

Distributed Generation (DG) Protection Overview

Literature Review for ES 586b

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University of Western Ontario

Andrew T. Moore, 250442203

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Distributed Generation (DG) Protection Overview

Abstract

One of the biggest changes happening to the distribution system is the introduction of distributed generation. One of the drivers behind this movement is the need to integrate renewable energy sources into the distribution system. Traditional protection schemes used in the distribution system need to be re-evaluated with the integration of DG associated with customer loads. The interconnection protection varies widely depending on factors such as: generator size, point of interconnection to the utility system (distribution or sub-transmission), type of generator (inductor, synchronous, asynchronous) and interconnection transformer configuration. Newer DG systems are utilizing electronic power converters which results in special consideration for DG protection. The impact of DG on existing systems must be examined through detailed simulations and protection studies. Examples of interconnection protection schemes are examined.

Introduction

Distributed Generation (DG) is loosely defined as small-scale electricity generation. For many DG applications the generation facility is co-located with the loads (at the point of consumption of the energy produced). The connection can be to the distribution network or on the customer side of the meter. For most DG the customer uses all of the output from the DG with any surplus delivered to the distribution system. If the customer requires more power than available from the DG, power is taken from the distribution system.

DG has become more apparent in the power system around North America for a variety of reasons such as: an alternative to constructing large generation plants, constraints on construction of new transmission lines and the demand for highly reliable power. DG has become more attractive as the cost of small generation decreases with technological innovation and changing economic and regulatory environment with the liberalisation of electricity markets (11).

Public concerns about climate change have resulted in a large interest in the use of renewable energy and the efficient use of cheap fuel alternatives. Another area of interest is in the development of systems combining the generation of heat and electricity known as Combined Heat and Power (CHP) and also called district heat & power. The deployment of renewable energy systems is bringing DG into utilities often as hybrid systems consisting of multiple generators in constructed as a MicroGrid as shown in Figure 1.

The MicroGrid concept is the bringing together of loads and micro-sources operating as a single system with the potential of providing both power and heat. The majority of the micro-sources must be power electronic based (inverter) to provide the required flexibility to insure operation as a single aggregated system (1). A MicroGrid is well suited for integrating renewable source with the grid as well as being utilized in high reliability systems.

Large DG applications are treated like all generators connected to the utility's transmission system requiring detailed impact assessments, protection studies, etc. Smaller systems (5MW or smaller) are usually connected to the sub-transmission and distribution systems and are integrated into the utility protection system. The addition of DG brings two perspectives for protection requirements, those of the generation owners and the perspective of the utility.

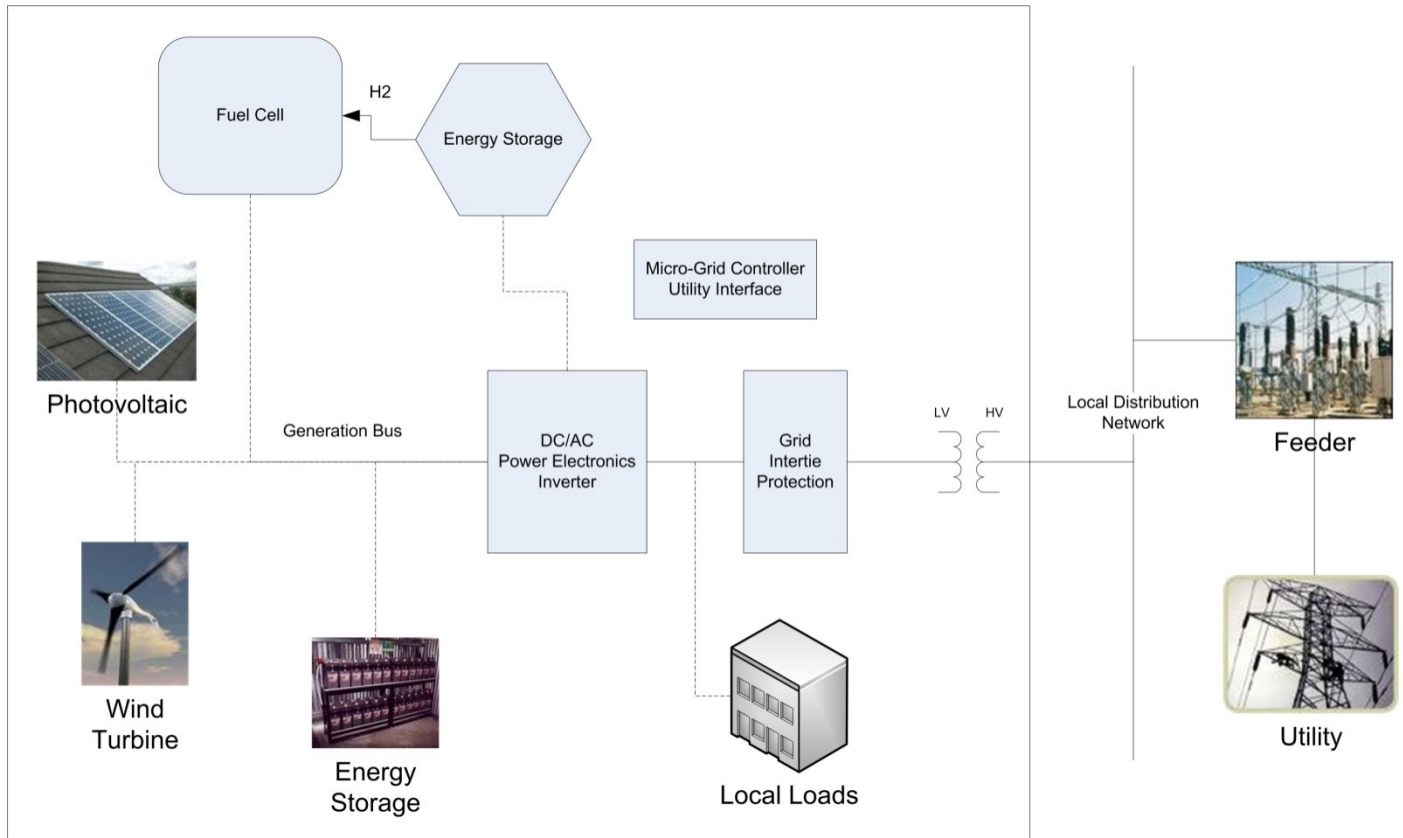


Figure 1 - MicroGrid Based Distributed Generation

The Generator desires to have protection from short circuits and abnormal conditions that could result in damage to the generator. Abnormal conditions can be imposed on the DG by the utility system such as: over-excitation, overvoltage, unbalanced currents, abnormal frequency and shaft torque stress due to utility breaker automatic reclosing. The Utility is concerned about damage that the DG may cause to their systems or to their customers due to unwanted fault current or changes to the existing protection scheme.

Typical Protection

The IEEE 1547 standard only provides limited real guidance and highlights only the important requirements. Newer standards are being developed towards more detailed requirements for the integration of DG with the distribution system. The current standards require the following:

- Not cause over-voltages or loss of utility relay coordination
- Disconnection when no longer operating in parallel with utility (81 O/U, 27, 59)
- Not energize the utility when the utility is de-energized

- No creation of unintentional islands
- Use “utility grade” relays
- Not cause objectionable harmonics
- Not cause loss of synchronization (no objectionable flicker)
- Not cause over-voltages

Interconnection

The DG protection is established from the Point of Common Coupling (PCC) and the interconnection transformer. The purpose of the interconnection protection is to protect the grid from the DG unit on the grid-side during parallel operations of the DG and the grid. The protection can be located either on the primary side of the interconnection transformer (Figure 2) or on the secondary side as shown in Figures 3.

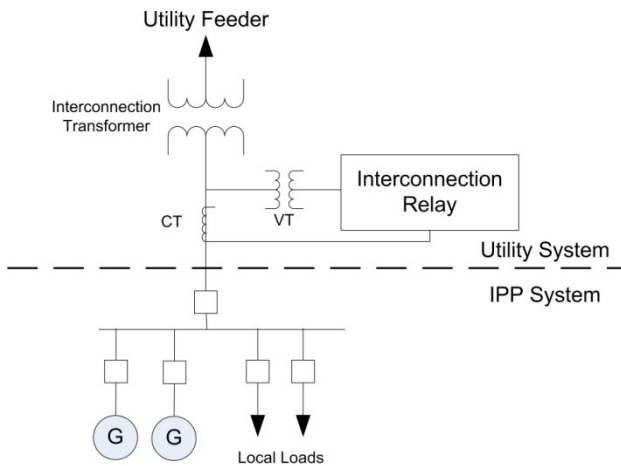


Figure 2 - Interconnection Protection at the Secondary

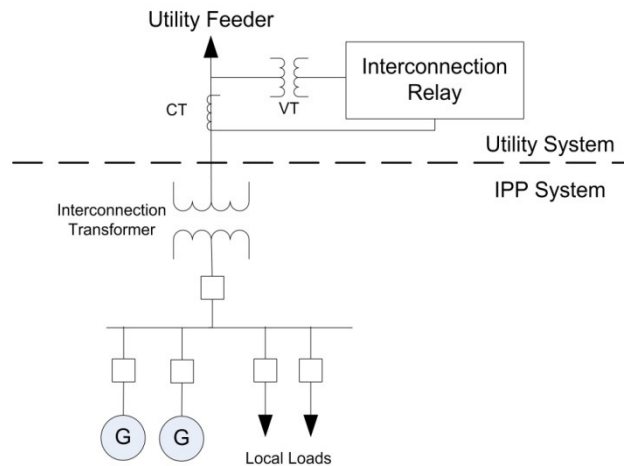


Figure 3 - Interconnection Protection at the Primary

The interconnection protection requirements are normally established by the utility and include:

1. Disconnect the generator when detecting an ‘islanding’ condition (no longer operating in parallel with the utility)
2. Protect the utility from damage caused by the DG (fault current, transient over-voltages, etc.)
3. Protect the DG from damage caused by the Utility (automatic reclosing, etc.)

Generator

The generator protection is installed at the generator side of the PCC and protects the DG from internal faults and abnormal operating conditions. Each generator will typically have its own protection to protect the equipment and is typically positioned at the terminals of the generator as shown in Figure 4. The protection is focused to provide detection of generator internal short circuits and abnormal operating conditions (loss of field, reverse power, over-excitation and unbalanced currents).

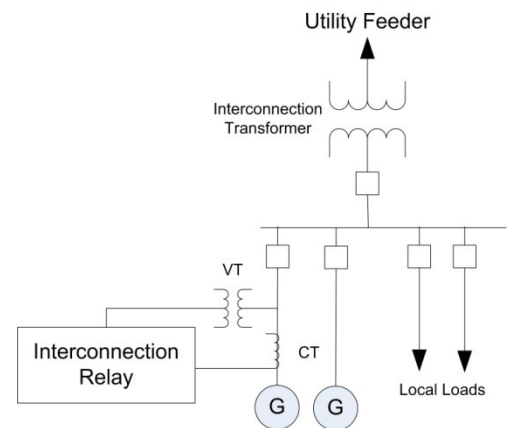


Figure 4 - Generator Protection

Utility Required Protection

Many utilities will require DG installations to conform in particular areas. The utility may provide detailed requirements in the following areas (2):

- Winding configuration of the interconnection transformer
- General requirements of utility-grade interconnection relays
- CT and VT requirements
- Functional protection requirements (810/U, 27 and 59)
- Settings of some interconnection functions
- Speed of operation

Factors Influencing DG Protection

Different energy sources may be used but it is the interfacing scheme used by the DG that will have the largest impact on the protection of the distribution system. A scheme based on direct coupling of rotary machines, such as synchronous or induction generators is different from a DG system connected using a power electronic converter. The type of interconnection transformer will also have a large influence on the protection schemes.

Types of DG

Generators can be divided into traditional and non-traditional generators. The traditional generators are based on combustion engines and are further divided into: Low Speed Turbines, Reciprocating and Diesel Engines and Micro-Turbines (MT). The non-traditional generators are divided into: Electrochemical Devices (such as fuel cells), Storage Devices (batteries, flywheels, etc.), and Renewable Devices (PV, wind, small hydro).

Distributed Generators can also be classified by the type of generator. Many of the non-traditional sources such as PV and fuel cells use a power electronic converter (inverter) for grid interfacing. The traditional internal combustion engines (rotary machines) are mainly synchronous generators and are interfaced directly to the grid. Wind turbines are considered rotary machines and are mainly induction type generators which can be interfaced directly with the grid. Some wind applications as well as some synchronous machines and micro-turbines are utilizing power electronic devices for grid interface as the benefits of the electronic interface justifies the additional cost and complexity.

Affect of Power Electronics

Power electronic inverters are capable of converting the energy from a variety of sources such as variable frequency (wind), high frequency (turbines), and direct energy (PV & fuel cells) (15). Inverter based DG are generally considered low power by utility standards from 1 kW up to a few mega-watts. Generators connected to renewable sources, are not reliable and so are not considered dispatchable by the utility and so are not tightly integrated into the power supply system. The inverter interface decouples the generation source from the distribution network and the islanding characteristics of the distributed generator are primarily determined by the inverter.

The inverters are classified by two types: line-commutated (thyristor based) and self-commutated inverters (IGBT or MOSFET based). The majority of commercial inverters are self-commutated and can be classified as either Voltage Source Inverters or Current Source Inverters. The Voltage Source inverter is the most common technique for DG

interfacing and are further divided based on the control mechanism into Current Controlled Scheme (CCS) or Voltage Controller Scheme (VSC).

The capabilities of the power electronic control allows the inverter to be used to supply controlled reactive power and mitigate power quality problems such as voltage deviation, total harmonic distortion (THD) and flickering. Since inverters monitor the voltage and frequency at their output terminals for control purposes, it is relative easy to implement a passive islanding detection technique based on detecting when the inverter voltage or frequency shifts outside a window centred around the nominal line voltage and frequency set points. Consideration still needs to be given to the case when a balanced load condition exists and voltage and frequency shift may be small or nonexistent after the utility is no longer present. Normally DGs are operated in a constant power and constant power factor control mode which makes it improbable that precise balance will occur when the utility is lost and an unintentional island formed. Inverters can also be used to implement active islanding detection schemes.

Inverters may be capable of supplying only twice the load current or less to a fault, so the orders-of-magnitude larger fault current on which conventional over-current protection is based is not present. For this reason inverter based DG is less likely to influence the existing utility protection with respect to fault current. Both the probability of islanding and the risks associated with the formation of an island are typically less for inverter based DGs than for synchronous generator based DGs (14). The IEA Task 5 study found that probability of islanding is very small. The study also showed that the risk of electric shock due to islanding of PV systems under worst-case PV penetration scenarios to both operators and customers does not increase the risk that already exists (17).

Interconnection Transformer

The choice of transformer plays an important role in the DG connection with the utility. All connections have advantages and disadvantages that need to be considered by the utility and distributed generation owner. The type of ground connection is classified as: solidly grounded, ungrounded or grounded through grounding impedance.

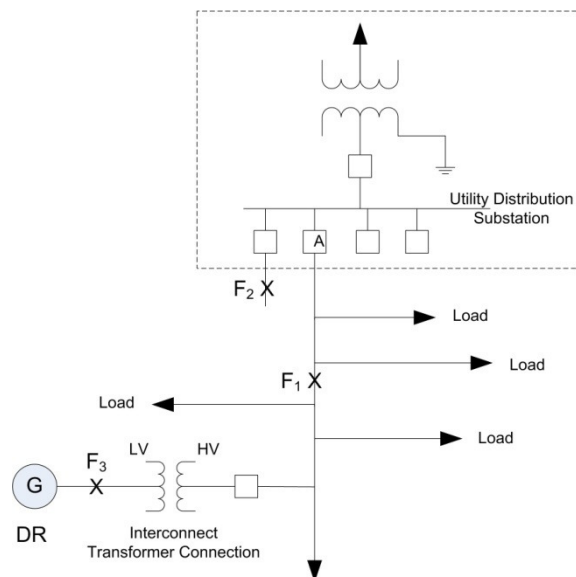


Figure 5 - Interconnection Transformer Types

Five transformer connections are widely used to interconnect a DG to the utility system. The choice of connection will affect the magnitude of over-voltages following single-phase faults and also on the magnitude of the fault

current supplied from the substation (10). There is no universally accepted “best” connection (7). The following table based on Figure 5 shows the possible choices and the advantages/problems associated with each connection.

Low Voltage (LV)	High Voltage (HV)	Problems	Advantages
Delta	Delta	Can supply the feeder circuit from an ungrounded source after substation breaker ‘A’ trips causing overvoltage	Provide no ground fault back-feed for fault at F1 & F2. No ground current from breaker A for a fault at F3
Gnd-Wye	Delta		
Delta	Wye		
Delta	Gnd-Wye	Provides an unwanted ground current for supply circuit faults at F1 and F2	No ground current from breaker A for faults at F3. No overvoltage for ground fault at F1
Gnd-Wye	Gnd-Wye	Allows source feeder relaying at A to respond to a secondary ground fault at F3	No overvoltage for ground fault if the gen neutral is Y-connected with a low impedance ground

Each utility will have established their preferences with regards to DG connection based on their best practice guidelines and experience. The following table is the preferred configurations for a DG step-up transformer for the Hydro One distribution utility (10).

System Voltage (kV) – Secondary	Generation Size	Preferred Interface Transformer High voltage side : Low voltage side (HVS:LVS)
27.6 kV	1 -2 MW	Gnd-wye : Delta Delta : Gnd-wye Gnd-wye : Gnd-wye
27.6/12/8 kV	200 kW – 1 MW	Gnd-wye : Gnd-wye Gnd-wye : Delta Delta : Gnd-wye
27.6/12/8/4 kV	50 kW – 200 kW	Gnd-wye : Gnd-wye
27.6/12/8/4 kV	10 kW – 50 kW	Gnd-wye : Gnd-wye

Wye-Wye

For a Wye-Wye transformer interconnection configuration, the major concern is that it provides a source of unwanted ground current for utility feeder faults. It also allows sensitivity-set ground feeder relays at the substation to respond to ground fault on the secondary of the DG transformer (F1) as shown in Figures 6 and 7. The affect of this it to require the utility to increase the feeder ground relay pickup and/or delay tripping to provide coordination. This reduces sensitivity and speed of operation for feeder faults and can increase feeder circuit wire damage.

Symmetric component analysis (Figure 7) establishes a zero sequence current source with a contribution to ground faults on the distribution system which is dependent on the status of the generator. When the generator is off line, there is no zero sequence source for ground faults on the distribution circuit. With this connection, there is no problem with overvoltage (7). A thorough understanding of the transformer connection and the possible fault scenarios is required to develop the appropriate protection scheme.

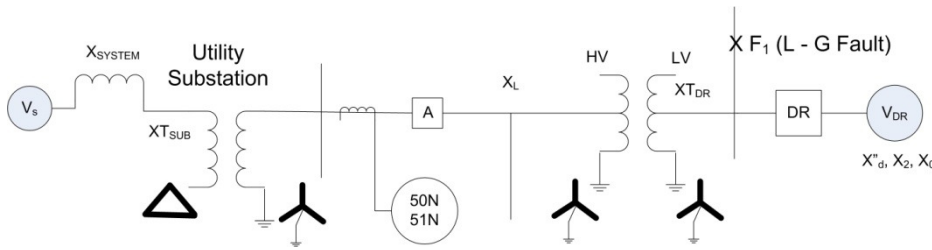


Figure 6 – Single Line Diagram for Gnd-Wye (Prime) to Gnd-Wye (Sec) Interconnection Transformer

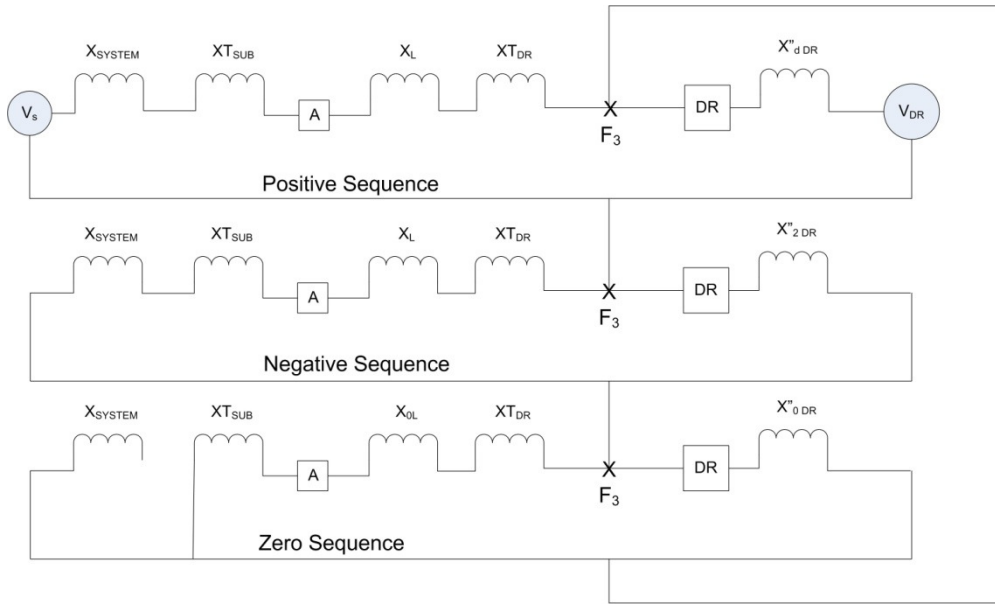


Figure 7 – Symmetrical Component Circuit for Gnd-Wye (Prime) / Gnd-Wye (Sec) Interconnection Transformer

Protection Issues with DG

Most utility systems use a traditional radial feeder system to delivery power to customer loads and implemented protection schemes only considering power flow in only one direction. The addition of DG changes energy flows which now can flow in either direction through system protection devices. The following protection issues must be considered when DG is being considered to be integrated with the utility: Short Circuit Power; Islanding; Reduced Reach of Impedance Relays; Reverse Power Flow; Voltage Profile; Auto Re-closure; Ferro-resonance; Grounding; and Safety.

Short Circuit Current

The proper coordination of relays, re-closers, fuses and other over-current devices must be based on the available fault current. Fault current will be dependent on the transformer connection of the DR. DG in-feeds which are connected via power electronic circuits produce no remarkable contribution to the short-circuit current of the network and can be neglected under protection aspects (3).

The protection strategy needs to be able to distinguish between faults that occur near the PCC. Any fault on the utility side and within the DG system needs to be identified correctly and the correct protection devices as well as the separation device must operate correctly. If the DR source (or combined DR sources) is strong compared to the

utility substation source, it may have a significant impact on the fault current coming from the utility substation. This may cause failure to trip, sequential tripping, or co-ordination problems (7). The protection may fail to detect fault current if:

- The fault is a phase-ground fault and the DG interconnection does not provide a primary ground current source.
- The DG is single-phase, connected to an un-faulted phase
- The fault is self-extinguishing once the high-current utility source is opened, and the fault current falls to a low value sourced by the DG

Islanding

Islanding is the condition when the DG is no longer operating in parallel with the utility system and may occur as a result of the following conditions:

- A fault that is detected by the utility, and which results in opening a disconnect device but which is not detected by the DG protection devices
- Accidental opening of the normal utility supply by equipment failure
- Utility switching of the distribution system and loads
- Intentional disconnect for servicing either at a point on the utility or at the service entrance
- Human error or malicious mischief
- Act of nature

After the detection of an autonomous MicroGrid (safely disconnected from utility), a new control strategy is activated to manage both the operation and protection of the MicroGrid. Once the island has been established, the auto reclosure process may occur to reconnect the island to the main utility. Once the island has successfully reclosed and joined the grid, the control strategy must revert to grid connected mode strategy to manage operation and protection. The operation of the protection equipment will need to react differently when operating in parallel with the utility and when operating as a stand-alone island as the fault current will drastically change between connected and isolated modes and impact protection schemes that are based on short-circuit sensing. The DG protection scheme will need to consider:

- Numerical relays using alternative setting groups for island operation
- Communication-based protection practices to yield an adaptive protection scheme that can fit both modes of operation
- Under-voltage protection which can provide time delayed protection if conventional over-current protection will not operate
- Re-synchronizing the islanded system
- Utility breakers or circuit reclosers are likely to reconnect the island to the greater utility system when out of phase

The critical issue with island operation is when the DG operates in its normal parallel mode of operation even when the connection with the utility system has been lost. In this circumstance the isolation device is not operated leaving the MicroGrid connected to the utility system. This continued operation under improper conditions is called unintended islanding. The major concerns with unintentional islanding are (13):

- Line worker safety can be threatened by DG sources feeding a system after primary sources have been opened and tagged out
- Public safety can be compromised as the utility does not have the capability of de-energizing downed lines.
- The voltage and frequency provided to other customers connected to the island are out of the utility's control, yet the utility remains responsible to those customers (liability issues if power quality affected resulting in damage to customer equipment)
- Protection systems on the island are likely to be uncoordinated, due to the drastic change in short-circuit current availability
- The island system may be inadequately grounded by the DG interconnection

Islanding Detecting Techniques

The area of islanding detection is area of much research and study. The following sections discuss some of the current techniques used for islanding detection (14, 17).

Communication Based Schemes

Methods not determined within the inverter are generally controlled by the utility or have communications between the inverter and the utility to affect an inverter shut down when necessary. Some of the communication based methods include: Transfer Trip, Impedance Insertion, Power Line Signalling (Carrier Communications) and Supervisor Control and Data Acquisition.

Passive Detection

Passive methods for detecting an islanding condition basically monitor selected parameters such as voltage and frequency and/or their characteristics and cause the inverter to cease converting power when there is a transition from normal specified conditions. The following are examples of passive detection methods:

- Over / Under Voltage
- Over / Under Frequency
- Voltage Phase Jump
- Detection of Voltage Harmonics
- Detection of Current Harmonics

Active Detection

Active methods for detecting an islanding condition introduce deliberate changes or disturbances to the connected circuit and then monitor the response to determine if the utility grid with its stable frequency, voltage and impedance is still connected. If the small perturbation is able to affect the parameters of the load connection within prescribed requirements, the active circuit causes the inverter to cease power conversion. The active methods include the following:

- Impedance Measurement
- Detection of Impedance at a specific frequency
- Slip-mode Frequency Shift
- Frequency Bias
- Sandia Frequency Shift
- Sandia Voltage Shift

- Frequency Jump

Non-Detection Zones

The evaluation of detection techniques is done through identification of the non-detection zone where unintentional islanding is possible. All anti-islanding schemes have some limitations which may include: High implementation costs, Need for coordination between the DG and the utility, Susceptibility to false detection of islanding (nuisance tripping), Possible non-detection of islanding under some conditions, and Possible reduction of utility power quality and voltage and frequency stability.

Reduced Reach of Impedance Relays

The introduction of DG affects the preset zone calculations made for Impedance relays. The voltage is changed with the addition of the DG which impacts the impedance seen at the relay. The change in the impedance makes an apparently increased fault distance. The result is that the fault has to be closer to the relay to operate it within the originally intended distance zone. The active area of the relay is therefore shortened meaning that its reach is reduced.

Reverse Power Flow

Standard protection schemes utilize directional over-current relays. Traditional radial feeders are configured assuming power flow in only one direction. The introduction of DG results in reverse power flow which was not considered in the original protection system design.

Voltage Profile

DG sources affect the voltage profile along a distribution line which may cause a violation of voltage limits and cause additional voltage stress for the equipment. The DG can provide beneficial voltage contribution in highly loaded or weak networks with respect to the local power quality. DG could influence a tap-changing transformer by changing the load on the transformer which may not allow the in-feed voltage to be regulated correctly (4).

Auto Re-closure

In order to secure the correct operation of automatic reclosing, and to prevent out-of-phase reclosure, DG units must be disconnected cleanly before the reclosure (16). When a DG unit continues to operate after a utility fault two problems may arise when the utility reconnection (auto re-closure) is initiated after a short interruption (4).

1. The fault may not have cleared since the arc was fed from the DG unit, therefore instantaneous re-closure may not succeed.
2. In the islanded part of the grid the frequency may change due to the active power unbalance. The re-closure would couple two asynchronously operating systems.

Ferro-resonance

Ferro-resonance can occur and damage customer equipment or transformers. Since fuses in three phases do not trigger simultaneously it may happen that a transformer is connected only via two phases for a short time. The capacitance of the cable is in series with the transformer inductance which could cause distorted/high voltages and currents due to resonance conditions (4).

Grounding

A DG transformer connection with ungrounded transformer primary windings will require analysis of all equipment (insulators, lightning arrestors, breakers, etc.) to handle over-voltage conditions when line-to-ground faults occur. A DG unit connected via a grounded delta-wye transformer (or ungrounded wye connection), earth faults on the utility line will cause ground currents in both directions, from the fault to the utility transformer as well as to the DG transformer. Another condition to be examined for some transformer configuration is when the utility earth connection is lost and the whole system gets unearthed (4).

Safety

The addition of DR to a feeder may create conditions that can result in equipment damage or failure. Improper operation of the protective devices may lead to unsafe conditions for equipment. For certain types and sizes of DR with delta high side transformer connections, back-feed on un-faulted phases under fault conditions can result in over-voltages that may cause customer and utility equipment damage. These failures may lead to unsafe conditions for both utility and customer operating personnel.

DG Impact Assessment

A system wide approach to protection is required when evaluating the impact/issues related to the introduction of a DG connection. Protection impacts can go back far into the system. For a fault on the grid the desired response may be to island – similar to a UPS equipped system. Speed of separation is dependent on critical load needs. Local system faults require the isolation of the smallest portion of the system. The addition of DG has an impact on existing system protection raising the following concerns: (7)

- Utility systems are designed for radial – one-way current flow and fault sensing
- Loss of the ground reference on a normally wye grounded distribution system
- Relays applied to radial systems may lack directional sensing, coordination for reverse faults and adequate sensitivity to detect some reverse faults
- Safety may be compromised
- Voltage control is affected
- Island operation of the DR
- Auto-reclosing schemes must be revised
- System area stability affected
- Breaker failure affected
- Ferro-resonance problem can occur

Impact Studies

The impact of DG on system protection should be analyzed following a structured approach. A variety of studies are recommended to analyze the protection-based penetration limits with consideration of the DG capacity, location and technology. The studies aid in determining mitigation strategies to increase the protection based penetration limit. The loss of coordination, de-sensitization, nuisance fuse blowing, bidirectional relay requirements and overvoltage, should be studied in order to arrive at the penetration limits of DG in an existing distribution system (10).

Loss of Coordination Study

Loss of coordination can take place between any pair of protective devices. Analysis of the short circuit current can lead to assessing the coordination to determine the DG impact. In normal operation, protection devices are coordinated such that the primary protection operates before the backup can take action. Interconnecting DG increases the short circuit level. Depending on the original protection coordination settings along with the size, location and type of the DG, uncoordinated situations may be found. In these situations, the backup operates before the primary, which results in nuisance tripping to some of the loads.

Sensitivity Study

The addition of DG may affect the fault current drawn from the main sub-station. This may change the protection's ability to "see" the fault. The fault current will be dependent on the type, size and location of the DG. The type of DG connection will need to be considered to determine the contribution of the utility and the DG to the fault current used in the sensitivity study.

Nuisance Fuse Blowing Study

A fuse saving strategy is employed by utilities to detect temporary faults and de-energizing the line and re-energizing it again using an auto-recloser. Often faults are temporary in nature so this strategy avoids unnecessary permanent service interruption. Adding DG may affect the timing coordination between re-closer and the fuse due to changes in fault current (from DG). Analysis of the fault current changes are done to determine the affect on the fuse saving strategies which may resulting in missed faults, fuse nuisance blowing or mis-coordination due to the DG.

Bi-directionality Study

The introduction of DG may cause protection devices to face reverse direction operation resulting in malfunctioning of the protection devices (radial feeders). Original protection designs did not considering reverse power flow from DG sources on radial feeders and adjacent laterals. Original protection schemes need to be reviewed to consider new bi-directional power flows.

Over-Voltages Study

The addition of DG may result in a temporary over-voltage due to ground fault conditions (grounding issues or transformer connection related). An overvoltage condition at the utility will need to be considered to protect the DG. Other potential problems include resonant over-voltages occurring during islanding conditions and over voltages may arise due to high DG power injection. The selection of the transformer interconnection needs to be considered with respect to DG grounding and faults.

Islanding Mode Study

The introduction of DG that can operate in islanding mode results in a complex problem that requires study to determine the necessary settings and changes needed for proper island operation. Operation as an island will be different and will likely require two approaches to protection: (1) operating in parallel with the utility and (2) operating as an island. Consideration of the method of islanding detection and reconnection is required in this analysis.

Simulations Studies

The investigation of DG impacts is accomplished through simulation by creating detailed models. Short circuit equations are used for modeling the behaviour of the DG source (synchronous generators, induction generators and

power electronic based generators). One of the power tools available for impact assessment is the CYMTCC and CYMDIST software packages. The transformer connection must also be included in the models. Simulation studies conducted by Natural Resources Canada – CETC (9) indicate that:

1. The addition of DG units within a feeder results in decreasing the source contribution to faults downstream of the DG while increasing the fault current itself
2. This effect is more pronounced for DG units controlling their terminal voltage such as directly coupled synchronous units
3. This effect is almost negligible for electronically coupled DG units acting as a constant current source
4. The effect of adding DG units to distribution feeder can produce blind zones for protection devices or upset the coordination between two (or more) protective devices and should be studied carefully

Interconnection Protection Methods and Practices

Protection Objectives

The protection strategy for the integration of DG is to achieve the lowest possible cost with the minimal impact on existing systems. One tool to consider is the use of multifunction digital relays which combine many relaying functions into a single relay package. The following table outlines the specific objectives of an interconnection protection system and the relay functional requirements to achieve each objective. (* = Rate of Change)

Interconnection Protection Objective	Protection Function Used
Detection of loss of parallel operation with utility System	81OU, 81R*, 27/59, 59I, TT
Fault back-feed detection	Phase Faults: 51V, 67, 21 Ground Faults: 51N, 67N, 59N, 27N
Detection of damaging system conditions	47, 46
Abnormal power flow detection	32
Restoration	25

Unintentional Islanding Detection

DG unintentional islanding can expose utility workers to hazards by circuits that otherwise would normally be de-energized and may pose threat to the public as well. When parallel operation is lost, the DG must separate itself from the utility system quickly to support the substation reclose attempt. Detecting the loss of parallel operation (unintentional island formation) is done by establishing an over/under frequency [81 O/I] and over/under voltage [27/59] “window” (typically +/- 5%) within which the DG is allowed to operate. Under most circumstances the voltage and frequency will quickly move outside of normal operation when parallel operation is lost.

A transfer trip [TT] may be required to be signalled by a reliable means of communication if the island can operate within the defined window – not tripping the loss of connection. For synchronous and induction DG an instantaneous overvoltage relay [59I] may be used to detect islanding. Another option is to use rate of change frequency [81R] protection to detect islanding.

Fault Back-Feed Detection

Small synchronous generators have very small fault current contribution because they are typically heavily overloaded after the utility sub-station breaker trips. Similarly induction generators only provide fault current for a short period of time. If the DG is of a larger capacity, protective relay functions 67, 21 and 51V are used to provide phase fault back-feed detection. For ungrounded interconnection transformers, neutral overvoltage relays [59N, 27N] provide the detection for supply ground faults. The VTs which supply these relays have their primary windings connected line-to-ground.

Damaging Condition Detection

Unbalance current conditions caused by open conductors or phase reversals on the utility supply circuit can subject the DG generator to a high level of negative sequence current. To prevent possible generator damage from the negative sequence current, a negative sequence over-current relay [46] is used. To provide protection from phase reversals (potentially caused during restoration) a negative sequence voltage relay [47] is used. For synchronous generators it may be advisable to include a loss of synchronization [78] protective relay to protect against potential shaft damage.

Abnormal Power Flow Detection

If the utility has a policy that the DG does not supply current to the utility (reverse power flow), a directional power flow [32] relay may be used to detect this condition for a predetermined amount of time. The DG will only be permitted to deliver power to the local loads in a “peak-shaving” type application.

Restoration

Once the DG to grid connection has been separated, the connection can be restored to operating in full parallel operation. Many utilities use an “instantaneous” reclose practice, where breakers and circuit reclosers reenergize the protected circuit without any intentional delay. Mechanical operating times typically result in an effective delay of about 150 to 200 ms from opening to reclosing. The detection of an islanding condition must be very fast to meet the reclosing speed even if an intentional delay is introduced (on the order of tenths of a second).

The potential for damaging a rotating DG by out-of-phase reclosing is widely understood and appreciated. Large mechanical torques and currents are created, which can damage the generator or related equipment. Many DG sources use power electronic inverters which have fast current-limiting functions for self protection which are somewhat protected from out-of-phase reclosing.

Under the condition when the DG does not match the local load at the time the utility is restored, the DG is automatically resynchronized. A synchro-check relay [25] can be used to supervise reclosing and handle the condition when the DG is under a “dead-bus” condition. The second condition is when the DG roughly matches the local load. A more sophisticated synchro-check relay is required which not only measures phase angle but also slip frequency and voltage difference between the utility and the DG. The relay will handle automatic, manual and supervisory reclosing.

Protection Functions

The following are the protection functions that are typically used for Small (10kw or less) DG applications:

Device Number	Function	Quantity
	Interconnect Disconnect Device	X
	Generator Disconnect Device	X
21	Distance	
25	Synchronizing Check	Manual/auto
27	Under-voltage Trip	3
27N	Neutral Under-voltage	
32	Power Direction / Reverse Power (Islanding)	1
40	Loss of Excitation	
46	Negative Phase Sequence Over-current (Phase unbalance, reverse phase sequence)	
47	Negative Sequence Voltage	
51V	Over-current, voltage restrained (Optional to prevent nuisance trips)	1
50	Instantaneous over current	
50/51	Instantaneous / Timed Over-current	3
50N	Instantaneous Neutral Over-current	
51G	Ground Over-voltage trip or ground over-current trip	
51N	Neutral time over current	
51V	Voltage-restrained over current	
TT	Transfer Trip	
59	Instantaneous Over-voltage trip (ferro-resonance)	3
59T	Over-voltage trip	3
59N	Neutral over-voltage	
60	Voltage Balance Relay	
60FL	Voltage Transformer Fuse Failure	
67/67N	Directional Over-current	3
79	Reclosing	
81O/81U	Over/Under Frequency trip	3
81R	Rate of Change of Frequency	
87	Differential	
	Anti-Islanding for inverters (IEEE 929, UL 1741)	y

Multi-Function Digital Relay

The modern multi-function digital relays have many functions and features that are well suited to the problems faced by interconnection protection. One of the benefits of the modern relay is dynamic adaption under user control and other features which include: self diagnostics, communication capability, and wave-form monitoring (oscillographic). An implementation using a multi-functional digital relay for interconnection protection is shown in Figure 8.

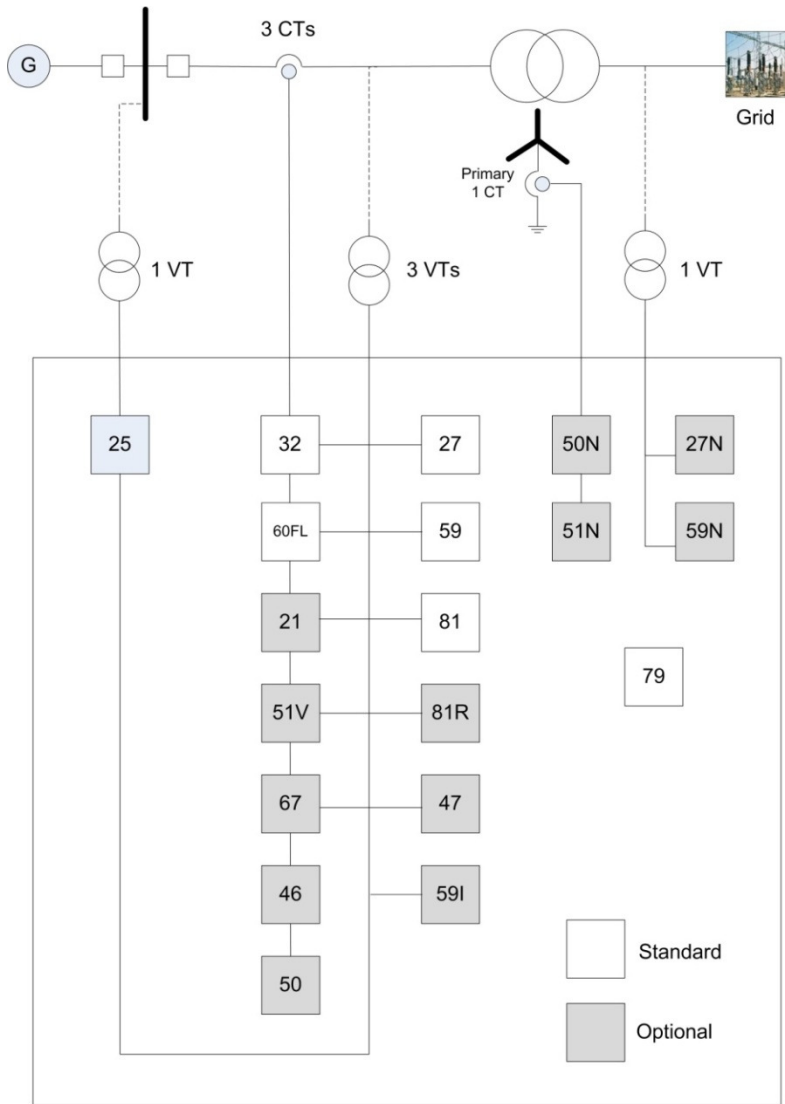


Figure 8 - One Line Diagram for a Multi-function Digital Interconnect Relay

Simple Protection Scheme

An example of a simple protection scheme is shown in Figure 9 (6). The elements [27, 59, 81U/O] provide basic detection of disturbances that will separate the DG from the utility. The system must return to its steady state (normal) conditions before restoring the system to parallel operation.

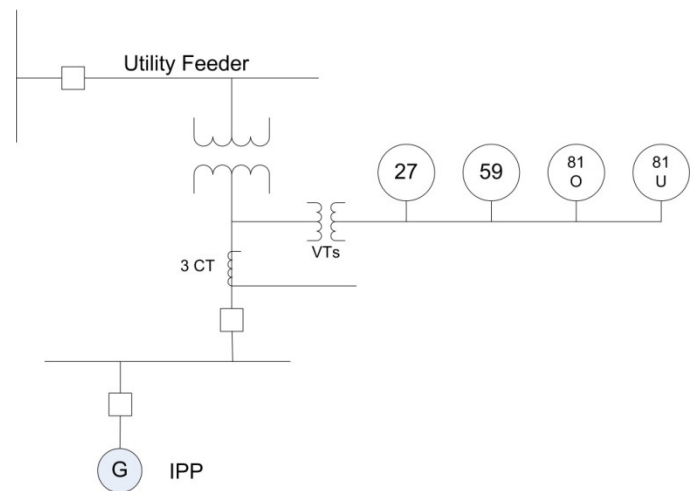


Figure 9 - Basic Interconnection Protection

Advanced Protection Scheme

Additional protective functions are added to the simple protection scheme to increase the level of protective elements to enhance the detection of harmful currents while operating in parallel (6). The additional components increase the complexity of the system as shown in Figure 10. Over-current protection for system fault conditions and unbalanced voltage and current [51C or 51V, 67, 46] and additional voltage protection [59N/G, 27N and 47] are the elements added for increased protection. Time over-current with voltage controller or voltage restrained control allows for more selectivity to differentiate fault current from overload current when system fault current levels and overload levels are close, due to a low system stiffness ratio. The addition of current unbalance [46] will assist in preventing unbalanced currents from damaging the interconnection equipment. The addition of the unbalanced voltage function [47] will add protection for open or high impedance grounded phases. The addition of 59N and 27N functions on the high side of a Delta-Wye transformer adds fault detection for phase to ground faults. The addition of 59N and 27N functions on the high side of a Delta-Wye transformer adds fault detection for phase to ground faults. The addition of an overpower device [32] to the interconnection gives the capability of controlling the import or export of power during normal operation. A synch-check device [25] must only permit the closing of the open breaker when the voltage, frequency and phase angle between the electric systems are within certain differential limits.

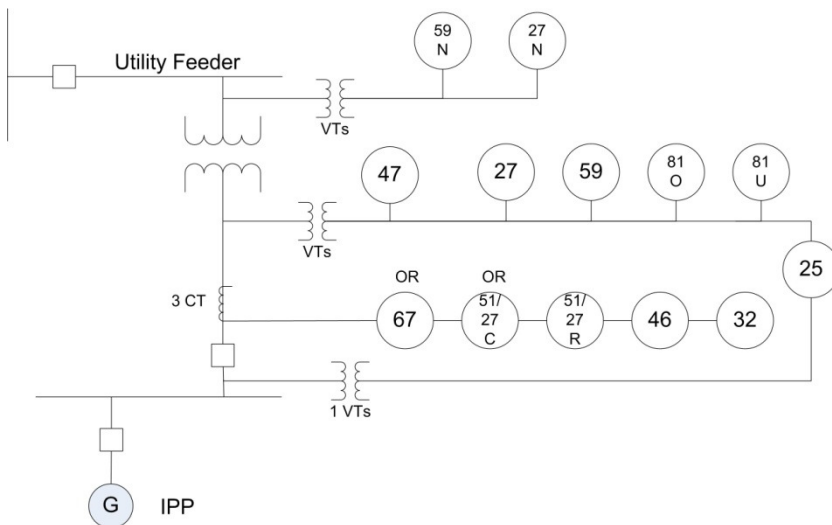


Figure 10 - Advanced Performance Protection

Summary

DG is making its presence felt in the distribution system across Canada and around the world. New generation is being added to the system as small scale sources located at customer locations next to load centres. In particular these sources are often renewable energy generators constructed as a MicroGrid. The impact of DG on the distribution system can be seen from two perspectives: the generation owners and the utility.

When connected to the utility grid, distributed generators need to be protected not only from short circuits, but from abnormal operating conditions. Many of these abnormal conditions can be imposed on the DG by the utility system. Utilities, on the other hand, are generally concerned with the installation of the power generators. Their concerns include personnel safety, the necessity that generator operations not cause harm or damage to the utility

system, and the requirement that the generators not cause problems for other utility customers. Utility liability concerns play a large part in the resistance that DG projects encounter.

The type of generator (synchronous, induction or power electronic based), size and location will impact the DG protection. The interconnection transformer also needs to be considered in the DG protection scheme. Protection systems will need to be revised to protect the utility system and its customers as well as the distributed generators. A systematic approach to studying the impact of the DG on the entire system is required. Some of the aspects to be considered includes: loss of coordination, de-sensitization, nuisance fuse blowing, bidirectional relay requirements and over-voltage.

One of the critical factors to manage is the islanding of the DG. MicroGrid based DG with the electronic power interfaces have islanding capabilities. Anti-islanding technology for inverter based DG is well developed and will provide adequate protection. The impact of integrating large amounts of DG remains somewhat uncertain in particular the active anti-islanding schemes. Anti-islanding remains a major technical barrier to DG acceptance into utility networks. Until anti-islanding is broadly accepted accessing the features of DG for grid support to improved grid stability when the grid is stressed will not be possible.

Protection schemes can be simple or complex. The protection will need to satisfy both the utility and generator needs as well as regulatory requirements. Each project will need to balance complexity and cost for the protection scheme for integrating new DG to the utility. Multi-function digital relays are a good option for an integrated protection solution.

Additional research is required in understanding how future distribution systems should be designed to simplify the integration of DG (towards a plug-and-play system). A simplified connection will encourage wider adoption of renewable energy generators likely as a hybrid MicroGrid. Some of the obstacles the grid of the future will need to consider include how islanded parts of the distribution systems can be operated and re-synchronized. Also the infrastructure requirements to allow DG to be dispatched centrally (if desired) should be considered. In addition to the understanding of interconnection to the traditional radial feeder system, an improved understanding of the impact on meshed networks is needed. High reliability systems will require a MicroGrid with low voltage ride-through capabilities for uninterrupted operation provided that the DG has sufficient generation available to support local loads during utility disconnections (island). The seamless reconnection of an island to the utility will also be required for these high reliable systems.

Definitions

Distributed Generation (DG) – Electric generation facilities connected to a distribution system through the point of common coupling. Distributed generation is a subset of Distributed Resources.

Distributed Resource (DR) – Sources of real electric power that are not directly connected to the bulk power system. It includes both generators and energy storage technologies.

Distribution System – Any facility that allows electric power to be delivered to a load regardless of ownership

IPP – Independent Power Producer

Island – A condition in which a portion of the Wires Owner’s system is energized by one or more power producer generators through their PCC(s) while electrically separated from the rest of the Wires Owner system.

MicroGrid - The CERTS MicroGrid concept is the aggregation of loads and micro-sources operating as a single system providing both power and heat. The majority of the micro-sources must be power electronic based to provide the required flexibility to insure operation as a single aggregated system. This control flexibility allows the CERTS MicroGrid to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security. (1)

Point of Common Coupling – Will be used to refer to the point where the electrical facilities or conductors of the Wire Owner are connected to the Power Producer’s facilities or conductors, and where any transfer of electric power between the Power Producer and the Wire Owner takes place

Standards

The following are some of the applicable standards relating to DG interconnection and protection: (12)

IEEE C37.95-1989 Guide for Protective Relaying of Utility-Consumer Interconnections

IEEE 929-2000 Recommended Practice for Utility Interface of Photovoltaic (PV) Systems

IEEE 242-2001 Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems

IEEE 1547 –2003, Standard for Interconnecting Distributed Resources with Electric Power Systems

CAN/CSA C22.2 No. 257 Interconnecting Inverter-Based Micro-Distributed Resources to Distribution Systems

CAN/CSA C22.3 No. 9, Interconnection of Distributed Resources with Electricity Supply Systems (Draft)

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