Microgrid: protection problems for smart energy management – a comprehensive review

The conventional unidirectional radial distribution system uses non-directional overcurrent relays, reclosers, fuses etc, as the protection devices. When a microgrid is formed in this distribution system, then all these devices become inadequate to fulfill the basic requirements for the complete protection. The microgrid causes the magnitude and direction of the fault current to change dynamically depending on the modes of operation (grid connected or autonomous mode) as well as type, number and position of distributed generators in the network. The microgrid in the existing distribution network turns the radial network more complicated. The researchers are studying various options of the microgrid protection. It is a major challenge of researchers to address protection issues which are hindrances to detect and clear the fault within the microgrid quickly ensuring minimum or no supply of energy disruption to its consumers. The present paper reports the comprehensive survey on existing research literatures in connection with various issues of microgrid protection and, hopefully, it would be useful to the researchers in the field of microgrid protection in finding relevant references and designing state-of-the-art methods.

Keywords: *Adaptive protection, grid-connected mode, islanded mode, microgrid, over current protection*

NOMENCLATURE

DER/DR	Distributed energy resources/distributed resources
DG	Distributed generator/generation
PCC	Point of common coupling
MGCC	Microgrid central controller
GC	Generator (DER) controller
LC	Load controller
CB	Circuit breaker
R	Relay
CT	Current transformer
PT	Potential transformer
F	Fuse
EC-DERs	Electronically coupled DERs
DOC/OC	Directional overcurrent relay
PMU	Phasor measurement units
GPS	Global positioning system

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1. Introduction

For smart energy management in a power system it is desirable that the protection scheme must meet the basic requirements such as discrimination, reliability, sensitivity, stability, and fast operation. The conventional distribution system is unidirectional and its protection is comprised low cost and simple protective devices like OC relays, circuit breakers, reclosers and fuses. Reclosers are necessary in a distribution system since 80% of all faults taking place in distribution system are temporary. Reclosers give a temporary fault a chance to clear before letting a fuse to blow. It is usual practice in USA to provide inverse OC relays at distribution sub-station, the reclosers at main feeder and the fuses on laterals. In Finland and majority of other European countries, definite time OC relays are used at the origin of primary distribution feeders and fuses at secondary sub-stations. In distribution systems in Malaysia, non-directional over-current protection is adopted because of the radial nature of the power system used. The traditional protection schemes are based on the assumption of a radial network structure with large fault currents. In today's competitive deregulated and rapidly evolving energy market, the new paradigm of DERs is gaining greater technical and economic importance across the globe as it gives many prominent benefits like the increased energy efficiency, reduced carbon emissions, improved power quality and reliability, reduced line losses and deferral of grid expansion etc. These benefits cannot be fully exploited with traditional method of integrating a limited number of stand-alone DERs with distribution networks. High degree of penetration of DGs (more than 20%) as well as their siting and sizing have considerable impact on operation, control, protection and reliability of the existing power utility as the integration of individual DER can cause variety of problems like local voltage rise, violations in thermal limits of certain lines and transformers, unintentional islanding etc. [1-5].

Once a microgrid is formed, the topology and characteristics are very much different from the traditional radial distribution network – a shift to a bi-directional network. A typical microgrid construction with protection arrangement is shown in Fig.1. The connection point of microgrid to utility is called PCC, which is usually on the primary side of the utility transformer and at this point the microgrid must meet the prevailing interface requirements, such as defined in draft standard IEEE P1547. MGCC is at the head of hierarchical control system. Second level of controllers in hierarchy is LC and GC. High speed circuit breaker (CB) or static switch is used at PCC to island it from upstream network, which is called the separation device (SD). MGCC exchanges messages in the form of data with LC, GC, and relays (R). Messages, in the context of protection, include relay set point change, co-ordination, re-synchronization etc. and various types of relays like over current, differential type, voltage based, distance, etc to name a few are used in accordance with the system design. Fuses (F) have shown as an exemplary protective device and may be replaced by the relays according to the importance of the system [5-6].

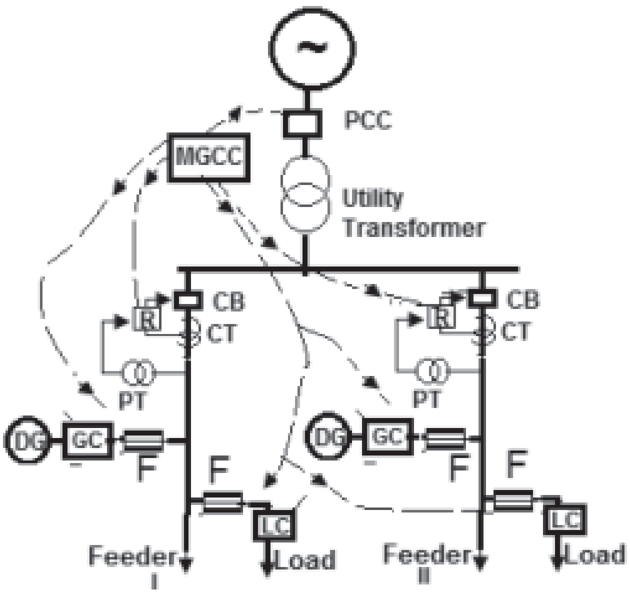

Fig.1 Illustrative microgrid construction with protection arrangement

Microgrids are intended for two modes of operation – normal grid connected mode and islanded mode. The protection system of the microgrid should be designed in such a way that it could be equally efficient in both modes of operations. The flow of current in a microgrid changes from unidirectional to bidirectional. In the islanded mode, on the other hand, fault currents are relatively small due to the limited current ratings of silicon switches that are employed in EC-DERs. Therefore, traditional overcurrent schemes are not effective for the protection of islanded microgrids. It is, due to the inverters having a low thermal overload capability, limiting their maximum output current to about 2–3 times the rated current. The protection of microgrids also face challenges of false tripping of feeder, nuisance tripping of protective devices, blinding of protection, unwanted islanding, out-of-synchronism recloser etc to name a few. So, researchers are striving to address all such issues to develop a protection system, which suffers from a minimum or no down time due to a fault. The present paper reports the comprehensive survey on existing research literatures in connection with various issues of microgrid protection and, hopefully, it would be useful to the researchers in the field of microgrid protection in finding relevant references and designing state-of-the-art methods [7-8].

2. Protection issues in microgrid

When a conventional distribution network is transformed into a microgrid, then existing protection schemes of the network faces some problems to work in the new system. There are several reasons behind these problems such as bi-directional nature of the microgrid, introduction of EC-DRs, topological change, change of operating mode from grid-connected to autonomous and so forth. It is important to know all these problems in details along with their consequences on the microgrid. Many researchers are working on these issues to ensure reliable and safe operation of the microgrid. Their works are mainly dedicated to develop a proper protective device with better selectivity, fast operation, flexibility, different setting opportunities and low price. And this protective device would be equally competent to both the normal grid-connected mode and autonomous mode. The major challenges faced in the protection of microgrid are addressed below.

2.1 Loss of Protection Coordination of Relays

A coordinated protection system maintains the selectivity among the protective devices (relays), so that faults are eliminated in the minimum possible time, isolating the smallest part of the network containing the cause of the fault and assure quality and reliable supply to rest of the consumers. The protection coordination depends on the capacity, type and location of the DERs/DGs in the microgrid. Moreover, depending on the ratio of the power generated by rotating-machine-based DGs to the power generated by EC-DRs, the fault current magnitude can vary over a fairly wide range. Consequently, the protection coordination is critically affected due to the limited fault current contribution by the EC-DERs (1.5 times the rated current) in the islanded mode and the conventional overcurrent protection becomes ineffective for the islanded mode of operation. The conventional distribution protection devices, like low cost and simple non-directional over-current relays (OC), circuit breakers, reclosers and fuses, are no longer relevant to maintain coordination in a bi-directional microgrid [6, 9-13].

2.2 Grid Separation Switches Issues

Normal mode of operation of the microgrid is grid-connected. To prevent the microgrid to feed fault at the grid side, the microgrid requires disconnecting at the PCC for autonomous operation. Due to faults on the utility grid there are voltage drops at the terminals of DGs. If the DGs are directly-coupled type, which are very voltages sensitive, then microgrid stability may endanger. The choice of the protection device is dependent on the required speed of operation, voltage level as well as the availability of fault current. After receiving a trip signal, most medium voltage breaker requires times from three to five cycles to interrupt the circuit. According to SEMI F47 standard, voltage from going below 50% at any point for three cycles or longer is not acceptable. The deterioration of both the sensitivity of the load and the stability are the concern of the researchers and a proper selection of higher speed of response of a SD at the PCC is required [12, 14-15].

2.3 Nuisance/Spurious Separation or False Trips Issues

Instead of removal of exact faulty feeder, healthy feeder is tripped off. Due to fault (F) at the feeder I (Fig.2), the relay of the healthy feeder II, where DG is located nearer to the substation, senses the major fault current (I_{DG}) and trip nuisance of healthy feeder II. DG current (I_{DG}) is more than the grid share (I_G) to the fault (F). Again, as per the emerging standards, it is mandatory to set the tripping values as well as to measure the voltage and frequency at the PCC. This measurement could not discriminate the fault position whether at the utility side or within microgrid. Not only the electromechanical relays/breakers, but sophisticated microprocessor based protection packages also suffer from false tripping. There is a nuisance (avoidable) trip of PCC breaker, as it is provided with fast tripping to have 'transfer trip' from substation breaker. Nuisance separations usually result in loss of load to microgrid consumers, but additionally they can result in incremental expenditure because of increased operation of the SD at the PCC, which will reduce its lifetime and increase labour to restore normal operations. IEEE standard P1574 requires minimization of nuisance trips. Especially in weak grids with long feeder length which is protected by definite over current relays false tripping can occur [12, 13-17].

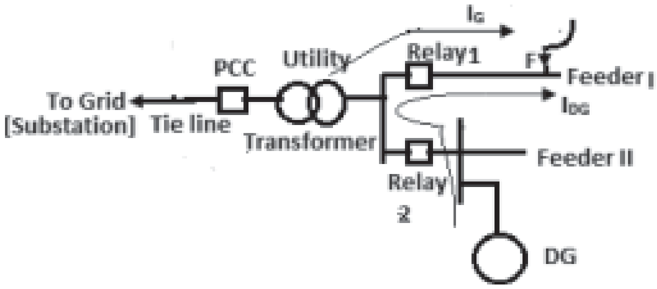

Fig.2 Nuisance separation

2.4 Blinding of Protection Issues

When DGs are contributed to the microgrid, the grid contribution to the total fault current will be reduced and thus never reaches the pick up current of the feeder relay. Both overcurrent relays and reclosers rely their operation on detecting the higher abnormal pick up current and so suffer malfunctioning i.e. blinding of operation (Tripping).

Thevenin equivalent across the fault point (F) of Fig 3 is shown in Fig 4. Z_{DG}, Z_G and Z_L are respectively the impedance of the DG, impedance of the grid and impedance of the feeder of length D.

$$r = \frac{d}{D}; \qquad I_G = \frac{Z_{DG}}{\left(Z_{DG} + rZ_L + Z_G\right)} I_F$$

$$I_{DG} = \frac{Z_G + rZ_L}{\left(Z_{DG} + rZ_L + Z_G\right)} I_F \qquad \text{... 1}$$

From grid (or Substation/relay location) bus, the DG and the 3-Φ fault position (F) at the feeder are respectively d and D distance away (Fig.3). Currents – I_F (fault current), I_G (grid current) and I_{DG} (DG current) - in the circuit are non-linear and dependent upon fault position (r), Z_L, Z_{DG} and Z_G. Z_{DG} is, again, dependent on the size of the DG and Z_G is high for weak grid. Due to the reduced grid contribution (I_G), in Eq (1), the impedance calculated by the distance relay, at the grid/substation bus, to the fault location will increase and causes protection under reach. With a relevant contribution by the DGs to the fault current, directly, affects the sensitivity and reliability of a protective system [17, 24].

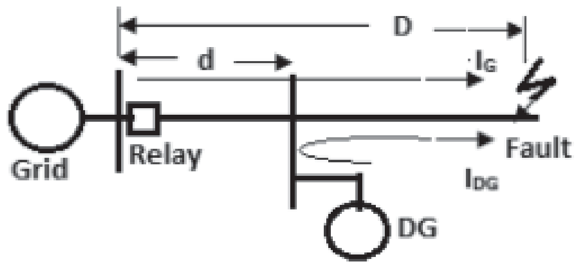

Fig.3 Sharing of currents by grid (I_G) and DG (I_{DG}) to the feeder fault

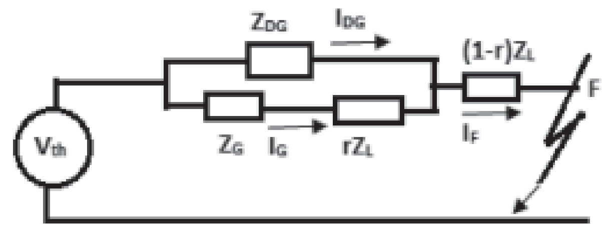

Fig.4 Thevenin equivalent circuit across the fault point (F)

2.5 Re-synchronisation Issues

Microgrid is normally operated in grid-connected mode. Whenever there are any disturbances/faults in the grid side, it is isolated from the grid and operates autonomously. After removal of this event microgrid is again connected to the grid. For every time reconnection of the islanded microgrid to the utility grid, synchronization is necessary. The microgrid must have the control scheme to bring all DERs in synchronization with grid based on the measurement of voltage on both sides of PCC. For microgrid with both directly-coupled DERs and EC-DERs, passive re-synchronization is done by the use of switched capacitor banks for voltage balancing. For a single DG use, either manual or automatic technique of synchronization is used, but for multiple DGs at various locations in the microgrid automatic technique should be integral to the microgrid design. The synchronization is done through the MGCC located at PCC and necessitates communication techniques. The grid requires to pick up the all previously disconnected loads and to stabilize the system. This process may require several seconds to several minutes, depending on the nature of the feeder and loads [12, 15-16].

2.6 Anti-islanding (Loss-of-Mains) Issues

Islanding refers to the condition when a portion of the grid becomes temporarily isolated from the main grid but remains energized by its own distributed generation resource(s). Islanding may be unintentional or intentional. Unintentional islanding, causing a potentially hazardous condition, occurs when a distributed generator fails to properly shut down during a grid disturbance. Unintentional islanding may cause some of the following issues: (1) Human safety issues since a portion of the system remains energized when it is not expected; (2) Loss of control over system frequency and voltage levels; (3) Insufficient grounding of the islanded network over DG interconnection; (4) Out of phase re-closure problems which may damage the equipment [17].

Whereas, due to reliability problem of the main grid, intentional islanding of microgrid may be desired that permits the microgrid to continue operating autonomously and provide uninterrupted service to local consumers during outages on the main grid. Also, this maintains uninterrupted revenue to the microgrid operator. The recently adopted IEEE standard 1547.4-2011 specifically addresses power systems that include intentional islanding. Utilities' concerns about unintentional islanding have been a major impediment to the widespread adoption of distributed generation. For the most part, these concerns have been addressed through anti-islanding features in grid-interactive inverters and the provisions included in standards such as Underwriters Laboratories (UL) 1741 and IEEE 1547. Interconnection protection, or anti-islanding, covers proper protection schemes to allow the distributed generation to run in parallel with the utility network and to avoid a local generator operating in islanding mode. In most cases the interconnection of the DG to the grid is closely monitored by the utility to impose the protection requirements and ensure that they are met. The interconnection protection can vary depending on the generator type, generator size, the point of generator interconnection to the grid, interconnection transformer configuration, etc. When any indication of islanding detection is obtained, it will be desirable to deactivate anti-islanding protection of DERs instantly by sending a trip blocking signal through MGCC using communication link. DG should be disconnected from the network in case of anomalies in voltage or frequency and when one or more phases are disconnected from the grid supply; Because of these issues, a DG unit should pass either one of the two anti-islanding standard tests, UL 1741 or IEEE 1547 before it can be installed. IEEE 929-1988 standard requires the disconnection of DG units once the microgrid is islanded. The Australian standard 4777.3 as well as IEEE 1547-2003 standard on the other hand requires all DGs to be shut down after a maximum delay of 2 s once islanding is detected. In order to achieve this, there must be a fast and reliable islanding detection method. There are various kinds of islanding detection methods in the literature – passive method, active method, hybrid method and communication-based method [18-21].

2.7 Islanded with Second Contingency Issues

If the microgrid is confined to a typical on-site distribution system, then MV side of the MV/LV transformer is usually protected by fuses. The fault current through the fuse varies with the mode of operations of the microgrid as well as with the position of the fault. In grid connected mode (Fig.5), the fault current (I_1) from utility, due to MV side fault at the utility transformer, becomes 20-50 times the maximum load current and it drops down to typically 10-20 times (I_2) for the LV side fault. Again, this MV side fault current (I, Fig.6) from DGs of the microgrid drops down to 5 times with isolated mode. These fuses have the extremely inverse current-time characteristics. So, for MV side fault the time of operation of these fuses in isolated mode are very slow compared to 0.1-0.2 seconds in grid-connected mode. Hence, when isolated from the utility due to contingency, if second contingency (Fig.6) happens at the MV side of the transformer the fault current from the DGs will jeopardize the coordination with protective devices of DGs. Replacing the fuses by MV circuit breaker and relays for overcome this problem is a costly proposition [8, 12, 15, 22-23].

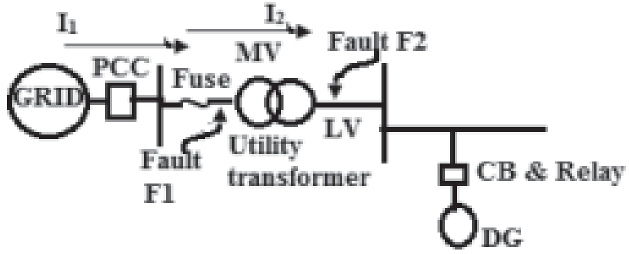

Fig.5 Grid-connected mode of operation ($I_1>I_2$)

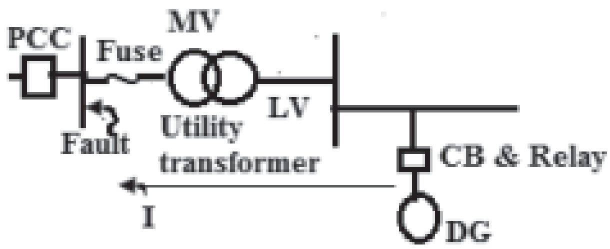

Fig.6 Isolated mode of operation ($I<I_2<I_1$)

2.8 Grid-connected (or, Fault Ride Through) Issues

When there is a fault at the upstream of the PCC (i.e. substation side), the microgrid shifts its operation from normal mode to isolated mode. During this process of change, the PCC senses the fault, first, and, thereafter, trips its breaker. According to IEEE 1547, the DERs/DGs should not stop operation before the switch at the PCC trips. So, these microsources must have the capability to carry the fault current during the period from PCC sensing the fault to clear it, known as the fault ride through (FRT) capability. There is a grid code in Australia, Europe and America that solar PV and wind generators should stay connected and contribute to the grid in case of severe grid voltage disturbance since the disconnection may further degrade voltage restoration during and after fault conditions. The grid codes in Australia [24] ascertain the wind turbine to withstand a 1.3 pu high voltage ride-through (HVRT) for about 60 ms when microgrid under transients. Low voltage occurrences are usually associated with the short circuit faults (symmetrical or asymmetrical) on the line between the microgrid and the main network. According to the international codes, a total fault clearance time of up to 150 ms is to be assured for the most onerous LVRT (low voltage ride-through) [12, 24, 25] .

2.9 Relay/Protective Setting Issues

Microgrid is a dynamic system and its network configuration changes. The status of the fault is also modified. The change of microgrid configuration happens due to many reasons like increase in local generation for export to grid, load-shedding in peak hours, bus-tie breaker operation, repair, seasonal load transfer etc to name a few. Under such changes typical single setting relays cannot protect the microgrid from faults. The relay must have adaptability to these changing situations. The relay settings should be re-calculated after each change in network topology or after installing each DG and calculation method needs to be easy. Again, the systems, where fuse and recloser are used, are lost coordination for DG connection or disconnection to the network - additionally, synchronization problems arise. The recloser settings need to be modified. When the relay settings are concerned for wind generators, short circuit response of doubly fed induction generator (DFIG) is quite different from synchronous generators [12, 15-16, 22, 27-29].

2.10 Inverter Issues

Many energy resources, like solar PV, microturbine, fuel cell etc. are connected to the microgrid with inverter interface having different constants as well as basic characteristics as per the design goals of particular manufacturer and/or application. Inverter fault current capability is less than twice the rated current of the inverter, if not specially designed for higher fault current. If there are significant numbers of EC-DERs in the microgrid, then change from grid-connected to autonomous operation may aggravate the concern of current-operated protection. The overcurrent protection technique will be functional if fault current magnitude could be raised to the desired level with proper placement and design of energy storage. Hence, faults within the microgrid need to be cleared with techniques that do not rely on high fault currents [15, 23, 30-31].

2.11 Grounding Issues

Choosing the appropriate grounding scheme is an important issue that involves many aspects of the power system, such as the reliability of the system, personal safety, transient overvoltage and insulation coordination of the system.The grounding issues of microgrid can strongly affect microgrid protection performance as well as protection coordination strategies. The adequate grounding of neutral and the installation frames of both MV/LV utility transformer as well as DR transformer are required for effective microgrid fault protection, insulation integrity and safety of personnel. Over voltage that is developed, is directly proportional to the magnitude of the fault current component discharged into the soil by the grounding network. Fault current distribution between the neutral and the ground and their magnitudes depend on the earthing system, the fault location and the operating mode of the microgrid (grid-connected or islanded). Transformer connection is most important issue to bring the X0/X1 ratio equal to or less than 3 - this value indicates the perfect grounding condition. Except grounded-wye/delta connection, transformer with delta/delta connection or delta-/wye connection or grounded- wye/grounded-wye connection can never be a ground source for the system. TN and TT (Fig.7) grounding schemes are widely applied for LVAC distribution networks. In both TT and TN systems with high-impedance grounding there is a difficulty to detect and locate faults and overvoltage can occur in the microgrid. In TN system with low-impedance grounding or solidly grounding or multiply solidly-grounding, fast fault clearing time is a great challenge in the microgrid protection; but in both TT and TN systems at an islanded operation mode of microgrids, fault current values are limited by inverter-based DGs, which cannot activate overcurrent protective devices. The TN-C grounding system (Fig.8) is not recommended for LVAC microgrids under consideration on safety requirements as the touch voltage may be unacceptable. [15, 23, 32-33].

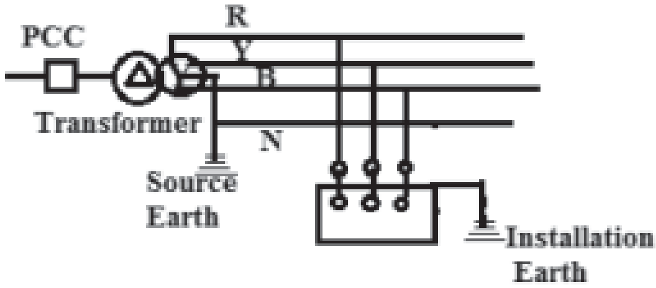

Fig.7 TT arthing system of microgrid

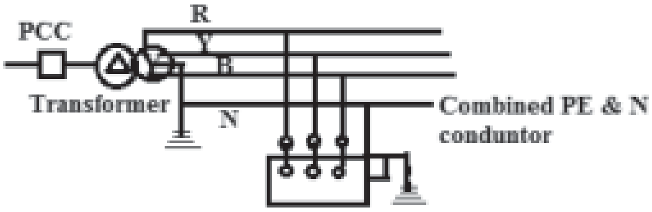

Fig.8 TN-C earthing system of microgrid

2.11 Load shedding Issues

If there is under frequency due to fault or equipment failure upstream to the PCC, the microgrid is forced to separate from the utility. Microgrid, designated for the area, is designed to supply autonomously the critical loads. For a microgrid, however, the nature of the technical problems depends on whether load is to be shed before or after separation. Under frequency relay is set to a tripped value to bring the load in balance with the available generation. The inertia constant of the microgrid is lower than that of the utility. When microgrid is separating due to deteriorating system frequency, there is a change of microgrid inertia constants after separation. A difficulty arises in advance shedding of load before reaching of mandatory trip frequency. It is the concern of the researchers how to shed load before separation [15, 21, 23].

2.13 Reclosure Issues

In a DG-recloser system (Fig. 9), due to presence of local DG the recloser current ($I_G < I_G + I_{DG}$ = fault current), which is the same as grid contribution (I_G), is reduced and there will be a problem of fault detection or delay in fault clearing as each recloser is equipped with dependent time-current characteristic. In Fig.10, the coordination between recloser

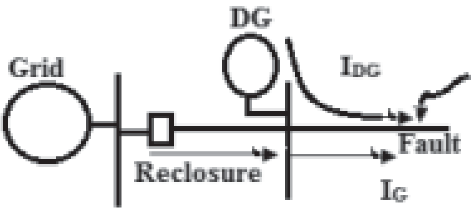

Fig.9 DG- reclosure system

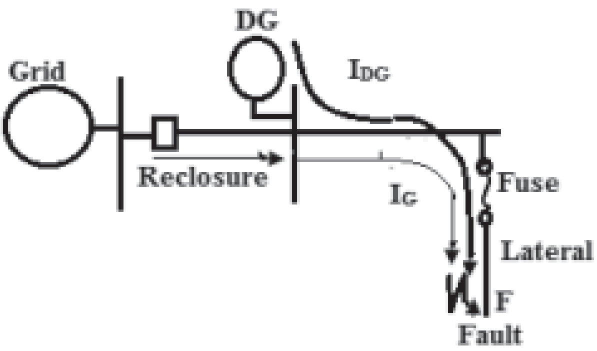

Fig.10 DG- fuse-reclosure coordination

and fuse is lost due to presence of local DG. With more penetration of local DGs there is a chance of unnecessary fuse blown out, instead of recloser, due to higher fuse current. Sometimes, temporary faults are cleared permanently and lead to unnecessary interruptions. Besides fault detection problems and lost of coordination, DG also causes unsynchronized reclosing - this can seriously damage the generator and causes high currents and voltage rise in neighbouring grids. The dead time of a recloser is referred to as the time between consecutive trip and closing operations and is usually in the range of hundreds of milliseconds up to seconds. During the dead time, though grid is isolated from the fault, but the arc is sustained by local DG, causing a temporary fault to a permanent and reliability of the microgrid is threatened [21-22].

2.12 Multi-point Islanding Issues

In many cases microgrid operates with multiple grid interconnection points. So complete isolation from grid is not happened. The part of the system works with grid reliability. The protection coordination becomes complicated as the number PCC increase. Cost-effective supervisory control system and fast communication infrastructures are the key features to form an integral part of synchronously operated multi-coupling-point microgrid. The authors of [34] has raised question to investigate the validation of whether the use of PMU with GPS and supervisory controllers with fast two-way communication infrastructures are feasible. The researchers are also concerned for stable operation with synchronism of multiple synchronous power islands under maximum load disturbances [9, 23, 34].

2.13 Communication Issues

In communication-based protection schemes, there is a central protection unit, which is an integral part of MGCC (Fig.1) and this central unit uses communication networks to interconnect devices and circuit breakers, measure and analyze the voltages and currents signals to determine the fault location and to send the trip signals to nearby circuit breakers. AC and DC microgrids, specially a meshed microgrid, must require communication based protection. Logical nodes, available in IEC61850 and IEC61850-7-420 communication standards, need to be developed to use as a new protective schemes and to monitor changes in the microgrid and to calculate the operating conditions at any given time. The IEC 61850 standard is missed standardization of sequential, combinational, rule base (or any other forms). The IEC 61850 only defines the unified information model for IEDs (Intelligent electronic devices). There is a shortage of function algorithms. To minimize the number of consumers as well as DGs affected by faults and disturbances, a high data rate communication and an adaptive multi-criteria algorithm are required. Increase data rate is done by multi input multi output (MIMO) technology. MIMO faces challenges of high energy consumption. Also, energy-efficiency of optical-wireless network system is still challenging. The communication systems are concerned with issues such as energy-efficiency, optimality of communication network, reliability and flexibility. The authors of pointed out the issues to be considered quality of service (QoS), strict delay or delay-tolerant manner of smart grid, and smart grid traffic volume, and link speeds. The requirement for continuous monitoring of the system variables and DG statuses for protection purposes raise the issue of huge load on the communication system [27,31, 35-38].

2.14 DC Microgrid Issues

A DC microgrid is a distribution system having DC loads, energy storage elements, and DGs as the main constituents. The protection scheme of DC microgrids poses many challenges, such as accurate fault detection and location, proper grounding schemes, proper design of DC circuit breakers, fast isolation of faulted areas and self-reconfiguration capabilities – the challenges are more critical due to the lack of standards and guidelines. The protection devices commercially available for DC systems are fuses, molded-case circuit breakers (MCCB), low-voltage CBs, and isolated-case CBs. The DCCBs (DC circuit breakers) are more expensive than their ac counterparts, especially in the level of medium voltage – therefore system would not be cost effective to use individual DCCBs for all the feeders of a microgrid. Also, due to low values of both the dc line reactance and line length of microgrid feeder, there is a fast rise of fault current and error in selectivity of fault location. Again, VSCs (voltage source converter) are vulnerable against faults on their dc side and the slow acting electromechanical circuit breakers (CBs) will face challenge [32, 38-41].

3. Conclusion

In the deregulated regime the microgrid is gaining tremendous popularity among power supply providers. Realization of future smart LV/MV microgrids, which is capable of both grid-connected as well as islanded modes of operations, requires that like all other technical issues, protection issues are to be solved. A selective, sensitive, reliable and cost-effective protection technique should be able to detect and to protect the microgrid against different types of faults – thus being approached towards smart microgrid. The aim of the present paper is to comprehensively review the existing research literatures in the context of problematic issues a protection scheme often faces. Issues are the foremost important to step into the solution. So, issues have been categorized into important heads for better perception and tackling. It can be concluded that more efforts are still needed to overcome the limitations of protection schemes and there are essentially more scope for work on high-speed communication technology, cyber security, FPGA (field programmable gate array) platform as well as for development of standards/protocol for safe and reliable operation of future microgrids.

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