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Review

Review of Neutral Grounding Modes, Resistor Monitoring, and Methodology for Transitioning to Resistive Grounding in 6–10 kV Distribution Networks

Iliya Iliev [1,*], Alexandr Nazarychev [2], Andrey Grigorov [2], Ivan Beloev [3], Konstantin Suslov [4,5,*] and Hristo Beloev [6]

1 Department of Heat, Hydraulics and Environmental Engineering, "Angel Kanchev" University of Ruse, 7017 Ruse, Bulgaria
2 Department of Electric Power Engineering and Electromechanics, Saint Petersburg Mining University, 199106 St Petersburg, Russia
3 Department of Transport, "Angel Kanchev" University of Ruse, 7017 Ruse, Bulgaria
4 Department of Power Supply and Electrical Engineering, Irkutsk National Research Technical University, 664074 Irkutsk, Russia
5 Department of Hydropower and Renewable Energy, National Research University "Moscow Power Engineering Institute", 111250 Moscow, Russia
6 Department of Agriculture Machinery, "Angel Kanchev" University of Ruse, 7017 Ruse, Bulgaria; hbeloev@uni-ruse.bg
* Correspondence: iki@uni-ruse.bg (I.I.); dr.souslov@yandex.ru (K.S.)

Abstract

With increasingly stringent requirements for the reliability and safety of medium-voltage distribution networks, the problem of selecting and monitoring the neutral grounding mode is becoming increasingly important. This review focuses on a comprehensive analysis of neutral grounding modes in medium-voltage distribution networks and on methods for detecting single-phase ground faults, which account for up to 80% of all faults. The review provides a comparative analysis of the main neutral grounding modes, namely isolated, compensated, resistive, and combined neutral. Their advantages and disadvantages are identified in terms of overvoltage levels, personnel safety, relay protection selectivity, and other factors. Modern and conventional methods for detecting single-phase ground faults are also considered. Particular attention is paid to the problem of monitoring the technical condition of neutral grounding resistors, since their latent failure can lead to unpredictable consequences. An analysis of existing monitoring methods is carried out, and the need for a combined method for continuous monitoring is substantiated. A significant part of the review is devoted to substantiating the phased conversion of 6–10 kV distribution networks with isolated or compensated neutral to resistive grounding. It also presents a methodological approach for determining the priority order of substation modernization based on calculating an integrated priority indicator using the analytic hierarchy process (AHP) and the pairwise comparison method. This approach allows heterogeneous technical and organizational factors to be taken into account and enables objective ranking of substations for conversion to resistive grounding.

Keywords: single-phase ground fault; neutral grounding modes; arc-suppression reactor; resistive grounding; relay protection; power supply reliability

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1. Introduction

Enterprises of the mineral resource complex (MRC) are often located at a considerable distance from cities; therefore, any damage to their electrical networks can have a critical impact on MRC operations [1,2]. Restoring damaged equipment in such networks cannot always be accomplished promptly [3,4], which makes the issue of power supply reliability for these enterprises highly relevant [5,6]. Single-phase earth faults (SPEFs) remain the most common type of fault [7,8]; therefore, a prerequisite for ensuring the reliability of the electrical network is the detection of the fault location during an SPEF and its selective isolation [9,10]. When an SPEF occurs in a network with an isolated neutral, the voltage of the faulted phase becomes zero, while the phase voltages of the healthy phases increase to line-to-line voltages. The vector diagram for an SPEF (phase C fault) is shown in Figure 1.

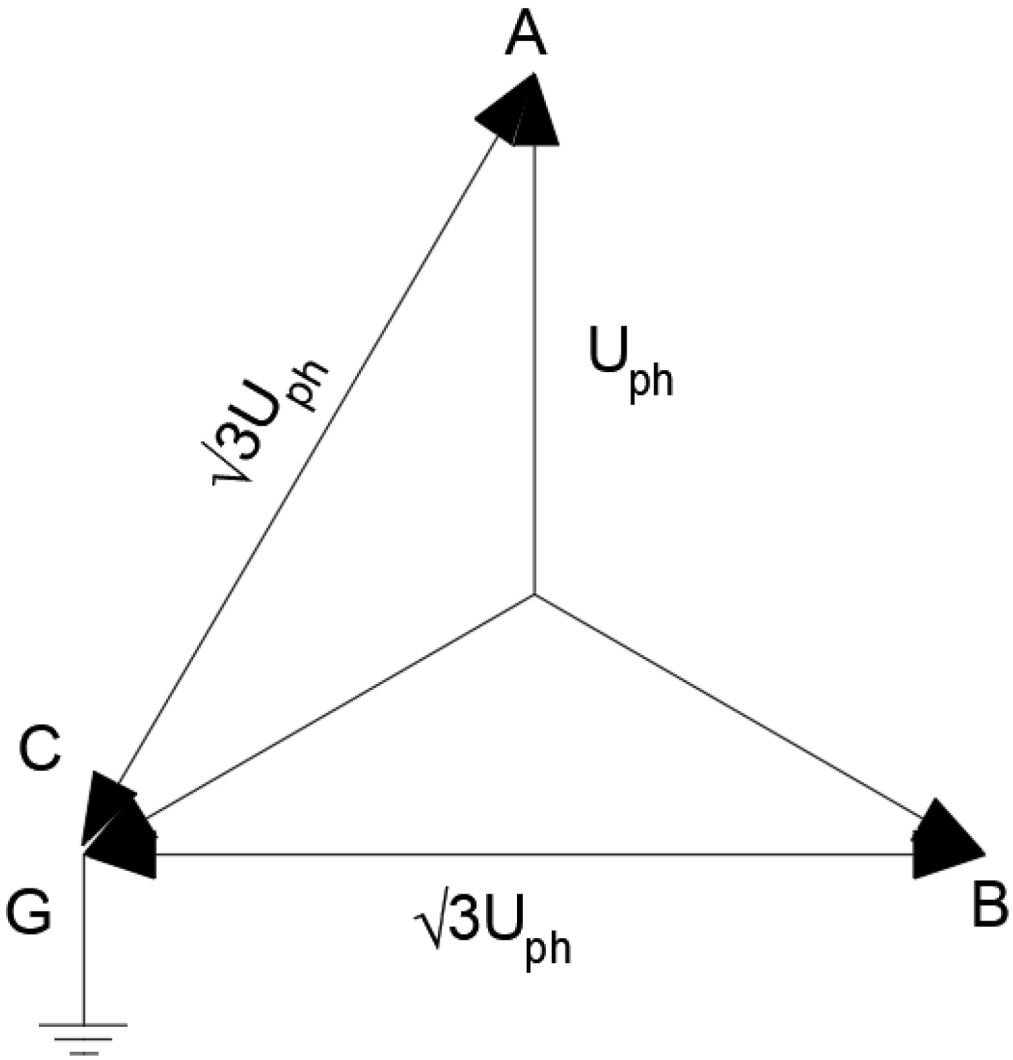


Figure 1. Vector diagram for a single-phase earth fault (phase C fault).

The neutral grounding mode can significantly affect the magnitude of the earth fault current. In a network with an isolated neutral, the fault current is primarily determined by the network's inherent capacitance and the fault resistance at the point of contact, and its magnitude will be relatively small [11]. A similar situation is observed when the neutral is grounded through a high-resistance resistor or in a compensated neutral system. In a compensated system, the arc-suppression coil (ASC) minimizes the reactive capacitive fault current. However, due to inevitable detuning and the residual active (resistive) current

from network leakage and reactor losses, the fault current does not drop to zero. While this significantly lowers the probability of arc reignition, it does not entirely prevent it. Such systems present the greatest challenge, as the fault current is relatively small and blends with the unbalance current.

The problem of SPEF detection in networks with a compensated neutral is examined in detail in [12]. The authors note that fault signals in resonant systems are weak and can easily be confused with normal disturbances, making their detection extremely difficult [13]. Traditional threshold-based methods often prove ineffective, and faults may be mistakenly identified as normal processes, such as load switching. Statistical data presented in [14] indicate that SPEFs account for approximately 80% of all faults in distribution networks. This underscores the exceptional importance of developing effective methods for their detection. A distinctive feature of SPEFs is the appearance of zero-sequence current and voltage, which are absent in other types of faults: two-phase and three-phase short circuits (SCs).

To detect zero-sequence current, a zero-sequence current transformer (ZSCT) can be used. It has a ring or rectangular core cross-section encompassing all three phases [15]. As the currents of the three phases pass through the wires serving as the primary winding, they create magnetic fluxes in the ZSCT. The resultant flux induces a current that flows through the ZSCT. The zero-sequence component typically appears when an SPEF occurs, and a zero-sequence current flows through the ZSCT. The wiring diagram of the current transformers forming a zero-sequence filter is shown in Figure 2. Currents I_A, I_B, I_C pass through the measuring current transformers, after which the vector summation of the measured values I_a, I_b, I_c is performed. The resultant current $\dot{I}_p$ is measured by the current transformer designated by the letter P in Figure 2 and equals the vector sum of $\dot{I}_a$, $\dot{I}_b$, $\dot{I}_c$.

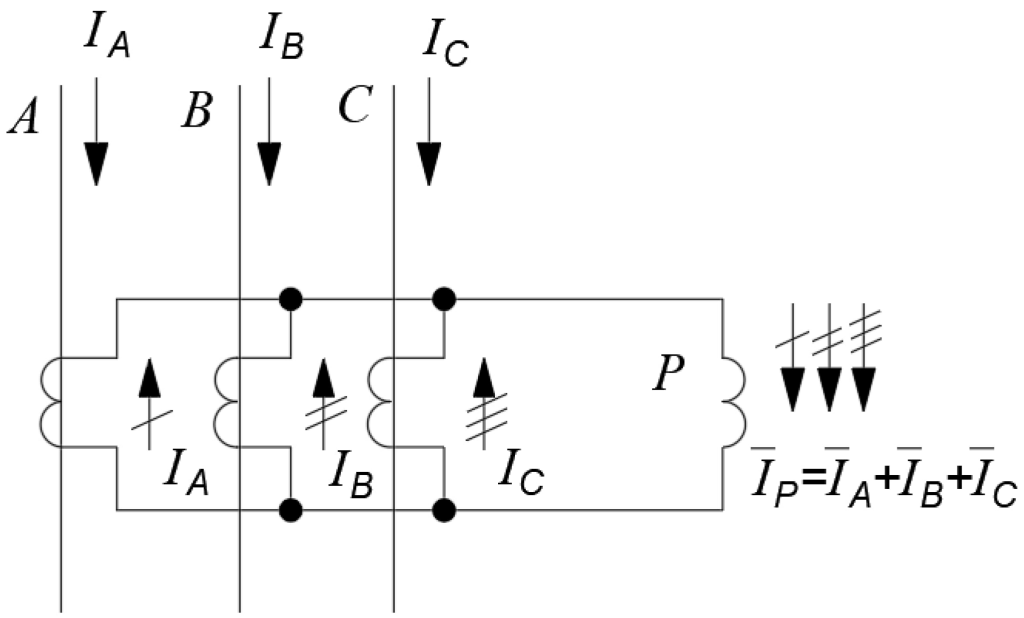


Figure 2. Connection diagram of current transformers in a zero-sequence filter.

An example of an oscillogram recorded during an SPEF is shown in Figure 3. This oscillogram was obtained from one of the power facilities in Russia. The facility where the SPEF occurred is a power cable line with a rated network voltage of 6 kV. The figure shows the onset of the SPEF. The relay protection detected both the zero-sequence current and the zero-sequence voltage; as a result, after a specified time delay, the cable line was tripped. The electrical network in which this single-phase fault occurred is relatively modern; it is

equipped with microprocessor-based relay protection devices, current transformers in all three phases, and ZSCTs. Consequently, this single-phase fault was detected immediately after its occurrence, and the line was tripped by the relay protection.

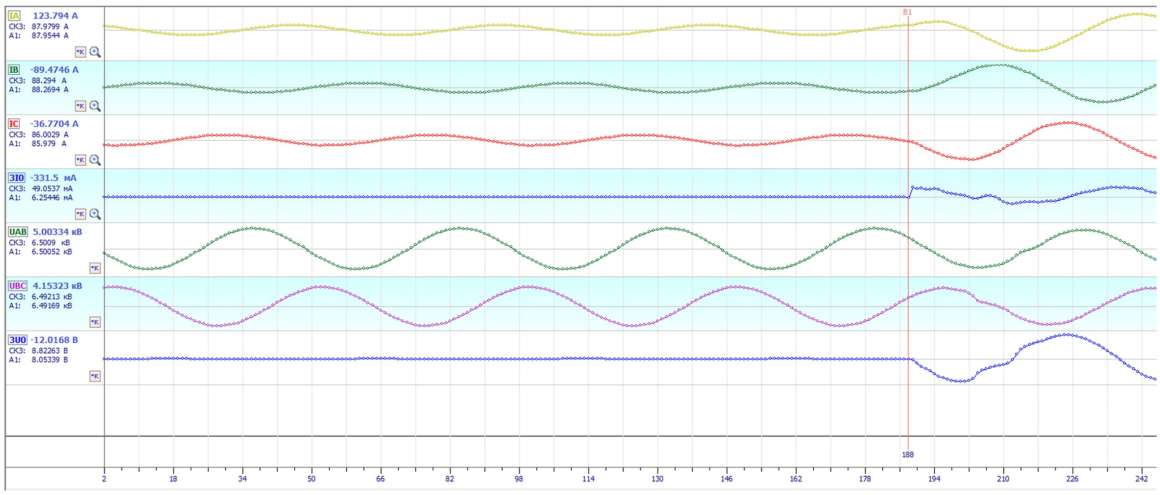


Figure 3. Oscillogram showing the moment of single-phase earth fault occurrence.

However, there are a significant number of substations with cable and overhead lines whose level of technical equipment remains rather low. Such substations are typically equipped with electromechanical relays, measuring current transformers installed in only two phases, and no ZSCTs. Such substations cannot detect single-phase faults, and since the fault current in an isolated neutral network is quite low, an SPEF can persist for a long time until it typically develops into a phase-to-phase short circuit. The resulting short circuit will then be tripped by the relay protection, since the short-circuit current is very high. In addition, single-phase faults can be accompanied by high overvoltages and lead to multipoint damage.

To detect zero-sequence voltage, voltage transformers (VTs) connected in an open-delta configuration are used. As with ZSCTs, under normal conditions, the geometric sum of the voltage vectors is also zero. Zero-sequence voltage typically appears specifically during single-phase earth faults. It should be noted that the neutral of the primary winding of the VT must be grounded; otherwise, phase voltages with respect to the neutral will be applied, and their sum will always be zero [16].

The majority of SPEF protection schemes are based on zero-sequence currents and voltages. For example, the SPEF protection algorithms of many manufacturers of microprocessor-based relay protection terminals are based on measuring zero-sequence currents and voltages, and the protection can be configured to respond to either of these quantities (zero-sequence current or voltage) or to operate when they appear simultaneously [17,18].

The methods for determining zero-sequence currents considered above are conventional ones [19,20]. Since approximately 2020, modern detection methods that use data on the current operating state of the network have been gradually introduced [21]. Based on an analysis of the scientific literature, five main groups of problems hindering the detection of SPEFs can be identified. Table 1 presents a systematization of these problems, indicating their causes and possible solutions.

Table 1. Problems in detecting single-phase earth fault currents.

Problem	Causes	Consequences	Sources
Low fault current	Isolated, compensated, or high-resistance grounded neutral; high fault resistance	Low sensitivity of protection	[22]
Non-linear nature of arc fault	Dynamic variation in arc resistance over time; insulation breakdown through non-metallic media	Instability of fault parameters; difficulty in threshold-based identification	[23]
Influence of the neutral grounding mode	Capacitive current compensation by an arc suppression coil (ASC)	Distortion of SPEF signals; reduced effectiveness of traditional methods	[19]
Complex network topology	Branched network structure; cable and overhead lines	Multiple signal propagation paths	[24]
External disturbances and noise	Switching processes; load unbalance; distortions	False tripping	[25]

Based on a synthesis of the research results presented in Table 1, all existing methods for detecting single-phase ground faults can be classified into five main categories Table 2 presents a systematization of these methods, indicating their advantages, disadvantages, and applications. It should be noted that the practical operating limits of these methods vary significantly; for instance, while transient methods are highly sensitive, they are physically constrained by the fault transition resistance.

Table 2. Classification of methods for detecting single-phase earth fault currents.

Method Category	Advantages	Disadvantages	Area of Application	References
Stationary methods	Simplicity of implementation; low computational costs	Low sensitivity during high-resistance faults; dependence on the neutral grounding mode; dependence on the accuracy of fundamental-frequency filters	Metallic faults	[17]
Transient methods	High sensitivity; independence from the neutral grounding mode	Complexity of signal processing; dependence on network parameters; performance degradation under high transition-resistance faults due to attenuation of high-frequency transient signals	Networks with isolated and compensated neutral	[17]
Signal injection methods	Efficiency under any neutral grounding mode	Requires additional equipment; possible impact on network operation; the injected signal may be masked by high background noise or capacitive currents	6–10 kV distribution networks; faults that are difficult to detect	[26]

Table 2. *Cont.*

Method Category	Advantages	Disadvantages	Area of Application	References
Wavelet methods	High accuracy of fault location	Complexity of implementation; requires synchronized measurements; requiring robust pre-filtering algorithms	Cable and mixed networks	[27]
Methods based on artificial intelligence	Adaptability; high accuracy; noise immunity	Requires large amounts of training data; difficulty of interpretation; vulnerability to atypical faults not present in the training dataset	Branched networks	[28]

The steady-state methods listed in Table 2 are the simplest and most widespread. When an SPEF occurs in the network, zero-sequence current and voltage appear, which are measured by instrument transformers. If the electrical network is not highly branched, the fault current is quite low [19]. The presence of active filtering and resonant modes in mining power networks significantly alters the amplitude-frequency response of the system [29]. This makes traditional fundamental-frequency measurements unreliable, and measuring zero-sequence current and voltage using instrument transformers becomes difficult. Therefore, methods that do not require accurate fundamental-frequency measurements, such as the fifth harmonic method or the negative-sequence current method, are used.

In [8,17], a new approach to SPEF diagnostics is proposed. This approach is based on reference values of steady-state zero-sequence currents. The idea is to overcome two problems inherent in existing steady-state methods: they provide poor fault identification and adapt poorly to changing network conditions. The authors show that with reference values, detection reliability increases under different operating conditions.

Transient methods analyze the high-frequency components of signals, making them more sensitive and less dependent on the neutral grounding mode in the network. The faulted section is determined by the difference in the waveform of transient zero-sequence currents. This works well in distribution networks with low fault currents. Ref. [26] confirms that transient methods are noticeably more effective than steady-state ones; however, complex signal processing is required, and network parameters affect the result. A critical practical limitation is that high-resistance faults act as a low-pass filter, severely attenuating the high-frequency transient components. Consequently, the sensitivity of transient-based methods significantly decreases under high-impedance fault conditions.

Signal-injection methods use a different approach: a test signal is deliberately injected into the network, and its propagation is analyzed to determine the fault location. They are reliable and effective under any neutral grounding mode, but additional equipment is required for signal generation and reception. During an SPEF, a fixed-frequency sinusoidal signal can be injected into the secondary winding of the voltage transformer (VT) of the faulted phase [30]. In [31], the signal is injected into the distribution system and then received at the terminals. As a result, the faulted line can be identified. There is also a method for 10 kV networks with frequency-coded signal injection, which requires fewer calculations and provides high accuracy [32].

Traveling-wave methods analyze how electromagnetic waves propagate along power lines during a fault. They offer high accuracy, but implementation is complex, and synchronized measurements from both ends of the line are required. In [33], the faulted line and the fault location are determined using the S-transform of the time–frequency voltage matrix. Ref. [34] proposes an improved double-ended method based on initial modal traveling waves, taking into account the distances between towers.

Artificial intelligence (AI)-based methods are currently the most advanced and rapidly developing area. They utilize neural networks that learn to recognize faults from a large training dataset. Ref. [35] proposes a method based on a combination of support vector machines (SVMs), which provides high accuracy and good noise immunity. In [36], a clustering algorithm is used for systems with low fault currents. Machine learning enables high accuracy even under strong noise and uncertainty of network parameters [37], but there are limitations associated with the need for large amounts of training data [38].

In medium-voltage electrical networks of 6–10 kV, in accordance with the Electrical Installation Code (PUE), four types of neutral grounding modes are permitted to be used [39]:

(1) Isolated.
(2) Grounded through an arc-suppression reactor.
(3) Grounded through a resistor.
(4) Combined, combining grounding through a resistor and through an arc-suppression reactor.

2. Methodology

To ensure transparency and reproducibility, the literature search was conducted using a systematic approach across the Scopus, Web of Science, Google Scholar, and eLibrary databases. The search covered a broad timeframe, with the majority of the analyzed sources (over 70%) published within the last 10 years (2015–2025), while also retaining older foundational studies. The search strategy utilized specific Boolean strings, such as ("neutral grounding" OR "NGR") AND ("single-phase earth fault" OR "SPEF") AND ("6–10 kV" OR "distribution network"). The search included various document types, such as peer-reviewed journal articles, conference proceedings, technical standards, and patents. The initial search yielded approximately 350 records. After removing duplicates, 320 documents were screened based on their titles and abstracts. Subsequently, 160 full-text documents were assessed for eligibility. The inclusion criteria allowed selection of peer-reviewed publications and technical documents in English or Russian directly related to 6–10 kV networks. Documents focusing solely on high-voltage transmission or low-voltage systems, as well as non-technical reports, were excluded. A total of 114 high-quality sources were finally selected for this review. The quality assessment of these studies was based on their methodological rigor, the presence of experimental or simulation validation, and their relevance to practical engineering applications.

The research methodology is based on the collection and analysis of publications dedicated to neutral grounding modes and the specifics of single-phase earth faults (SPEFs). The criteria for selecting sources include their relevance, scientific significance, and applicability in the operational conditions of 6–10 kV distribution networks, according to the following stages:

- Classification of neutral grounding modes and SPEF detection methods: Based on the collected data, the existing neutral grounding modes are systematized. In addition, modern and traditional SPEF detection methods are classified. These include methods based on the analysis of steady-state conditions, transient processes, signal injection, and others. Their advantages, disadvantages, and areas of application are considered.
- Comparative analysis of neutral grounding modes: A detailed review of the advantages and disadvantages of each neutral grounding mode is performed. Factors such as arc overvoltage levels, personnel safety, relay protection selectivity, and the ability of the network to continue operation during an SPEF are analyzed, which allows determining the most effective solutions for various network topologies, such as cable or overhead lines.

- Analysis of methods for monitoring the condition of neutral grounding resistors (NGRs): Particular attention is paid to the problem of hidden faults in NGRs. Passive, active, and combined methods for NGR condition monitoring are classified. The effectiveness of methods such as visual inspection, current or voltage measurement, the use of resistive dividers, active signal injection, and combined monitoring systems is analyzed in terms of their applicability in normal mode, emergency modes, and modes where the NGR is disconnected from the network.
- Development of a methodology for prioritizing the transition of the network to resistive grounding: At the final stage, an approach to the phased transition of distribution networks to resistive neutral grounding is justified and developed. A multi-criteria decision-making method, specifically the Analytic Hierarchy Process (AHP), is applied. The criteria are ranked through pairwise comparisons, after which a comprehensive priority indicator is calculated, allowing for an objective determination of the sequence for transitioning substations to resistive grounding.

The research methodology described above provides a comprehensive approach to studying the subject, combining theoretical analysis of physical processes with engineering practice. The results obtained enable the formulation of scientifically substantiated conclusions and recommendations aimed at improving power supply reliability, electrical safety, and relay protection selectivity in medium-voltage distribution networks.

3. Comparative Analysis of Neutral Grounding Modes

As noted in [40], the neutral is a key element affecting the safety and stability of distribution networks, especially with the increasing share of cable lines and increasing capacitive currents [41]. Ref. [42] provides a detailed analysis of the advantages and disadvantages of various neutral grounding modes in cable networks. The authors substantiate the preference for specific neutral grounding modes in different scenarios. The most common neutral grounding mode in Russia, historically used in networks with voltages above 1 kV, is the isolated neutral, which is used in approximately 80% of cases (Figure 4). The advantage of this grounding mode is the low SPEF current. The SPEF current depends on the capacitance formed between the conductors and the ground. During an SPEF, the voltage of the healthy phases increases to line-to-line voltages; however, this does not affect the operation of consumers. Therefore, in the event of an SPEF in networks with an isolated neutral, continued operation for a limited time is permitted [43].

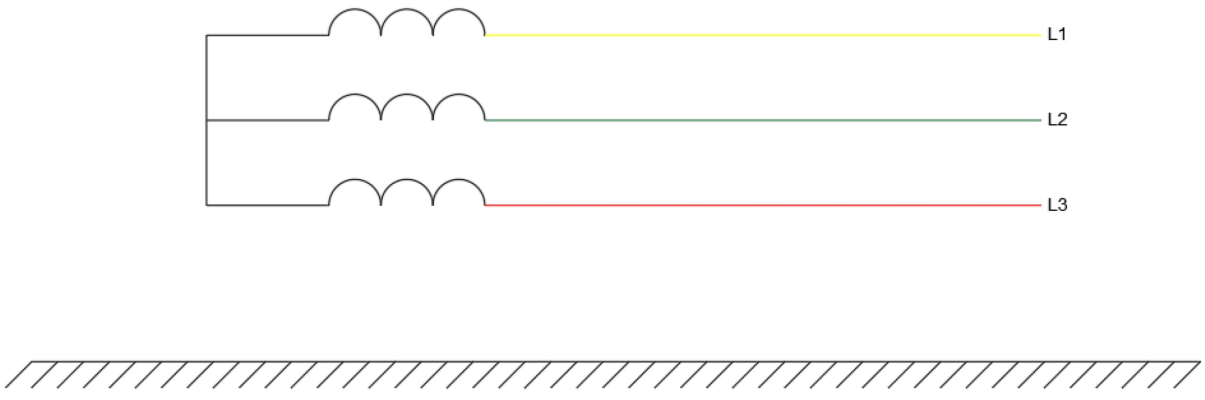


Figure 4. Schematic representation of the isolated neutral grounding mode.

Although widely used in Russia, this type of neutral has not been widely adopted in other countries. The main disadvantages of networks with an isolated neutral are as follows [44]:

- The voltage of the healthy phases increases to line-to-line voltages, which in turn increases the probability of insulation breakdown and the occurrence of two-phase or three-phase short circuits (SCs); therefore, the insulation of electrical equipment must be rated for line-to-line voltages, which increases the cost of electrical equipment.
- Since SPEFs are typically accompanied by an arc, overvoltages are also possible due to the intermittent nature of such an arc, which repeatedly re-ignites and extinguishes. In this case, overvoltages can reach values equal to four times the phase voltage (4Uph), which can also lead to the SPEF developing into multiphase short circuits.
- The SPEF current is determined by the network capacitance and is many times lower than the current of a two-phase or three-phase SC, which makes it difficult to determine the fault location.
- At the fault location during an SPEF on overhead lines (OHLs), a step voltage occurs, which is dangerous for both humans and animals and can lead to electric shock.
- There is a significant (several-fold) increase in the RMS value of the current at the fault location during intermittent arc SPEFs due to the free components of the transient process.
- The probability of electrical machine damage caused by the current at the fault location increases, primarily during intermittent arc SPEFs.

The neutral grounding mode via an arc suppression coil (ASC) (Figure 5) has also been used in Russia and other countries for a relatively long time. To date, this neutral grounding mode is used in approximately 17% of cases in 6–10 kV networks.

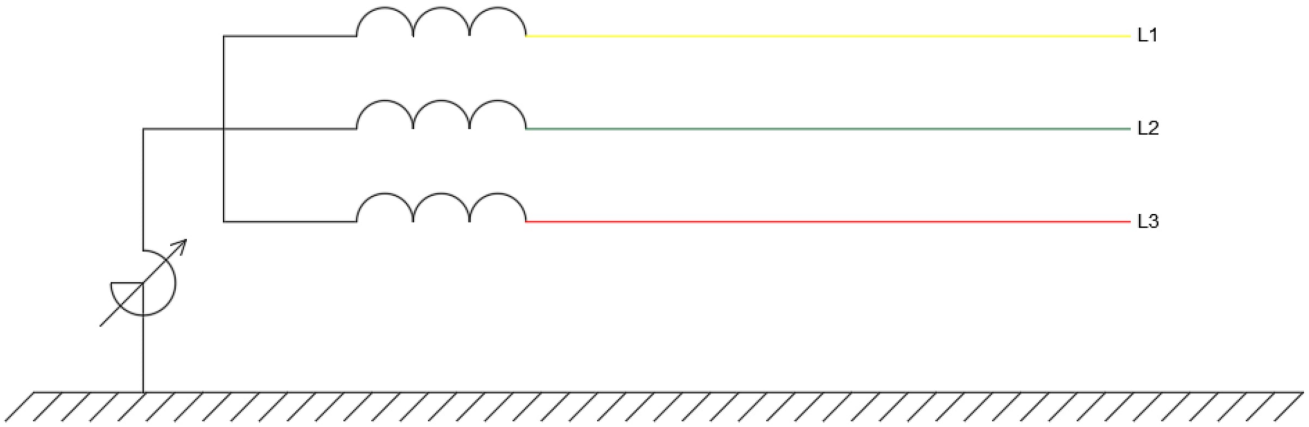


Figure 5. Schematic representation of the neutral grounding mode through an arc-suppression reactor.

This neutral grounding mode is particularly widespread in networks where the capacitive component of the SPEF current is unacceptable. Large capacitive currents are caused by the need to use long underground cable lines in confined spaces, for example, in urban networks [45,46].

The disadvantages of networks with a compensated neutral include the following:

- The complexity and cost of automatic control systems for the ASC. Maximum efficiency requires fast ASC tuning to the SPEF current. Also, depending on the network size, a very wide control range may be required, since the SPEF currents at the beginning and at the end of the line can differ significantly.
- It should also be noted that when using an ASC, providing selective protection against SPEFs becomes problematic. In the event of an SPEF on any of the outgoing feeders, the SPEF current will flow through all ZSCTs. Moreover, the current flowing through the current transformer will be equal to the capacitive current of the corresponding feeder; therefore, it is difficult to provide protection responding to the capacitive current

component. At the same time, non-selective SPEF protection based on the presence of zero-sequence voltage on the buses is possible. If present, the faulted feeder is identified by sequentially disconnecting all feeders until the zero-sequence voltage disappears [47].

The neutral grounding mode via a resistor can be divided into two groups depending on the resistor used (Figure 6):

- Low-resistance grounding.
- High-resistance grounding.

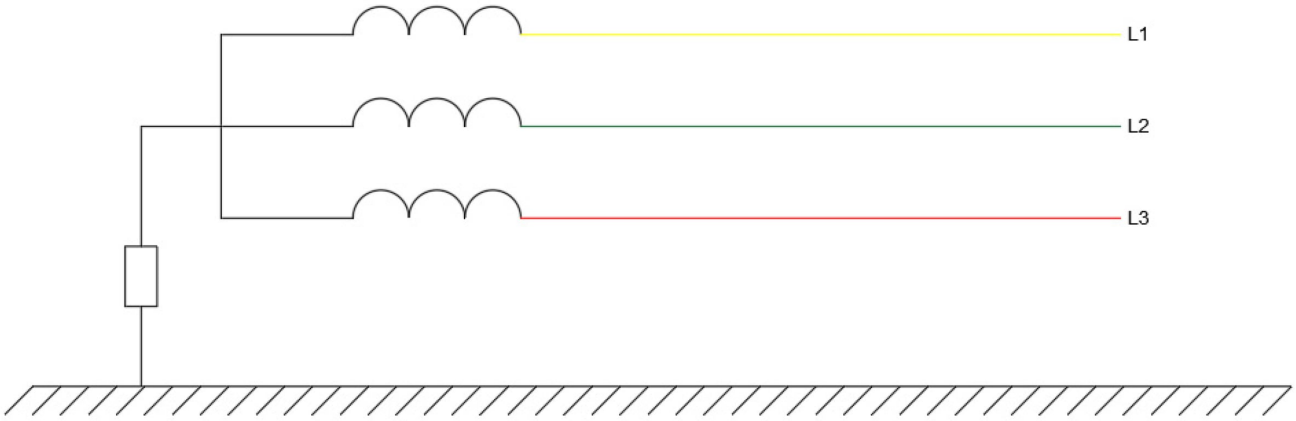


Figure 6. Schematic representation of the neutral grounding mode through a resistor.

If the inherent capacitive current of the network is large, low-resistance grounding is applied. The inherent capacitive current at which low-resistance grounding is applied is typically 10 A, although the resulting fault current in this case significantly exceeds 10 A and can reach hundreds of amperes.

Since the SPEF current in this case is substantial, continued operation with protection acting as an alarm (rather than a trip) is no longer possible, and such an SPEF must be tripped in the shortest possible time. When installing a low-resistance resistor, its resistance should be selected so that the active component of the SPEF current is approximately twice as large as the capacitive component of the network [48]. Thus, the total current, consisting of the active and capacitive components (for example, when the active component is twice as large as the capacitive one), will be increased by a factor of $\sqrt{5}$ compared to the capacitive component. Such a current has significant advantages:

- With such high SPEF current values, such faults are very easy to detect;
- While the capacitive component of the SPEF current flows through all outgoing lines, the active current component flows only through the faulted feeder; therefore, simple selective relay protection can be organized in this case;
- Minimization of the risk of personnel being exposed to step voltage due to the rapid tripping of the faulted section.

The main advantages of high-resistance grounding are:

- Reduced probability of ferroresonance phenomena;
- No need for immediate tripping of the faulted feeder, with protection acting as an alarm;
- Similar to low-resistance grounding, the possibility of organizing simple selective protection based on the active current component.

A specific feature of SPEFs in overhead lines (OHLs) is that they can be self-clearing; in this case, immediate tripping of the faulted feeder is not required [49,50].

The presence of nonlinear loads such as electric arc furnaces (EAFs) in the network leads to time-varying voltage–current characteristics, voltage flicker, and harmonics, which complicate the operation of relay protection and require special measures to ensure selectivity and sensitivity [51]. However, the application of a combined mode, consisting of neutral grounding through an arc suppression coil (ASC) with a shunt resistor, merits separate consideration (Figure 7). In this case, when an SPEF occurs, the neutral is grounded through the ASC, which tunes to the SPEF current and creates an inductive current component that compensates for the capacitive current component, reducing the total current to almost zero. Reducing the SPEF current to zero helps avoid ferroresonance phenomena, and with the current reduced to zero, the arc will not reignite after extinguishing, thereby eliminating the intermittent arc effect. As a result, it is possible to continue operation for a certain period despite the presence of an SPEF. The underlying assumption is that the SPEF in this case is unstable and will disappear on its own after the arc is extinguished. However, if the fault proves to be sustained, the resistor is activated. After a specified time delay, the resistor is connected in parallel with the ASC. As a result, the resistor creates an active current component that flows through all feeders, but only in the faulted feeder is its magnitude sufficient to trigger the relay protection. The resistor installed in this case is of the low-resistance type, and its resistance is selected so that the current it creates is sufficient for the selective operation of the relay protection.

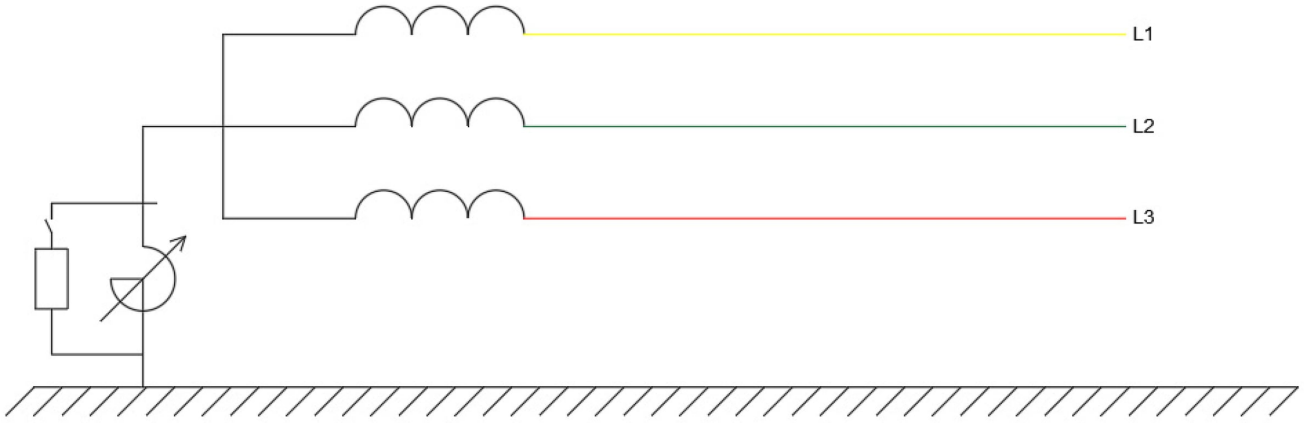


Figure 7. Schematic representation of the neutral grounding mode through an arc-suppression reactor with a shunt resistor.

Ref. [52] presents a comparison of the two most popular modes: grounding via an arc suppression coil (ASC) and low-resistance grounding. The grounding modes are compared in terms of criteria such as arc overvoltages, protection selectivity, and fault statistics. The authors conclude that in cable-dominated networks, low-resistance grounding is preferable, whereas the resonant (compensated) mode remains preferable for overhead lines (OHLs).

Based on an analysis of various sources, all modes applied in practice can be grouped into four main categories. Since combined grounding is a combination of two separate grounding modes, it is considered separately, outside these four categories. Table 3 presents a systematization of these modes, indicating their areas of application, advantages, and disadvantages.

Table 3. Systematization of neutral grounding modes.

Neutral Grounding Mode	Application Area	Advantages	Disadvantages	Sources
Isolated neutral	Networks with low capacitive currents (primarily OHLs)	Low steady-state SPEF current; possibility of continuing operation during a fault; simplicity	High arc overvoltages; difficulty in detecting the fault location; danger to insulation	[53]
Compensated neutral	6–10 kV networks with significant capacitive currents (cable-overhead)	Fault current limitation to 5–10 A; possibility of continuing operation during a fault	Complexity of ASC tuning; risk of ferroresonance; low protection sensitivity during faults	[54]
Low-resistance grounding	6–10 kV cable networks	Overvoltage limitation; high selectivity of relay protection; simplicity of implementation	High SPEF currents (hundreds of amperes); consumer disconnection at every fault; stringent requirements for grounding devices	[7]
High-resistance grounding	6–10 kV networks with low fault currents	Overvoltage reduction	Difficulty in selecting optimal resistance; low protection sensitivity	[55]

As can be seen from the table, no single mode is superior in all respects. The isolated neutral offers an advantage in terms of cost but is inferior in terms of protection and overvoltage performance [56]. The compensated neutral offers a balanced trade-off, especially in OHLs [57]. Low-resistance grounding is preferable for cable networks with a high level of automation, where rapid tripping is required and a power supply interruption is acceptable [58]. In addition, combined grounding offers the advantages of both the compensated neutral and low-resistance grounding.

The combined grounding mode is not included in Table 3 since it is not a separate neutral grounding mode but rather a combination of two of the aforementioned modes. Although it enables the advantages of these modes to be combined, the implementation of the combined mode requires substantially higher capital costs.

4. Monitoring the Condition of Arc-Choking Reactors

The operation of an arc suppression coil (ASC) during a single-phase earth fault (SPEF) is based on the fact that it creates an inductive current component at the fault location that compensates for the capacitive component [59,60]. As a result, the inductive current balances the capacitive current, and the total current at the fault point is reduced to a very low value. As a result, in networks with a compensated neutral, the faulted line need not be tripped for a certain period during an SPEF [61].

There are also combined solutions that include not only ASCs but also low-resistance shunt resistors. Such a combined approach enables an increase in the reliability of medium-voltage networks and a reduction in the damage associated with SPEFs.

Under normal operating conditions, the inductive reactance of the ASC significantly exceeds its active resistance. Various methods are used to regulate the inductance and, consequently, the inductive reactance: changing the number of turns, adjusting the air gap in the core, and using magnetic biasing [22].

The most common arrangement remains the installation of the ASC directly in the network neutral. In the practice of power companies, rod-type ASCs with distributed air gaps are the most widely used. Their inductance is regulated by tapping the working winding using an off-circuit tap changer (OCTC) [62]. With proper tuning and minor

changes in the phase resistances of the network, such devices provide highly effective compensation of the capacitive current component. The arc-suppression efficiency is defined as the ratio of the number of earth faults that self-cleared or were cleared by personnel to the total number of such faults. There are various examples of arc-suppression reactors with smooth regulation [63]. Figure 8 shows a schematic diagram of an arc-suppression reactor with its automatic control system. The capacitor and resistor banks are used to regulate the bias current, which makes it possible to change the inductive reactance of the reactor and tune it to resonance with the network capacitance.

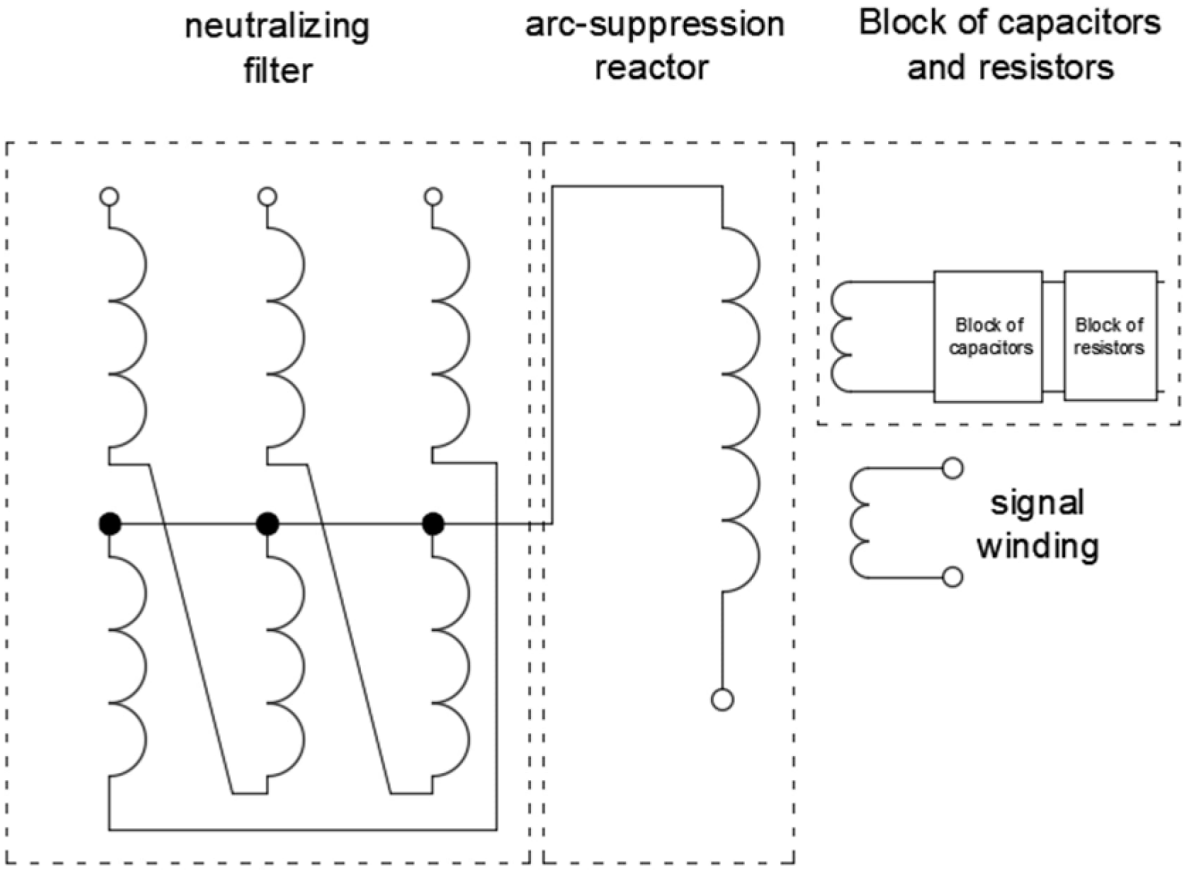


Figure 8. Schematic diagram of an arc-chasing reactor with blocks of capacitors and resistors.

The problem of compensating the capacitive current component during an SPEF encompasses not only the choice of the neutral grounding mode but also the design of arc suppression coils (ASCs) and the selection of the automatic compensation control method [64]. One relevant technical solution is a combined design in which the neutral grounding transformer and the 6–10 kV ASC are placed in a single tank. Such an arrangement enables a reduction in dimensions and simplifies the operation of the equipment. Various methods can be used for the resonant tuning of reactors and the compensation of the capacitive current component during an SPEF, including plunger-type ASCs and capacitor-controlled reactors.

In plunger-type reactors, the inductance is regulated by changing the size of the non-magnetic gap in the core [65]. Since the magnetic core is manufactured according to a two-limb design, the central limb is divided into two parts to regulate the inductive current, which allows the gap height to be varied.

The coil inductance can be adjusted by various methods. In the symmetrical configuration, the gap is adjusted simultaneously on both sides of the central axis of the core. This design provides a smoother control characteristic.

In the asymmetrical configuration, only one part of the core remains movable. The design of plunger-type reactors is well-established. If production requirements are strictly met, their service life may exceed 30 years [66]. The operating principle of capacitor-controlled reactors is based on connecting capacitors to an auxiliary secondary winding. Capacitive current compensation is achieved by changing the equivalent capacitance of the capacitor bank. The capacitances of the banks are selected to provide up to 128 or 256 control steps. This approach enables a relatively smooth variation in the compensation current.

The advantages of such reactors include:

- The absence of moving mechanical elements;
- High speed of parameter adjustment;
- Convenience and clarity of monitoring the network's capacitive current.

Despite the aforementioned advantages, capacitor-controlled ASCs are a relatively new development, as they have only been in use for 15–20 years, and operational experience to date is limited. In a capacitor-controlled reactor, a parallel circuit is formed that includes the inductance L of the main winding and the capacitance C of the bank connected to the auxiliary winding. In series with these elements, the inductances of the power transformer, the neutral grounding transformer, the cable line, and, if present, a current-limiting reactor are also included in this circuit. Since the capacitance of the secondary circuit is regulated over a wide range, there may be several frequencies at which resonance occurs. At current resonance in the parallel LC circuit, the capacitors on the secondary side of the ASC experience increased current, which can lead to their premature failure.

The linearity of the voltage–current characteristic (V–I characteristic) is directly related to the inductive reactance of the coil, which, in turn, determines the accuracy of capacitive current component compensation [59]. If linearity is disturbed, the efficiency of capacitive component compensation decreases [64]. In this case, during intermittent SPEFs, overvoltages occur in the network, which can be accompanied by multipoint damage. A number of factors affect the linearity of the V–I characteristic, including the number of movable cores in the plunger, the cross-sectional shape of the magnetic core, and the number of yokes. The linearity of the V–I characteristic is also affected by the magnetic flux density in the magnetic system and the active part utilization coefficient.

The active part utilization coefficient K_a must exceed 2.0 (to be verified against the original source). It is under this condition that the V–I characteristic nonlinearity remains within 1% at the nominal phase voltage of the network. For plunger-type ASCs, the magnetic flux density is recommended to be maintained in the range of 0.9–0.95 T [67]. However, some manufacturers design reactors for 1.5–1.6 T. Practice shows that during an SPEF, reactors with a significant shortage of active materials begin to saturate. Their inductive reactance drops sharply, resonant tuning is disrupted, and overvoltages occur in the network. This can lead to multipoint damage. This is especially common in spring and autumn. As a result, a significant number of cable lines are damaged, which also affects consumer power supply. At the same time, when saturated, the reactor begins to draw increased current, creating a risk of overheating and damage.

5. Monitoring the Technical Condition of the Neutral Grounding Resistor

As previously mentioned, resistive neutral grounding has a number of significant advantages compared to an isolated neutral. Low-resistance grounding enables selective tripping of SPEFs and prevents SPEFs from developing into phase-to-phase short circuits

(SCs). High-resistance grounding enables limitation of overvoltages during an SPEF and allows the SPEF to remain un-tripped for a certain period. According to manufacturers' data, the average service life of a neutral grounding resistor (NGR) is 30 years. Over such a long period of operation, the resistor is subjected to numerous external influences that alter its technical characteristics: loosening of connections in current-carrying parts, corrosion, among others (Figure 9). Figure 9 illustrates the development of corrosion during operation. Like any other equipment, an NGR can fail [68,69].

NGR failure can occur for many reasons, including poor-quality welded joints [68], exposure to wildlife [70], high-frequency oscillations [71], various vibrations [72], third-harmonic effects [73,74], among others. Cooling conditions must also be taken into account, since the resistor heats up after an SPEF occurs. This is especially true for low-resistance NGRs, where the active current can exceed 1000 A. If a new SPEF occurs within a short time, the resistor may not have time to cool down, which may result in damage during the new SPEF.



Figure 9. Example of corrosion in a grounding system.

NGR failure is a serious problem, since operating a network with a damaged NGR is dangerous [68]. The operation of the electrical network depends on the specific type of damage. A break in any conductor will cause the neutral grounding mode to revert to an isolated neutral. Relay protection configured for resistive grounding will not trip during SPEFs, and the electrical network will continue to operate with a single-phase earth fault. In this case, dangerous overvoltages may occur in the network and equipment may be damaged. For example, cables with cross-linked polyethylene (XLPE) insulation are not designed for the prolonged presence of an SPEF in the network [75], as they degrade rapidly. In addition, personnel are exposed to step voltage. Thus, NGR failure or damage can lead to significant consequences.

NGR failures are a widespread problem in the industry. Changes in the resistance value of such resistors pose serious risks to safety and the operation of protection systems. Statistics contain numerous examples where a failed NGR was the exact cause of an accident. Specifically, the following cases are mentioned:

- Systematic failures in the Middle East: An energy company in the Middle East experienced several NGR failures at its distribution substations over a period of several years. The NGR failures resulted in the system becoming ungrounded, which created a risk of overvoltages on the healthy phases and damage to equipment insulation [76].

- At the Laiwui power plant (Obi Island), an NGR failure led to a power outage lasting more than 12 h. The cause was an excess of the calculated short-circuit current: the actual current reached 442 A, whereas the NGR was rated for 300 A. This caused the conductor to heat up to 2000 °C and ignite. In addition, a decrease in the NGR resistance from 39.8 Ω to 27.9 Ω was recorded, indicating internal degradation [77].
- A study published in 2005 described the failure mechanism of NGRs at 26 kV substations of Public Service Electric and Gas (PSE&G). The cause was identified as local high-frequency oscillations arising from the self-inductance of the resistor and the phase-to-neutral coupling capacitance of the transformer during ground faults on the feeders [78].

The simplest way to check an NGR, as with any other equipment, is a scheduled visual inspection. Faults such as a poor-quality bolted connection can be found during inspection before an earth fault occurs; however, such an inspection evaluates the equipment's condition only externally. Furthermore, a fault may occur after the inspection, meaning that a visual inspection confirms the NGR's serviceability only at the moment of inspection. Therefore, NGRs must be diagnosed throughout their entire service life [79]. In some countries, regulatory documents specify requirements for mandatory NGR monitoring [80].

However, unlike power transformers, for which measuring current and voltage transformers are sufficient for monitoring, continuous NGR monitoring cannot be performed using the same means. In the normal operating mode of the network, the neutral voltage is determined only by unbalance, and the neutral voltage will be relatively low, as will the current flowing through the NGR in normal mode. However, in the event of an earth fault, the phase voltage of the network, which can reach tens of kilovolts, will be applied to the neutral, and a very high current will flow through the resistor [81]. Consequently, if the monitoring device is designed to monitor the resistor in normal mode, it will be damaged in the event of a fault. Conversely, if the device is capable of withstanding very high voltages and currents, it will not be able to detect the negligible voltages and currents present in normal operation compared to fault conditions.

The resistance of the NGR also affects its failure rate. For example, high-resistance NGRs are assemblies of a large number of resistive elements. The numerous connections, fasteners, and other potentially unreliable points mean that failures in high-resistance NGRs occur much more frequently than in low-resistance ones [70]. In contrast, a low-resistance NGR typically has a single winding, so there are significantly fewer points that could cause a failure [82]. Furthermore, a high-resistance NGR is installed in the network on the assumption that an SPEF does not need to be tripped for a certain period. In this case, the capacitive fault current, as well as the active current component caused by the resistor, will flow through the NGR. Although the current magnitude in this case is low enough that the SPEF does not need to be tripped, the resistor will heat up and gradually wear out. This is especially important in northern regions, where ambient temperatures can be very low. In this case, the resistor will constantly heat up to certain values as a result of SPEFs and, after disconnection, cool down to sub-zero temperatures. Various methods for NGR monitoring exist, differing in complexity and effectiveness. Neutral grounding resistors are produced by various manufacturers [83]. Figure 10 shows a connection diagram of a neutral grounding resistor to the network through a neutral-forming transformer. When the power transformer windings are delta-connected and have no neutral point, an artificial neutral must be created using a neutral-forming transformer to connect the neutral grounding resistor.

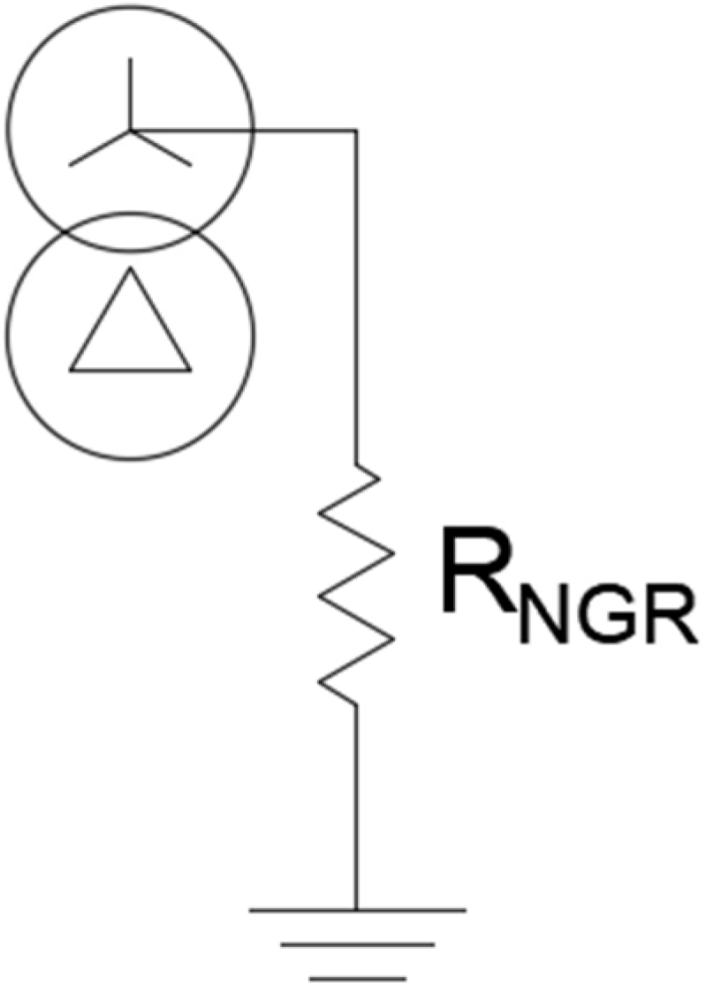


Figure 10. Connection diagram of the neutral grounding resistor to the network through a neutral-forming transformer.

5.1. Method 1: Visual Inspection

The simplest method for NGR monitoring, requiring no additional equipment, is a visual inspection of the neutral grounding resistor. Such an inspection can be performed periodically, thereby monitoring the condition of the NGR. Despite the apparent simplicity of visual inspection, this method enables confirmation of the NGR's serviceability only at the moment of inspection [70]. The NGR can fail immediately after the visual inspection, and a subsequent single-phase earth fault (SPEF) may lead to significant consequences. However, this monitoring method provides NGR condition control, albeit to a limited extent [84].

5.2. Method 2: Measurement of the Current Passing Through the Neutral Grounding Resistor

This method is classified as a passive method. A current transformer (CT) is installed on the cable connecting the neutral grounding resistor to measure the current flowing through the NGR. As previously mentioned, even under normal network operating conditions, there is some voltage at the neutral due to network unbalance. Therefore, current will flow through the NGR in both normal and fault modes. An abnormally high current detected by the CT would indicate resistor damage, for example, due to an internal short circuit within the resistor enclosure [84]. A complete absence of current would indicate that the resistor is not connected to the neutral and that the electrical circuit is open.

However, the current flowing in normal mode may be so small that the CT is unable to measure it. This creates a problem, as this method cannot accurately determine whether the NGR has failed open or the unbalance is so small that the current is too low to be measured. Furthermore, this method cannot detect partial damage to the resistor. A high-resistance NGR consists of numerous resistive elements. If several elements short out, the total resistance of the resistor will change, and the resulting fault current at the fault location may become unacceptable. Since this method uses only a CT, it is impossible to determine a change in the NGR's resistance. One implementation of this method is shown in Figure 11.

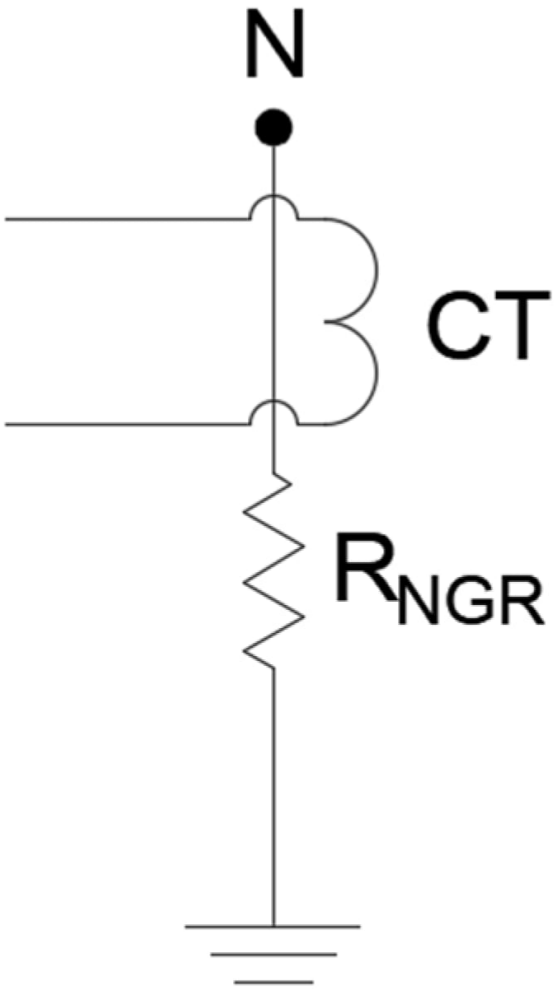


Figure 11. Method 2.

5.3. Method 3: Measurement of the Current Passing Through the Neutral Grounding Resistor and the Neutral Voltage

This method is also classified as a passive method and is an improvement over Method 2. This method includes not only a current transformer (CT) measuring the current flowing through the NGR, but also a voltage transformer (VT) measuring the neutral voltage. One of the implementations of this method is shown in Figure 12. By measuring the current flowing through the NGR and the neutral voltage, the resistance value of the NGR can be calculated using a simple formula:

$$R_{NGR} = \frac{U_N}{I}, \quad (1)$$

where I is the current measured by the CT; U_N is the neutral voltage; and R_{NGR} is the NGR resistance.

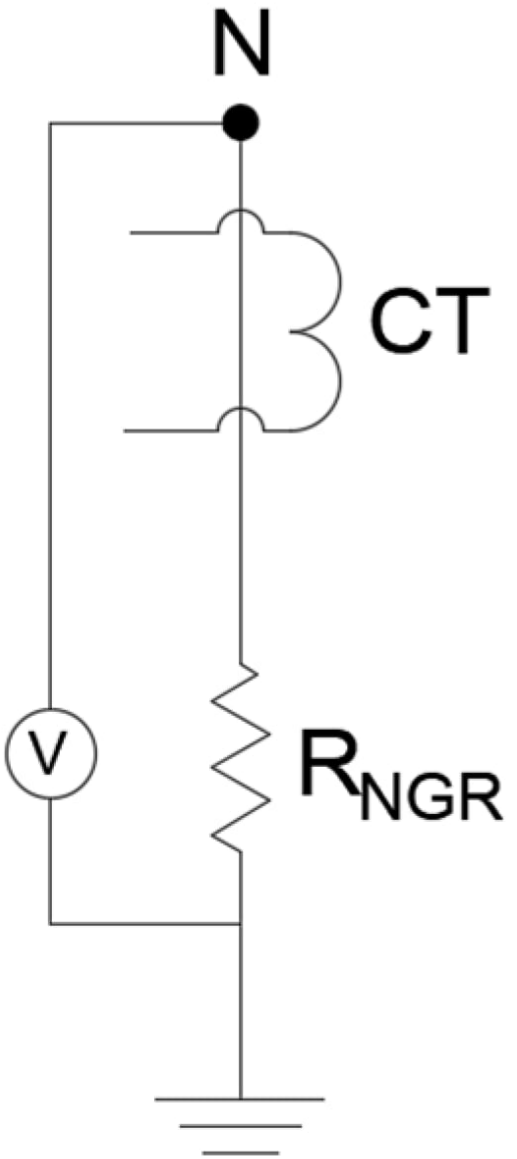


Figure 12. Method 3.

Unlike the previous methods, this method allows for the detection of partial damage to the NGR based on the change in its resistance. However, determining the resistance is only possible provided that the neutral voltage and the current flowing through the NGR are sufficient for accurate measurement. This method is highly effective during single-phase earth faults (SPEFs); however, under normal network operation, the measured values are quite low, which casts doubt on the accuracy of the determined NGR resistance.

One way to increase the effectiveness of this method is to measure the zero-sequence voltage taken from a VT connected in an open-delta configuration, instead of measuring the neutral voltage. Various studies indicate that measuring zero-sequence voltage is more effective than measuring neutral voltage, since the minimum measurement limit for zero-sequence voltage is lower than that for neutral voltage [82,85]. Therefore, by measuring the zero-sequence voltage, it is possible to determine the NGR resistance under normal operating conditions with greater accuracy compared to measuring the neutral voltage.

5.4. Method 4: Using a Resistive Voltage Divider

This method is also classified as a passive method. It is very similar to Method 3; however, unlike that method, it uses a resistive voltage divider. The use of a resistive voltage divider improves the accuracy of NGR resistance monitoring because the voltage measurement range of a resistive divider is wider than that of neutral voltage and zero-sequence voltage measurements [86]. While the lower measurement limit for neutral voltage is about 10% of the nominal value and the lower limit for zero-sequence voltage is 1%, the use of a resistive divider allows this limit to be reduced to 0.1%. This provides sufficient accuracy for NGR resistance monitoring [85]. One implementation of this method is shown in Figure 13.

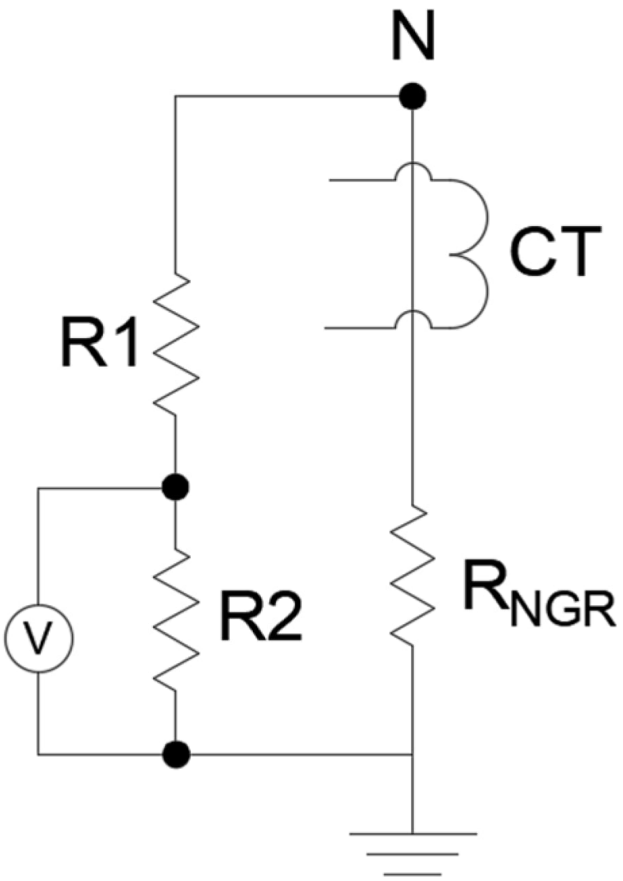


Figure 13. Method 4.

5.5. Method 5: The Use of a Limiting Resistor and a TVS Diode

Like the previous ones, this method is classified as passive, and it is very similar to Method 4. Unlike the previous method, it uses a limiting resistor connected in series with a TVS (Transient Voltage Suppressor) diode instead of a resistive divider. The limiting resistor limits the neutral voltage to levels safe for measuring instruments, whereas the TVS diode is required when the neutral voltage exceeds acceptable levels. In normal mode, the TVS diode has a high resistance. When a certain voltage is exceeded, the TVS diode resistance drops sharply and it begins to conduct current, thereby protecting the measurement circuits. It should be noted that once the voltage exceeds the permissible limit, the NGR resistance can no longer be monitored. The TVS diode is selected such that it remains in a non-conducting (off) state during normal network operation [87].

In the event of an SPEF, the TVS diode will begin to conduct current, protecting the equipment; however, this makes the method ineffective during SPEFs [88]. In normal mode,

this method demonstrates higher NGR monitoring efficiency compared to the previous methods. Its main disadvantage is that it cannot be applied in fault modes due to the high neutral voltages. One implementation of this method is shown in Figure 14.

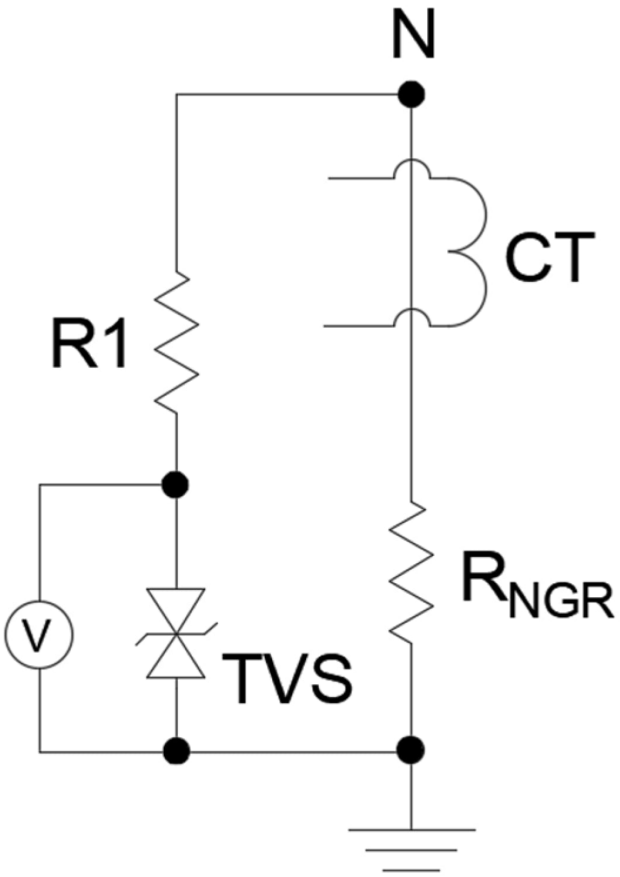


Figure 14. Method 5.

5.6. Method 6: Active Current Measurement Method

As previously stated, the problem with NGR condition monitoring is that under normal operating conditions, the current flowing through the resistor and the neutral voltage are very low, while during a single-phase earth fault (SPEF), they become very high. To monitor the condition of the resistor, active methods do not rely on the network's current and voltage; instead, they generate their own signals for subsequent monitoring.

This method is classified as an active method. It is very similar to Method 2; however, unlike Method 2, it does not measure the current flowing through the NGR. Instead, a dedicated device generates a current that flows through the NGR. For monitoring purposes, either a direct current (DC) signal [89] or a signal with a frequency different from the network frequency can be used. By measuring this current, the condition of the resistor can be monitored. In normal mode, the circuit is closed, and the current flows freely through the resistor, with the current magnitude remaining constant. If a break occurs, this indicates an open-circuit failure. A change in the current indicates a change in the resistor's parameters.

5.7. Method 7: Active Method of Measuring Current and Voltage

This method is also classified as an active method. The method includes a direct current (DC) voltage source, a measuring resistor R_1 of low resistance, a protective resistor R_2, and a TVS diode [90]. Direct current flows through the measuring resistor R_1, the protective resistor R_2, and the NGR. Knowing the resistances of $R1$ and $R2$, the source voltage, and

the voltage drop across R_1, the NGR resistance can be calculated [91]. A DC source is used because direct current does not leak into the network, since line capacitances present a very high resistance to DC.

The advantage of this method compared to Method 5 is the use of a signal source to determine the resistance; therefore, even a low neutral voltage under normal conditions will not affect the measurement accuracy. This method also enables monitoring of the resistor condition even when it is disconnected from the network. Furthermore, this method can be applied to monitor generators [92,93]. One implementation of this method is shown in Figure 15.

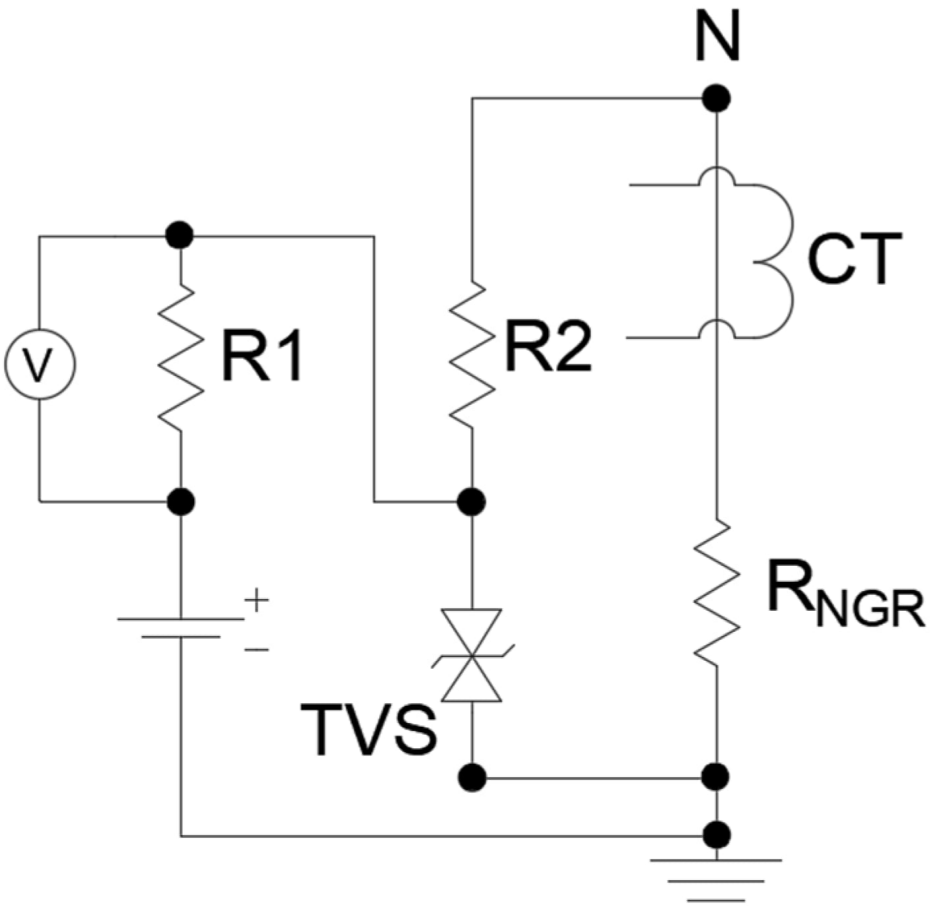


Figure 15. Method 7.

However, this method has a number of disadvantages. A sufficiently high neutral voltage will distort the DC source signal, which may lead to incorrect results. In addition, a TVS diode is required to protect against excessively high voltage; in the event of an SPEF, this method, like Method 5, cannot be used. Nevertheless, this method demonstrates high efficiency in monitoring the condition of resistors in normal or disconnected states.

5.8. Method 8: Combined Method

Active and passive NGR monitoring methods were previously discussed. It was noted that each of them has a number of advantages and disadvantages. Thus, some methods perform well under normal network operating conditions, when the neutral voltage is low and the current flowing through the resistor is low, as well as when the resistor is disconnected from the network; however, these methods are not applicable in fault modes when the neutral voltage becomes high. At the same time, other methods are

specifically designed to operate in fault modes and are of little use under normal network operating conditions.

To solve these problems and ensure continuous NGR monitoring, it is advisable to use a combination of several methods so that the resistor can be monitored continuously under various network operating modes.

Combined methods enable continuous NGR monitoring. For example, there are devices that combine several methods for NGR condition monitoring [87,94].

The devices manufactured by Bender and Littelfuse have a similar design and identical NGR monitoring methods. There is also an NGR monitoring device from the Canadian company I-Gard, the Sigma3-C [95].

Figure 16 shows a schematic diagram of a typical device for monitoring neutral grounding resistors. This control device includes an additional auxiliary device that enables measurement of the voltage at the transformer neutral, transmission of the signal generated by the device itself, and also provides protection against high neutral voltage.

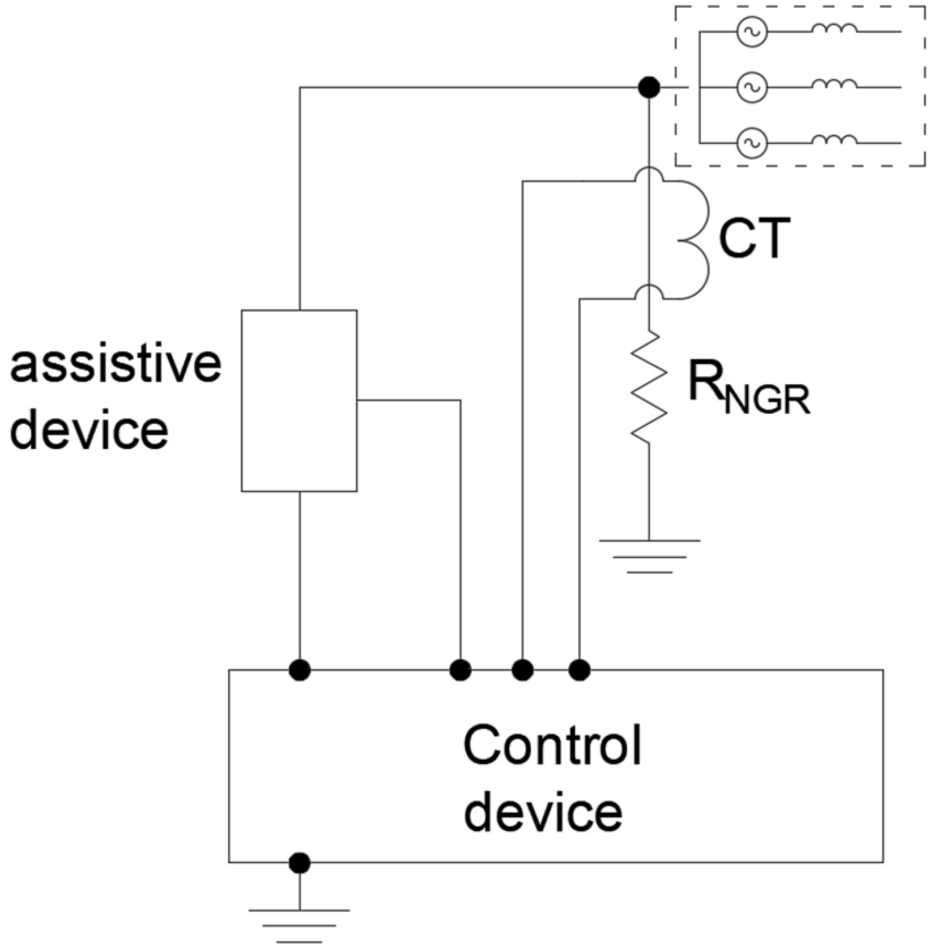


Figure 16. Schematic diagram of a device for monitoring the technical condition of a neutral grounding resistor.

Littelfuse has a patent that describes a device for monitoring the condition of a resistor [96]. Furthermore, this company holds other patents for similar devices and methods [97].

Under normal network operating conditions, when the neutral voltage is sufficiently low, the active method is used. The device generates an active signal that flows through the NGR. As previously mentioned in the description of Method 7, this enables calculation of

the NGR resistance and thereby monitoring of the NGR condition under normal network operation, as well as monitoring of the condition of a disconnected NGR. At the same time, if the neutral voltage becomes sufficiently high, for example, due to severe unbalance or the occurrence of an SPEF, the device will use Method 5. In this case, the magnitude of the neutral voltage and the current flowing through the NGR will be sufficient for accurate measurement by the CT and VT.

The combined method enables continuous NGR monitoring in all operating modes, including normal network operation, fault mode with an SPEF, and the disconnected state of the NGR. Naturally, implementing the combined method requires significantly more equipment and, consequently, higher cost; however, the consequences of NGR failure are considerably more severe.

Comparing all the previously discussed methods, it can be stated that the combined NGR monitoring method is the most effective, as it provides continuous monitoring of the resistor's condition and, consequently, the highest efficiency compared with the other methods. The considered methods are compared below, and the results are summarized in Table 4.

Table 4. A comparison of the considered methods for monitoring the state of a resistor.

Method	Implementation Complexity	Advantages	Disadvantages	References
Method 1	Very easy	Simplicity, requires no additional equipment	Confirms serviceability only at the moment of inspection; does not protect against sudden failures after inspection	[88]
Method 2	Easy	Simplicity of implementation	In normal mode, the current is too low for accurate measurement	[98,99]
Method 3	Easy	Allows detection of partial damage (change in NGR)	In normal mode, voltages and currents are too low for accurate measurement	[68]
Method 4	Medium	High accuracy. Lowers the lower measurement threshold to 0.1%	In normal mode, voltages and currents are too low for accurate measurement	[98]
Method 5	Medium	Higher efficiency in normal mode	Cannot be applied in emergency modes	[98]
Method 6	Complex	Allows detection of open-circuit failure or parameter changes	Allows monitoring of circuit integrity and detection of changes in resistor parameters	[89]
Method 7	Complex	High accuracy, allows calculation of NGR resistance and detection of its changes	Cannot be monitored in emergency modes	[100]
Method 8	Very complex	Continuous monitoring in all NGR operating modes	Requires significantly more equipment and, consequently, higher costs	[87,94,95,97]

In a 10 kV substation, an NGR rated at 36 Ω was equipped with an active monitoring device utilizing high-frequency signal injection. The system continuously injected a low-amplitude AC signal into the neutral circuit. Over a period of six months, the monitoring system recorded a gradual drift in the measured resistance from 36 Ω to 41 Ω. This drift was caused by the degradation of the resistor's internal connections and overheating due to

harmonic currents. Because the active method is independent of the power frequency fault current, it successfully detected this degradation before any single-phase earth fault (SPEF) occurred, allowing for scheduled maintenance and preventing an unexpected failure.

6. Need for Transition of 6–10 kV Distribution Networks to Resistive Neutral Grounding

The numerous disadvantages of isolated and compensated neutrals necessitate changing the neutral grounding mode to resistive grounding [101]. Depending on the inherent capacitive current, resistive grounding will be either high-resistance or low-resistance. The procedure for transitioning to resistive grounding should be considered separately.

As noted in [81], there is currently a pressing need in Russia to transition 6–10 kV networks of various purposes from an isolated neutral or a neutral grounded via an arc suppression coil (ASC) to resistive neutral grounding. The use of a resistor enables the construction of selective protection to detect the faulted feeder, as well as the prevention of arc and ferroresonance overvoltages, which are dangerous for electrical equipment (especially voltage transformers, VTs) and maintenance personnel.

Ref. [102] notes that in recent years, 10 kV networks in China have been actively developing, with the share of cable lines in urban networks increasing. This leads to a significant increase in capacitive currents during single-phase earth faults (SPEFs). The traditional neutral mode does not enable timely fault elimination, which can lead to the spread of the fault due to the intermittent arc and resonant overvoltages, and to cable insulation breakdown.

Ref. [103] examines the economic feasibility of transitioning an existing urban 6–10 kV cable distribution network from compensated neutral grounding to low-resistance grounding. Using a 10 kV network section as a case study, it is shown that the transition project is economically justified, and its implementation will improve the reliability of power supply to consumers.

Based on the statistical data and expert assessments presented in [104–107], which characterize the equipment of Russian 6–10 kV distribution networks as of 2025, Figure 17 shows that much of the equipment is heavily worn. Some equipment has already exceeded its standard service life by a factor of two and is still in operation. All this leads to a decrease in the reliability of the electrical network; heavily worn cable lines are damaged frequently, including as a result of SPEFs.

If the neutral mode is isolated, SPEFs, as mentioned earlier, can be accompanied by high overvoltages caused by the intermittent arc. Quite often, SPEFs lead to multipoint damage due to these high overvoltages. Worn cable lines can no longer withstand such high overvoltages and are damaged. Moreover, cable lines on adjacent feeders, which initially had no faults, are often damaged as well. As a result, the occurrence of an SPEF leads to the tripping not only of the faulted cable line but also of many other feeders.

Paper [108] notes that resistive grounding is relatively simple to implement in radial distribution systems. It is impossible to transition all substations to resistive grounding simultaneously. The process of changing the neutral grounding mode should occur gradually, starting with the most critical substations. Substations that supply non-critical consumers, lack redundancy, among others, should be transitioned to resistive grounding last.

When determining the priority, various factors must be used. Multiple factors must be taken into account simultaneously, since the same factor may have different degrees of importance under different initial conditions. Furthermore, the number of factors itself may vary depending on the specific situation.

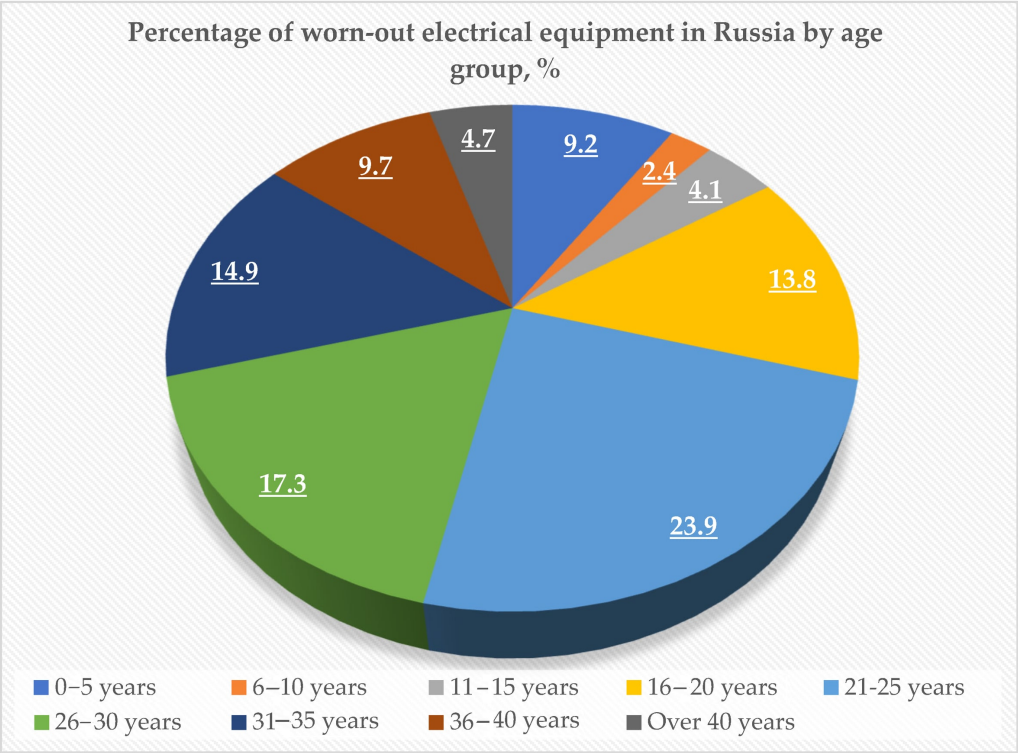


Figure 17. Distribution of electrical equipment by age groups.

To account for the importance of each individual factor, a weighting coefficient can be assigned to each factor, with the coefficient value determining its significance [109]. The substations will be compared with each other based on a specific set of factors. To determine the significance of each factor, the pairwise comparison method is proposed. Each factor is compared with the others, the most important factor is identified, and the degree of importance of each factor relative to the most important one is determined. Once the importance of each factor is determined, the weighting coefficients for each factor are calculated. To compile a priority list among all substations, a comprehensive priority indicator is proposed [110–113]:

$$\Pi\sum j = (a_1\Pi_1) + (a_2\Pi_2) + \ldots + (a_6\Pi_6) + (a_7\Pi_7) = \sum (a_i\Pi_i)_N, \quad (2)$$

where $\Pi\sum j$ is the integral (comprehensive) priority indicator; П1–П7 are priority indicators for each criterion; a1–a7 are weight coefficients of significance for each criterion; I is the number of criteria, $i = 1, 2, 3, 4, 5, 6, 7$; and N is the number of substations $N = 1, 2, 3, \ldots, n$.

This expression is universal and can account for a varying number of criteria and different degrees of importance. The criteria may include reliability, cost-effectiveness, the feasibility of implementing resistive grounding, among others [114]. In this case, the number of criteria is assumed to be 7, but it can be any other number.

When determining the values of the weighting coefficients, the decision-making process takes place under multicriteria conditions, where it is necessary to consider not only the relative importance of each factor compared with the others, but also to verify the adequacy of the final conclusions. Furthermore, it is important to assess how applicable the data obtained are in practice, for example, in operating urban electrical networks, to ensure uninterrupted power supply to consumers. To date, there are effective algorithmic and algebraic methods for processing qualitative data regarding the priorities of the criteria. An adaptive method for analyzing choice stability has also been proposed, based on a parametric description of preferences, which enables study of the consequences of both full and partial parameter adjustments [115].

Numerous studies confirm that human subjectivity inevitably manifests when solving multicriteria problems. At the same time, humans often successfully solve complex problems. This has led to the emergence of a scientific hypothesis regarding the existence of a threshold in human information processing capacity, which is directly related to the dimensionality of the task. To test this assumption, a series of experiments was conducted. Analysis of the results showed that human cognitive capabilities when evaluating alternatives are limited to an average of 6–8 criteria. Within this range, the evaluations generally remain stable and consistent. However, if the number of criteria exceeds this threshold, the subjects' behavioral strategy changes markedly. Furthermore, these changes manifest differently in domain experts compared with novices [116].

The criteria are ordered in a linear sequence. The highest-priority indicator, possessing the maximum weighting coefficient, is placed first, and the sequence concludes with the least significant criterion, which has the minimum weighting coefficient. As a method, Approach No. 7 presented in [117] is proposed.

In this case, the ranked list of criteria can be presented in the following form:

$$K_1 > K_2 > K_3 > K_4 > K_5 > K_6 > \ldots > K_n. \quad (3)$$

In addition, this approach allows for the calculation of the most adequate (acceptable) weighting coefficients, which can be applied not only in abstract hypothetical models but also in real-world systems.

The application of the method for calculating weighting coefficients is based on the following key advantages:

- It permits the assignment of equal weights (equal significance) to two or more parameters;
- It enables the formation of a pronounced contrast (a substantial difference) between the weights of adjacent criteria;
- The resulting weight values are suitable for direct application in operating power supply systems.

The approach is based on pairwise comparison using a floating preference scale. First, it is necessary to construct a pairwise comparison matrix, which is populated with coefficients k_{ij}. Here, all diagonal elements of the pairwise comparison matrix are equal to one and must satisfy the following condition:

$$k_{ij} \cdot k_{ji} = 1. \quad (4)$$

The approach under consideration is based on the Analytic Hierarchy Process (AHP) proposed by T.L. Saaty [118], which is considered one of the most widely used tools for the pairwise comparison of criteria. When forming the pairwise comparison matrix, the following rule is applied: if the criterion in row i has priority over the criterion in column j, the corresponding element of the matrix is assigned the value k_{ij}. If, however, the criterion in the row does not dominate the criterion in the column, the reciprocal of the preference coefficient, i.e., $1/k_{ij}$, is entered into the corresponding element of the matrix.

For the results obtained using this method to be correct, the matrix must be fully consistent with the judgments of the decision-maker. To achieve this, the following conditions must be satisfied by the matrix elements:

- The consistency condition for the matrix elements, formulated as follows: $k_{ik} = k_{ij} \cdot k_{jk}$.
- The transitivity condition for the matrix elements, according to which if $ki_k \geq k_{ij}$ and $k_{ij} \geq k_{jk}$, then $k_{ik} \geq k_{jk}$.

After the pairwise comparison matrix is populated, the values of C_i, i.e., the eigenvectors of the criteria, are calculated sequentially:

$$C_i = (k_{i1} \cdot k_{i2} \cdot \ldots \cdot k_{in})^{1/n}. \quad (5)$$

Next, the weighting coefficients of these criteria, α_i, are determined using the following expression:

$$\alpha_i = \frac{C_i}{\sum_{i=1}^{n} C_i}. \quad (6)$$

The second row of Table 5 presents the calculation results for the indicator γ. The value of γ represents the degree of superiority of the weighting coefficient of the most important criterion over the weighting coefficient of the least important criterion; that is, the maximum preference ratio of the criteria importance indicators, determined by Equation (7):

$$\gamma = \frac{k_1}{k_n} = \frac{\alpha_1}{\alpha_n}. \quad (7)$$

Table 5. Assessing the impact of the number of criteria on the value of γ when using the floating preference method.

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**
$\gamma = \frac{\alpha_1}{\alpha_n}$	3.31	4.86	6.73	8.84	11.33	14.18	17.09
CR	0.008	0.012	0.015	0.02	0.025	0.03	0.036

Table 5 presents the calculation results for the consistency ratio (CR). At the same time, according to [118], it is assumed that if the consistency ratio is less than 10%, the results are considered consistent and reliable. As shown in Table 5, even for 9 criteria, the consistency ratio is significantly less than 10%. Therefore, for the 7 criteria considered in this study, the consistency ratio is less than 10%, and the results can be trusted. The consistency ratio is determined according to the methodology presented in [118].

An example calculation is provided for 10 real substations in a large city based on 7 criteria. The following criteria are used for the calculation: K_1—reliability criterion; K_2—technical and economic feasibility criterion; K_3—redundancy availability criterion; K_4—capacitive current compensation efficiency criterion; K_5—criterion for the share of cables with XLPE (cross-linked polyethylene) insulation; K_6—power grid development criterion; K_7—power grid reconstruction criterion. The criteria were determined from actual statistical data obtained from the substations under consideration. The weighting coefficients used in the calculation were obtained from the expert assessment of employees of a large power grid company. The methods for calculating the criteria, their physical meaning and units of measurement, as well as the data sources used for their determination, are presented in [110,111]. The determined weighting coefficients are shown in Table 5. The values of the criteria calculated for 10 real substations and the comprehensive priority indicator are shown in Table 6.

The dependence of the weighting factor on the importance of the criterion is shown in Figure 18.

From Table 7, we will create a prioritized list based on the comprehensive priority indicator and present the results in Table 8.

However, the transition of networks to resistive neutral grounding is associated with a number of technical and organizational problems that must be taken into account when planning the measures listed in Table 9.

Table 6. The values of the weighting coefficients for 7 criteria.

	K1	K2	K3	K4	K5	K6	K7	Ci	α_i
K1	1	2	3	3	3	4	4	2.62725	0.3216
K2	0.5	1	2	2	2	3	3	1.66851	0.2043
K3	0.333	0.5	1	1	1	2	2	0.94372	0.1155
K4	0.333	0.5	1	1	1	2	2	0.94372	0.1155
K5	0.333	0.5	1	1	1	2	2	0.94372	0.1155
K6	0.25	0.333	0.5	0.5	0.5	1	1	0.52098	0.0638

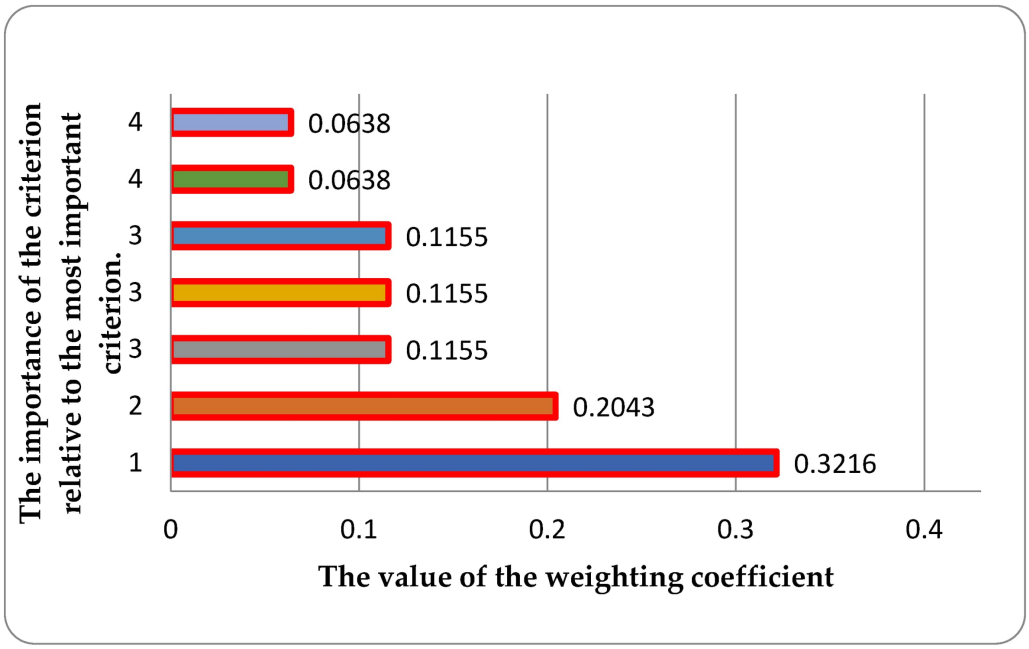


Figure 18. The importance of the criterion relative to the most important criterion.

Table 7. The values of individual criteria and the value of the comprehensive priority indicator.

The Name of the Substation	K1	K2	K3	K4	K5	K6	K7	Comprehensive Priority Indicator
A	0.902	0.746	0.600	0.393	0.418	0.080	0.132	0.750
B	0.037	0.006	0.871	0.669	0.947	0.411	0.089	0.496
C	0.966	0.205	0.675	0.680	0.450	0.354	0.115	0.275
D	0.878	0.776	0.252	0.402	0.318	0.129	0.451	0.762
E	0.910	0.585	0.885	0.580	0.764	0.460	0.098	0.398
F	0.306	0.758	0.208	0.862	0.726	0.701	0.325	0.324
G	0.058	0.313	0.034	0.877	0.876	0.702	0.312	0.600
H	0.518	0.377	0.276	0.083	0.266	0.783	0.451	0.560
I	0.373	0.984	0.116	0.260	0.400	0.378	0.351	0.376
J	0.759	0.599	0.246	0.497	0.413	0.309	0.671	0.598

Table 8. Prioritized list of substations to be converted to resistive grounding.

Priority Number	The Name of the Substation	Comprehensive Priority Indicator
1	D	0.762
2	G	0.600
3	J	0.598
4	A	0.575
5	H	0.560
6	B	0.496
7	E	0.398
8	I	0.376
9	F	0.324
10	C	0.275

Table 9. Problems of transitioning to resistive neutral grounding and solutions.

Problem	Nature of the Problem	Solutions
Consumer disconnection during single-phase earth faults	With low-resistance grounding, every single-phase earth fault leads to line disconnection	Backup power sources
High costs for organizing grounding	Significant capital investments required	Phased transition
Need to replace/reconfigure protection and automation systems	Existing protections are not designed for resistive mode	Replacement with microprocessor-based protection units
Selecting the optimal resistor resistance	Resistance must provide a compromise between current and overvoltages	Consider network topology, reserve availability, overhead lines, etc.
Ensuring thermal withstand of the resistor	The resistor must withstand the fault current during the protection operating time	Selection of resistors with appropriate characteristics

One of the pressing issues in the transition to resistive grounding is that grounding modes are changed sequentially. Most substations are interconnected, and some consumers may be supplied from one substation as the primary source and from another as the backup source. The transition to resistive grounding will mean that adjacent substations have different grounding modes. If power from the primary source is interrupted for any reason, the backup source, which has a different grounding mode, will be activated. However, the protection systems are configured to operate under a resistive grounding mode. If the grounding mode changes to another type, for instance, from resistive to isolated, the protection may fail to operate in the event of single-phase earth faults (SPEFs). As for microprocessor-based relay protection devices, they can be configured so that the protection schemes and settings automatically switch to those intended for an isolated neutral grounding mode. However, this problem is especially pronounced when a substation is equipped with legacy electromechanical relays, whose settings can only be changed manually. In this case, ensuring the correct operation of the relay protection requires adjusting a significant number of electromechanical relays, which is a highly labor-intensive

task. Therefore, the process of transitioning to resistive neutral grounding must take into account the issues currently associated with power generation in distribution networks.

The causes of NGR failures during the conversion to cable networks are examined in [68]. It is shown that an increase in the capacitive fault current creates additional thermal and mechanical loads on the resistors, necessitating their recalculation. Using a 10 kV cable line as a case study, it is demonstrated that resistive neutral grounding reduces the overvoltage factor during SPEFs and ensures the reliable operation of zero-sequence protection. It is recommended to use low-resistance NGRs for networks with high capacitive currents.

7. Conclusions and Future Directions

This paper indicates that SPEFs remain the dominant type of fault in medium-voltage networks, and their consequences and the feasibility of locating them depend critically on the neutral grounding mode adopted. Each of the considered neutral grounding modes has specific advantages (simplicity, current limitation, overvoltage limitation, selectivity) and disadvantages (ferroresonance risks, tuning complexity, high currents, detection problems).

It is established that the isolated neutral, which is traditional in Russia and used in approximately 80% of cases, causes severe overvoltages due to arcing, complicates the determination of the faulted section, and poses a danger to personnel. The compensated neutral effectively reduces the fault current but requires complex automatic tuning systems. Resistive grounding, by contrast, enables simple and reliable selective protection based on the active current component and limits overvoltages. The combined mode (ASC + shunt resistor) is recognized as the most flexible, since it provides short-term operation during a fault with arc compensation, followed by selective tripping via resistor shunting.

It is noted that NGR condition monitoring is an important objective. The paper justifies the need for continuous NGR monitoring, since a latent failure drives the network into an unintended operating mode, rendering existing protections inoperative. The conducted analysis showed that passive and active methods are individually of limited effectiveness. It is concluded that only combined methods integrating active and passive approaches are capable of providing continuous and reliable NGR monitoring.

Since the simultaneous conversion of all substations to resistive grounding is impossible, an algorithm for prioritizing the sequence of substation conversions to resistive grounding is proposed. The approach is based on calculating a comprehensive priority indicator using the pairwise comparison method. This allows various factors (the importance of consumers, availability of backup supply, type and condition of equipment) to be taken into account and enables ranking of substations for conversion to resistive grounding.

Thus, the choice of neutral grounding mode should result from a multicriteria technical and economic analysis. The choice depends on whether the network is predominantly overhead or cable, on the proportion of transient faults, on the capacitive current, on the availability of backup power supply, on the protection settings, and on other parameters.

Future research will focus on the development of intelligent systems for continuous monitoring and diagnostics of neutral grounding resistors. A promising direction is the integration of the acquired data (resistance, current, temperature, and humidity) with digital twin and Industrial Internet of Things (IoT) technologies to model degradation processes and predict the remaining useful life (RUL) of the equipment. To improve prediction reliability, it is advisable to use machine learning and explainable artificial intelligence methods, which will enable the identification of hidden wear patterns and make the logic of the algorithms transparent to operational personnel. Regarding the control of neutral grounding modes, a promising direction is the development of adaptive tuning algorithms for arc-suppression reactors that take into account the dynamics of

harmonic distortion from distributed generation and active consumers, as well as further improvement of the methodology for prioritizing the conversion of 6–10 kV networks to resistive grounding by supplementing the comprehensive priority indicator with additional individual criteria to improve the accuracy of the methodology.

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