frac{du_N}{dt}. \quad (33)$$

If we take into consideration that $\frac{1}{\omega_{st} L_{BSA}} \gg 3G_0 + G_{BSA}$, then it can be considered that $i_G(t) \approx 0$ and $i_L(t) \approx i_C(t)$.

In such a way, if $t=0$ is considered as the beginning of the transient process, then equations (22) and (33) take the following form:

$$\begin{aligned} u_N(0) &= U_{Nm} \cdot \sin\varphi_{N0}; \\ i_L(0) &= 3C_0 \cdot \frac{du_N}{dt}\Big|_{t=0} = 3C_0 \cdot \omega_{st} \cdot U_{Nm} \cdot \cos\varphi_{N0}. \end{aligned} \quad (34)$$

The solutions of this system will be as follows:

$$\begin{aligned} U_{Nm} &= \sqrt{(u_N(0))^2 + \left(\frac{i_L(0)}{3C_0 \cdot \omega_{st}}\right)^2}; \\ tg\varphi_{N0} &= 3C_0 \cdot \omega_{st} \cdot \frac{u_N(0)}{i_L(0)}. \end{aligned} \quad (35)$$

In such a way, the initial conditions for solving the differential equation are different depending on the moment in time when the arc extinguishes. If we assume that the electric arc will extinguish at the first zero crossing of the free component of the grounding current, then the current through the ASC will be approximately equal to zero ($i_L(0) \approx 0$), because one half-period of the free component ($\frac{T_1}{2}$) is much smaller than the time constant of the ASC and the current in the ASC does not show any significant changes. In such a way, considering $i_L(0) = 0$, from (35) we obtain: $U_{Nm} = u_N(0); \varphi_{N0} = 90°$. Therefore, the neutral voltage will change according to the law:

$$u_N(t) = u_N(0)\cdot e^{-\frac{\partial}{2}\cdot\omega t}\cdot\sin(\omega_{st}t+90°) = u_N(0)\cdot e^{-\frac{\partial}{2}\cdot\omega t}\cdot\cos\omega_{st}t\,. \tag{36}$$

As mentioned above, since in the general case $e_A(t)+u_N(t)\neq 0$, a process of restoring the voltage on the faulty phase will occur with an angular frequency ω_2 there will be a voltage peak during the restoration of the voltage on the faulty phase. If the electrical stiffness of phase A at the defect location is higher than this threshold voltage (u_{pr}), then the voltage on the faulty phase will change according to the relationship:

$$u_A(t) = e_A(t)+u_N(t) = E_m\cdot\sin\left(\omega\left(t-\frac{T_1}{2}\right)+\frac{3\pi}{2\omega}\right)+$$
$$+u_N(0)\cdot e^{-\frac{\partial}{2}\cdot\omega\left(t-\frac{T_1}{2}\right)}\cdot\cos\omega_{st}\left(t-\frac{T_1}{2}\right)+U_{Am}\cdot e^{-\delta_2\cdot t}\cdot\cos\omega_2(t-\frac{T_1}{2}) = \tag{37}$$
$$= -E_m\cdot\cos\omega\left(t-\frac{T_1}{2}\right)+u_N(0)\cdot e^{-\frac{\partial}{2}\cdot\omega\left(t-\frac{T_1}{2}\right)}\cdot\cos\omega_{st}\left(t-\frac{T_1}{2}\right)+U_{Am}\cdot e^{-\delta_2\cdot t}\cdot\cos\omega_2(t-\frac{T_1}{2}).$$

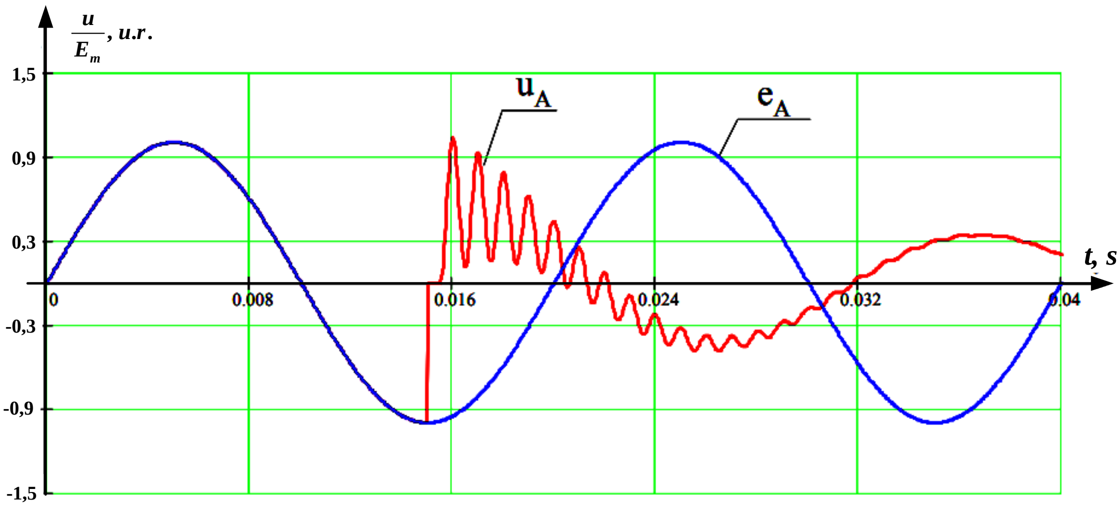

Figure 7. The voltage on the faulty phase during the extinction of the electric arc over the course of two periods of industrial frequency.

Result $u_N(0) = 1,48\cdot E_m$. If the following parameters of the transient process are accepted: $\partial = 0,05$, $\omega_1 = \omega_2 = 2\pi 1000$, δ_2=200, then the voltages on the faulty phase and on the neutral will take the form presented in Figure 7 (the voltage values are reported relative to the amplitude value).

In the case when the electric arc extinguishes at the zero crossing of the forced component, from equations (27) and (28), it can be observed that the quantities representing the reactive and active components of the grounding current, relative to this current, i.e.:

$$\upsilon = 1-\frac{I_{L1}}{I_{C1}} = \frac{I_{C1}-I_{L1}}{I_{C1}} = \frac{I_{r1}}{I_{C1}};\ \partial = \frac{I_{a1}}{I_{C1}}, \tag{38}$$

Here, index *1* indicates the fundamental harmonic; I_{r1} – the residual current.

The forced component of the grounding current can be expressed as the active and reactive components:

$$i_{pp} = -E_m\cdot 3\omega C_0\cdot(\partial\cdot\sin\omega t+\upsilon\cdot\cos\omega t). \tag{30}$$

At the moment of arc extinction, the current passes through zero ($i_{pp}=0$), from which it follows that:

$$\partial \cdot \sin \omega t + \upsilon \cdot \cos \omega t = 0 \quad sau \quad \varphi_{st} = \omega t_{st} = arctg\left(-\frac{\upsilon}{\partial}\right), \tag{40}$$

where t_{st} is the time interval between the moment of zero crossing of the e.m.f. of the faulty phase and the grounding current, and φ_{st} is the phase angle corresponding to this time.

Since, until the zero crossing of the forced component of the grounding current, the transient process initiated at the arc ignition practically diminishes, the neutral voltage at the moment of extinction will be $u_N(t) = -e_A(t)$, hence $e_A(t) + u_N(t) = 0$. This means that the high-frequency component, which was present when the arc extinguished at the first zero crossing of the free component, will be absent in this case. The voltage restoration process is described by the relationship:

$$u_A(t) = u_{Afr}(t) + u_{Alb}(t) = E_m \cdot \left(\sin\left(\omega \cdot t + \varphi_{st}\right) - e^{-\frac{\partial}{2}\cdot\omega\cdot t} \cdot \sin(\omega_{st} t + \varphi_{st}) \right), \tag{41}$$

where: $u_{Afr}(t) = E_m \cdot \sin\left(\omega \cdot t + \varphi_{st}\right)$ – the forced component, s equal to the e.m.f. of phase A, but with the initial phase that $e_A(t)$ has at the moment of arc extinction, in other words φ_{st};

$u_{Alb}(t) = u_N(t) = E_m \cdot e^{-\frac{\partial}{2}\cdot\omega\cdot t} \cdot \sin(\omega_{st} t + \varphi_{st})$.

The presence of ASC significantly reduces the speed of voltage restoration on the faulty phase, but it plays a positive role because it provides a longer time for deionizing the faulty location and reduces the probability of re-ignition of the electric arc.

2.3. Transients during a single-phase to ground fault in medium voltage networks with the neutral treated by ASC and resistor

Treating the neutral through the ASC in parallel with a resistor is called combined treatment. The processes that occur when grounding a phase in this case do not fundamentally differ from the case of treating the neutral only through ASC. This is because the presence of the resistor only changes the conductance between the neutral and the ground (Figure 8), which means that the relationships deduced for the case of treating the neutral through ASC alone are valid in this case as well, with the addition of the resistor's conductance (G_R) in the appropriate places.

In other words, the resistor will affect the attenuation coefficient:

$$\partial = \frac{3G_0 + G_{ASC} + G_R}{3\omega C_0}. \tag{42}$$

And, to a negligible extent, the frequency of free oscillations of the transient process:

$$\omega_{st} = \omega \cdot \left| \sqrt{\left(\frac{\partial}{2}\right)^2 - (1-\upsilon)} \right|. \tag{43}$$

The use of this neutral treatment scheme is relevant for overhead lines where there is an asymmetry in phase-to-ground capacitances. In such cases, tuning the ASC to resonance or with a small deviation from resonance leads to the neutral shift in normal operation. If the asymmetry is pronounced, a displacement voltage appears on the neutral that exceeds the permissible voltage of $0.15 \cdot U_{f.nom}$ [14, 15].

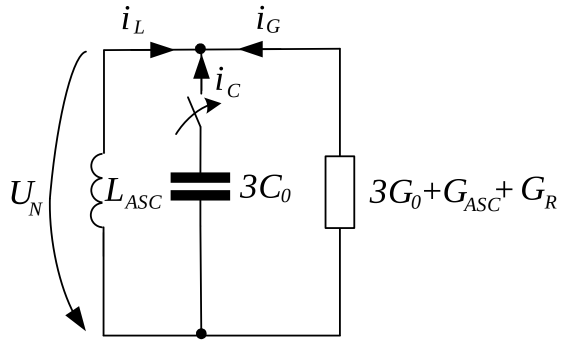

Figure 8. The simplified equivalent circuit of a medium-voltage network with the neutral treated by an ASC in parallel with a resistor.

To ensure this voltage, in some cases, it is necessary to detune the ASC by not less than 20% [16], which reduces the effectiveness of the ASC in both stabilized grounding operation and transient operation. An alternative solution to this problem is connecting a resistor in parallel with the ASC, which, when chosen correctly, allows tuning the ASC close to resonance while keeping the neutral voltage within the required limits.

In some studies, for example in [17], it is proposed to use the resistor in parallel with the ASC in all cases, even when the phase-to-ground capacitances are equal, with the aim of reducing overvoltages during grounding through electric arc. This is justified by the fact that installing the resistor is more economically convenient than installing ASC with automatic fine-tuning capability.

In this case, the value of the resistor must be chosen based on two conditions:

- to ensure that the neutral displacement voltage in normal operation does not exceed $0.15U_{f.nom}$;
- to limit overvoltages during single-phase fault with intermittent electric arc, in case of the maximum possible detuning of the ASC that may occur in practical operation.

Derived from the first condition, the value of the resistor will be chosen according to the condition:

$$U_N \leqslant 0.15U_{f.nom}. \tag{44}$$

The neutral voltage is determined using the relationship:

$$U_N \approx U_{N\ m.g.} \cdot q, \tag{45}$$

where: $U_{N\ m.g.}$ is the voltage that arises due to the asymmetry between the phase-to-ground capacitances of the network:

$$\underline{U}_{N\ m.g.} = \frac{\underline{E}_A \cdot j\omega \cdot C_{0A} + \underline{E}_B \cdot j\omega \cdot C_{0B} + \underline{E}_C \cdot j\omega \cdot C_{0C}}{j\omega \cdot (C_{0A} + C_{0B} + C_{0C})} = \frac{\underline{E}_A \cdot C_{0A} + \underline{E}_B \cdot C_{0B} + \underline{E}_C C_{0C}}{C_{0A} + C_{0B} + C_{0C}}. \tag{46}$$

$q=\dfrac{X_{ASC}}{R_{ASC}+R_N}=\dfrac{B_{ASC}}{G_{ASC}+G_R}$ is the quality factor of the ASC, and it can reach high values: *q=20..200*.

Taking into consideration (44) and (45), we can write:

$$U_{N\ m.g.}\cdot q \le 0.15U_{f.nom}. \tag{47}$$

Or:

$$U_{N\ m.g.}\cdot \frac{B_{ASC}}{G_{ASC}+G_R} \le 0.15U_{f.nom}. \tag{48}$$

From (48), the conductance of the resistor can be determined:

$$G_R \ge \frac{U_{N\ m.g.}\cdot B_{ASC}}{0,15U_{f.nom}} - G_{ASC}, \tag{49}$$

and the resistance of the resistor:

$$R_N=\frac{1}{G_R}\le \frac{0.15\cdot U_{f.nom}}{U_{N\ m.g.}\cdot B_{ASC}-0.15U_{f.nom}\cdot G_{ASC}}. \tag{50}$$

3. Results and discussion

For the "Central 110/10 kV Substation Balți" state variables will be calculated in a stabilized state for single-phase-to-ground faults, considering the treatment of the neutral through ASC in parallel with a high-value resistor.

At the Substation two power transformers of ТДН-16000/110/11 type are installed, with the parameters: ΔPsc=85 kW, Usc=10.5% and the connection scheme Y0/Δ-11; Additionally, each bus section is connected to a transformer for creating an artificial neutral (TNA) of ТМПС-630/10.5/0.23 type with the parameters: ΔPsc=8.63 kW, Usc=5.5%, ΔP0=0.997 kW, I0%=0.49%, I1n=34.6 A and the connection scheme Y0/Δ-11; In the neutral of each TNA two ASCs are connected, of type: РЗДСОМ-380/10 and РЗДПОМ-480/10.

The calculated total capacitances are as follows: for section 1– C_{01}=13.34 μF; and for section 2 – C_{02}=13 μF, the grounding current is I_{pp} =73 A.

The calculation will be performed for section 1, feeder number 2. The feeder number 2 diagram and the grounding location are indicated in (Figure 9).

For the analyzed power station, the treatment of the neutral through the combined ASC with a high-value resistor is examined. Considering that the ASC operates in over-compensation mode (*k=1.1*), it follows that the capacitive current will not exceed 8 A.

From the catalog, a resistor with a resistance value of R_n=*500* Ω is selected so that the current through it does not exceed 10 *A*.

The impedance of the resistor with a resistance value of $R_N=500\ \Omega$:

$$\underline{Z}_N=\frac{\underline{Z}_{ASC}\cdot R_N}{\underline{Z}_{ASC}+R_N}=\frac{(1.033+j76.426)\cdot 500}{(1.033+j76.426)+500}=12.377+j74.38\ \Omega.$$

According to the deduced expressions, the operating parameters are calculated for the variant with the neutral treated with ASC and the neutral combined with ASC in parallel with a high-value resistor. The obtained results are presented in Table 1.

The obtained results demonstrate that the combined treatment of the neutral using ASC in parallel with a 500 Ω resistor leads to a reduction in the neutral voltage (in normal operation) by approximately 3.5 times. This creates a more favorable operating condition for the network and allows integration within the limits of the neutral displacement voltage values specified by the current regulations [18] (p.542).

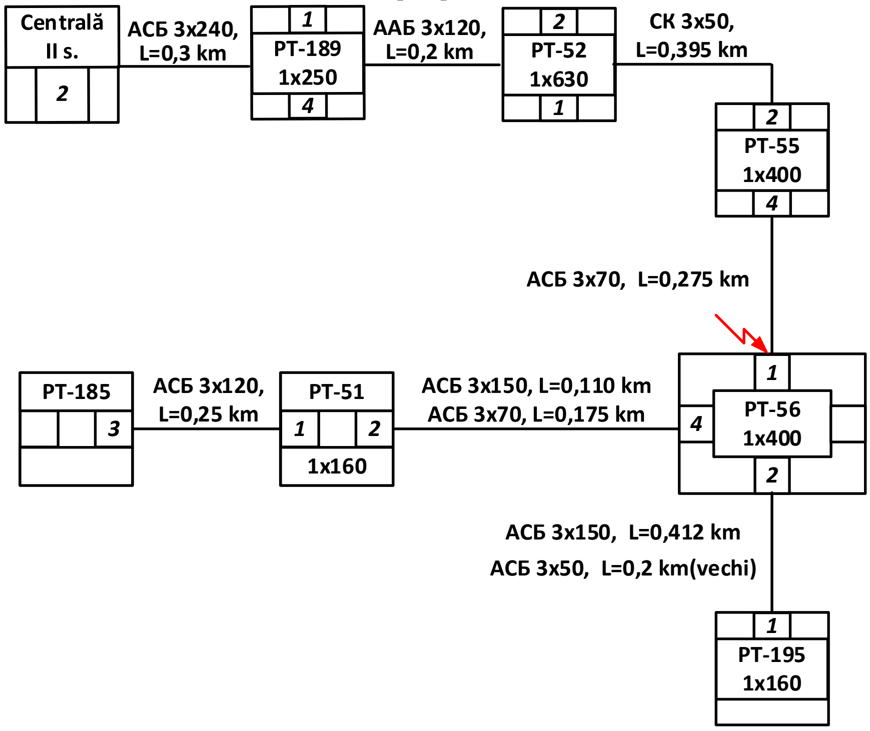

Figure 9. Structural diagram of feeder 2 at the „Central 110/10kV Substation Balti".

Table 1

The results of calculating the operating parameters

The treatment method	The neutral voltage in normal operating conditions with 5% asymmetry in phase-to-ground capacitances, U_N, V	The neutral voltage during single-phase fault condition, U_N, V	The fault current, I_{PP}, A
Neutral treated by ASC	$U_N = 1846\ V\ (32\%\ of\ U_f)$	$5.536 \cdot e^{-j178.88°}$	$2.424 \cdot e^{j4.5°}$
Neutral treated by ASC and a high-value resistor	$U_N = 526.5\ V\ (9\%\ of\ U_f)$	$5.771 \cdot e^{j179.92°}$	$13.04 \cdot ej^{1.45°}$

Based on numerous implementations and positive outcomes, the authors [9] recommend using the combined neutral treatment where this method exhibits maximum efficiency, specifically in extensive and physically worn cable networks, as well as in overhead or mixed networks. This includes cases where significant asymmetry in phase-to-ground capacitances is observed or when using ASC with stepped regulation.

5. Conclusions

In the Republic of Moldova, the 35 kV networks are exclusively overhead and, in the majority of cases, operate with isolated neutral and a certain degree of asymmetry. Therefore, it is considered necessary to transition these networks to compensated or combined neutral treatment regimes.

The 6-10 kV networks in the Republic of Moldova are primarily overhead and mixed, with an advanced degree of wear. Connecting a high-value resistor in parallel with ASC, during normal operation of the electrical network, will lead to a reduction in the neutral voltage caused by source voltage asymmetry and asymmetry in phase-to-ground capacitances.

In the case of combined neutral treatment, ASC and the resistor are connected in parallel. In this configuration, ASC will ensure the reduction of single-phase fault current, while the resistor will dampen overvoltages and oscillations caused by detuning of ASC. This solution will reduce the number of network disconnections and stabilize the single-phase-to-ground fault arc.

A promising method for the combined neutral treatment of 6-35 kV networks [9, 19] involves bypassing ASC with a low-voltage 500 V resistor, connected to its auxiliary winding through a normally open switch. This method allows for the combination of positive properties of both compensated and resistive neutral treatment.

Conflicts of Interest: The authors declare no conflict of interest.

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