

Review Article

Solar Energy Integration and Potential Challenges in Distribution Network: A Comprehensive Review

Abstract: Solar photovoltaic (PV) power generation has emerged as a viable option among all other available energy options. The solar energy is unpredictable and variable in nature. Moreover, the distribution grids are not designed to accommodate high penetration of these sources. Therefore, such penetration poses the technical challenge like reverse power flow, voltage variation, harmonic distortion, poor power quality, malfunctioning of protective devices, overloading and underloading of feeders. Such challenges need to be addressed when solar PVs are added to the conventional grid system. The grid must have capacity to withstand and simultaneously take the corrective action against these occurrences. Therefore, there is a serious need to study these issues and further to develop control strategies to eliminate them. This paper presents various issues and challenges associated with high level PV integration in the distribution network and discussed the remedies to obtain the clean power supply.

Key words: Photovoltaic (PV), Overvoltage, Harmonics, Faults and Protection, Distribution Network.

1. INTRODUCTION

Any power system face various challenges each as dynamically changing power demand and supply scenario, old infrastructure, compound interconnected networks, consumers demand, need to lower the carbon emission, new type of loads, and integration of large number of renewable generating sources. The increasing energy demand at reduced cost with more reliable power supply are motivating the existing power systems to use solar energy sources as an alternative for the future energy. The advantages of solar energy as a fuel are; free and inexhaustible, environmental friendly, silent operation and economically viable. It has a potential to supply a significant rising demand of the energy in a sustainable and renewable manner [1].

Moreover, these are installed near the load centers therefore provides additional advantages such as reduction in transmission lines congestion, reduction in transmission and distribution losses, helps in maintaining the required voltage profile, improves system stability and reliability [2].

To extract the bulk power from solar PV plants into the grid, the unpredictable energy from this source is the cause of main concern. Effective output of solar PV plants varies with the availability of sun in the sky. Due to the seasonal variation the random output can have adverse impact and presents a lot of challenges in the distribution system. Moreover, the distribution systems are traditionally designed to operate in radial fashion which carries power in one direction, the integration of solar PV plants changes this scenario and introduces bidirectional power flows in the system. With the increasing level of penetration, solar PV generators present various technical challenges on grid operation, which can eventually limit further penetration of these plants [3-4]. These issues and operating challenges need to be explored to ascertain the befitting solution for mitigation in order to accomplish the distribution grid goals.

The remaining paper is organized as follows. Section 2 briefly describes the PV integration technique. Section 3 presents potential challenges associated with PV integration to distribution system. Section 4 concludes the paper

2. PV INTEGRATION TECHNIQUE

PVs are installed near the load centres due to the additional advantages such as reduction in transmission lines congestion, reduction in transmission & distribution losses, helps in maintaining the required voltage profile, improves system stability and reliability. The solar PV integration to the distribution network is done according to the schematic as shown in Fig. 1, where the LV feeder usually feeds the load of varying nature. PV generates DC power which is then converted to AC using converter and then it is connected to step up transformer to achieve the required voltage level.

3 POTENTIAL CHALLENGES ASSOCIATED WITH PV INTEGRATION TO DISTRIBUTION SYSTEM

The renewable energy sources are unpredictable and variable in nature. Moreover the distribution grid is not designed to accommodate high penetration of these sources. Therefore such penetration poses the technical challenge like power quality, reverse power flow, voltage variations and the other impacts on the grid which requires the immediate concern of the utilities [5-6]. The current vs. voltage ($I_{pv}-V_{pv}$) and power vs. voltage ($P_{pv}-V_{pv}$) curves, under

different operating conditions are used to represent the electrical characteristic of PV cell. The specifications of the module are given in Table 1[7].

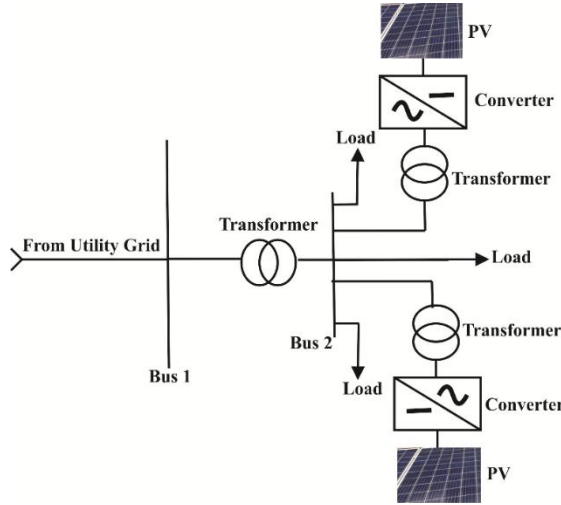


Fig.1 Grid-tied Solar PV System

Table 1: Specifications & Parameters of Solar PV system

S. No.	Parameter	Rating / Specification
1	Optimum Operating Voltage (V_m)	35.2 V
2	Optimum Operating Current (I_m)	7.95 A
3	Open - Circuit Voltage (V_{oc})	44.8 V
4	Short - Circuit Current (I_{sc})	8.33 A
5	Maximum Power at STC (P_{max})	280 Wp
6	Module Efficiency	14.4%
7	Operating Temperature	-40 °C to +85 °C
8	Maximum System Voltage	1000 V DC

The electrical characteristics of the PV cell at different levels of the irradiance ranges from 200 W/m^2 to 1000 W/m^2 and constant temperature of 25 °C is presented in Figs. 2(a) and 2 (b). It is clear from figures that the variation in irradiance directly changes the short-circuit current and output power of the cell. However, the open-circuit voltage of cell is negligibly affected. Fig. 2 (c) and 2 (d) shows that the change in temperature at constant irradiance has a profound effect on open-circuit voltage and output power of the cell but negligible effect on short-circuit current. Fig. 3(a) shows the variation in open circuit voltage with irradiance, while Fig. 3(b) shows the

variation in MPP current with irradiance. These two figures precisely show how the irradiance affects the performance of PV cell.

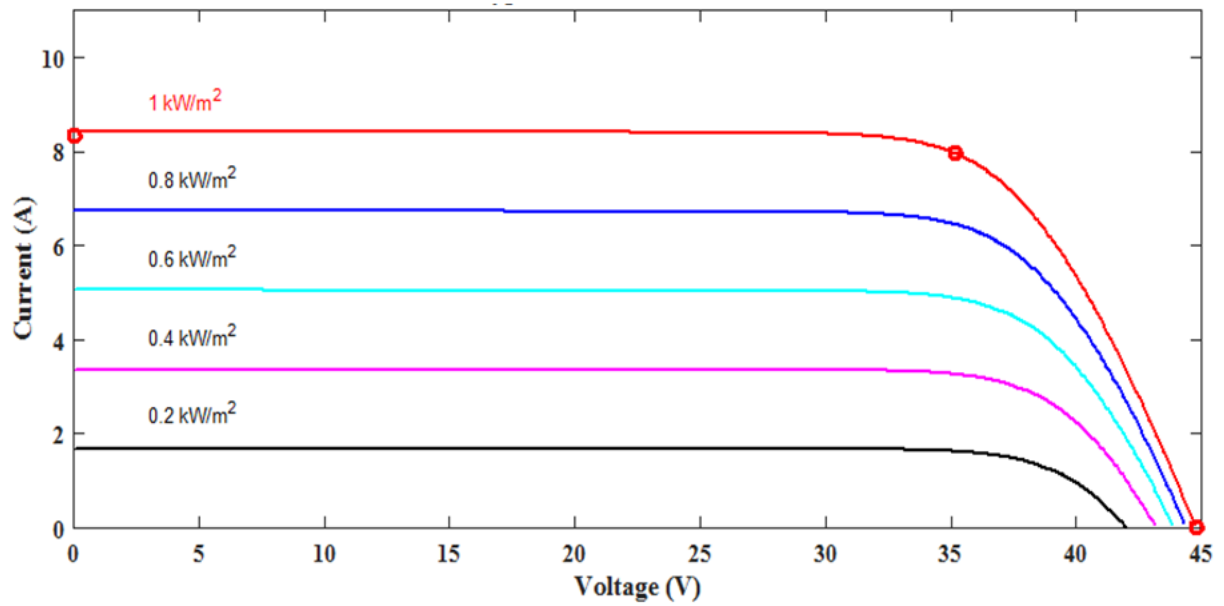


Fig. 2(a) Dependence of current/voltage characteristics on irradiance

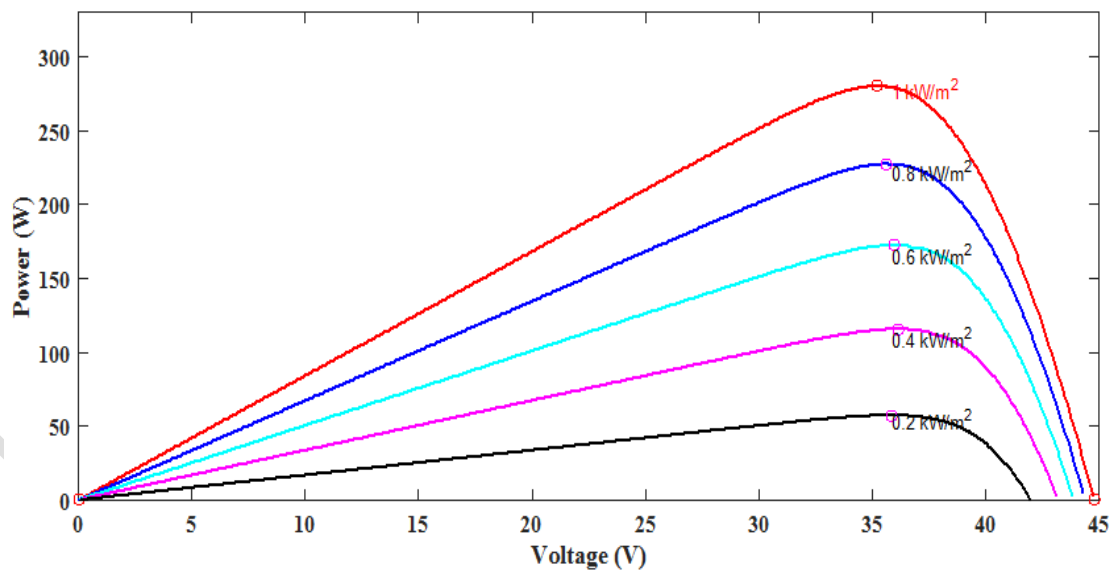


Fig. 2(b) Dependence of power/voltage characteristics on irradiance

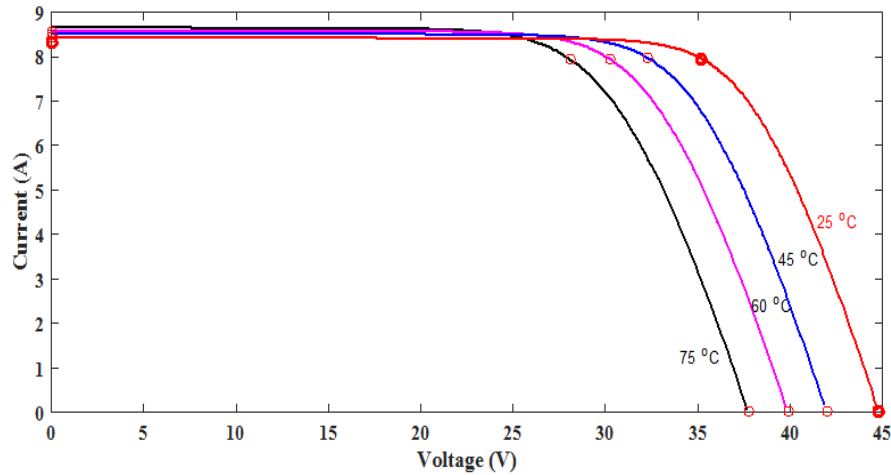


Fig. 2(c) Dependence of current/voltage characteristics on temperature

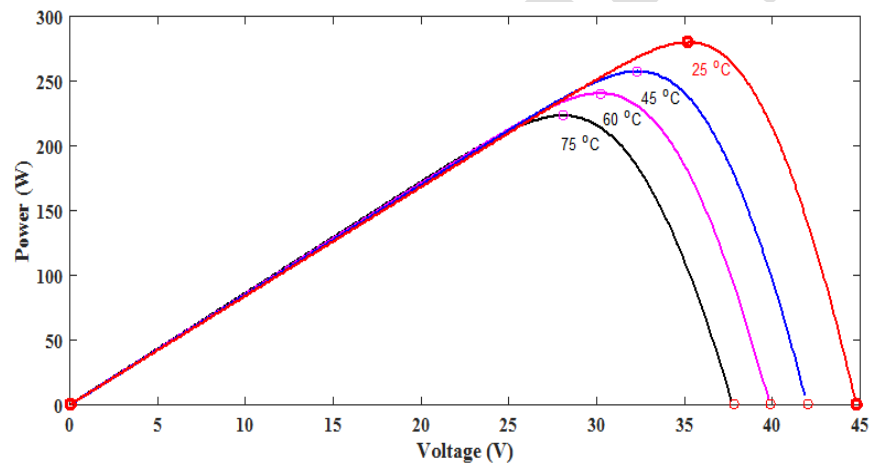


Fig. 2(d) Dependence of power/voltage characteristics on temperature

The increasing energy demand at reduced cost and higher reliability requirement are motivating the existing power systems towards using solar energy sources as an alternative for the future energy. The advantages of solar energy as a fuel are; free and inexhaustible, environmental friendly, silent operation and economically viable. It has a potential to supply a significant rising demand of the energy in a sustainable and renewable manner [1]. Moreover, these are installed near the load centers therefore provides additional advantages such as reduction in transmission lines congestion, reduction in transmission and distribution losses, helps in maintaining the required voltage profile, improves system stability and reliability [2].

The solar energy is unpredictable and variable in nature. Moreover, the distribution grids are not designed to accommodate high penetration of these sources. Therefore, such penetration poses the technical challenge like reverse power flow, voltage variation, harmonic distortion, poor power quality, malfunctioning of protective devices, overloading and underloading of feeders [2, 8]. Such challenges need to be addressed when solar PVs are added to the conventional grid system. The grid must have capacity to withstand and simultaneously take the corrective action against these occurrences in order to achieve the smart grid objectives of clean and uninterrupted power supply.

Therefore, there is a serious need to study these issues and further to develop control strategies to eliminate them [9]. Various issues and challenges associated with high level solar PV integration and remedial solution to operate the interfacing inverters at lagging power factor and turning off the capacitor banks when solar PV system delivers the optimum output are provided in references [10-12]. More rigorous issues that need to be addressed are discussed in subsequent sections.

3.1 Voltage Rise, Regulation and Unbalance

Change in weather conditions and seasonal variation causes uneven solar irradiation, such condition creates voltage fluctuations in the output of PV systems. Performance of PV modules also depends on solar irradiance, cell temperature, crystalline structure and the load resistance. Moreover, cloudy or low brightness situations produce voltage and power fluctuations, which affect the network operational performance drastically.

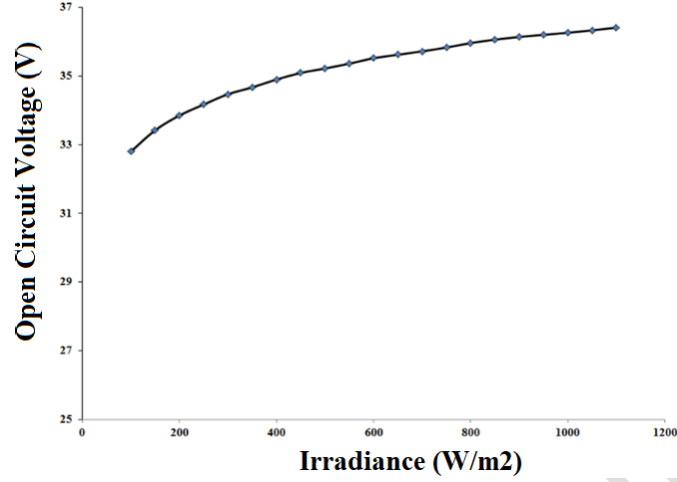


Fig. 3(a) Variation of voltage with irradiance

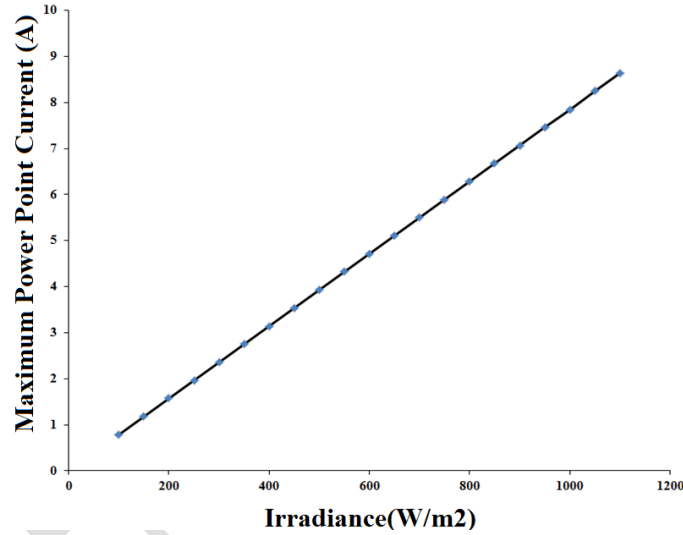


Fig. 3(b) Variation of current with irradiance

The effect of moving cloud results the variations in PV system output have been studied in references [13-14]. Literature also reports the slow and fast voltage regulation due to passage of cloud near PV arrays. These investigations emphasized on the capacity of utility generation to respond to the variations in PV system output. Impact of abrupt passage of cloud pool over the PV module has been reported in references [15-18]. It has also been reported that such condition affects the output of solar PV at the point of common coupling. Further due to change in environmental condition entire covering of PV array is also likely, which along with unexpected

rise in load demand affects the system performance severely. The utilities must be equipped to overcome such situation by supplying reserved energy to the system [15-18]. In [19-20] comprehensive three-phase power system models are utilized to study the PV impacts in terms of circuit voltage rise, voltage unbalance, and reverse power flow.

The effect of cloud transients on the centrally located PV system was examined and found that transients limit the maximum level of solar PV penetration up to 5% only [21].

The passage of cloud over the PV array affects the voltage level and produces voltage fluctuation at the point of common coupling (PCC) [22].

The incidents of voltage variations in the PV output due to variation in season from variably cloudy to sunny day at a large PV installation is observed and reported that due to change in irradiance very short duration voltage variation occurs at the PCC [23].

Voltage variation during the summer and winter at different loading conditions is a common phenomenon. The addition of PV increases the current level in cables, which is one of the limiting factors in the process of integration [24].

The event of transient voltages due to passage of cloud over the solar PV plant causes the short duration overvoltage and voltage fluctuation in the lines that poses extra duty on regulator operations [25].

The reasons of voltage variation in randomly distributed solar PV farm as the change in irradiance and passing of clouds has been quantified in [26]

The authors in [27] reported experimental results of a test performed on interfacing inverters from different company. The paper reports the appearance of transient overvoltage in the grid caused by these inverters. It reports phase to neutral transient overvoltage up to 3.5 per-units, which resulted in damage of sensitive equipment and other electronic meters for most of the inverters.

The voltage regulation problem due to grid connected PV systems under peak and light load conditions in a residential electricity network in another issue reported in [28]. In one more study on LV distribution network with varying levels of solar PV penetration. It is observed a change in network voltage occurs as the level of integration rises [29]

It is observed that voltage drop and power loss reduces when the solar PVs are installed near the load centers. However, with the large penetration levels the impact on the voltage profile becomes significant especially during high irradiation and small load situations. The increased

feeder voltage restricts the maximum PV penetration to the system in order to maintain the required voltage profile [30].

The transient over voltage can occurs in the system due to the fault which involves ground or due to ineffective grounding with PV integrated distribution system [31].

Further, the over and under voltage due to the excess installation of PV at the customer installations. This voltage variation caused the tripping of the protective devices [32].

A study to observe the voltage variation issues in a domestic area with varying level of solar PV penetration has also been performed. The voltage deviation rate in the domestic region depends on certain aspects such as impedance of the transformer, length and impedance of distribution feeder, and quantum of integration. The overvoltage problems can be minimized by adopting the following measures such as curtailment of solar PV power under low load conditions, storage of excess energy to meet the peak demand, inverters reactive power control, controlling the transformer and feeder impedance through the on load tap changers and line regulators [33].

It is observed that overvoltage problem in large PV installations is more critical. The overvoltage can be mitigated up to some extent by controlling the reactive power control [34].

The very high PV penetration level (e.g. 300%) may produce negative impacts in the system [35].

Considering the different locations of solar PVs installation such as at the beginning of feeder, mid of feeder, end of feeder, and at random points the steady state voltage and current limit violation can be observed. However, if a single PV system is connected at large distant feeder the tolerance of system reduces [36].

Under variable load conditions the output of the PV inverters changes in stochastic manner, which produces the output voltage of variable magnitude and frequency and creates flicker [37-39]. This may happens due to frequent change of transformer tapping [40]. The undesirable voltage fluctuation may lead to undue operation of load tap changer which reduces the life expectancy of load tap changer [41] [42]. Such situation also affects the performance of flexible AC transmission system (FACTS) devices [43]. Small size PV units connected to grid through single phase inverters produces considerable voltage unbalance on the other hand large centralized PV units connected to medium voltage (MV) network do not produces voltage unbalance. Occurrence of voltage unbalance depends on types of inverters and the voltage level at which their output is connected [44-47].

The theoretical technique to determine the solar PV penetration level is by determining an index expression considering the power losses and voltage variation. This expression is then modified allowing the time varying load models and stochastic solar PV power generation [48].

The solution such as transformer tap changing, PV power factor control and generation curtailment to improve the voltage profile is proposed through the unbalanced three phase power flow analysis to assess the voltage profile of PV integrated distribution network [49]. The optimal operation of the three phase inverters is required to reduce the voltage imbalance. Furthermore, the voltage imbalance can be reduced by the unbalanced power can be transferred from highly loaded phase to lightly loaded phase by adopting efficient inverter control mechanism [50]

A compensation scheme for the transitory induced overvoltage in grid-tied PV systems using the inverter voltage regulation through controller is suggested [51]. Some mitigation measures like storage and generation shedding to tackle the voltage rise problem of the system to fully utilize the renewable power generation are suggested [52].

In some situations, the rise in voltage occurs in distribution networks due to uncontrolled active power injection. The control strategy maintains a balance between active and reactive power dispatch such that any variation in voltage is automatically corrected. The regulation scheme can be designed in such a way that distributed generation (DG) is considered as a power dispatcher entity by distribution system operator which keeps the network voltage to the required level [53]. The occurrence of voltage imbalance due to single phase roof top solar PV installations in a domestic supply network is also observed. Higher voltage imbalance is observed at feeder end than at starting. The voltage imbalance mitigation technique and its effectiveness are checked using stochastic evaluation approach [54].

A study on two distribution feeders having same voltage level and maximum loading conditions is performed by adding different level of PVs considering the hoisting capacity of the feeders. The response of each feeder is distinctive in terms of voltage profile even though the penetration level is same, this may be due to operating power factor of the inverter, capacity of solar PV and location characteristics [55].

In [56] the potential impact of distributed PV generation on a low voltage (LV) network in New Zealand has been investigated, possible maximum limits of solar PV penetration and measures to

alleviate overvoltage problems are reported. Results show that overvoltage problems can be expected in future, particularly in urban areas.

This can be summarized that the output of solar PV integrated system changes due to change in atmospheric conditions and system disturbances. The voltage and power output of modules fluctuates with change in climate conditions, variation in atmospheric temperature, uneven solar insolation and cloud transients. The passage of cloud near solar array causes slow and fast change in output voltage. The simultaneous change in load demand and atmospheric conditions affects the system performance severely. Under variable load conditions solar PV inverters produces the output voltage of variable magnitude and frequency and creates flicker.

The output voltage of solar PV system at the PCC also fluctuates due to occurrence of ground fault, which results in protective devices tripping and reduces the reliability of the system. Solar PVs are installed near the load centers to reduce the voltage drop and power loss. However, with the large penetration levels the impact on the voltage profile becomes significant and reverse power flow can occur especially during high irradiation and small load situations.

Under such disturbing conditions the utilities are equipped with on load tap changers and line regulators to maintain the flat voltage profile but their optimal and synchronized operation is a difficult task. Therefore, a strategy is required to maintain the synchronized and optimal operation of controlling equipment to cater the need of smart distribution grid stockholders.

3. 2 Harmonics and Power Quality

The problem of power quality in LV connected solar PV arises mainly due to current and voltage imbalance [57]. Harmonic distortion is one of the growing power quality problems that debase the performance of power system. One of the causes of harmonic distortion in LV grid is increase of power converters and nonlinear loads. Transformer and rotating machines due to their inherent nonlinearities also create harmonic distortions [58] Various standards that address the requirements for the quality of the electric power supply must be carefully analyzed [59]. Solar PV system might introduce harmonics in the distribution network [60-61].

The harmonics are created during conversion of DC to AC power by the interfacing inverters [62].

The harmonic order and its magnitude will depend on the power inverter technology, modulation technique, method of commutation and the existence of high or low frequency coupling transformer and interconnection configuration [63-66] Large quantity of harmonics are produced

by thyristor based inverters but modern insulated gate bi-polar transistor (IGBT) based inverters employ pulse width modulation (PWM) technology and therefore, able to provide clean output that meets the IEEE/IEC requirements for harmonic standards [67].

Number of solar PV units connected to grid system and the interaction between grid components and PV units further intensify the harmonic distortion. The effect of PV interfacing inverters on the quality of power is studied in [68]. The experimental result indicates that the value of total current harmonic distortion depend on the output power of the inverter. This dependence decreases proportionally with reduced power converter rating. Figs. 4(a) to 4(f) presents the converter generated harmonics and their spectrum at bus 2 at different irradiance levels. It is clear that variation in irradiance affects the converter generated harmonics.

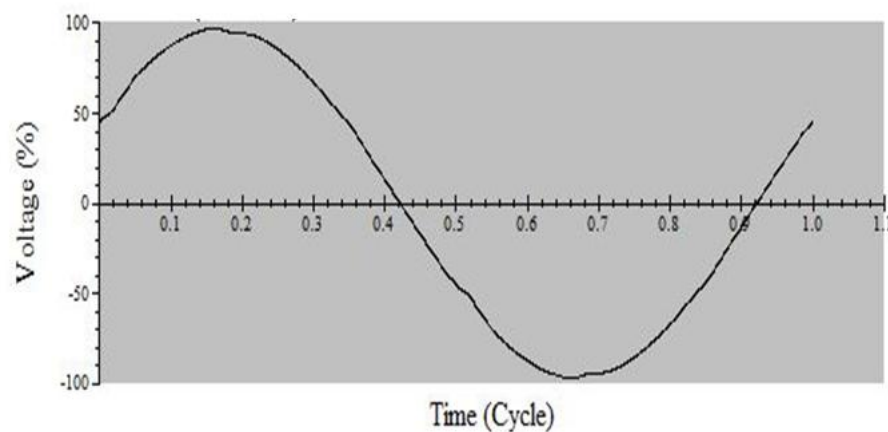


Fig. 4(a) Converter Generated Voltage Harmonics at bus 2 at irradiance 1000 W/m^2

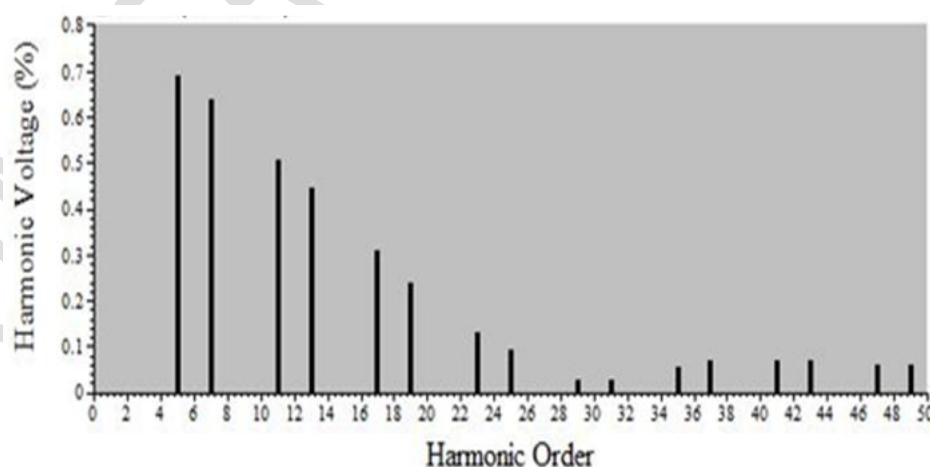


Fig. 4(b) Spectrum of Harmonic voltage at bus 2 at irradiance 1000 W/m^2

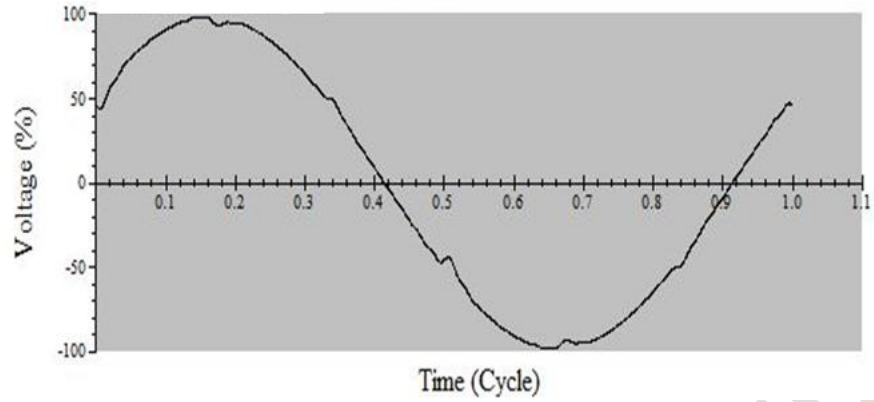


Fig. 4(c) Converter Generated Voltage Harmonics at bus 2 at irradiance 800 W/m^2

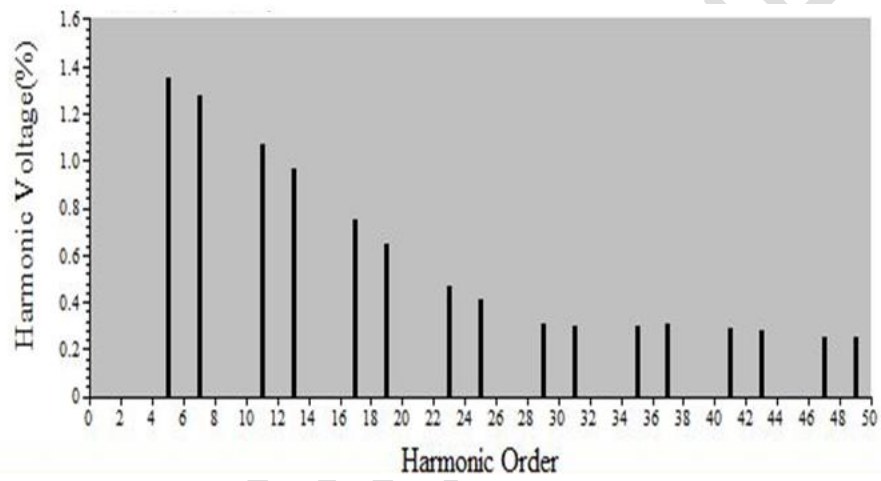


Fig. 4(d) Spectrum of Harmonic voltage at bus 2 at irradiance 800 W/m^2

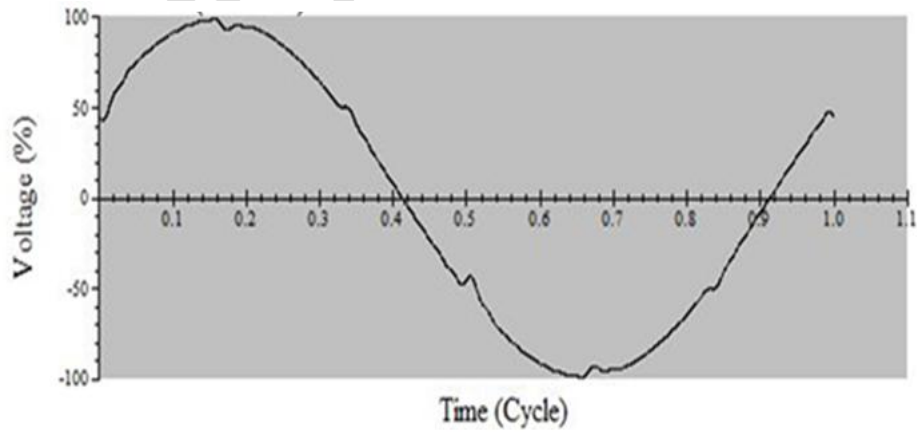


Fig. 4(e) Converter Generated Voltage Harmonics at bus 2 at irradiance 600 W/m^2

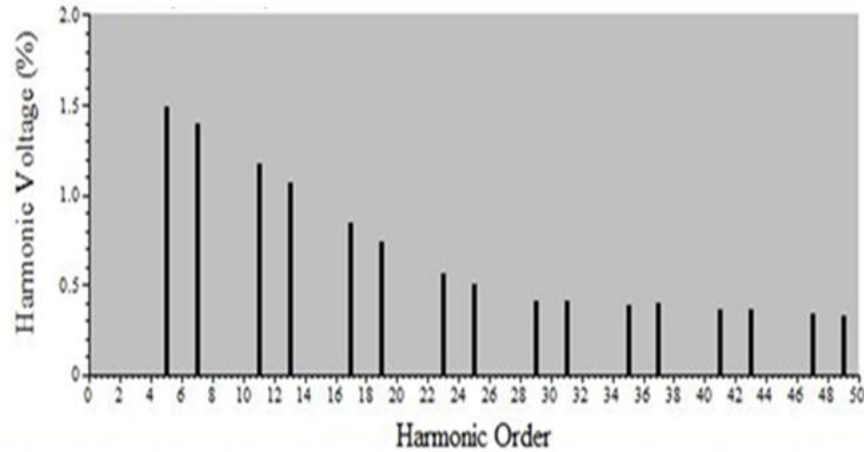


Fig. 4(f) Spectrum of Harmonic voltage at bus 2 at irradiance 600 W/m²

In addition, the level of harmonics also depends on the location of solar PV in a power system. The harmonic distortions produced by high voltage solar PV will be less than the harmonic distortion produced by LV solar PV [69]. Harmonic distortion shortens lifetime of electronic equipment creates excessive power loss, abnormal temperature rise and requires de-rating of the load. In addition harmonic results the overheating of transformer, overheating of neutral conductor and malfunction of protective devices, which jeopardize the stability and reliability of the system. Therefore, harmonic alleviation strategies for PV penetrated power systems must be measured, analyzed, and identified [65, 70-72]

The harmful effects of current and voltage harmonics on the performance of protection system was observed. It is found that harmonic distortions activate the false tripping of overcurrent and under frequency relays and affect the reliability of the system. However, the instantaneous operation of overcurrent relays is not much affected [73].

The electronic relays are not exception. It is reported that voltage harmonics may cause delayed operation of the relay. Excess harmonic distortions may result in complete failure of the protection system [74]. It is observed that directional distance relay also operate in a wrong fault location [75].

It is observed a single frequency harmonics alters the steady state performance of the protective relays and changes the relay operation [76].

The PV system connected to the distribution grid through a PWM inverter causes the malfunction of harmonic-sensitive equipment due to excessive injection of harmonic current in the system [77]

The permissible DG resources, which can be connected on a distribution feeder before the harmonic limits are exceeded is one important study [78].

Interfacing power inverters produce harmonic distortions and increases total harmonic distortion (THD) at the point of common coupling (PCC). However, the harmonic generation by an individual PV inverter satisfies the power quality standards. The inverter topology has a profound effect on harmonic generation and if the topology is not appropriately selected then the harmonic resonance may occurrence between inverters and network components [79-80].

The limit of voltage harmonic distortion depends on the stiffness of the network with low equivalent series impedance. High pulse power electronic inverter produces current harmonics and usually appears at high orders with small magnitudes. Such high order current harmonics may trigger resonance in the system at high frequencies [81-82].

The power quality problems due to distributed inverters and associated components. The deterioration in power quality occurs due to processing of power between the inverters and distribution network. The interaction between system capacitance and large number of inverters can create parallel and series resonance phenomenon [83]

The harmonics problem creates the negative impact on distribution system and the possibility of disruption to other customers from multiple grid connected inverters. Valuable approach for the inverter design and control issues was presented in order to improve the power quality [84].

Different solar radiation conditions and different generation scenarios also can also create harmonics. Measured data of temperature and global solar radiation has been used in the analysis and a comparison is made between simulation and measurement results [85]. The PV system injects a highly distorted current in distribution network during low solar irradiance. This is due to unnecessary high frequency switching of the PV inverter. Also, sometimes these PV inverters may be disconnected and connected unenviably from the grid. The current distortions depend strongly on the solar radiations. It was observed that the harmonic currents differ much under different generation conditions from summer to winter. In general the current distortion is high for low generation conditions and low for peak generation conditions. In modern PV inverters, the harmonics are in compliance to the standards under rated test conditions. Nonetheless, these PV inverters are negatively interacting in the real network [86]. The current harmonic emissions usually depend on the type of inverter, filters, and control strategy etc. In addition, if the

distribution network has highly nonlinear loads combined with PV inverters can induce undesirable harmonic components [87].

The generation of current harmonic by solar PV inverters and subsequently their interaction with residential nonlinear loads is also observed. Such interaction excites the harmonic resonance in the network [88].

The impact of harmonics on the performance of overcurrent relays is also observed that the relay operating time reduces considerably due to harmonics. Moreover, the relay performs differently with variation in current distortion [89-90].

The generation of harmonics due to asymmetrical solar radiation under several weather conditions restricts the acceptable penetration level [91]. In MV network due large penetration of solar PV, Harmonic resonance problem at the interconnection point of the grid is reported in [92]. Harmonic resonance in grid current and/or voltage occurs due to interaction between grid components and inverter output impedance at certain frequencies [93]. The effect of harmonic resonance results the tripping of sensitive equipment.

Distortion in Current waveform due to grid-tied PV inverters is much more serious than voltage waveform. The dominant causes for high THD are identified as low load operation of inverter, which rises from low solar radiation [94-95]

Power quality problem specifically the resonance and harmonics issue in a residential locality are also observed due to PV integration. The occurrence of resonance in LV distribution network due to harmonic interaction between DG and nonlinear loads is unavoidable [96]. Harmonics associated with flicker and voltage unbalance is also one serious issue in large solar PV installation connected to LV or MV networks [97]

The harmonic interaction between the grid and interfacing inverters can cause harmonic resonance. The resonance occurs due to grid impedance variation. The impedance constraint may be one of the constraint for inverter design in order to limit the harmonic distortions in the network [98].

Harmonic current generation is also seen between light emitting diode (LED) lamps and a PV panel. The operating conditions changes the level of harmonic emission from PV panels. Harmonic emission will be more with the reduction in output power [99] At low generation and low irradiance levels the PV system has high current harmonics with respect to fundamental current [100-102].

The DG integration level can be enhanced using the optimization algorithm (e.g PSO) to get the optimal system parameters [103-104]. In addition to harmonics the grid connected PV plants provide the path for the flow of electromagnetic interference (EMI) current [105]. Specific guidelines are required to get the reliable operation of the plant from an electromagnetic compatibility (EMC) point of view [105].

References [106-107] analyzed the existence of strong electromagnetic interference current at radio frequencies on the AC and DC lines due to the high frequency switching of inverters and standardized the EMC level of solar PV system.

This can be summarized that the harmonic distortion is one of the major power quality problems that degrade the power network performance. The inherent nonlinearities present in electrical power equipment and connected loads generate lot of harmonics in the network. However, integration of solar PV increases unexpected harmonics in the distribution network. The interfacing inverters technology and their locations are the main factors responsible for harmonics generation. These harmonics create variety of problems and may even lead to harmonic resonance which endangers the stability and reliability of the system. Therefore, a proper harmonic analysis and mitigation strategy is required to provide the clean power to modern electricity consumers.

3.3 Faults and System Protection

In conventional radial power delivery system, power flow is unidirectional. However, with the addition of renewable energy sources the direction of power flow changes. The bidirectional power flow causes inadvertent operation of the protective relays and a direct threat to the reliability of system. Such situation poses extra duty on protection system to maintain the continuity of supply. The protection issues that arise at the time of integration are: reverse power flow, fault current capacity, malfunctioning of protection relays, reduced reach of distance relays, unintentional tripping, auto re-closing, anti-Islanding, selectivity and grounding. The protection devices should have synchronized control in order to address these issues. The power flows is bidirectional between PV inverters and grid, any event of large power quality disturbance may force the protection system to disconnect the PV array or to shut down the inverters [108] The fault current contribution of inverter interfaced DG is usually low due to the non-overload characteristics of semiconductor switches and mainly determined by their thermal limit [108-109] The inverter based DGs employs their own internal protection against

overcurrent for the safety of semiconductor switches. This current is in the range of two to three times the rated load current. If the fault current is less than its setting, inverter internal protection will not detect it [110]. Therefore, the inverter based DG affect network protection in different way when an electrical fault occurs in comparison to machines based DG [111-113]. Moreover, the small capacity DG cannot supply the fault current continuously due to their poor inertia unlike the conventional rotating machine generators [114]. The study of fault current characteristics of inverter based DG requires a broad review of various protection design aspects. An increase in fault current with DG as compared to no DG scenario has been reported [115]. In case of interfacing inverters the fault current contribution depends on the maximum current level and duration for which the current limiter is set to respond. The fault contribution of inverters depends on their capacity. For small size inverters it is less than a cycle while for large size inverters it can be much longer. Moreover, a single small inverter contribute less fault current but in case of many small units, or few large units, the short circuits levels can cross the level sufficient to create miss-coordination between protective devices, like fuses or relays.

The PV systems which are connected to other sources of energy such as batteries, inverters, standby generators, and the utility grid, causes occurrence of unexpected ground faults due to flow of leakage current through stray inductance, capacitance and resistance which requires a proper ground fault protection scheme [116].

The contribution of fault current from the network is always higher than the contribution of fault current from the DG [117-118].

The DG does not affect the rating of the fuse-based protection. Therefore, no major replacement in the protective devices such as fuses is required [119]. The fault current from the DG may blind the overcurrent protection meaning that circuit current fed by a inverter can decrease the current seen by the feeder relay or fuse, preventing or retarding correct operation. Moreover, in a weak systems, during a high resistive fault, inverter-connected DG although, change the grid contribution to the fault current. The influence of PV inverter to faults depends on some factors such as the generating size of the PV, the distance of the PV from the fault location. This could affect the reliability and safety of the distribution system [120]. In the case of one small DG embedded in the system, it will have little effect on the increase of the level of short circuit currents. On the other hand, if many small units or a few large units are installed in the system, they can alter the short circuit levels sufficient to cause fuse-breaker miss-coordination. This

could affect the reliability and safety of the distribution system. In [121] the effects of inverter-based induction and synchronous DGs on the secondary network's voltage profiles are investigated and the possibility of over and under voltage are explored by using probabilistic DG power distribution. It is also mentioned that with DG penetration in the network there is a chance of network protector tripping. Indeed, incidents such as cascaded network protector trips, transformer overloads, and reclose issues are very likely in the presence of DG due to reverse power flow. The fault analysis method has been proposed in some literature with inverter based DGs. The conventional fault analysis method has been extended so that the DGs can be included in the analysis [122]. The fast response time of inverter based DGs make it necessary to consider their fault current contributions during the subtransient period as well as transient period. A method has been developed to capture the inverter behavior during a fault period. The method has been implemented on the prototype feeder to estimate fault currents under both balanced and unbalanced fault conditions.

Furthermore, that DG affect the operation and coordination of the distribution network protection. The fault current from the DG units that are coupled to the network with a power electronic converter is different from that of conventional DG units with an electrical machine directly coupled to the network. However, proper controlling of converter based DG units can minimize the negative influence on the distribution network protection [123].

The radial structure distribution systems would be changed to weakly meshed structure in the future with the integration of DG. Therefore, a short-circuit fault-analysis method for such unbalanced weakly meshed distribution systems has also been proposed in [124]. Modern inverter design has extensively improved protection scheme. Protective relaying function has been incorporated in their control circuitry and any deviation outside the limits of voltage and frequency will cause the inverter to shut down and disconnect from the utility line within a few cycles. Anti-islanding protection is also implemented in present grid-connected inverters, it prevents the inverter from continuing to work when the grid is not energized [125-126]. Reference [127] presents the sensitivity of the PV inverter due to power quality disturbance, malfunctioning of protection devices and spurious tripping of the inverters due to such events, which has the negative impact on the performance of system. A severe power quality problem like harmonic resonance can also trip protection devices and cause damage to sensitive equipment [92, 128]. An optimal solution for the mal-function problem of protective gears using

the symmetrical components of fault analysis is presented in [129]. The fault contribution of a grid-connected PV system in the event of an unplanned islanding and unavoidable effects on the protective devices is addressed in [130]. The steady-state and transient characteristics of the network changes due to high penetration of PV systems on the occurrence of various disturbances, such as change of solar irradiance, tripping of PV generation and three-phase short circuit [131-132]. The reach of an impedance relay gets affected due to mismatch in impedance between downstream and upstream locations. There is also possibility that due to high impedance fault the over current protection may not operate in sufficient time [133]. The issues like Fault Ride-Through and LV Ride-Through capability of the system, effect on voltage stability due to occurrence of fault in a large grid connected PV system and simultaneous protection and control challenges has been addressed in [134]. Due to rapid growth in solar PV integration to grid, potential frequency stability problem was observed in Germany. The increase in frequency above thresholds required immediate disconnection of PVs [135]. Faults in PV arrays affect the performance and reliability of the entire system. Line-line and ground faults in PV arrays cause fire hazard, damage the PV module, connecting cables and large amount of energy loss. Usually to protect the PV arrays, high rupturing capacity (HRC) fuses or circuit breakers are employed. These devices provide the protection only if the fault current magnitude is high [136-137]. In PV modules ground fault develops because of the solar cell short circuiting to grounded module frames or insulation failure of cables. Ground fault generates a DC arc, which may become a fire hazard. Line to line fault occurs due to incidental short circuit between current carrying conductors or insulation failure of cables [138].

The inverter control logic plays an important role in determining the fault behavior of solar or wind DG. The appearance of transient overvoltage during the clearance of single phase to ground fault when the breaker opens. This overvoltage can result the failure of transformer and other grid equipment [139].

The performance and required setting of protective relay has to be evaluated again with changing fault current profile due to PV integration [140].

The study on LV distribution network by considering the effect of DG on fuse protection, auto recloser and protection requirement at the time of mains failure is important to analyze in PV integrated network. Performance of protection system is further analyzed by varying the relay

settings and loads for different type of faults. It is observed that the most challenging protection issues is the incapability of high speed reclosing for DG [141]

Serious operating challenges on the protective gears due to PV integration in the LV downstream secondary networks has been observed in low PV penetration levels subsequently a large number of protective gears can malfunction and voltage collapse may occur. Moreover, the PV power can affect the reclosing action of the protective gears [142]

The fault current contribution due to DG affects the performance of overcurrent relay which threatens the reliability of the network [143]

The nature and characteristics of protection system for conventional power distribution system plays important role, when the power flows from upstream to the downstream grid with the integration of DG. An adaptive protection scheme independent of size, number, and placement of DG in the distribution system and provides an acceptable solution to the identified problems [144] Miscellaneous protection issues associated with DG integration such as fuse coordination, feeding faults after utility protection opens, impact on interrupting rating of devices, effect of transformer connections and grounding are discussed in [145-146].

The fault characteristics of the voltage controlled and current controlled inverter interfaced DG are quite different. The fault current levels and duration directly depends on the inverter control mode [147]

Conventional overcurrent protection used for instantaneous and time delay tripping of the feeder breaker may loss the protection coordination and protection sensitivity with the addition of DG. The distance relays are inherently directional and their characteristics can be easily shaped according to the changing system conditions [148]

The impact of fault current contributed by dispersed generation on network protection devices is quite different in case of PV integrated network [149].

There is a possibility to loose protection coordination with DG integration and it is necessary to check the coordination among protection devices including fuse-recloser after each unit of DG integration [150]. In order to mitigate the protection coordination problem due to DG integration, a solution technique with distance protection scheme is presented in [151]. The utility of fault current limiters to maintain the protection coordination in distribution network is also appreciated [152].

The directional overcurrent relay coordination problem due to renewable integration in the power system is also explored [153].

The authors in [154] proposed a noble overcurrent protection scheme where the settings of relay can be altered in real time basis based on the fault current level and the DG connection status. The scheme works on the principle of dividing the distribution network in different zones and each zone is controlled by independent breaker but high cost and complex communication and control circuitry are the disadvantages. In [155], authors presented an adaptive protection and control scheme with overcurrent relay for DG integrated distribution network. The scheme optimally controls the setting of relay considering the variation in load and generated power.

A new technique has been presented to maintain the recloser-fuse coordination in DG penetrated distribution system. This technique performs two actions simultaneously viz. coordination investigation and enhancement. The main drawback of this approach is that it straightway reduces the causes of losing coordination. Therefore, it does not provide the solution for all kinds of faults. Furthermore, it does not consider all the DGs located at different places rather considers one DG at a time and analyzes the system [156].

An adaptive current protection scheme is presented to accomplish the coordination between various protective relays for DG integrated distribution network [157].

The protection system mal-functioning issues in presence of DG is presented. The study proposed the changes needed in the distribution network in order to increase DG penetration and provide better service to customers [158].

An adaptive scheme of overcurrent relay suitable for grid connected or islanded operation. It is observed that fault current levels are different in islanded and grid connected operations. Therefore, overcurrent relays are not suitable for such changeover situations. The scheme gathers information on level and changes the operating characteristics of relay depending on the operating conditions [159].

Genetic algorithm (GA) based scheme is proposed to establish the coordination between the overcurrent relays considering the transient nature of the network, as the relay settings obtained by steady state coordination method are incorrect. The scheme is used along with the dynamic model of the relay in order to get the optimum coordination in a real distribution network [160].

An adaptive voltage protection scheme for distribution networks utilizing intelligent electronic devices (IEDs) to store line parameters and collect real time voltage and current data is proposed

in [161]. An adaptive overcurrent protection scheme which employed IEC 61850 based communications to automatically adjust the protection settings of all overcurrent relays in response to the impact of DG and islanding operation is presented in [162]. The genetic optimization algorithm is applied to determine the optimal placement and allowable limits of connecting DGs in the distribution network [163].

A technique utilizing orthogonal components of the grid voltages to control the interfacing inverter. Such technique controls the modified inverter power rather than actual inverter power. The altered inverter power is employed to provide balanced and sinusoidal currents. In this way the proposed technique controls the grid injected current to during the faults at DG terminals. This effectively controls the fault current without involving actual series impedance, fast switching or complex controlling circuitries [164].

This can be summarized that the PV integration in the radial distribution network changes the electrical characteristics and presents critical challenges like change in direction of power flow, change in short circuit (SC) level, and protection system malfunction. The protective equipment in the conventional system have specific fault level to interrupt or withstand the SC current reasonably. However, integration of PV in the conventional network affects the calculated fault level. The SC current contribution of large scale integration exceeds the non PV fault level situation. This may cause the undesirable islanding, protection coordination issues, reliability issues of system and blocks the process of integration. Therefore, an intensive fault analysis is needed before integration to achieve the smart distribution grid objectives.

4. Conclusion

Solar PVs are expected to play a promising role in meeting future electricity demand. The integration of PV provides various advantages but the existing grid system like in India is not compatible enough to accommodate large number of such systems in power system network. Moreover technological changes such as information communication technology along with advanced instrumentation and control is also required to make the existing system responsive. Various issues and challenges have to be addressed in order to move towards the smart grid era. The modern loads demand clean power supply with highest reliability but the existing distribution grids are unable to fulfill such requirement. Moreover, the grids are incompetent to accommodate the PVs near the load centers due to the number of challenges such as:

- Weak grid system and aging infrastructure

- Slow and sluggish electromechanical protection system

The issues that need to be addressed and require potential solution when solar PVs are added to the conventional grid system are as under:

- Voltage variation and reverse power flow: A strategy is required to maintain the synchronized and optimal operation of controlling equipment to cater the need of distribution grid stockholders.
- Overloading and underloading of feeders: Assessment of feeder loading to ensures the ampacity of conductors.
- Harmonic distortions and power quality: A proper harmonic analysis and mitigation strategy is required to provide the clean power to modern electricity consumers.
- Change in fault level of system: An intensive fault analysis is needed before integration to ensure the stability and reliability of distribution network.

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