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A Design Guide to Neutral Grounding of Industrial Power Systems

THE PROS AND CONS OF VARIOUS METHODS

NEUTRAL GROUNDING OF INDUSTRIAL POWER SYSTEMS has always been a controversial topic. Historically, systems with ungrounded neutral were dominant because of the service continuity with a ground fault on the system. This resulted in high system availability because there was no need to trip after the first ground-fault inception. However, as industrial power systems became more complex,
transient overvoltage during a ground fault became more severe, making ungrounded-neutral systems less attractive. On the contrary, the ability of grounded-neutral systems to limit overvoltages made them more popular. Over time, ungrounded systems in North America started to disappear, except legacy systems, and almost all new industrial systems are designed with grounded neutral. With myriad grounding methods, the question is which is the most appropriate method to use? Each method has its pros and cons, making the choice of the appropriate one dependent on the application. For each grounding method, this article presents a brief description of selection criteria used for evaluation and their pros and cons.

**Challenges with Ungrounded Systems**

In the early days of industrial power systems, the convention was to use ungrounded systems. Back then, systems were small enough that ground faults, which constituted the majority of faults, were self-extinguishing [1]. Hence, service continuity was guaranteed, and therefore, ungrounded systems were more favorable. With the continuous growth in the size and complexity of electrical systems, substantial steady-state and/or transient overvoltages started developing on unfautled phases, causing neutral-voltage instability.

During a line-to-ground fault, the voltage stress imposed on the insulation of the healthy phases can lead to an insulation failure, escalating the fault to a double line-to-ground fault. The fault escalation is attributed to the neutral-voltage instability because of the significant increase in the neutral voltage to ground (during normal operation, neutral voltage to ground is zero). Fault escalation was constantly observed on ungrounded industrial power systems [2]. Therefore, the majority of new industrial power systems are grounded systems, where an intentional connection of the system’s neutral to ground is made.

Two methods can be employed to connect the system’s neutral to ground: a direct connection, known as **solidly grounding**, or a connection via impedance, known as **impedance grounding**. Impedance grounding is further divided into three subcategories based on the nature of the device used to connect the system’s neutral to ground: resistance grounding, reactance grounding, and ground-fault neutralizer (also known as tuned-reactance grounding or Peterson coil grounding). Resistance and reactance grounding can either be low or high according to the permitted magnitude of the ground-fault current.

As neutral-grounded systems became the standard practice in North America, the challenge for system designers was to choose the most appropriate grounding method for the application. In other words, the question became should the system’s neutral be connected directly to ground with no deliberate impedance (i.e., solidly grounded), or should a grounding device (i.e., an impedance) be used to connect the system’s neutral to ground? If impedance grounding is selected, then what type (i.e., low- or high-resistance grounding, low- or high-reactance grounding, or ground-fault neutralizer) and what value should be used?

This article tries to answer those questions to help engineers understand the performance differences between grounding methods and then select the most appropriate method for the application at hand.

**History of Neutral Grounding**

**Neutral-Voltage Instability Problem**

During normal operation of a balanced ungrounded three-phase system, the system’s neutral is always at ground potential [2]. In this case, neutral is loosely connected to ground through the system’s line-to-ground capacitances. These capacitances are inherent in insulated cable circuits and open-wire distribution circuits. Power transformers and rotating machines have a significantly smaller contribution.

When a line-to-ground fault occurs, the voltage of the faulted phase collapses. Depending on the fault impedance, the phase voltage can get close to ground (zero) potential. As a result, the voltage of the system’s neutral elevates, assuming a significantly higher voltage with respect to ground. This neutral-voltage instability results in overvoltages to appear on unfautled phases. Those overvoltages originate because of the capability of the line-to-ground capacitances to hold any charge (and thus voltage) placed upon them, up to the point at which the system’s insulation breaks down because of the increased voltage stress.

**Historical Development of Neutral Grounding**

As mentioned before, earlier industrial three-phase power systems were operated as delta ungrounded because only three conductors were required to operate three-phase loads. Ungrounded systems permitted continuous operation of the system under the first ground fault. Accordingly, an unscheduled service interruption after the inception of the first line-to-ground fault was not required. This was a huge advantage for an operator of a continuous-process plant [2].

In the 1940s, ungrounded systems suffered from multiple insulation failures under particular conditions. Further investigation revealed that, when a ground fault occurred on one phase, the unfaulted phases experienced steady-state and/or transient overvoltages to ground. Those overvoltages were not only the main cause of insulation failures but also became hazardous to personnel. Motor-winding insulations were particularly damaged by those overvoltages. Oftentimes, a motor insulation failure resulted in considerable motor-core damage requiring expensive repairs.

As a remedy for the overvoltage problems on new designs, delta-wye transformers with solidly grounded neutrals were introduced to replace the conventional delta-delta connected transformers. On the existing delta-delta ungrounded systems, the practice was to connect one of its delta corners or the midpoint of one phase winding to
ground. Solidly grounded systems successfully eliminated the overvoltage problems. However, they suffered from severely high ground-fault currents that approached the three-phase fault levels, (1,000–20,000 A). This could result in devastating burn-downs of particular equipment, creating hazards to personnel.

The next step forward was the introduction of low-resistance grounded systems to limit the excessive ground-fault currents encountered in solidly grounded systems. The idea was to use a grounding resistor in such a way that the ground-fault current was limited to a value between 50 to 1,000 A, with 400 A being a typical value.

For low-resistance grounding to operate in a safe manner, the faulted circuit must be removed from service at the occurrence of the first ground fault. Service loss was of great concern to the operators and designers of continuous-process plants. To address this concern, high-resistance grounding was introduced.

High-resistance grounding is realized by inserting a high resistance between the system's neutral and ground. This limits the ground-fault current to a safe value approaching that of an ungrounded system. Therefore, a high-resistance grounded system can continue to operate with the first ground fault uncorrected, significantly improving service continuity. The first ground fault must be located and removed immediately after its inception to prevent it from escalating to a phase-to-phase fault. This immediate fault clearing is crucial for ground faults in motor and generator windings.

**Methods of Neutral Grounding**

In general, any neutral-grounding method requires a connection of the system's neutral to ground at one or more points. According to the nature of the grounding connection, those methods can be divided into two categories: solid grounding and impedance grounding. Depending on the impedance type, impedance grounding can be further divided into resistance grounding and reactance grounding. In all those cases, the generator or transformer impedance being grounded is in series with the grounding device. The different methods of neutral grounding and their zero-sequence equivalent circuits are shown in Figure 1 [3].

With a few exceptions, some form of grounding is generally required by the National Electrical Code (NEC). Grounding requirements for different applications are described in the NEC. There are two main reasons for neutral grounding [3]:

1) Controlling the voltage-to-ground level (within predictable limits) to limit the voltage stress on the phase conductors' insulation. Moreover, voltage control reduces the shock hazard to personnel who may come in contact with live conductors.

2) Providing a low-impedance path to the ground-fault current. This enables the ground-fault relays to detect any unwanted connection between the phase conductor(s) and ground and to initiate a trip signal to clear the fault.

**Neutral-Grounding Devices**

IEEE Standard C57.32 [4] is a revision of IEEE Standard 32 that has been used for decades. IEEE Standard 32 was developed by the Neutral Grounding Subcommittee of the C62 Surge Protective Devices Subcommittee. IEEE Standard 32 had become outdated, with the last real revision occurring in 1971. Since many of the devices described in the standard were best covered in the IEEE Transformers Committee C57 standards, IEEE Standard 32 was moved there for revision with a change in the title to IEEE Standard C57.32. The new standard covers neutral-grounding resistors (NGRs), neutral-grounding reactors, ground-fault neutralizers, neutral-grounding transformers, and combination systems. More modern calculation methods and current technology are included. Each device has its own section now, rather than many common tables that required a lot of going back and forth within the standard.

Resistance, reactance, and ground-fault neutralizers are discussed in the section “Mathematical Analysis of Neutral-Grounded Systems” [4]. Those devices are connected into neutral of a grounded wye system. Neutral-grounding transformers are used to derive a neutral from an ungrounded system. A combination system consists of any configuration of the previously discussed devices together, such as a grounding transformer with an NGR connected to neutral of the transformer.

**Grounding Transformers**

Grounding transformers are used to derive a neutral when one has an ungrounded system. These are often used to ground generator outputs to a power system, such as standard power generation, wind farms, or solar farms. They are either wye-delta or zigzag-grounding transformers. The parameters of the grounding transformer should be specified with the required system voltage, basic insulation level, continuous neutral current, fault current magnitude, duration of the fault current, and the required ohms per phase. The ohms-per-phase value may limit the entire amount
of the ground-fault current or a portion of the expected current. Other system impedances and possible combinations with grounding resistors or reactors in neutral may comprise the balance of the impedance for fault-current limitation. Grounding transformers are subject to repetitive system overvoltages as well as thermal and mechanical stresses during the fault. The fault durations usually last for many seconds or even minutes. A grounding transformer must be designed with this in mind versus a standard power or distribution transformer, which is usually only required to handle a fault condition for a matter of cycles or maybe up to 2 s. IEEE Standard C57.32 gives a limit of 3% continuous current versus the fault current, although higher continuous-current percentages may be specified [4].

Wye-Delta Grounding Transformer
This is often used for either simplicity or when the delta winding is used for station service. It is a rather standard transformer as far as the vector relationship goes. If a fault occurs on a phase of the ungrounded system to which the wye winding is connected, it conducts through neutral and into the three phases of the transformer winding, while the transformed fault current circulates in the delta winding. A faulted ungrounded system with a wye-delta grounding transformer is shown in Figure 2 [3].

While it is a more routine transformer construction, it still must be designed for the more stressful requirements of a grounding transformer. Often, a user will mistakenly assume that he or she can purchase a standard wye-delta transformer for this purpose. This may work for some time, but it will not have the useful life of a properly designed grounding transformer. The negative to a wye-delta transformer is that the electrical kilovoltampere and physical kilovoltampere (based on the coil parts) are the same, unlike a zigzag grounding transformer. So wye-delta is more expensive than a zigzag grounding transformer.

Zigzag Grounding Transformer
It has six coils (two on each limb), as shown in Figure 3 [3]. Each limb has two identical coils (a1 and a2) that are wound in the opposite direction. The first coil on each limb is connected conversely to the second coil on the next limb. The other terminals of the second coils are all connected to form neutral. The voltage to neutral (i.e., phase voltage) is the phasor sum of the voltage across two coils from the opposite phases. Phase a voltage, e.g., is the sum of the voltage across coils b1 and c1. As shown in Figure 4, the voltage across each coil is one-third of the system's line-to-line voltage. The same current flows in all coils.

During a ground fault, the fault current flows up through neutral as shown in Figure 3 [3]. The fault current distributes itself through the three phases by either direct electrical connection or by induction through the coils on the same limb of the transformer core.

Because of the physical construction of a zigzag grounding transformer, the physical kilovoltampere is only 57.7% (1/√3) of its electrical kilovoltampere. Therefore, the zigzag grounding transformer is physically smaller than the wye-delta grounding transformer. To explain this concept, assume a 13.8-kV system with a 300-A continuous neutral current (i.e., 100 A per phase). For a standard wye-delta transformer, the electrical and physical kilovoltampere are equal to \( \sqrt{3} \times 13.8 \text{ kV} \times 100 \text{ A} = 2,390 \text{ kVA} \). For a zigzag grounding transformer, the electrical kilovoltampere is the same (2,390 kVA). Recall that all coils \((a_1, a_2, b_1, b_2, c_1, \text{ and } c_2)\) are identical and rated at 4.6 kV (one-third of the system voltage). Therefore, the physical kilovoltampere is \(3 \times 4.6 \text{ kV} \times 100 \text{ A} = 1,380 \text{ kVA} \). The ratio of the physical kilovoltampere to the electrical kilovoltampere is 0.577. This is why it is recommended that the transformer impedance be specified in ohms per phase. If specified
in per unit impedance, there could be confusion about the base kilovoltampere (whether electrical or physical kilovoltampere).

A zigzag grounding transformer is not a real transformer; its function is not to transfer power from a primary power source to a secondary one but to act as a reactor and limit the fault current. This is another reason the impedance should be specified in ohms per phase, similar to a reactor.

**Fundamentals of Neutral Grounding**

**Design Criteria**

It is important to understand that the selection of a neutral-grounding method is a tradeoff: there is no one size fits all. The goal is to select a grounding method that best suits the application. The selection involves the type and magnitude of the grounding device to be inserted between neutral and ground.

For any given system, there are four factors that should be evaluated before selecting a grounding method [1]:

1) the sensitivity and selectivity of the ground-fault protection system
2) the permissible magnitude of the ground-fault current
3) the required degree of the surge-voltage protection
4) the limitation of system transient overvoltages.

To analyze the effect of any grounding method, a three-phase phasor diagram and a single-phase equivalent circuit are used. A phasor analysis is used to develop the relationship between voltages and currents flowing through different phases during normal and faulted system operation. On the other hand, a single-phase equivalent circuit provides a better understanding of the overvoltage-inducing mechanisms (transient and/or steady state) and the effect of different neutral-grounding methods on fault current. Therefore, both methods are complementary and should be used together to develop a full understanding of the power system’s performance.

**Single-Phase Equivalent Circuit**

A simplified three-phase power system is shown in Figure 5 [5]. The three-phase cable carrying power from the source, which is usually a transformer secondary, to the load is represented by a set of three inductive reactances, $X_l$ (also includes the transformer secondary reactance). Since phase conductors are physically in parallel with the earth, a distributed capacitance exists between each phase conductor and ground. This distributed capacitance is modeled by the capacitive reactance $X_c$ (the suffix 0 indicates the zero-sequence component). To simplify the analysis, the phase capacitive reactances to ground are assumed to be balanced. It is worth mentioning that the phase-to-phase capacitances are not modeled because they have no contribution to the ground-fault current. The three-phase voltage sources shown are the Thevenin equivalent voltage of the system.

During the normal operation of the power system shown in Figure 5, the capacitive reactance acts like a load, and current is always flowing through it. This current is referred to as the charging current. $X_c$ is often neglected because it is several orders of magnitude larger than $X_l$. Typical values for $X_l$ and $X_c$ are 0.19 and 1,200 $\Omega$, respectively. Therefore, the distributed capacitances’ connection points can easily be moved before the inductive reactance (i.e., between the voltage sources and $X_l$).

A further simplification can be made to the circuit by obtaining the Thevenin equivalent reactance of the parallel combination of the three $X_c$ (i.e., $X_c/3$). The simplified circuit is shown in Figure 6(a) [5]. Because this is a balanced three-phase circuit, the single-phase equivalent circuit shown in Figure 6(b) [5] can be used to analyze the system.

Note that $V_F$ represents the line-to-ground voltage of the faulted phase. For instance, to model a line-to-ground fault on phase $C$, $V_F$ equals the voltage of phase $C$ to ground. A line-to-ground fault of impedance $Z_F$ is represented by connecting $Z_F$ between the output terminals of Figure 6(b) [5].

**Mathematical Analysis of Neutral-Grounded Systems**

A good understanding of the performance and shortcomings of ungrounded systems provides the background...
needed for analyzing the impact of a grounding device. Therefore, ungrounded systems will be covered briefly before starting the analysis of various grounding methods.

**Ungrounded Systems**

Although neutral of an ungrounded system has no intentional connection to ground, the system’s distributed capacitance establishes such a connection. Therefore, an ungrounded system is technically a capacitive-grounded system, as shown in Figure 7(a) [3].

During normal operation of a balanced three-phase system, the per-phase capacitive charging current, \( I_{C0} \), and the phase voltages to ground are also balanced (i.e., equal magnitudes and 120° displacement). A three-phase ungrounded system and the phasor diagram are shown in Figure 7(a) and (b), respectively [3]. Note that neutral of the distributed charging capacitances is connected to ground. This has the effect of holding the system’s neutral at ground potential.

In case of a line-to-ground fault, there will be no current flowing through the faulted-phase capacitance to ground (since no potential difference across it now exists, assuming a solid short circuit). Because of the collapse of the faulted-phase voltage to zero, the voltage of the system’s neutral elevates from ground potential to the phase potential. Therefore, the voltage across the two healthy phases for the distributed capacitance to ground will increase from a line-to-ground level to a line-to-line level. Accordingly, their capacitive charging currents will also increase by a factor of \( \sqrt{3} \).

Assume a ground fault on phase C, as shown in Figure 8(a) [3]. Now, the line-to-ground voltages have a 60° phase shift (instead of 120°). Therefore, the sum of the capacitive charging currents to ground (which also equals ground-fault current, \( I_c \)) is no longer zero. It has a magnitude of \( 3I_{C0} \) (i.e., three times the original per-phase charging current) and leads the original neutral-to-ground voltage \( (V_{NC} = -V_{CN}) \) by approximately 90° as shown in Figure 8(b) (remember that the phase C voltage is zero) [3].

Referring to Figure 6(b) [5], the only impedance limiting \( I_c \) is \( X_{C0}/3 \), which is typically large. The magnitude of the ground-fault current is low enough that automatic tripping is not required. Therefore, system availability is high, which is very attractive in mission-critical applications such as refineries and auxiliary systems in powerhouses.

Ironically, the main advantage of ungrounded systems (i.e., service continuity during the first ground fault) is itself the main problem. While the magnitude of the ground-fault current may not necessitate tripping, the two healthy phases experience abnormal overvoltages. Such overvoltages usually result in a second ground fault (i.e., escalating the existing line-to-ground fault to a double line-to-ground fault with much higher fault-current magnitude).

The overvoltages induced are steady state or transient. Steady-state overvoltages are usually caused by ground faults or contact with high-voltage systems, whereas transient overvoltages are caused by intermittent ground faults and switching surges. It is worth mentioning that steady-state overvoltage does not imply a long duration of time. Usually, the duration of the overvoltage is quite limited because of insulation(s) failure, resulting in a second line-to-ground fault or a double line-to-ground fault. In this case, protective devices will respond to isolate the faulted
This is a serious problem for solidly grounded generators and motors because the stator damage could leave the machine unrepairable. A greater arc-flash hazard and higher earth potential gradients for employees at the workplace are two other problems. Therefore, it is important to clear ground faults in the shortest possible times. This creates another problem because the interruption of such high fault currents imposes so much stress on circuit breakers, hence shortening their lifetime.

Despite these problems, there are applications where the use of a solidly grounded system is advantageous. The degree of grounding provided in the system is typically used to evaluate the benefits of a solid connection to ground. More details on this topic and on the concept of effectively grounded systems can be found in [2].

**Resistance-Grounded Systems**

Grounding neutral via a resistance is a common practice in North America, especially for industrial power systems. The equivalent circuit of a resistance-grounded neutral system is shown in Figure 10 [5]. Resistance grounding may either be low or high. The distinction is based on the magnitude of the ground-fault current permitted to flow. Both low- and high-resistance grounding are designed to limit the transient overvoltages to 250% of the system’s voltage. Because of the elevation of the neutral voltage with respect to ground, resistance-grounded systems must be protected using surge arresters rated for ungrounded systems [1].

**Low-Resistance Grounded Systems**

In this case, the NGR has a value that is much smaller than $X_{co}/3$ and much larger than $X_L$. For example, on a 13.8-kV system, a $X_{co}/3$ magnitude is 1,000–2,000 $\Omega$, while $X_L$ is a fraction of an ohm [5]. For such a system, a typical value of the NGR is 20 $\Omega$.

Since $X_{co}/3 \gg R \gg X_L$, the equivalent impedance of the circuit in Figure 10 is approximately the NGR. Also, the system’s total charging current ($3I_{co}$) is much smaller than the NGR current ($I_G$) and, therefore, can be neglected. So the fault current $I_G \approx I_R = V_F/R$. This approximation is used to size the NGR ($R = V_{in}/I_{o}$), where $V_{in}$ is the line-to-neutral voltage and $I_{o}$ is the desired ground-fault current. This approximation results in the following two observations:

- The magnitude of $I_G$ is determined almost exclusively by the NGR, and it is typically limited to a value close to the load current. For example, in a 13.8-kV system, a typical 20-$\Omega$ resistor will limit the value of $I_G$ to 400 A.
- The equivalent circuit of Figure 9 is predominantly resistive. Therefore, switching the transients associated with clearing the ground faults is not significant.

Low-resistance grounding is used extensively in medium-voltage systems of 15 kV and below, especially on large rotating machinery. Low-resistance grounding is

**Solidly Grounded Systems**

Connecting the system’s neutral directly to ground with no intentional impedance (i.e., zero impedance) has the effect of shorting out the system's charging capacitances, as shown in Figure 9 [5]. The downside of shorting $X_{co}/3$ is that the only impedance controlling the magnitude of the ground-fault current is $X_L$, which is typically small. Accordingly, the system will experience high single-phase-to-ground-fault currents with a magnitude close to the three-phase ground-fault current. In some extreme cases, the magnitude of the single-phase ground-fault current exceeds the three-phase ground-fault current. This condition exists when the system’s zero-sequence reactance is smaller than its positive-sequence reactance (i.e., $X_0 < X_L$). Such a condition is typically encountered in solidly grounded generators and in close electrical proximity to wye-connected transformer banks.

The flow of high ground-fault currents has a few adverse consequences. Severe burn damage at the point of the fault is always associated with such high currents.

![Figure 9](image1.png)

**Figure 9.** The equivalent circuit of a solidly grounded system [5].

![Figure 10](image2.png)

**Figure 10.** The equivalent circuit of a resistance-grounded system [5].
popular in medium-voltage systems because of the dam-
age reduction to expensive equipment, since the ground-
fault current is limited to hundreds, instead of thousand, of amperes. Another application of low-resistance ground-
ing is found in mining systems supplying portable equip-
ment via trailing cables.

High-Resistance Grounded Systems
The value of the resistor is selected such that the magni-
tude of the NGR current \( I_o \) is equal to or slightly greater
than the total capacitance charging current \( 3I_{c0} \). Accord-
ingly, the value of the NGR is almost equal to or slightly
smaller than the magnitude of the system’s total charging
capacitive reactance \( (R \leq X_{c0}/3) \). Therefore, the magni-
tude of the ground-fault current is
\[
I_G = \sqrt{I_R + (3I_{c0})^2} \approx \sqrt{2} I_R = \sqrt{2} V_F/R,
\]
where the size of the NGR in terms of system param-
eters is \( R \geq V_n/3I_{c0} \) or, in terms of the fault current \( I_o \),
\( R \geq \sqrt{2} V_n I_dI_c \).

In low-voltage systems, the capacitive charging cur-
rent is usually on the order of 1–2 A. Therefore, a high-
resistance grounded system designed using the described
criterion will result in a total ground-fault current of 2–3 A
(5 A is a typical value).

Accordingly, immediate tripping of ground faults is not
required because of the low ground-fault current
magnitude. The fault location and scheduled service inter-
ruption must be determined to clear the fault. Therefore,
high-resistance grounding improves the system’s availabil-
ity. In other words, the main advantage of ungrounded
systems (i.e., service continuity) is restored. Typically, the
protection philosophy used for high-resistance grounded
systems is detection and alarm, rather than immediate tripping.

The main disadvantage of high-resistance grounded
systems is a result of its design criterion (i.e., \( R \leq X_{c0}/3 \)).
On the basis of this assumption, the system’s distributed
charging capacitance can no longer be neglected in the
equivalent circuit analysis. The net impedance between N
and G is (assuming \( R = X_{c0}/3 \))
\[
R(-jX_{c0}/3) \quad \frac{R}{R - jX_{c0}/3} = \frac{R}{2(1 - j)} = \frac{R}{\sqrt{2}} e^{-35^\circ} = \frac{R}{\sqrt{2}} \angle -45^\circ.
\]

The magnitude of the neutral-to-ground equivalent impedance
is significantly large. Therefore, a significant amount
of voltage will appear across this impedance
during a line-to-ground fault. This voltage will have the
steady-state value of the system’s line-to-neutral voltage.
In other words, the voltage of the system’s neutral is ele-
vated to the line-to-ground voltage. The voltage-to-ground
level of the two unfaulted phases assumes the value of the
line-to-line system voltage.

Such significant displacement in the voltage of the
unfaulted phases during ground faults requires special
consideration when selecting insulation for power cables,
if the application is an alarm only (i.e., automatic fault
clearing is not enabled). Typically, the insulation capa-
bility of power cables is selected assuming that the phase-
to-ground voltages will not suffer from being significantly
unbalanced for prolonged intervals. If the application
requires fault alarming, rather than immediate tripping,
cables with a higher-voltage rating must be specified.

One of the main advantages of high-resistance ground-
ing is the rapid discharge of any trapped voltage across
the system charging capacitance, \( X_{c0}/3 \). When the con-
dition \( R \leq X_{c0}/3 \) is satisfied exactly, the circuit between
N and G becomes a resistance–capacitance circuit
with a time constant of 1 electrical radian (\( \approx 2.7 \) ms).
Historically, systems with ungrounded neutral suffered
from repetitive restriking voltage because of gradual volt-
age building up across \( X_{c0}/3 \) [2]. This condition resulted
in devastatingly high phase-to-neutral voltages. With a
time constant of 2.7 ms, it is practically impossible for this
restriking voltage phenomenon to occur [5].

Reactance-Grounded Systems
In this case, the system’s neutral is connected to ground
via a reactor, as shown in Figure 11 [5]. Similar to resis-
tance-grounded systems, the magnitude of the ground-

\[
G \quad \frac{\text{Figure 11. The equivalent circuit of a reactance-grounded system}}{[5].}
\]
since the magnitude of the inductive reactance is much smaller than the system capacitive reactance, \(X_{3c0}/3\). Therefore, for all practical purposes, \(X_{3c0}/3\) can be neglected.

To prevent serious transient overvoltages, the magnitude of the ground-fault current should be at least 25% (i.e., \(I_{3c0} = \frac{1}{4}I_3\)) and preferably 60% (i.e., \(X_{3c0} = \frac{1}{10}I_3\)) of the three-phase fault current, where \(X_0\) is the sum of the source's zero-sequence reactance plus three times the grounding reactance.

In general, low-reactance grounding is not an alternative to low-resistance grounding because the ground-fault current permitted in reactance-grounded systems is considerably higher than that permitted in resistance-grounded systems.

Typically, the cost of neutral-grounding reactors increases as their inductance decreases. This relationship is valid to an inductance threshold, below which it is not economically feasible to build reactors. Therefore, it may not be practical to design a low enough reactance-grounded system. Low-reactance grounding is relatively uncommon and is usually reserved for applications where there is a need to increase the system's zero-sequence reactance [3].

High-Reactance Grounded Systems
As the name implies, high-reactance grounding is realized by installing a high-value inductive reactance between the system's neutral and ground. In this case, the magnitude of the ground-fault current is 5–25% of the three-phase fault current. In practice, high-reactance grounding is not used because of excessive overvoltages.

Tuned-Reactance-Grounded Systems (Ground-Fault Neutralizer)
A ground-fault neutralizer is an adjustable reactor connected between the system's neutral and ground, as shown in Figure 12 [3], where resistance \(r\) is depicting reactor losses. As mentioned previously,
a ground-fault neutralizer is a special case of high-inductance grounding. Similar to low-reactance grounded systems, this connection creates a parallel LC circuit between neutral and ground. In this case, however, the system’s capacitive reactance, \(XC_0/3\), cannot be neglected because its value is comparable to the inductive reactance of the ground-fault neutralizer. This LC combination can be used to create a parallel resonance condition, giving this grounding system its most attractive characteristic.

The reactor \(X_R\) in Figure 11 is selected, or tuned, such that it resonates with the distributed capacitance \(XC_0/3\) of the system. Therefore, the resultant ground-fault current is predominantly resistive in nature and with low magnitude. Both the ground-fault current and the line-to-neutral voltage are in phase, and, therefore, their zero crossings occur simultaneously. This is important because ground faults occurring in air, e.g., insulation flashover, could be self-extinguishing.

The design criterion for a ground-fault neutralizer is \(X_R = XC_0/3\). This condition implies that the equivalent impedance between neutral and ground at the fundamental frequency is infinite, i.e., an open circuit exists between neutral and ground. In other words, a tuned-reactance-grounded system resembles an ungrounded

<table>
<thead>
<tr>
<th>Table 3. Pros and cons of neutral-grounding methods</th>
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<tbody>
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<td><strong>Pros</strong></td>
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| Ungrounded neutral | • Service continuity up to 1 h, as permitted by the NEC, is possible, thus allowing a planned shutdown of electrical equipment.  
• In 240 V or lower, a 60-Hz intermittent ground fault may be self-extinguishing and not escalate to arcing multiphase faults.  
• The ground-fault current due to a first ground fault is of little danger to human safety because of its low magnitude (up to 8 A at 4.16 kV or lower). |
| Solidly grounded neutral | • Transient overvoltages associated with creating or clearly ground faults are controlled to within reasonable limits.  
• The method supports single-phase to ground loads. |
| Low-resistance grounding | • Ground-fault currents are limited to modest values by the ohmic rating of the resistor.  
• There is no significant concern for transient overvoltages associated with ground faults. |
| High-resistance grounding | • The fault current is limited to a slightly higher value than the system-distributed charging current.  
• The first ground fault does not require automatic tipping.  
• Transient overvoltages are reduced to 250% of nominal system voltage.  
• A signal tracing or pulse system will facilitate locating a ground fault.  
• The method eliminates flash hazards to personnel associated with high ground-fault currents.  
• The need for and expense of coordinated ground-fault relaying is eliminated. |
| Tuned-reactance grounding | • Design criterion must be met exactly, which requires returning if the system’s distributed capacitance changes due to switching.  
• The method includes noneffective grounding, which requires special considerations when applying surge protection.  
• The method does not support single phase-to-ground loads. |

| NEC, is possible, thus allowing a planned shutdown of electrical equipment.  
• In 240 V or lower, a 60-Hz intermittent ground fault may be self-extinguishing and not escalate to arcing multiphase faults.  
• The ground-fault current due to a first ground fault is of little danger to human safety because of its low magnitude (up to 8 A at 4.16 kV or lower). |
| Solidly grounded neutral | • Transient overvoltages associated with creating or clearly ground faults are controlled to within reasonable limits.  
• The method supports single-phase to ground loads. |
| Low-resistance grounding | • Ground-fault currents are limited to modest values by the ohmic rating of the resistor.  
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• The method does not support single phase-to-ground loads. |
system during normal operation. When the first line-to-ground fault occurs, the ground-fault current will have no path to flow through (remember that at the fundamental frequency, the connection between neutral and ground is an open circuit). As a result, 1) fault-point damage, 2) mechanical stress on current-carrying conductors, 3) thermal stress, 4) earth-potential gradients, and 5) arc flash hazards do not exist [5].

Unlike an ungrounded system, an electrical connection with predefined impedance exists between neutral and ground of a tuned-reactance-grounded system, at all nonfundamental frequencies. Therefore, tuned-reactance-grounded systems do not suffer from those problems related to nonfundamental frequencies (i.e., transient response and overvoltages) that ungrounded systems experience. The main disadvantage of this system is that, to satisfy the design criterion \( X_g = X_C/3 \) at all times, complex and expensive controls are required to match any changes in the power system because of switching or reconfiguration.

**Comparison of Neutral-Grounded Systems**

The design of a neutral-grounding system is always a compromise between competing objectives, such as ground-fault current magnitude or overvoltages on unfaul ted phases. Therefore, it is important to understand the operational characteristics, features, and pros and cons of each method.

**Operational Characteristics**

The selection of the appropriate neutral-grounding method is based on a variety of considerations, including operational characteristics as summarized in Table 1 [2].

**Qualitative Comparison**

Table 2 presents a qualitative comparison of the different neutral-grounding methods [2]. Although the merits of each characteristic feature relative to the grounding method cannot be evaluated in only two (black or white) categories, this form of presentation should be helpful as an initial orientation. The final selection should recognize pertinent weighting factors and application limitations pertaining to the system at hand. The reader is encouraged to refer to [2] for more details.

**Pros and Cons**

To determine which grounding method to use, it is important to understand the pros and cons of each method. Table 3 summarizes the pros and cons of the most common neutral-grounding methods [3].

**Applications**

As mentioned previously, designing a neutral-grounded system is a tradeoff between conflicting objectives. Therefore, it is not possible to assume one set of universally acceptable criteria to design a neutral-grounded system.

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### Table 4. Applications of neutral-grounding methods [5]

<table>
<thead>
<tr>
<th>Grounding Method</th>
<th>Typical Applications</th>
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| Ungrounded neutral                     | • The method is generally not recommended on new systems.  
• The method may exist on legacy systems although a retrofit is usually recommended.  
• Marine systems may be a special case. |
| Solidly grounded neutral (effective grounding) | • The method is the preferred practice for high-voltage transmission systems.  
• The method is the preferred practice on medium-voltage utility distribution systems in North America.  
• The method is commonly applied on low-voltage systems serving single-phase-neutral loading.  
• The method is not recommended for medium-voltage distribution in industrial workplaces. |
| Low-resistance grounding                | • The method is the preferred practice for medium-voltage distribution in industrial workplaces.                                                |
| High-resistance grounding               | • The method is the preferred practice for unit-connected generator applications (with automatic tripping).  
• The method is commonly applied in continuous-process industrial applications, 5 kV and below, in conjunction with traceable fault technology.  
• The method may be used at higher voltages with automatic fault detection and tripping.  
• The method is the cost-effective retrofit for legacy ungrounded systems. |
| Low-reactance grounding                 | • The method is used as the solution for managing high ground-fault currents in substations.  
• The method is used as the solution for generator grounding to support single-phase loading.  
• The method requires extensive application engineering. |
| Tuned-reactance grounding               | • The method is rarely seen in North America today.  
• The method is commonly applied in medium voltage utility distribution applications in Europe and the United Kingdom. |
| Other practices—including corner of the delta and midpoint grounding | • These approaches have been used as retrofit solutions for legacy ungrounded systems. In general, these are compromise solutions and are not currently recommended practices. |
However, general practices and application trends can be summarized as shown in Table 4 [5].

Conclusions
With the availability of various neutral-grounding methods, it is important to understand the operational characteristics of each. The design and selection of the most appropriate grounding method is always a compromise between competing objectives. Therefore, performance requirements of the power system should be carefully evaluated to choose the most appropriate method.

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