The Influence of the Treatment Mode of the Neutral in the 6-35 kV Networks on the Displacement Voltage in the Quasi-Stationary Regime

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Abstract - **In the work are analyzed the quasi-voltage surges in the 6-35 kV networks with the neutral treatment by the electric arc compensation coil, mixed - by the compensation coil in association with the resistor, through the resistor. It determines the displacement voltage of the neutral. It is analyzed the influence of the degree of asymmetry on the displacement voltage of the neutral. There are presented the ways of connecting the neutral treatment devices: the electric arc compensation coil, the low voltage and medium voltage resistors, the low value resistor and the high value resistor. It is shown that the introduction of a resistor in neutral causes the active component to appear in the grounding current instead of the defect. This fact plays an important role in reducing the overvoltages, making selective current protections and increasing the reliability of the operation of the electrical installations. The selection of the optimum neutral grounding method is made for a long period of time, it involves a large volume of investments and a very careful technical foundation, so that the chosen solution is as best as possible for the network considered. For each grounding method, this article presents brief description and calculation of the neutral displacement voltage.**

Cuvinte cheie: *supratensiuni, bobină de compensare, rezistor de legare la pământ, rezistor de valoare mică, rezistor de valoare mare, transformator pentru crearea neutrului, neutru izolat, neutru compensat, curent de punere la pământ, deplasarea neutrului.*

Keywords: *overvoltages, compensation coil, neutral grounding resistors, low resistance grounding, high resistance grounding, earthing transformer, isolated neutral, compensated neutral, earth power current, neutral voltage displacement.*

INTRODUCTION

The problem of treating the neutral in 6-35 kV distribution networks is of particular importance for the distribution of electricity because it influences: insulation level; the size and ways of limiting the network surges; the operating conditions of the switches; protection systems; reducing consumer downtime; security of personnel and electrical equipment for single-phase defects.

In the Republic of Moldova 6-35 kV power distribution networks are extended and constitute about 2100 km for 35 kV networks and about 20 000 km the length of 6 -10 kV power lines (including underground power lines about 500 km). The functioning of these networks directly affects the quality of the distribution services, the reliability and continuity indicators in the electricity supply of the final consumers such as: SAIFI (System Average Interruption Frequency Index) - The Average Frequency Index of Network Interruptions; SAIDI (System Average Interruption Duration Index) - System Average Duration of Network Interruptions (System; CAIDI (Customer Average Interruption Duration Index) - average duration of an interruption, Duration and number of unscheduled interruptions, etc. The values of these indicators are set in the Regulation on the quality of electricity transmission and distribution services [1].

The operating practice shows that the vast majority of unscheduled interruptions in the distribution networks are caused by the deterioration of the insulation of these networks in relation to the earth - single-phase faults. This type of faults constitutes 75% of the total number, and 80% of the single-phase faults develop in multiphase short circuits [6] which leads to an increase in the number of disconnections of the large short circuit currents, the reduction of the operating cycle of the switches, the possible refusal of the AAR , etc. The vast majority of single-phase faults turn to multi-phase faults, due to the intermittent electric arc instead of the arc faults and overvoltages. The character of the occurrence of these phenomena, the value of the surges, the value of the grounding current and other important factors are in close correlation with the way of treating the neutral distribution networks.

Until 2003 the Norms for the Installation of Electrical Installations (NAIE) allowed the operation of electrical networks with voltage 3-35 kV only with the isolated neutral and with the compensated neutral (grounded by means of the compensation coil (CC)). From 01.01.2003, it was implemented the last (7th) edition of these norms [2], which operate in the space of CIS countries, and which in point 1.2.16, provides the possibility to operate the electrical networks with the voltage 3-35 kV, both with the isolated neutral as well as the neutral grounded by means of an compensation coil or resistor.

There are no clear recommendations in NAIE, regarding the use of the neutral treatment methods in the 6-35 kV electrical networks. In point 1.2.16 are indicated, only the values of capacitive currents, starting from which their compensation must be used. The lack of clear recommendations regarding the use of the neutral treatment modes is related to the complexity of their formulation for the great diversity of 6-35 kV electricity networks (rural electrical networks, urban electrical networks, etc.) and the need to take into account many specific restrictions and issues.

In the Republic of Moldova MV networks operate with the isolated neutral and the compensated neutral. As a rule, CC in operation are already outdated, with inductance stepping (type ЗРОМ, РЗДСОМ) and a small percentage - with continuous adjustment. The implementation of the combined or resistive neutral was not achieved.

At the same time, in the CIS area, where the common normative acts (NAIE, the Rules of technical exploitation, etc.) are in force, there are many achievements of treating the neutral networks of MV networks through resistor or combined - in Russia, Ukraine, Belarus, Kazakhstan, Uzbekistan. In Russia, Belarus is developing normative acts regarding the design and operation of these networks with different way of treating the neutral [3,4].

THE MODES FOR CONNECTION OF THE COMPENSATION COIL AND RESISTOR IN THE NEUTRAL OF MEDIUM VOLTAGE NETWORKS

The compensation coils and/or the neutral treatment resistors are mounted in the electrical transformer stations, being connected to the neutral point of the power transformer winding with the star connection scheme. In the 6-35 kV networks such possibility is available in the case of transformers with three windings fig.1 (a). If the neutron is not accessible (usually the 6-10 kV wiring diagram of the transformer is in a triangle) there are used special transformers for the artificial creation of the neutral (TNA artificial neutral transformer). This type of transformer can serve any 6-10/0.4 kV transformer star with accessible neutral/triangle scheme. The connection of the secondary winding in the triangle ensures a low homopolar reactance of the transformer. A small homopolar reactance can be obtained at the zigzag connection transformers, which are called homopolar sequence filters (HSF) [9].

Compensated Neutral - grounded through CC:

- the CC mounting in the 35 kV networks can be made at the accessible neutral of the 35 kV winding of the 110 (220) / 35/10 (6) kV transformer, fig. 1 (a);
- mounting CC to HSF with zigzag connection scheme (fig.1, b);
- mounting CC to TNA connected to the terminals of the power transformer (fig.1, c);
- mounting CC to the TNA connected to the 6-10 kV bus-bars of the transformation station (fig.1, d).

It should be noted that in variants (c) and (d) it is inadmissible to connect the CC to the TNA connected by fuse safety because in the case of melting the fuse in a phase it causes an asymmetrical compensation regime.

The ground neutral via CC in parallel with a resistor (R_N). It is recommended to connect them to the neutral of the transformer through separators, which will allow their independent use:

- mounting CC and RN to TNA fig. 2(a) or HSF, shown in fig. 1(b). It is applied for the connection of medium voltage resistors (6.10, 35 kV);
- mounting CC and RN at the primary winding of the TNA fig. 2(b). It is applied for connection of low voltage resistors (≤ 500 V).

The high-value resistors are connected in permanent mode of network operation and in the case of single-phase defects, the working time should not exceed 6 hours. The small value resistors are connected for a duration of 1-3 s when the grounding arc is passed in the stable combustion phase [11].

Grounded neutral by resistor (RN) [8,10]:

- mounting the R_N to the accessible neutral of the 35 kV winding of the transformer 110 (220)/35/10 (6) kV, fig.1(a);
- mounting the RN to the TNA fig. 1 (c) or FSH fig. 1(b). It is applied for the connection of medium voltage resistors (6.10, 35 kV);
- mounting the RN to the secondary TNA fig.3. It is applied for connection of low voltage resistors (≤ 500 V).

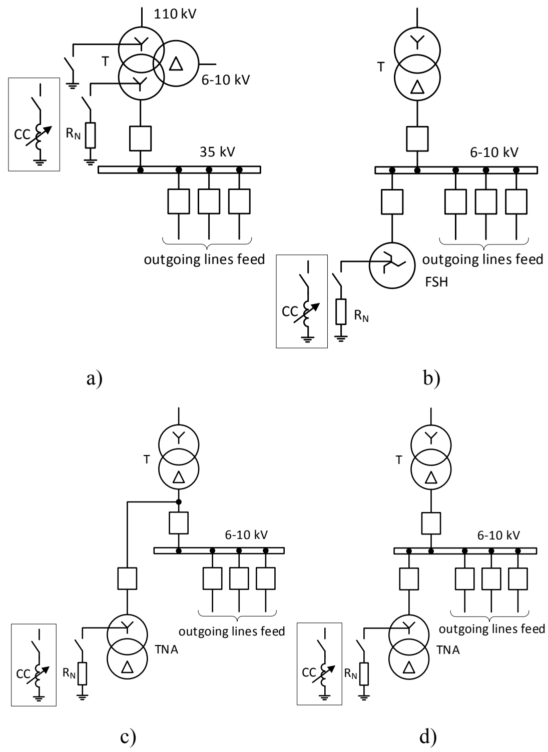

Fig.1. The schemes of the connection of CC or the neutral treatment resistor.

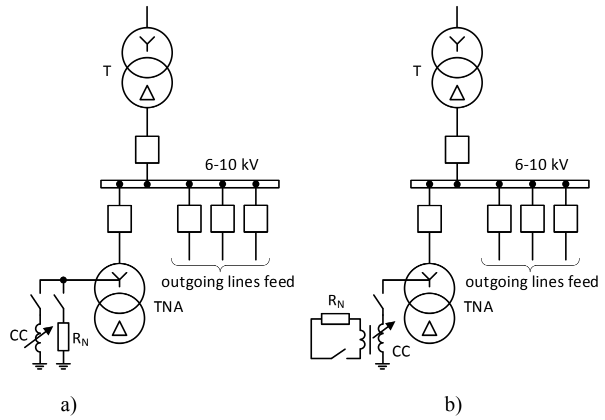

Fig.2. The schemes of the connection of CC in parallel with R_N resistor.

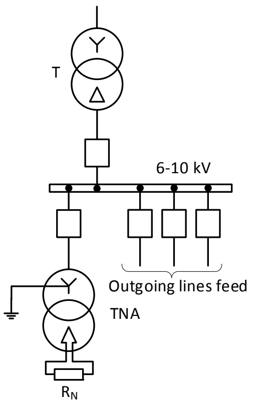

Fig.3. The schemes of the low voltage RN connection.

QUASI-STATIONARY OVERVOLTAGES IN MEDIUM VOLTAGE ELECTRICAL NETWORKS WITH DIFFERENT WAY OF TREATING THE NEUTRAL

The simplified equivalent scheme of a network with the isolated neutral is shown in Fig. 4. Here, they are not taken into account the active resistances and inductive longitudinal reactances of the generators, transformers as well as the admittances between the phases of their lines and their load which are connected to the constant voltage source. These parameters practically do not influence the stresses of the phases towards the earth. The admittances have a pure reactive character, determined by the own capacities of the air lines or in the cable.

We will examine the most important operating regimes.

The isolated neutral mode (switches C1, C2 in fig. 1 are disconnected) and the $\underline{Y}_{AA}, \underline{Y}_{BB}, \underline{Y}_{CC}$ *admittances have different values*

For the scheme shown in Fig.4 the systems of equations are made up:

$$\begin{cases} \underline{E}_A = \underline{U}_A - \underline{U}_N; \\ \underline{E}_B = \underline{U}_B - \underline{U}_N; \\ \underline{E}_C = \underline{U}_C - \underline{U}_N. \end{cases} \tag{1}$$

$$\begin{cases} \underline{I}_A = \underline{Y}_{AA} \cdot \underline{U}_A; \\ \underline{I}_B = \underline{Y}_{BB} \cdot \underline{U}_B; \\ \underline{I}_C = \underline{Y}_{CC} \cdot \underline{U}_C. \end{cases} \tag{2}$$

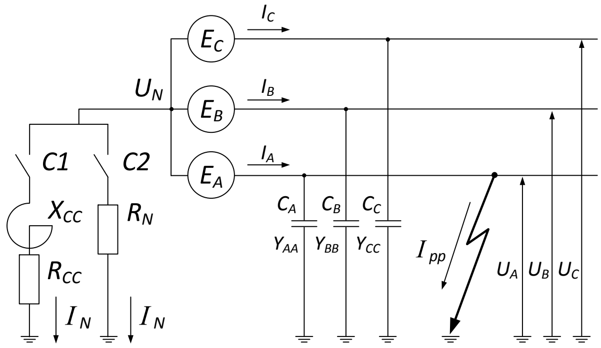

Fig. 4. Equivalent network scheme.

In the case of the isolated neutral according to the Kirchhoff law one can write the equation:

$$\underline{I}_A + \underline{I}_B + \underline{I}_C = 0. \tag{3}$$

Substituting (1) and (2) into (3) are obtained the following results:

$$\underline{U}_N = -\frac{\underline{E}_A \cdot \underline{Y}_{AA} + \underline{E}_B \cdot \underline{Y}_{BB} + \underline{E}_C \cdot \underline{Y}_{CC}}{\underline{Y}_{AA} + \underline{Y}_{BB} + \underline{Y}_{CC}}. \tag{4}$$

In a balanced ($\underline{E}_A + \underline{E}_B + \underline{E}_C = 0$) and symmetrical ($\underline{Y}_{AA} = \underline{Y}_{BB} = \underline{Y}_{CC}$) netwok the voltage on the neutral will be equal to zero $\underline{U}_N = 0$ and the phase voltages $\underline{U}_A = \underline{E}_A$, $\underline{U}_B = \underline{E}_B$, $\underline{U}_C = \underline{E}_C$.

In a balanced ($\underline{E}_A + \underline{E}_B + \underline{E}_C = 0$) and asymmetric ($\underline{Y}_{AA} \neq \underline{Y}_{BB} \neq \underline{Y}_{CC}$) network the voltage on the neutral will have a value different from zero. The displacement of the neutral will cause the voltages in relation to the earth to increase. $\underline{U}_A, \underline{U}_B, \underline{U}_C$.

Based on the expression (4) it can be determined the capacity of the network C and the grounding current. For this, in one of the phases will be connected an additional capacity (Fig. 5):

$$\underline{U}_N = -\frac{C_S}{3 \cdot C + C_S} \cdot \underline{E}_A \ \ or \ \ \underline{U}_N = U_{f.nom} \cdot \frac{C_S}{3 \cdot C + C_S}, \tag{5}$$

where E_A is the emf faze „A”, $U_{f.nom}$ - rated phase voltage.

Knowing the value of Cs and the displacement voltage of the neutral it can be determined the capacity of the network C.

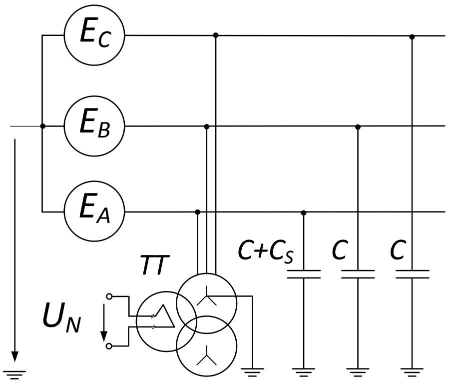

Fig. 5. Diagram regarding the determination of the network's capacity with respect to the earth.

From the relation (4) it follows that if $\underline{Y}_{AA} \neq \underline{Y}_{BB} \neq \underline{Y}_{CC}$, then, it takes place the displacement of the neutral voltage. The displacement of the voltage of the neutral is influenced both by the degree of insemination of the electrical networks and by the way of treating the neutral. Next, it is analyzed the influence of the neutral treatment mode on the displacement of the neutral voltage in the quasi-stationary regime.

Compensated neutral mode - grounded through the compensation coil CC (switch C1 and C2 disconnected)

For the evaluation of the displacement voltage of the neutral it is used the active bipolar theorem [3], taking into account the asymmetry of the network and the CC resistance (Fig. 6).

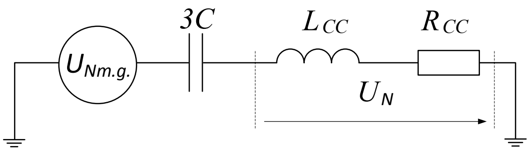

Fig. 6. Equivalent scheme for the evaluation of the displacement of the neutral treated by CC.

The voltage on the ground-neutral via CC is evaluated with the relation:

$$\underline{U}_N = \frac{\underline{U}_{N\,m.g.} \cdot (R_{CC} + j\omega L_{CC})}{R_{CC} + j\omega L_{CC} \cdot (1-k)} \,. \tag{6}$$

If $k = \dfrac{1}{3 \cdot \omega^2 C \cdot L_{CC}} = 1$,

then

$$\underline{U}_N = \frac{\underline{U}_{N\,m.g.} \cdot (R_{CC} + j\omega L_{CC})}{R_{CC}} = \underline{U}_{N\,m.g.} \cdot \left(1 + \frac{j\omega L_{CC}}{R_{CC}}\right), \tag{7}$$

and respectively the voltage module of the neutral:

$$U_N = \left|\underline{U}_N\right| = U_{N\,m.g.} \cdot \sqrt{1 + \frac{\omega^2 L_{CC}^2}{R_{CC}^2}} \approx U_{N\,m.g.} \cdot q \,, \tag{8}$$

where q is the quality factor of CC and has high values $q = \dfrac{X_{CC}}{R_{CC}} = 20 \ldots 200$.

Therefore, the voltage on the neutral U_N can reach considerable and dangerous values for insulation.

Grounding a phase with the grounded neutral through the resistor (switch C1 disconnected, switched C2)

The current that crosses the resistor is determined by the relation:

$$\underline{I}_N = \frac{\underline{U}_N}{R_R + jX_T} \,, \tag{9}$$

where X_T is the homopolar succession reactance of the transformer of the transformer creating the neutral.

The grounding current is determined as follows:

$$\underline{I}_{pp} = \underline{E}_A \left(3j\omega C + \frac{3}{3R_R + jX_T} \right). \tag{10}$$

If the resistance of the neutral has high values $R_R \gg X_T$, the reactance of the transformer X_T can be neglected and then the grounding current is determined from the expression:

$$I_{pp} = U_f \cdot \sqrt{\left(\frac{1}{R_R}\right)^2 + \left(3 \cdot \omega C\right)^2} \,. \tag{11}$$

From the relation (11) it is observed that the introduction of a resistor in neutral determines the occurrence of the active component in the grounding current instead of the defect. This fact plays an important role in reducing overvoltages and increasing the reliability of the operation of electrical installations.

Grounded neutral regime through resistor

We will evaluate the displacement of the neutral U_N by taking into account the asymmetry of the network and the resistance of the resistor R_R. It is applied the active bipolar theorem (Fig. 7) in which the idle voltage is the voltage on the neutral, expressed by the relation (5), determined for the regime of the isolated neutral and the asymmetric network.

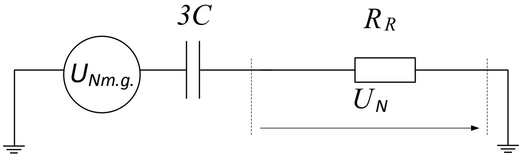

Fig. 7. Equivalent scheme for evaluating the displacement of the neutral treated by a resistor.

The current passing through the resistor is determined as follows:

$$\underline{I}_N = \frac{\underline{U}_{Nm.g.}}{R_R + \frac{1}{j\omega C}} = \frac{\underline{U}_{Nm.g.}}{\frac{j3R_R\omega C + 1}{j3\omega C}} = \frac{\underline{U}_{Nm.g.} \cdot j3\omega C}{1 + j3R_R\omega C}. \quad (12)$$

Neutral voltage:

$$\underline{U}_N = \underline{I}_N \cdot R_R = \frac{\underline{U}_{Nm.g.} \cdot j3R_R\omega C}{1 + j3R_R\omega C} = \frac{\underline{U}_{Nm.g.}}{1 + \frac{1}{3R_R\omega C}}, \quad (13)$$

and voltage module respectively:

$$\left|\underline{U}_N\right| = \frac{\left|\underline{U}_{Nm.g.}\right|}{\left|\underline{Z}\right|} = \frac{U_{Nm.g.}}{\sqrt{1 + \left(\frac{1}{3R_R\omega C}\right)^2}}. \quad (14)$$

Impedance:

$$\left|\underline{Z}\right| = \sqrt{1 + \left(\frac{1}{3R_R\omega C}\right)^2},$$

if $R_R = 800\ \Omega$, $\omega = 314 s^{-1}$, $C_0 = 0,3 \cdot 10^{-6}\ F/km$, $l = 100\,km$, impedance results:

$$\left|\underline{Z}\right| = \sqrt{1 + \left(\frac{1}{3 \cdot 800 \cdot 314 \cdot 0,3 \cdot 100 \cdot 10^{-6}}\right)^2} = 1,01\ \Omega.$$

As $\left|\underline{Z}\right|$ reaches values close to the unit, it turns out that treating the neutral with a high resistance resistor does not practically change the neutral's displacement to the situation when the neutral is isolated, regardless of the resistance value of the resistor.

Ground neutral regime through CC parallel to a resistor

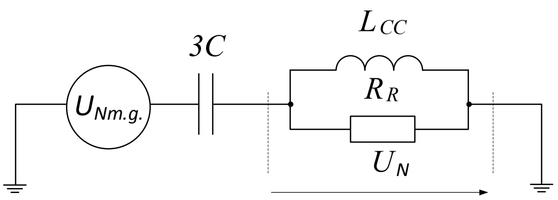

Fig. 8. Equivalent scheme for evaluating the displacement of the neutral treated by CC parallel to the resistor.

In this case the equivalent impedance of the neutral will be:

$$Z_{ech} = \frac{j\omega L_{CC} \cdot R_R}{j\omega L_{CC} + R_R}. \quad (15)$$

Total equivalent impedance:

$$\begin{aligned} \underline{Z}_\Sigma &= \frac{1}{j3\omega C} + \frac{j\omega L_{CC} \cdot R_R}{j\omega L_{CC} + R_R} = \\ &= \frac{j\omega L_{CC} + R_R + j3\omega C \cdot j\omega L_{CC} \cdot R_R}{jR_R 3\omega C - 3\omega^2 L_{CC} C} = \\ &= \frac{\left(j\omega L_{CC} + R_R\right) - R_R 3\omega^2 L_{CC} C}{jR_R 3\omega C - 3\omega^2 L_{CC} C}. \end{aligned} \quad (16)$$

Neutral current:

$$\begin{aligned} \underline{I}_N &= \frac{\underline{U}_{Nm.g.}}{\underline{Z}_\Sigma} = \frac{\underline{U}_{Nm.g.}}{Z_{ech} + \frac{1}{j\omega C}} = \\ &= \frac{\underline{U}_{Nm.g.}\left(j3R_R\omega C - 3\omega^2 L_{CC} C\right)}{\left(R_R + jX_{CC}\right) - R_R \cdot 3\omega^2 L_{CC} C}. \end{aligned} \quad (17)$$

Neutral voltage:

$$\begin{aligned} &\underline{U}_N = \underline{I}_N \cdot R_\Sigma = \\ &= \frac{\underline{U}_{Nm.g.} \cdot \left(j3R_R\omega C - 3\omega^2 L_{CC} C\right)}{\left(R_R + jX_{CC}\right) - R_R \cdot 3\omega^2 L_{CC} C} \cdot \frac{j3R_R\omega L_{CC}}{R_R + j\omega X_{CC}}. \end{aligned} \quad (18)$$

Considering that $3\omega^2 \cdot L_{CC} \cdot C = 1$ it is obtained:

$$\begin{aligned} \underline{U}_N &= \frac{\underline{U}_{Nm.g.} \cdot j3R_R\omega C \cdot jR_R\omega L_{CC}}{\left[\left(R_R + jX_{CC}\right) - R_R\right] \cdot \left(R_R + jX_{CC}\right)} = \\ &= \frac{\underline{U}_{Nm.g.} \cdot \left(-R_R^2 \cdot 3\omega^2 L_{CC} C\right)}{\left(R_R + jX_{CC}\right) \cdot \left(R_R + jX_{CC}\right) - R_R\left(R_R + jX_{CC}\right)} = \\ &= -R_R^2 \cdot \frac{\underline{U}_{Nm.g.}}{jR_R X_{CC} - X_{CC}^2} = -\frac{\underline{U}_{Nm.g.} \cdot R_R^2}{X_{CC}^2 \cdot \sqrt{R_R^2 + X_{CC}^2}}. \end{aligned} \quad (19)$$

Since the resistance of the resistor is lower than the CC reactance, there is a pronounced reduction in the displacement voltage of the neutral.

CASE STUDY

It is determined the displacement voltage of the neutral in a network with the isolated neutral, asymmetric with the nominal voltage 10 kV. The additional capacity, connected according to Fig. 5, has the value of 2.5 mF. The voltage measured at the terminals of the winding diagram of the voltage transformer constitutes 21 V. In the case of transformers for insulation control, the ratio between the number of turns of the primary winding and the winding with the open triangle diagram is determined in such a way that at the single phase fault in the network 10V when the voltage on the neutral becomes equal to the phase voltage $\underline{U}_N = 10/\sqrt{3}\ kV$, the voltage at the winding terminals with the open triangle scheme, relative to the primary voltage, will be 100 V.

The capacity of the network is determined according to the relation (5):

$$\frac{\underline{U}_N}{U_{f.nom}} = \frac{C_S}{3 \cdot C + C_S};$$

$$3 \cdot C = \frac{(U_{f.nom} - \underline{U}_N) \cdot C_S}{\underline{U}_N} = \frac{(100-21) \cdot 2.5 \cdot 10^{-6}}{21} =$$
$$= 9.405\ mF.$$

Grounding current according to the relationship (9):

$$I_{pp} = \sqrt{3} \cdot 10 \cdot 10^3 \cdot 314 \cdot 9.405 = 51\ A.$$

The displacement voltage of the neutral will be:

$$\underline{U}_N = U_{f.nom} \cdot \frac{C_S}{3 \cdot C + C_S} =$$
$$= \frac{10 \cdot 10^3}{\sqrt{3}} \cdot \frac{2.5}{9.405 + 2.5} = 178.5\ V.$$

It is determined the displacement voltage of the neutral in a network with the compensated neutral. $U_{Nm.g.}$ is the voltage of displacement of the neutral in the network with the isolated neutral, considered by reference. According to the relation (15) and having a CC with the quality factor $q = 20$:

$U_N \approx 178.5 \cdot 15 = 3.57\ kV$ which constitutes 64.3% > 15 % permissible according to the technical rules for the operation of power stations and electrical networks [7].

It is determined the voltage of displacement of the neutral in a network with the grounded neutral through the resistor. It is expected the use of a resistor with resistance $R_R = 150\ \Omega$.

According to relation (21) the displacement voltage of the neutral will be:

$$\underline{U}_N = \frac{178}{\sqrt{1 + \left(\frac{1}{3 \cdot 150 \cdot 314 \cdot 3.135}\right)^2}} = 72.1\ V\ ,$$

which constitutes 0.7% and is a much lower value compared to the case of the neutral treatment by CC.

It is determined the displacement voltage of the neutral in a network with the grounded neutral by CC parallel to a resistor. It is planned to install CC with reactance $X_{BS} = 150\ \Omega$ and resistor with resistance $R_R = 90\ \Omega$. According to the relation (26) the displacement voltage of the neutral will be:

$$\underline{U}_N = -\frac{178 \cdot 90^2}{150^2 \cdot \sqrt{90^2 + 150^2}} = 0.366\ V\ ,$$

which confirms the above conclusion.

CONCLUSIONS

The regime of the isolated neutral has a number of shortcomings and is already overcome, other ways of treating the neutral must be used.

Choosing how to treat the neutral in the 6-35 kV electrical networks is an extremely complicated problem at their design and operation stages.

Neutral treatment through a low-value resistor is intended to create large ground currents, necessary for the selective and safe operation of relay protection.

Treating the neutral through a high-value resistor provides protection against overvoltages and does not worsen the electric arc extinguishing conditions, and the active component of the current created by the resistor is sufficient for the selective operation of simple current protection, which may work. at the signal or at the disconnection depending on the conditions of ensuring the continuity of the electricity supply.

The results of the calculations show that in the quasi-stationary regime the treatment of the neutral by resistor or mixed results in the pronounced reduction of the displacement voltage of the neutral.

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