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# PROTECTION OF DISTRIBUTED GENERATION (DG) INTERCONNECTION

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## 1. INTRODUCTION

To mitigate the effects of the climate change by reducing the emission of $CO^2$ carbon dioxide and the use of fossil fuel generation, Renewable Energy Sources (RES) such as wind power and Distributed Generation (DG) have been developed during the last decade.

With the penetration of DG plants and the increase of two-way power flows at sub-transmission and distribution level, the need of adapting the network's stability and control principles has significantly increased. This has resulted into the progressive development of adequate grid codes setting some acceptable operational bandwidth for wind generators with regard to fault levels, power quality and supply stability.

Penetration of DG and RES will continue for the next decades by also impacting the design and the operation of distribution and transmission systems, creating new challenges for protection engineers and system operators (no dispatchable or controllable generation). They introduce a fault current source that requires changes in the protection philosophy of distribution/transmission feeders and at the same time implementation of protection functions for the DG interconnection.

The functionality of the DG interconnection protective IED can be divided in three main categories:

- Protection of the system from the impact of the distributed generator when a fault occurs on the distribution feeder
- Protection of the generator against system faults and unsynchronised auto-reclosure.
- Protection of the interconnection transformer when a fault occurs in it or on the secondary side

After discussing the requirements for protection and protection related to the interconnection of distributed generators to the distribution and transmission systems, the paper describes the functionality of multifunctional relays that can be used to perform such functions. The paper analyzes the requirements for DG interconnection protection as defined in the IEEE standard P-1547 [1] and practices in different countries.

## 2. NEEDS FOR NEW STANDARDS AND REGULATIONS

The increase of the DG penetration in distribution systems with the emergence of large DG plants such as wind power connected to sub-transmission network has pushed recently some countries to develop new regulations or revise their existing grid codes to cope with these new scenarios.

Different DG connection criteria exist for distribution and transmission systems. Most of the 10 MW and smaller DGs are connected to the utility grid at distribution (generally radial up to 35 kV networks) and sub-transmission level (generally meshed from 35 kV and above). In transmission systems, DG is normally connected to a dedicated or existing substation, directly or through a dedicated line or tapped connection to an existing two-ended line.

Due to the saturation of the land sufficient wind opportunities to reach the expected financial rate of return are diminishing. Therefore, new interest towards offshore wind has been raised. Figure 1 presents the



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combined interest of reducing the associated visual and noise disturbance to the public as well as showing promising wind potential. Building wind farms offshore however requires larger initial investment and so the associated return on investment equation directly results in a need to increase the associated site generation density.

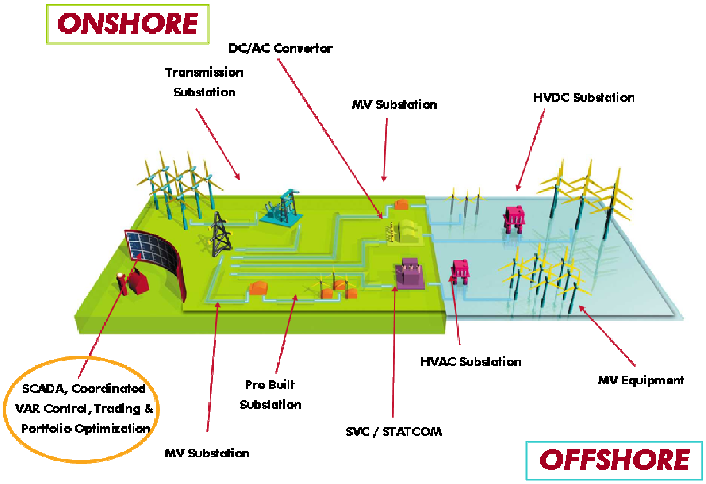


**Figure 1: Off and Onshore Wind farm**

This situation has raised new electrical network connection challenges as these new offshore wind farms will soon reach a similar size as conventional power plants operating in transmission networks. As a result, their configuration and operational model will be adapted as compared to the traditional wind farms connected to distribution networks whose reduced capacity have been ignored in the generation response models used by transmission network operator.

## 3. PROTECTION AND AUTOMATION REQUIREMENTS

### *3.1. Introduction*

With the integration of DG and RES new issues related to Protection and Automation are being considered such as stability, voltage profile, voltage transient, congestion, balancing of active / reactive power, losses, fault ride through capability, short circuit levels, power quality, control and monitoring and protection coordination.

Typical protection requirements at the utility/DG interconnection are:

- Detection of faults within the DG plant that can be feed by the utility power system or abnormal operating conditions that lead to voltage or frequency out of normal limits.
- For any disturbance in the network, immediate tripping by very sensitive and instantaneous relays in order to prevent an islanding operation for small power plants.
- For large power plants, and in many cases also for medium size power plants utilities put forward requirements that generating plants contribute to the stability of the network and remain connected for external disturbances by coordinating (delaying) the relays with the network protection and imposing “ride through” requirements. A number of utilities tend to put forward similar requirements for the small power generating plants.
- The greater capability to withstand faults should not affect the sensitivity for the islanding detection, so a compromise between sensitivity for islanding detection and stability under external disturbances is needed.

### *3.2. System consideration*

In order to validate the choice and the design of the DG Interconnection protective relays to be used, a preliminary study should be undertaken by the utility to model the steady state and dynamic system performance.

Following point should be considered:

- Characteristics of the network at the interconnection point ,
- Voltage profile and power transfer capability at the interconnection point,
- Type of interconnection to the network,
- The potential fault current contribution from the DG to the utility grid and vice versa,
- The dynamic response of the DG units to utility grid faults and disturbances and capability of the DG units to maintain stability on loss of the utility connection,
- Redundant protection policy of the utility grid at interconnection point (line protection, transformer protection, breaker failure protection, etc.),
- Auto-reclosing policy on the utility grid,
- Coordination requirements with utility protections,
- The system of ground fault protection when the DG is operated in "islanding mode".

Other factors to be considered when designing a DG interconnection protective scheme are also the technology of the turbine (dynamic response of synchronous / asynchronous machines, wind turbines, etc.) and the system grounding.

A detailed assessment of the dynamic response of the generator is required to determine the needed control equipment and protection relay settings and understand the response to system disturbances. The interconnection protective IED is designed to avoid tripping under transient conditions from which the overall system will recover stable operation. It is particularly relevant to examine the dynamic frequency response of the DG generators under fault, load rejection and generation rejection when operating in parallel with the utility network.

### *3.3. Dynamic Performance and System Grounding*

The main protection of a DG interconnection IED is to disconnect the generator when it is no longer operating in parallel with the utility grid. With a grounded transformer connection (e.g. HV grounded star, LV delta) the transmission system remains grounded if the utility end of the transmission system is opened. This is appropriate considering that transmission equipment ratings (e.g., surge arresters) are sized for grounded operation. A disadvantage with this connection is that the ground current seen by the Line protection installed at the substation utility, can be reduced and the fault not detected. The majority of the transmission system is solidly grounded as well as the DG connections.

In the evaluation of the DG installation, the consequences of ungrounded operation must be evaluated. An analysis must be made as to whether or not the transmission system can be temporarily ungrounded. The classic situation where this can occur is when the utility end of the transmission line has tripped but the DG units remains connected through a power transformer with an HV delta connection. In such a situation for a ground fault on an ungrounded network, there is a risk of overvoltage on the unfaulted phases. In some cases, where transmission lengths are long and where there is minimal connected load, the overvoltages on unfaulted phases can rise considerably above phase-to-phase voltage value. If ungrounded operation is to be considered, studies need to be performed to determine whether resizing of surge arresters or other equipment needs to be made.

### *3.4. DG transformer connection*

The DG transformer connection provides the connection and transformation from the DG generator bus to the point of interconnection/common coupling with the utility grid.

Only two transformer connections are discussed, HV star connected - LV delta connected and HV delta-LV star connected. The discussion is restricted to these two types (even though there are considerable variants) because these represent the two extreme cases of either a strong source of zero sequence current to the HV system and a connection with no zero sequence source of current to the HV system.

***HV star connected - LV delta***

This connection is typical for most DG installations as well as generator facilities owned and operated by the utility. The connections offer the advantage of:

- Zero sequence isolation between the HV and LV windings, ensures that the HV system is not a source of ground fault current for generator winding faults,
- Trapping of third harmonic currents (and multiples thereof) in the delta winding is a benefit,
- An HV grounded connection (with LV delta) ensures grounded transmission line operation if the remote utility bus breakers open for any reason

Though this is a standard connection for most installations, it can cause problems if the proponent of the DG project proposes a tapped connection into an existing transmission line with a single breaker. The DG installation will reduce the reach and sensitivity of relays at the utility buses.

***HV delta - LV star grounded connected***

Though this is not the preferred approach, this connection can manifest itself in several ways. When an existing industrial complex proposes to add self-generation for export to the utility the existing HV customer transformer connection may be a delta connection.

The second instance is for the case where a DG is added to the distribution system, and the transformer in the utility substation imposes an HV delta source to the transmission system.

## 4. IMPACTS OF DG INTERCONNECTION ON UTILITY PROTECTION

Connection of DG to utility networks has various impacts on the performance of the existing protection schemes, mainly it concerns the distribution and radial networks. Their importance depends on the penetration and size of the DG units:

- Reduction of fault detection sensitivity and speed of operation in tapped connections (protection might not be able to detect the fault)
- Increasing of fault levels may exceed the capacity of the switches. The fault current contribution will depend on the type of generation used. For example, full converter wind turbine generators only provide a small contribution to the fault level.
- Reduction of the impedance relay reach,
- Unnecessary tripping of utility breaker for faults in adjacent lines due to fault contribution of the DG (sympathetic tripping),
- Changes in the value and direction of short circuit currents, depending on the generator is connected or not, which affect the coordination and time operation of overcurrent relays,
- Unintended islanding (loss of mains) which can lead to preventing the automatic reclosure, unsynchronized reclosure and in some cases operation of parts of the system without effective grounding,
- Reclosing coordination,
- Out of step conditions,
- Over-voltages due to resonance conditions,
- System protection performance (load shedding protection, WAP, SPS, etc.),

It is important to notice that high penetrations could imply substantial changes of the utility protection system and even of the network topology.

## 5. IEEE STANDARD P-1547

Up until recently, the existence of DG was limited and therefore, had little impact on the operation of the electric power system. Consequently, the regulatory framework and connection requirements have been restrictive to protect the integrity of distribution systems. However interconnection of DG plants to the utility's grid remains problematic due to the lack of standards among utilities. It should be noted also that there are no or limited standard models or tools to evaluate the impact of DG generation which does not ease the integration of DG plants into the electric power system planning and operation.

Recently more supportive regulations have been implemented or currently are under revision in many countries or states. The IEEE standard P-1547 called "Standard for Interconnecting Distributed Resources with Electric Power Systems" has been in place for several years (2003). Because adoption of any standard is the prerogative of individual states or countries, acceptance and use of a Standard can be slow.

This standard establishes criteria and requirements for interconnection of distributed resources (DR) with electric power systems (EPS). This document provides a uniform standard for interconnection of distributed resources with electric power systems. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection.

As reported in some previous technical papers [2] and [3], the IEEE P1547 standard does not provide enough guidance on some issues such as the DG interconnecting transformer grounding, special interconnection protection practices and reclosing coordination.

## 6. PRACTICES IN DIFFERENT COUNTRIES

Similar practices as described in section 7, are used for DG interconnection protection in many countries which are under-/over-voltage relays, under-/over-frequency relays, df/dt relays, phase and ground overcurrent relays complemented with a transformer differential relay.

TSOs and DSOs have developed rules and technical specifications for connecting DG plants to the distribution or transmission systems, to ensure the security and quality of supply. These technical requirements are included in the Grid Codes defined by the utilities. A generic grid code can be defined which could be common across the majority of the utilities. However some specific issues will be defined for the transmission system part as well as setting recommendations, etc. depending of the DG power plant size. Some specific requirements also exist e.g wind farms (voltage/frequency operating ranges, fault ride through capabilities, regulation requirements).

With growing DG penetration levels and connection voltages there is an increased need for high performance anti-islanding protection. Taking into account current relay offerings the implementation of anti-islanding protection is always a question of compromise between sensitivity and stability as well as between the performance and cost. Traditionally, the stability aspect was of lesser importance as the network operation did not depend on the presence of DG. This situation is gradually changing and reliable islanding detection is becoming increasingly more important. New solutions are needed as the limitations of the existing methods may eventually pose a barrier to further integration of DG. The use of active methods and alternative communication technologies to improve performance should be considered.

## 7. INTERCONNECTION PROTECTION

### *7.1. Introduction*

Small-scale generators can be found in a wide range of situations. These may be used to provide emergency power in the event of loss of the main supply. Alternatively the generation of electrical power may be a by-product of a heat/steam generation process, or other renewable sources such as wind, biomass and solar. Where such embedded generation capacity exists it can be economic to run the machines in parallel with the local utility network. This can reduce a site overall power demand or peak load. Additionally, excess generation may be exported and sold to the local utility network. If parallel operation is possible great care must be taken to ensure that the embedded generation does not cause any dangerous conditions to exist on the utility network.

Utility networks have in general been designed for operation where the generation is supplied from central sources down into the network. Generated voltages and frequency are closely monitored to ensure that values at the point of supply are within statutory limits. Tap changers and tap changer control schemes are optimized to ensure that supply voltages remain within these limits. Embedded generation can affect the normal flow of active and reactive power on the network leading to unusually high or low voltages being produced and may also lead to excessive fault current that could exceed the rating of the installed distribution switchgear/cables. The fault current contribution will depend on the type of generation used. For example, full converter wind turbine generators only provide a small contribution to the fault level.

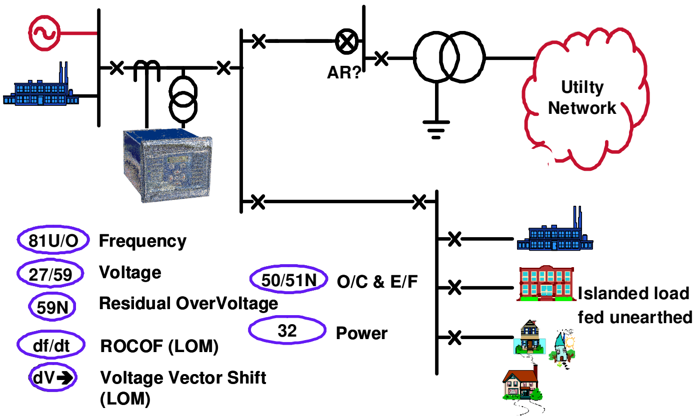


**Figure 2:Co-generation/Embedded Machines**

It may also be possible for the embedded generators to become disconnected from the main source of supply but be able to supply local load on the utility network. Such islanded operation must be avoided for several reasons

- To ensure that ungrounded operation of the utility network is avoided
- To ensure that automatic reclosure of system circuit breakers will not result in connecting unsynchronized supplies causing damage to the generators
- To ensure that system operations staff cannot attempt unsynchronized manual closure of an open circuit breaker.
- To ensure that there is no chance of faults on the utility system being undetectable due the low fault supplying capability of the embedded generator
- To ensure that the voltage and frequency supplied to utility customers remains within statutory limits

Before granting permission for the generation to be connected to their system the utility must be satisfied that no danger will result. The type and extent of protection required at the interconnection point between utility system and embedded generation will need to be analyzed.

Utilities are more concerned by the possible damages generated by the DG interconnection on their equipment and quality of supply (customers). DG owners on the other hand are more concerned by the possible damages generated by the Utility Grid interconnection due to power system faults which can seriously damage their generators etc. Most DG interconnection relays include the following protection functions:

- Phase Fault and Ground Overcurrent elements (51-51G) to protect against overloads and short-circuits inside the DG installation. Depending on the size of the transformer, short-circuit protection may be provided by a transformer differential relay.
- Over and Under-frequency elements (81O-81U) to disconnect the plant under unstable conditions of the network, prevent undesirable island operation and self-excitation of the generator. Additionally, df/dt and voltage vector shift can be used to detect loss of the grid supply and prevent undesirable island operation.
- Over and Under-voltage element (59, 27) to prevent the islanded operation of the generator with an abnormal voltage or a malfunction of the exciter control.

Typical protection functions provided by DG interconnection protective IED are as follows:

| | |
|---|---|
| 50/51 | Directional phase overcurrent (4-stage) |
| 51N SBEF | Directional standby earth fault (4-stage) |
| 51N SEF | Directional sensitive earth fault (4-stage) |
| 64 | Restricted earth fault |
| 59N | Neutral displacement (2-stage) |
| 27 | Undervoltage (2-stage) |
| 59 | Overvoltage (2-stage) |
| 81U | Under frequency (4-stage) |
| 81O | Over frequency (2-stage) |
| 32 | Reverse/Low forward/Under Power (2-stage) |
| df/dt | Rate of change of frequency |
| □□(t) | Voltage vector shift |
| | Breaker fail and back trip |
| VTS | VT supervision |
| CTS | CT supervision |

Additional protection features are discussed in the following sections.

### *7.2. <u>Loss of Main Protection</u>*

If the capacity of an embedded generator exceeds the locally connected load it is conceivable that it could supply the local load in island mode. Fault clearance may disconnect part of the utility system from the main source of supply resulting in the embedded generation feeding the local loads, i.e. a 'Loss of Mains' or 'Loss of Grid' condition. This is illustrated in Figure 3. A fault at F will result in the tripping of CB1 disconnecting substations S1, S2 and S3 from the main source of supply. Also note that transformer T1 was supplying the earth connection for S1, S2 and S3, this earth connection is lost when CB1 opens. Should the load at substations S1 and S2 greatly exceed the rating of EG1, the generator will slow down quickly and underfrequency and/or undervoltage relays could operate to disconnect EG1 from the system. The worst scenario is when the external load is smaller than the generator rating; in this case the generator can continue to operate normally supplying the external loads. The local system will now be operating ungrounded and overcurrent protection may be inoperative at S1 and S2 due to the low fault supplying capacity of generator EG1. The embedded generator may also lose synchronism with the main system supply leading to serious problems if CB1 has auto reclosing equipment.

An even more serious problem presents itself if manual operation of distribution switchgear is considered. System Operation staff may operate circuit breakers by hand. In these circumstances it is essential that unsynchronized reclosure is prevented as this could have very serious consequences for the operator, particularly if the switchgear is not designed, or rated, to be operated when switching onto a fault. To protect personnel, the embedded machine must be disconnected from the system as soon as the system connection is broken, this will ensure that manual unsynchronized closure is prevented.

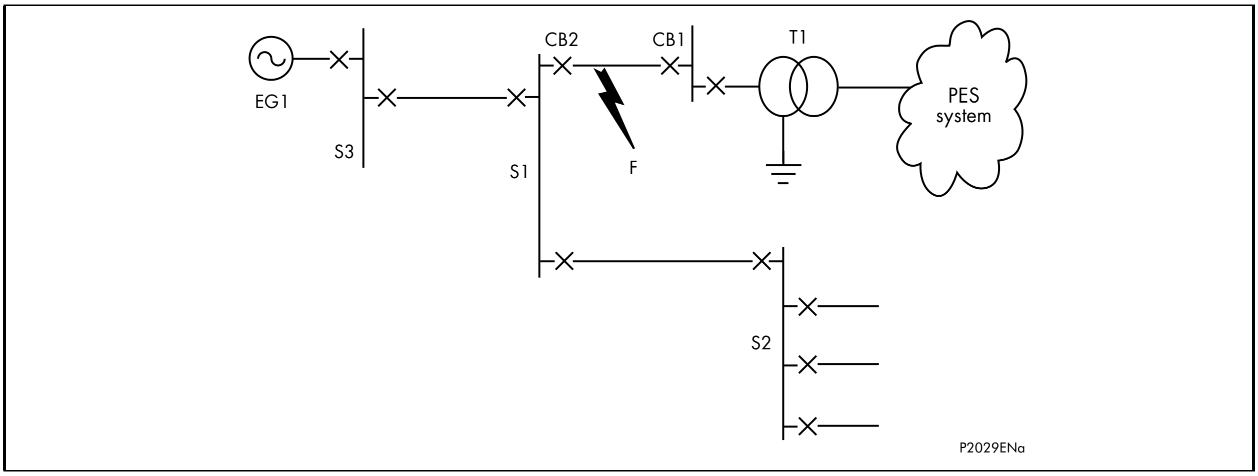


**Figure 3: Typical system with embedded generation**

Where the embedded generator does not export power under normal conditions it may be possible to use directional power or directional overcurrent protection relays to detect the export of power under loss of mains conditions. If export of power into the system is allowed it may not be possible to set directional relays using settings sensitive enough to detect the loss of the mains connection. In such circumstances a Rate of Change of Frequency and/or Voltage Vector Shift protection can be applied. These detect the slight variation in generator speed that occurs when the main supply connection is disconnected and the generator experiences a step change in load.

The type of protection required to detect Loss of Mains conditions will depend on a number of factors, e.g. the generator rating, size of local load, ability to export power, and configuration of supply network etc. Protection requirements should be discussed and agreed with the local Public Electricity Supplier before permission to connect the embedded generator in parallel with the system is granted.

A number of protection elements that may be sensitive to the Loss of Mains conditions such as Rate of Change of Frequency, Voltage Vector Shift, Over Power Protection, Directional Overcurrent Protection, Frequency Protection, Voltage Protection. Application of each of these elements is discussed in the following sections.

### *7.3. Rate of Change of Frequency Protection*

When a machine is running in parallel with the main power supply the frequency and hence speed of the machine will be governed by the grid supply. When the connection with the grid is lost, the now islanded machine is free to slow down or speed up as determined by the new load conditions, machine rating and governor response. Where there is a significant change in load conditions between the synchronized and islanded condition the machine will speed up or slow down before the governor can respond.

The rate of change of speed, or frequency, following a power disturbance can be approximated by

$$^{df}/_{dt} = \frac{\Delta P.f}{2GH}$$

Where

P = Change in power output between synchronized and islanded operation

f = Rated frequency

G = Machine rating in MVA

H = Inertia constant

This simple expression assumes that the machine is running at rated frequency and that the time intervals are short enough that AVR and governor dynamics can be ignored. From this equation it is clear that the rate of change of frequency is directly proportional to the change in power output between two conditions. Provided there is a small change in load between the synchronized and islanded (loss of mains) condition the rate of change of frequency as the machine adjusts to the new load conditions can be detectable. The change in speed of the machine is also proportional to the inertia constant and rating of the machine and so will be application dependent.

Care must be taken in applying this type of protection as the prime consideration is detecting the loss of grid connection. Failure to detect this condition may result in unsynchronized re-connection via remote re-closing equipment. However if too sensitive a setting is chosen there is a risk of nuisance tripping due to frequency fluctuations caused by normal heavy load switching or fault clearance. Guidance can be given for setting a rate of change of frequency element but these settings must be thoroughly tested on site to prove their accuracy for a given machine and load.

### *7.4. Voltage Vector Shift Protection*

An expression for a sinusoidal mains voltage waveform is generally given by the following:

$$V = Vp \sin (wt) \quad \text{or} \quad V = Vp \sin \theta(t)$$

Where

$$\theta(t) = wt = 2\pi ft$$

If the frequency is changing at constant rate $R_f$ from a frequency $f_o$ then the variation in the angle $\theta(t)$ is given by:

$$\theta(t) = 2\pi \int f \, dt,$$

which gives

$$\theta(t) = 2\pi (f_o t + t R_f t/2),$$

and

$$V = V \sin \{2\pi (f_o + t R_f/2)t\}$$

Hence the angle change $\Delta\theta(t)$ after time t is given by:

$$\Delta\theta(t) = \pi R_f t^2,$$

Therefore the phase of the voltage with respect to a fixed frequency reference when subject to a constant rate of change of frequency changes in proportion to t2. This is a characteristic difference from a rate of change of frequency function, which in most conditions can be assumed as changing linearly with time.

The voltage vector shift function is designed to respond within one to two full mains cycles when its threshold is exceeded. Discrimination between a loss of mains condition and a circuit fault is therefore achievable only by selecting the angle threshold to be above expected fault levels.

### *7.5. Reconnection Timer*

As explained previously due to the sensitivity of the settings applied to the df/dt and/or the Voltage Vector Shift element, false operation for non loss of mains events may occur. This could, for example, be due to a close up three phase fault which can cause operation of a Voltage Vector Shift element. Such operations will lead to the disconnection of the embedded machine from the external network and prevent export of power. Alternatively the loss of mains protections may operate correctly, and auto re-closure equipment may restore the grid supply following a transient fault.

Disconnection of an embedded generator could lead to a simple loss of revenue. Or in cases where the licensing arrangement demands export of power at times of peak load may lead to penalty charges being imposed. To minimize the disruption caused, some relays include a reconnection timer. This timer is initiated following operation of any protection element that could operate due to a loss of mains event, i.e. df/dt, voltage vector shift, under/over frequency, power and under/over voltage. The timer is blocked should a short circuit fault protection element operate, i.e. residual overvoltage, overcurrent, and earth fault. Once the timer delay has expired the element will provide a pulsed output signal. This signal can be used to initiate external synchronizing equipment that can re-synchronies the machine with the system and reclose the CB.

### *7.6. Power Protection*

Where the local licensing agreement prevents the export of power into the local supply Over Power protection may be used as a simple Loss of Mains protection. In these cases the element can be used to provide alarm and trip stages allowing the machine operators to closely monitor the machine export capability.

### *7.7. Sensitive Power Protection function*

The minimum standard 3 phase power protection setting can be restrictive for some applications. For example for steam turbine generators and some hydro generators a reverse power setting as low as 0.5%Pn is required. A sensitive setting for low forward power protection may also be required, especially for steam turbine generators which have relatively low over speed design limits.

The sensitive power protection measures only one-phase active power, as the abnormal power condition is a 3-phase phenomenon. Having a separate CT input also means that a correctly loaded metering class CT can be used which can provide the required angular accuracy for the sensitive power protection function. A compensation angle setting $\theta C$ is also be provided to compensate for the angle error introduced by the system CT and VT.

### *7.8. Over Power Protection*

The Over Power function is a directional element that will operate when power flows in the forward direction. From the convention, this means power flowing away from the busbar into the interconnection feeder or out of the protected machine.

Over Power protection can be used as simple overload indication, or as a back up protection for failure of governor and control equipment, and would be set above the maximum power rating of the machine.

Alternatively the Over Power function can be used as protection against excessive export power for an embedded generator. In some installations the machine may be allowed to operate in parallel with the external supply but the exportation of power into the external supply may be forbidden. In these cases a simple Over Power element can be used to monitor the power flow at the interconnection circuit breaker and trip if power is seen to be exported into the system. For small standby generators this may be accepted as the Loss of Mains protection.

### 7.9. Low forward power protection function

When the machine is generating and the CB connecting the generator to the system is tripped, the electrical load on the machine is cut. This could lead to generator over-speed if the mechanical input power is not reduced quickly. To reduce the risk of over speed damage, it is sometimes chosen to interlock non-urgent tripping of the generator breaker with a low forward power check. This ensures that the generator set circuit breaker is opened only when the output power is sufficiently low that over speeding is unlikely. The delay in electrical tripping, until prime mover input power has been removed, may be deemed acceptable for 'non-urgent' protection trips; e.g. stator earth fault protection for a high impedance earthed generator. For 'urgent' trips, e.g. stator short circuit protection the low forward power interlock should not be used. With the low probability of 'urgent' trips, the risk of over speed and possible consequences must be accepted.

The low forward power protection can also be used to provide loss of load protection when a machine is motoring. It can be used for example to protect a machine which is pumping from becoming unprimed or to stop a motor in the event of a failure in the mechanical transmission. A typical application would be for pump storage generators operating in the motoring mode, where there is a need to prevent the machine becoming unprimed which can cause blade and runner cavitation.

### 7.10. Reverse power protection function

Reverse Power protection may be used where the interconnection relay is being used to protect a small generator. A generator is expected to supply power to the connected system in normal operation. If the generator prime mover fails, a generator that is connected in parallel with another source of electrical supply will begin to 'motor'. This reversal of power flow due to loss of prime mover can be detected by the reverse power element.

The consequences of generator motoring and the level of power drawn from the power system will be dependent on the type of prime mover.

### 7.11. Transformer magnetising inrush

When applying overcurrent protection to the HV side of a power transformer, it is usual to apply a high set instantaneous overcurrent element, in addition to the time delayed low-set, to reduce fault clearance times for HV fault conditions.

This is important where low-set instantaneous stages are used to initiate auto-reclose equipment. In such applications, the instantaneous stage should not operate for inrush conditions, which may arise from small teed-off transformer loads for example. However, the setting must also be sensitive enough to provide fast operation under fault conditions.

### 7.12. Directional overcurrent protection

If fault current can flow in both directions through a relay location, it is necessary to add directionality to the overcurrent relays in order to obtain correct co-ordination. Typical systems that require such protection are parallel feeders (both plain and transformer) and ring main systems, each of which are relatively common in distribution networks.

### 7.13. Negative phase sequence overcurrent protection

When applying traditional phase overcurrent protection, the overcurrent elements must be set higher than maximum load current, thereby limiting the element's sensitivity. Most protection schemes also use an ground fault element, which improves sensitivity for earth faults. However, certain faults may arise which can remain undetected by such schemes. Any unbalanced fault condition will produce negative sequence current of some magnitude. Thus, a negative phase sequence overcurrent element can operate for both phase - phase and phase - ground faults. Negative phase sequence overcurrent elements give greater sensitivity to resistive phase-to-phase faults, where phase overcurrent elements may not operate. Voltage dependent overcurrent and underimpedance protection is commonly used to provide more sensitive back-up protection for system phase faults on a generator than simple overcurrent protection. However, negative phase sequence overcurrent protection can also be used to provide sensitive back-up protection for phase-phase faults. Note, negative phase sequence overcurrent protection will not provide any system back-up protection for 3 phase faults.

For rotating machines a large amount of negative phase sequence current can be a dangerous condition for the machine due to its heating effect on the rotor. It may be required to simply alarm for the presence of negative phase sequence currents on the systems. Operators may then investigate the cause of the unbalance.

### 7.14. Residual overvoltage / neutral voltage displacement protection

This type of protection can be used to provide ground fault protection irrespective of whether the system is connected to ground or not, and irrespective of the form of ground connection and ground fault current level.

Where embedded generation can be run in parallel with the external distribution system it is essential that this type of protection is provided at the interconnection with the external system. This will ensure that if the connection with the main supply system is lost due to external switching events, some type of reliable ground fault protection is provided to isolate the generator from a ground fault. Loss of connection with the external supply system may result in the loss of the ground connection, where this is provided at a distant transformer, and hence current based ground fault protection may be unreliable.

### 7.15. Undervoltage protection

The undervoltage element is used to prevent power being exported to external loads at a voltage below normal allowable limits. Under voltage protection may also be used for back-up protection for a machine where it may be difficult to provide adequate sensitivity with phase current measuring elements.

For an isolated generator, or isolated set of generators, a prolonged undervoltage condition could arise for a number of reasons. This could be due to failure of automatic voltage regulation (AVR) equipment or excessive load following disconnection from the main grid supply. Where there is a risk that a machine could become disconnected from the main grid supply and energize external load it is essential that under voltage protection is used. The embedded generator must be prevented from energizing external customers with voltage below the statutory limits imposed on the electricity supply authorities.

### 7.16. Overvoltage protection

An over voltage condition could arise when a generator is running but not connected to a power system, or where a generator is providing power to an islanded power system. Such an over voltage could arise in the event of a fault with automatic voltage regulating equipment or if the voltage regulator is set for manual control and an operator error is made. Over voltage protection should be set to prevent possible damage to generator insulation, prolonged over-fluxing of the generating plant, or damage to power system loads.

When a generator is synchronized to a power system with other sources, an over voltage could arise if the generator is lightly loaded supplying a high level of power system capacitive charging current. An over voltage condition might also be possible following a system separation, where a generator might experience full-load rejection whilst still being connected to part of the original power system. The automatic voltage regulating equipment and machine governor should quickly respond to correct the over voltage condition in these cases. However, over voltage protection is advisable to cater for a possible failure of the voltage regulator or for the regulator having been set to manual control.

### 7.17. Negative phase sequence (NPS) overvoltage protectipn

Where an incoming feeder is supplying a switchboard which is feeding rotating plant (e.g. a motor), correct phasing and balance of the ac supply is essential. Incorrect phase rotation could result in any connected machines rotating in the wrong direction. For some hydro machines 2 phases can be swapped to allow the machine to rotate in a different direction to act as a generator or a motor pumping water.

Any unbalanced condition occurring on the incoming supply will result in the presence of negative phase sequence (NPS) components of voltage. In the event of incorrect phase rotation, the supply voltage would effectively consist of 100% negative phase sequence voltage only.

This element monitors the input voltage rotation and magnitude (normally from a bus connected voltage transformer). This element could be used as a check for hydro machines that the phase rotation is correct to operate the machine in the selected mode as a generator or motor.

The NPS overvoltage element can also be used to provide an additional check to indicate a phase-ground or phase-phase fault is present for voltage controlled overcurrent protection in the Programmable Scheme Logic.

### 7.18. Thermal overload protection

Thermal overload protection can be used to prevent electrical plant from operating at temperatures in excess of the designed maximum withstand. Prolonged overloading causes excessive heating, which may result in premature ageing of the insulation, or in extreme cases, insulation failure.

Overloads can result in stator temperature rises which exceed the thermal limit of the winding insulation. Empirical results suggest that the life of insulation is approximately halved for each 10°C rise in temperature above the rated value. However, the life of insulation is not wholly dependent upon the rise in temperature but on the time the insulation is maintained at this elevated temperature. Due to the relatively large heat storage capacity of an electrical machine, infrequent overloads of short duration may not damage the machine. However, sustained overloads of a few percent may result in premature ageing and failure of insulation.

### *7.19. Line Protection*

Line protection is needed to disconnect the DG plant infeed for transmission line faults. Line protection requirements are driven by:

- transformer connections of the DG,
- transmission line relaying practises of the utility grid (main 1, main 2, redundancy, different principle, different hardware, etc.),
- critical fault clearance time,
- form of connection to the DG (tapped connection or radial circuit),
- size of connected DG and main transformer.

## 8. EXAMPLE OF GRID CODE (WIND FARM)

Clear rules are required to ensure that the power system operates efficiently and safely. In this respect, wind energy technology is evolving to keep up with ever stricter technical requirements. There are continuous changes in grid codes, technical requirements and related regulation, often introduced at very short notice and with minimum involvement of the wind power sector.

Grid codes and other technical requirements should reflect the true technical needs for system operation and should be developed cooperatively between TSOs, the wind energy sector and authorities. Costly technical requirements should only be applied if they are based on a truly technical rationale and if their introduction is required for reliable and stable power system operation. As large energy systems operate with little storage capacities mostly for economic reasons, the guiding principle is to balance demand and supply continuously and, where necessary, to replace other capacity within very short lead times. As each national electricity system operates under tight security and quality standards, these so-called “ancillary services” have to be relied on to “secure” and “fine-tune” the electricity provided, independent of whether intermittent renewable are connected to the grid or not.

Security standards dictate that the electricity grid must be designed to withstand outages of certain magnitude and high loads without losing service, so-called 'N-1' or 'N-2' events. Overall system reliability is determined by the “loss-of-load probability” which can be defined as "the probability that the load will exceed the available generation".

Quality standards define the exact nature of the electricity service delivered, the frequency and voltage being two important variables of this. This mandates that the operator keeps variations in frequency and voltage within specified limits so as not to damage electrical appliances.

Keeping these two above criteria in mind, an operator has to enable enough reserve capacity to be able to maintain the specified security and quality of electricity supply in the face of major events. Two commonly considered events are the outage of the largest individual generating unit on the grid or the loss of the most significant transmission line.

AWEA (American Wind Energy Association) identified on last 2004, more than 4 major technical areas of concern:

- *Low voltage ride-through (LVRT) capability for wind plants and wind turbines:* AWEA recommended adoption of an LVRT requirement developed by E.ON Netz (Figure 3), if required, on a case-by-case basis. E.ON Netz is a German grid operator faced with a significant and growing penetration of asynchronous wind generation capacity on the German grid. The E.ON Netz standard requires that the machine stay connected for voltages at the terminals as low as 15% of nominal per unit for approximately 0.6 s.
- *Supervisory control and data acquisition (SCADA) equipment for remote control:* AWEA recommended the requirement of equipment to enable remote command and control for the limitation of maximum plant output during system emergency and system contingency events and telemetry equipment to accommodate reliable scheduling and forecasting information exchange.
- *Reactive power capability:* AWEA recommended that wind plants connected to the transmission system be capable of operating over a power factor range of ±0.95.
- *Current wind turbine simulation models:* AWEA recommended that transmission providers and wind turbine manufacturers participate in a formal process for developing, updating, and improving engineering models and turbine specifications used for modeling the wind plant interconnection.

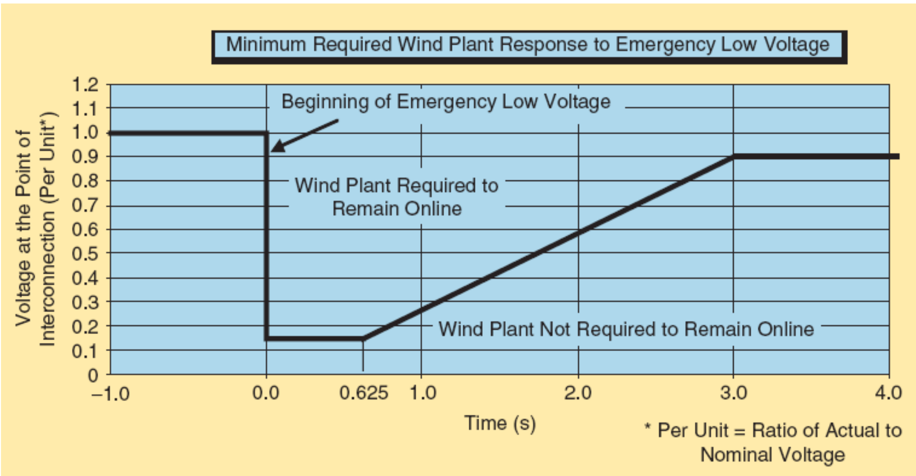


**Figure 4: LVRT requirement for wind generation facilities per FERC**

## 9. RESTORATION PLAN

During the System Disturbance that occurred on November 4th, 2006 in Europe, the final report highlighted the lack of TSO control over the DG plants. It should be noted that after a few minutes, wind farms were automatically reconnected to the grid, being out of the TSOs' control.

This unexpected reconnection had a very negative impact, preventing the dispatchers or system operators from managing the situation. Additionally, certain TSOs in the North-Eastern area were not able to reduce the power output from generation connected to the transmission and distribution grid in a sufficiently short time necessary for the frequency restoration. The TSO control usually applies to generation connected to the transmission grid since traditionally the generation connected to the distribution grids has not had a significant impact on the power system as a whole. However, the recent rapid development of DG plants, mainly wind farms, has changed the situation dramatically. The wind generation in some areas significantly influences the operation of the power system due to its high share in the generation and intermittent behaviour dependent on weather conditions.The negative role of wind generation performance on November 4 was evident. Due to uncontrolled behaviour of wind generation it was not possible to maintain a sufficient power exchange balance in some control areas after the split.

## 10. DG VISIBILITY

Today, most TSOs do not have available real-time data on the power generated in the distribution grids. In view of the rapidly growing share of such generation, this has multi-dimensional consequences:

- No real-time knowledge of the total balance between supply and demand,
- No real-time knowledge of the generation started in DSO grids and possible tripping/reconnection in case of a frequency or voltage drop,
- No real-time knowledge of generation started in DSO grids and possible impact on grid congestion in the high voltage grid.

Additionally, certain TSOs have no control over the generation (e.g. cannot reduce or stop wind power generation). Bearing in mind the growing amount of installed power of wind generation, this situation could lead to serious power balance problems especially in over-frequency areas.

## 11. CONCLUSION

Selection of the DG interconnection protective relay is based on several criteria such as power system characteristics, the dynamic response of the generator, the system grounding, the DG transformer connection, etc., as well as the protection policy of the utility and coordination requirements.

The interconnection protection IED design can be summarized as follows:

- Disconnection of DG plants when no longer operating in parallel with the utility grid,
- Protection of the utility grid from damage caused by connection of the DG plants (voltage transients, fault current supplied by DG, reclosing without check sync, etc.).
- Protection of the DG plant from damage caused by the utility grid.
- Coordination with other protective relays should be made to prevent unnecessary trips.
- Possible implications on utility protections must be analysed when a DG is connected, depending on the characteristics of the network, such as the loss of coordination or sensitivity, reclosing co-ordination, etc.

## 12. REFERENCES

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