Distribution System Neutral Grounding Methods and Transformer Winding Configurations

EPRI Distribution Grid Operations and Planning Team

Project Manager
A. Kelly

3002011000

December 2017

Disclaimer of Warranties and Limitation of Liabilities

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Acknowledgments

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigator
S. McGuinness

A. Kelly EPRI International

This report describes research sponsored by EPRI.

EPRI would like to acknowledge and thank the members who took the time to complete the neutral grounding and transformer connection survey in 2017, and provided very useful comments on their utilities' experiences

This publication is a corporate document that should be cited in the literature in the following manner:

Distribution System Neutral Grounding Methods and Transformer Winding Configurations . EPRI, Palo Alto, CA: 2017. 3002011000.

Abstract

The neutral grounding method is one of the most important elements to consider when utilities plan and operate their distribution system. The specific neutral grounding method chosen by the utility can have significant impacts on reliability of service, safety, protection coordination, power quality, equipment ratings among many others.

This report is intended to be a primer that illustrates the fundamentals of neutral grounding and transformer winding configuration as they relate to distribution system protection. It documents international practice and includes information from international standards. This report should not be used as a design instructional manual. Readers should refer to and follow industry technical and safety design guidelines and processes in relation to neutral grounding practices and design and refer to the EPRI Engineering Guide for Distributed Storage and Generation for more detailed information.

Keywords

DER

Distribution
Grounding
Neutral
Protection

Acronyms and Abbreviations

- ASC: Arc Suppression Coil
- CT: Current Transformer
- DER: Distributed Energy Resources
- NG: Neutral Grounding
- OC: Overcurrent
- PT: Potential Transformer
- RCC: Residual Current Compensation
- SAIDI: System Average Interruption Duration Index
- SAIFI: System Average Interruption Frequency Index
- Trafo: Transformers

Table of Contents

Introduction and 2017 Survey Results

Introduction and Background to Project

Aim: Review Neutral Grounding Methods

- To review historical justifications and issues
- Review previous EPRI research
- Take into account modern technologies and practices

If Changing Neutral Grounding Method

- Document potential benefits and challenges
- Practical experience from utilities who have actually changed neutral grounding method from engineering literature.

Investigate Impact of Modern Technologies

- Transformer winding configuration for inverter-interfaced DER
- Power electronic solutions to neutral grounding issues

This work aims to document the benefits and challenges associated with neutral grounding with particular emphasis on protection and reliability impacts.

It is not intended as a proposal for utilities to change NG method

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Existing EPRI Research and Standards

- EPRI Engineering Guide for Integration of Distributed Storage and Generation (2012) (ID: 3002005774)
- EPRI Substation Grounding Grids (2011) (ID: 1021921)
- EPRI Distribution Grounding Handbook (1996) (ID: TR-106661-V1)

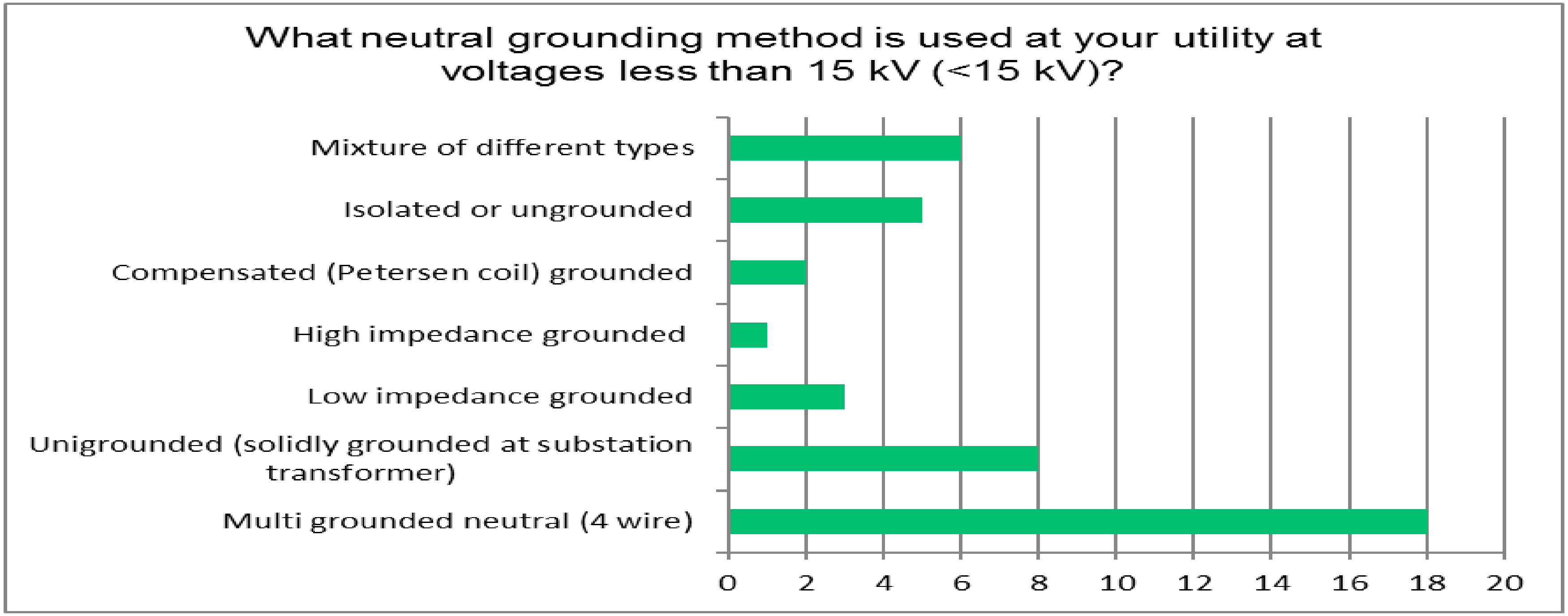
Selected International Standards on Grounding

- IEEE142 (Green Book) Grounding of Industrial and Commercial Power Systems
- IEEE C62.92.(Part 4) Guide for application of Neutral Grounding in Electrical Utility Systems
- IEEE Standard 80, Standard 837 (Substation grounding)
- IEC 60364 (Electrical Installations for Buildings)

This document is not intended to be a substitute for information in the above documents. Intention is to build on the information with practical experience and impact of modern technologies.

EPRI Neutral Grounding 2017 Survey Results

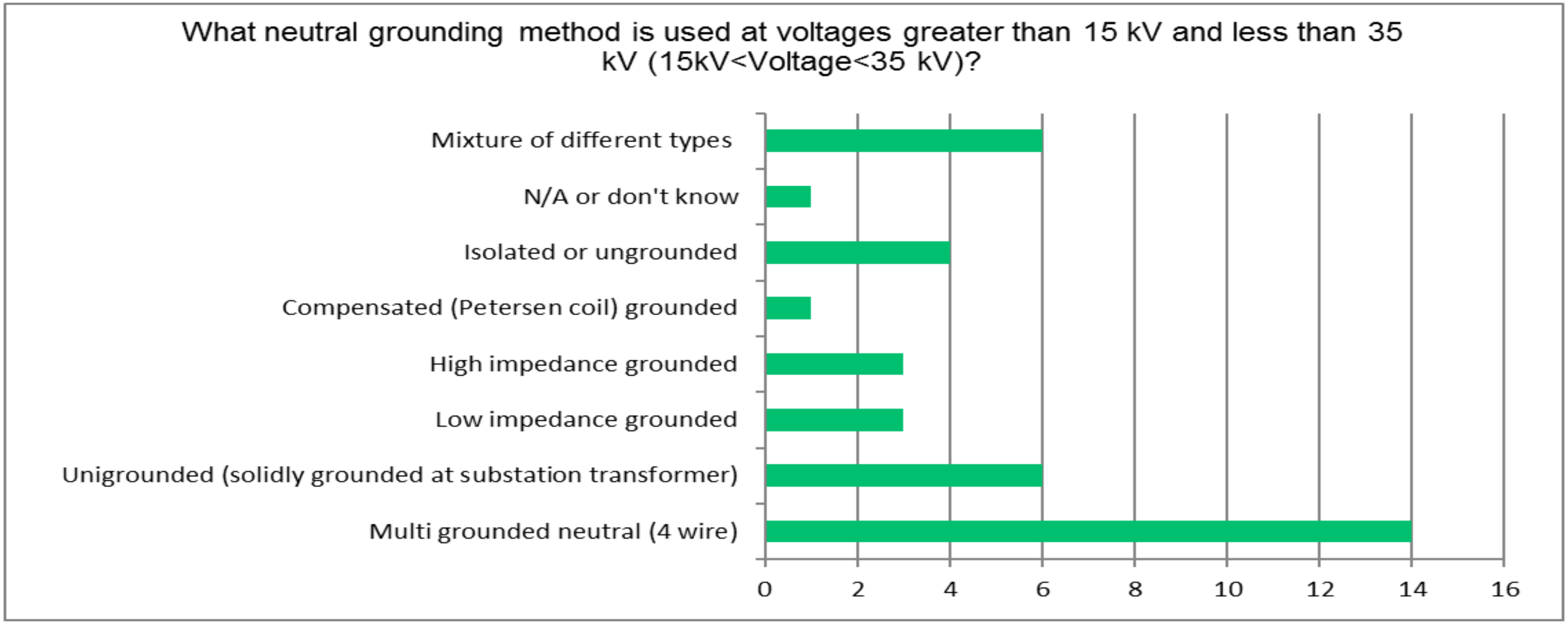
- Four wire multi grounded neutral is by far the most used among EPRI members for systems less than 15 kV
- Some utilities use a mixture of neutral grounding methods.



ELECTRIC POWER RESEARCH INSTITUTE

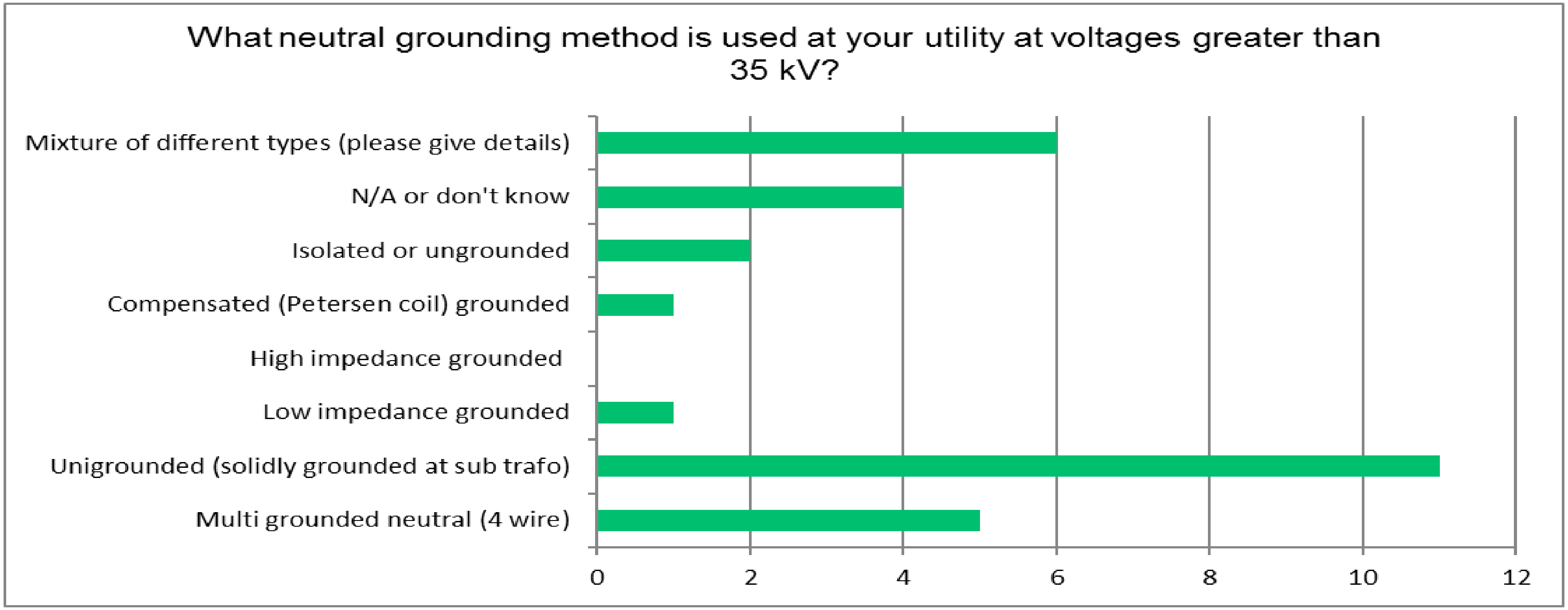
EPRI Neutral Grounding 2017 Survey Results

- Four wire multi grounded neutral is by far the most used among EPRI members for systems between 15 and 35 kV
- Some utilities use a mixture of neutral grounding methods.



EPRI Neutral Grounding 2017 Survey Results

- For systems greater than 35 kV solidly grounded at substation transformer is the most used method by EPRI members that contributed to the survey.
- Some utilities in the survey do not operate above 35 kV.



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Neutral Grounding Methods Overview

Grounding of Electrical Systems

- Various characterizations of grounding methods under different criteria currently are available
  - IEEE 142 (Green Book)
  - EPRI Distribution Grounding Handbook

- Details and information from standards and engineering literature are summarized in the table on next page

	Solidly Grounded	Reactance Grounded: Low Reactance	Reactance Grounded: High Reactance	Resistance Grounding: Low Resistance	Resistance Grounding: High Resistance	Resonant Grounding / Arc Suppression	Ungrounded / Isolated
Current for Phase-to-Ground fault in percent of Three Phase current	Varies (may be 100 % or greater)	Usually designed to produce 25 % to 100 %	5 % to 25 %	Less than 20 %	Less than 1 % but not less than system charging current	Nearly 0 %	Less than 1 %
Transient Overvoltages / Arcing Grounds	Not Excessive / Unlikely	Not Excessive / Unlikely	Not Excessive / Possible	Not Excessive / Unlikely		Not Excessive / Unlikely	Very High / Likely
Surge Arresters Connections	Grounded Neutral	Ungrounded Neutral		Ungrounded neutral		Ungrounded neutral	Ungrounded neutral
Apparatus Insulation	Full insulation at windings and lower insulation level at neutral	Partially Graded (insulation level can reduce from full insulation at windings to reduced insulation level at neutral)		Partially Graded (insulation level can reduce from full insulation at windings to reduced insulation level at neutral)		Partially Graded (insulation level can reduce from full insulation at windings to reduced insulation level at neutral)	Full insulation throughout the system
Protection Considerations	Normal	Normal		Normal		Requires special considerations	Difficult to coordinate
Localization of faults on system they occur on	Effects of fault localized to system they occur on	Effects of fault localized to system they occur on	Fault causes overvoltage on other phases of conductively connected network	Fault causes overvoltage on other phases of conductively connected network		Fault causes overvoltage on other phases of conductively connected network	Fault causes excessive voltage on other phases of conductively connected network
Circuit Availability During Faults	Circuit must be deenergized to clear faults	Circuit must be deenergized to clear faults		Circuit must be deenergized to clear faults		Circuit remains in service for most faults. May need to be deenergized for some faults	Should remain in service for short lines. May need to be deenergized for faults on longer lines
Adaptability to interconnection between networks or partial networks with different neutral ground method	Can be connected to other systems with protection coordination	Can be connected to other systems with protection coordination		Can be connected to other systems with protection coordination		Cannot be interconnected with other systems	Cannot be interconnected with other systems
Operating Considerations with Neutral Grounding Method	No special considerations	No special considerations		No special considerations		Taps on ASC may need to be changed. Difficulties arise when interconnecting systems. Fault location difficult	Possibility of double faults adds complications. Fault location difficult
Other Remarks	Generally used on systems (1) 600 V and below (2) over 15 kV	Generally used on systems (1) 600 V and below (2) over 15 kV	Not generally used due to excessive overvoltages	Generally used on systems of 2.4 kV to 15 kV particularly where large rotating machines are connected	Used on systems 600 V and below where service continuity is desired	Best suited for application in most MV industrial and commercial systems isolated from utility by trafo	Not recommended due to overvoltages, double faults and faults remaining on the system with circuit deenergization

Typical International Practices for Transformer Neutral Grounding

- Most countries do not have single neutral method and some have a combination of different methods for different voltage levels or different areas of the network.
- Table below highlights some of the neutral grounding practices in use in different countries around the world

Solidly Grounded Neutral	High Impedance Grounded Neutral	Low Impedance Grounded Neutral	High Resistance Grounded Neutral	Resonant/ Compensated/ Peterson Coil/ Arc Suppressed Neutral	Ungrounded / Isolated Neutral
Argentina, Australia (parts), Brazil, Canada, Colombia, Chile, Mexico, New Zealand, South Africa (parts), Spain (parts), USA	Used on Synchronous Generators	Chile (parts), France (parts), India, Netherlands, Portugal, South Africa (parts), Peru (parts), Spain (parts), UK	Used on Industrial Sites	Australia (parts), Austria, China (parts), Denmark, Finland, France (parts), Germany, India (parts), Ireland, Italy (parts), Japan, Malaysia, Norway, Romania (parts), Sweden	China (parts), Ireland (parts), Italy (parts), Japan, Russia, Peru, Romania (parts), Spain (parts) Some Inverter Interfaced Generators

Source: Protection of Distribution Systems with DER – Final Report 2015 CIGRE,

EPRI Neutral Grounding survey 2017

Neutral Grounding Context Around the World

- North American most common method for systems less than 35 kV is the 4-wire multi-grounded neutral system
  - HV/MV Substation trafo is typically delta/wye grounded (D/YG).
  - Neutral is typically solidly grounded or it can be low impedance grounded to limit ground fault current levels
- Other most methods are used in western USA (15 kV and below)
  - Uni-grounded at substation wye or delta-connected 3-wire system.
  - Neutral grounded (either solidly or with low impedance) in the substation and no neutral carried on overhead line feeder. However, neutral is carried on underground cable feeders
- European and Asian System characteristics:
  - 3 wire systems unigrounded at substation
  - Grounding method is country and system dependent but primarily: solidly grounded, low impedance or resonant grounded
  - There are also many ungrounded (isolated) neutral systems < 10 kV in Europe and parts of Asia and the USA. Some utilities are moving from ungrounded systems to other systems as will be documented elsewhere in this report

Resonant Grounded Systems – Brief Overview

- "Resonant Grounding" term used interchangeably with "Arc Suppression Coil", "Petersen Coil", "Compensated Grounding", "Ground Fault Neutralizer"
- Used widely around the world, but particularly popular in Europe.
- Also used where continuity of supply to customers is very important or where there are critical loads which are very sensitive to voltage disturbances.
- Method:
  - A high impedance reactor is inserted between the transformer neutral and ground. All other neutrals are isolated from ground.
  - The reactor is sized (tuned) to resonate with the zero sequence capacitance of the system it is connected to.
  - Perfect resonant grounding tuning results in very low ground fault currents, usually current is not large enough to sustain an arc, and negligible voltage dip
  - Result is that for most transient single line to ground faults the arc self extinguishes without the need for a breaker operation, so customers are unware a fault has occurred.
- In industrial site installations, high resistance grounding is also frequently used to protect against the impact of low voltage and limit fault current, but high resistance grounded systems have the disadvantage of needing a breaker to open to clear the fault – (fault may not self extinguish) although the systems can survive extended periods with the fault on the system before an operator acts.
- The Arc Suppression Coil is tuned to compensate the total shunt capacitance of the downstream feeders prior to commissioning
  - If the downstream shunt capacitance changes over time due to additional feeders or laterals the reactor may need to be re-tuned.
  - Modern coils have adjustable taps making the change process more straight forward.
- Equipment for resonant grounding will generally be more expensive than for the other methods of grounding systems.
- It is typically more difficult to find exact fault location compared to other neutral grounding methods.

IEEE Guide for the Application of Neutral Grounding in Electrical Utilities Part IV Distribution, IEEE, New York, 2002

Distribution Planning for the Modern Grid, EPRI Palo Alto CA, 2016 - 3002007977

Ungrounded (Isolated) Systems – Brief Overview

- Ungrounded or isolated systems have no intentional connection between the system neutral and ground. They can be considered as a "capacitive grounded" system, if the system is balanced, the capacitive reactance to ground is assumed to be balanced in the system
- During normal, balanced operation of the system the neutral of the system is at ground potential.
- In the case of a single phase to ground the faulted phase falls to ground potential but the voltage on the un-faulted phases rise by a factor of $\sqrt{3}$.
- The resonant condition between inductive reactance of the system and capacitance to ground can result in transient overvoltages during unbalanced faults. These overvoltages can cause equipment damage and safety risks if insulation is not appropriately specified. Equipment must be insulated to line-line voltage level in ungrounded systems.
- Service continuity is maintained during ground faults provided a secondary phase to ground fault does not occur. If a secondary phase to ground fault occurs while the primary fault is still on the system, this effectively becomes a phase to phase fault which will result in overcurrent protection acting to open the breaker and clear the fault
- Protection coordination can be difficult with ungrounded systems. The presence of ground faults can be detected using zero sequence voltage relay on the broken delta of potential transformer.
- Locating the fault is more difficult and may require switching operations on feeders or loads to find and clear the fault. Wattmetric or Varmetric relays can also provide effective ground fault relaying on ungrounded systems.
- In the past, ungrounded systems were widely used as they were cost effective and had low short circuit current. However, in more recent years, some utilities are retrofitting ungrounded grids with Peterson Coils or solid grounding to improve grid reliability.

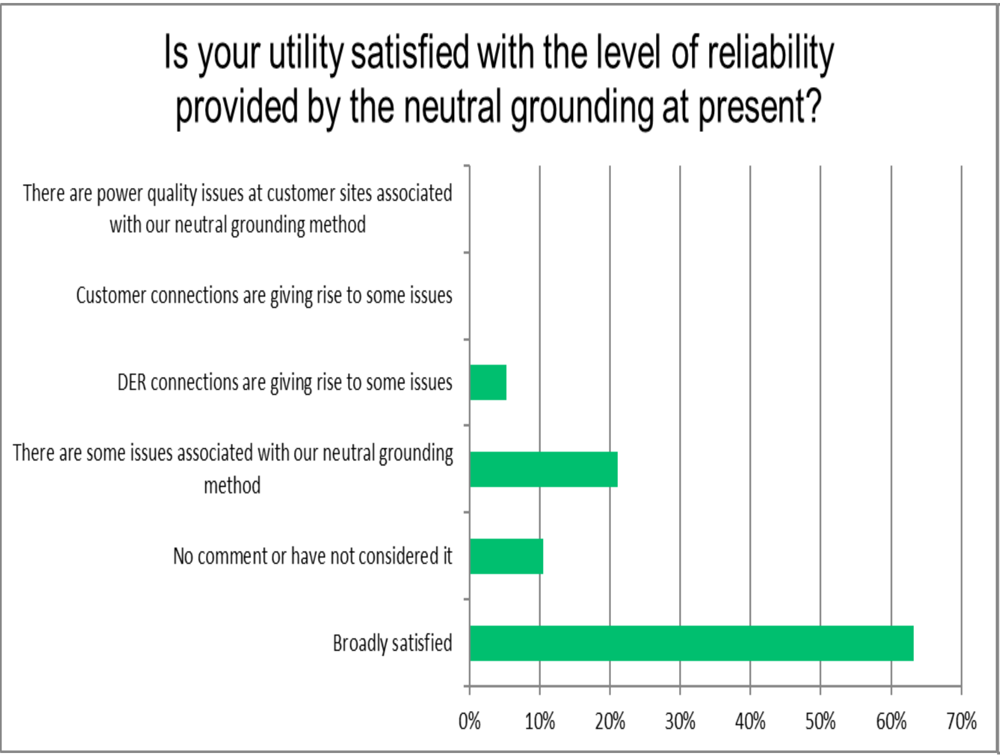
IEEE Guide for the Application of Neutral Grounding in Electrical Utilities Part IV Distribution, IEEE, New York, 2002

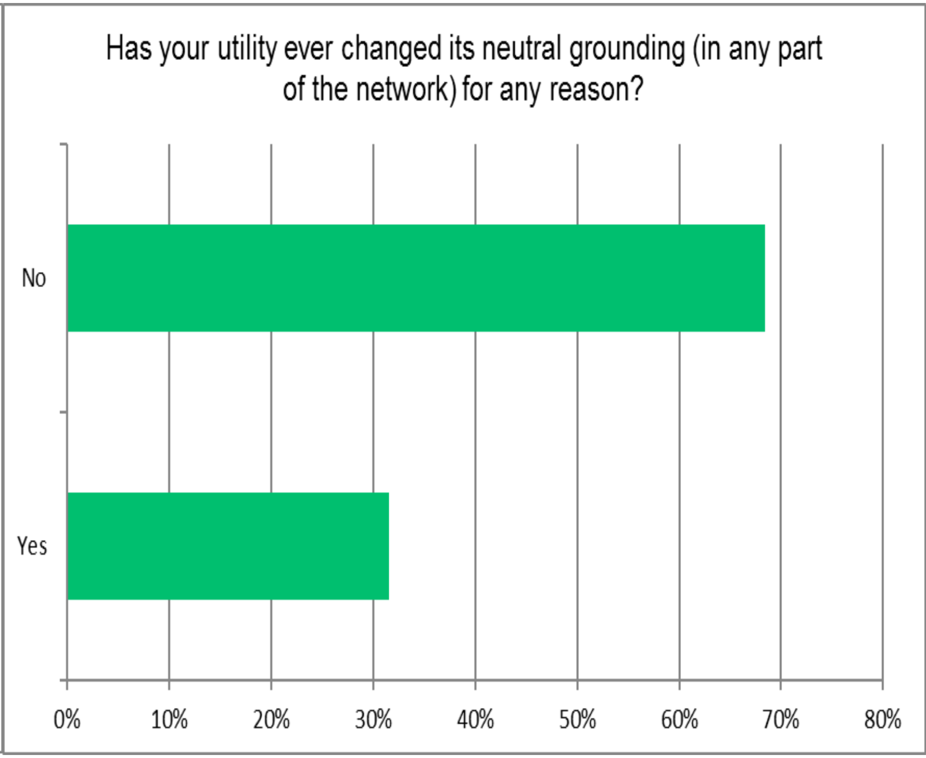
Distribution Planning for the Modern Grid, EPRI Palo Alto CA, 2016 - 3002007977

Changing Neutral Grounding Method

EPRI Neutral Grounding 2017 Survey

- The majority of utilities that responded to the EPRI survey are broadly satisfied with level of reliability provided by the neutral grounding method on their systems at present and over 30 % of survey respondents have changed the neutral grounding method of some part of their network in the past.
- In recent years some utilities around the world have made efforts to change their neutral grounding method for a number of reasons. These will be documented in this section





Reasons To Assess Neutral Grounding Method

Recent Network Development Assessment

- Load increase or decrease. Load profile or load characteristic changes
- Generation – synchronous and inverter-interfaced DER increase or decrease
- Reliability requirements and key performance indicators by regulatory bodies (SAIDI, SAIFI etc)
- Load/Voltage unbalance issues on a network

Fault Level Assessment

- Increasing or decreasing short circuit power on the system
- Information from operator of sub-transmission or transmission system about upcoming system changes

Protection Coordination / Safety

- Issues with detecting faults or coordinating protection settings
- Safety issues to general public and operators

Equipment Overvoltage / Insulation Coordination

- Equipment damage due to overvoltages during faults

Capital costs of replacements / Long Term Planning

- Design, planning and operation of system with different neutral grounding method(s)
- Improvements in technology, power electronics, controllers, remote control

International Examples of Utilities Changing Neutral Grounding Method

Some examples from engineering literature of international utilities that have changed their neutral grounding methods in recent years and the issues that were encountered.

Italy (ENEL)	China (State Grid)
Spain (Iberdrola)	Brazil (RGU Sul)

Each system described under the headings: System & Historical Context, Justification for Changing Neutral Grounding Method, New System, Protection Impacts

International Examples – ENEL, Italy

- ENEL Distribution Network Ground Assessment
  - CIRED 2003 Session 3, Paper 7 http://www.cired.net/publications/cired2003/reports/R%203-07.pdf

System & Historical Context

- System: HV=132 kV or 150 kV; MV=10 kV,15 kV or 20 kV radially-operated
- Approx. 1,600 medium voltage substations in total
- Approx. 38% of network is cable

Justification for changing neutral grounding method

- Prior to the 1960s the MV system was ungrounded (isolated neutral)
- Isolated neutral offered simple operation principles and low short-circuit current
- However, issues with greater insulation stress and intermittent arcing, environmental constraints, and more underground cables
- Developed a plan to migrate from ungrounded system to impedance grounded
- Initial trials (2000-2002) included 10% of the network becoming impedance grounded
- Aim was to reduce single-phase fault current and reduce the number and duration of outages due to transient ground faults

International Example – ENEL, Italy

New Neutral Grounding System

- Each transformer neutral now normally grounded through impedance instead of being isolated.
- Neutral impedance depends on fault level in the station can be a resistance, reactance, Peterson coil or a combination
- Neutral impedance has a remotely-operable disconnect installed so grid can be returned to isolated neutral if required
- Payback period (based on regulatory incentives) - including all asset costs - was just over 4 years

Protection Impacts

- Had to upgrade protection to ensure performance adequate for both isolated and impedance-grounded situations
- Upgraded to Wattmetric and Varmetric protection. These measure zero-sequence real and reactive power to determine fault location independent of neutral grounding method.
- Trip times:
  - Around 0.4 seconds when neutral is isolated
  - Around 10 seconds when neutral is impedance-grounded (long trip times are permitted as the fault current is very small, there is negligible voltage dip, and most arcs self-extinguish without requiring reclosers to trip)
- Big reduction in unscheduled outages found, as shown in table below:

Fault Duration	Fault Type	Number of faults With Isolated Neutral (Year: 2001)	Number of fault With Impedance-Grounded Neutral (Year: 2002)	Reduction
Transient (<1s)	Phase to Ground	2380	301	**-87%**
	Total	4340	1875	**-57%**
Short (<180s)	Phase to Ground	780	366	**-53%**
	Total	1878	1122	**-40%**
Long (>180s)	Phase to Ground	401	287	**-28%**
	Total	1063	717	**-33%**

International Examples – State Grid, China

- Suitable Methods for Neutral Grounding of Xining's Distribution Networks
  - CIRED Session 5 2017 http://cired.net/publications/cired2017/pdfs/CIRED2017_0393_final.pdf

System & Historical Context

- Xining Province (in northwest China) System: HV=110 kV MV=35 kV and 10 kV
- 1.4 GW of load today; expected to grow to >2.0 GW by 2020.
- There are 860 km of 110 kV lines, 170 km of 35 kV lines, 2470 km of 10 kV lines, (55% cables)
- Given this growth rate an assessment was carried out to analyse current practices and propose neutral grounding methods for the 2020 scenario

Justification for changing neutral grounding method

- More underground cable to be used in future and many new 110 kV stations being built to accommodate the load growth. The utility had high reliability requirements, so wanted to review grounding before making major capital investments.
- Existing Grounding Methods on Network:
  - 110 kV system: Low impedance grounded neutral on 330 kV/110 kV Auto-Transformers
  - 35 kV system: Combination of isolated and resonant grounded neutrals. Petersen coils were installed, but because some isolated and resonant-grounded networks became interconnected, this resulted in overvoltages during ground faults so the Peterson coils had to be taken out of service.
  - 10 kV system: Combination of isolated and resonant grounded neutrals.
- These neutral grounding methods were assessed on whether they will be suitable for the 2020 system

International Example – State Grid, China

New Proposed Neutral Grounding Systems

- Recommended New Neutral Grounding Methods Based on Consultant Report:
  - 110 kV System: No changes. Low impedance grounding should remain on auto-transformers because a change would also unnecessarily effect the grounding on the 330 kV network.
  - 35 kV: Reinstate resonant grounding. Ungrounded systems not recommended for the 35 kV system
  - 10 kV: Combination of low impedance, high impedance and resonant grounding depending on network characteristic and capacitive earth current on the part network. See table below
- Where networks have both isolated and resonant-grounded neutrals, split the networks so a single grounding type is used.

Protection Impacts

- The solution is proposed and has not been implemented yet. Protection performance will be assessed on the networks with ground fault trials.
- Resonant grounding requires resonance curve studies and measurements to find the charging current I_{ce} so that the Petersen coil can be tuned appropriately
- Protection coordination on feeders is required if neutral ground method is changed

	Type of 10 kV network	
	Networks with overhead line share	Pure cable networks
$I_{ce} < 35A$	**High-impedance neutral grounding**	**Low-impedance neutral grounding**
$I_{ce} > 35A$	**Resonance grounding**	**Low-impedance neutral grounding**

Source: http://cired.net/publications/cired2017/pdfs/CIRED2017_0393_final.pdf

International Examples – RGU Sul, Brazil

- Resonant Grounding Applied in Brazil
  - CIRED 2017 http://cired.net/publications/cired2017/pdfs/CIRED2017_1250_final.pdf

System & Historical Context

- RGE Sul: Utility in Southern Brazil with 1.3 million customers. 82 substations.
- MV system comprises of 13.8 kV and 23.1 kV voltage levels

Justification for changing neutral grounding method

- In Brazil most utilities have solidly grounded systems. This leads to reportedly high ground fault current levels.
- Safety concerns are highlighted as a major issue in the paper. In 2012 there were 292 deaths related to distribution utilities in Brazil. **4 deaths on RGE Sul systems alone.**
- Work initiated to attempt to find methods to reduce short circuit level and to help reduce safety issues while also maintaining reliability and continuity of service

International Example – RGU Sul, Brazil

New Proposed Neutral Grounding Systems

- International grounding practices examined to assess current practices with grounding around the world
- As a trial project the utility installed a passive resonant grounding system in 1 substation
- Installed an active resonant ground system at 2 substations.
  - Active resonant grounding uses a Petersen coil in parallel with a Residual Current Compensator inverter and a system controller. This system uses power electronics to continuously assess the capacitance of the network and when ground fault is detected it injects residual current to neutralize ground fault and maintain continuity of supply

Migration Work and Protection Impacts

- Single-phase transformers would ground the grid, so existing single phase transformers were replaced with three phase transformers and the single phase loads were connected phase-to-phase.
- Insulation assessments were required on all equipment to ensure they were suitable for line-line voltage.
  - For example; insulators, surge arresters, potential transformers, voltage regulators, transformers, capacitor banks etc. must have adequate insulation.
- Protection settings and coordination were reviewed on all feeders and equipment.
- New system means overcurrent protection now sensitive to fault resistances up to **3 kΩ** (used to be only sensitive up to 40 Ω)
- Initial installations in 2009; initial reporting period found:
  - No safety incidents or fatalities reported
  - Transient ground faults were reduced by 50 %
  - There was a significant reduction in customer outages

Source: http://cired.net/publications/cired2017/pdfs/CIRED2017_1250_final.pdf

International Examples – Iberdrola, Spain

- Active Earthing System For MV Networks By Power Electronics
  - CIRED 2009 and 2011 http://www.cired.net/publications/cired2009/main_sessions/Session%201/Main%20Session%201%20pdfs/Block%201/S1%200158.pdf
  - http://www.cired.net/publications/cired2011/part1/papers/CIRED2011_0560_final.pdf

System & Historical Context

- Iberdrola installed active grounding system as a pilot project on one 30 kV/13.2 kV 10 MVA substation in Northern Spain
- Passive neutral grounding techniques discussed earlier (resistor, inductor etc). With active resonant grounding the neutral impedance is effectively dynamically variable

Justification for changing neutral grounding method

- Active resonant grounding could provide all the advantages of other grounding methods.
- Also beneficial for preventative maintenance: Controlled overvoltages can be applied to the system to check insulation integrity on the equipment.

New System

- Power electronic system with a controller in series with a neutral reactor on the transformer neutral. The controller takes voltage and current measurements from MV feeders.
- Grounding method can be dynamically varied between ungrounded, impedance grounded to solidly grounded depending on grid conditions
- During Normal Operation the system is high impedance grounded. During single phase faults the system becomes Resonant Grounded within 100 ms of fault inception.

International Examples – Iberdrola, Spain

Protection Impacts

- For low impedance or solidly grounded systems – no changes required to overcurrent protection
- For ungrounded or high impedance grounded systems - overcurrent protection must be delayed > 100 ms.
- For permanent faults: either a dedicated Wattmetric or Varmetric relay or a bypass breaker to temporarily solidly ground the system to allow earth fault overcurrent protection on feeders to trip.
- Insulation assessment required on all of the MV network as it acts as a resonant network during faults. Equipment insulation must be rated for line-line voltage

May be future EPRI research on active grounding systems to assess protection impacts

- Complex solution and may be very expensive with additional capital and operational maintenance requirements
- Results and impacts assessed as part of future updates to this report

Transformer Winding Configuration Overview

Considerations When Presented with an Interconnection Transformer Winding Configuration

- Transformer winding should not exacerbate existing distribution system issues
- Developers may want to use older transformers that were designed for a different application. Ensure transformer is compatible with utility standards and policies
- Transformer should not cause damaging ground fault overvoltage to utility & customer equipment, loads
- Transformer should not be “too strong” of a grounding source that may desensitize existing utility relaying. Low impedance reactor may be required.
- Interconnections should not increase ground fault current above utility thermal equipment ratings
- Transformer should limit exposure of DER equipment to ground faults that are too high and/or too frequent
- Circulating harmonic currents within grounded step-up transformers, or on DER side can cause issues on the transformer

Engineering Guide for Integration of Distributed Storage and Generation. EPRI, Palo Alto, CA: 2012. 1024354.

Distribution Generation Interconnection Transformer and Grounding Selection, IEEE PES General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, 2008 – R Dugan, R Arritt

Transformers for DER

Utilities should be aware of the system issues that may develop with different interconnection transformers

- There is not one best transformer for all DER or for all systems. (Pros and Cons for each)
- Preference may often be to stick to "normal" transformer winding configuration as they are known and understood

DER addition to distribution networks, likely to exacerbate some existing system issues and may create new issues - for example:

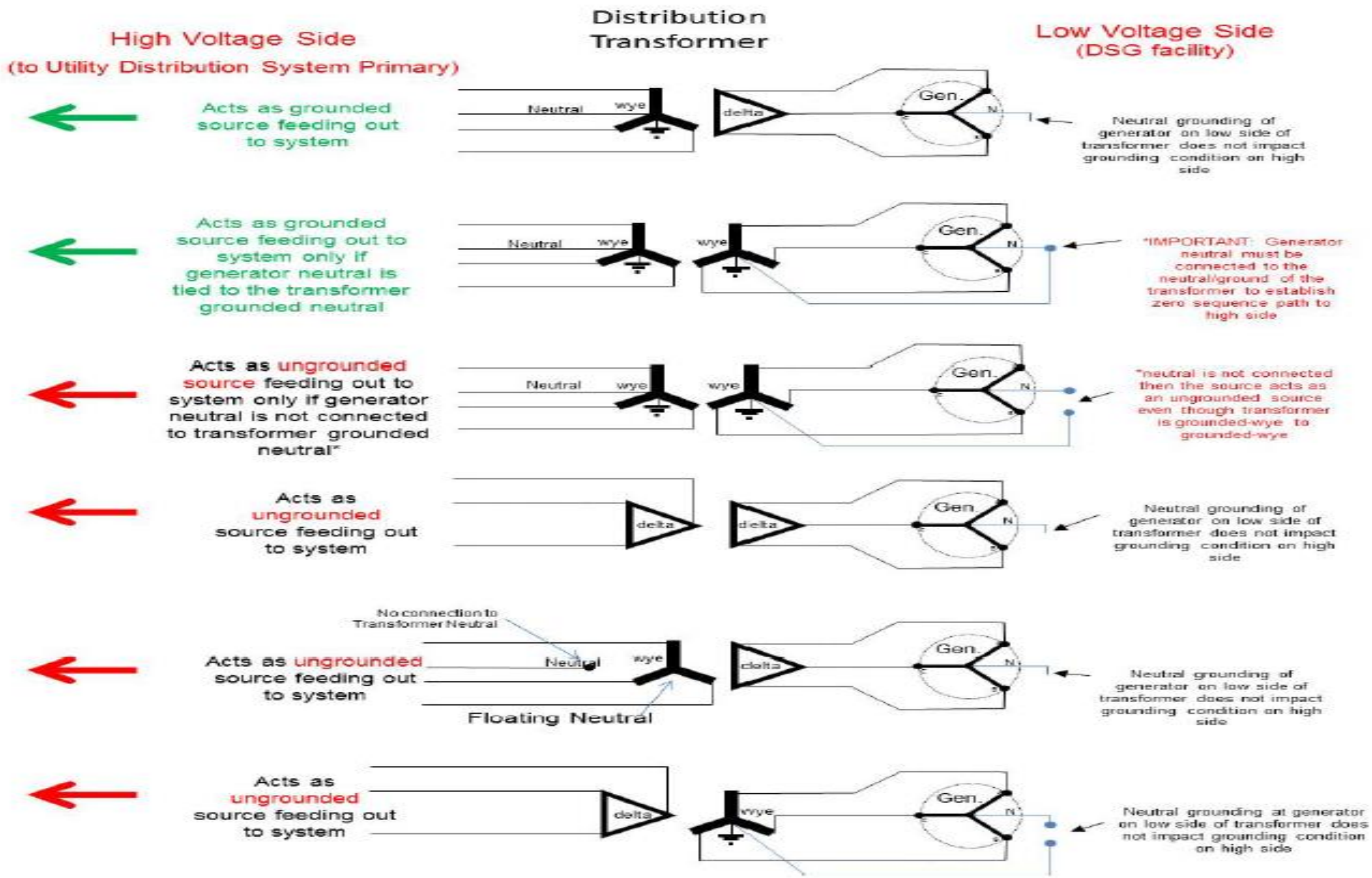
- Harmonics
- System overvoltages
- Protection settings coordination
- Islanding of load and DER
- Arc flash categorization

DER developer may be focussed on costs, not the most optimal interconnection transformer for the grid / other customers

Direct connection of DER to utility system is generally discouraged and can be problematic

- Interconnection transformer allows the system and DER to be isolated via protection from each other.

Summary of Transformer Winding Configurations for DER from - EPRI Engineering Guide for DER

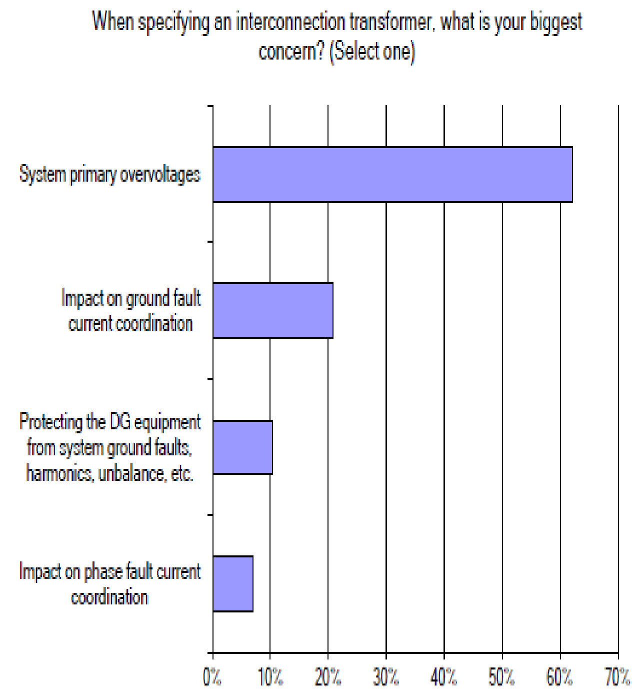


Engineering Guide for Integration of Distributed Storage and Generation. EPRI, Palo Alto, CA: 2012. 1024354.

Grounded Wye (Utility) – Grounded Wye (DER)

- 2017 & 2013 EPRI Distribution Utility Survey: By Far the most common DER grid transformer connection type
- Most Common concern: System Primary Overvoltages

- Advantages of YG/YG
  - Can be most economical solution at higher MV voltage levels, due to smaller transformer size, commonly available transformer – much experience with this type of trafo.
  - Protection - no phase shift between utility & DER.
  - Prevents zero sequence current circulating on DER side.
  - Less concern for ferroresonance in cable-fed installations for three legged core trafos. However, for five legged core YG/YG transformers in cable fed installations at all voltage levels, ferroresonance can cause severe overvoltages. This may cause damage and failure of arresters, customer equipment and in the worst case - damage to the transformer*



- Disadvantages of YG/YG
  - Both sites grounded allows a path for Zero Sequence Current to flow from utility -> DER and DER -> utility. Will feed ground faults on both sides and be exposed to utility voltage dips.
  - Wye Grounding allows zero sequence harmonic current from DER to utility. (may require trafo buried delta winding), especially on synchronous DER
  - DER may not provide an effectively grounded source.
    - Generator needs a suitably low impedance neutral reactor.
    - Inverter neutrals also need a low impedance reactor for effective grounding.

** Ferroresonance in Grounded Wye/Wye Transformers, EPRI, Palo Alto CA, 2006 - 1018824*

Engineering Guide for Integration of Distributed Storage and Generation. EPRI, Palo Alto, CA: 2012. 1024354.

Distribution Generation Interconnection Transformer and Grounding Selection, IEEE PES General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, 2008 – R Dugan, R Arritt

Delta (Utility) – Grounded Wye (DER)

- Common connection in Europe and North America
- Advantages
  - Delta winding traps 3rd harmonic currents – protecting utility (but the DER side is unprotected, circulating 3rd harmonic current can cause transformer damage) if harmonic current is significant
  - No grounding on utility side prevents zero sequence current flow through the transformer, limits impact of the single line to ground faults on utility side on DER and limits contribution to ground faults from DER to utility.

- Disadvantages
  - For larger units (above 100 kVA) Generator cannot provide an effectively grounded source if islanded. This may result in utility side equipment overvoltages. Overvoltage protection and robust anti-islanding protection required on utility side if Delta connected on utility side.
  - Prone to ferroresonance in cable dominated installations.
  - Under voltage or islanded condition harder to detect from DER side.
  - More innovative methods may be required for islanding detection.

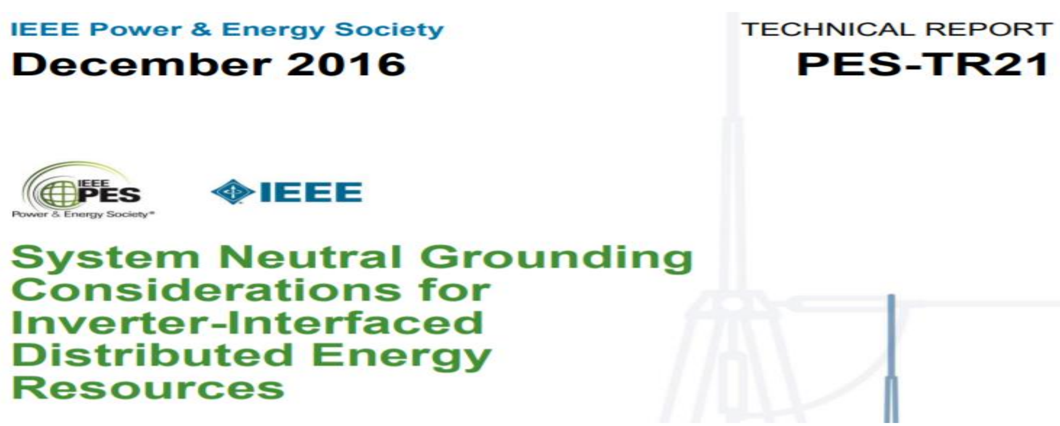
Grounded Wye (Utility) – Delta (DER)

- Not common for MV load serving but increasingly common for HV generation connection and considered to be an effective connection method.
- Advantages
  - DER side Delta winding traps 3rd harmonic current, so will not flow to or from utility or damage the generator, but may circulate in the transformer causing heating
  - Ground on utility side provides zero sequence current source for utility SLG faults, so protection more sensitive.
  - Ground on utility side presents effective ground to the utility and limits overvoltage on utility side equipment and limits the impact of island formation.
- Disadvantages
  - Grounded primary provides a strong SLG fault infeed, increases fault current and may cause equipment damage. (May need a neutral reactor to limit 3Io)
  - Relaying in subs and feeders in vicinity of this transformer may have to be altered (ground fault pickups and timers)
  - A grounding reactor on utility side may increase Xo and limit high ground fault current
  - Can increase costs due to impact on protection design and coordination changes

ELECTRIC POWER RESEARCH INSTITUTE

Inverter Based DER Transformer Considerations

- Inverter based DER neutrals tend to be ungrounded or high impedance grounded.
- This limits duty on isolating transformer and limits ground current contribution to a utility ground fault
- Inverters can be made effectively grounded if the grounding option is available on the inverter. If so, inverters may be either grounded with low impedance reactor or via grounding transformers.


IEEE Power & Energy Society

December 2016

TECHNICAL REPORT

PES-TR21

IEEE PES Power & Energy Society

IEEE

System Neutral Grounding Considerations for Inverter-Interfaced Distributed Energy Resources

Source: IEEE PER Technical Report PES TR-21

DER Interfaced Grounding Considerations

Transformer Winding Configuration

IEEE PES Technical Report TR21 – System Neutral Grounding Considerations for Inverter Interfaced DER

Key Learnings

- Ensure simulation tool(s) model DER according to latest standards, validated and with manufacturer data.
- Inverter based DER should not be modelled as a synchronous generator
- With high inverter DER penetration, feeder load model must be modelled accurately
- Where DER inverter output approximately equals feeder load grounded loads on the feeder may provide effective grounding for ground faults
- Supplemental grounding source (grounding transformer) may not be necessary unless inverter DER much greater than total feeder load
- Depending on the load composition grounding transformer may increase overvoltages for SLG faults

EPRI are conducting ongoing research on the modelling of DER in planning and operations studies for distribution systems and the bulk electricity system.

Refer to EPRI Reports:

DER Modeling for Transmission Planning Studies Detailed Modeling Considerations, EPRI, 2017

Wind/PV Short-Circuit Phasor Model Library and Guidelines for System Protection Studies, EPRI, 2016

Guide to DER Short-Circuit Response and Impact on Protection, EPRI, 2017

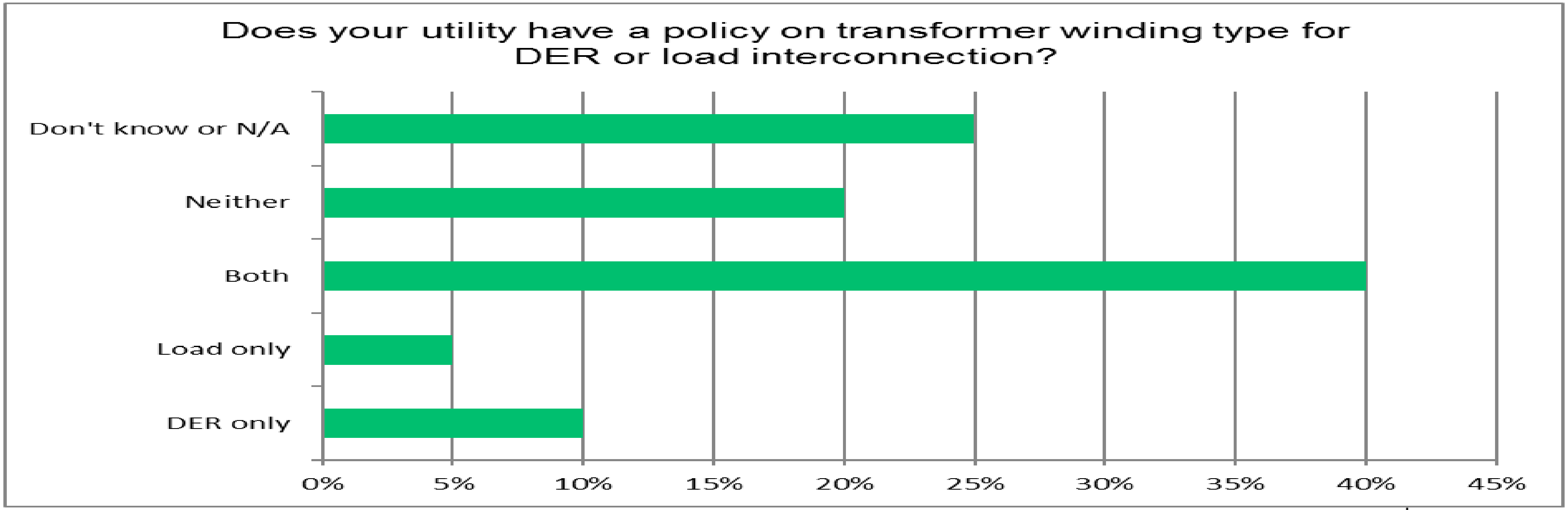
Modelling and model accuracy are crucial to DER and grounding considerations

EPRI Engineering Guide For Integration of DER Table 2-1
Characteristics of Three Phase Transformer Connections for DER Applications

Type of Distribution System	Transformer Connection Used	Advantages	Disadvantages
Four-Wire Multigrounded Neutral	YG/D	Prevents utility-side overvoltages during faults (acts as a ground source).	Triplen harmonic currents already present in the utility system will flow into this type of connection - may overheat trafo (grounding impedance required on Y side to limit this)
		Good for power converters that can't be grounded.	This winding arrangement would not usually be available as the existing transformer at most customer sites.
		Provides isolation for power converters from transient overvoltages for utility system ground faults.	Desensitizes feeder ground-fault protection by acting as a strong ground source
		Ferroresonance is not likely for 3 legged core	
	YG/YG	Prevents utility-side overvoltages during faults (only if the generator is effectively grounded).	The generator itself must be effectively grounded if this type of transformer bank is to act as an effectively grounded source (this is sometimes not possible).
		Prevents zero-sequence circulating current on low side.	Ferroresonance is likely for 5 legged core constructed trafos
		Commonly available as the existing transformer configuration at customer sites.	
	D/YG	Sometimes available as the existing transformer configuration at customer sites.	Larger units above 100 kVA pose the very real threat of causing damaging overvoltages during utility ground faults.
			Could cause ferroresonance during single-phase operation.
	D/D	Provides best isolation for transient overvoltages from utility side ground faults from reaching the power converter.	Larger units above 100 kVA pose the very real threat of causing damaging overvoltages during utility ground faults or islanded operation.
		Good for power converters that can't be grounded.	Ferroresonance is likely in cable dominated installations
Three wire Ungrounded System	D/D	Should provide good performance.	No ground reference makes ground-fault detection more difficult.
	D/YG	Should provide good performance.	Unbalanced output on generator could create zero-sequence circulation on delta high-side winding.
		Provides a ground reference on the generator side.	

Results and Comments from the 2017 Survey

- Most utilities who responded to the survey have a specific policy on which transformer types are permitted when connecting DER and load. There is a wide variation on what utilities use.
- Comments from the survey
  - *"We require solidly grounded connections; ideally a YG/YG transformer. If the customer wants to connect to the utility via delta then a ground bank is required."*
  - *"DER All generation must be isolated from the Utility primary distribution system by a transformer in order to properly integrate the grounding scheme of the generator to the grounding scheme of the distribution system. In most cases, the preferred transformer configuration is wye grounded - wye grounded. However, depending on line configuration, other transformer connections may be preferred and will be determined by Utility. "*
  - *"Per Technical Guidelines require YG/YG configuration"*
  - *"Most load connections are delta (utility) to YG Customer. For DERs, any connection except YG/D"*
  - *"DER must have grounding source in interconnection (either grounded wye transformer at utility side (preferred) or installation of grounding transformers. Load interconnections typically require wye-wye triplex core transformer."*
  - *"Delta high-side, wye-grounded low-side is not allowed"*



ELECTRIC POWER RESEARCH INSTITUTE

Conclusions, Recommendations, Survey Results

Conclusions, Recommendations

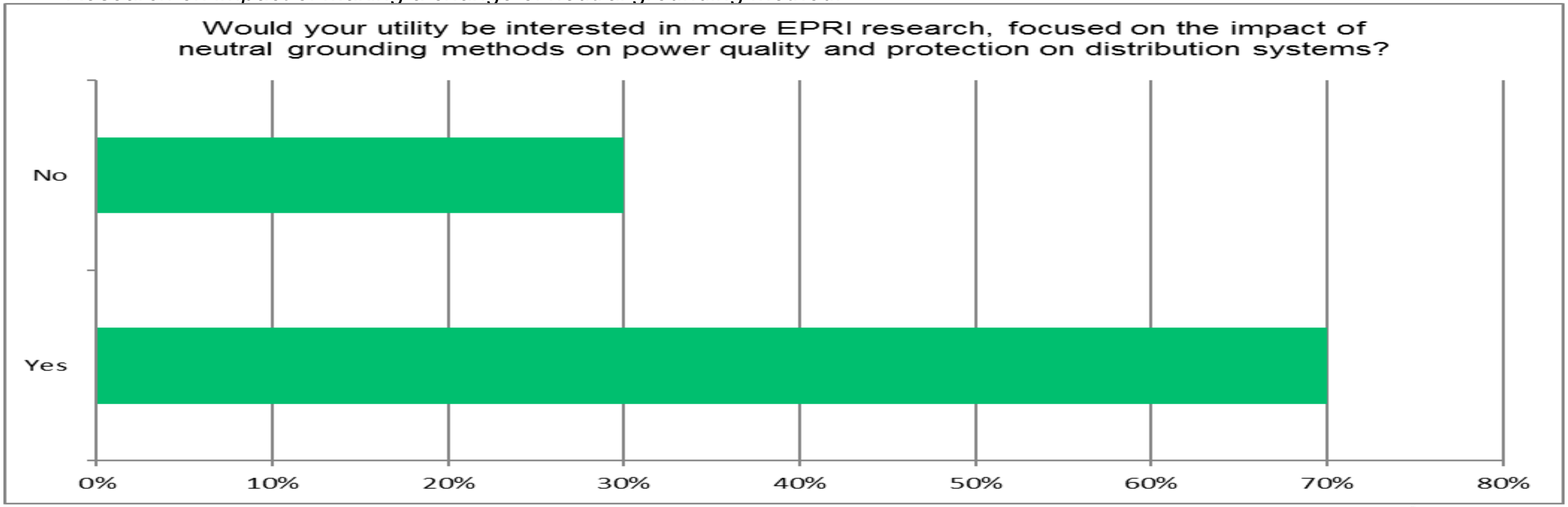
- **Conclusions and Recommendations**
  - Changing neutral grounding method on some or all of the network has been shown to provide reliability benefits in some scenarios, based on documented international experience. There are many considerations when evaluating whether to change neutral grounding method. Some of these are documented in the report based on the prior experience of utilities changing their neutral grounding method.
  - There is no one right answer to what the best transformer winding type for interconnecting DER to utility systems is. Utilities surveyed in 2017 also showed differences in policies for interconnection transformer for load and DER. Each transformer winding type has advantages and disadvantages that are documented in this report. Depending on the system, issues that particular utilities are facing (overvoltage, harmonics, ferroresonance, protection coordination etc.) it is recommended that due consideration is given to the interconnecting transformer winding configuration that is proposed by the DER developer, so as not to exacerbate the existing issues.

Conclusions, Recommendations - 2

- **Conclusions and Recommendations**
  - Research and experience with inverter based DER is evolving. Issues on which there is a lot of ongoing work within EPRI include: grounding, response to faults, islanding among others. EPRI will continue to identify the issues utilities are facing, conduct research into the issues and report on the findings.
  - Some future work and research is required into active grounding techniques using power electronics, in particular their impacts on distribution protection settings coordination and the costs and benefits of these solutions.
  - With the retirement of experienced engineers over the last number of years and decreased focus on power systems in university courses added to complexity of issues now faced by distribution utilities, utilities are requiring more educational information, techniques and tools to ensure the systems are planned and operated as effectively as possible

Results and Comments from 2017 Survey

- A majority of utilities surveyed in 2017 are interested in more research around neutral grounding methods for protection, power quality
- Comments from the survey
  - *"Impact on quality of service indicators (SAIDI/SAIFI) of different neutral grounding methods"*
  - *"Overvoltage issues"*
  - *"Protection at interface between different neutral earthing treatments"*
  - *"Ground potential rise with the addition of DER. Understanding the interaction between inverters and the different grounding methods"*
  - *"With retirement of experienced engineers over the next several years and universities not producing engineers with power system engineering degrees, the research should be focused on educating utility distribution engineers and DER system owners, designers, installers and operators on the pros and cons of various intertie transformer winding configurations, which intertie transformer configuration enables integration of DER with utility feeders that are Multigrounded, unigrounded, etc, and protection required for detection of various fault types"*
  - *"Probably not, as we are most concerned about transmission system ground fault detection. Distribution ground fault detection and grounding isn't a huge issue."*
  - *"Research on impact of making a change of neutral grounding method."*



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Together…Shaping the Future of Electricity

Export Control Restrictions

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002011000

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com