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# Renewable distributed generation: The hidden challenges – A review from the protection perspective

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ABSTRACT

This review paper is focused on the impact of distributed generation (DG) on distribution system protection. The integration of DG is transforming the traditional radial distribution system into a multi-source system that requires protection that is capable of maintaining proper coordination under bi-directional and variable power flow conditions. The multiple types of DGs with different short circuit characteristics mean that the protection must also be effective under conditions of unpredictable fault currents. New grid code requirements demand that DGs remain connected under fault conditions to provide grid support and improve system reliability and security of supply. A discussion is given of the traditional protection techniques for the distribution system and the shortcomings of such techniques when DGs are integrated into the system. The paper also presents a wide survey and review of recent techniques proposed by various researchers to mitigate the effects of DG integration on the performance of distribution system protection. Centralised and distributed techniques have been proposed that include deployment of intelligent smart devices and communication systems to enhance and provide novel ideas for solving the protection problem. The implementation challenges of these techniques are discussed and proposals for the future given.

**Contents**

## 1. Introduction

The energy policies that are being promulgated by governments world-wide to promote the exploitation and use of renewable energy resources [1–4], and the parallel de-regulation of the energy sector

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that now permits open and non-discriminatory access for small and medium independent power producers (IPPs) to the national grids [5–8], has seen an increasing number of distributed generation (DG) units based on renewable energy being integrated into the power grids. According to the REN21 *Renewables 2014 Global Status* report [9], over the past few years the costs of electricity generation from onshore wind and, in particular, solar PV, have fallen sharply. This has seen renewables accounting for more than 56% of net additions to global power capacity in 2013 [9].

In South Africa, the Integrated Resource Plan (revised 2013) of the government projects an output of 17,800 MW from renewables, representing 21% of envisaged total energy output, by 2030 [1]. The renewable sources will primarily be wind, concentrated solar power (CSP) and solar photo-voltaic (PV), with these preferred technologies being added at an average of 800 MW per annum [1].

Studies [10,11] identified sites with viable potential for the installation and generation of electricity from wind and solar renewable resources in South Africa. The studies put the maximum potential wind capacity at approximately 76.6 GW. Most regions of the country are also considered viable for solar resource with the PV potential estimated at 886 GW, much higher than the potential wind capacity.

Renewable energy generation systems being installed worldwide range from household scale systems of a few kW up to utility-scale systems of tens to hundreds of MW. Currently, some of the utility scale renewable projects that are being developed in South Africa fall under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) initiated by the South African government and managed by Eskom, the country's predominant power utility company. The approved IPPs sell the generated power to Eskom.

The traditional power system has a vertical architecture and consists of large generating stations located at a relatively few locations [12] with stable power outputs. DG units are being integrated into the grid through the low to medium voltage networks [13–15], though the very large DGs such as wind farms (above 50 MW) are connected at sub-transmission and transmission level [16]. Integration of huge numbers of DGs of smaller capacity, that are dispersed according to the resource availability, is leading to fundamental changes to the topology of the power network, especially at the distribution level, that may ultimately transform the power system architecture to a horizontal one.

This increasing integration of DGs has raised many technical concerns such as impact of the DGs on voltage regulation, supply security and reliability, system stability, equipment control, protection, islanding and safety [16–19]. The system energy management protocols also need to be reviewed because of the uncertainty of the DG contribution [20], considering the stochastic behaviour of renewable sources that is dependent on weather conditions, leading to network reconfigurations when the DGs are not active, or islanded.

This review paper is focused on the impact of the DGs on system protection, but with the realisation that the other above-mentioned technical concerns can be mitigated through proper system protection and control [18,21]. A discussion is given of the traditional protection techniques for the distribution system and the shortcomings of such techniques when DGs are integrated into the distribution system. The paper also presents a wide survey and review of recent techniques proposed by various researchers to mitigate the effects of DG integration on distribution system protection performance. The implementation challenges of these techniques are discussed and proposals for the future given.

This paper is organised as follows: Section 2 discusses the impact of DG penetration on the traditional distribution system protection. Section 3 reviews protection strategies proposed for the future DG-integrated distribution system. Section 4 reviews issues of stability and islanding related to integration of DGs. The conclusions are presented in Section 5.

## 2. The impact of DG penetration on distribution network protection

Traditional distribution networks are generally radial by design and the protection strategies that are in use assume single-source in-feed and radial current flows [22–26]. Simple and low cost time–current graded protection is applied and the overcurrent devices can be easily coordinated to give discriminative clearance of faults [5,25,27,28].

However, integration of DGs that are fundamentally active devices transforms the distribution network into a multi-source system allowing two-way power flows. With the DGs also contributing to the fault currents, the protection philosophy that assumed radial or one-way flow of currents from a single source no longer applies, resulting in unpredictable operating times of the existing protection devices leading to possible loss of coordination [22–24,26,29–31]. In addition, connecting variable DG to the system will have the effect of producing variable fault levels and currents, further compromising the protection coordination.

The loss of protection coordination impacts negatively on the reliability of the distribution system. Studies [21,32–34] have shown that the reliability of the traditional distribution system is degraded significantly by the loss of protection coordination resulting from high penetration of DGs.

Two particular cases of mis-coordination can be identified that result from incorporation of DGs: protection 'blinding' and sympathetic (false) tripping. 'Blinding' occurs when the sensitivity of a protective relay is reduced. It can be shown [35] that fault currents seen by an upstream protective device may be reduced by the presence of a DG located downstream of the protective device. The effective reduction will depend on the relative short circuit impedances of the main source and the DG, and the impedance of the feeder to the point of fault. The upstream protection device may thus be 'blinded' to downstream faults and fail to pick up.

Sympathetic tripping occurs when a protective device in one feeder operates for a fault in another, upstream or parallel, feeder when the protection device's security is lost as a result of current 'back-feed' towards the fault from incorporated DGs [35]. These currents would otherwise not exist in the absence of the DGs. This is false tripping as the fault is in an entirely non-related zone. This problem would not arise with directional elements but most of the overcurrent protection devices used on the distribution network are non-directional and will pick-up bi-directional faults. Directional feature would require voltage transformer (VTs) which are not installed at most points on the distribution system.

DGs may also create problems with fuse saving [36]. Fuses are commonly used on the distribution system for protection of lateral feeders. The protection philosophy applied is for the fuse to clear permanent faults and an upstream protection device such as an auto-recloser to clear the transient faults and save the fuse. However, a DG inserted at an intermediate location may continue supplying fault current leading to the possible loss of the fuse for transient faults.

Another complication arises where multiple types of DGs are installed. Studies [4,29,37] have shown that DGs have different short circuit characteristics and contribute fault currents to varying degrees depending on the type. Four main types of DG can be identified [38]: (1) synchronous generators directly coupled to the grid such as hydro micro-turbine generators or thermal generators with CSP systems; (2) asynchronous generators directly coupled to the grid such as squirrel cage induction generators (SCIG) and wound rotor induction generators (WRIG); (3) doubly-fed asynchronous generators, with power converter in the rotor circuit (DFIG); and (4) power converter interfaced units, with or without a rotating generator such as photo-voltaic (PV) and fully controlled wind generator (FCWG).

The type 1 and 2 DGs are characterized by high short-circuit current contribution that may reach 10 per unit (p.u.) of the rated current, depending on the reactance of the generator and connecting transformer [29,32,39–41]. However, for type 2 (asynchronous) DGs, the currents will decay rapidly and may reach values below the rated current, mainly because the asynchronous generator does not have an independent excitation system. This phenomenon makes it difficult for a relay to pick up the fault. The DFIG (type 3) will usually have a crowbar scheme for protection of the rotor circuit. With the crowbar activated, the rotor is short-circuited and the DFIG behaves like the conventional asynchronous generator [38], with a large initial current that quickly decays. The type 4 (converter interfaced) DGs are characterized by a limited contribution to short-circuit currents of up to 4 p.u. of the rated current. The rapid response of the inverter control ensures that this current is quickly reduced to below the withstand level of the power electronic devices [29,39–41].

Network operators have recently introduced regulations (grid codes) that require the DGs on the distribution network to have the capability to ride through faults and remain connected for a defined duration dependent on the severity of the disturbance [42]. The DGs must not only remain connected but must provide active and reactive power support to maintain the system frequency and voltage following fault clearance. To meet these requirements, DG manufacturers introduced the control techniques that, however, also have impact on the short circuit behaviour of the various types of DGs [42]. The control techniques are not standardised and have introduced uncertainty in the fault current contribution of the DGs [38].

From the above discussion, it is apparent that integration of DGs requires protection that is capable of maintaining protection coordination under bi-directional and variable power flow conditions. The protection must also operate correctly under the conditions of unpredictable fault currents. The traditional distribution protection is designed for radial current flows of predictable magnitudes, and will fail under unpredictable current flow conditions. The growing penetration of DGs, therefore, makes distribution network protection an important research topic on the future of power systems [18,43,44].

The DG integration raises two other important issues: violation of short-circuit ratings and islanding. In the presence of DGs, fault current is supplied both from power system and DG. This can result in increased short circuit current which can surpass breaker capacity. The ratings of circuit breakers and other installed devices thus need to be re-assessed following installation of DGs; the design short-circuit capacities should not be exceeded.

The integration of DGs raises possibilities of islanding, when part of a network may keep on operating as an island following the opening of a circuit breaker or breakers at some point in the network to clear a fault. Islanding has been considered undesirable for various reasons, including difficulty with voltage and frequency control, problems with reconnecting the island, poor power quality in the islanded system, safety issues and the difficulty of clearing arcing faults if the DGs remain connected [44,45].

### 2.1. *Current protection practices with DG penetration*

Current utility industry practice, based on standards including the IEEE 1547 [31,46], requires that protection systems be installed to ensure the disconnection of the DGs from the network in the event of a power system disturbance or fault. This is necessary for protection of the DG, to prevent islanding [35], and also to ensure that the DGs do not contribute to the short-circuit currents and the system protection can operate according to the original coordination settings without the DG units [13–15,46,47].

The practice of disconnecting the DGs every time a fault occurs may lead to unnecessary blackouts [48] making the DG supply, and as a consequence the distribution system, very unreliable. Further, because of the increased contribution of the DGs to network security, the indiscriminate disconnection of un-faulted DGs is not desirable and neither is it acceptable in a deregulated and competitive multi-owner energy market [18]. Additionally, reliability can be improved significantly if the affected areas have the capability to separate from the grid with the DGs continuing to feed the islanded system, in which case no blackouts are experienced and there is no loss to the owners of un-faulted DGs that continue supplying power.

Some system operators have recently introduced grid codes that require the DGs to ride through faults and remain connected to provide ancillary services – frequency and voltage support at point of connection. The DG protection is still required to trip if a disturbance (such as low voltage resulting from a short circuit) of a defined severity is not removed after a defined duration [49]. Whilst connected, the DG will contribute fault current and the distribution system protection coordination is not certain. Inverter and other control techniques introduced by manufacturers to give DGs fault-ride-through capability result in fault current contributions of less than the DG rated current. The DG will thus have little impact on protection operation but this may lead to difficulties in detecting and isolating the faults [42].

## 3. Protection strategies for the future distribution network

As discussed in Section 2, integration of DGs requires protection that is capable of maintaining proper coordination under bi-directional and variable power flow conditions. The protection must also be effective under conditions of unpredictable fault currents. The protection must also allow islanding to improve the reliability of the distribution system. New grid code requirements demand that the DGs remain connected for a short time under fault conditions; this requires protection that is fast to enable quick fault clearance and recovery of the voltage. New protection strategies thus need to be realised and adopted to replace the existing industry practice of indiscriminately disconnecting DGs in the event of fault or abnormal condition on the power network.

Currently, distribution system applications tend towards low-cost solutions [5,25,27] based on the philosophy that protection on the distribution system should just be sufficient to ensure safety and minimise damage. This practice is a consequence of economic considerations due to the huge number of distribution and supply points that need protective devices. Hence, a suitable compromise must be reached between economy and complexity for any future protection strategy for the distribution system incorporating DGs. Any fundamental shift from the basic time–overcurrent protection strategies on the distribution network will require considerable capital investment leading to higher electricity costs.

A wide range of strategies that attempt to improve protection coordination in the presence of DGs have been proposed in the literature, and these are discussed and critically reviewed in the following sections, according to the criteria established above.

### 3.1. *Economy-driven strategies: performance enhanced traditional strategies*

Economic considerations have led to development of solutions that attempt to retain the traditional protection system structures and devices so as to offset any new capital investments. Such solutions have been proposed in [22,26,31,33]. These solutions are based on the premise that for any given network, the optimum locations, sizes of DGs, maximum DG penetration levels, and also protection settings, may be identified that minimise incidents of loss of protection coordination and hence improve system reliability [21].

However, the flexibility for selection of appropriate DG locations and capacity may not be available in practice; and such flexibility may actually offset the benefits, and the very principle, of distributed generation. Some optimisation constraints might also be imposed such as locating the DGs to minimise system losses [50–52]. The minimum acceptable level of loss of protection is not defined, nor how this can be characterised. These solutions, in effect, do not solve the problem as any changes to DG penetration, capacity or disconnections will lead to changes in fault levels and further loss of protection coordination. Any such developed strategy is network and time specific and no generic attributes can be derived for application elsewhere.

The traditional protection scheme may be enhanced by employing adaptive protection principles where the protective devices such as relays respond to the changing system conditions and adapt (the settings) according to the actual system state. The devices will need information about the current status of the network and, hence, communication systems need to be implemented. The concept of the smart grid [37,53], the next generation power system that will be characterised by two-way communication, has helped promote these communications-based solutions [18,25].

Research presented in [54] employs adaptive protection within a traditional relay-recloser-fuse protection structure but using digital relays and reclosers. The relay located at the substation, runs an algorithm that detects possible locations of DGs using current measurements at all recloser and fuse locations, and then depending on the relative current magnitudes, adapts or shifts the recloser fast curves for sustained recloser-fuse coordination. This technique is, however, only effective up to a certain level of DG penetration, above which the fault currents fall outside the recloser-fuse coordination range. Additionally, the measurements and communications requirements far exceed the cost of the fuses making this technique not viable.

Solutions suggested in [19,25,31,55] employ a central computer to adjust the settings of the protection devices on receipt of information about the network configuration and DG connections or disconnections, in the attempt to retain coordination between the devices. However, coordination may not exist during the time between network reconfiguration and calculation of the new settings [47]. These solutions assume the protection devices have all been upgraded to, or replaced by, digital relays.

Some researchers [30,47] suggest solutions for the distribution system protection that share some characteristics with the complex and high-cost transmission system protection, such as current differential and distance schemes. The transmission system, however, consists of large generating stations located at a few and stable locations. In contrast, integration of huge numbers of DGs complicates the application of these protection schemes because of the potential substantial generation changes and power network reconfigurations, especially where islanding is allowed [47]. For example, the distance scheme, though it has many advantages when compared with overcurrent feeder protection, will suffer from the problem of under-reaching where DGs are connected at several nodes along the distribution feeder. These DGs create infeeds that cause the impedance presented to an upstream relay to be higher than the actual [56].

### 3.2. *Non-traditional fault identification and location*

The techniques proposed in Section 3.1 attempt to maintain protection coordination in the presence of DGs, but have deficiencies and limitations that hinder their possible application. The traditional protection structure may thus need to be changed. The concept of the smart grid, and its underlying communication-based structure, has promoted a substantial paradigm shift in the approach towards the protection of DG-integrated distribution systems. Communications-based solutions are being promoted that attempt to detect and locate faults within the distribution network. The appropriate circuit breakers are then identified to trip and clear the fault.

Solutions proposed by [27,28] attempt to detect and locate a fault by facilitating data communications between intelligent electronic devices (IEDs) in the distribution network and a central computer that runs an algorithm to identify the appropriate circuit breakers to trip and clear the fault, based on the system measurements and DG statuses. The algorithm proposed in [28] iteratively searches, through impedance calculations, for the faulted section. Once the section has been identified appropriate circuit breakers are tripped to isolate that fault. However, the iterative nature of this algorithm may lead to excessive fault clearance times. Unrealistic assumptions are also made such as having fixed loading conditions for the algorithm to work correctly.

Research work in [27] considers the application of neural networks to determine the fault location. The algorithm iteratively searches for the paths with installed DGs that are feeding the fault. Once the paths have been identified appropriate circuit breakers are tripped to isolate the fault. However, the training requirement of neural network algorithms to determine the weights, that may be large in number considering the structure, may prove difficult. Questions may arise as to whether the neural network will perform correctly when some combination of inputs is presented to it [48]. The structure and depth of the neural network may also lead to slower response and excessive fault clearance times.

Solutions suggested by [18] apply simpler algorithms but are applicable to distribution networks within an urban setting that allow possibility of temporary switch-over to ring configuration. The algorithm depends on the current, voltage and directional signals received from remote IEDs to generate trip or block signals that are send back to the IEDs on the faulted path. Installation of VTs is thus required at all points to generate the directional signals. The suggested algorithm is, however, not applicable to a typical rural network consisting only of radial feeders.

The work presented by [15] proposes a centralised architecture where off-line fault calculations are used to adapt the short circuit (SC) data of the network to the current system configuration. A run-time algorithm is used to compare these SC data with the actual system measured currents in order to locate a fault and determine the faulted zone and the circuit breakers that must be tripped. The short circuit data needs to be updated following every network reconfiguration or DG connection or disconnection.

Centralised control in protection and control has its drawbacks. Failure of the central computer, or the communication system, will disable the protection for the entire distribution network for the length of time it takes to restore services. A distributed approach has advantages in this respect in that failure of one node will only affect a localised portion of the distribution network. Hence, solutions with distributed architecture have been proposed that attempt to detect, classify and determine the fault location using relay 'agents' and peer-to-peer communications [23,24,57].

An agent is defined as an intelligent device that is capable of autonomous action within an environment to meet its design objectives [58–62], which is the protection function in this instance. The IED agents are located at points on the distribution network such that the network is divided into several sections or zones. The agents exchange data through a communication network, essentially transforming the traditional protection systems on the distribution network into a complex, network-wide, distributed protection system.

Using the known locations and capacities of the DGs, some coefficients, that effectively represent the expected normal and abnormal current flows at each busbar for each type of fault, are calculated and stored in the IED and are subsequently used for the classification and identification of a fault and its location. The agents measure the bus currents at which they are located, sharing this information with other agents, and compare the values with the calculated coefficients in order to detect, classify and determine the fault location. These coefficients, however, have to be re-calculated for each 'agent' in the event of changes to the network topology or DG penetration, thereby imposing huge computing and communication overheads on the protection system.

### 3.3. *Development of new relay characteristics*

Reference [30] proposed a new relay characteristic for protection of DG-integrated distribution systems. The proposed relay has an inverse time-admittance characteristic where the operating time of the proposed relay depends on the measured line admittance. The relay measures the admittance of the protected line and is thus sensitive to the location of the fault on the feeder.

Relays of this type can be coordinated in a similar manner to simple time–overcurrent relays. However, more work is required to prove its functionality and implementation as its complexity is likely to be comparable to that of impedance relaying. This relay type may not function correctly with inverter-interfaced DGs that limit the fault current to a fixed level, in which case the fault current presented to the relay is independent of fault location. The control strategies of such inverter-interfaced DGs need to be reviewed to ensure the DG contributes variable fault current that depends on fault location. This will enable such relays to detect and isolate faults effectively [30].

Additionally, it can be shown [35] that fault currents seen by an upstream protective device may be reduced by the presence of a DG located downstream of the protective device. The effective reduction will depend on the relative short circuit impedances of the main source and the DG, and the impedance of the feeder to the point of fault. An upstream admittance protection relay may thus 'see' a reduced current causing the relay to over-reach.

### 3.4. *Further challenges with the non-traditional approaches*

The adaptive and other communication-based solutions described above assume zero fault impedance. A lot of faults will likely be arcing faults [30], which may cause the measured fault current values to be different from the expected values stored in the central computer, or those used to adjust the settings of the protective devices, leading to problems of under- or over-reaching and the erroneous tripping of circuit breakers. The effects of fault resistance on the performance of these strategies need to be investigated and mitigated.

Additionally, the requirement for continuous monitoring of the system variables and DG statuses for protection purposes will impose huge load on the communication system. No specific communication techniques are suggested in the literature, except that the smart grid will make such communications possible. In traditional protection schemes, especially at transmission level, signalling is initiated only when some event is detected [5]. Data networks capable of transferring data in real time in a secure manner and with adequate latency will be required to achieve high speed protection and control. However, the use of emerging protocols such as the IEC61850 for the transmission of critical data such as GOOSE[1] and Sampled Values (SV) of currents and voltages has been investigated in [63] for possible application on the distribution system, outside of the substation for which the protocol was initially intended.

Ultimately, the practical implementation of adaptive protection, as well as relay 'agents', requiring intelligent devices and data communication networks will require a huge initial capital investment in the replacement of traditional relaying with digital relays and communication networks [15,24].

Back-up protection strategies in the event of communication failure between the centralised protection unit and the remote IEDs are not formulated in the proposed strategies such as those given in [15,25,27,28,31]. It will be necessary for the strategies with centralised computing to have a fall-back strategy whereby the protection must operate based solely on local measurements [47]. Primary and back-up protection systems are usually required to operate on different principles [5].

Most of the proposed protection strategies in the literature assume the existence of suitable fault detection techniques without explaining what they are. Fault detection in distribution systems incorporating DGs may be difficult due to the variable fault levels. This is exacerbated by the low fault current contribution of inverter-interfaced DGs [30,48]. This problem becomes critical when islanding is allowed and fault infeed from the grid is removed resulting in very low fault levels in the created microgrid. The control strategy of inverter-interfaced DGs should be reviewed to ensure these DGs contribute to the fault and aid in the detection and isolation of the fault [30].

Some researchers such as [15,18] developed and used test systems, including the necessary system data, based on the networks in their particular regions or countries leading to the development of strategies peculiar to the particular network topology, but not transferable to networks with different topologies. The test systems formed the basis for evaluation of the levels of DG penetration that have impact on the fault levels, and consequently the system protection. The proposed protection strategies were implemented on these network models to validate compliance with the specified performance requirements. However, other studies [19,22] used one or other of the IEEE standard distribution test networks [64,65]. The IEEE test systems are well documented allowing for the simulation of numerous scenarios due to the large set of available data [65]. This also allows for the generation of generic results, which is not possible with a practical system [65].

In addition to the test system topologies not being universal, most of the proposed solutions are also DG-technology specific and may not be applicable to distribution systems incorporating multiple technologies that have different dynamic behaviours and short circuit current contributions.

## 4. Other technical issues arising from integration of DGs

### 4.1. *System stability*

A typical power system is a high-order multi-variable process whose dynamic performance is influenced by a wide variety of incorporated devices and their controls [66]. Faults or disturbances will cause variations in power flows, rotor angles and bus voltages that may lead to possible stability issues. Stability is a major topic in power system design and operation, including protection [48]. The integration of huge amounts of DGs that are fundamentally

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[1] GOOSE is an acronym for Generic Object Oriented Substation Event

active devices introduce additional behaviours and controls that need to be studied. The simple voltage-behind-the-impedance models that had traditionally been used for the DGs are not adequate for such studies.

Understanding the behaviour of the individual generating units is important for power system stability. During a fault, the generating units must supply sufficient short-circuit current to ensure correct coordinated operation of the protection devices. Following fault clearance, the generating units should recover and supply active power as fast as possible without undue oscillations, and further, supply reactive power, or reduce reactive power consumption, in order to support quick voltage recovery [67].

Traditionally, stability has not been an issue at the distribution level as the network was considered passive, and the voltage sources were represented by simple static Thevenin models [13,18]. Faults on the distribution network were considered not to have an impact on the behaviour of generating units located on the transmission system [18].

However, firstly, because of the increasing contribution of DGs to network security, disconnection of large numbers of DG units following system disturbance or fault, according to current practice, will lead to significant imbalance between the generation and demand leading to possible system instability. Secondly, the high DG penetration, especially of PV, has the effect of reducing the effective system inertia leading to reduced system dynamic performance [20,68]. Traditionally, the power system is required to have adequate inertial energy that may be called upon instantly to stabilise the dynamics when abnormal conditions occur. The stabilisation requires both real and reactive energy and control [69].

How DGs may contribute inertia to the power system is a topic under extensive discussions. PV, for example, may need to provide the equivalent inertia by electronic means using stored energy in order to maintain the system capability [69]. Wind generators may also provide equivalent inertia by extracting the kinetic energy stored in rotational parts of the wind turbines through a converter control strategy referred to as “synthetic inertia” [70]. The integration of CSP-based thermal generation DG offers the opportunity for integrating synchronous machines into the energy mix and improving the system inertia [71]. Currently, however, only utility-scale CSP systems are being integrated through the transmission system. Research is required to develop down-scaled versions for integration at the distribution level. Such systems will introduce significant inertia and spinning reserve into the distribution system that are necessary components for successful islanding.

Most of the strategies from the literature proposed for the protection of the DG-integrated distribution system attempt to address the issue of coordination between protection devices but do not discuss the impact of the protection strategies on the dynamic performance and stability of the system [68]. Significant research has been done on the stability problem but from the control perspective, to establish control strategies that aid in maintaining system stability for the DG-integrated distribution system [72]. The stability issue also needs to be viewed from the protection perspective and any proposed protection scheme need to be evaluated against the dynamic response and stability of the system.

The stability problem is complicated by the integration of DGs of a variety of technologies. Little is reported in the literature [73] on the stability problems arising from the interaction of the multiple types of DGs and between DGs and active loads, especially with regard to small-signal stability following islanding of a section of the distribution system. Small-signal dynamic interactions have been extensively investigated for high voltage transmission systems, but very little at the distribution level [16]. However, small-signal stability studies in [73,74] conclude that dynamic interactions among DGs in a distribution network significantly affect the small-signal stability of the system.

### 4.2. *DG interface requirements on protection*

Current industry practice requires the disconnection of DGs to avoid islanding due to various challenges including difficulty with voltage and frequency control, problems with reconnecting the island, poor power quality in the islanded system, safety issues and difficulty of clearing arcing faults while DGs are connected [16,44,45,75]. The disconnection is also done to eliminate their interference with the network following faults or other system disturbances. However, to ensure continuous energy supply with high levels of reliability and quality, updated grid codes for the distribution system issued by various network operators in several countries specify that the DGs should remain connected and support the grid during contingencies [76].

As far as voltage support is concerned, under normal conditions DGs operate on power factor (PF) between 0.95 leading to 0.95 lagging and are not allowed to actively regulate the voltage at the point of coupling to the grid. This is done to prevent excessive voltages being generated and causing a safety hazard to persons and equipment [16,20,46]. However, it has been shown [16] that, with a high penetration of DGs, this practice of PF control of the DGs may actually lead to voltage regulation and instability problems, with the voltage either dipping below the lower limits or exceeding the upper limits depending on whether the DG is operating on lagging or leading PF. It is then shown that a combination of PF and voltage control modes at identified locations is necessary for improved reliability and stability, by allowing the DGs to absorb or inject the necessary vars.

Faults on the system will result in voltage drops that may be sufficient for the DG protection to trip. The voltage must recover quickly to remove this possibility and ensure that the DGs are able to ride through any transient voltage sags. The response of conventional voltage regulators is slow [77] but the DGs themselves, in particular the inverter-interfaced DGs, can quickly supply the necessary vars to restore voltage and prevent the DG from tripping on low voltage [77]. Hence, it is desirable for the DGs themselves to participate in voltage control. Updated grid codes issued by network operators require DGs to have such capability.

Power system stability may be compromised by depressed voltages leading to cascaded, or sympathetic, tripping of the DGs. Voltage dips resulting from faults or other causes may lead to significant imbalances between instantaneous mechanical power input and electrical power output and, if sustained, will lead to loss of synchronism and disconnection of the DG, which may lead to further disconnection of other DGs [16]. For inverter-interfaced DGs the depressed voltage may cause the interface protection to trip on under-voltage, the result of which may overload some feeders leading to operation of overcurrent protection [29]. The DGs should be able to ride through these voltage dips, which is possible only if the protection acts to remove the cause and allow the voltage to recover within the critical clearing time of the DG.

The PQ problems encountered also depend on the design variations of the DGs, especially with regard to wind turbines [78]. These problems include reactive power consumption and power fluctuations resulting from wind variations leading to severe voltage fluctuations and significant power system transients and harmonics and high line losses [78]. The multiple types of DGs respond differently, placing differing requirements on the protection [79].

### 4.3. Islanding

Current industry practice requires the disconnection of DGs to avoid islanding. However, disconnection of large amounts of DG compromises the reliability of the supply, which can be improved if islanding of the affected part of the network is allowed, with the DGs remaining available during and after fault occurrence. It is also desirable for the DGs to remain connected to support voltage recovery [20,79] by having fault-ride-through capability.

Research is on-going [48] in the development of control concepts for islanded microgrid systems. Micro-grid voltage and frequency control are some of the important challenges regarding its implementation despite the numerous benefits of micro-grid operation. Power from the DGs must be controlled to match the load requirement and hence there should be a control scheme to regulate the power flow from the DG and maintain quality and reliability of supply [80]. The control scheme used should allow accurate power sharing and provide voltage and frequency regulation.

Protection is also a major challenge especially regarding the issue of inverter-interfaced DGs. The inverter fault currents are limited by the rating of the power electronic devices. Fault currents in islanded inverter-based microgrid may not have sufficient values to use traditional overcurrent protection techniques [81]. The protection must operate correctly in either of the two operating modes – grid-connected or islanded. The same protection strategies must operate correctly for both islanded and grid-connected operation. Hence, faults within the microgrid need to be cleared with techniques that do not rely on high fault currents.

The research in the literature is focused on the development and control of microgrids with well-defined topologies including known single or multiple PCC (point of common coupling) to the grid. Following the fault occurrence, however, the islanded system will be defined by the locations of the circuit breakers that trip to isolate a fault. Thus, the constituent components of such an island are not predefined. The research into microgrids needs to be widened to include the situation where the DGs in an unpredetermined section of the network can be successfully islanded to continue supplying the localised load.

## 5. Conclusion

The traditional distribution protection fails in its function when a significant amount of DG is integrated into the distribution system. The DGs affect the short circuit current magnitudes and direction of flow, reducing the sensitivity of the relays and causing the protection to lose coordination.

Various protection strategies proposed by many researchers for protection of DG-integrated distribution systems were reviewed. To a greater extent the suggested protection strategies are applicable to networks with specific structures or topologies, or are designed for a specific DG technology due to the differing short circuit behaviours of the DGs. The proposed strategies need to be enhanced and formulated for application to a general distribution system with multiple types of DG. This would require review also of the control strategies of inverter-interfaced DGs so that they contribute sufficient fault current to facilitate detection and isolation of faults.

Stability at the distribution level is now an important topic due to the expected high penetration of DG, and protection schemes need to be evaluated against the dynamic response and stability of the system. This was found lacking in the currently proposed strategies. The protection system employed should also facilitate transition into islanded operation to improve supply reliability. This capability is not apparent in the currently proposed solutions.

Protection schemes with both centralised and distributed architecture are proposed in the literature. However, looking at the limitations and deficiencies of each type, a hierarchical algorithm for protection may be desirable. The distributed algorithms will protect against local faults with minimum communication requirements, reducing the impact of communication link failure. Local protection systems are often not capable of protecting against system-wide disturbances, such as those caused by transient and voltage stability problems, for which a higher-level centralized algorithm may be implemented.

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