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ANALYSIS OF THE NEUTRAL GROUNDING MODES INFLUENCE ON THE RELIABILITY CHARACTERISTICS OF LOCAL SYSTEMS WITH RENEWABLE ENERGY SOURCES

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Abstract

When comparing the performance indicators of electrical networks with different types of neutral grounding, along with the fulfilment of the requirement to ensure reliability of power supply to consumers, serious attention is drawn to the main network parameters influencing the performance of power supply systems. Analysis of research and its results, reported above, on the influence of the neutral ground of power networks on the reliability and electrical safety conditions of the power supply systems as a whole, on the damage of distribution networks and electrical equipment as well as on the working capacity of relay protection devices, provides an opportunity to estimate each specific operation mode of the neutral and to develop recommendations aimed at strengthening the positive indicators of the corresponding modes. Other things being equal, reliability of power supply to electrical receivers or reliability of distribution networks is mainly determined by the damage to network elements and the performance of relay protection devices. The degree of influence of these factors on the reliability of distribution networks depends on the neutral mode, which in turn determines the level of internal overvoltages and the nature of transient processes at earth fault.

Keywords: electric networks, protection, reliability, ground failure current, electrical safety, system with isolated neutral, system with resonant grounding, system with low-impedance neutral grounding.

1. RELEVANCE

The rapid development of renewable energy systems in Europe and the world creates new directions for their application. One of these areas in recent years has been the use of a distributed generation system to provide power to non-traction consumers of railway transport [1-4]. Such systems are called local systems and in their specificity of work, structure and execution: they significantly differ from general-purpose systems [5-9]. A feature of the work of these systems is the provision of power to consumers of the first and second categories, namely: circuits of automatic and semi-automatic blocking, signalling, communications, outdoor track lighting, automatic heating control systems for buildings etc. [10-12]. Accordingly, for such networks it is necessary to determine the indicators on which the reliability of providing electric energy depends [13-15]. The reliability and safety of maintenance of these systems is largely determined by the neutral grounding method, which is established according to the instructions of normative and technical documents and by technical and economic comparison according to established criteria. In many countries of the world, these conditions have developed historically, under the influence of various factors that changed during the development of networks [16-19]. Today, prerequisites have arisen to analyse these factors of influence on the reliability, efficiency and safety of servicing local networks.

In accordance with [16] medium voltage (MV) networks can have system with isolated neutral or system with resonant grounding or system with low-Impedance neutral grounding (resistance) [20]. When comparing the performance indicators of electrical networks with different types of neutral grounding, along with the fulfilment of the requirement to ensure reliability of power supply to consumers, serious attention is drawn to the main network parameters influencing the performance of power supply systems, these include:

- insulation levels and overvoltage resistibility (overvoltage protection) [21, 22];
- provision of single-phase-to-ground failure protection and its performance;
- selectivity of protection actions against ground failures;
- safety protection from the effect of touch and step voltages at earth failure.

Other things being equal, reliability of power supply to electrical receivers or reliability of distribution networks is mainly determined by the damage to network elements and the performance of relay protection devices.

At the same time, the main indicators of failure will be following:

- the probability of failure Q (t);
- MTTF T_0 ;
- the average recovery time $T_{R.}$

The degree of influence of these factors on the reliability of distribution networks depends on the neutral mode, which in turn determines the level of internal overvoltages and the nature of transient processes at earth failure. The level of overvoltage has a decisive influence on the first and second indicators, and the nature of transient processes - on the third [23].

Distribution networks MV with system with isolated neutral are most common, but such operation mode of the network neutral is not always optimal in terms of the specified earlier criteria. Power supply systems with a fully insulated neutral, as compared to networks with other neutral modes, do not require additional capital expenditures. However, the operational costs of such networks due to their greater damage rate as well as due to the power outages, are significantly greater than those in the networks operating with other neutral modes [20, 24].

The efficiency of the capacitive current compensation and the performance system with resonant grounding largely depends on the tuning mode of the compensating device. In this context, most researchers give preference to the resonant inductance tuning (it is extremely difficult to provide it in dynamic networks) of the compensating device with a network capacity relative to the earth. From an economic point of view, distribution networks with the compensation of the capacitive ground failure current require additional capital expenditures on the arc suppression reactors and devices for their connection. With regard to operating costs, they are significantly less than those in the networks with an isolated neutral due to a lower level of damage to the elements of the system. With resonance tuning of the compensating device and minor disorders of compensation in electric networks, the value of dielectric strength in relation to the operating overvoltages increases up to 30% [25, 26].

Electrical networks with a neutral resistor have, in comparison with system isolated neutral and resonant grounding, higher reliability because of the suppression of transient processes accompanying single-phase ground failures, the reduction of damage to the elements of the power supply system (the latter is caused by a significant decrease of internal overvoltages) and the elimination of ferro-resonance processes. Considerable additional capital costs for the implementation of networks with a neutral resistor, as compared to networks with a fully isolated neutral, at the earth failure currents will be greater than 5 ... 10 A. In this case, it is required to include a high-voltage resistor and devices for its connection into the neutral network, which in addition to switching devices may also include special transformers needed for the connection of resistors. In networks with ground-failure currents up to 5 A, additional capital costs decrease practically to zero, since in this case it is possible to manage available in the network measuring transformers and low-voltage resistors [21].

2. EFFECTS OF THE NEUTRAL MODE ON THE PHASE CHARACTERISTICS OF EMERGENCY CURRENTS

In local systems, the earth failures are the most common damages (up to 70-85% of the total number of accidents) [27, 23]. In such networks, possible overvoltages can reach 3.95 the phase voltage value. Hence greater attention and higher requirements to the operational performance of protection devices, otherwise the unreasonable interruptions in power supply to responsible consumers (under the mistaken a protective actions) or further development of the failure is probable (in case of protection failure, transition of a single-phase earth failure into a double one is possible).

To study phase characteristics of voltage and zero sequence currents, we use the equivalent circuit (Fig. 1), which is presented in the form of two attachments connected to one power transformer [28].

Given that, we believe that conductance of appropriate phase-to-ground insulation of the controlled connection ($\underline{Y}_{A1} = \underline{Y}_{B1} = \underline{Y}_{C1} = \underline{Y}_1$) and the rest of the distribution network ($\underline{Y}_A^{'} = \underline{Y}_B^{'} = \underline{Y}_C^{'} = \underline{Y}^{'}$) are related by the formula $\underline{Y}_1^{'} + \underline{Y}^{'} = \underline{Y}$ ...

Then $\underline{Y} = \dfrac{1}{R} + j\omega C;\ \underline{Y}_1 = \dfrac{1}{R_1} + j\omega C_1;$

$$\underline{Y}_K = \frac{1}{R_K} - j\frac{1}{\omega L};\ \underline{Y}_N = \frac{1}{R_N};\ \ y = \frac{1}{r};\ y_i = \frac{1}{r_i}.$$

The Figure 1 shows the zero sequence current filter *TA* installed on the damaged connection and intended to isolate the zero sequence current $\underline{I}_0$ in the monitored line; currents flowing through the conductance of phase-to-ground insulation of the monitored line ($\underline{I}_{A1}, \underline{I}_{B1}, \underline{I}_{C1}$), and currents flowing through the appropriate phase conductance of the external network ($\underline{I}'_A, \underline{I}'_B, \underline{I}'_C$) ; $\underline{I}_{g1}, \underline{I}_g$ - single-phase ground failure currents in the monitored line and in the external network, respectively; I_N - current flowing through the conductance of the network neutral point with respect to ground. We proceed from the fact that a single-phase earth failure can occur in the supervised line ($y_1 \neq 0$) or in the external network ($y \neq 0$).

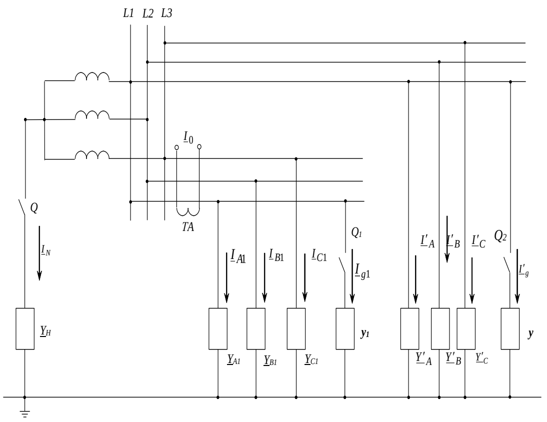

Fig. 1. The equivalent circuit diagram of the distribution network for study of phase characteristics of voltage and zero-sequence currents

2.1 System with isolated neutral ($Y_N = 0$)

By using the basic laws of electrical engineering for the presented equivalent circuit diagram, we have done necessary transformations and obtained a mathematical equation for the zero-sequence current in the case of an error in the monitored line:

$$\underline{I}_{0C} = -3 \cdot \underline{U}_0 \cdot \underline{Y}' = -3 \cdot \underline{U}_0 \cdot (\underline{Y} - \underline{Y}_1)$$

or

$$\underline{I}_0 = -3 \underline{U}_0 \left[\frac{(R_1 - R) + j\omega (C - C_1) \cdot R \cdot R_1}{R \cdot R_1} \right], \qquad (1)$$

Where *R* and *C* are, respectively, the insulation resistance and the capacity of the whole electrically connected network with respect to ground; R_1 and C_1 are, respectively, the active insulation resistance and the capacity of the supervised connection with respect to ground.

Equations for the intrinsic current of the monitored line (zero-sequence current in the monitored line with an external earth failure) are as follows:

$$\underline{I}_{0C} = 3 \cdot \underline{U}_0 \cdot \underline{Y}_1$$

or

$$\underline{I}_{0C} = 3 \cdot \underline{U}_0 \frac{1 + j\omega \cdot C_1 \cdot R_1}{R_1}$$

The analysis of the equations (1) and (2) shows that in the network with the fully isolated neutral, the zero-sequence current in the failure line is determined by the zero-sequence voltage and insulation parameters of the external network with respect to ground, that is, by the isolation parameters of the entire network with respect to ground, excluding insulation of the faulted connection, whereas the intrinsic current of the monitored connection (zero-sequence current in the supervised line with external faults) is determined by the zero-sequence voltage and insulation parameters with respect to ground, only in relation to the supervised connection. From the obtained expressions, it can be concluded that on the basis of the appearance of voltage and current of the zero sequence it is possible to establish the fact of asymmetric insulation damage, and by their magnitude to assess the degree of this failure. The presence of these indicators can be used to build diagnostic models.

Using these equations, with account of their imaginary and real parts, we obtain formulas that determine the phase dependence of the zero-sequence current vector:

$$\varphi_{01} = 180^0 + arctg \frac{\omega \cdot (C - C_1) \cdot R_1 \cdot R}{R_1 - R}, \qquad (3)$$

and the phase dependence of the intrinsic current vector of the monitored line (the current of the zero sequence in the monitored line with the external single-phase-to-ground fault)

$$\varphi_{02} = arctg(\omega \cdot C_1 \cdot R_1), \qquad (4)$$

in relation to the zero sequence voltage vector on the insulation parameters with respect to ground of the whole network and of the controlled connection.

The analysis of the obtained equations (3) and (4) shows that taking into account the real values of the insulation parameters, relative to the earth, of the whole network and of a separate connection, and also taking into account the actual interrelation of the capacitive and active insulation resistance, the following conclusions can be drawn:

- the angle between the zero-sequence current vector and the zero-sequence voltage vector does not depend on the completeness of the closure (the transient resistance at the closing point) and it is almost 270 el. degrees, or minus 90 el. degrees;

- the angle between the intrinsic vector of the monitored line (zero-sequence current in the monitored line with the external single-phase-to-ground fault) and the zero-sequence voltage vector is determined by the isolation parameters relative to the ground only of the controlled connection and it is almost 90 el. degrees.

2.2. Compensated neutral network upon condition ($\underline{Y}_N = \underline{Y}_K = \frac{1}{R_K} - j\frac{1}{\omega L}$)

For this network, we similarly obtain the equations [6, 18] for the zero-sequence current in case of damage in the controlled line:

$$\underline{I}_0 = -\underline{U}_0 \times [\frac{\omega L\cdot(3R_1\cdot R_K - 3R\cdot R_K + R\cdot R_1)}{R\cdot R_1\cdot R_K\cdot \omega L} - j\frac{R\cdot R_1\cdot R_K\cdot(\nu - 3\cdot\omega^2\cdot C_1 L)}{R\cdot R_1\cdot R_K\cdot\omega L}], \quad (5)$$

for the intrinsic current of the monitored line (zero sequence current in the monitored line with the external earth fault):

$$\underline{I}_{0C} = -3\cdot\underline{U}_0\frac{1+j\omega\cdot C_1\cdot R_1}{R_1}, \quad (6)$$

and also the formulas determining the phase dependence of the zero sequence current vector:

$$\varphi_{01} = 180° - arctg\frac{R\cdot R_k\cdot R_1\left(\nu - 3\omega^2\cdot C_1\cdot L\right)}{\omega\cdot L\left(3R_k\cdot R_1 - 3R_k\cdot R + R\cdot R_1\right)}, \quad (7)$$

and the phase of the intrinsic current vector of the monitored line with respect to the zero-sequence voltage vector on the insulation parameters

$$\varphi_{02} = arctg(\omega\cdot C_1\cdot R_1) \quad (8)$$

with respect to the zero sequence voltage vector from the insulation parameters relative to the earth of the whole network, the controlled connection and the degree of the compensating device detuning $\nu = 1 - 3\cdot\omega_2\cdot C\cdot L$ from the resonance mode with the network capacity.

The analysis of the equations (5) - (8) shows that at the single-phase earth fault in the network with a compensated neutral, taking into account the actual values of insulation parameters relative to the ground of the whole network and of the separate connection as well as taking into account the actual values of the arc suppression reactor parameters, we can state:

- the zero sequence current in the faulty line is determined by the zero sequence voltage and the insulation parameters of the external network relative to the ground, i.e. the insulation parameters of the entire network relative to the ground (including the compensating device parameters), minus the insulation parameters of the damaged connection;
- the angle between the zero-sequence current vector and the zero-sequence voltage vector does not depend on the completeness of the closure (transient resistance at a closing point) and is determined to a large extent by the value of detuning of the compensating device from the resonant mode and for resonance tuning it is approximately 180 el. degrees; when the compensating device is detuned from the resonance mode both in the direction of overcompensation and under compensation, the current vector deviates by an angle of respectively up to plus 90 el. degrees and minus 90 el. degrees, so the range of angle variation between the zero-sequence current vector and the zero-sequence voltage vector is theoretically 180 el. degrees;
- the intrinsic current of the controlled connection is determined by the zero-sequence voltage and the insulation parameters with respect to ground only of the controlled connection;
- the angle between the intrinsic current vector of the monitored line and the zero-sequence voltage vector is determined by the insulation parameters with respect to ground only of the controlled connection and it is almost 90 el. degrees.

2.3 Network with a neutral resistor ($Y_N = Y_R = 1 / R_N$).

For such a network, in accordance with the equivalent circuit diagram (Fig. 1), the formulas [3, 4, 7] for the studied currents and their phase characteristics are as follows:

$$\underline{I}_0 = -\underline{U}_0 \times [\frac{\omega L\cdot(3R_N\cdot R_1 - 3R\cdot R_N + R\cdot R_1)}{R\cdot R_1\cdot R_N} - j\frac{R\cdot R_1\cdot R_N\cdot\omega(C - C_1)}{R\cdot R_1\cdot R_N}]; \quad (9)$$

$$\underline{I}_{0C} = -3\cdot\underline{U}_0\frac{1+j\omega\cdot C_1\cdot R_1}{R_1}; \quad (10)$$

$$\varphi_{01} = 180° + arctg\frac{R\cdot R_N\cdot R_1\cdot\omega\left(C - C_1\right)}{3R_N\cdot R_1 - 3R\cdot R_N + R\cdot R_1}; \quad (11)$$

$$\varphi_{02} = arctg(\omega\cdot C_1\cdot R_1), \quad (12)$$

and their analysis shows that in case of a single-phase earth fault in the network with a neutral resistor:

− the zero-sequence current in the faulty line is determined by the zero sequence voltage and the insulation parameters of the external network with respect to ground as well as by the resistance value of the neutral resistor, and the phase of this current in relation to the zero sequence voltage vector does not depend on the completeness of the closure and in contrast to the networks with a fully insulated neutral it is not fixed and depends on the resistance value of the resistor, besides it can theoretically take values in the range from 180 to 270 el. degrees in relation to the zero-sequence voltage vector; for the real network insulation parameters with respect to ground and the recommended resistance value of the resistor, this angle is approximately 225…240 el. degrees, i.e. in contrast to the network with a fully isolated neutral, a shift of the emergency current vector is possible by an angle from 30 to 45 el. degrees;

− the intrinsic current of the controlled connection is determined by the zero-sequence voltage and insulation parameters with respect to ground only of the controlled connection, and the angle between the vector of this current and the zero-sequence voltage vector is determined in the same way as in the networks with a fully isolated and compensated neutral − by the insulation parameters relative to the ground only of the controlled connection and it is almost 90 el. degrees.

When constructing diagnostic models, it's must be taken into account the fact that the position of the zero-sequence current vector with respect to the zero-sequence voltage vector is generally determined by the nature and mode of the network neutral ground, and the phase of the intrinsic current of the controlled connection (zero-sequence current in the monitored line with the external single phase-to-ground fault does not depend on the neutral operation mode − it is determined only by the parameters of the directly controlled connection and practically it is rigidly linked to the zero-sequence voltage.

3. EFFECTS OF THE NEUTRAL MODE ON THE PERFORMANCE OF GROUND-FAILURE PROTECTION

At present, in the distribution networks, the ground failure protection devices, responsive to the steady-state parameters of the emergency mode, which can conditionally be divided into three types: current (maximum) protection - devices that react to the zero sequence current; voltage protection - devices that respond to the zero sequence voltage; directional protection - devices that respond to the zero sequence power [17, 24, 29].

Studies have shown that the use of simple current protection in networks with a fully isolated neutral is justified by the sensitivity conditions under the capacitance of the protected line 5…7.5 times less than the capacity of the entire electrically connected network. If the specified condition is not observed, selectivity of its operation is disrupted. The necessity of fulfilling this condition significantly limits the application area of current protection devices, particularly if to take into consideration the fact that, while in operation, the capacity of network, as well as of individual lines, varies greatly. The ratio of the zero sequence currents in case of external earth fault and in the protection zone, as well as the conditions ensuring selectivity performance of the current protection devices, make it difficult to use them in networks with a compensated neutral. In networks with the capacitance current compensation in the steady-state ground-fault mode, when adjusting the compensating device in resonance with the network capacity relative to the earth, as well as with insignificant disorders from the resonance mode, the zero sequence current of the protected connection (intrinsic current) is nearly always greater than the closing current and the zero sequence current in the case of an error in the protected connection. This circumstance practically excludes the possibility of applying current protection devices in networks with a compensated neutral. The most favourable conditions for the application of simple residual-current protective devices are created in networks with a neutral resistor due to the suppression of transient processes, however it is difficult to achieve the operational performance of current protection devices in case of faults through the transition resistances.

Protective devices responding to the zero-sequence voltage are characterized by the simplicity of their circuits and elements; in local networks they are mainly used either in the form of backup units for networks with high security requirements The principal drawback of such protective devices is an inability to ensure the performance selectivity. In system with resonant grounding, application of such protectors is also practically impossible because of the high value of the neutral bias voltage at resonance (or close to resonance) tuning of the arc suppression reactor.

Devices of directional protection against single-phase ground failure, responding to the parameters of the steady-state closing mode, ensure the operation selectivity due to the phase comparison of the zero sequence current and voltage. Such devices are largely used only for networks with a fully isolated neutral, since in such networks the angles between zero sequence currents and voltages practically do not depend on the parameters of the network insulation and the transition resistance at the fault point in case of one- phase ground failure and they are practically fixed.

The presence of transient processes accompanying the occurrence of a phase-to-ground failure and primarily the shutdown of the damaged connection should be considered as the determining reasons for the unsatisfactory operation of the directional protection devices in networks with a fully isolated neutral. The reason for this lies in the transient process which accompanies the process of recovery of phase-to-ground voltage and which is oscillating, damping and rather lengthy, with a frequency close to the industrial one.

The reasons, causing false operation of existing directional protection devices, should also include the imperfection of circuitries. From this group of reasons special attention should go to the following ones [30, 31]:

- insufficient detuning of devices through the zero sequence current and voltage channels from higher harmonic components, the level of which can be significantly high, especially at closures through the alternating arc;
− a wide angular operating area that is approximately 180−210°, which leads to a time coincidence of the compared signals due to their

phase distortions caused by angular errors of current and voltage transformers as well as phase shifts of signals directly in the device circuit, etc.

In networks with a compensated neutral, the specified principle of protection implementation is impossible, as in these networks the angles between zero sequence currents and voltages are determined mainly by the tuning mode of the compensating device and the value of the transition resistance at a point of damage and it may vary within 180 ° (from minus 90° to plus 90°) which practically excludes the selectivity principle of the protection operation [29].

In networks with a neutral resistor, perspectives of using the directional protection devices from single-phase earth faults, operating on the basis of phase comparison of the zero sequence current and voltage can be considered good for the following reasons:

- in such networks, the false operation of devices from transient processes is practically excluded, because the presence of a neutral resistor greatly suppresses the duration and amplitude of the transient processes;
- the angular error for the values, recommended for quarry networks and introduced by superimposing an active component of the earth fault current on the network, is in the range of 30 ° ... 40 ° and it refers exclusively to the zero sequence current in the faulty line.

The current ground-failure protection devices, which received their application in networks with a compensated neutral, are devices responding to the higher harmonic components of the zero sequence current.

Reliable functioning of the devices under consideration is possible only at a sufficiently high level and stability of the natural harmonics used for the protection operation. The absence of a compensating device (network with a fully insulated neutral) and the inclusion of the resistor in the neutral network contribute to a decrease in the level and spectrum of natural harmonics.

A general lack of the devices responsive to higher harmonics in the zero sequence current is a complex dependence of the structure and level of natural harmonics on: the number of lines, the tuning mode of the compensating reactor, the resistance at the point of fault, as well as the presence of interferences.

Investigations have shown that for the single-phase ground failure through the transition resistance of several tens of ohms, the level of the higher harmonics components sharply decreases. So, with a change in the coefficient of the closure completeness from 1 to 0.4, the zero sequence current for the 5th harmonic decreases 11.5 times, for the 7th harmonic − 16 times, for the 11th harmonic − 25 times [27,32].

Protection devices responding to the transient process parameters are used in system with resonant grounding, since for the protection implementation of the ground fault capacitive current compensation doesn't allow, as a rule, the usage of simpler and more reliable principles based on the parameter checkout of the zero sequence currents and voltages.

To the shortcomings of the earth-fault protection devices, responding to the amplitude and wave characteristics of the transient process, which largely limit their spread in the quarry distribution networks, it is necessary to include the following ones:

- the inrushes of the initial capacitive current as well as the currents and voltages of waves of the transient discharge process are determined, to a significant extent, by the values of voltage and its phase at the moment the earth fault occurs. At the same time, the aerial quarry electrical networks are characterized by a high probability of a mechanical insulation damage, which can occur at the moments when the voltage of the damaged phase hasn't reached its highest value yet and when the transient process hasn't actually arisen;
- the presence of a transition resistance at the point of the phase-to-ground fault leads to a decrease in the amplitude and time characteristics of the transient process. Operational experience with distribution networks shows that when the value of the transient resistance is of the order of hundreds of ohms, the transient process practically does not arise;
- the absence of repeated actions of the protective devices when the signal is acknowledged in the conditions of a steady earth fault.

The ground-failure protection devices that react to the network-imposed currents of non-industrial frequency can be used in networks with any neutral mode. The disadvantage of such devices is the absence of operation selectivity (the transformer is usually switched off).

For the devices reacting to the superimposed alternating current of non-industrial frequency, the value of the superimposed current is composed of the components determined, in addition to the voltage level of the source U_s, by the value of the transition resistance r at the fault location and the sum of the phase network capacities with respect to ground:

$$\underline{I}_{v.s} = \underline{I}'_{v.s} + \underline{I}''_{v.s} = \frac{\underline{U}_{v.s}}{z+r} + \frac{\underline{U}_{v.s}}{z+3x_c}, \qquad (13)$$

where z - is the value of the total resistance of transformer windings, line resistance and ground resistance for the current of the superimposed frequency; x_c - is the capacitive resistance of one phase of the entire network with respect to ground (for the superimposed frequency).

The second component of the superimposed current is apart from the transition resistance value and rises with an increase of the network capacity and of the control voltage frequency. This component is distributed across all transmission lines of the network in proportion to their capacities.

A general lack of the protection reacting to the superimposed current of both low and high frequency is the impossibility of creating highly sensitive devices, since it is necessary to avoid the leakage of operating current through the capacitance of the protected line.

In addition, one must note the possibility of false operation of protection devices during the transient processes, since the spectrum of currents in the transient process can contain components of operating frequency [33].

The principle of superimposing the operational voltage of non-industrial frequency on the protected network is most preferable for system with resonant grounding both by the simplicity implementation of the protection device itself and operational source.

4. INFLUENCE OF THE NETWORK NEUTRAL MODE ON ELECTRICAL SAFETY CONDITIONS.

In accordance with the electrical safety conditions, when a person directly touches the current-carrying parts of the distribution networks, none of the proposed neutral operation modes can be considered as an advantageous one. Regardless of the neutral mode with account of the real insulation parameters of the distribution networks, as well as the action time of protection devices and used switching equipment, the current value passing through the human body will significantly exceed the safe levels. None of the protective devices can guarantee safe outcomes when a person touches current-carrying parts in networks with any neutral mode at a voltage of 6 kV and higher. Even in the networks with the compensation of the capacitive fault current, the presence of a transient process arising at the moment of touching one of the phases, the benefits of such networks, in respect to electrical safety, are practically reduced to zero. At the moment of touching, the so-called free current of the compensating device will pass through the human body, the frequency of which is determined by the physical parameters of the electrical network and the arc-suppression device, and its value is approximately 25% of the capacitive fault current [28].

Therefore, with regard to the distribution networks MV, one should speak about the indirect electrical safety of people from the effect of touch and step voltage, when operating electrical networks.

The degree of danger of an electrical network for a person who touches the energized electrical equipment and installations housings because of the damage of one of the phases depends, to a large extent, on the neutral mode.

Especially this study is of interest for the widespread mode of unstable closure (through an alternating arc). In this mode, which in networks with an isolated neutral at certain network parameters poses danger to humans, in networks with a neutral resistor the danger of touching the frames of damaged equipment significantly decreases due to a sharp reduction in the duration of the transient process as well as to a decrease in the amplitude of the earth fault current inrushes.

When superimposing an additional active current equal to at least 50% of the capacitive current at the earth fault location, it is interesting to analyse the touch and step voltages arising on the earthed enclosures of electrical equipment with the alternating arc faults in the network. Since the touch and step voltages are determined by the earth fault current (flowing from the grounding electrode), it makes sense to consider the effect of the active neutral resistance on the value of this current in the transient mode.

For the air-cable distribution network, which can be represented in the form of *L, C, r* of the contour (without taking into account the longitudinal active resistance of the network), connected to the instantaneous phase voltage $U = U_m \cos(\omega t)$; at the beginning of the closure as well as throughout the entire process of burning of the alternating (or intermittent) arc free and steady-state components of the emergency current arise. The maximum inrush of a free capacitive current with sufficient accuracy for practical calculations is determined by the formula [21]:

$$i_{fr} = \frac{U_m}{\beta \cdot L} \cdot e^{-\delta t} \cdot \sin(\beta \cdot t),$$

or

$$i_{fr} = \sqrt{2} I_C \cdot K \cdot e^{-\delta t} \cdot \frac{\omega_{fr}^2}{\beta \cdot \omega} \cdot \sin(\beta \cdot t), \quad (14)$$

where U_m – is the maximum value of the voltage on the damaged phase; *K* – is the voltage multiplicity of the damaged phase at the moment of breakdown; $\delta = r/(2L)$ – is the damping coefficient of the free circuit current; $\beta = \sqrt{\delta^2 - \omega_{fr}} = \sqrt{\frac{r^2}{4L^2} - \frac{1}{3L \cdot C}}$ – is the angular frequency of natural oscillations; $\omega_{fr} = \sqrt{\frac{1}{3L \cdot C}}$; *L* – is the zero-sequence equivalent inductance of one phase; *r* – is the earth fault resistance, keeping in mind that the minimum possible resistance for the arc combustion is taken equal to the resistance of the quarry grounding network − 4 Ohm.

Calculations performed by the expression (14) show that initial values of the free circuit current can be tens of times greater than the amplitude of the steady-state capacitive current I_C in the event of a ground failure. At several repeated one after another extinctions and ignitions of the arc, free current surges are also repeated. The effective value of the current for one period of the industrial frequency (assuming that the arc goes out and ignites once per period) with the accuracy sufficient for practical purposes can be determined by the formula [21]:

$$i_{fr} = \frac{0.013}{\sqrt{r \cdot C}} K \cdot I_C, \quad (15)$$

So, for example, in the network voltage of 6 kV with I_C = 10 A, r = 4 Ω and K=1 the effective value of free current will be I_{fr} = 38 A.

When grounding the network neutral through the resistor that provides creation of an active component of the failure current at the level of 50 – 100 % of the capacitive one, in case of an arc closure to grounded electrical equipment, the effective value of the resulting failure current will decrease 1.4…2.8 times compared to the possible value in the same network with a fully isolated network neutral [22]. This reduction occurs owing to the effective limitation of overvoltages in the network after each break in the arc of the earth failure.

|In view of the overvoltage reduction on the undamaged phases (up to 2.2…2.4 *U*), as a result of the superimposition of the active current, the probability of developing single-phase failures in the closures of two phases at different points of the network also significantly decreases.

5. COMPARATIVE ESTIMATION OF THE NEUTRAL MODE EFFICIENCY IN TERMS OF LOCAL DISTRIBUTION NETWORKS

An analysis of the above results of studies of the degree of influence of the neutral grounding method on the operational characteristics of autonomous power supply systems, as well as the performance of relay protection devices, allows us to evaluate each method and develop practical recommendations aimed at their further development.

5.1. System with isolated neutral

An insulated neutral system is widespread and has extensive operating experience. However, such a grounding method network neutral mode is not always optimal in terms reviewed of the criteria specified earlier.

Taking into account possible changes in the lowering coefficients, for the actual parameters of distribution networks, the maximum voltage between the healthy phases and the ground is at a level of 4.5 of phase voltage. For these same networks, the theoretical maximum of the neutral point displacement voltage is a threefold phase voltage.

Besides, the single-phase earth failures in networks with an insulated neutral are accompanied by transient processes arising at the moment of failure occurrence and at the moment of disconnection of the damaged section (the process of voltage recovery in the network), which support a significant part of false responses of the ground-failure protective devices.

The disadvantages of networks with an insulated neutral may include: the instability of the neutral voltage, favourable conditions for the occurrence of arc closures, ferro-resonance phenomena, increased touch and step voltages in case of arc ground failures, increased multiplicities of internal overvoltages, etc.

5.2. System with resonant grounding

When grounding the neutral through the arc suppression reactor (tuned inductance), the overvoltages of arc closures is smaller and, what is especially important for insulation, they last for a relatively short time interval (usually about half a period). However, this advantage is minimized when the compensation mode is detuned by more than 5% of the resonance value. Also, the disadvantage of the neutral grounding system through the arc suppression reactor is the complexity of providing resonant tuning. Therefore, for small currents, the use of this type of grounding is not economically feasible.

If to assess the reliability of power supply to electric consumers by the damage of network elements and by the operating quality of the relay protection, it should be noted that application of compensated networks, where the protective shutdown action is required, is constrained by the second condition. As for the damage rate of the elements of distribution networks, one must note that this indicator directly relates to the tuning mode of the compensating device, since it is the degree of the compensating device detuning from a resonant mode that determines the level of overvoltages in the network under single-phase earth failures.

Figure 2 shows that with the resonant tuning of the compensating device, as well as with its detuning within 5%, even theoretically, the overvoltages on the undamaged phases cannot exceed more than $2.75U_f$. The decrease in the level of overvoltage is due to the creation of a convenient path for the drainage of static charges in phases due to the inclusion of the inductance of the arc suppression reactor in the neutral of the network [27].

An increase in the degree of compensation detuning from 5 to 30...40% leads to a rapid increase in the level of overvoltages. It should be noted that with a detuning of the compensating device by 20% of the resonant one, the effectiveness of the compensating devices in terms of limiting overvoltages during earth faults is practically not felt in comparison with networks with a completely isolated neutral.

The overvoltage in the neutral of the network is approximately 1.5...2 times less than the frequency of overvoltages in the undamaged phases, that also helps to reduce the damage to the elements of the power supply system.

From an economic point of view, distribution networks with capacitive earth fault current compensation require additional capital costs for arc suppression reactors and devices for their connection. With regard to operating costs, they are significantly less than in networks with a completely isolated neutral due to the less damage to the system elements. With a resonant adjustment of the compensating device and with insignificant compensation mismatches in electrical networks, the margin of dielectric strength of insulation in relation to the impacting overvoltages increases to 30%.

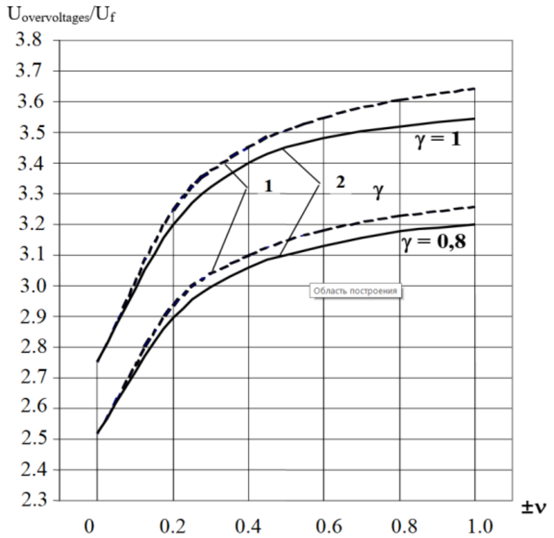

Fig. 2. Dependences of the maximum overvoltage multiplicity on the degree of compensation detuning in the mode:
1 - overcompensation; 2 - undercompensation

5.3. System with low-Impedance neutral grounding (active resistance)

The system with low-impedance neutral grounding (active resistance), as compared to other neutral grounding systems, have higher reliability due to the improved performance of the protection devices against single-phase earth failures (suppression of post-accidental transient processes), the elimination of ferro-resonance processes and the reduction of the damage to the elements of the power supply system. The latter is conditioned by a significant decrease in internal overvoltages. As the active component of the failure current increases with respect to the capacitive component, the overvoltage multiplicity decreases to 2.4 provided that active and capacitive failure currents are equal.

The magnitude of overvoltage in a three-phase network with an active resistance in the neutral is determined by the expression:

$$U_{ov} = \sqrt{3} \cdot U_f \cdot \sin(\phi_{ig} + 30^0) + U_f\left[\sin\phi_{ig} - (\sin\phi_{arc} - 0.2)e^{-k_a(\phi_{ig}-\phi_{arc})}\right] \times \frac{C(1-d)}{C+C_M}, \quad (16)$$

where ϕ_{ig} – phase of voltage of the damaged phase at the moment of ignition, rad.; ϕ_{arc} – phase of the voltage of the damaged phase at the moment of arc extinction, at which the bias voltage reaches its maximum; k_a is the ratio of active and capacitive fault current components.

Figure 3 shows the dependence of the maximum multiplicity of internal overvoltages in the network with a resistor in the neutral on the ratio of the active and capacitive components of the single-phase earth fault current, obtained taking into account the most unfavorable conditions according to expression (16).

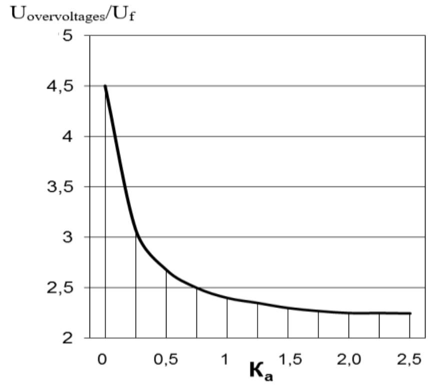

Fig. 3. Dependence of the maximum multiplicity of overvoltage in a network with a resistor in neutral from the ratio of the active and capacitive components of the fault current

As the active component of the fault current grows in relation to the capacitive component, the overvoltage ratio decreases to 2.4, with the active and capacitive fault current being equal. Figure 3 shows that a further increase in the active component practically does not lead to a significant decrease in the overvoltages ratio.

From the point of view of providing the single-phase ground failure protection, as well as the quality of its performance (which is directly related to the electrical safety and continuity of power supply to electrical receivers), the power networks with a neutral resistor, in other words, with the overlay of the additional active component on the ground failure current, can be considered as the most favourable ones. In such networks, currents and directional devices used in the insulated neutral networks show more reliable and efficient operation by suppressing the transient processes. On condition of providing the single-phase ground failure protection, the electrical networks with a compensated neutral are in the most unfavourable position.

According to the conditions of electrical safety of power networks, when a person directly touches the current-carrying parts, none of the possible neutral operation modes can be considered as a favourable one. According to the conditions of indirect danger, preference should be given to electrical networks, then the electrical network with the neutral resistor should be considered as the most favourable one.

With the development of autonomous networks and an increase in the total capacity of the earth failure, the combined neutral mode of the network is advisable. It takes place when the resistor and the arcing reactor are connected in parallel to the neutral of the network. In this case, in addition to creating the inductive component of the current of a single-phase earth failure, the active component is simultaneously superimposed on the network. The value of the active component imposed on the compensated network should be at the level of 30 - 50% of the capacitive component, that is, be selected from the condition:

$$I_a = (0.3...0.5) \cdot I_C. \tag{17}$$

The recommended values of the emergency current active component, ensure the suppression of transient processes in the event of ground failures, the increased efficiency of ground-failure protective devices (signalling), the exclusion of the ferroresonance phenomena, which leads to an increase in the level of electrical safety and reliability, as well as to the improvement of performance characteristics, adequate to the power supply systems only with the neutral resistor, even at the detuning of an arc suppression reactor to 50% of the resonance compensation mode [34-35].

Fig. 4 shows a comparison between the zone of maximum multiplicity of overvoltages on the degree of detuning compensation from the resonant mode in a network with the compensated neutral (zone 1) and in a network with the combined neutral operation mode (zone 2).

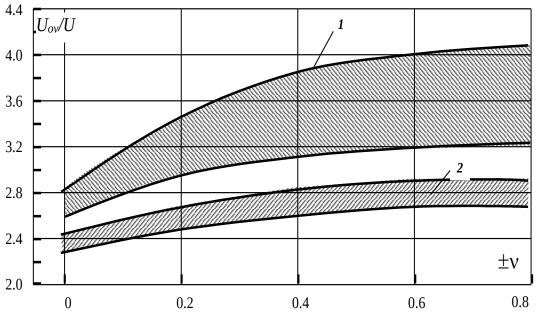

Fig. 4. Dependence of the multiplicity of internal overvoltages at earth failures on the degree of detuning compensation mode: 1 - in a network with the compensated neutral; 2 - in a network with the combined neutral grounding

The upper and the lower boundaries of the zones correspond to the values of the coefficient overvoltage reduction, equal respectively to 1 and 0.8, which takes into account network physical characteristics, relative damage location, etc.

6. CONCLUSIONS

1. The carried out studies allowed to establish the fact that the reliability of distribution networks in local systems is determined by the failure rate of network elements and the effectiveness of relay protection devices. The degree of influence of these factors on the reliability of distribution networks depends on the neutral mode, which in turn determines the level of internal overvoltages and the nature of transient processes at single-phase-to-ground failures.
2. As regards the provision of earth failure protection as well as of its performance (that is directly related to the electrical safety and the power supply continuity to electrical consumers), electrical networks with the resistor in a neutral can be considered as most advantageous ones, where the current and directional protection devices applied in the networks with the insulated neutral, due to the suppression of transient processes, show more reliable and effective operation. In terms of provision of the single-phase-to-ground failure protection, electric grids with the compensated neutral are in the most unfavourable position.
3. The lowest level of operational reliability corresponds to the networks with the fully isolated neutral, as well as to the ones with the compensated neutral in case of compensation detuning to 20% and higher from the resonant value. This is because of the high level of damage to the elements of power supply systems by the effect of internal overvoltages and of ferroresonance phenomena.
4. In the case of compensated networks in which it is difficult to provide a resonant tuning mode, it is recommended that the combined neutral mode of operation, with the creation of an active component, be at the level of 30 … 50% of the capacitive one, that provides performance indicators adequate to power supply systems with only a resistor in the neutral, even during malfunctions arc suppression reactor up to 50% of the resonant compensation mode.
5. None of the considered methods of neutral grounding allows to achieve the required level of reliability in autonomous systems and requires the use of additional devices that continuously monitor the above indicators.

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