ELECTRIC POWER RESEARCH INSTITUTE

Geomagnetically-Induced Current (GIC) Reduction Device Application Guide

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ABSTRACT

Solar disturbances can initiate a terrestrial geomagnetic disturbance (GMD) that can result in the flow of very low frequency geomagnetically induced currents (GIC) in power systems. These quasi-dc currents can cause part-cycle saturation of the power system's transformers, which can lead to a number of adverse consequences including potential damage to transformers, system voltage collapse, and misoperation of protection systems. One of the mitigation measures being considered within the industry is the use of GIC reduction devices (GRDs). GRDs are devices intended to reduce or eliminate the flow of GIC in particular transformers or transmission lines. Application of GRDs requires considerable technical diligence to ensure that the devices provide the desired function and do not introduce adverse impacts on the transmission system's equipment and reliability. This guide provides a comprehensive review of the factors critical to the specification and design of GRDs and the assessment of their impacts on the power system. This guide also details the technical studies that should be performed when GRD deployment is planned and specified.

Keywords
Geomagnetic disturbance
GMD
Geomagnetically induced current
GIC
GIC reduction devices
Solar storms

EXECUTIVE SUMMARY

Background

Solar disturbances can initiate a terrestrial geomagnetic disturbance (GMD) that can result in the flow of very low frequency geomagnetically induced currents (GIC) in power systems. These quasi-dc currents can cause part-cycle saturation of the power system's transformers, which can lead to a number of adverse consequences including potential damage to transformers, system voltage collapse, and misoperation of protection systems.

The Federal Energy Regulatory Commission (FERC) has directed the North American Electric Reliability Corporation (NERC) in Order 779 to develop mandatory standards for operational response to GMD events, and to perform assessments of system vulnerability to GMD. In response, NERC has developed standards EOP-010-1 and TPL-007-1, respectively, in response to the FERC mandates. The FERC order 779 requires that owners and operators of the Bulk Power System develop and implement a plan to "…protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event…" The FERC order further states that "…These strategies could, for example, include automatically blocking geomagnetically induced currents from entering the Bulk-Power System…"

The NERC Standard TPL-007-1, developed in response to FERC Order 779, requires development of a Corrective Action Plan if GMD impact studies indicate non-compliant performance. This standard references a list of appropriate GMD mitigating measures contained in the NERC GMD Task Force GMD Planning Guide. One of the suggested measures in the Planning Guide is the use of GIC reduction devices (GRDs). GRDs are devices intended to reduce or eliminate the flow of GIC in particular transformers or transmission lines. GRDs can take the form of neutral devices, connected between the neutral terminals of transformers and ground, or series devices installed on transmission lines.

Transmission systems in North America have conventionally been designed to be effectively grounded, and as a near-universal rule, the neutrals of wye-connected HV transformer windings have been solidly connected to ground without any intentional impedance. Effective grounding limits overvoltages and is critical to the proper function of protection systems. A neutral GRD inherently places impedance between the neutral of a transformer and ground. This impedance causes an elevation of the neutral voltage, and may result in or increase elevation of unfaulted-phase voltages during ground faults. Thus, the impacts on insulation coordination and overvoltage protection must be closely scrutinized.

Significant potential impacts of neutral GRDs include:

- Increasing voltages imposed on equipment, and potentially disrupting insulation coordination.
- Modification of fault current; increasing or decreasing current magnitude and shifting fault current phase angle, depending on the GRD impedance and design.
- Interfering with protective relaying schemes.

The potential for these impacts depends greatly on the type and design of the GRD, and how they are applied to the system.

Series GRDs are essentially series capacitors, but typically have much less impedance than a conventional series capacitor applied to enhance system transient and dynamic stability or redirect load flow. Unlike neutral GRDs, the industry has extensive experience with series capacitors. The low impedance of a series GRD, optimized for GIC blocking rather than line impedance compensation, results in less potential interaction with system performance than a conventional series capacitor [1].

Scope of Guide

Application of GRDs requires considerable technical diligence to ensure that the devices provide the desired function and do not introduce adverse impacts on the transmission system's equipment and reliability. This guide provides a comprehensive review of the factors critical to the specification and design of GRDs and the assessment of their impacts on the power system. This guide also details the technical studies that should be performed when GRD deployment is planned and specified.

The principal focus of this guide is on neutral GRDs, as this option has gained the greatest industry attention and is widely assumed to be a more economical solution than series GRDs. In contrast, series GRDs benefit from the extensive utility industry experience with series capacitors for impedance compensation. Because series GRDs represent a much more limited deviation from established practice, and are not receiving the same degree of consideration by the industry, the coverage of series GRDs in this guide is intentionally limited.

While GRDs may also provide mitigation of certain electromagnetic pulse (EMP) impacts caused by high-altitude detonation of nuclear weapons, the scope of this guide does not specifically address this application.

GRD Deployment and Rating

GRDs may be deployed to achieve mitigation of GIC flow in specific transformers, or to achieve system-wide objectives. In most cases, GRDs will be deployed at a certain subset of transformers or line, in order to obtain the greatest mitigation effectiveness for a given investment.

There are various objectives that can be chosen for a GRD deployment plan. Examples include:

- Reducing or eliminating GIC from particularly vulnerable transformers.
- Reducing GIC in all transformers to less than a prescribed threshold.
- Reducing the system-wide impacts of GIC
- Eliminating all GIC flow in the system's transformers

The plan for GRD deployment, including choices of the type of GRD and the system locations, depends on the overall objectives.

A GRD should be designed to reliably perform its intended function, and continue to perform this function through a defined range of system events without failure. GRD ratings that need to be addressed include:

- Steady-state quasi-dc voltage due to the GMD

- Steady-state alternating currents, including both fundamental and harmonic components
- Fault currents
- Other transient and temporary currents caused by switching events

These rating issues are application dependent, and it is critical to properly specify GRD ratings and consider GRD failure modes and effects, so that the GRDs can positively contribute to system security and reliability.

GRD Impacts

Application of neutral GRDs requires careful analysis of the potential impact on insulation coordination. Of particular concern are neutral voltages, bus voltages, and voltages across transformer windings during steady-state, temporary (fault), and transient conditions. GRDs that have low impedance, and that also have low thresholds for their internal voltage limitation functions (MOV, gaps, bypass switches, or combination thereof) will cause the least impact.

GRDs will change faults currents to some degree. Capacitive GRDs will tend to increase fault current magnitude, which may be problematic in locations where fault currents are at the limits of equipment capabilities. However, GRD overvoltage limitation characteristics also have substantial effect on the degree to which the GRD affects fault currents.

Changes in current and voltage phase angle relationships can be problematic for protective relay systems. Of particular concern are relay schemes using zero-sequence voltage, tertiary current, or neutral current for directional relay polarization. Low-frequency oscillations in neutral current may also affect the accuracy of digital relays to identify fundamental-frequency phasor quantities.

GRDs, including capacitive GRDs, are unlikely to cause subsynchronous resonance (SSR). Also, for low and intermediate GRD impedance values (low, intermediate, and high GRD impedance ranges are defined in the body of this guide) harmonic resonance is not a major concern.

GRD Application Studies

Transmission systems are usually designed to be solidly grounded, and the application of a neutral GRD presents situations for which the industry does not have a strong basis of experience. Therefore, prudence requires that technical system studies be performed in order to specify a neutral GRD in order to integrate it with the transmission system. Failure to perform these studies can result in a GRD that:

- Does not achieve the desired GIC mitigation or does not reliably remain in service, particularly in the midst of a GMD event, thus endangering system security.
- Becomes damaged during normal service conditions, or as a result of ordinary contingency conditions.
- Results in damage or failure of other equipment.
- Interferes with system protection such that failure to trip for faults or false tripping in the absence of a fault occurs.

Application of a series GRD also requires study. The industry, however, has substantial experience with applying series capacitors for line impedance compensation, and application of a series GRD requires similar considerations and practices for the most part. There are some aspects of series GRD application, however, that differ from conventional series capacitor application, such as the deployment strategy for GIC mitigation and geomagnetically-induced voltage withstand specifications. In contrast to the ac aspects of series GRD application, which are in common with conventional series capacitor applications, the industry does not have extensive experience with GIC redirection using series devices. [1]

The types of studies that should be considered for GRD application include:

- GIC flow study to define deployment plans and determine specifications for GRD.
- System imbalance study to determine neutral GRD steady-state rating.
- Fault study to determine impacts on fault current and the ability of GRDs to remain in service.
- Harmonic study, particularly for GRDs with relatively high capacitive impedance, to determine GRD ratings.
- Electromagnetic transients study to define GRD performance during transient and fault conditions.
- Insulation coordination study to assess the impacts on existing equipment insulation and surge arresters.
- System protection study to ensure proper function of transformer and line protection relays with installation of the GRD.
- GRD design, to either specify the details of the GRD design, or to evaluate designs offered by vendors in light of the requirements of the specific application.

This guide provides details of the scope, objectives, software tools, and data required for each of these studies.

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1 INTRODUCTION

1.1 Background

Solar disturbances, such as coronal mass ejections, can initiate terrestrial geomagnetic disturbance (GMD) when charged particles emitted from the sun interact with the earth's magnetic field. GMDs can result in the flow of very low frequency geomagnetically induced currents (GIC) in power systems. The physics of this phenomenon have been extensively documented in the literature [2]. Basically, the transmission lines and the return path through the earth, closed through grounded-wye transformers, form a loop enclosing the slowly-changing magnetic field produced by auroral electrojet currents flowing in the upper atmosphere. Because the spectral content of the GIC induced in this loop is composed of very low frequencies, it can be considered essentially dc (i.e., quasi-dc) for most practical purposes related to power system impacts.

The voltage induced in the transmission line-earth loop integrates to impose a quasi-dc flux bias on the transformers closing the loop. This includes both grounded-wye transformers closing the connection between the transmission system and earth, as well as the series windings of autotransformers providing a dc path between different transmission voltage levels. The flux bias results in asymmetric, or part-cycle, saturation of the transformers, producing unusually large and highly-distorted exciting currents.

Asymmetric saturation of a transformer can have direct impact on the transformer itself, and may also have profound impacts on the power system performance via the large exciting currents drawn from the transmission system, regardless of whether the saturation poses any risk to the transformer. The potential for direct impacts of GIC saturation on transformers is widely recognized and is presently the subject of much controversy. Some have speculated that a severe but credible GMD event could result in the wide-scale failure of numerous critical power transformers [3]. Others, including many transformer experts, see the risk as limited to particular and generally-limited number of transformer designs, and assert that widespread transformer damage is unlikely [4]. The fundamental-frequency reactive current absorbed by GIC-saturated transformers can potentially lead to excessively low voltages and possible voltage instability. The harmonic components of the exciting currents can lead to abnormal levels of voltage and current distortion with consequent impacts on capacitor banks, generators, protective relays, and other equipment. The impacts of harmonics can cause tripping of reactive power sources at a time when the system is stressed, potentially accelerating voltage instability.

The Federal Energy Regulatory Commission (FERC) has directed the North American Electric Reliability Corporation (NERC) in Order 779 to develop mandatory standards for operational response to GMD events, and to perform assessments of system vulnerability to GMD. In response, NERC has developed standards EOP-010-1 and TPL-007-1, respectively. NERC Standard EOP-010-1 has been approved by the FERC and became effective beginning in January 1, 2015. Regulatory approval of Standard TPL-007-1 is pending at the time of this report.

Regarding the requirements for GMD impact assessment, FERC Order 779 requires owners and operators of the Bulk Power System to develop and implement a plan to "…protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event…" The FERC order further states that "…These strategies could, for example, include automatically blocking geomagnetically induced currents from entering the Bulk-Power System…" The NERC Standard TPL-007-1 requires, in the event a GMD vulnerability assessment indicates non-compliant system performance, a Corrective Action Plan. This standard references a list of appropriate GMD mitigating measures contained in the NERC GMD Task Force GMD Planning Guide. One of the suggested measures in the Planning Guide is the use of GIC reduction devices (GRDs).

GRDs are devices intended to reduce or eliminate the flow of GIC in particular transformers or transmission lines. GRDs can take the form of neutral devices, connected between the neutral terminals of transformers and ground, or series devices installed on transmission lines. Diagrams of various GRD design approaches are provided in [5]. A neutral blocking device (NBD) is one form of neutral GRD in which all quasi-dc current between transformer neutral and ground is blocked. Various types of GRDs have been proposed, and several types have been built and installed on a very limited basis. These devices all use either capacitors to completely block quasi-dc GIC flow from their path, or resistance to reduce the flow. At least one type of capacitive GRD is now being commercially offered.

Because GRDs installed in series with transmission lines must carry the normal positive-sequence load current, resistive devices are infeasible due to excessive losses. Losses are not only important from an economic standpoint, but the power rating of a resistive GRD with enough resistance to significantly affect GIC flow would need to be impractically large if it must carry load current on a continuous basis. Therefore, a practical series GRD must be a capacitive device.

1.2 Impacts of GRDs

Transmission systems in North America have conventionally been designed to be effectively grounded[1], and as a near-universal rule, the neutrals of wye-connected HV transformer windings have been solidly connected to ground without any intentional impedance. In exceptional cases, HV transformer neutrals are sometimes grounded through small inductances in order to limit fault currents. These inductances are sufficiently small so as to maintain effective grounding. Effective grounding limits the rise of voltage-to-ground of unfaulted phases during transmission ground faults, and facilitates the detection of ground faults by protective relay systems.

A neutral GRD inherently places impedance (or effective impedance such as by use of a rapidly-switching power electronic device [6]) between the neutral of a transformer and ground. This impedance causes an elevation of the neutral voltage, and may result in, or increase elevation of, unfaulted phase voltages during faults. Thus, the impacts on insulation coordination and overvoltage protection must be closely scrutinized. Neutral GRDs may increase or decrease

[1] Effective grounding is defined in IEEE C62.92.1 grounding of sufficient effectiveness such that the Coefficient of Grounding less than 0.8. Coefficient of grounding is the ratio of the maximum unfaulted-phase voltage to ground during a ground fault, divided by the unfaulted phase-to-phase voltage magnitude.

ground fault currents or change their phase relationship. Changes in fault current magnitude and phase angle may potentially impact the performance of protective relay systems. As a practical matter, most neutral GRDs will have some means of limiting the peak voltage (ac plus dc components) across the device, thus tending to mitigate the impacts of their impedance.

Series capacitors are routinely used in bulk power transmission to reduce system to reduce transmission path reactance. There are a number of widely recognized impacts of series capacitors, including the increase of circuit breaker transient recovery voltages (TRV) during fault clearing, and the potential for subsynchronous resonance. To provide meaningful impedance compensation, conventional series capacitors applied for this purpose have a fundamental-frequency capacitive reactance that is a substantial percentage of the line's impedance. Conventional series capacitors will inherently provide GIC blocking. However, a series capacitor device installed solely for GIC blocking need not have such a large capacitive reactance. A series GRD with small fundamental frequency impedance will have a substantially reduced potential for the adverse impacts normally associated with higher-impedance series capacitors installed for compensation purposes.

1.3 Scope of Guide

Application of GRDs requires considerable technical diligence to ensure that the devices provide the desired function and do not introduce adverse impacts on the transmission system's equipment and reliability. A prior EPRI report [5] has examined some GRD impacts by using a case study approach. This guide takes a wider approach, in order to provide readers with a comprehensive understanding of the critical factors to the specification and design of GRDs and the assessment of their impacts. This report provides a guide to the technical studies that should be performed, or considered for performance, when GRD deployment is planned and specified.

The primary focus of this guide is on neutral GRDs, as this option has gained the greatest industry attention and is widely assumed to be the more economical solution. Also, the imposition of a device between transformer neutrals and ground is a substantial departure from the conventional practice of solidly grounding the neutrals of transformer windings connected to HV and EHV transmission systems. In contrast, series blocking devices benefit from the extensive utility industry experience with series capacitors for impedance compensation. Because series GRDs represent a much more limited deviation from established practice, and are not receiving the same degree of consideration by the industry, the coverage of series GRDs in this guide is intentionally limited.

This guide covers devices intended to reduce GIC, and does not cover schemes and devices intended only to mitigate the effects of GIC in transformers, such as dc flux nulling schemes.

This guide focuses on:

- How GRDs may be applied to reduce the impact of GMDs on particular transformers and on the overall system performance,
- Rating considerations to ensure that the GRDs can fulfill their desired role and remain in service as expected,
- The potential impacts of GRDs on insulation coordination, fault currents, system protection (relaying), and resonant interactions,

- GRD failure mode and effects considerations, and
- Studies required to select, specify, and evaluate GRD applications

Although there are a few commercially-offered GRD solutions, this guide approaches the above topics from a generic viewpoint. The guide is not intended to favor one solution over another, but is rather focused on objective description of the specification and evaluation considerations of each approach.

While GRDs may also provide mitigation of certain electromagnetic pulse (EMP) impacts caused by high-altitude detonation of nuclear weapons, the scope of this guide does not include this application.

PART 1
FUNDAMENTAL CONCEPTS

2
GRD VOLTAGE LIMITATION

Faults and other system events drive high currents through both series and neutral GRDs. These high currents could cause excessive voltage across the GRDs if means are not provided to limit the voltage. Without voltage limitation, impractical GRD voltage ratings would be required, system protection coordination would be disrupted, and in the case of neutral GRDs, insulation levels of transformers and other equipment may be exceeded.

Therefore, GRD voltage limitation is a key factor of the GRD design and application. In addition to protecting the GRD itself, overvoltage limitation also modifies and generally reduces the impact that the GRD has on system performance during faults and other high-current events. Therefore, a review of the various GRD overvoltage limitation options is provided in this section, as background prior to categorization of the GRD types and discussion of the GRD impacts in later sections.

2.1 GRD Without Voltage Limitation

If the impedance of a GRD is sufficiently small, such that the voltage across the GRD inherently does not exceed acceptable limits for even the worst case GRD current, then overvoltage limitation may not be needed. A GRD that does not require overvoltage limitation (except for brief transient periods, such as the first cycle or two of a fault) is categorized in this guide as a "low impedance GRD."

A capacitive GRD could be designed to have a fundamental-frequency reactance such that the product of the most severe fault current magnitude times this reactance does not result in excessive voltage. However, fault currents often have large dc offset components. These will initiate low-frequency neutral voltage oscillations creating peak magnitudes far in excess of the fundamental-frequency voltage. This is illustrated in Figure 2-1 which shows neutral voltage for a simulation of a ground fault at the GSU transformer high-voltage bus in the system model shown in Figure 2-2. This transformer is modeled with a 1.0 ohm capacitive neutral GRD that does not have any means of voltage limitation. The symmetrical fault current for this case (i.e., without inclusion of the dc offset), without the NBD, is 6.38 kA rms, and is increased to 7.44 kA rms with the NBD inserted. The peak voltage across the NBD reaches 40 kV peak, which is more than 3.8 times the peak 60 Hz voltage component. The 60 Hz component of voltage is barely visible on top of the large-magnitude oscillation at around 11 Hz. The oscillation in neutral voltage also causes a low-frequency voltage component to be superimposed on the bus voltage as shown in Figure 2-1.

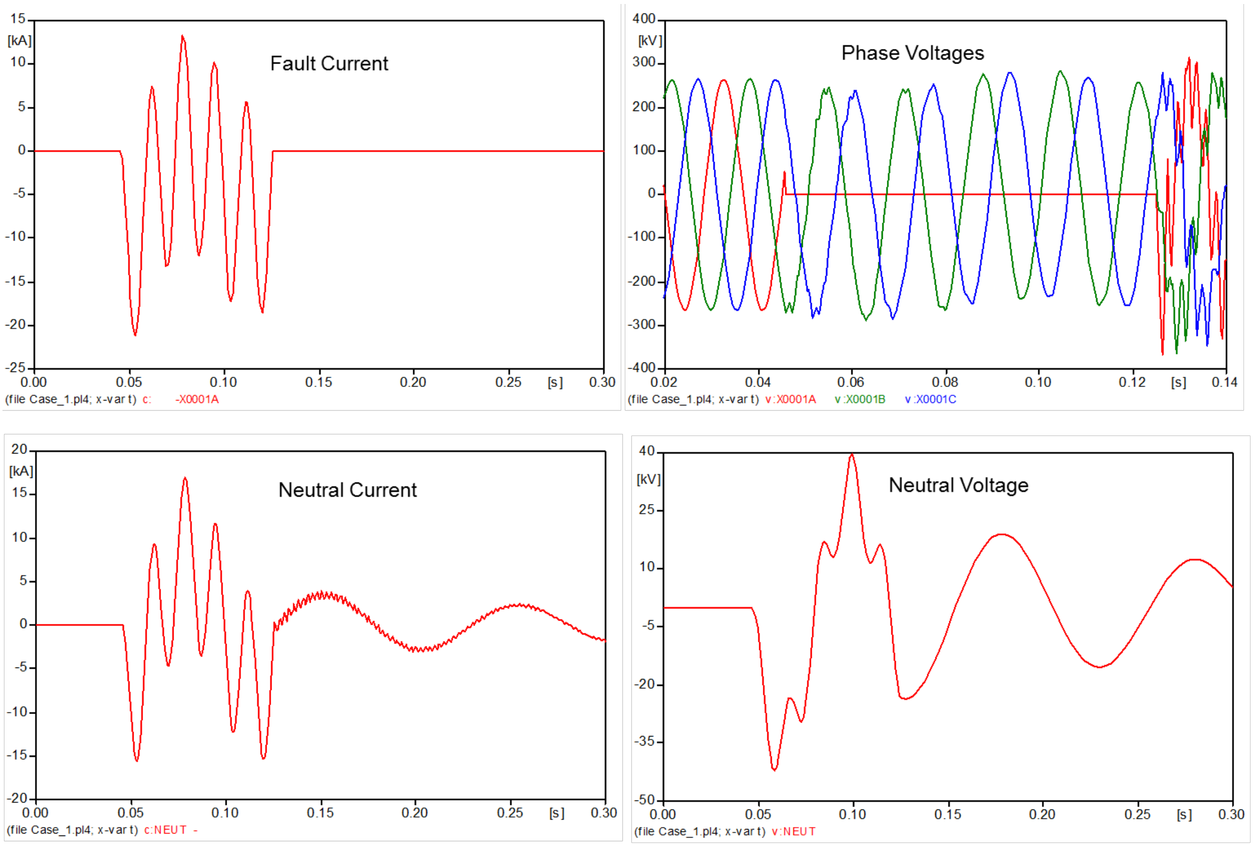


Figure 2-1
Voltages and currents for simulation of a ground fault adjacent to a transformer with a capacitive neutral GRD, without neutral voltage limitation.

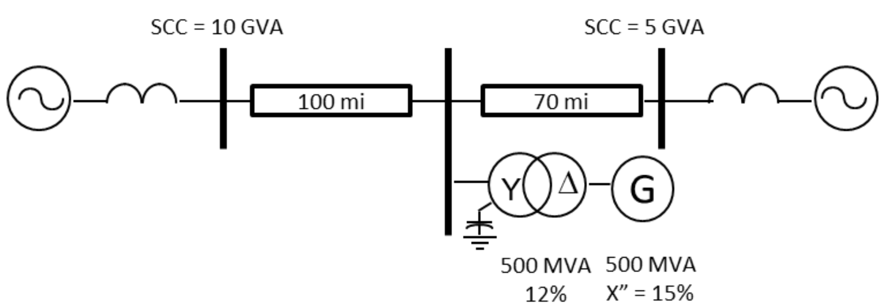


Figure 2-2
System model used for Figure 2-1

Because of the low-frequency oscillatory overvoltages inherent to a capacitive GRD, only a low-impedance resistive GRD, in practice, can be used without overvoltage limitation. A low-impedance resistive GRD does not provide a complete blockage of GIC; but it may reduce GIC sufficiently to meet some objectives. A resistive GRD, however, is only feasible for a neutral application because losses would be excessive for a series resistive GRD that has sufficient resistance to produce any significant mitigation of GIC magnitude.

The allowable voltage across a neutral GRD, and the neutral current magnitudes that may drive steady-state, temporary, and transient voltages across a resistive device are discussed later in this report.

2.2 MOV Voltage Limitation

Metal-oxide varistors (MOVs) are the active element in modern surge arresters, used to limit transient voltages. These devices have highly nonlinear resistance, such that when voltage is increased above a threshold, the device conducts sufficient current to effectively limit the voltage rise above that threshold. MOV have limitations to the energy they can absorb without either immediate failure, or post-transient thermal instability leading to delayed failure. In typical surge arrester applications, the primary role of the arrester is to limit short-duration transient voltages, such as caused by lightning impulses or switching transients. The voltage rating of the arrester is selected such that the arrester will not conduct a large amount of current during longer-duration temporary overvoltage (TOV) conditions lasting multiple cycles or seconds. Effectively, the TOV and maximum continuous operating voltage (MCOV) parameters define the minimum arrester rating that can be safely applied, and the impulse and switching surge voltage protective levels provided by the arrester are an outcome defined by the selected arrester rating.

A GRD is subjected to high fault currents, as well as other transient currents. All practical GRD designs require limiting the voltage across the GRD. Due to the high currents involved, an ordinary surge arrester could not survive providing voltage limitation for such events. There are three options that have been proposed or used in GRDs to address temporary voltage limitation using MOV:

1. High-current MOV banks
2. Sacrificial arresters
3. MOV with bypass

High-Current MOV Banks

Sufficient number of varistor units may be placed in parallel to divide the current duty such that the varistor can provide GRD voltage limitation during fault events. This approach is routinely used to protect conventional series capacitors (applied for line impedance compensation) and has been used for at least one series capacitor dc blocking device application.[2]

Use of MOV to limit temporary overvoltages (overvoltages persisting for multiple fundamental-frequency cycles) is a very non-trivial application, and there are several challenges to this approach. The number of parallel MOV columns is large for any realistic short-circuit current duty. The V-I characteristics of the MOV columns must be closely matched to obtain adequate current sharing. Individual MOV blocks tend to have random variations in their characteristics. In conventional series capacitor applications of MOV voltage limitation, MOV blocks with offsetting variations are placed in series to assemble columns with well-matched aggregate characteristics. For a GRD, the voltage limitation is low, and thus a smaller number of MOV

[2] The primary purpose of the series blocking device that used this approach was not to block GIC, but rather to block stray dc ground currents caused by an HVDC system. However, the application is practically identical to a GIC blocking application.

blocks are used in series for each column. The smaller number of blocks makes achieving a good V-I characteristic match significantly more difficult than is the case for the much higher voltage MOVs used for conventional series capacitors.

The V-I characteristics of MOV change with age and discharge history. As a result, it is generally not feasible to replace a failed MOV column with a new column. Instead, spare columns need to be included in the initial design, and failed columns are simply disconnected, leaving the remainder to perform the desired function. An MOV "bank" capable of fault current duty is also physically large, and can be expensive.

Sacrificial Arresters

There have been proposals for GRDs that use "sacrificial" MOV arresters. The arrester acts like a "voltage fuse," and fails to a short-circuited condition when its energy capability is exceeded. In the proposed GRD design using this concept, the arrester is a single-column device that is not intended to survive grid fault currents, and a mechanical bypass switch is included in the design to back up the sacrificial arrester.

A key requirement of a sacrificial MOV design is that the MOV must reliably fail to a short circuit. When an MOV column fails, a fault arc is developed within the arrester housing. Pressure relief vents, designed into station-class arresters, blow out and transfer the arc outside of the housing such that the arrester housing does not suffer mechanical failure. The vendor offering the sacrificial arrester approach has performed laboratory tests to confirm the appropriate failure mode for high current conditions. It is also important that an arrester fail safely to the shorted condition during longer duration, lower-current events that exceed the MOV's capability. Such events may cause damage to the arrester housing prior to the development of sufficient pressure to cause pressure relief operation. Appropriate monitoring of the MOV current may also be used to mitigate this issue by closing a bypass switch to remove duty prior to housing damage.

When a GRD with a sacrificial MOV is shorted by either MOV failure or bypass device operation, it is no longer capable of blocking GIC. Depending on how GRDs are deployed in a transmission system, the GIC flow can potentially be concentrated at the circuit location having the nonfunctional GRD. The consequences of this on both equipment and system performance during a GMD need to be evaluated. It may be necessary to remove a transformer from service if a sacrificial arrester in a neutral GRD connected to that transformer fails or is permanently bypassed.

Proponents of the sacrificial MOV concept have justified the approach by estimation of the statistical probability of a system fault during the relatively small period of time that a GRD would need to be placed in service (bypass switched opened) during GMD events. There are a number of considerations which should be made when evaluating this argument:

1. While the statistical probability of a fault precisely at the location of a GRD during a GMD may be small, there is greater probability if the GRD is vulnerable to MOV failure for more remote faults. Determination of the "failure radius" is critical to evaluation of this approach.
2. Other non-fault events may cause abnormal currents in a GRD. Such events may include switching of nearby transformers, or large capacitor banks; such events are of increased likelihood during a GMD as generation units and capacitor are brought on line and

equipment that was out of service for maintenance is recalled to service. The vulnerability of the GRD’s MOV for such events must be evaluated.

3. GMDs are unusual events, and there are reasons to hypothesize that fault events may be slightly more likely than the average probability, as a result of the GMD. Transformers are stressed by GMD, and it is possible for a transformer fault to occur as a result. Equipment out of service for maintenance may be returned to service when a GMD alert is issued, and the switching involved may result in slightly increased probability of fault occurrence.

For the reasons stated above, use of sacrificial arresters is not an attractive voltage limitation alternative and is not recommended as a preferable approach.

MOV with Bypass

In most series capacitor applications designed for impedance compensation, MOV limitation is designed to withstand a certain magnitude of fault current and fault duration that may not be the worst-case condition. For faults with higher-magnitude current, or longer durations, the MOV is bypassed by another means, such as a spark gap, mechanical switch, or electronic switch. Such an approach can also be used for GRD applications.

2.3 Spark Gaps

Spark gaps can be used to bypass a GRD. Gaps can be divided into two categories:

1. Passive gaps that sparkover to a short-circuited state whenever the voltage across the gap causes breakdown of the gap’s insulation.
2. Triggered gaps in which the insulation breakdown is triggered by a control, which uses a pilot gap to inject plasma to cause the main gap to spark over.

Consistency and reliability has been an issue with passive gaps. Gap sparkover is inherently a statistically defined process, even under controlled conditions. In uncontrolled conditions, gap sparkover voltage is affected by atmospheric conditions as well as contaminants (including insects) and previous gap duty. At the lower sparkover voltages typically needed for GRD applications, the influence of contaminants and previous gap duty, which may leave the surfaces of the gap pitted or melted, may be more significant. GRD schemes depending on passive gaps require extensive testing to confirm their accuracy, consistency, repeatability, and reliability.

Triggered gaps can be fired based on conditions other than the voltage across the gap. For example, a triggered gap may be fired based on the total energy duty in an MOV that is in parallel with the gap. Triggered gaps are more complex and costly, but may be more consistent and reliable.

When a gap sparks over, the gap will remain in a conductive mode until the current through the gap is either interrupted or diverted into a bypass breaker. When gaps are used to bypass a capacitive GRD, a current-limiting inductor is needed to reduce the magnitude and frequency of the capacitive discharge current.

It is of questionable prudence to base the limitation of voltages potentially damaging to other critical equipment, such as transformers, solely on gap protection. Passive gaps have a very pronounced increase in sparkover voltage for faster wavefronts such as may be caused by lightning transients. The controls of a triggered gap are not fast enough to protect against excessive fast-front transients. Therefore, a gap solution should be backed up by a surge arrester when the voltage across the gap is critical to equipment insulation protection. The gap voltage-limitation characteristics for fault duty must then be coordinated with the TOV capabilities of the arrester applied, such that the insulation-protecting arrester is not subject to failure from fault currents or other longer-duration events.

2.4 Bypass Switchgear

Various forms of bypass switches and breakers can be used to limit voltage across a GRD by creating a short around the GRD when voltages reach a threshold value. The bypass switchgear may consist of one or more of the following:

- A mechanical switch or breaker,
- A solid-state power electronic switch, such as back-to-back thyristors.
- High-power electron tubes

Mechanical Bypass Switches

Mechanical switches and breakers arranged to bypass a GRD are typically are used in conjunction with another means of voltage limitation, such as MOV or a gap. Mechanical switches and breakers have operating times that are too slow to adequately protect insulation from transient voltages. Breakers, however, can interrupt current to insert or reinsert a GRD into service by opening the bypass path. Breakers usually depend on zero crossing of alternating current to perform circuit interruption. If GIC (dc) magnitude exceeds the crest value of the ac components of GRD current, there will not be a current zero. Only if a breaker can develop an arc voltage exceeding the dc voltage that drives the direct current (in the case of pure dc through the GRD) or sufficient dc voltage to reduce the direct current sufficiently to produce current zeroes (in the case of superimposed direct and alternating current) will the breaker interrupt. Certain types of switchgear, such as air-magnetic, have arcing properties that are particularly capable of dc interruption.

Solid-state electronic devices, such as thyristors, can also be used as GRD bypass devices. These devices can be turned on to bypass a GRD with much greater speed than a mechanical switch can close. However, this speed is generally insufficient to protect equipment against fast transient voltages. Because of this, and the fact that the electronic devices themselves are quite sensitive to transient overvoltages, the devices need to be used in conjunction with surge arresters. The bypassing thresholds of the electronic switch controls need to be coordinated with the TOV withstand capabilities of the arrester such that the arrester will not be damaged by GRD voltages during system faults and other long-duration events.

Power electronic devices are sensitive to high currents and fast rates of current rise. When used to bypass a capacitive GRD, substantial inductance is required to limit the dI/dt. Cooling of the power electronic device is critical to avoid excessive semiconductor junction temperatures. Passive heat sinks may remove and slowly dissipate the accumulated thermal energy in the device for brief transient current duty. However, if the device is subject to continuous or recurrent duty, some form of active cooling may be necessary. Individual semiconductor devices may not have sufficient voltage capability for the application. In this case, multiple devices may need to be placed in series, with proper attention to snubber and grading circuits used to evenly distribute the voltage stress over the series devices.

Thyristor switches can only interrupt at current zeroes. If GIC magnitude exceeds the peak alternating current component through a thyristor switch, then it will not interrupt. A mechanical bypass breaker, capable of dc interruption, can be used to divert current from the thyristor switch, or complex forced-commutation circuits can be used to generate an artificial current zero. Other electronic devices such as IGBTs (insulated-gate bipolar transistors), IGCTs (integrated gate-commutated thyristor), and GTOs (gate turn-off thyristors) are capable of interrupting direct current. These devices, however, have more limited voltage and current capability, or require complex high-current gate driver circuits.

High power electron tubes have been suggested as an alternative means of electronic bypass switching. These tubes are purported to have faster switching times and greater voltage and current capabilities than solid-state electronic devices. A neutral blocking and bypass device introduced by Advanced Fusion Systems, LLC is based on such a tube.

3
GIC REDUCTION DEVICE TYPES

In this section, the various types of GRD designs are categorized in order to facilitate the discussions of GRD impacts and application issues in later sections of this guide. GRDs are generically categorized by the type and magnitude of impedance used to reduce or block GIC, (resistance or capacitance) and the circuit location where the GRD is applied (series or neutral). The nomenclature assigned to the different types is specific to this report, and has not been defined by any standard or established industry practice.

3.1 Low-Resistance Neutral GRD

A low-resistance neutral GRD is defined as a device installed between the neutral of a grounded-wye transformer and earth (substation ground mat), and having a resistance sufficiently small such that no limitation of the voltage across the GRD is required for worst-case fault currents and other similar low-frequency currents having durations of multiple cycles. Constraints on the allowable voltage include insulation coordination, maintenance of effective grounding, and proper operation of system protection systems. A low-resistance GRD should make only a small impact on system ground fault currents.

A resistor may have significant parasitic inductance, such that a lightning impulse current or similar fast-front transient may cause excessive voltage across the GRD. Also, the GRD may be located at some distance from the transformer neutral due to installation space constraints. Therefore, it is typically necessary to apply a surge arrester directly to the transformer neutral. Temporary voltages during faults, and continuous voltages across the GRD, need to be coordinated with the neutral arrester's TOV and MCOV capabilities, respectively.

Due to the low resistance of the ground loops formed in transmission systems, in which GICs are induced, a low-resistance neutral GRD may reduce GIC magnitude sufficiently in some cases. The issue of effectiveness is discussed later in Section 5 of this guide.

3.2 High-Resistance Neutral GRD

A high-resistance neutral GRD has sufficient resistance such that the voltage across the device needs to be limited during faults and other transient events by MOV and/or bypassing devices such as a gap or switch (mechanical or electronic). Without voltage limitation or bypassing, the high-resistance neutral GRD would otherwise significantly reduce fault current magnitudes, disrupt effective grounding of the transmission system, interfere with system protection coordination, and potentially apply damaging temporary overvoltages to surge arresters and other equipment.

With voltage limitation or bypassing, these adverse impacts are mitigated to an extent defined by the device's resistance, overvoltage limitation threshold, and the severity of the disturbance. The non-linear characteristics of the device add complexity to the application analysis, as discussed later.

Depending on the type of voltage limitation and the physical location of the GRD relative to the transformer neutral bushing(s), the high-resistance neutral GRD may need to be supplemented by a surge arrester at the transformer neutral in order to protect the transformer's neutral bushing and the neutral end of the transformer winding from impulse transients (e.g., lightning surges). If the GRD voltage limitation is provided by MOV, and the GRD is physically adjacent to the neutral, then a separate arrester may not be necessary. If the overvoltage limitation is provided by a gap or bypass switch, then the supplemental neutral arrester is prudent. The temporary overvoltage withstand rating of this arrester needs to be coordinated with the overvoltage limitation characteristics for ground faults and other multiple-cycle events.

High-resistance neutral GRDs provide much more effective reduction of GIC magnitudes than low-resistance GRDs, but still will allow some GIC to flow in the neutral.

3.3 Low-Impedance Capacitive Neutral GRD

A capacitive neutral GRD is a GIC blocking capacitor connected in series between the neutral of a transformer and ground, and is often called a "neutral blocking device" (NBD). A low-impedance capacitive neutral GRD is defined by capacitive impedance that is small enough where overvoltage limitation does not have to perform continuously for the worst-case ground fault event. Depending on the point of wave timing of the fault occurrence, the dc-component of fault current can cause a voltage across the GRD that is many times the symmetrical voltage (product of symmetrical fundamental-frequency fault current in the neutral times the fundamental-frequency capacitive reactance). For a practical device, clipping of the low-frequency voltage component using MOV is necessary. Voltage limitation by a shorting action, such as by a gap or bypass switch, would render a performance that is essentially the same as described later for an intermediate-impedance device. Therefore, devices for which the primary overvoltage limitation is by a shorting device are excluded from this category.

Because, by definition, a low-impedance capacitive neutral GRD has MOV voltage limitation, it does not need to be backed up by a separate neutral-protecting surge arrester if the device is located physically close to the transformer neutral.

3.4 Intermediate-Impedance Capacitive Neutral GRD

A capacitive neutral GRD having a capacitance sufficiently large (i.e., capacitive reactance sufficiently small) such that the zero-sequence resonance created is well below the fundamental frequency, but the capacitive reactance is sufficiently large to require bypass in order to withstand worst-case transmission system ground faults, is classified as an intermediate-impedance capacitive neutral GRD in this guide. In the case of a grounded-wye delta transformer, this resonance is below the fundamental frequency if the GRD's capacitive reactance is less than one-third of the transformer's impedance. Impedance of the transmission system connected to the transformer's wye terminals will normally be inductive and will further reduce the zero-sequence resonant frequency. Thus, if the transformer plus GRD alone have a resonant frequency below fundamental, then system resonance at fundamental should not occur. (Fundamental resonance can potentially result in extreme currents and voltages, or may cause current phase reversals affecting protection.). For autotransformers, calculation of resonance between the capacitive GRD and the transformer are much more complicated, as will be discussed later in this guide.

The bypass, or protecting shorting, means can be a gap, mechanical switch or breaker, or an electronic switch. The device may also have MOV voltage limitation, but within this definition, this MOV is not capable of withstanding severe ground faults without bypassing. When an MOV is used, and the GRD is located physically close to the transformer neutral, a separate neutral-protecting surge arrester is not needed. Otherwise, it is prudent to apply such an arrester. The TOV and MCOV capabilities of this arrester need to be coordinated with the extended-duration voltages to which the arrester is exposed.

Where a bypass switch or breaker is used with a capacitive GRD, inductance must be added to the circuit in order to limit the magnitude of capacitor discharge currents and current rates-of-rise.

3.5 High-Impedance Capacitive Neutral GRD

A capacitive neutral GRD that has a capacitive reactance greater than, or equal to, the transformer's zero-sequence reactance is defined here as a high-impedance capacitive neutral GRD. This type of device is vulnerable to resonance at fundamental and higher frequencies, and may lead to neutral instability; issues discussed later in this guide.

There have been proposals to use MOV alone, between a transformer neutral and ground, without any explicit impedance in parallel. Such a neutral GRD, however, is inherently in parallel with the transformer's neutral bushing capacitance. Typically, this capacitance provides a greater 60 Hz admittance (smaller 60 Hz impedance) than the leakage resistance of an MOV arrester at an applied voltage well below its conduction "kneepoint." Therefore, unless the transformer is always grounded by another nearby ground source, the transformer is essentially "grounded" only by the bushing capacitance and such a GRD is functionally a very-high-impedance capacitive-neutral GRD.

3.6 Conventional Series Capacitor

Series capacitors are often used in transmission lines to reduce the effective fundamental-frequency series impedance of the line, increasing the practical power capacity of long transmission lines for which the capacity is otherwise constrained by system angular (transient) stability limitations. Series capacitors also inherently block the flow of quasi-dc GIC in a transmission line. Note that a series resistor is not a practical means of reducing GIC due to the fact that positive-sequence load current would pass through the resistor creating excessive losses and resistor heating.

Modern series capacitors use high-current multi-column MOV to protect the capacitors from excessive voltage during system faults. In a conventional series capacitor, a spark gap and a parallel switch are used to protect the MOV bank from excessive energy duty for high fault currents. Typically, designs use bypassing to limit MOV energy for "internal faults" (i.e., faults on the same line on which the series capacitor is applied) because the line must be deenergized anyhow to clear the fault. For external faults (faults on other lines or substation buses, beyond the line ends), it is common to design the MOV bank to withstand the duty without bypassing so that the series capacitor can provide its impedance compensation function immediately after the fault is cleared. The controls for the triggered gap, bypassing switch, and monitoring functions, and the need to either locate and power these controls on the elevated insulated capacitor platform, or communicate the inputs and outputs of ground-mounted controls to and from the platform across the line potential, all add complexity and cost to the series capacitor.

A series capacitor applied solely to block GIC would not have to have as large an impedance as one applied for compensation purposes. The capacitor would still, however, need to be protected from overvoltage and so the design of the series GRD has essentially the same considerations as a conventional series capacitor. The series GRD, however, has less impact and potential for system interaction than a higher-impedance series capacitor installed to cancel line reactance.

3.7 Passive Series Capacitor

It is also possible to design a series capacitor with sufficient MOV energy capability such that there is not a need for triggered gaps or automatic bypass switches for worst-case fault conditions. The combination of capacitors and MOV can provide a completely passive device without the complexities of controls. While such a passive design has been rarely used for impedance-compensating series capacitors, the concept is particularly attractive for a series GRD application due to the very small capacitive reactance that results in a relatively small voltage across the device during fault conditions. A passive series dc blocking device has been installed by Hydro Quebec on a 735 kV ac transmission line to block HVDC system ground currents from flowing through the ac line [7]. While not specifically intended for GIC, the function is identical. The series blocking device was located near the midpoint of the line to minimize the maximum short-circuit current available.

4

CIRCUIT MODEL REPRESENTATION

Foundational to discussions of GRD impact and interaction with the system is understanding how the characteristics of these devices are represented in power system modeling. For some aspects of design and integration, analysis and simulation is performed with electromagnetic transient simulation programs on a phase-by-phase basis (i.e., three-phase representation) where the components of the GRD are modeled explicitly. However, some forms of analysis are most efficiently performed using fundamental-frequency analysis tools using symmetrical component representation. Two issues presented in this section are the fundamental-frequency effective impedance characteristics of GRDs that have their voltage limited by MOV, and the representation of GRD impedances in symmetrical component models.

4.1 Fundamental-Frequency Impedance of GRD

A GRD with MOV voltage limitation is a nonlinear device. When the peak voltage across the device exceeds the MOV conduction threshold, the GRD's fundamental-frequency impedance decreases as the current increases further. It is the fundamental-frequency impedance that is most relevant to fault current determination and relay coordination.

Resistive GRD

For simplification, a high-current MOV bank can be idealized to a perfect voltage clamp. When the product of GRD current times the resistance is less than the voltage protective level of the MOV, the current in the MOV is ideally zero. When the voltage across the resistance would otherwise exceed the protective level, the ideal MOV conducts enough current such that the voltage across the GRD is clamped to the protective level. Actual MOV banks have extremely nonlinear resistance, such that this approximation is quite good for the purposes of analyzing the effective fundamental-frequency resistance of a resistive GRD when conducting current greater than the critical current crest current V_{PL}/R. V_{PL} is the voltage protective level of the MOV, and R is the linear resistance of the GRD that is in parallel with the MOV.

With this slight approximation, a normalized relationship between effective fundamental-frequency resistance and current magnitude can be defined that can be universally applied. This relationship is shown in Figure 4-1. The normalized current is in per-unit of the V_{PL} divided by resistance. Note that this is a peak current. The normalized resistance is in per-unit of the GRDs linear resistance. For example, consider a resistive GRD with a 5Ω resistance and a 20 kV MOV protective level that is conducting a 20 kA rms symmetrical fault current. This fault current has a 28.3 kA peak magnitude, which is 7.07 p.u. This yields an effective resistance of 0.18 p.u. of the actual linear resistance, or 0.9 ohms.

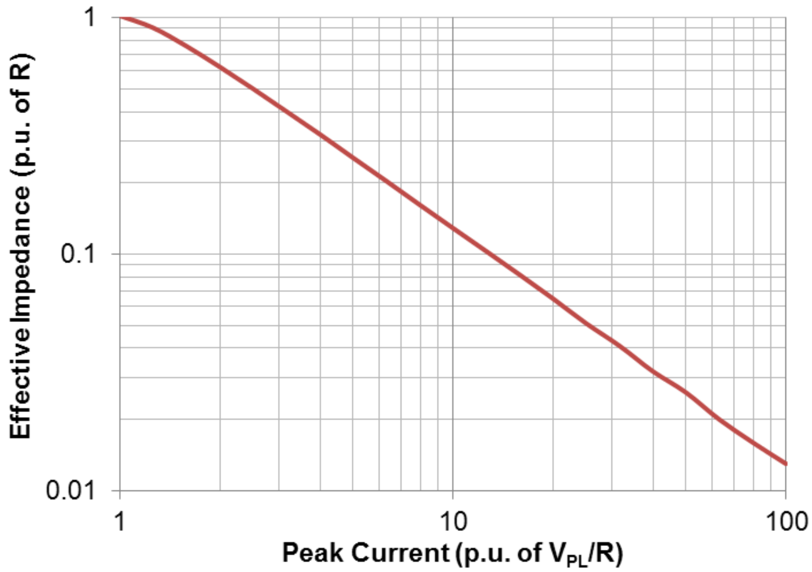


Figure 4-1
Effective fundamental-frequency resistance of a resistive GRD as a function of current.

Fault current dc offset can change the effective fundamental-frequency resistance of the GRD by driving the MOV into conduction at different points of the cycle. The offset current can also cause the GRD to be nonlinear at a fundamental-frequency current less than the critical current defined above. Figure 4-2 provides normalized curves of effective fundamental-frequency resistance as a function of fundamental current, for different amounts of current offset expressed in percent of the peak ac current magnitude.

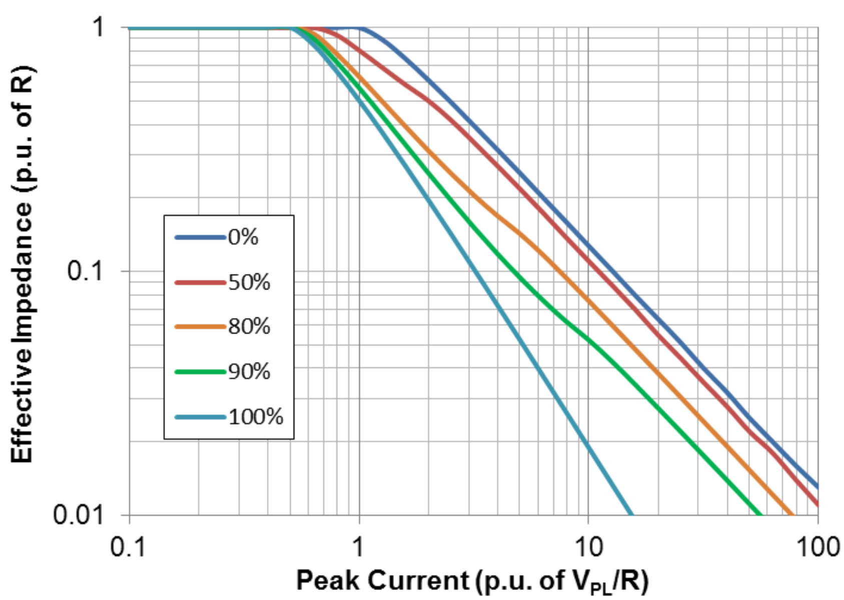


Figure 4-2
Effective fundamental-frequency resistance of a resistive GRD as a function of ac current, for various degrees of percent dc fault current offset

Capacitive GRD

Similar normalized curves for effective fundamental frequency impedance of a capacitive GRD, with MOV voltage limitation, are provided in Figure 4-3. For a capacitive GRD with MOV voltage limitation, however, the impedance angle changes with current magnitude. For current producing a peak voltage at or below the MOV protective level, the GRD appears purely capacitive. At fault current magnitudes increasing beyond this threshold, the impedance magnitude decreases and becomes increasingly resistive. The same normalized curves are plotted in terms of resistance and capacitive reactance in Figure 4-4.

DC offset in the current will also reduce the impedance of an MOV-limited capacitive GRD. However, the voltage offset caused by the dc charging the capacitor increases with time. Therefore, the impact on impedance is time-dependent, and normalized curves that take into account the nonlinear impact of current offset on fundamental impedance are not possible.

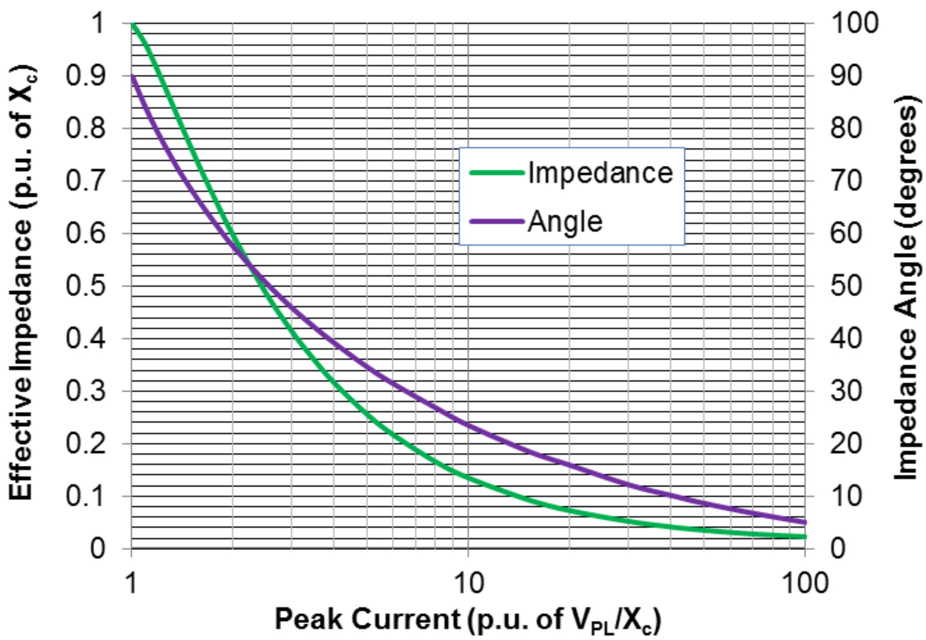


Figure 4-3
Effective fundamental-frequency impedance of a capacitive GRD as a function of current.

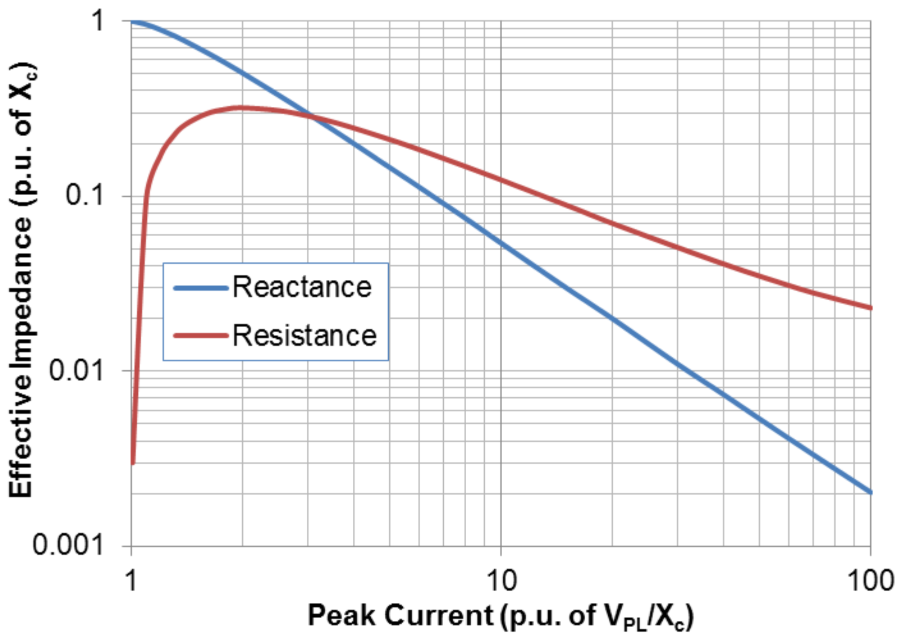


Figure 4-4
Effective fundamental-frequency resistance and reactance of a capacitive GRD as a function of current

4.2 Symmetrical Component Representation of GRD

Power system fault analysis is typically performed using symmetrical components. While the representation of linear series GRD impedance in symmetrical component models is rather obvious, sequence representation can be complicated by the nonlinearity of a series GRD driven into varistor overvoltage limitation. The symmetrical component representation of neutral GRDs can be complex in the case of autotransformers.

Series GRD

The impedance of a series GRD appears in series with the transmission line sequence impedances in the positive, negative, and zero sequence circuits. As discussed previously in this section, the impedance of a GRD may be nonlinear, either caused by MOV or bypass operation via a gap or switch. However, this nonlinear behavior cannot be modeled as separate nonlinearities in the sequence domain. The nonlinearity can only be correctly represented in the phase domain.

Neutral GRD on Grounded-Wye Delta Transformers

A neutral GRD connected between the neutral of the wye winding of a wye-delta transformer is represented by impedance three times the GRD physical impedance, in the zero-sequence model only, and in series with the shunt impedance representing the transformer's leakage impedance. The diagram in Figure 4-5 shows the sequence model of the transformer and neutral GRD combination. The impedance of the GRD (Z_n) has a factor of three because the neutral conducts the zero sequence currents of all three phases.

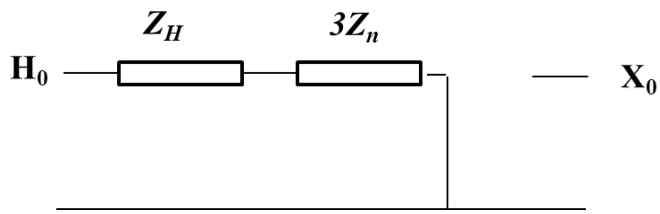


Figure 4-5
Zero sequence model of a grounded-wye delta transformer with neutral impedance (grounded-wye winding is assumed to be on the H terminal side)

Neutral GRD on Autotransformers

Zero sequence current flow through an autotransformer from the H to X terminals (high voltage to the lower transmission voltage), or X to H, causes current flow through the neutral equal to three times the common-winding current. The impedance of a neutral GRD, therefore, appears both in the series path between H and X in the zero sequence model of all autotransformers, as well as in the shunt zero-sequence path of autotransformers with delta tertiaries.

The analysis of the zero-sequence characteristics of an autotransformer without tertiary is far simpler than the more typical case of an autotransformer with tertiary. This simpler case is derived first, based on the circuit diagram for one phase shown in Figure 4-6.

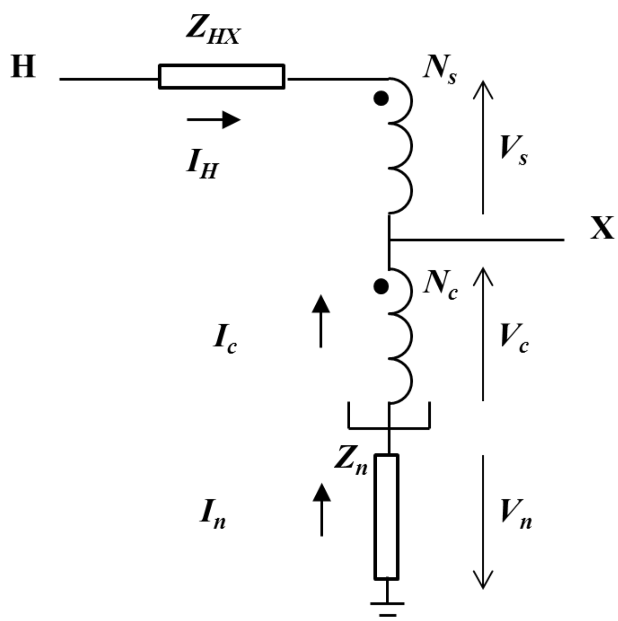


Figure 4-6
Circuit diagram of an autotransformer with neutral impedance

If the X terminals of the autotransformer are short-circuited ($V_X = 0$), and a zero-sequence voltage (V_H) is applied to the H terminals, Kirchoff's Voltage Laws can be applied to two loops in the circuit to arrive at the following equations:

$$V_c - V_n = 0 \tag{4-1}$$

$$V_H - I_H \cdot Z_{HX} - V_s = 0 \tag{4-2}$$

In Equation 4-2, the impedance Z_{HX} is the series impedance of the transformer itself, referred to the H terminal. The neutral voltage V_n is equal to $3 \cdot I_c \cdot Z_n$, so substituting this into Equation 4-1 and solving for the common winding voltage V_c yields:

$$V_c = 3 \cdot I_c \cdot Z_n \tag{4-3}$$

Applying the physical turns ratio of the autotransformer $N_c/(N_c+N_s)$, the series winding voltage V_s is:

$$V_s = \left(\frac{N_s}{N_c} \right)^2 \cdot 3 \cdot I_H \cdot Z_n \tag{4-4}$$

The terminal no-load voltage ratio of the autotransformer n is related to the physical turns ratio by:

$$n - 1 = \frac{N_s}{N_c} \tag{4-5}$$

Substituting Equation 4-5 into Equation 4-4, and then into 4-2, the effective zero sequence impedance seen from the H terminals is:

$$V_H / I_H = Z_{HX} + 3 \cdot (n-1)^2 \cdot Z_n \tag{4-6}$$

The zero sequence model for an autotransformer with a neutral impedance, but without a delta tertiary winding, is shown in physical units in Figure 4-7. It can be seen that the neutral impedance appears as series impedance between the H and X terminals. In a per-unit model, the ideal transformer is no longer part of the model, but the neutral impedance must be on the H terminal impedance base.

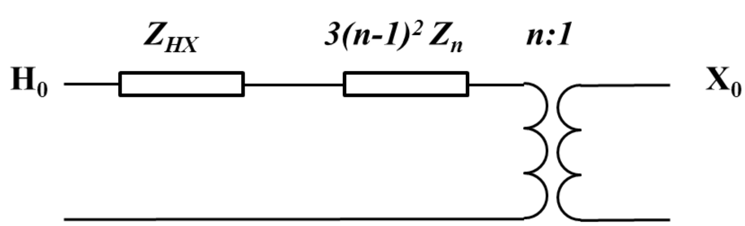


Figure 4-7
Zero sequence model of an autotransformer, without delta tertiary and with neutral impedance, in physical units

The per-unit zero sequence model for an autotransformer with both a delta tertiary and a neutral impedance is shown in Figure 4-8. In this model, Z_{HX}, Z_{HY}, and Z_{XY} are the per-unit leakage impedances of the transformer from the H to X, H to Y (tertiary), and X to Y terminals, respectively. The neutral impedance is in per-unit on the H winding impedance base. It can be seen that the neutral impedance appears in each of the legs of the star model of the transformer, affecting both the through-impedance and the shunt impedances seen from the H and X terminals.

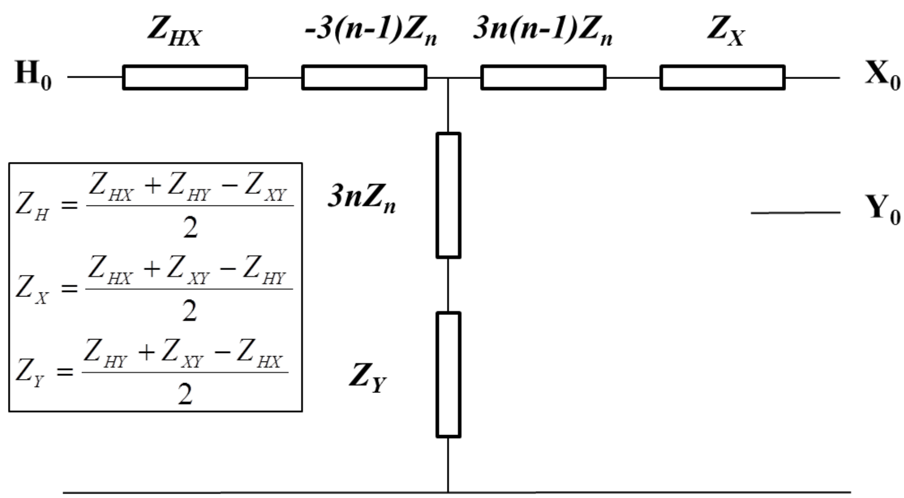


Figure 4-8
Zero sequence model of an autotransformer with delta tertiary and neutral impedance, in per-unit

Shared Neutral GRDs

Using a common neutral GRD for multiple transformers causes the zero sequence models of the transformers to be coupled. Zero-sequence current flowing into one transformer will result in a neutral voltage that is seen by the other transformer, and can affect or even drive zero sequence flow in the other transformer.

Where multiple autotransformers share a common neutral GRD, the series zero-sequence voltages between the H and X terminals are coupled. To model this coupling, 1:1 ideal transformers (assuming the voltage ratios of the transformers are the same) are required in the model to provide the coupling, even in a per-unit model. The per-unit zero-sequence model for two autotransformers, without delta tertiaries, is shown in Figure 4-9. The zero-sequence model for multiple autotransformers, with tertiaries, and sharing a common neutral GRD is outside of the scope of this guide.

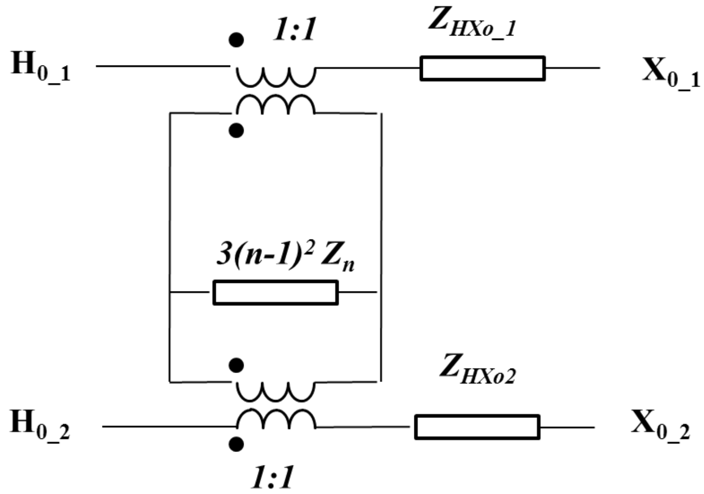


Figure 4-9
Per-unit zero sequence model for two autotransformers, with identical voltage ratios and without delta tertiaries, sharing a common neutral impedance.

PART II
GRD DESIGN AND APPLICATION

5 GRD DEPLOYMENT AND EFFECTIVENESS

GRDs may be deployed to achieve mitigation of GIC flow in specific transformers, or to achieve system-wide objectives. In most cases, it is anticipated that GRDs will be deployed at a certain subset of transformers or line, in order to obtain the greatest mitigation effectiveness for a given cost [8].

5.1 GRD Device Effectiveness

Series GRD Deployment Effectiveness

For practical reasons, all series GRDs are capacitive devices. Because the capacitance provides a near-infinite impedance to the quasi-dc GIC, such a device will block virtually all GIC flow in the path in which it is installed.

The principal consequences of GIC are due to flow of GIC into power transformers. For a wye-delta transformer, a capacitive GRD in series with the wye-winding phase terminals, all GIC is eliminated. For an autotransformer or a grounded wye-wye transformer (which are exceedingly rare in transmission systems), blocking GIC on one set of terminals still allows GIC to flow via the other transmission-voltage terminals. Because the higher voltage side is typically connected to longer lines that usually have lower per-mile resistance, series blocking on the higher-voltage side will typically provide a substantial reduction of the net GIC. The effectiveness of series blocking only on the higher-voltage side of an autotransformer depends on the system configuration and line orientation, and may not be particularly effective in some cases.

A series GRD can also be installed directly on a transmission line. GIC flow through that line will be eliminated, but the amount of reduction of net GIC in transformers located at or near the line terminals depends on the electrical configuration of the transmission network, its geographic layout, and whether other lines also have GIC blocking. An advantage of a GRD located in the middle of a long transmission line is that the worst-case short-circuit current duty required imposed on the device is substantially reduced compared to location at the line terminations. Because of the substantial reduction of available short circuit current, a passive series capacitor approach is much more practical in a mid-line application than at a substation.

Neutral GRD Effectiveness

A capacitive GRD in the neutral of a wye-delta transformer blocks all GIC from that transformer. However, a capacitive GRD in the neutral of an autotransformer does not block all GIC because a path for GIC from the H to X bushings via the series winding is not blocked. Blocking GIC flow through the neutral may substantially reduce the net GIC, and thus reduce the transformer saturation impacts. Only through detailed GIC flow analysis, considering the actual transmission network electrical configuration, geographic configuration, and all possible geo-electric field orientations, can the effectiveness of a GRD deployment be evaluated. The analysis should not only consider the benefits of net GIC reduction in the transformer to which the neutral GRD is applied, but also the impacts potentially imposed on other transformers. In a partial deployment of neutral GRDs, where GRDs are installed on a fraction of the transformers in a system, installation of a neutral GRD on one transformer may shift a substantial portion of the GIC flow to other nearby transformers.

A carefully designed partial deployment of neutral GRDs may yield a large decrease of overall system GMD impact, relative to the number or percentage of transformers with GRD applied, as quantified by a system-wide metric. Examples of a system-wide metric are total transformer reactive losses due to GIC, average bus voltage, or least bus voltage. However, a poorly chosen deployment plan can potentially increase impacts by shifting GIC from transformers that are less sensitive to GIC, either in terms of reactive losses in proportion to net GIC (i.e., “K factor”) or in terms of thermal sensitivity, to transformers with greater sensitivity.

Any GIC analyses, and thus the GRD deployment plans that can be designed by such analysis, are inherently approximate. For example, the geo-electric field may not be uniform due to deep-earth geologic discontinuities that are not known. Also, the system configuration can change due to planned and unplanned system outages. Therefore, uncertainties need to be considered in the evaluation and deployment schemes. More robust approaches, with effectiveness less dependent on uncertain factors, may be preferred.

As mentioned previously, a resistive series (in-phase) GRD is not practical because of the large steady-state current and consequent losses and resistor power rating requirements. Because neutral current is not typically large during normal steady-state conditions, neutral GRDs can be either resistive or capacitive. A capacitive GRD blocks all GIC, whereas a resistive GRD reduces the GIC magnitude by increasing the total path resistance. Depending on the configuration of the transmission system, the GIC may be displaced to other paths or reduced overall. Where resistive GRDs are being considered, an added dimension to the GIC flow analysis used to plan deployment is the specification of the GRD resistance.

Total deployment of capacitive neutral GRD, i.e., GRDs in the neutral of all but one grounded-wye transformer, will not completely eliminate GIC (One transformer should be grounded to establish a dc voltage reference point for the system.). Non-uniformity of the geo-electric field can induce circulation of GIC in transmission loops, and where the loops are closed through the series windings of autotransformers, transformer saturation will still occur. While total neutral GRD deployment will substantially reduce GIC impacts, the system can still sustain adverse impacts such as voltage depression and unusual harmonic distortion as a result of GIC flowing through transformers of other interconnected transmission systems. Where total blocking is implemented, the dc voltage blocking requirement of each neutral GRD increases because the electric field intensity will be integrated over the distance from the grounded-neutral reference point.

5.2 Deployment Strategies and Objectives

There are various possible objectives for a GRD deployment plan. Examples include:

- Reducing or eliminating GIC from particularly vulnerable transformers
- Reducing GIC in all transformers to less than a prescribed threshold
- Reducing the system-wide impacts of GIC
- Eliminating all GIC flow in the system’s transformers

The plan for GRD deployment, including choices of the type of GRD and the system locations, depends on the overall objectives. Reducing GIC in a particular transformer is the simplest objective. This might be the preferred option when a particular transformer is known to have a design that is highly susceptible to GIC, or perhaps when a specific transformer is particularly critical to grid security or public safety. Another objective may be to reduce GIC in all transformers below a threshold that has been determined to be acceptable from a risk of transformer damage standpoint. This threshold can be defined in terms of an absolute net GIC magnitude (Amps), or more appropriately in proportion to the transformer's rating. Where the primary GMD concern is system security, the deployment objective may be to mitigate some measure of adverse system performance, such as total reactive power losses or voltage behavior. Reference [8] describes a systematic approach to optimizing GRD deployment. Total elimination of GIC in the system's transformers is the most extreme objective, and requires deployment of a very large number of GRDs and at least some of the devices must be series GRDs in order to block GIC circulation through autotransformer series windings.

6
GRD RATING

A GRD should be designed to reliably perform its intended function, continue to perform this function through a defined range of system events, and not fail for any credible contingency that may occur. GRD ratings that need to be addressed include:

- Steady-state quasi-dc voltage due to the GMD
- Steady-state alternating currents, including both fundamental and harmonic components
- Fault currents
- Other transient and temporary currents caused by switching events

6.1 Steady-State DC Voltage

In order to block or reduce GIC, a GRD must be capable of withstanding the quasi-dc voltage induced in the transmission system by the GMD that is the driver of the GIC. In the very simple case of a neutral GRD in a system without other GRDs, the maximum possible dc voltage withstand requirement is usually little more than the product of the maximum geo-electric field intensity times the length of the longest transmission line terminated at the substation (assuming that the stations at the remote end of the transmission lines have grounded-wye transformers without GRDs applied). However, with wider deployment of multiple GRDs, system analysis is needed to determine the dc voltage across each GRD, whether a neutral or series device. This analysis must consider any electric field orientation, at the maximum intensity anticipated. Power flow software tools with GMD analysis add-on applications model the dc network for GIC flow, can include GRD in the analysis, and should be capable of providing the voltages across GRDs as output for an assumed geo-electric field scenario.

Application of a conservative safety factor to the GRD dc voltage specification is prudent because there are significant modeling uncertainties and exceeding this rating could potentially result in either device failure, or protective bypassing of the device at the time when the device's function is most needed. Either failure or bypassing may result in a concentrated GIC flow through the path for which the GRD had been applied.

In most cases, the dc voltage withstand requirements are minimal relative to other stresses the GRD must endure. However, if total deployment of neutral GRDs to all or all but one grounded wye transformers is contemplated, the dc voltage withstand requirements may become quite large. Consider the extreme example of deployment of capacitive neutral GRDs to all but one grounded-wye transformers in the entire North American Eastern Interconnection (one neutral is grounded to establish a voltage reference). The geographic extent of the Eastern Interconnection is approximately 4000 km (Northeastern New Mexico to Nova Scotia, or South Florida to Saskatchewan). At an average electric field strength (wide area averaging is appropriate in this example) of 2 V/km, the dc voltage withstand requirements for GRDs at the extremes of the system would be 8 kV if the grounded-neutral reference point were established at the opposite side of the system. If the reference location is chosen at the center of the system, the dc voltage withstand requirements at the extremities would be approximately 4 kV. Considering ac voltages that also appear across the GRD, and the limitations of the relatively low insulation level of transformer neutrals, the dc voltage requirements in such a wide deployment plan can be quite significant to the device design. When additional GRDs are contemplated for a system with existing GRDs, the dc voltages across the existing GRDs must be reevaluated.

6.2 Series GRD Steady-State AC Duty

The steady-state alternating current duty of a series GRD is usually dominated by the fundamental-frequency load flow current, including both real and reactive components. Under normal conditions, steady-state harmonic current components are generally insignificant relative to the fundamental current. However, in a severe GMD, when a partial GRD deployment is made, there will be an atypical amount of harmonic current flow in the transmission system. Because capacitors have impedance that decrease with frequency, capacitors are relatively robust with regard to harmonic currents, and a practical series GRD would never cause a harmonic resonance, these harmonic currents are not expected to be of significance to series GRD rating requirements.

6.3 Neutral GRD Steady-State Fundamental-Frequency AC Duty

Transmission systems are rarely perfectly balanced, and there will almost always be a steady-state current flow through transformer neutrals, which are typically small relative to phase currents. The neutral current will have a fundamental-frequency component, due to transmission system imbalance, as well as harmonic components.

Line Imbalance

Fundamental-frequency zero-sequence voltages in the transmission system are primarily caused by the flow of positive sequence current through untransposed transmission lines, and the application of positive-sequence voltage to the unbalanced line charging of untransposed lines. Because distribution systems are decoupled from the transmission system in the zero sequence, load imbalance does not contribute to zero sequence (neutral) currents in the transmission system. The series impedance and shunt admittance matrices of an untransposed transmission line, in the sequence component domain, have off-diagonal terms. These off-diagonal terms represent cross-coupling of the sequence components. Figure 6-1 shows the series sequence impedance and shunt sequence admittance (line charging) matrices for a typical 500 kV line with flat conductor configuration. The Z01 term indicates the series zero-sequence voltage (V0) caused by flow of positive sequence current (I1). Similarly, the Y01 term indicates the zero-sequence current (I0) caused by applying the positive-sequence voltage (V1).

$$Z_s = \begin{pmatrix} 0.459 + 1.586i & 0.018 - 0.013i & -0.021 - 0.008i \\ -0.021 - 0.008i & 0.025 + 0.598i & -0.047 + 0.028i \\ 0.018 - 0.014i & 0.048 + 0.027i & 0.025 + 0.598i \end{pmatrix} \qquad Y_s \cdot 10^6 = \begin{pmatrix} 4.977i & -0.155 + 0.09i & 0.155 + 0.09i \\ 0.155 + 0.09i & 7.232i & 0.468 - 0.27i \\ -0.155 + 0.09i & -0.468 - 0.27i & 7.232i \end{pmatrix}$$

Figure 6-1
Series sequence impedance and shunt sequence admittance matrices for a typical 500 kV line with horizontal conductor configuration

In the simplified case of a single transmission line terminated by a grounded-wye delta transformer with a neutral GRD, the current driven through the GRD due to line series impedance imbalance can be approximately analyzed by representing the transmission line by the Norton equivalent circuit shown in Figure 6-2 (a). Second order effects, such as the negative sequence current (I_2) creating zero-sequence voltage via the Z_{02} term, are ignored. If this were a Thevenin model, the source voltage would be the product of $Z_{01} \cdot I_1$, where I_1 is the positive-sequence current of the line, and the source impedance would be Z_{00}. The Thevenin model can be converted to the Norton equivalent shown in Figure 6-2by substituting a current source equal to the Thevenin source voltage divided by the source impedance, and placing the source impedance in parallel (shunt) to the source. A Norton representation is convenient for combining the effects of series impedance imbalance and shunt admittance imbalance.

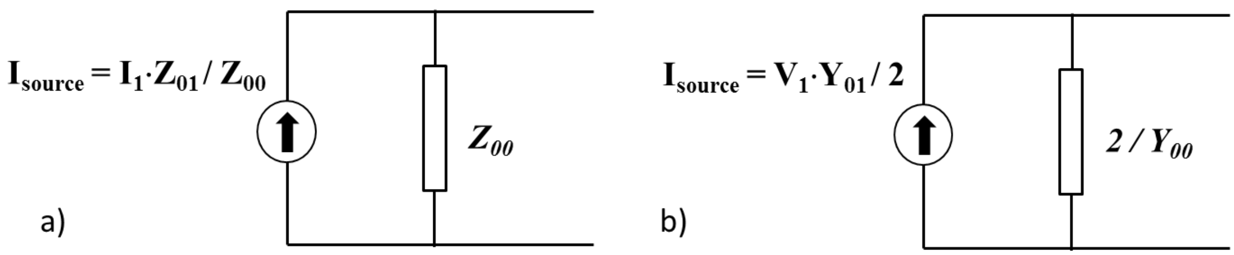


Figure 6-2
Norton equivalent circuits representing zero sequence current contributions from line series impedance and shunt admittance imbalance

Similarly, the GRD current due to line charging imbalance can be approximately analyzed by the circuit shown in Figure 6-2 (b), in which the V_1 $Y_{01}/2$ is the magnitude of a Norton-equivalent current source, and the shunt admittance of this source is one half of the zero-sequence self-admittance Y_{00} (the one-half factor assumes that the line is represented by a simple pi model).

It should be noted that the zero-sequence current contributions from line series impedance imbalance are functions of the line current magnitude and angle, which are highly variable in practice. In contrast, the contributions from shunt admittance imbalance are functions of the voltage, which varies little, and approximately the same voltage magnitude and phase angle is imposed on each line terminated at a substation bus. Therefore, the shunt admittance contributions are more likely to constructively superimpose if all of the lines have similar imbalance and are phased in the same configuration. In the worst case, all of the line impedance imbalance and shunt admittance imbalance contributions to zero sequence current through the neutral GRD could be in phase.

Impact of Neutral GRD on Current

Looking into a transformer neutral, the net fundamental-frequency impedance of any realistic transmission system is resistance plus inductive reactance. (An exception would be if nearly all of the other transformers in the system have capacitive GRDs.) Application of a resistive neutral GRD to this neutral will inherently reduce the steady-state fundamental-frequency neutral current. A capacitive neutral GRD, however, may cause neutral current to increase by cancelling some or all of the neutral's inductive reactance. When the capacitive reactance of the GRD equals one-third of the zero-sequence inductance, fundamental frequency resonance occurs, maximizing current. Fundamental frequency resonance in steady-state conditions may result in excessive GRD current duty, and may elevate the neutral voltage excessively. Generally, a fundamental-frequency resonance between a capacitive neutral GRD and the transformer plus system is a situation to be avoided.

The minimum reactance of a capacitive GRD, installed on the neutral of a grounded-wye-delta transformer, which can result in fundamental-frequency resonance, is one-third of the transformer's leakage reactance referred to the wye-winding side. Any additional system zero-sequence reactance, in series with the transformer's impedance, will normally be inductive and will allow a greater capacitive reactance before reaching resonance. The calculation of minimum capacitive reactance causing resonance for an autotransformer, however, is more complex. Assuming both the H and X terminals of the autotransformer are connected to infinite buses, the minimum capacitive reactance causing resonance for an autotransformer without a delta tertiary can be calculated by Equation 6-1. For an autotransformer with a delta tertiary, the minimum reactance can be calculated by Equation 6-2.

$$X_{critical} = \frac{X_{HX}}{3 \cdot (n-1)^2} \tag{6-1}$$

$$X_{critical} = \frac{1}{12} \cdot \frac{X_{HX} \cdot (X_{HX} - 2X_{XY} - 2X_{HX}) + (X_{XY} - X_{HY})^2}{(n-1) \cdot (n \cdot X_{HY} - X_{XY}) + n \cdot X_{HX}} \tag{6-2}$$

In Equations 6-1 and 6-2, X_{HX}, X_{HY}, and X_{XY} are the terminal-to-terminal leakage reactances of the transformer in per-unit and n is the transformer nominal terminal voltage ratio.

The minimum capacitive reactances for an autotransformer, that can potentially result in fundamental resonance, are quite small. Example values of critical neutral capacitive reactance for typical autotransformer parameters are shown in Table 6-1. It should be noted that the values in this table were calculated with infinite buses at the transformer terminals, and system zero-sequence impedance will tend to increase these minima.

Table 6-1
Critical neutral capacitive reactances permitting fundamental-frequency resonance for example transformer parameters

Rating	Nominal Voltages		Transformer Reactances			Critical X_n	
MVA (3ph)	V_H (kV L-L)	V_X (kV L-L)	$\%X_{HX}$	$\%X_{HY}$	$\%X_{XY}$	X_n (%)	X_n (Ω)
1200	765	345	10	41	29	0.99	48.2
1000	500	345	8	51	37	3.40	84.9
600	500	230	8	30	18	0.64	26.8
450	345	230	7	30	17	1.50	39.6
750	345	230	8	52	36	2.75	43.6
450	345	138	7	40	27	0.47	12.5
600	345	115	7	26	17	0.28	5.5
300	230	115	7	50	37	1.08	19.1
750	230	115	7	50	37	1.08	7.6

6.4 Determination of Steady-State Neutral GRD AC Ratings

It is critical that the specifications and design of a neutral GRD adequately consider the maximum fundamental current, in order that the GRD can reliably remain in service and without damage when needed. There are several different approaches to determining the fundamental current specification, including:

- Monitoring neutral currents over a long period.
- Detailed system imbalance analysis.
- Simplified bounding analysis assuming a worst-case zero-sequence bus voltage.
- Detailed bounding analysis considering characteristics of nearby transmission lines.

Neutral Current Monitoring

Neutral currents of an operating transformer can be monitored over a long period of time, perhaps several years, to estimate the range of current magnitudes over a wide range of seasonal loading conditions and system contingencies. Statistical analysis of the recorded data may be performed to more accurately estimate maximum values with a desired degree of confidence. However, such an approach does not inherently take into account the full range of system contingencies and flow conditions that may affect these currents, particularly the atypical operating conditions that might be present during a severe GMD event.

Unless the proposed neutral GRD impedance is very small, the GRD will change the neutral ac current magnitudes from those measured on a transformer without the GRD present. In the worst case, resonance of a capacitive neutral GRD with the system can result in neutral currents that are an order of magnitude or more greater than neutral currents prior to GRD installation. Therefore, measured values must be corrected for the effect of the GRD impedance. Ideally, each individual measurement sample should be corrected considering the actual transmission system zero-sequence impedance present at the time of the sampling. This, however, is impractical. Instead, it will be necessary to correct measured neutral currents assuming worst-case system zero-sequence impedance conditions.

Detailed Imbalance Analysis

An alternative to a very lengthy monitoring program, of possibly uncertain accuracy in predicting worst-case conditions, is detailed system modeling and analysis. The detailed calculation of steady-state neutral currents requires extensive load flow analysis in a software program capable of representing system imbalance; either in the symmetrical component domain or the phase domain with full three-phase analysis.

The imbalance analysis requires model data that are not frequently used in transmission planning. The cross sectional dimensions of the transmission line as well as conductor data and earth resistivity at 60 Hz are needed to calculate the full series impedance and shunt admittance matrices of each line. In addition, the phasing of each line (e.g., Phase A in the center, Phase B on the right, Phase C on the left, etc.) must be exactly known. Any line transpositions must also be accurately modeled.

The contributions to neutral current from each line have a complex relationship to the current magnitude and relative phase angle with respect to voltage. Furthermore, the relationship of line flows to the neutral flow of autotransformers is even more complex because the neutral current is also a function of the zero-sequence current flow between the voltage levels through the autotransformer. Therefore, a sufficiently complete analysis requires exhaustive consideration of all possible real and reactive power flow patterns in the transmission system.

The system model should have the impedances of all GRDs represented. Alternatively, for a single GRD, the analysis could be performed with the neutral open and short-circuited. From the open-circuit voltage and short-circuit current, a Thevenin equivalent can be derived for the system, including the transformer, as seen from neutral. This can allow evaluation of different GRD impedances without re-performing the system imbalance analysis. Use of worst-case Thevenin source voltage with worst-case Thevenin impedance is conservative (slightly pessimistic), because the conditions producing each may not be the same. When multiple neutral GRDs are being considered, the Thevenin equivalent process can also be used, but the impedances will be a matrix because the impedance of a GRD at one location will affect neutral currents at other GRD locations.

Software tools to conveniently perform this analysis are not widely available. Except where specialty software is available, the best widely-available option is the steady-state (initialization) analysis capability of electromagnetic transient (EMT) analysis programs. These programs, however, do not have the convenience of loadflow programs, and require specialized expertise to use.

Simplified Bounding Analysis

An alternative to detailed analysis is a bounding calculation approach. Zer0-sequence voltages in a typical transmission system are usually less than a certain value, typically 0.01 p.u. A conservative assumption of the maximum zero sequence bus voltage can be used to estimate an upper limit to possible neutral current.

For a grounded-wye/delta transformer, such as a GSU, the neutral current is calculated using Equation 6-3:

$$I_n = \frac{3 \cdot V_0}{Z_{HX} + 3 \cdot Z_n} \tag{6-3}$$

In Equation 6-3, V_0 is the zero-sequence voltage applied to the transformer's wye terminals, Z_{HX} is the impedance of the transformer, and Z_n is the neutral GRD impedance.

The zero-sequence impedance of a grounded-wye/delta transformer, such as a GSU, is equal to the transformer's leakage impedance. This impedance is typically 0.08 p.u. or greater on the transformer's base. If a neutral GRD has insignificantly-small impedance, the neutral current would be no greater than 0.375 p.u. on the transformer's phase winding current base for a 0.01 p.u. zero sequence voltage at the transformer's terminals (on the grounded-wye winding). A capacitive GRD would increase the neutral current, and a resistive GRD would decrease it. For a given GRD application evaluation, the actual neutral GRD impedance should be used. It should be noted that this analysis ignores the zero-sequence impedance of the system that is in series with this observed zero-sequence voltage. Thus, this estimate is conservative for ordinary conditions, when resistive, low-impedance capacitive, or intermediate-impedance capacitive neutral GRDs are considered. Also, with very wide-scale deployment of capacitive GRDs, the external system zero-sequence impedance could potentially be capacitive.

For high-impedance capacitive neutral GRDs, ignoring the system impedance may not be conservative because these devices, by definition, have a resonant frequency above fundamental when their transformer is connected to an infinite bus. Connection to a bus with finite short-circuit strength can potentially move the resonant frequency down to the fundamental, leading to much higher neutral current than calculated by this simple analysis.

Autotransformers pose a much more complicated situation, as the neutral current depends on the zero sequence voltages on both the H and X terminals, as well as the difference in these voltages. Neutral currents, in per-unit on the base of the H terminal, can be calculated using Equation 6-4 for given terminal zero sequence voltages V_H and V_X (each in per-unit on their respective bases):

$$I_n = \frac{V_H \cdot \left(2Z_{XY} + n \cdot \left(Z_{HX} - Z_{HY} - Z_{XY}\right)\right) + V_X \cdot \left(2n \cdot Z_{HY} + Z_{HX} - Z_{HY} - Z_{XY}\right)}{12Z_n \cdot \left(\left(n-1\right) \cdot \left(Z_{XY} - n \cdot Z_{HY}\right) - n \cdot Z_{HX}\right) + Z_{HY} \cdot \left(Z_{HY} - 2Z_{XY} - 2Z_{HX}\right) + \left(Z_{HX} - Z_{XY}\right)^2} \tag{6-4}$$

In Equation 6-4, Z_{HX}, Z_{HY}, and Z_{XY} are the terminal-to-terminal leakage impedances of the transformer in per-unit. V_H and V_X are the zero-sequence voltages behind the source impedances, and n is the terminal voltage ratio.

For autotransformers without a tertiary, or which have a high tertiary impedance (or effective tertiary impedance in the case of a three-leg core-form transformer without an actual tertiary winding), the key factor is the difference in the per-unit zero-sequence voltages on the H and X terminals. The worst case is for the two zero-sequence voltages to be 180° out of phase, which is a realistic situation. For autotransformers with more typical delta winding impedances (on the order of approximately 0.3 p.u. or less on the main winding MVA base), zero-sequence voltages in phase with each other may provide the worst case.

This bounding analysis approach requires that a conservative estimate is made of the worst-case zero-sequence bus voltage. The resulting steady-state neutral currents from this simple analysis, however, will be quite high. If the neutral GRD design is sufficiently robust to accommodate such currents, then more detailed analysis may not be needed. However, if the currents based on this estimate cannot be practically accommodated, then either detailed system analysis, or an alternative modified analysis approach described below, will be needed.

Detailed Bounding Analysis Considering Line Characteristics

A modified bounding analysis can be performed to determine neutral GRD fundamental-frequency current rating requirements that avoid both the excessive conservatism of the simply bounding analysis (assuming a conservative V_0 is assumed) and the extensive network modeling required by the previously-described detailed analysis. This modified approach considers the actual characteristics of the transmission lines connected to the buses to which the GRD-protected transformer or autotransformer is connected.

This approach converts each transmission line connected to the bus into zero-sequence Norton equivalent circuits for the series impedance imbalance and shunt admittance balance components. A "line" in this case is the total line length out to the next significant grounding source (i.e., a bus with a grounded-wye delta transformer or an autotransformer with a delta tertiary). Thus, switching stations without transformers are ignored and the "line" continues on. Line positive sequence currents, which "drive" the series impedance imbalance contributions, can be conservatively assumed to be equal to the rated current of the line.

The Norton equivalents for each line are paralleled. This means that the source currents are summed, and the equivalent shunt impedances are paralleled. Summation of the equivalent source current requires consideration of the known and unknown phase relationships between each. Because nearly the same positive-sequence voltage is applied to each line, the equivalent current sources related to shunt admittance imbalance should be added vectorially (i.e., as phasors). It is important that the calculations of line sequence impedances are based on the actual phasings of the lines. If phasing is not reliably known, then algebraic summation (summation of magnitudes as scalars, not phasors) is conservative. Because the current phase angles, related to the real and reactive power flows, on each line can vary widely, it is reasonable but conservative to algebraically sum the series impedance imbalance contributions. The total series impedance contribution is then summed algebraically with the resultant shunt admittance imbalance contribution. The resulting Norton equivalent source can be converted to a Thevenin equivalent, and the resulting voltages and impedances, along with the transformer and neutral GRD parameters, can be used to calculate neutral current. For a grounded-wye delta transformer, the neutral current due to transmission imbalance on the wye side can be calculated by Equation 6-3.

For autotransformers, the composite equivalent sources are calculated separately for the H (HV) and X (LV) sides. The Thevenin source voltages and equivalent impedances for each side, in addition to the transformer and GRD neutral impedance values, can be applied to Equation 6-5. It is recommended that the source voltages be applied as scalars, and calculation of neutral current made for both voltages in the same polarity, and with opposite polarities, to determine the worst case neutral current for specification purposes.

$$I_n = \frac{V_H \cdot (2(Z_{XY} + Z_{Xs}) + n \cdot (Z_{HX} - Z_{HY} - Z_{XY})) + V_X \cdot (2n \cdot (Z_{HY} + Z_{Hs}) + Z_{HX} - Z_{HY} - Z_{XY})}{Denom.}$$

$$\begin{aligned} Denom. = {} & 12Z_n \cdot ((n-1) \cdot (Z_{XY} - n \cdot Z_{HY}) - n \cdot Z_{HX}) + Z_{HY} \cdot (Z_{HY} - 2Z_{XY} - 2Z_{HX}) + \\ & (Z_{HX} - Z_{XY})^2 - 12Z_n \cdot (n^2 \cdot Z_{Hs} + Z_{Xs}) - 4Z_{Xs} \cdot (Z_{HY} + Z_{Hs}) - 4Z_{Hs} \cdot Z_{XY} \end{aligned} \tag{6-5}$$

In Equation 6-5, Z_{HX}, Z_{HY}, and Z_{XY} are the terminal-to-terminal leakage impedances of the transformer in per-unit. Z_{Hs} and Z_{Xs} are the source impedances of the imbalance equivalent circuits in per-unit on the transformer base. V_H and V_X are the zero-sequence voltages of the imbalance equivalent circuits, and n is the terminal voltage ratio of the transformer.

This analysis method does inherently limit consideration to the imbalance of only the immediately adjacent transmission lines. Imbalance of other more remote lines may also contribute to neutral currents. However, the approach of considering worst-case phasing of each adjacent line's currents (by algebraically summing their contributions) is believed to more than offset the optimistic limitation of analysis to the first tier of lines.

6.5 Neutral GRD Harmonic Current Duty

In addition to fundamental frequency current, transformer neutral currents typically have substantial harmonic content. These harmonics are primarily due to the zero-sequence components of transformer exciting currents, and to a much lesser extent harmonics injected by loads, generators, FACTS devices, and HVDC converters. The transformer harmonic exciting current contribution is not limited to only the transformer at which the neutral current is measured, but also includes harmonics injected by other transformers in the system.

In addition to neutral current harmonics due to transformer magnetization, there may also be harmonic currents due to other sources in the distribution and transmission system. Harmonics caused by loads, however, do not directly result in zero-sequence harmonics (i.e., neutral current harmonics) at the transmission level. This is because distribution systems, industrial loads, and generators are always interconnected to the transmission system through transformers that provide zero-sequence isolation (typically delta HV, grounded-wye MV). Likewise HVDC systems and FACTS devices at the transmission level use transformer and device connections that block zero sequence currents. Therefore, any transmission system neutral harmonics due to these sources are the result of transformation of positive and negative sequence currents to the zero sequence by transmission line imbalance. While fundamental-frequency impedance imbalance of transmission lines is small, the imbalance can be greatly magnified at harmonic frequencies near resonances. Even transposed transmission lines can present significant imbalance at harmonic frequencies.

A common misconception is that only harmonics with orders that are multiples of three (triplens) appear in neutral currents. This is true for magnetizing current harmonics only if all transformers in the system are three-phase banks of single-phase units, providing an identical magnetic characteristic in each phase, and these transformers are excited by perfectly balanced positive-sequence voltage. A large percentage of transformers in a transmission system, however, are three-phase units. The magnetic circuits of three-phase transformers are not the same for each phase, and thus the symmetrical components of the transformer exciting current include nontriplen harmonic orders in the zero sequence and triplen orders in the positive and negative sequences [9]. Harmonics from any source and any harmonic order, injected into the transmission system in the positive and negative sequences can be transformed to the zero sequence by transmission imbalance.

These steady-state harmonic components in the neutral current, during normal system conditions, are generally not critical to low-resistance and low and intermediate impedance capacitive neutral GRDs. High capacitive impedance GRDs may be particularly vulnerable to harmonics because these GRDs can create zero-sequence resonances at harmonic frequencies, which can greatly amplify the amount of harmonic neutral current. High resistance neutral GRDs may also be vulnerable to harmonic voltages which appear across the devices.

Where a partial GRD deployment is made (GIC is not blocked in all transformers of a system or in neighboring systems), GIC will continue to flow through many or even most transformers, albeit at a generally reduced magnitude. This GIC flow will produce transformer saturation, which will tend to increase harmonic zero-sequence current magnitudes during GMD above typical levels. Because it is essential for a GRD to remain in service during a GMD, the GRD must be rated for this increased neutral current.

The increased neutral GRD duty due to GIC saturation can result from both the remaining GIC flow in that transformer (e.g., flow through an autotransformer series winding, or where a resistive GRD is used), and also from GIC flow in other transformers. Zero sequence harmonics can potentially be magnified at locations other than their point of injection by system resonances. Detailed evaluation of neutral GRD duty requires coupling the results of GIC flow studies, including consideration of all geo-electric field orientations, with detailed network analysis of zero-sequence fundamental and harmonic propagation, considering transmission system configuration variations and contingencies. The coupling between the GIC and ac flow analyses require transfer functions from net GIC to fundamental and harmonic exciting currents for each transformer [10]. Creating these transformer GIC-to-exciting-current transfer functions requires modeling of the transformer magnetic circuit topology, which is relatively simple for single-phase transformers but much more complex for three-phase transformers.

Even if a total GRD deployment eliminates all GIC saturation, there is the potential that the failure or protective bypassing of one GRD could increase the neutral current duty on other GRDs, causing some of these devices to either fail or protectively bypass. Such a cascading scenario must be avoided as the effectiveness of the GRD deployment plan is threatened. Therefore, a GRD contingency evaluation should be included in the determination of GRD ac neutral current rating. In addition to consideration of bypassing of individual GRDs, this contingency evaluation should consider any common-mode events such as transmission system faults that cause multiple GRD to bypass (robustness of GRD for faults is discussed later in this section).

An alternative to these extensive analyses to determine increased neutral GRD current duty during GMD would be to apply a conservative multiplying factor to the steady-state current duty without GMD present. However, this guide cannot suggest an appropriate factor to use, as there have been no case studies on actual transmission systems that can be used to calibrate such a suggestion.

Because low and intermediate impedance capacitive GRDs present even lower impedance to harmonic currents, and capacitor units are quite tolerant of substantial harmonic current, the harmonic current issue is of much less relevance to this type of GRD than a resistive GRD. Allowing ample margin in the capacitor ac current specification may be an acceptable alternative to the extremely complex harmonic studies described above. Particular caution is recommended for high-impedance capacitive GRDs because of the potential for the GRD itself to become involved in a lightly-damped zero-sequence resonance at harmonic frequencies.

Fault Current Duty

Faults in the transmission system greatly increase currents through both series and neutral GRDs, and withstanding fault currents is one of the greatest challenges of GRD design. Series GRDs are exposed to high currents by all types of faults, but neutral GRDs are only exposed to substantial fault currents by ground faults. (A three-phase fault on an untransposed transmission line will temporarily cause increased neutral current in approximate proportion to the ratio of fault current magnitude to load current magnitude.). Fault currents have not only a fundamental-frequency (symmetrical) component, but also a dc offset that depends on the point-on-wave of fault occurrence. Faults that occur near ac voltage zero result in the greatest fault current offset.

GRD Fault Withstand Strategies

GRDs must survive faults without equipment failure, but whether the device remains in service through the fault, bypasses during a fault but returns to service immediately following fault clearing, or bypasses and remains locked out are matters of GRD design and application strategy. For a GRD to remain in service without bypassing during fault conditions, a means of limiting voltage across the GRD, such as MOV, is usually required. The MOV needs to have the energy capability to withstand the defined fault duty. If the GRD is bypassed and remains bypassed after a fault (locked-out condition) during a GMD event, the GIC flow through the path otherwise mitigated by the GRD is likely to be greater than without GRD mitigation (if there are multiple GRDs applied) because the flow from other paths blocked by other GRDs are likely to be diverted to the path with the bypassed GRD [11]. If a GRD is designed to protectively bypass during faults, but return to function immediately after the fault is cleared, the device must have bypass switchgear capable of interrupting the GIC flow and the GRD must withstand the transient reinsertion voltage across the device.

Fault Ride-Through Without Bypass

Although challenging, it is possible to design a GRD to withstand the most severe fault conditions without bypassing. Practically, this requires a low-impedance GRD design, either resistive or capacitive.

As previously explained in Section 1.1, resistive GRD can only be used in neutral applications because the losses would be excessive in a series application. A low resistance GRD may also have limited GIC reduction capability. For a low-resistance neutral GRD, the product of the GRD resistance times the neutral current during the fault, including both the fundamental frequency and offset components, must be within the temporary overvoltage capability of the surge arresters that are necessary to protect the transformer neutral from transient surges. The GRD’s resistor must have sufficient energy capability to withstand the worst case fault current magnitude and duration.

More effective GIC mitigation is provided by capacitive GRDs, and capacitive GRDs can be used in both series and neutral applications. Fault current offset is a particularly significant issue for low-impedance capacitive GRD designs. The capacitive impedance of such devices can be made sufficiently low such that the product of the symmetrical fault current times the impedance results in ac voltage peaks that do not cause excessive voltage. The fault current offset, however, will initiate low-frequency oscillations with a prospective voltage magnitude across the GRD that far exceeds the fundamental-frequency voltage. Figure 2-1 previously illustrated the magnitude of the low-frequency voltage oscillation relative to the fundamental-frequency voltage across the GRD. To make the GRD design feasible, overvoltage limitation is needed. For a non-bypass design, the overvoltage limitation can be provided by MOV. The same simulation case is repeated in Figure 6-3 with MOV limiting the GRD voltage to a level just above the symmetrical voltage peak (1.414 times the product of the symmetrical rms fault current times the GRD capacitive reactance). The duration of the fault, and the simulation are extended in this later simulation to illustrate the control of the low-frequency oscillation provided by the MOV. The MOV conducts during the immediate post-fault period to suppress the low-frequency oscillation caused by the fault offset, but does not conduct significant current on a continuous basis during the remainder of the fault period or after the fault is cleared. With such a low-impedance capacitive neutral GRD design, the fault duration becomes a much less significant factor, and it can be possible to design such a device to survive worst-case fault duty without bypassing.

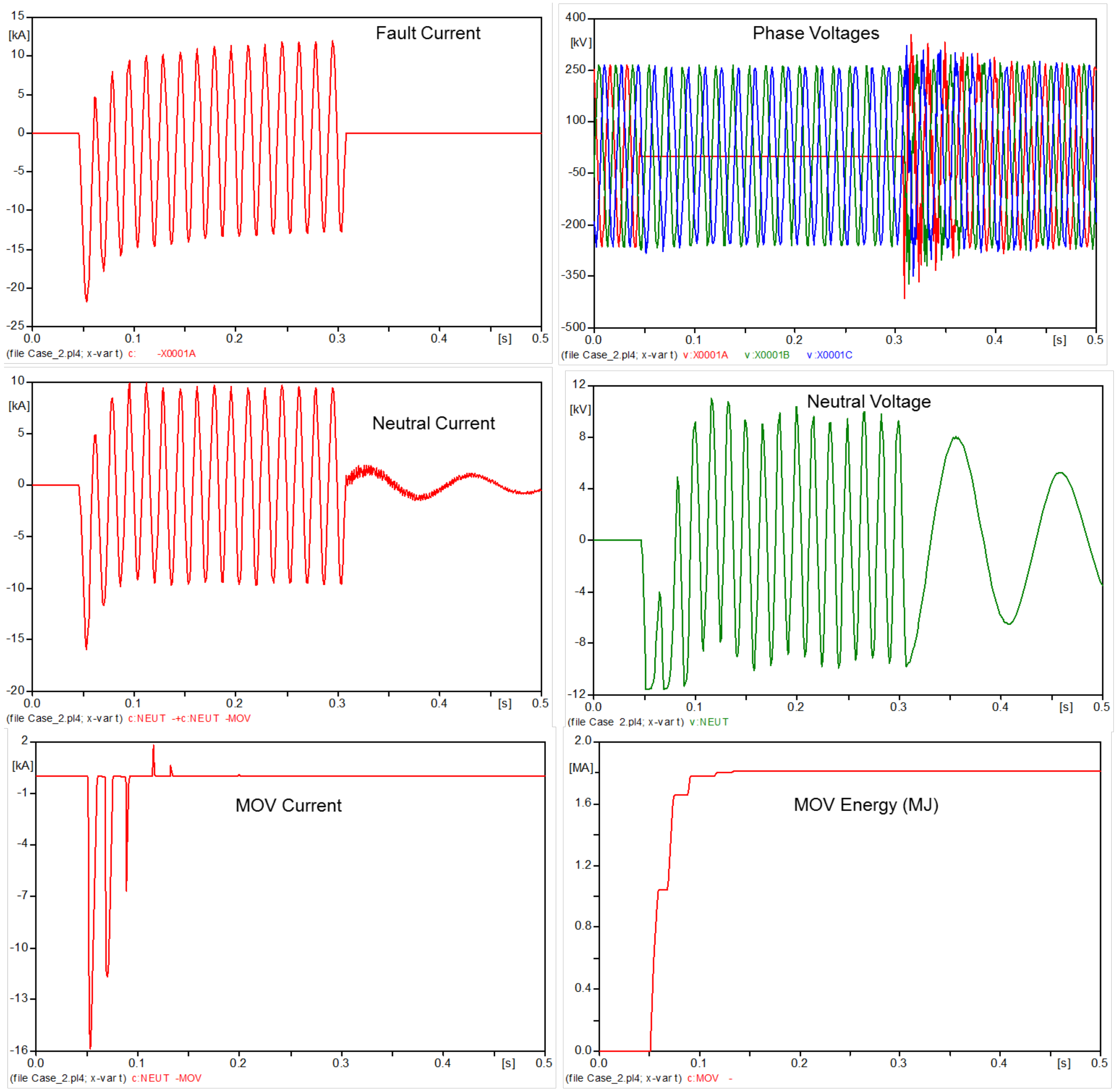


Figure 6-3
Results for repeat of the same fault as shown in Figure 2-1, except an MOV with 12 kV protective level is in parallel with the low-impedance capacitive neutral GRD. (Fault duration extended for illustration.)

Protective Temporary Bypass Strategies

A GRD may be protected from fault currents by bypassing the device during faults by using a mechanical switch, gap, or power electronic switch. Designs can use more than one of these methods, such as gaps or electronic switches for immediate action, followed by mechanical bypass switch closing to remove the fault current from the gap or electronic device. Bypass using mechanical switching alone requires the use of MOV to limit voltage until the switch can close.

Bypassing of the GRD can be used as a protective means for all faults, or only for faults with current greater than a defined level of severity. Where bypassing is not used for all faults, MOV with substantial energy capability is generally required to limit GRD voltages during non-bypass fault events. A strategy of bypassing for all faults increases the probability that a GRD will bypass during a critical GMD period, and the desirability of automatic GRD reinsertion capability becomes more significant.

Conventional series capacitors are typically designed so that they bypass only for faults that are located on the line on which the series capacitor is located (internal faults). This same strategy can be used for series GRD. For an internal fault, the line will be de-energized to clear the fault, so the bypassing does not detract from the GIC mitigation function. The GRD can be reinserted before the line is re-energized (reclosed), without any need for direct current interruption and without a reinsertion transient.

When a passive series GRD design approach is used, the MOV voltage limitation needs to be rated for the worst case fault magnitude and duration. Because MOV heating is cumulative, and only limited cool-down can occur during a line open period during a reclosing sequence, the duty from multiple consecutive faults may need to be considered in the GRD fault rating.

A neutral GRD only experiences significant fault current duty during ground faults. A neutral GRD can be designed to bypass for all ground faults, or only for the most serious faults. When a neutral GRD is bypassed during a GMD event, the transformer to which the neutral GRD is connected will experience unmitigated GIC flow. If other GRDs are deployed in the system, and are not bypassed, the GIC flow through the transformer with the bypassed GRD may be substantially greater than if the same GMD event were to occur with no GRD deployment in the system. This is because the GIC flow that is blocked from flowing through the active GRDs is likely to be concentrated in the unprotected neutral.

Reinsertion of a bypassed neutral GRD during a GMD event requires the bypass switch to have dc interruption capability. When the GIC is interrupted by the bypass switch, a voltage transient will result. For a resistive GRD, the initial voltage is simply the product of the GIC times the resistance. Parasitic inductance in the circuit, however, may cause a short-duration transient voltage in excess of this amount. In a simple system with a single capacitive neutral GRD, the magnitude of this transient reinsertion voltage is:

$$V_{pk} = I_{GIC} \cdot \sqrt{\frac{3 \cdot L_0}{C}} \tag{6-6}$$

In Equation 6-6, I_{GIC} is the <u>per-phase</u> GIC, L_0 is the zero-sequence inductance of the circuit, and C is the capacitance of the GRD. The zero sequence inductance L_0 includes the inductance of the transmission system, but is often dominated by the inductance of the transformer to which the GRD is connected. Where there are multiple neutral GRDs in a system, the transient reinsertion voltage performance is more complex, and generally requires simulation to determine its magnitude.

If the primary overvoltage limitation means for the GRD is MOV, then the reinsertion transient must be within the energy capability of the MOV. The reinsertion may occur immediately following a fault event, so the reinsertion transient duty may be cumulative with the fault duty. If a voltage threshold is used to trigger GRD bypass (e.g., simple spark gap), rather than an MOV energy threshold, the reinsertion transient must not result in triggering another bypass.

Permanent Bypass and Sacrificial Component Strategies

GRD designs using sacrificial components have been commercially offered. These GRD must remain locked out following faults until the sacrificial components are replaced. This approach has been justified by the statistical improbability of a fault at the GRD location during the relatively small amount of time that a GRD would need to be placed in service during a GMD alert. However there are other factors to consider:

- The strategy of maintaining the GRD in the bypass mode except when a specific GMD condition is detected provides no protection or delayed protection for GMD-like events, such as EMP, that can occur without warning.
- Depending on the GRD design, a fault need not be directly at the GRD location in order for the sacrificial component to intentionally fail. If the GRD design is not sufficiently robust, faults quite distant from the GRD location could cause this failure. If so, the probability of fault occurrence is markedly increased.
- There are several reasons to speculate that fault probabilities during a GMD are at least somewhat greater than average. These reasons include:
  - The power system components are under stress during a GMD, particularly if a partial GRD deployment strategy is chosen. One such stress is potentially excessive transformer heating that could possibly lead to a transformer fault. Another is that, during a GMD, harmonic distortion of voltage may be so great that the voltage peaks are substantially above the MCOV rating of surge arresters. Arrester thermal instability, leading to fault across the arrester, is a potential outcome.
  - When a GMD alert occurs, a typical operating procedure for utilities is to recall to operation all possible components that are on maintenance outage, to increase system robustness. The switching involved in returning equipment to service inherently causes a finite increase in the probability of fault occurrence.

Application studies for GRDs using a permanent bypass protection approach need to determine the “radius of vulnerability”; i.e., the extent of the transmission system zone wherein a fault will result in the permanent GRD bypass or sacrificial GRD component failure. The consequences of any GRD bypassing should also be evaluated, considering the GIC flow that results, and the impact that this GIC flow makes on the individual system components (e.g., transformers) and the overall system performance. With knowledge of the extent of vulnerability, estimation of the probability of a fault within this zone during a GMD alert condition, and the consequences of a permanent GRD bypass during a GMD, an informed decision can be made regarding acceptability of this GRD design approach.

6.6 Transients Other Than Faults

System events other than faults can impose transient and temporary duties on a GRD. These events include switching of lines, capacitor banks, transformers, etc. Also included is insertion of the GRD into operation (i.e., opening a bypass switch). To the extent that such events may take place during a GMD event, it is essential that the GRD remain in operation. Temporary bypassing of GRDs during these transients is relatively inconsequential from the standpoint of GIC impacts, provided the GRDs are immediately reinserted following the transient event. The design of the GRD, however, must ensure that the reinsertion is successful even during worst-case GMD conditions. Failure or permanent bypassing of a GRD, however, is not acceptable for these routine events.

GRD Insertion

Insertion of a GRD into a circuit is typically executed by opening a bypass switch, diverting current from the bypass branch into the GRD's impedance. Without the presence of significant GIC, the current interrupted by bypass opening is ac, and interruption would generally occur at a current zero. The resulting change in impedance of the GRD from zero to a finite value stimulates a transient that is normally oscillatory, with voltage peaking in excess of the final steady-state value. The magnitude, frequency, and damping of this transient response is dependent on the entire circuit, including the transformer (in the case of a neutral GRD) or line (in the case of a series GRD) and the remainder of the transmission system, in addition to the impedance characteristics of the GRD itself.

If a GRD is inserted, or reinserted, while GIC is flowing, there may be no current zeroes. This is particularly the case for neutral GRDs. Thus, the GRD bypass switch will generally need to be capable of dc interruption. (Transformer saturation caused by the GIC may result in neutral harmonic currents with peak magnitude exceeding the GIC, thereby causing current zeroes during steady-state conditions. This saturation, however, may be initially delayed due to circulating currents in the transformer's delta winding. As a result, neutral GRD reinsertion, following a GRD bypass, is likely to require interruption of current without natural current zeroes.) "Chopping" of dc will generally stimulate much more severe transients than interruption of an alternating current.

The resulting GRD insertion voltages should not be allowed to endanger the insulation level of any equipment and should not trigger a subsequent bypass action. Where MOV is used to limit GRD voltage, the insertion transient should not create excessive energy duty. When reinsertion immediately follows a fault, the energy duty caused by reinsertion may be cumulative to the energy duty imposed by the prior fault. Transient simulation is necessary to evaluate the transients and equipment duties caused by insertion of GRDs.

Short-Term Overload

In addition to faults, tripping of generators, loads, and lines can stimulate electromechanical power oscillations (i.e., "power swings") in the transmission system. In addition, these and other events can also result in short-term overloads in excess of normal line rating. Series GRDs need to be designed with sufficient short-term overload capability in order to withstand such events without damage or long-term bypassing. While such events primarily affect positive-sequence current flow, the fundamental current in transformer neutrals due to positive-to-zero sequence coupling resulting from line imbalance will also increase proportionately. Therefore, such short-term overloads are also a consideration for neutral GRDs as well.

Transformer Energization

Energization of a transformer will result in very substantial currents in the neutral of the switched transformer, due to magnetic inrush. If a neutral GRD is intended to not be in a bypassed mode when its transformer is energized, the GRD needs to be capable of withstanding worst-case energization conditions. Without residual transformer flux, the most severe inrush on a given phase results from energization at voltage zero. With consideration of residual flux, the worst-case energization timing may vary. The most severe neutral current severity may not coincide with voltage-zero energization on each phase, however. This is because the worst neutral current results when the inrush current components are in phase (i.e., zero sequence). This coincidence is not readily predictable, particularly with consideration of remnant (residual) transformer flux. Therefore, a Monte-Carlo type of simulation analysis is needed to determine neutral GRD duty from transformer energization.

A reasonable operating strategy is to always place a neutral GRD into the bypass mode prior to energization of the transformer to which the GRD is connected, provided that the GRD can be inserted in the presence of GIC. The impacts of transformer energization are not limited to the transformer that is energized, however. Energization of a transformer injects zero-sequence fundamental and harmonic currents into the transmission system. Depending on system impedance characteristics and resonances, neutral GRDs on other transformers may experience a substantial increase in current, persisting for many seconds, following energization of another transformer. Because the inrush event is generally not balanced between the phases, due to different points on wave of the energization, harmonic currents that appear in the zero sequence are not limited to harmonic orders that are multiples of three (triplen harmonics). Therefore, an anti-resonance (impedance resonance) near any of the low-order harmonic frequencies can amplify the neutral current of a transformer caused by energization of another transformer.

A phenomenon called “sympathetic inrush” can occur when one transformer is energized, and another nearby transformer exhibits the symptoms of inrush. This is caused by the dc component of the inrush current of the energized transformer interacting with the system resistance to cause a dc voltage component of the bus voltage. This dc voltage component, over time, integrates to develop a dc offset flux on the cores of other nearby transformers, resulting in asymmetric saturation similar to that produced by GIC or energization. With neutral GRDs applied to other transformers, the transformers are usually not driven into sympathetic inrush, but dc voltage component will appear across the GRD. In the case of a capacitive GRD, zero-sequence oscillations will be stimulated.

Unless it can be determined that a transformer never needs to be switched during a GMD event, it is necessary to ensure that GRDs can survive transformer energization events. If bypassing occurs during transformer energization, the GRD must be able to be automatically reinserted. Failure of a sacrificial component should not occur for a transformer energization.

Transformer Deenergization

Because switchgear opening the phases of a transformer will normally open at current zero, there will be a brief period of under one-half cycle duration when only one or two phases will be energized, even if the breaker poles open simultaneously. This unbalanced period may be longer if the poles do not open simultaneously, which may be the case when switching is performed using circuit switchers. This period of imbalance will result in some neutral current. It is immaterial if a neutral GRD should bypass, or MOV should conduct, during such an event, as long as there is no damage to the GRD or other equipment.

It is possible for a breaker or circuit switcher pole to fail to open (“hung pole”). Because this condition places the nonlinear magnetizing inductance of the transformer in series with the GRD, ferroresonance is a possible result for a capacitive neutral GRD. This could potentially result in a sustained elevated voltage across the neutral. While bypassing will eliminate this phenomenon, it is possible for the voltage to remain just below the bypass threshold. This voltage could also cause MOV to conduct. Ferroresonance tends to be a very low-current event, so MOV rated to withstand fault current for even a brief duration is likely to be able to sustain this low-current condition for a quite long period. The neutral voltage could also be continuous at a magnitude just below the conduction level of the MOV. Therefore, if this ferroresonant condition could occur, the bypass voltage threshold or MOV voltage protective level may need to be coordinated with the continuous voltage capability of all equipment exposed, including the transformer neutral and the GRDs capacitors. If a time-overvoltage protection is used to initiate bypass, then this protection needs to be coordinated with the temporary overvoltage capability of equipment instead of the continuous voltage ratings.

In some system configurations, it is possible for a line or capacitor bank to be deenergized along with a transformer having a neutral GRD. The trapped charge on the line or capacitor bank will result in an oscillatory ring-down through the transformer. Because the ring-down is unlikely to be balanced, it is likely to subject the neutral to current. The GRD needs to be designed to survive such an event, if possible, or otherwise self-protect via bypassing. An alternative is to initiate bypass for any tripping of the transformer.

Line, Cable, and Capacitor Bank Energization

Energization of transmission lines, cables, and capacitor banks can cause transient currents in GRDs. Due to the high-frequency nature of these transient currents, very little transient voltage appears across series capacitor GRDs and low and intermediate impedance capacitive neutral GRDs. Neutral GRDs of a high resistance or high-impedance capacitive design may experience significant transient voltages. GRDs need to be designed to withstand such switching events, as they are likely to occur in the midst of GMD events (particularly capacitor bank energization). It is preferable that such events do not cause GRD bypassing, and if bypassing does occur, the GRD should be capable of immediate reinsertion.

7 GRD FAILURE MODES AND PROTECTION

Evaluation of GRD designs should not be limited to expected duties and correct performance of the device. Actual duties may exceed expectations and GRD components may fail. A good GRD design will provide some protection of the device from duties beyond its design capabilities, and will include protections that will identify failures and take appropriate actions.

7.1 Excessive Duty

It is not feasible to build power equipment capable of enduring every possible imposed duty. Reasonable, but conservative, design requirements need to be established but the possibility remains that duties may exceed the design values. Some of the potential causes for excessive GRD duties are:

- Delayed transmission fault clearing due to breaker or relay failure, perhaps extending longer than the delayed clearing assumption used for the GRD specification.
- Occurrence, or reoccurrence, of a fault when the GRD is in the process of insertion or reinsertion.
- Transformer breaker “hung pole” (one or two phases remaining open for an extended period), resulting in high continuous neutral current.
- Steady-state neutral current exceeding predictions due to inaccuracy in modelling this factor.
- Multiple fault events in short succession.
- Greater GRD stresses than anticipated, including dc voltage stress and ac stress resulting from GIC saturation of other unprotected transformers, due to GMD intensity greater than the design value.

7.2 GRD Failure Modes

All equipment is subject to failures. Prudent review of GRD designs considers the failure mode effects and outcomes to ensure that the consequences of failure are limited and do not endanger personnel, transmission system reliability, or high-valued equipment (e.g., power transformers). The failure mode effects analysis should consider each component of the GRD, and each function that the component and the GRD overall perform.

Some examples of failure modes that should be considered include:

- Failure of MOV under high-current conditions.
- Failure of MOV under long-duration low-current conditions (where the MOV housing could become thermally damaged or weakened prior to any pressure relief event).
- Failure of capacitor units to short-circuited (fuseless units) or open-circuited (fused units) states.
- Failure of bypass switch to successfully interrupt current.
- Failure of bypass switch to close.

- Failure of a triggered gap to trigger.
- Contamination of a passive gap, causing sparkover at less voltage than designed.
- Erosion of a gap, causing sparkover at higher voltage than the design value.
- Failure of control system to detect GIC flow and initiate GRD insertion (for designs where the GRD is normally bypassed and is to be automatically inserted when GIC is detected).
- Misinterpretation of fault current offset or transformer inrush or sympathetic inrush as GIC, initiating neutral GRD insertion while neutral current is excessive.

For any identified failure mode, the analysis should consider what happens next, what risks result if this event happens, and how the system will respond to the subsequent actions. For example, a failure might result in bypassing of a neutral GRD during a GMD event. With other GRDs in the system remaining functional, the transformer to which the bypassed GRD is connected may have GIC flow that far exceeds the level if there were no GRDs in the system. The analysis would then need to consider if the resulting GIC poses a material risk to the transformer. If it does, then it may be desirable to devise a protection scheme where the transformer is tripped if the GRD is protectively bypassed for any extended period. The consequences of the transformer tripping on transmission system security (steady-state performance and transient stability performance) should then be considered.

The severity of failure mode effects should be weighed in consideration of the probability of occurrence. For example, fault current levels and backup clearing times are generally known with considerable accuracy. Failures caused by excessive fault current, therefore, can be assumed to be of low probability. However, some of the rating factors used for the GRD design are inherently speculative, such as steady-state neutral current and geomagnetically-induced voltage across the GRD. The uncertainties of these duties need to be compared to the degree of conservatism used to determine the GRD ratings in order to assess the risk of occurrence.

7.3 GRD Internal Protection

A GRD should have some degree of self-monitoring and internal protection. The outputs of the protection can trigger alarms, initiate GRD bypass, or trip the transformer or transmission line to which the GRD is connected.

Some of the protective functions that may be considered include:

- GRD overvoltage (instantaneous and time)
- GRD overcurrent (instantaneous and time)
- Bypass switch failure (voltage following closing order, current following opening order)
- MOV energy monitor (integration of energy with thermal analogue)
- GRD impedance
- Capacitor unit balance.

PART III
GRD SYSTEM IMPACTS

8 INSULATION COORDINATION IMPACTS

8.1 Principles of Insulation Coordination

Application of GRDs in a power system requires that the impacts on insulation coordination be considered. Insulation coordination is defined in IEEE Standard C62.82.1-2010 as:

"The selection of the insulation strength of equipment in relation to the voltages, which can appear on the system for which equipment is intended and taking into account the service environment and the characteristics of the available protective devices."

In practice, insulation coordination involves the selection and application of overvoltage protection devices (surge arresters) to coordinate with the maximum continuous operating voltage (MCOV) and temporary overvoltage (TOV) capabilities of the overvoltage protective device, and the insulation levels of the protected equipment. The conventional procedure for insulation coordination, outlined in IEEE Standard C62.22-2009, is:

1. Determine maximum continuous operating voltage and temporary overvoltage magnitudes and durations.
2. Select surge arresters having sufficient MCOV and TOV capabilities.
3. Determine the protective levels for the critical surge waveshapes: lightning impulse full wave, lightning front-of-wave, and switching impulse.
4. Determine surge arrester locations relative to the protected equipment
5. Select insulation strength (BIL) of the protected equipment
6. Calculate protective ratios for lightning and switching impulses and determine adequacy of protection.
7. If protection is inadequate, consider alternatives such as increasing the insulation level, place the arresters closer to the protected equipment, or considering different surge arresters, and repeat the process.

This conventional insulation coordination procedure, however, may need to be modified for the application of a neutral GRD because the insulation levels of equipment, other than the GRD, are typically already fixed. Also, a GRD may have an overvoltage protection scheme that is able to withstand TOV conditions in a way different than conventional surge arrester applications by either safely conducting high current during TOV events, intentionally failing to a shorted mode, or through bypass of the device by a mechanical or electronic switch or a spark gap.

8.2 Insulation Coordination Considerations for Neutral GRD

The neutrals of wye-connected HV and EHV transformer windings are conventionally connected to the substation ground mat by a very short, highly conductive lead. A neutral GRD places impedance in this path that will affect the insulation coordination of the transformer and other equipment in the substation. There are three aspects of the impact of a neutral GRD on insulation coordination:

1. Elevation of the transformer neutral bushing potential to ground,
2. Increasing the continuous operating voltage and temporary overvoltage that must be withstood by surge arresters protecting the transformer's high-voltage bushings, and
3. Increasing the possible voltage across the transformer winding, between the HV terminals and the neutral.

Figure 8-1 illustrates the voltages affected by the GRD. Each of these must be considered when determining the allowable transient voltage protective level, temporary overvoltage, and continuous voltages at the transformer neutral, across the neutral GRD.

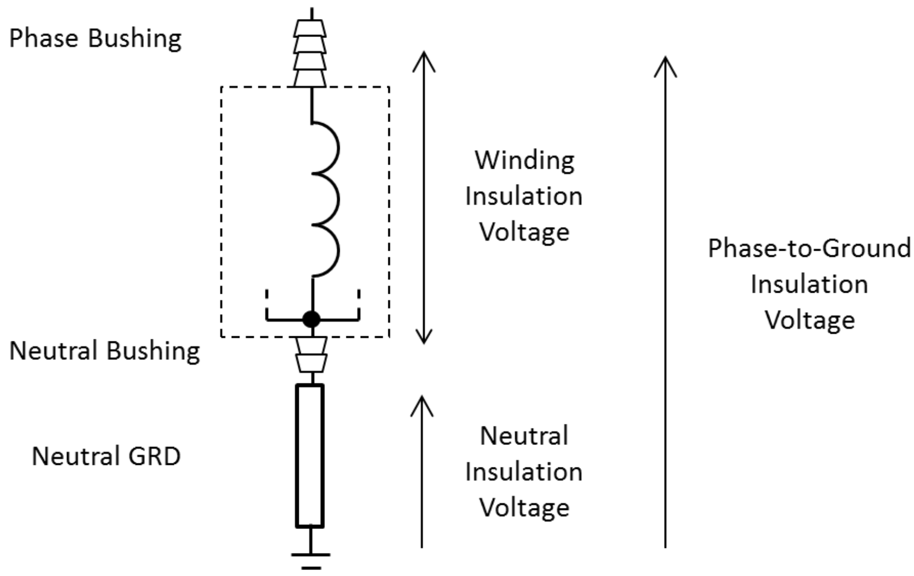


Figure 8-1
Insulation voltages of relevance to neutral GRD application

Transformer Neutral Insulation Protection

Although the neutral and GRD equipment should not be exposed to a direct lightning strike in a properly designed substation, there are various non-obvious paths for lightning and other fast-front transients to appear on the neutral of a transformer to which a neutral GRD is protected. The neutral is also potentially exposed to switching surge transients caused by the operation of the GRD (e.g., insertion by opening a GRD bypass switch). Therefore, it is prudent to ensure robust protection of the transformer's neutral insulation level, no matter what phenomenon exposes the neutral to a transient voltage.

The basic lightning impulse insulation level, or BIL, of neutral bushings used in Class II power transformers (HV winding voltage 115 kV through 765 kV), intended for grounded-wye application, is specified in IEEE Standard C57.12.00-2010 as 110 kV. The voltage protective level of the GRD and/or any other neutral surge protection must provide adequate insulation protective margin for this insulation level, inclusive of any lead-length and separation distance effects. Front of wave, lightning full wave, switching, and low-frequency insulation withstands should be considered.

In an existing substation, location of a GRD immediately adjacent to a transformer may be difficult, and it may be necessary to locate the GRD at some distance from the transformer neutral, with interconnection of the GRD to the transformer neutral via a cable or bus bar. Inductive and traveling-wave effects may result in a substantially greater impulse voltage at the transformer neutral than is limited across the GRD. Whenever a GRD is located at any other location than immediately adjacent to the transformer neutral, an additional surge arrester should be applied directly at the transformer neutral.

It is of questionable prudence to protect transformer neutral insulation solely with a spark gap, unless there is a very large margin between the gap's guaranteed sparkover voltage for impulse-type surges and the neutral BIL. GRD overvoltage protection based on switching is not sufficiently fast to provide protection of the transformer neutral insulation from impulse surges. Therefore, unless the neutral GRD uses MOV for overvoltage protection and the GRD is located adjacent to the transformer, a transformer neutral protection arrester is generally necessary.

Neutral Arrester Voltage Duties

Any temporary or continuous voltages across the GRD must be coordinated with the neutral-protecting arrester's TOV and MCOV capabilities. The neutral arrester's MCOV is defined by the maximum steady-state ac voltage and the maximum quasi-dc voltage across the GRD during a GMD event. The neutral voltage during steady-state may also have substantial harmonic distortion due to the typically large harmonic content of the transformer neutral current. During high-current conditions, such as faults, the neutral voltage may be distorted by the "clipping" action of MOV, if used.

The quasi-dc voltage component across the GRD during a GMD will produce a small dc offset in the neutral voltage at the substation. This results in a slightly higher peak voltage in one polarity than in the other, and this voltage can persist for an extended duration relative to the thermal time constants of surge arresters.

Surge arrester TOV and MCOV capabilities are specified in terms of rms voltage with the implicit assumption that the voltage a fundamental frequency sinusoid. Because surge arresters, due to their extreme nonlinearity, are sensitive to the peak magnitude of voltage, the impact of the distorted neutral voltage with a dc component can be conservatively assumed to be equal to an equivalent rms voltage having a peak value equal to the applied voltage. Therefore, for purposes of neutral arrester MCOV and TOV duty determination, the equivalent rms duties are equal to 0.707 times the peak voltage resulting from the combined ac and quasi-dc components.

Phase Arrester Impacts

The voltage across a neutral GRD may increase the continuous and temporary voltages from phase to ground at the bus to which the transformer is connected, thus increasing the MCOV and TOV duty requirements of the phase to ground arresters connected to the bus. The MCOV requirement can be conservatively assumed to be 0.707 times the peak steady-state neutral voltage plus the maximum positive-sequence phase-to-ground voltage (i.e., the normal MCOV). This is because the phase relationship of the neutral voltage to the phase voltages is poorly defined, so it is reasonable to assume that the neutral voltage component will add directly to one phase.

The relationship between neutral voltage and phase fundamental-frequency voltage is more defined during high-current fault events that typically cause maximum TOV. Capacitive neutral GRDs will tend to decrease unfaulted phase fundamental-frequency overvoltage during ground faults, provided that the GRD impedance remains capacitive. However, any offset in the fault current will drive neutral voltage oscillations that are at sub-fundamental frequency, as was shown previously in Figure 2-1. These oscillations are superimposed onto the phase-ground voltage, and can drive high phase voltage even if the fundamental component of the neutral voltage is not in phase with the unfaulted phase voltage. Furthermore, if the GRD voltage is limited by MOV, the impedance of the GRD becomes progressively more resistive at increasing fault current, thereby decreasing grounding and creating a neutral voltage that is in phase with unfaulted phase voltage. Therefore, the phase-bus arrester TOV withstand requirement may need to be increased by an amount as great as 0.707 times the neutral GRD's MOV protective level (the TOV specification is an rms quantity and an MOV protective level is specified as peak voltage) or the GRD bypass threshold voltage.

For resistive neutral GRDs, phase arrester TOV specifications also need to be increased. For a resistive neutral GRD using bypass overvoltage limitation, the phase arrester TOV duty increases by 0.707 times the bypass voltage. Figure 8-2 shows unfaulted phase voltage as a function of the ratio of the GRD resistance to the system impedance seen from the neutral connection, for various bypass voltage thresholds. During a single-phase fault, the system impedance is $(Z_0 + Z_1 + Z_2)/3$. The ratio of system zero sequence impedance to positive sequence impedance, without the GRD, is assumed to be one in Figure 8-2, and the values shown do not include the effects of fault current offset. Fault current offset will result in a proportional increase in a resistive neutral GRD voltage (50% offset yields a 50% increase in voltage from the symmetrical results shown), unless a bypass neutral voltage threshold is reached. It should be noted that while bypassing may remove neutral voltage during high-current events, the GRD bypass protection does not preclude a less-severe ground fault or other transient from creating a voltage just below the threshold that persists for as long as the event.

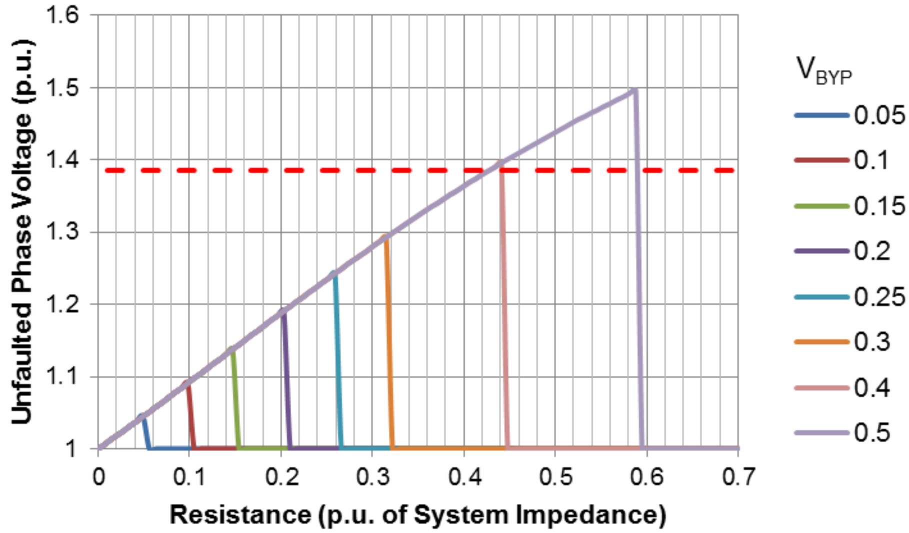


Figure 8-2
Unfaulted phase voltage for a resistive neutral GRD using bypass overvoltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various GRD bypass voltage thresholds. Note: system Z0/Z1 = 1 is assumed.

Figure 8-3 shows similar results for an MOV-protected resistive neutral GRD. The phase TOV impacts are slightly more severe than for a bypass GRD overvoltage limitation strategy, for equal bypass voltage threshold and MOV protective level. This is because, in high-current conditions, the MOV causes the GRD to remain in the circuit and contribute the fundamental-frequency resistance of the conducting MOV. At these current levels, the bypass removes the GRD impedance from the circuit.

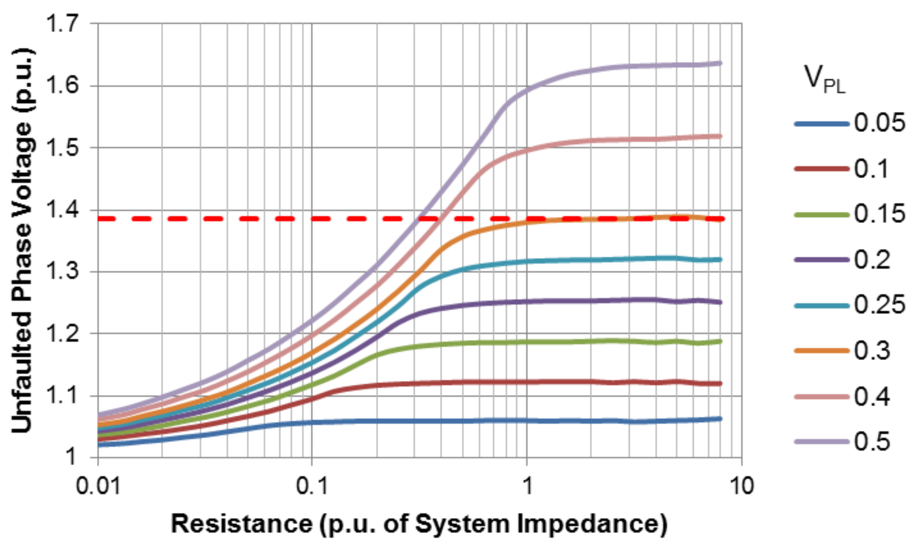


Figure 8-3
Unfaulted phase voltage for a resistive neutral GRD using MOV overvoltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various MOV protective levels. Note: system Z0/Z1 = 1 is assumed.

It is recommended that phase arrester TOV withstand requirements should be determined using electromagnetic transient simulation. The TOV duty specification for phase arresters should be based on 0.707 times the peak sustained phase voltage (lasting for multiple cycles) determined by the simulations. This is because the extreme nonlinearity of the arresters makes their TOV duty much more closely aligned with peak voltage than an rms measurement. The duration of temporary overvoltage events need to be considered, including both faults with normal and delayed clearing, and other events such as transformer inrush that may produce elevated voltage for an extended duration.

Surge arresters connected to the bus must have sufficient margin between the normal MCOV and TOV level and the arrester withstand capabilities to accommodate the voltage shift caused by the neutral GRD. Where this margin does not exist, it may be possible to increase the voltage rating of the surge arresters. This will decrease the impulse and switching surge protection margins provided by the arresters to equipment such as transformers, breakers, etc., affording less protection to equipment at all times including periods when the GRD is bypassed out of service. It may be possible to regain some or all of the protective margin by installing arresters closer to the protected equipment (if not already adjacent to the equipment terminals) or by using different arresters (e.g., multi-column arresters) to reduce the impulse surge discharge voltage.

In most cases, the decreased insulation protection margin will still be greater than the recommended minimum value. However, it should be recognized that decreased margin inherently increases risk of insulation failure, even where protective margins are above the recommended minimum. Insulation voltage withstand can decrease with age and thermal stress, so the BIL of aged equipment may not be equal to its original tested value.

Transformer Winding Insulation Protection

Grounded-wye transformer winding insulation is tested with the neutral solidly grounded, such that voltage across the winding is equal to the test voltage applied to the HV terminal. Therefore, the tested insulation level across the winding is the same as the HV terminal insulation level. A neutral GRD can potentially create a situation where the voltage across a wye transformer winding can be greater than the phase-to-ground voltage at the HV terminal, if the neutral voltage is at an opposite polarity from the voltage on one of the HV phase terminals. Unless surge arresters protecting the transformer are connected from phase to neutral instead of phase to ground, the protection of the winding insulation provided by the phase-to-ground arresters is compromised, to some extent. Arresters are generally not installed from phase to neutral, and installing arresters between these points may pose practical difficulties.

For the neutral GRD to cause increased winding voltage, the neutral voltage must be of opposite polarity from the phase-to-neutral voltage. It is very possible for the steady-state voltage across the neutral GRD to be of opposite polarity from a surge (e.g., lightning) arriving on the HV phase terminal. The steady-state voltage across the GRD, however, is most likely to be of small magnitude relative to the transformer winding insulation level and therefore is unlikely to be of great significance. However, if the neutral voltage is elevated to the maximum potential (MOV clipping voltage, or just below a gap or bypass device triggering voltage) at an opposing polarity from an incoming phase surge, the presence of the GRD inherently decreases the overvoltage protection of the winding's layer-to-layer and turn-to-turn insulation provided by the phase-to-ground arresters.

Scenarios where a phase surge of opposite polarity occurs at the same time as maximum neutral voltage are somewhat obscure. However, conservative insulation coordination practice does not question how surges might happen, but only evaluates the protection provided by the installed surge arresters. With this conservative view, the maximum possible winding voltage is the sum of the phase-to-neutral surge arresters' voltage protective level, and the voltage protective level of the neutral overvoltage limitation. To maintain the same overvoltage protection margin for the winding, with the neutral GRD as had been the case without the neutral GRD, the voltage protective level of the phase-to-ground arresters would have to be reduced. This is frequently not possible. Therefore, in most cases, the addition of the neutral GRD will reduce the transformer insulation's protective margin while the GRD is in the neutral circuit (bypass switch open). While there may be sufficient existing margin to accommodate the reduction while maintaining protective margin above the recommended minimum, there is inherently a degree of increased risk. This risk is present only when the neutral GRD is placed in service (bypass switch opened) and can be minimized by limiting the maximum neutral voltage. Alternatively, phase-to-neutral arresters may be installed to provide direct winding insulation protection.

8.3 Insulation Coordination for Series GRD

For a series GRD, the voltages which can appear across the device and the insulation strength of the device are within the control of the device design. Voltages from the device to ground are the same as seen from line to ground by other devices such as line insulation, and in practice are not significantly affected by the design of the device.

Because series GRDs are at line potential, they are typically constructed on insulated platforms. Signals from control and protection devices at ground level must be communicated to the platform level by insulated means, typically fiber optics. The requirements for the insulated platform and isolated controls and auxiliary power sources for the platform equipment add greatly to the cost of series GRDs, as is the case for all series capacitor applications.

9
FAULT CURRENT IMPACTS

The impedance of GRDs, and the nonlinearity and variability of their impedance, modify fault current magnitudes. Increased fault current can impact buswork and substation equipment, most notably circuit breakers. Any changes in fault current can potentially affect protection coordination.

9.1 Bypass-Limited Designs

GRD designs that have a shorted-bypass type of overvoltage limitation scheme either present their linear impedance to the network or zero impedance (or near-zero impedance if the bypass path should have a small inductor or resistor for transient current limitation). Such schemes will generally not affect the maximum short-circuit current magnitude if the bypass is near-instantaneous (voltage-triggered gap or electronic bypass) because very high currents will trigger the bypass, removing the influence of the GRD. If the bypass is not instantaneous (e.g., a mechanical bypass or a bypass triggered based on a delayed quantity such as accumulated voltage, current, or MOV energy), the GRD will have impact on the fault current prior to the bypass action but not thereafter. Depending on the delay, the momentary fault current ratings of equipment may change, but interrupting current requirements might not be affected if the bypass action always occurs prior to switchgear contact parting.

Figure 9-1 and Figure 9-2 show fault current magnitude and fault current phase angle shift as functions of the impedance of a resistive GRD and the bypass voltage threshold (V_{PL}) , for a shorted-bypass GRD with instantaneous bypassing. The GRD impedance is in per-unit of the circuit impedance (not including the GRD impedance) for the respective fault. This circuit impedance is Z_1 for a three-phase fault involving a series GRD and is $[Z_0 + Z_1 + Z_2]/3$ for a single phase fault involving either a series or neutral GRD. In Figures 9-1 and 9-2, the circuit impedance is assumed to have an X/R ratio of 20. As the GRD resistance increases, relative to the circuit impedance, fault current magnitude is reduced and the phase angle of the fault current increases (becomes less lagging). However, before the fault current magnitude decrease becomes very large, the voltage across the GRD reaches the bypass level. Because the bypass action shorts out the GRD, no fault current change occurs for larger GRD resistance. Zero fault current offset is assumed; fault current offset will tend to cause bypassing at an even lower current value, further minimizing impact. Figures 9-1 and 9-2 illustrate that GRDs with either low impedance or a low bypass threshold voltage have limited impact on fault current.

Figure 9-3 shows similar results for a capacitive GRD with voltage-triggered bypass. Compared to a resistive GRD, the capacitive GRD has a greater impact on fault current magnitude prior to reaching a given bypass threshold voltage across the GRD. This is because the capacitive reactance creates partial cancellation of the predominately inductive circuit impedance. The capacitive GRD, however, has near-negligible impact on the phase angle of fault current. If the capacitive GRD reactance is greater than the circuit reactance, and there is no GRD voltage limitation, the GRD would cause a 180° shift in fault current phase angle. This, however, imposes a voltage across the GRD which is equal to or greater than the system voltage, which is infeasible for a practical GRD to withstand. Therefore, fundamental-frequency resonance of the overall fault circuit, when a capacitive GRD is applied, is not a realistic concern. In a practical bypass-protected GRD, the bypass voltage threshold will be reached well before the GRD capacitive reactance reaches the resonant point.

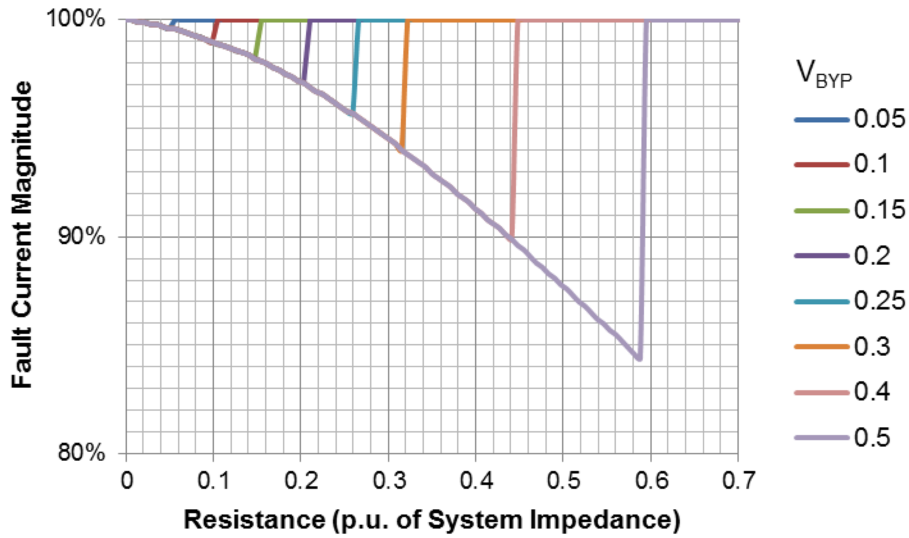


Figure 9-1
Impact on fault current magnitude of a resistive neutral GRD, using bypass voltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various bypass voltage thresholds.

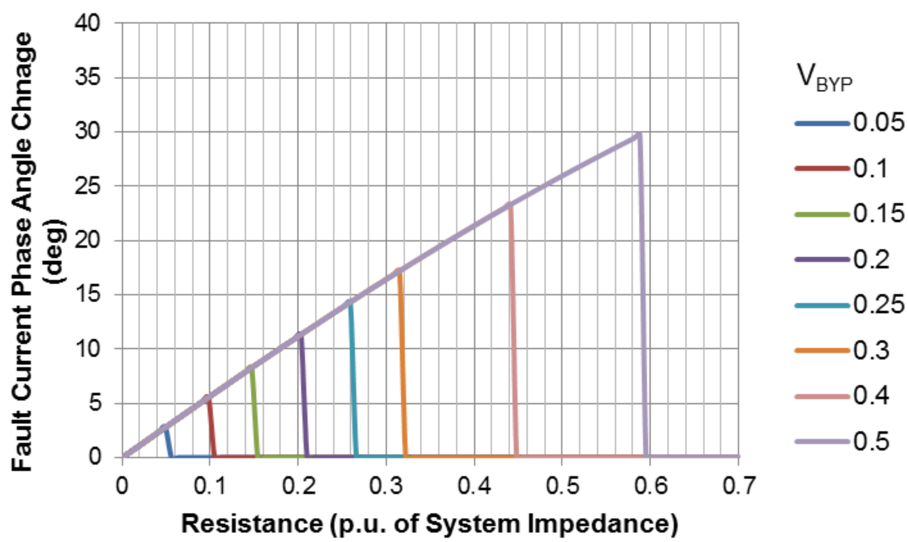


Figure 9-2
Impact on fault current phase angle of a resistive neutral GRD, using bypass voltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various bypass voltage thresholds.

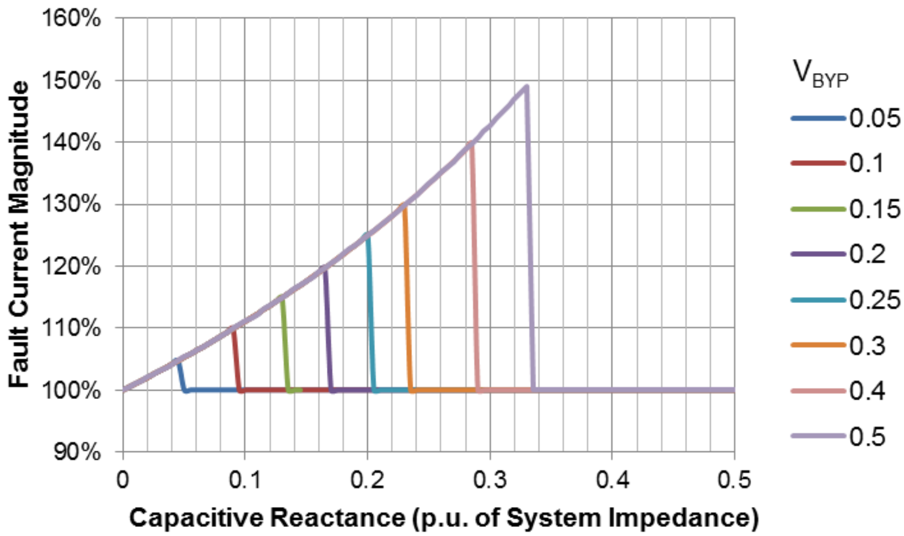


Figure 9-3
Impact on fault current magnitude of a capacitive neutral GRD, using bypass voltage limitation, as a function of the ratio of GRD capacitive reactance to system impedance without the GRD, for various bypass voltage thresholds.

9.2 MOV-Limited Designs

As an alternative to bypassing, a GRD design may use high-current MOV to limit voltage during faults. The impact of such a GRD on fundamental-frequency fault current can be determined either by iterative analysis using the effective impedance shown previously in Figure 4-1 to Figure 4-4, or by time-domain simulation. Figure 9-4 and Figure 9-5 show that the impacts of an MOV-limited resistive GRD on fault current magnitude and fault current phase angle are a function of both the GRD impedance and the voltage protective level (clamping voltage) of the MOV (V_{PL}). This analysis assumes an ideal MOV, with zero incremental resistance above the conduction threshold. For MOV designed for conduction of fault current, typically using many MOV columns in parallel, the incremental resistance of the MOV bank in conduction generally has little effect on the results.

Unlike a bypass-protected GRD, the impact of a resistive GRD with MOV voltage limitation on fundamental-frequency fault current magnitude and angle do not drop to zero when the peak voltage reaches the MOV conduction threshold (voltage protective level or V_{PL}), but rather the impact becomes roughly constant for higher GRD resistances.

The impact of an MOV-protected capacitive GRD on fault current is more complex than a resistive GRD. As the capacitive reactance of the GRD increases relative to the circuit impedance, the fundamental-frequency fault current magnitude initially increases as shown in Figure 9-6. As the capacitor voltage is more and more limited by the MOV, however, the impedance of the GRD becomes more resistive and less capacitive, decreasing the fault current magnitude. In contrast to a bypass-protected capacitive GRD, the impact of the MOV-protected GRD on fault current phase angle is large at high values of capacitive reactance, particularly where a high protective level is used. This is shown in Figure 9-7. The MOV-protected capacitive GRD, with a feasible voltage that is well below the system voltage magnitude, never becomes fundamental-frequency resonant with the system (current phase angle change is always less than 90°) because of the shift toward a more resistive effective fundamental-frequency impedance at higher voltage levels across the GRD.

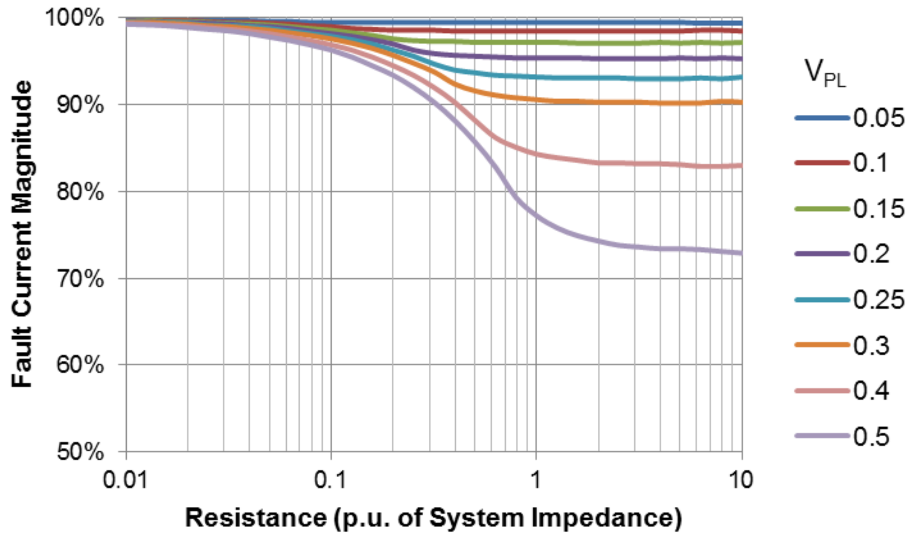


Figure 9-4
Impact on fault current magnitude of a resistive neutral GRD, using MOV voltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various MOV voltage protective levels.

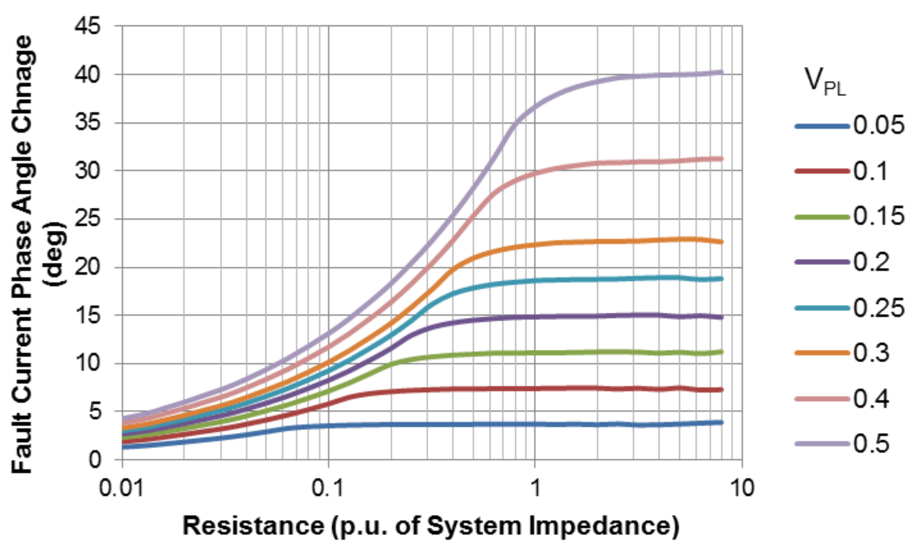


Figure 9-5
Impact on fault current phase angle of a resistive neutral GRD, using MOV voltage limitation, as a function of the ratio of GRD resistance to system impedance without the GRD, for various MOV voltage protective levels.

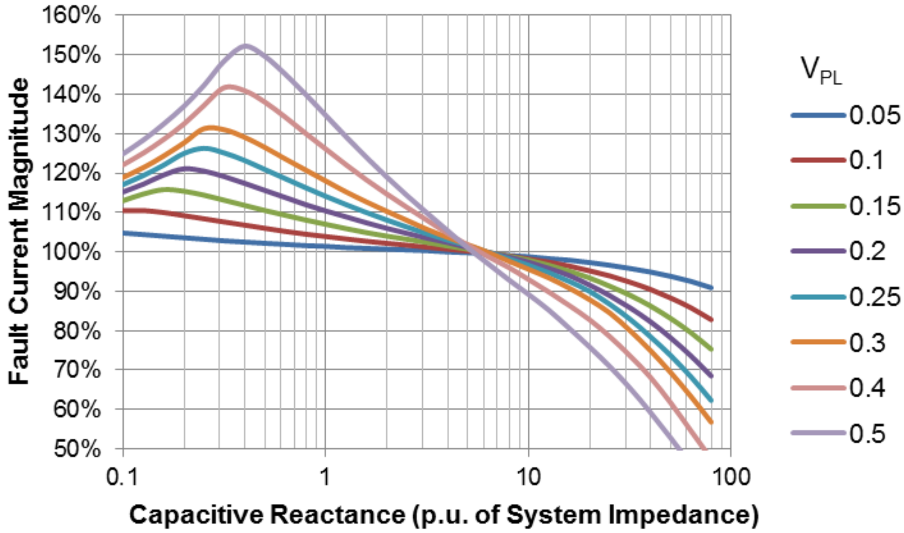


Figure 9-6
Impact on fault current magnitude of a capacitive neutral GRD, using MOV voltage limitation, as a function of the ratio of GRD reactance to system impedance without the GRD, for various MOV voltage protective levels.

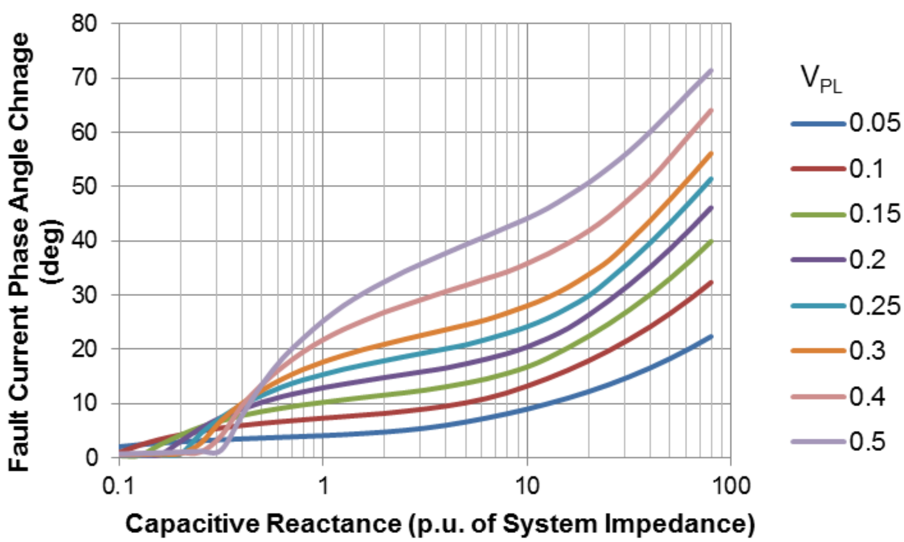


Figure 9-7
Impact on fault current phase angle of a capacitive neutral GRD, using MOV voltage limitation, as a function of the ratio of GRD reactance to system impedance without the GRD, for various MOV voltage protective levels.

10
PROTECTIVE RELAYING IMPACTS OF GRD

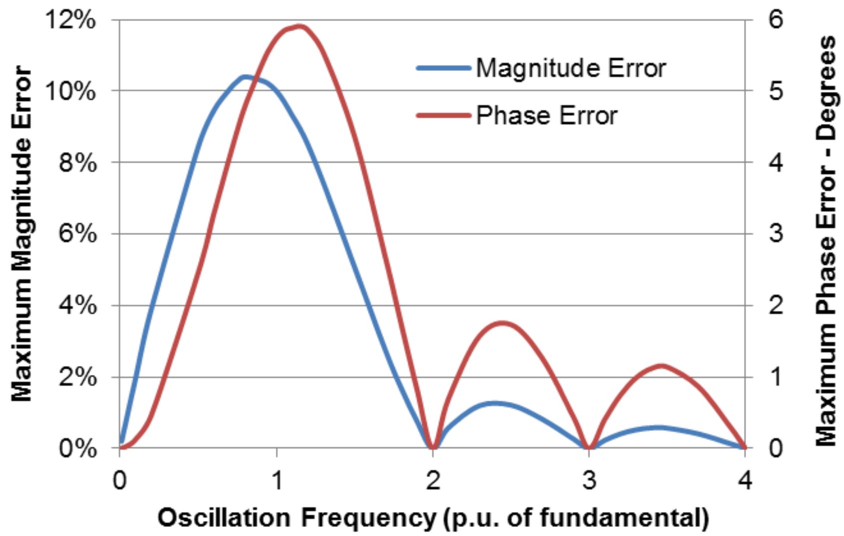
Introduction of either series or neutral GRDs to a system can have an impact on protective relaying. Neutral GRDs only have an impact on ground faults and protections sensing ground or zero-sequence current. Series GRDs, however, can affect both phase and ground current protections. The degree of protection system impact depends on the GRD impedance magnitude, whether the GRD impedance is resistive or capacitive, and the type and thresholds of GRD overvoltage limitation.

10.1 Off-Fundamental Current Oscillations

Capacitive GRDs interact with system inductance to create resonant circuits that can be stimulated by faults and other disturbances. Capacitive neutral GRDs create a resonance that appears only in the zero sequence. Stimulation of these resonances results in oscillations that are at a frequency less than the fundamental frequency for a low or intermediate impedance capacitive neutral GRD or any practical series capacitive GRD. A high-impedance capacitive neutral GRD may create resonances at frequencies that might be above or below the fundamental frequency. These oscillations will decay depending on the system damping, or also damping provided by the GRD if the GRD includes a resistance along with the capacitance, and should not be of a continuous nature.

For a GRD using only MOV limitation, without bypassing, the magnitude of the oscillations will be clamped to the protective level of the MOV. After the oscillations decay below this voltage magnitude, the MOV will have very little influence on the further decay of oscillations. Where a bypass type of GRD overvoltage protection is used, the maximum oscillation magnitude will be as great as the bypass voltage threshold. A more severe disturbance will cause bypass and there will be no oscillations. However, there is always the possibility that a remote fault will initiate oscillations just below the bypass threshold, and will continue until naturally damped.

These non-fundamental oscillations may cause relays to incorrectly determine fundamental frequency phasor quantities. Most digital relays sample their input voltages and currents 32 or 64 times per fundamental cycle, and then perform a Fourier transform to determine fundamental magnitude and phase. This process eliminates all influence of signals at integer harmonics of fundamental. Sub-fundamental and super-fundamental signals (at other than integer multiples of fundamental) will create errors in the Fourier transform process. The error will appear as a positive or negative offset in the transduced fundamental magnitude and angle, oscillating at the frequency of the off-fundamental signal. Figure 10-1 shows the maximum error in the transduced fundamental magnitude and phase, as a function of the frequency of the off-fundamental signal, over a full cycle of the off-fundamental. The results shown are for the off-fundamental signal at 10% of the fundamental magnitude. The amplitude results are linearly scalable to any magnitude of off-fundamental signal, and the phase angle results are approximately linear with off-fundamental signal strength.



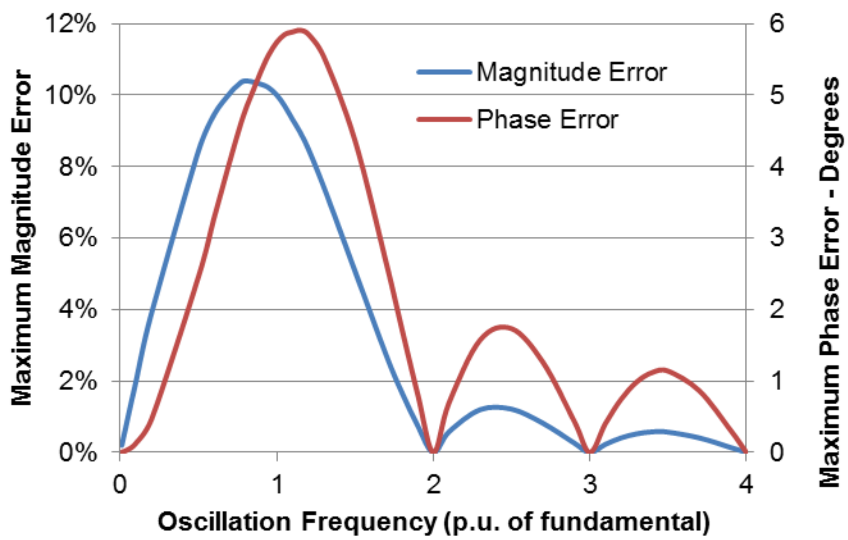


Figure 10-1
Maximum magnitude and phase error for FFT identification of a fundamental-frequency quantity with a non-fundamental oscillation, having a magnitude 10% of fundamental. Results are measurement over one fundamental cycle.

The error in fundamental current phasor identification can cause distance relays to respond in a manner other than expected. This may cause under-reaching or over-reaching, and could potentially cause a false trip or failure to trip. The zero-sequence oscillations caused by neutral GRDs will affect each phase equally, and therefore should not affect phase, positive sequence, and negative sequence relays. Ground and neutral relays, however will be directly affected.

Relay impact is minimized by choosing a GRD capacitance resulting in oscillations well-separated from the fundamental, and by a design that keeps GRD voltage low. This generally points toward a low capacitive impedance design. Where non-fundamental oscillations caused by capacitive GRD have potential material impact on relay coordination (i.e., little margin to accommodate fundamental phasor error, oscillation frequencies approaching fundamental, high GRD voltages), detailed studies should be executed to investigate performance. Simulations with the actual relay hardware in the loop, using real-time simulation, or off-line simulations with injection of the simulated signals into relay hardware, is recommended to fully account for the relay's input signal processing characteristics.

10.2 Series GRD Impacts on Protection

The utility industry has considerable experience with series capacitors installed for impedance compensation, and the impacts on protective relaying are well documented. Detailed discussions of relaying issues related to series capacitors, and their solutions, are provided in References [12], [13], and [14]. In summary, these issues are:

- Voltage inversion, causing directional relay elements to incorrectly indicate fault direction. Voltage inversion occurs for phase elements when the net impedance between the relay location and the fault location is capacitive (line reactance to the fault is less than the series capacitor's reactance). For directional elements responding to sequence quantities, the inversion results when the relevant sequence impedance behind (on the source side) of the relay is net capacitive.
- Current inversion, causing incorrect directional and differential discrimination. Current inversion occurs when there is a fault on the line with the series capacitor (internal fault), and the total impedance on one side of the fault is inductive, and capacitive on the other side. Line differential relays will incorrectly indicate that the fault is external; i.e., not on this line. Directional relays will incorrectly indicate fault direction for this condition.
- Modification of the effective line impedance used by distance relays, resulting in overreaching.

A series GRD installed solely for GIC blocking, and without any line impedance compensation objective, will typically have a small capacitive reactance and a very low voltage limitation threshold. Therefore, the potential for achieving voltage or current inversion are greatly reduced, or even eliminated if the GRD is located mid-line rather than near a line termination. A small GRD reactance will also minimize the effective line distance error for distance relays.

10.3 Capacitive Neutral GRD Protection Impacts

Neutral GRDs will only have significant impact on ground relays and relays that use zero-sequence voltage, neutral current, or delta tertiary current for polarization. Phase reversal or phase shifts of voltages and currents used for polarization of directional relay elements, caused by neutral GRDs, can make these signals unsuitable for relay polarization [15].

Capacitive Neutral GRDs without MOV Voltage Limitation

Other than the off-fundamental frequency oscillation impacts on relay phasor identification, discussed previously, capacitive neutral GRDs that do not use MOV voltage limitation should not significantly affect the polarization unless the capacitive neutral reactance causes a reversal of voltage or current polarity. This shift in I_0 or V_0 phase angle requires a fundamental-frequency resonant condition. It was previously stated in this guide that fundamental-frequency resonance of the entire fault circuit is not a realistic condition because the voltage on the GRD would exceed the voltage limitation of any practical GRD design, and the GRD will no longer present capacitive impedance. However, a local resonance can occur that causes the ground fault contribution of a particular transformer, with capacitive neutral GRD, to reverse in polarity even though there is no reversal of the total fault current. If the ground current contribution is not large, such as the case of a fault remote from the transformer location, the GRD current may not be as high as to cause bypassing.

Polarity of the neutral current of a wye-delta transformer (e.g., GSU) can reverse only if the capacitive reactance of the neutral GRD exceeds one-third of the transformer's leakage reactance, assuming the transformer is connected to an infinite bus. External system zero-sequence inductive impedance increases the critical capacitive reactance value. When GRD capacitive reactance exceeds the critical value, the phase reversal cannot be compensated by simply reversing the sign of the polarization in the relay function because the phase reversal is a function of the system impedance, which is variable, and the GRD will bypass for severe faults but not bypass for remote faults.

For an autotransformer, the situation is considerably more complicated because the neutral current is not only a function of the zero-sequence voltage applied to the transformer, but also the zero-sequence current flow through the transformer between the HV (H) and LV (X, not the tertiary) terminals. Because of this, autotransformer neutral current is not a preferable zero-sequence polarization source [16]. Instead, delta tertiary current is often used. Without a GRD, the tertiary current is a reliable polarization source. Neutral capacitive reactance, however, can cause phase reversal of the tertiary current as well. The impedance model previously shown in Figure 4-8 can be used to determine the zero sequence flows in or out of the HV and LV terminals. Equation 6-2, which gives the conditions for neutral GRD resonance, also provides the minimum neutral capacitive reactance that can result in tertiary-current phase reversal.

Zero sequence bus voltage is also commonly used as a directional relay polarization source. If a transformer with a capacitive neutral GRD is a significant ground source for the location of the potential transformers, phase reversal may also result. This requires, at a minimum, that the zero-sequence impedance of the ground source becomes net capacitive if it is assumed that the remainder of the system presents an inductive zero-sequence impedance (the normal situation, but might not be the case with widespread deployment of capacitive neutral GRDs). The ground source of a grounded-wye delta transformer with neutral GRD becomes capacitive if the capacitive reactance exceeds one-third of the transformer's leakage reactance. For an autotransformer, the critical reactance is provided by Equation 10-1, and is the same whether the polarization voltage is either from the H terminal side or the X terminal side:

$$X_{critical\_H} = \frac{1}{12} \cdot \frac{X_{HY}{}^2 - 2X_{HY} \cdot (X_{XY} + X_{HX}) + (X_{XY} - X_{HX})^2}{n^2 \cdot X_{HY} + n \cdot (X_{HX} - X_{HY} - X_{XY}) + X_{XY}} \qquad (10\text{-}1)$$

In Equation 10-1, X_{HX}, X_{HY}, and X_{XY} are the terminal-to-terminal leakage reactances of the transformer in per-unit, and n is the transformer nominal terminal voltage ratio. The other terminal from the one where zero-sequence voltage is measured is assumed to be connected to an infinite bus. Finite zero-sequence inductive system impedance at these terminals will increase the critical capacitive reactance, so the capacitive reactance values provided by these equations are bounding values.

Capacitive Neutral GRDs Using MOV Voltage Limitation

For faults where the neutral GRD voltage, including any effects of fault current offset, is below the conduction level of the MOV, the impacts on polarizing values is the same as previously discussed for bypass-protected GRD. When voltages are high enough to cause significant GRD conduction, the effective fundamental-frequency impedance becomes less capacitive and more resistive with increasing conduction. This causes a variable phase shift in the currents and voltages used for polarizing quantities. Unless the GRD capacitive reactance is very small, the presence of the GRD may make these polarization sources unreliable. Alternative polarization quantities (e.g., negative sequence polarization) that are unaffected by the neutral GRD may need to be substituted.

Wide Deployment of Capacitive GRDs

The preceding discussions of conditions where capacitive neutral GRDs may cause inversion of zero sequence voltage and current polarizing quantities assume that the external system, beyond the transformer to which the capacitive GRD is applied, has an inductive driving point impedance. This is the normal case, but may not apply if high-impedance capacitive neutral GRDs are widely deployed in the system. This could result in the system driving point zero-sequence impedances being net capacitive, or variable between capacitive and inductive due to GRD bypass action. In such a case, zero sequence polarization throughout the system would be unreliable for use in protection systems. This issue should not occur, however, if all capacitive neutral GRDs are of the low-impedance or intermediate impedance design, as defined in this guide.

10.4 Resistive Neutral GRDs

Resistive neutral GRDs will cause a phase shift in the polarizing current. This phase shift is variable, changing with fault magnitude if the GRD is voltage-limited by MOV, and abruptly changing if bypass voltage limitation is used. In the case of neutral current or tertiary current polarization, the phase shift can be significant unless the GRD resistance is quite small, and a small GRD resistance will not provide much GIC mitigation. If zero-sequence bus voltage is used, the impact of the phase shift depends on the relative contribution of the ground source having the resistive GRD. Therefore, directional relays will need to be polarized by quantities other than neutral current or tertiary current, or in some cases zero-sequence voltage.

11 RESONANT INTERACTIONS

Resistive GRDs should not cause resonant conditions. Capacitive GRDs, however, inherently interact with system inductance to produce a resonant circuit. Industry experience with issues like subsynchronous resonance and harmonic resonance have raised concern regarding the potential for capacitive GRDs to cause undesirable resonant interactions.

11.1 Subsynchronous Resonance

Subsynchronous resonance (SSR) has been a significant issue for the application of series capacitors intended for transmission line impedance compensation. This phenomenon results when a series resonance in the system is at a frequency that is at the 60 Hz complement of the natural torsional frequency of a nearby turbine-generator. The resonance can cause negative electrical damping that can potentially allow mechanical torsional oscillations, where one part of the turbine-generator shaft system twists relative to .other parts, to become unstable and grow in magnitude. This phenomenon has resulted in turbine-generator shaft failure in power plants.

Risk of SSR for Series GRD

A series GRD is essentially a series capacitor. However, if the objective is only GIC mitigation and not impedance compensation, a very low capacitive reactance, on the order of a few percent of line reactance provides the most efficient solution. A general rule-of-thumb is that series capacitors providing less than 30% compensation are unlikely to destabilize turbine-generator torsional oscillation modes [17]. Therefore, SSR is not a significant concern for GRD designed to provide only GIC mitigation. For series capacitors intended for both impedance compensation and GIC mitigation, the established industry practices for SSR screening, mitigation, and protection apply.

SSR Risk for Capacitive Neutral GRD

Turbine-generators are always connected to the transmission system via transformers that block zero sequence. In a perfectly balanced transmission system, a neutral GRD appears only in the zero-sequence network and is not “seen” by the generator. Transmission imbalance, however, does provide a small amount of coupling between the line-mode sequences (positive and negative) and the zero sequence (ground mode). The line imbalance coupling between zero and positive sequence for a transmission line can be roughly quantified by the factor:

$$\frac{Z_{01} \cdot Z_{10}}{Z_{00}{}^{2}}$$

For the example 500 kV transmission line for which the impedance parameters are provided in Figure 6-1, the coupling factor is 0.018%. Effectively, this means that a capacitive neutral GRD would need to have a reactance equal to 166,666% of the transformer’s reactance in order to be the equivalent of a series (phase) capacitor providing the critical 30% compensation. Thus, there is no cause for concern that a capacitive neutral GRD could engage in SSR during steady-state conditions.

During a ground fault, the positive, negative and zero sequence networks are much more tightly coupled. While a subsynchronous resonance condition could be seen by a generator during a fault, torsional oscillations tend to take a period of time to build up to damaging levels. Coupling to the zero sequence also provides much more resistive damping than the positive sequence network alone, so the extra damping may further slow torsional oscillation buildup, or even eliminates the negative torsional damping completely. Transmission faults are usually cleared in a much shorter time than the buildup of oscillations in an ordinary series capacitor situation, so SSR is of little concern even during faults, unless the neutral GRD has a high capacitive reactance, a high overvoltage limitation threshold, and the transmission ground fault has exceptional duration.

11.2 Harmonic Resonance

Low-impedance and intermediate-impedance capacitive neutral GRDs will, by definition, only cause a resonance that is below fundamental frequency, and thus cannot cause a harmonic resonance. There are no significant sources of continuous stimulation of sub-fundamental zero-sequence resonances. Likewise, a practical series GRD will also not create a harmonic resonance.

A high-impedance capacitive neutral GRD can create a resonance above fundamental frequency. If its capacitive reactance is sufficiently high, the resonances may be at or near harmonics of the fundamental. This can be of concern if there are sources to drive the resonances. Because of its neutral location, the resonances can only be driven by zero-sequence harmonic currents and voltages. As previously discussed in Section 6.5, the harmonics may be at any harmonic orders, and not just at the “triplen” harmonics (multiples of three). The triplen harmonics, however, will usually, but not always, be of the greatest magnitude. Except during GMD events, the odd-order harmonics in the system will be of much greater magnitude than the even-order harmonics. During a GMD however, asymmetric (i.e., “half cycle”) saturation of transformers due to GIC can cause greatly elevated levels of both even- and odd-order harmonics. Even if all GIC is blocked from the transformer with the neutral GRD, harmonics from other transformers that do have GIC flow can stimulate resonance of the capacitive neutral GRD. (This is the case unless every transformer in the transmission system, including interconnected neighboring systems, has GIC blocking.)

A harmonic resonance can cause greatly amplified harmonic currents through and voltages across a high-impedance capacitive neutral GRD. This is a matter primarily of GRD steady-state rating, as previously discussed in Section 6.3. Zero sequence harmonics are not a significant power quality concern because distribution systems and customer loads are only coupled to the transmission system via transformer connections that block zero-sequence current and voltage.

11.3 Other Resonance Issues

Low and intermediate impedance capacitive neutral GRD inherently create a resonance below fundamental frequency. There is not usually any source in this frequency range that can continuously stimulate this resonance. An exception is electric arc furnaces whose load currents typically have significant subsynchronous content. Such loads are always connected to the transmission system by transformers that do not couple the load to the transmission-side zero-sequence network. Thus, such loads will not stimulate a subsynchronous zero-sequence resonance formed by a capacitive neutral GRD, except indirectly and weakly via transmission line impedance imbalance. Zero-sequence resonances created by capacitive neutral GRDs, however, will be transiently stimulated by faults and other events such as transformer energization. This transient behavior was discussed previously in this guide in Sections 2 and 6.

Ferroresonance is a non-linear phenomenon that can only loosely be called a “resonance.” This phenomenon only occurs when a nonlinear inductance, such as the magnetization characteristic of a transformer is topologically in series with a capacitance. While a neutral GRD may appear to be in series with a transformer, this is not the case in a balanced system. The phase relationships of current and voltage during balanced conditions causes the transformer neutral to be at zero voltage, with or without the neutral connected to earth. As a result, the neutral GRD does not appear at all in the positive sequence network. It is only during severely unbalanced situations, such as a circuit breaker hung pole during transformer deenergization, that places the GRD’s capacitance in series with the transformer’s inductance. This potential for ferroresonance was previously discussed in Section 6.7.

PART IV
STUDIES

12
GRD APPLICATION STUDIES

Transmission systems are designed to be solidly grounded, and the application of a neutral GRD presents situations for which the industry does not have a strong basis of experience. Therefore, prudence requires that technical system studies be performed in order to specify a neutral GRD integrate it with the transmission system. Failure to perform these studies can result in a GRD that:

- Does not provide the level of GIC mitigation desired.
- Does not reliably remain in service, particularly in the midst of a GMD event.
- Becomes damaged during normal service conditions, or as a result of ordinary contingency conditions.
- Results in damage or failure of other equipment.
- Interferes with system protection such that failure to trip for faults or false tripping in the absence of a fault occurs.

Application of a series GRD also requires study. The industry, however, has substantial experience with applying series capacitors for line impedance compensation, and application of a series GRD requires similar considerations and practices for the most part. The lesser reactance of a GRD optimized only for GIC mitigation reduces or eliminates some of the issues confronted in a typical series capacitor application. There are some aspects of series GRD application that differ from conventional series capacitor application, such as deployment strategy and geomagnetically induced voltage withstand specifications.

This section provides guidelines for the studies that should be considered for GRD application. Covered are the scope, purpose, applicability, analysis tools, model requirements, critical cases and conditions, and utilization of results for each study. The study details are organized by study discipline, rather than end result, because that is how the study effort is usually performed for the greatest engineering efficiency. Study inputs needed from other studies as well as study outputs are described. The study input and output path is necessarily somewhat circuitous. As in many complicated system projects, the studies are interleaved and may need to be performed iteratively with studies modified based on the findings of other studies.

The recommended study plan is admittedly extensive. As the industry gains experience with GRD application, it may be found that some of this study becomes unnecessary. However, for the near-term future, GRDs are not a “plug and play” component.

12.1 GIC Flow Study

Purpose, Objectives, and Scope

The GIC Flow Study performs analysis of GIC in a transmission system. For GRD application studies, the objectives are to:

- Define the GRD deployment strategy, determining the location of all GRDs, and in the case of resistive neutral GRDs, the neutral resistance specification.
- Evaluate the effectiveness of the proposed GRD deployment on the basis of performance objectives such as reduction of GIC in specific transformers or on the basis of system-wide GMD impacts reduction (e.g., total transformer reactive power loss due to GIC).
- Specify the quasi-dc voltage withstand capability of each GRD.
- Evaluate the system and equipment impacts of GRD unavailability or bypassing.
- Determine the GIC flowing through any bypassed GRD, if the operational plans call for re-inserting the GRD following a bypass event.
- Determine the level of GIC in unprotected or partially-protected transformers for use in harmonic studies, including cases where one or more GRD in the system is bypassed.

This study may need to be coupled with transient studies that may define which GRDs may be bypassed for a particular fault event.

Applicability

This study is required for all GRD types. For resistive GRDs, an added dimension is the determination of the resistance value.

Analysis Tools and Models

The GMD analysis can be performed using the GMD-analysis add-software options now offered by the major transmission system loadflow software vendors.

As with any GMD study, a large-scale transmission model is required. The model needs to include neighboring transmission systems to an extent dependent on the size of the system under study, and the topology of the system. In addition to standard loadflow model data, the models for GMD analysis require additional information such as geographic coordinates of substations and substation ground mat resistances to earth. More information on GMD modeling can be found in Reference [18].

Critical Cases and Conditions

The study must consider geomagnetic electric fields oriented in any direction. Typically, studies are performed with the E-field varied in 10° to 30° steps, for a range of 180 degrees. (Results for the remaining 180° are a mirror image.) A prudent safety factor should be applied to the GRD dc voltages determined in this study.

Inputs from and Outputs to Other Studies

Inputs:

- From GRD Design:
  - Critical fault current magnitude requiring GRD bypass.
- From Fault Study and/or Electromagnetic Transients Study:
  - Fault current magnitudes for various fault locations. (The fault current magnitudes and critical fault currents are required to determine the extent of GRD bypassing for the fault locations; i.e., for any fault location, which GRDs will be required to bypass for the fault.

This information is particularly important for GRD designs where the GRD does not immediately and automatically reinsert. For designs where immediate reinsertion occurs, this information is also of value in order to determine the GIC magnitudes that need to be interrupted during reinsertion, as these GIC values may depend on the bypass status of other GRDs.)

Outputs

- To all other studies:
  - GRD deployment plan; i.e., locations and configurations of all GRDs.
- To Harmonic Study:
  - Magnitude of GIC in each transformer for a range of scenarios, including various GMD E-field orientations and GRD bypass scenarios. This is used to calculate harmonic current injections by these transformers.
  - To Electromagnetic Transients Study:
  - Maximum GIC through a bypassed device to determine device insertion transient.
- To GRD Design:
  - GRD resistance (resistive neutral GRD only)
  - Quasi-dc voltage due to GMD
  - Maximum GIC through a bypassed GRD in order to determine interruption requirement for device insertion
- To Insulation Coordination Study:
  - Quasi-dc voltage due to GMD

12.2 System Imbalance Study

Purpose, Objectives, and Scope

Study of transmission system imbalance is necessary to specify the steady-state fundamental-frequency current withstand of neutral GRDs.

Different approaches to this analysis are described in Section 6.4.

Applicability

This study is only required for neutral GRDs.

Analysis Tools and Models

For detailed analysis, the preferable tool is a three-phase loadflow program that fully represents system imbalance, and the peculiarities of zero-sequence neutral current flow in all types of transformers including autotransformers. Such a tool is not known to be commercially available. As an alternative, the steady-state (phasor) initialization functions of electromagnetic transient programs may be used. Such programs require specialized expertise and are cumbersome for representing extensive systems. They also tend to be inconvenient tools for studying the large number of individual cases required to perform a detailed imbalance analysis. A fairly extensive system model is required for detailed analysis, typically extending into neighboring transmission systems at least a bus or two. The model requires detailed cross-sectional configuration information for each line, as well as the phasing configuration (e.g., B on the left, A on top, etc.)

For the "detailed bounding analysis" approach described in Section 6.4, no specialized tools are required once the impedance and admittance matrices for each transmission line are calculated. Various line constants programs exist, including those embedded with electromagnetic transient programs. With the matrices determined, the analysis can be performed with general mathematics software (e.g., MATLAB, MathCAD, etc.). The study requires detailed data (configuration, phasing) for each transmission line adjacent to a neutral GRD location.

The simple bounding analysis requires no software, and only the GRD impedance, transformer impedance, and estimates of zero-sequence bus voltages are needed. The latter is critical, and a conservative estimate of maximum zero-sequence voltage is recommended.

Determination of neutral currents from measurements requires monitoring data over a long period of time. Correcting the neutral currents, observed without a GRD, to the current with the GRD present requires use of a short-circuit program and database to determine system zero-sequence driving point impedances.

Critical Cases and Conditions

For detailed analysis, a wide variety of loadflow conditions, including various generation dispatches, load levels, etc., as well as line and transformer outage contingencies are needed to determine worst-case neutral GRD current.

The other analysis methods discussed in Section 6.4 inherently estimate worst-case conditions without such a broad analysis.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - GRD deployment plan.
- From GRD Design:
  - GRD impedance.

Outputs

- To GRD Design:
  - Maximum steady-state fundamental current for device rating.
- To Insulation Coordination Study:
  - Maximum steady-state fundamental current for determining maximum continuous operating voltage across device.

12.3 Fault Study

Applicability

Fault analysis, using ordinary phasor-domain short-circuit analysis tools is used to study currents and voltages during transmission faults for GRD that retain linearity (i.e., no MOV voltage limitation) during fault conditions, and for which bypass behavior is not subject to non-fundamental-frequency behavior during faults. Effectively, this limits the applicability of this type of study to resistive GRDs that do not use MOV overvoltage limitation.

For other types of GRD, the study purpose and scope below must be met by use of electromagnetic transient simulation, described later in this section. Phasor-based fault analysis might be used for screening conditions for such GRD, but the nonlinearity of MOV voltage limitation and triggering of bypass by low-frequency voltage oscillations initiated by fault offset makes phasor-based tools insufficiently valid for final GRD specification. Some phasor-based fault analysis software may have nonlinear impedance models that are intended for representation of series capacitors. These models may be of potential use in representing GRDs using MOV overvoltage limitation.

Purpose, Objectives, and Scope

The purpose of fault analysis in the context of GRD application study is to:

- Determine fault current ratings of GRDs.
- Identify which GRDs may bypass for a specific fault event.
- Determine results needed as input for the protective relaying impacts study described later, such as polarization phase shifts, apparent impedance, etc.

Analysis Tools and Models

The study described here uses conventional fault analysis software. For neutral GRDs, the software must have the capability to properly represent neutral impedances on autotransformers, and provide the currents through these neutral impedances during faults.

Where conventional fault software is inadequate, this scope must be transferred to the Electromagnetic Transients Study scope.

Critical Cases and Conditions

For specification of GRD fault current withstand duty, the study cases need to consider system configurations and conditions maximizing this current. For series GRD this is usually maximum-strength system conditions and close-in faults at either side of the series device. The critical fault events may either be three-phase or single-phase faults, depending on the Z_0/Z_1 ratio at the location. For neutral GRDs, maximized fault currents may be for conditions providing minimum positive-sequence (maximum three-phase fault strength) but with other grounding sources in the area removed if consistent with contingency analysis practices. Faults adjacent to the protected transformer will normally cause the maximum fault current, and only single-phase faults will be critical.

Where GRDs are bypassed by faults, it is important to evaluate the extent of GRD bypassing for any fault location. This is needed as input to the GMD analysis study in order to determine the impacts of such bypassing on the resulting system performance and equipment exposure to GIC. If the GRDs are automatically and immediately reinserted (bypass opened), then system and equipment effects are not as critical, but the GMD analysis needs to determine the GIC flow through the devices as input to the electromagnetic transient study of the GRD reinsertion transient. Note that the GMD study needs to determine the GRD deployment plan as input to the short circuit analysis, but the short-circuit study provides bypassing information to the short-circuit study.

Fault currents and voltages, including phase angles, at various locations may be required assess performance and coordination of transmission system protective relay. This is particularly true in situations where the GRD may affect relay reach or directional relay polarization.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - GRD deployment plan.
- From GRD Design:
  - GRD impedance.
  - GRD overvoltage protection details (e.g., protective bypass voltage threshold, MOV voltage protective level, etc.)

Outputs

- To GRD Design:
  - Maximum GRD fault current magnitude.
  - Fault current magnitudes for fault locations for which bypassing is not desired.
- To GIC Flow Study
  - GRD fault current magnitudes for various fault locations.
- To GRD Design:
  - Maximum fault current magnitude.
- To Insulation Coordination Study:
  - Maximum fault current
  - Maximum GRD voltage
  - Unfaulted phase voltages
- To System Protection Study:
  - Fault currents and voltages during faults, as needed to support relay performance evaluation and coordination.

12.4 Harmonic Analysis

Purpose, Objectives, and Scope

The purpose of harmonic analysis is to evaluate the harmonic currents and voltages imposed on a GRD for steady-state conditions.

Applicability

Harmonic analysis is particularly important for high impedance capacitive and resistive neutral GRDs. For intermediate impedance capacitive GRD and low-impedance resistive GRD, harmonics are not as likely to be of similar importance as for a high-impedance design, but harmonics may be a rating factor worthy of consideration. If not considered for these devices, then margin should be allowed in the GRD ratings to accommodate harmonic duty. Harmonics are unlikely to be of significance to a low-impedance capacitive GRD because capacitive impedance decreases with increasing frequency and these devices will not engage in a harmonic resonance.

Analysis Tools and Models

Harmonic analysis software capable of three-phase representation is needed for analysis of the zero-sequence harmonics affecting neutral GRDs. Preferably, this software should allow representation of phase imbalance as well. In addition to dedicated harmonic analysis software, electromagnetic transient simulation tools have the capability of performing frequency-domain analysis, but they can be cumbersome for modeling extensive systems.

Harmonic sources for this study are primarily GIC-saturated transformers. Lookup tables or functions describing harmonic current as a function of GIC may be used in combination with GIC magnitudes through system transformers determined in the GIC Flow Study. The harmonic injection functions should be specific to the type of transformer, as the harmonic injections of the various transformer types (shell-form, 5-leg core form, etc.) due to GIC substantially differ.

Harmonics created by GIC in transformers are predominately in the lower orders, below 10^{th} harmonic. Low-order harmonics require a relatively extensive transmission system model in order to obtain accurate results.

Critical Cases and Conditions

It is very difficult to predict the system conditions that may lead to worst case harmonic voltages and currents, as harmonic resonances are sensitive to small changes in the system. A wide range of GIC flow cases should be used to obtain the different possible harmonic injection patterns. For each injection scenario, analysis of a range of system conditions including generator commitments, capacitor bank status, and line outage conditions should be included in a comprehensive study.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - GRD deployment plan.
  - GIC flow through transformers for various GMD orientations, and GRD bypass scenarios.
- From GRD Design:
  - GRD impedance.

Outputs

- To GRD Design:
  - Harmonic current magnitudes for GRD steady-state voltage and current rating.
- To Insulation Coordination Study:
  - GRD harmonic voltages.

12.5 Electromagnetic Transients Study

Purpose, Objectives, and Scope

The Electromagnetic Transients Study purpose is to assess all aspects of GRD performance that cannot be appropriately studied using phasor-based or frequency-domain tools, and thus require modeling in an electromagnetic transients (EMT) program to incorporate transient and non-linear behavior.

The objectives of the Electromagnetic Transients study include:

- Determination of the ability of a GRD to remain in service for various degrees of fault severity and other system disturbances.
- Quantify the magnitude and duration of transient and temporary overvoltages affecting the GRD and other equipment, including transformers and bus surge arresters.
- Assess the potential for undesirable system interactions such as ferroresonance.

EMT programs could also be used to study system behavior during a GMD, particularly harmonic performance, as an alternative to separate GIC flow studies and phasor-domain harmonic analysis. The potentially long settling times into the steady-state, combined with the need to use relatively small time steps to accommodate modeling of nonlinearities (e.g., transformer saturation) can make the use of EMT programs for this purpose quite unwieldy.

The Electromagnetic Transients Study also must assume the scope of the Fault Study if the nature of the GRD design does not permit accurate analysis of fault behavior by the use of phasor-domain fault analysis tools.

Applicability

An Electromagnetic Transients Study is recommended for all types of GRD applications.

Analysis Tools and Models

The Electromagnetic Transients Study requires the use of an EMT program such as EMTP-RV, ATP, or PSCAD. Alternatively, the study could be performed on a real-time simulator platform (RTDS, or Opal-RT).

A number of different types of phenomena are within the scope of EMT studies related to GRD application. The simulation models used for the studies must be appropriate for the particular phenomena to be investigated. Most of the phenomena requiring study involve relatively low frequencies, so either the model must either cover a large physical extent of the transmission system, or termination impedances at the ends of more limited-extent network models should have appropriate frequency-dependent characteristics. Proper modeling of transformer saturation characteristics is important for some study aspects, such as transformer energization inrush. If performance of the system with GIC is to be modeled, accurate transformer modeling is of paramount importance, including representation of the magnetic circuits of three-phase transformers. Also, if GIC is to be modeled, the resistances at dc and ac, including ac frequencies that are a low-order harmonic of the fundamental, can be drastically different. This is particularly true of transmission line zero sequence parameters (GIC is a "zero sequence flow"), and transformers for which ac resistance has significant conductor eddy loss components that are not present at dc. Thus, specific attention must be given to the frequency-dependence of network component characteristics, particularly if dc (GIC) and ac harmonic phenomena are to be simultaneously simulated.

For single-GRD studies with the remainder of the system grounded in a normal manner, the study model should extend at least a couple of buses away from the GRD location even if GIC effects are not to be simulated. When a large-scale deployment of GRD is considered, the potential for interaction between GRD locations may dictate the need for a more extensive system representation. For all studies, accurate fundamental-frequency driving point and transfer impedances for all model termination points are of critical importance. It may be necessary to have multiple sets of driving point and transfer impedances in order to evaluate different conditions of the wider system (e.g., heavy load, light load, etc.).

Critical Cases and Conditions

The types of cases that should be included in this study include:

- Transmission faults at a wide range of locations. For neutral GRD, ground faults will be the critical fault type. For series GRD, either single-phase ground faults or three-phase faults will be critical.
- Energization of the transformer to which a neutral GRD is connected, unless the design will have interlocks to ensure the GRD will be always in a bypassed state when the transformer is energized.
- Energization of other nearby transformers. Energization at or near voltage zero is typically the worst-case condition for inrush transients.
- Deenergization of a transformer with neutral GRD, along with pre-charged transmission line or capacitor bank, if this contingency is a possibility.
- Insertion (opening of bypass) of GRD during maximum GIC flow.
- Line and capacitor bank energization (important for high-impedance GRD only)

Inputs from and Outputs to Other Studies

<u>Inputs:</u>

- From GIC Flow Study:
  - GRD deployment plan.
  - GIC flow through transformers for various GMD orientations, and GRD bypass scenarios.
- From GRD Design:
  - GRD impedance.

- GRD overvoltage limitation design (e.g., MOV characteristics, voltage threshold for bypass triggering, etc.)

Outputs

- To GRD Design:
  - Transient GRD voltage and current.
  - Evaluation of GRD overvoltage protection strategy, including assessment of the tendency for the protection strategy to bypass the GRD for remote faults and other disturbances.
  - MOV energy dissipation for faults and other events.
- To Insulation Coordination Study:
  - GRD voltages.
  - Unfaulted phase voltages.
- To System Protection Study:
  - Characterization of non-fundamental oscillations caused by GRD that may affect relay accuracy.

Note: If the characteristics of the GRD do not allow fault analysis to be performed using conventional phasor-based fault analysis software, the entire scope of the Fault Study must be transferred to the Electromagnetic Transients Study, including all inputs and outputs.

12.6 Insulation Coordination Study

Purpose, Objectives, and Scope

The purpose of the Insulation Coordination Study is to ensure that the insulation levels of all equipment, including both GRDs and the equipment to which the GRDs may be connected, are protected from all known overvoltage stresses, including transients not directly involving the GRD. The study also assesses the ability of surge arresters to withstand continuous and temporary overvoltages.

The study specifies ratings of surge arresters applied primarily for impulse and switching surge overvoltage protection, including surge arresters applied to other equipment and other locations, such as at the high-voltage bus for a neutral GRD application. The specification of MOV within the GRD, intended to conduct high currents during fault and other similar conditions, has been defined into the GRD Design task. Where adequate insulation coordination cannot be obtained with existing surge arrester locations, the study may specify different or additional arrester locations.

The scope of this study, as defined here, is an engineering "paper" study, relying on simulation results from other studies (particularly the Electromagnetic Transients Study), but not including modeling or simulation within this scope.

Applicability

The need for an Insulation Coordination Study is most critical for a neutral GRD application, due to the potential impact of a neutral GRD on the transformer's neutral insulation, and the impact on high-voltage phase insulation and overvoltage protection.

For series GRD, insulation coordination involves only a routine is needed to ensure that the GRD insulation, including insulation to ground, is adequately coordinated with overvoltage protection.

Key Considerations

For a neutral GRD, protection of the transformer neutral insulation level must be assured. This includes impulse transient events not directly related to the GRD. The surge protection of the neutral insulation must also be coordinated with the temporary voltages allowed by the GRD, such that the neutral surge arresters are not damaged.

In addition to coordination of overvoltage protection of the neutral, a neutral GRD will potentially allow increased differential voltage across the transformer's high-voltage winding(s), and phase TOV levels may be increased by the presence of the GRD. Thus, the insulation coordination of the station at the high voltage level must also be evaluated.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - Quasi-dc voltage due to GMD
  - GRD deployment plan
- From System Imbalance Study:
  - Maximum steady-state fundamental current for determining maximum continuous operating voltage across device.
- From Fault Study:
  - Maximum fault current
  - Maximum GRD voltage
  - Unfaulted phase voltages
- From Harmonic Study:
  - GRD harmonic voltages.
- From Electromagnetic Transients Study:
  - GRD voltages.
  - Unfaulted phase voltages.

Outputs

- To GRD Design:
  - Maximum allowable temporary voltage
  - Maximum allowable continuous voltage

Other Required Data

Performance of the Insulation Coordination Study for a neutral GRD application requires, as a minimum, the following data that are not results of other GRD application studies:

- BIL of transformer neutral

- BIL of all equipment connected to the HV bus (or buses, in the case of an autotransformer)
- Existing surge arrester ratings and locations

12.7 System Protection Study

Purpose, Objectives, and Scope

The System Protection Study ensures that existing line, transformer, and other protection systems are functional and properly coordinated with the addition of GRDs. This study may specify changes to protection schemes to accommodate the GRD. Self-protection of the GRD is defined to be within the GRD Design scope, and is not addressed in this scope.

Applicability

This study is necessary for any GRD type.

Key Considerations

For series GRD, the potential for phase inversion and change of distance relay reach should be considered.

For neutral GRD, the main consideration is inversion or phase shift of polarizing quantities.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - GRD deployment plan
- From Fault Study or Electromagnetic Transients Studies:
  - Fault currents and voltages during faults.
- From Electromagnetic Transients Study
  - Characterization of non-fundamental oscillations caused by GRD that may affect relay accuracy.
  - Fault currents and voltages not supplied by a phasor-based Fault Study

Outputs

- To GRD Design:
  - Limitations to GRD characteristics imposed by protection issues.

Other Required Data

Performance of System Protection Study requires the details of all the protection schemes, including settings, for all lines, transformers, buses, and other equipment adjacent to the GRD location.

12.8 GRD Design

Purpose, Objectives, and Scope

The GRD Design takes different form whether the GRD is to be custom-designed for the application, or if a vendor's standard design is to be used.

A bespoke (custom) design requires:

- Selection of the GRD impedance (if capacitive; if resistive, the impedance is specified as part of the GIC Flow Study) such that steady-state voltages are within GRD and system limitations.
- Overvoltage protection scheme design, including specification of MOV clamping voltage, bypass approach, gap characteristics, bypass triggering thresholds, coordinated with device ratings and the constraints of external equipment and insulation coordination.
- Specification of components to withstand steady-state, temporary (e.g., fault), and transient voltages, currents, and energy.
- Selection of bypass switchgear capable of GIC interruption during device insertion.
- Design of self-protection to detect any internal faults or device component failures, and to take corrective action that does not place other components or the system at risk.
- Controls to automate device insertion and reinsertion.

Where a vendor's existing GRD system product is to be applied, the GRD Design task entails evaluation of the suitability of the design to meet the requirements of the application.

Applicability

This study is necessary for any GRD type.

Inputs from and Outputs to Other Studies

Inputs:

- From GIC Flow Study:
  - GRD deployment plan
  - GRD impedance (if resistive)
  - Quasi-dc voltage due to GMD
  - Maximum GIC through a bypassed GRD in order to determine interruption requirement for device insertion
- From System Imbalance Study:
  - Maximum steady-state fundamental current for device rating.
- From Fault Study:
  - Maximum GRD fault current magnitude.
  - Fault current magnitudes for fault locations for which bypassing is not desired.
- From Harmonic Study
  - Harmonic current magnitudes for GRD steady-state voltage and current rating.

- From Electromagnetic Transients Study:
  - Transient GRD voltage and current.
  - Evaluation of GRD overvoltage protection strategy, including assessment of the tendency for the protection strategy to bypass the GRD for remote faults and other disturbances.
  - MOV energy dissipation for faults and other events.
- From Insulation Coordination Study
  - Maximum allowable temporary voltage
  - Maximum allowable continuous voltage
- From Protection Coordination Study
  - Limitations to GRD characteristics imposed by protection issues.

Outputs

- To GIC Flow Study
  - Critical fault current magnitude requiring GRD bypass.
- To System Imbalance Study
  - GRD impedance.
- To Fault Study
  - GRD impedance.
  - GRD overvoltage protection details (e.g., protective bypass voltage threshold, MOV voltage protective level, etc.)
- To Harmonic Study
  - GRD impedance.
- To Electromagnetic Transients Study
  - GRD impedance.
  - GRD overvoltage limitation design (e.g., MOV characteristics, voltage threshold for bypass triggering, etc.)

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A
LIST OF ACRONYMS

ATP	Alternative Transients Program
BIL	basic insulation level
EHV	extra high voltage
EMP	electromagnetic pulse
EMTP	Electromagnetic Transients Program
EMT	electromagnetic transients
FACTS	Flexible Alternating Current Transmission System
FERC	Federal Energy Regulatory Commission
GIC	geomagnetically induced currents
GMD	geomagnetic disturbance
GRD	GIC reduction devices
GTO	gate turn-off thyristor
HVDC	high-voltage direct current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated-gate bipolar transistor
IGCT	integrated gate-commutated thyristor
MCOV	maximum continuous operating voltage
MOV	metal-oxide varistor
NBD	neutral blocking device
NERC	North American Electric Reliability Corporation
pu	per unit
rms	root mean square
RTDS	real time digital power system
SSR	subsynchronous resonance
TOV	temporary overvoltage

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