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Photovoltaic penetration issues and impacts in distribution network – A review

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ABSTRACT

The solar energy generation has grown significantly in the past years. The importance of PV penetration in power system as a major element of renewable energy source has seen it being widely used on a global scale. Despite its promising success, PV penetration presents various issues and its impact on the distribution system has to address for seamless integration in the power system. In this paper, a comprehensive overview on important issues affecting the distribution system as a result of PV penetration is presented. Pertinent issues such as voltage fluctuation, voltage rise, voltage balance, and harmonics and their effect on the system are discussed in details. The islanding issues, which are of critical importance to the stability and integrity of the system, are also thoroughly reviewed. Details on different islanding techniques – remote and local techniques and their advantage and disadvantages are shown. Therefore, this paper can provide useful information and serve as a reference for researchers and utility engineers on issues to be considered with regards to PV penetration.

Contents

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1. Introduction

Utilization of green energy resources has grown in the past decade, annually. The aims of Renewable Energy Sources (RESs) are to provide a technically and economically improvised integration of RESs in power system networks and at the same time to reduce the need for support the increasing demand in future and reduce CO_2 emission. Although, these new technologies are free from pollution, however, the integration of RESs in power system network will cause some issues. For instance, some types of RESs such as Photovoltaic (PV) and wind generation can cause oscillation in the power system's voltage and frequency. This is due to the intermittent nature of these types of RESs. Hence, intermittent sources, especially PVs, create new challenges in the electric power system. Integration of PVs in electric power system further leads to different issues for electrical engineer such as power quality, power imbalance between generation and load demand, voltage and frequency variation [1–3].

In recent years, PV technology has been developed quickly and made this technology viable even for small scale power generation in distribution system. Solar PV capacity for grid-connected system around the world was 10 GW in 2007, 16 GW in 2008, 24 GW in 2009 and 40 GW in 2010 [4]. The solar PV market has been steadily growing and the growth curve from 1995 to 2012 can be seen in Fig. 1.

In terms of globally installed capacity, PV is the third most important renewable energy source after hydro and wind power [5]. For instance in European Union (EU), PV represents about 37% from all new capacity of energy sources installed in 2012. Therefore, typical studies are carried out to investigate possible adverse impacts on the power quality, protection coordination and operation of distribution feeders. These investigations also examine the interactions of distribution equipment such as on load tap changers and status of capacitor banks [6]. Therefore, increasing penetration of PV in distribution level applies more stress on the utility voltage regulation devices and can even cause them to malfunction.

In this regard, the technical issues of utility power system on the grid side and the PV side need to be considered for safe operation of PV and to maintain reliability of the grid. This article which considers PV integration issues in distribution system will help utility companies with these new types of renewable sources. In addition, it will help researchers and utility engineers to reduce the limitation related to PV interconnection.

2. PV installed capacity and generation scale

Renewable energy installation in recent years has seen further growth. This has hugely contributed to the awareness on the importance of renewable energy and government policies in revising energy priorities to ensure adoption and significant growth of renewable energy. The cost of renewable energy has also dramatically declined over the years, thus making them competitive compared to non-renewable energy sources such as fossil powered power. The bar chart in Fig. 2 shows the total power generation capacity in Giga Watt (GW) for renewable energy resources on a global scale [7].

The amount of renewable power capacity for the three main renewable energy resources – hydro, solar and wind are analyzed. The Concentrating Solar thermal Power (CSP) and solar hot water capacity are also considered as entities for solar PV energy. It can be clearly observed that the hydropower constitutes as major percentage of renewable energy resource. This is due to the constant availability and huge capacity of hydro power in many different parts of the world. Solar PV and wind power, which are intermittent in nature, have limited availability based on their geographical location. In 2013, the total installed capacity of hydropower is 1000 MW, solar PV and wind power are at 783 MW and 318 MW, respectively [8].

Another important observation that can be viewed is that the total generation capacity in 2013 has decreased in comparison to 2012. This is in correlation to the global investment level in renewable energy resources. Fig. 3 shows the global investment (billion USD) in renewable energy by region from 2004 till 2014.

Majority of the regions in 2013 have experienced a drop in total investment in comparison to 2012. The decline in investment is mainly attributed to shifts on uncertainties in renewable energy policy as well as reduction on technology costs. Despite the decrease in investment, the ratio of installed capacity for solar PV in 2013 with respect to 2012 is at 22.85%. This ratio is greater than hydropower and wind which are at 16.22% and 14.89% respectively.

The global installed capacity of renewable energy has reached 480 GW, while the contribution of EU-27 was 210 GW. Global installed capacity of wind has reached to 318 GW in 2013 due to great installation capacity by China and Canada. Europe's installed

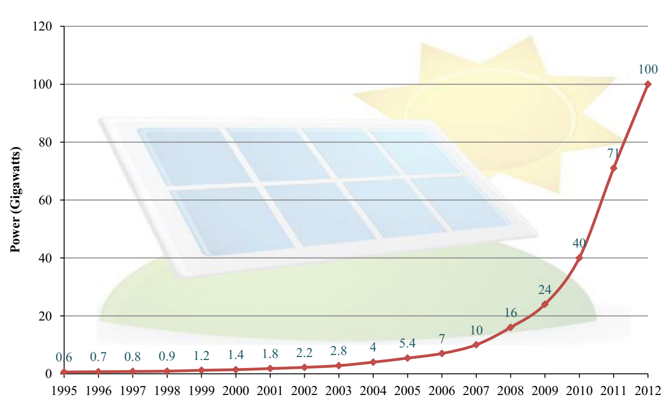

Fig. 1. Generation power of PV market around the world.

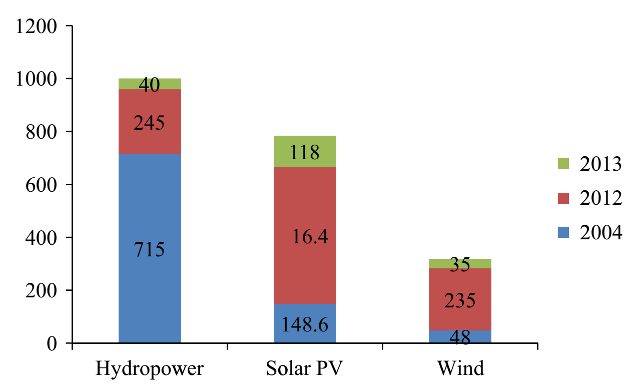

Fig. 2. Renewable energy power capacity in GW.

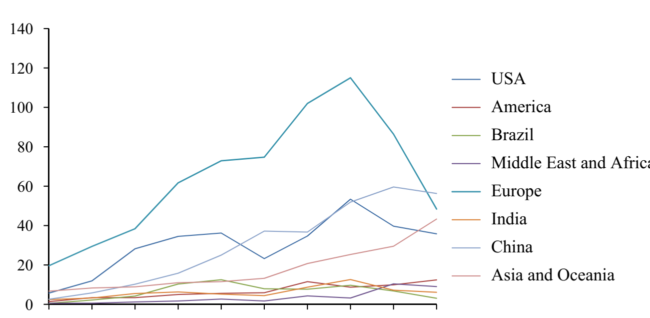

Fig. 3. Global investment in renewable energy by region (billion USD).

wind capacity achieved to almost 121.5 GW in 2013 compared to 110 GW at the end of 2012 [9]. The world installed capacity of solar energy (including PV, the CSP and solar hot water capacity) surpassed 783 GW at the end of 2013. In 2013, the contribution of European countries for solar energy was almost 114 GW.

PV generation could be connected either to transmission or distribution system. However, based on PV generation scales, they can be classified in three categories such as utility-scale, medium-scale and small-scale [10]. Utility-scale plants are either connected in distribution substation or conventional feeders of transmission system in size of 1–10 MW. This type of PV generation is normally three phased and need some interconnection transformers in order to connect to the power system in parallel.

Medium-scale of PV generations is from 10 to 1000 kW and connected in distribution level. PV generation in medium-scale is installed in small or large buildings such as government sites, commercial building or residential complexes. Capacity range of small-scale generation is up to 10 kW and it is connected to the residential voltage level. Due to low voltage level of small-scale PV generation, transformer is not required for installation. These types of PV are usually single phase and mainly include distributed rooftop PV. However, distribution systems have been designed as passive network in a radial style. With regards to this, the interconnection of PVs may cause some issues and impacts that need to be carefully considered and studied.

3. Impact of PV in distribution system

The major impacts of PV integration could be identified as voltage variations and unbalance, current and voltage harmonics, grid islanding protection, and other power quality issues, such as flicker and stress on distribution transformer [11,12]. These impacts can be summarized as either steady-state or dynamic in nature:

i. Voltage fluctuation in feeder, consist of voltage rise or fall and unbalanced voltage.
ii. Malfunction operation of voltage regulation equipment such as on load tap changer, line voltage regulators and capacitor banks.
iii. Possibility of overload in distribution feeders.
iv. Variation of reactive power flow due to malfunction operation of capacitor bank devices.
v. Malfunction operation of overcurrent and overvoltage protection devices.
vi. Islanding operation and islanding detection in case of grid disconnection.
vii. Reliability and security of the distribution system.

The severity of these issues depends on the penetration level of PV, configuration of distribution system and the location of PV in distribution system. In such cases, high level of PV penetration can inject power to transmission network which can affect the voltage level and protection setting of the distribution system. The distribution system is operating as an active network in these conditions. Therefore, potential problems associated with high penetration levels of PV in distribution system will be investigated in the following sections.

4. Voltage fluctuation and voltage regulation problem

Implementation of PVs in distribution system can cause voltage fluctuation and voltage unbalance due to the intermittent nature of these types of RESs. These issues can be introduced into the network due to rapid alternations between clouds and sunshine [13]. Furthermore, it should be noted that the voltage change of the distribution system is sensitive to short term fluctuations. These problems also raise the possibility of operation malfunction of voltage regulation equipment which have been installed in distribution network. Hence, the impact of PV for voltage issues is categorized as follow:

4.1. Voltage fluctuation effects

Voltage quality can be affected by the intermittency of PV power output in distribution system [14]. Generally, for PV generation type, climate changes can create irradiance fluctuations either for a short or long period of time. Therefore, this can affect the voltage output of PV in Point of Common Coupling (PCC). The voltage problem of distribution system that has been connected with PV can be characterized as voltage rise, voltage unbalance and flickers in the network.

4.2. Voltage rise

In the distribution feeders, PV arrays are situated close to the loads can cause the reduction of power flow, network upgrade deferral, voltage profile, minimization of losses, etc. Furthermore, high penetration of PV in distribution feeders introduces many technical issues to the distribution networks including low voltage stability, high losses, voltage rise, power fluctuations, etc. Due to high penetration of PV, the resulting power is not only responsible for load compensation, but also causes reverse power flow into the distribution network. In addition, significant reverse power flow might create some unbalance which includes:

- Voltage rise in distribution feeder.
- Protection desensitization and potential break of protection synchronization.
- Increase of short circuit current which tends to reach harmful level.

However, voltage rise is one of the most influential issues in the distribution feeder. The rise and regulation of voltage depend on different PV penetration levels in the distribution feeders as follows:

- At low PV penetration level (5%), inverters do not make a significant impact on the feeder's voltage regulation during peak load.
- At medium PV penetration level (10%), inverter voltage support can help to reduce the size of the conventional voltage support capacitors by nearly 40%.
- At high PV penetration levels (30–50%), PV inverters might be sufficient to provide all of the feeder voltage support.

There are several methods to control the feeder voltage such as installing fixed or switched capacitors, control of On-Load Tap-Changing (OLTC) transformers, reactive power control method, Battery Storage (BS) systems, etc. Ref. [15] has reported that voltage rise depends upon PV penetration levels. The authors considered different levels of PV penetration on low voltage distribution network in both summer and winter season separately. The voltage has risen up to 5 V on LV distribution network in both summer and winter season at midday with 50% PV penetration which exceeds the limitation of 250 V and this should be unacceptable. However, this voltage rise can be limited with maximum PV penetration of around 30%. In [16–18], power curtailment has been suggested for understanding voltage rise impacts caused by high penetration of PV. Power curtailment technique might not be

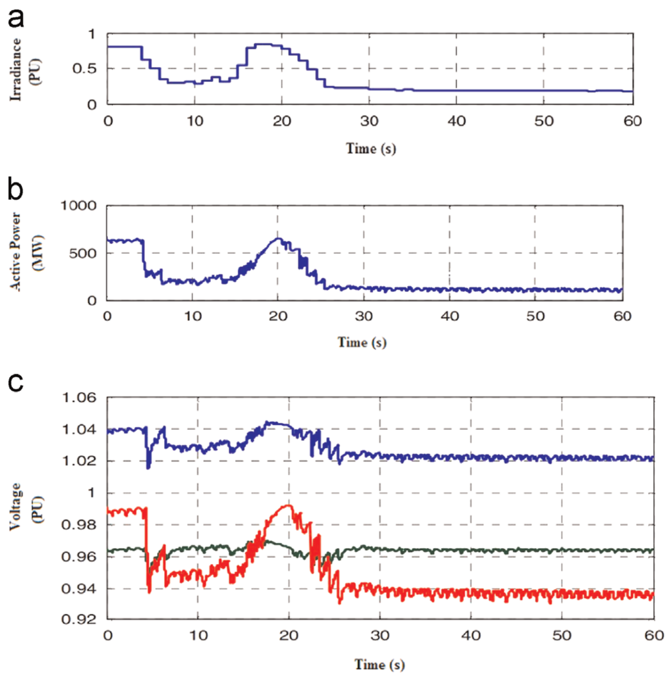

Fig. 4. The effect of variable irradiance of 10% PV penetration on irradiance (a), active power (b) and voltages (c) [20].

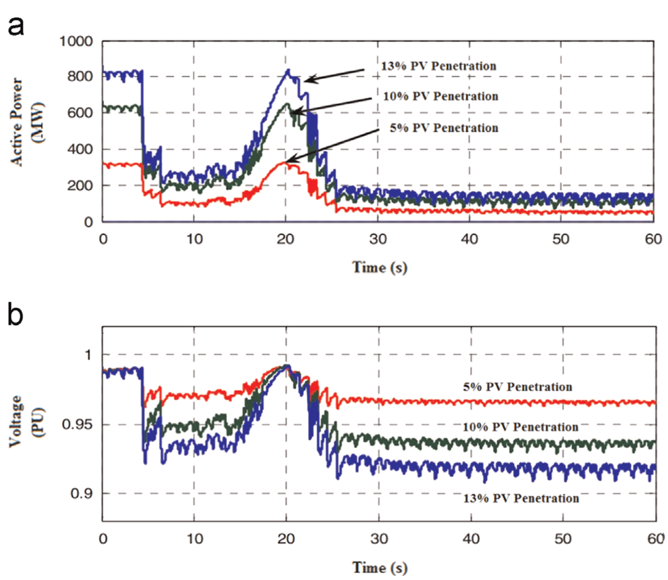

Fig. 5. The effect of 5%, 10% and 13% PV penetration on active power (a) and voltage (b) [20].

an efficient solution economically. This procedure needs to evaluate the highest PV power generated in every weather circumstances, but it is tough to obtain that information when solar irradiance changes rapidly.

Large number of PV injection in a LV distribution network results in significantly large injection of real power into the feeder which causes voltage rise in the distribution feeder. Reactive power based PV inverter is proposed to mitigate this problem [19–22]. This not only offers reactive power support but also provides voltage regulation.

In [21], the irradiance data for one-minute has been captured in Fig. 4(a). The active power output of the PV in accordance with the irradiation for penetration of 10% is presented in Fig. 4(b). The bus voltages of few selected buses are also shown in Fig. 4(c).

The comparison of the active power output and voltage of one bus for a PV penetration of 5%, 10% and 13% have been presented in Fig. 5. The active power output of the PV generation is shown in Fig. 5(a). The voltage of the bus for three level penetration of the PV is also illustrated in Fig. 5(b).

Yan et al. [23,24] developed a method to support PV reactive power and evaluate its effectiveness. Aghatehrani et al. implemented a local method which can be detect without widespread communication system and additionally, it considers the inverter losses linked through the reactive power production [22]. This method has been applied on IEEE-123 bus system by taking into account measurements from two PV systems. The system is applied to imitate the output fluctuation and fluctuation power index based on the Wavelet Transform (WT). The voltage can be reduced up to 2.4% in that method in contrast 0.35% with unity power factor operation. Stetz et al. reported 3 types of reactive power based on PV inverters decentralized voltage control techniques [25]. Among them, static reactive power supply technique was able to raise the absorption capability of the LV network exclusive of additional equipment, while the maximum absorption capability was obtained through dynamic reactive power techniques.

The dynamic reactive power control technique provides the reactive power only if the magnitude of voltage is equal or more than the defined value, thus unwanted reactive power provision can be avoided when it is operated in the normal condition. Since the inverter-coupled PV units shift to conventional generation, majority of their behavior must be harmonized. Regarding reactive power injection to the system, PV inverters have lack of properties due to their reactive power injection might be restricted via the feeder voltage levels. Perhaps, this problem may be fixed through coordinated control of inverters and utility equipment. Moreover, R/X ratio of LV distribution feeder is higher than transmission line. Therefore, reactive power support method may obtain extra loss on the feeder because of high current flow. To overcome this problem, BS devices incorporated with PV systems can be used. The battery storage device is able to store the excess power from the PV array during daytime and delivers the unused energy during evening peak load time or at night [26–28].

Ueda et al. categorized operation of battery into three modes namely schedule mode, minimizing reverse power mode and voltage control mode [27]. Schedule mode can charge the battery depending on the schedule. Minimizing reverse power mode can charge the battery at any moment until the battery becomes fully charged. Voltage control mode can charge the battery if the output terminal voltage of unified PCS's can cross the set point. Among these three modes, voltage control mode shows better performance. A balancing control technique for BS system has been suggested in [29,30].

Ref. [31] studied the Battery Energy Storage (BES) units and integration of PV system. In this study, the PV unit is taken into account as a nondispatchable source as its output will be able to regulate while the BES unit is taken into account as a dispatchable source. For this purpose, a Self-Correction Algorithm (SCA) has been developed for sizing several BES and PV arrays taking into account the time-varying demand and probabilistic generation which optimally tunes the power factors. Combination of BES and PV units with optimal PF dispatch for every load level minimizes the loss of energy significantly. Therefore, it is necessary to improve voltage stability with unity PF which is carried out based on the IEEE 1547 standard.

In [26], a distributed storage system has been proposed for this purpose. The excess energy produced from PV is used to charge the battery during day time. Afterwards, this stored energy can be utilized in the evening when demand reaches the peak level. An intelligent control technique has been developed for battery operation which makes proper charging and discharging efficiently use the available stored energy. The cost of BS system is highly expensive. Several studies have been carried out about the economical benefits of setting a storage system based on battery in a PV network in order to reduce voltage fluctuation [17,32]. Omran et al. [17] have discussed different methods such as installing damping load and power curtailment method instead of BS system separately. Among these, BS system shows better performance individually, but combination of power curtailment and BS system is found to be the most economical solution.

Ref. [32] recommended a model in which a distribution network operator controls the output of energy storage systems of commercial consumers when a particular time duration in exchange for providing a partial financial support of the initial cost of the storage system. The recommended model relates supportive operation systems among customer-owned energy storage systems and distribution system operators. Liu et al. suggested an online tap changing transformer to minimize the voltage rise [33]. The developed technique relies on the reduction of reverse power flow throughout the lightly loaded system by enabling the charging controller of energy storage systems. The control strategy is proposed for voltage rise mitigation under high PV penetration while energy storage system is closed to each PV. Azzouz et al. developed an adaptive fuzzy based OLTC control for high penetration of PV into distributed system to minimize the voltage rise [34]. The fuzzy algorithm can detect the highest and lowest voltage of the system to estimate the step change in the OLTC reference voltage.

4.3. Voltage unbalance

Unnecessary voltage increase in the LV distribution feeder can cause harmful effects on household equipment especially electronic devices. In a 3 phase network, voltage unbalance happens if the voltage magnitude of every phase is not same or if there is a difference in phase angle between whichever 2 phase voltages. It is stated that 1% of the voltage unbalance is able to produce 6–10 times current unbalance [35]. Therefore, motor windings temperature can increase excessively which could reduce the lifetime of an induction motor effectively.

The voltage unbalance on PCC is probable to increase with the increasing PV systems in the LV distribution networks. Voltage unbalance can be estimated by a factor called Voltage Unbalanced Factor (VUF) which is defined as follows:

$$VUF = \frac{V^-}{V^+} \times 100\% \tag{1}$$

V^+, V^- are positive and negative sequence voltage respectively.

The acceptable limit of VUF is up to 2% in Malaysia according to [35]. The VUF increases with the increasing output of PV power. The VUF at the PCC exceeds the acceptable limit of 2% at the time between 12.00 p.m. and 2.00 p.m. when there is peak output power of PV [35]. As a result, voltage unbalance occurs during this interval. Ref. [23] reported that in a geographically large region, PV power can be reduced due to cloud gathering in one spot. Whereas, the same cloud leaves from another spot cause the raising of PV power output. Therefore, the production of PV power could be stabilized if the entire feeder is extended in a wide area. Hence, the cloud effect is not a great concern for large area PV system. Consequently, for a small region, there is a high probability that the output power can be influenced by clouds. Therefore, this system can be affected by voltage fluctuation. In an unbalanced network, PV voltage fluctuation will turn voltage unbalanced in every phase. Therefore, a method was proposed to investigate variation of phase voltage due to PV power fluctuations. This system was developed without any power electronic equipment such as STATCOM, storage or SVC.

Ref. [36] noticed that at 40% of DG penetration, the system largely depends on DGs to satisfy loads which are a concern for voltage regulation. The unexpected failure of DGs, mostly as a result of false tripping throughout voltage may cause unacceptable voltage unbalance in the system. Yan et al. reported that, in a small area, impact of cloud on voltage stability turns severe if the network contains 40% of PV penetration [24]. Perhaps, this limit depends on the configuration of distribution networks.

5. Harmonics

Due to the penetration of PV systems in distribution network, the harmonic distortion of current and voltage waveform is becoming an important issue. It is due to conversion of dc current in order to synchronize with the ac main supply by utilizing inverter. According to current practice and techniques, inverter inherent non-linearity results in harmonics can be injected in the ac main supply [37]. In this regards, the power system quality is an important issue in distribution system which is connected to PV sources. Hence, PV inverters are the main source to inject current harmonics into the distribution system [38]. Current harmonic can also cause the voltage harmonic and Total Harmonic Distortion (THD) in the system. These harmonics contribute to increasing losses in distribution system through heating.

The maximum penetration level of PV inverters that can be installed is based on acceptable harmonic voltage distortion levels within distribution system as determined in [37]. Penetration level

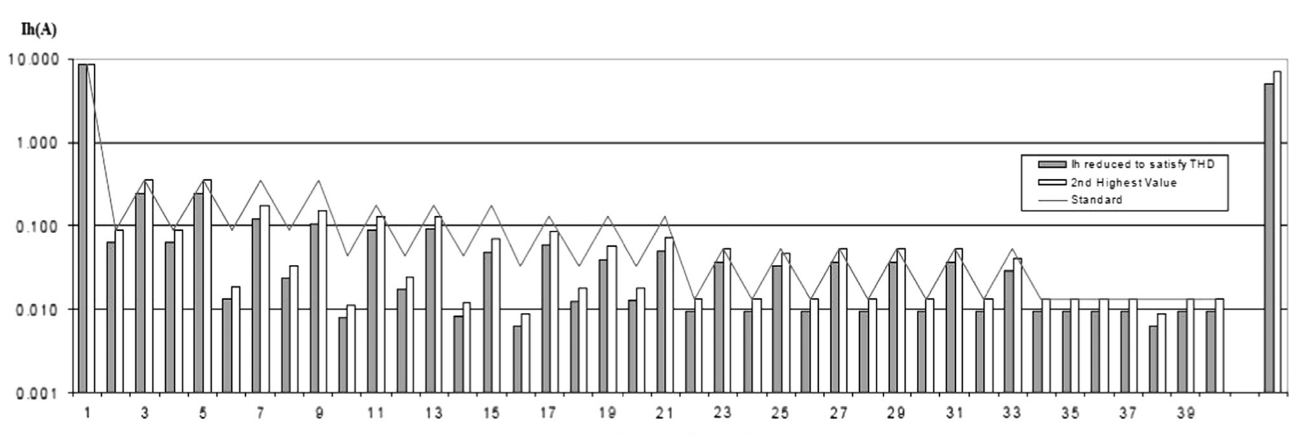

Fig. 6. Harmonic current magnitudes of 2 kW inverter and recommended emission limits [41].

of PV inverters is defined as the rating of the network service provider MV/LV distribution transformer supplying the LV distribution as given in (2):

$$P_{level}(\%) = \frac{n_{pvis} \times n_{dist} \times S_{inv}}{S_{tx}} \times 100\% \quad (2)$$

The total number of PV inverters per distributor is n_{pvis}, the number of LV distributors connected to the distribution transformer is defined as n_{dist}, the rating of PV inverter unit in MVA is defined by S_{inv} and the distribution MV/LV transformer rating in MVA is S_{tx}. Based on the mentioned formula, Latheef et al. [37] determined the acceptable range of penetration level of PVs. In this research, an inverter rating is selected as 2 kW. In this regard, the harmonic current magnitudes of a 2 kW inverter representation has been shown and compared with the standard levels. The harmonics current magnitude of the inverter is represented in Fig. 6.

Acceptable penetration level of residential grid connected photovoltaic inverter system installation is obtained based on 6%, 12% and 14% for overhead conductor, aerial bundled conductor and under-ground cabling of LV distribution feeders, respectively. This paper claims that the current harmonic, I_h, can also be reduced to 30%, with the possibility of better filtering.

The PV harmonic behavior of a 20 kW inverter as a function of the solar radiation in different weather condition is considered in [39]. The measurement results which have captured the harmonic impact of the 20 kW PV plant in several weather conditions is presented in this research too. The harmonic profile of the current and fundamental current are captured at the PCC. It can be obviously seen that the power injected to the LV grid was proportional to the output current of the PV at the PCC and as a consequence to the solar radiation.

In Fig. 7, the fundamental and the harmonic currents of the captured data according to this research is presented [39]. As a result, the 3rd order harmonic shows severe peak especially during sunrise and sunset. The amplitude of the 3rd order harmonic in these times of the day is about 40–50% of the amplitude of the fundamental current which is considerably high.

Impact of the Similar PV plant in different points of the LV distribution network is simulated and then the distortion of the current and voltage waveform harmonic is investigated in this research. It can be concluded that no violation in the harmonic limits occurred based on international standards such as IEEE 1547, 2003 [40].

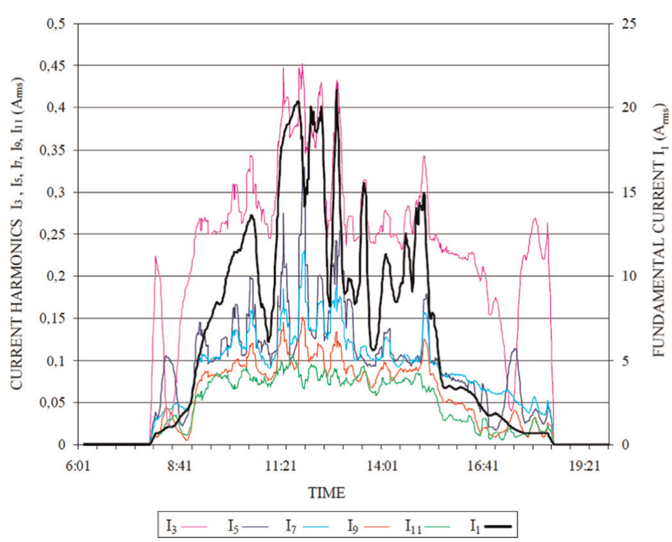

Fig. 7. Fundamental, 3rd, 5th, 7th, 9th and 11th order of current harmonic within day [42].

6. Islanding detection and islanding operation

The islanding scenario can be defined as the situation where RES present in the system maintain the scheduled voltage and frequency within permissible limit after the system is disconnected from the grid [41]. Fig. 8 shows a typical system configuration of the islanding detection in which the PCC acts as the interface point between the grid and the local distribution system.

Islanding is often undesirable and mainly considered as a final initiative to save the system before total system collapse [42]. This is because:

- Safety hazard – The segment of the system up to PCC might still be energized during islanding mode. The power system personnel might not be aware of this and if he accidentally comes in contact with the system, he could be fatally electrocuted.
- System damage – Asynchronous phase voltage between the PV system and power grid during reclosure could damage the equipment connected to the system.

Since the risk posed by system islanding is quite serious, regulatory bodies impose stringent conditions and standards to

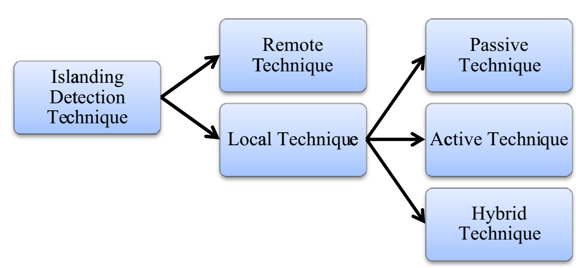

Fig. 9. Islanding detection technique overview.

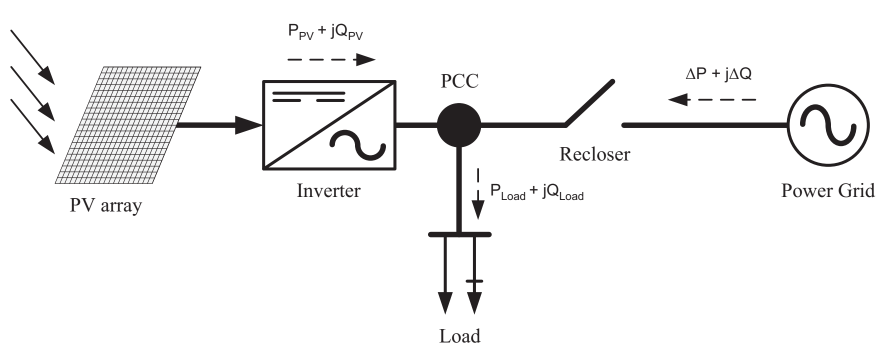

Fig. 8. Typical system configuration.

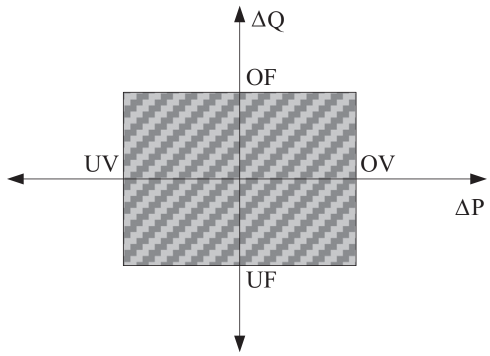

Fig. 10. Non detection zone of OUV and OUF.

ensure that the risk is minimized. Due to the reasons listed above, it is of critical importance that islanding detection has to be quick and as accurate as possible. Several control schemes and strategies have been developed to successfully detect islanding scenarios. Fig. 9 shows a brief overview of the islanding detection techniques.

The islanding detection technique falls into two main categories – remote technique and local technique. The local islanding detection technique can be further subdivided into three categories which are the passive, active and hybrid technique.

6.1. Remote technique

Remote islanding detection technique is islanding scheme which relies on the communication between utilities and PV units [43]. This technique is highly reliable as it eliminates Non Detection Zone (NDZ) however the drawbacks are that it is expensive to implement and complex communication technique is involved. The common remote islanding detection techniques are:

a. Power Line Carrier Communication (PLCC) [44–46]
In this system configuration, a low energy signal is continuously sent by a transmitter placed near the grid protection switch. The PLCC signal is then detected by a receiver at the DG side. In the event the PLCC signal is not detected, it indicates islanding detection and the inverter operation is ceased.

b. Supervisory Control and Data Acquisition (SCADA) [47,48]
This detection method utilizes wide communication network and advanced sensors. Sensors are deployed to monitor the system's states and this crucial information is transmitted back to the control center through the communication links. In the event of islanding, the sensors will pick up the changes in the frequency and voltage values and thus information is sent to the control center on the status of the system.

c. Signal Produced by Disconnect (SPD) [48,49]

Analogous to PLCC, the communication channels are utilized to detect the islanding scenario. However, the communication medium differs in this method as signal is sent to DG through microwave link, telephone line or any other means. Since the state of the switch is directly communicated to the inverter, the inverter is continuously aware of the switch condition.

6.2. Local technique

i. Passive technique

In passive detection, the techniques heavily depend on measured system parameters as the index to determine the state of the system. As such, no controllers are required. System parameters that are considered include variation in voltage, frequency, phase angle etc. The common techniques available are:

a. Over/Under-Voltage Protection (OVP/UVP) and Over/Under-Frequency Protection (OFP/UFP) [48,50,51]
Two of the most important system parameters in the system are the voltage and frequency. Since the system is subjected to disturbances, the voltage and frequency values might be affected. The (OVP/UVP and OFP/UFP) relays are placed in different places in the system to detect these parameter deviations. The tolerance levels of the voltage and frequency magnitude are based on defined standards. At the PCC, the power balance is given as:

$$P_{LOAD} = P_{PV} + \Delta P \tag{3}$$

$$Q_{LOAD} = Q_{PV} + \Delta Q \tag{4}$$

The active power, P is directly proportional to the voltage while the reactive power, Q is directly proportional to the frequency. In that case, if the $\Delta P \neq 0$, the changes in the voltage is detected by the OVP/UVP and vice versa, if $\Delta Q \neq 0$, sudden phase shift in the load voltage is detected by the OFP/UFP and the inverter is disconnected. These changes are detected to determine the islanding condition. Fig. 10 shows how the NDZ (shaded region) for the OUF and OUV is mapped.

b. Voltage Phase Jump Detection [50,52,53]
In this method, the system is monitored to detect a sudden variation or "jump" in the inverter's terminal voltage and its output current. If the phase shift is greater than the predetermined threshold value, the inverter is disconnected. A phase Locked Loop is usually used to synchronize the inverter current with the grid voltage.

c. Voltage and Current Harmonics Detection [48,50,54]
The THD of the signal is monitored to detect islanding scenario. During normal operation, the $THD \approx 0$, which means that voltage with a low level of distortion, is supplied to the load. When islanding occurs, the THD level increases. The two main reasons for harmonic increment in the system during islanding are due to current harmonics introduced by the PV inverter and distorted voltage response of the transformer.

d. ROCOF [55,56]
ROCOF – The rate of change of frequency (df/dt) dynamically varies when an imbalance occurs in the system due to islanding. The change of frequency is due to the change of speed in the turbine and rotor of the machine. ROCOF relays are set in the system and any fluctuation in the ROCOF over a predetermined set of time (islanding) will trigger the relay to disconnect the system.

e. ROCOP [44,57]
ROCOP – The rate of change of power (dp/dt) of system during islanding will be greater if compared with normal operation. Tipping is initiated when the ROCOP exceeds the predetermined trip setting value.

f. Detection Based on State Estimators [58]

A grid-voltage sensorless control is utilized in this method with the use of resonant controllers for single phase systems. Kalman filter based algorithm is further used to detect the energy mismatch between the third and fifth harmonic. This variation in the energy value is used to detect the islanding event in the system.

i. Active Technique

In the active detection method, perturbation are intentionally created and injected at the output of the inverter. The power

Table 1
Common islanding techniques' strength and weakness.

Remote technique	Strength	Weakness
Power line carrier communication (PLCC)	• Effective for system with multiple DGs • Quality of DG's output power is not degraded • Existing PLCC signals intended for other purposes can be utilized	• High cost for transmitter and receiver • Signaling error which might result in non-islanding detection
Supervisory control and data acquisition (SCADA)	• Highly effective in detecting unintentional islanding	• High cost of implementation due to large number of sensors and additional features • Economically infeasible for small scale DG installation
Signal produced by disconnect (SPD)	• Efficient system management and additional supervision due to coordination between the DG and utility • Can be used for multiple DGs	• Expensive to implement as additional communication wiring is required for each inverter and DG if telephone line is used • Microwave links would require license from relevant commissioning authority • Design and permitting complications
Local technique		
a) Passive technique		
	Strength	Weakness
Over/under-voltage and over/under-frequency (OVP/UVP and OFP/UFP)	• Low cost in implementation	• Large Non Detection Zone (NDZ) • Reaction time of protection equipment might vary
Voltage phase jump detection	• Ease of implementation • Quality of inverter's output power and system transient response is not affected	• Complexity in selecting appropriate threshold value • Large Non Detection Zone (NDZ)
Voltage and current harmonics detection	• Highly effective in detecting islanding	• Difficulty in selecting proper trip threshold value • Cannot be used for system with multiple inverters
ROCOF	• Requires low active power imbalance to detect islanding	• Susceptible to mal-operation
ROCOP	• Highly effective for unbalanced loads	• Difficult to determine proper trip setting
Detection based on state estimators	• Very low Non Detection Zone (NDZ) • Highly efficient in islanding detection • Fast in detecting islanding	• Complex programming technique required
b) Active technique		
	Strength	Weakness
Impedance measurement (IM)	• Small Non Detection Zone (NDZ)	• Ineffective for multiple inverters • Exact value of impedance threshold is required
Harmonic injection	• Highly effective in detecting islanding	• Difficulty in selecting proper trip threshold value • Cannot be used for system with multiple inverters
Slip-mode frequency shift (SMS)	• Small Non Detection Zone (NDZ) • Easy to be implemented • Highly effective for multiple inverters	• Inverter output power quality is degraded • Possible loss of stability due to frequency variations
Active phase shift (APS)	• Highly effective for multiple inverters • Can be used for system with parallel RLC loads with resonant frequency equals to the line frequency	• Ineffective for loads with large inertia
Active frequency drift (AFD)	• Easily implemented for multiple inverters	• Power quality degradation • NDZ depends on chopping factor
Frequency jump	• Effective in islanding detection with sophisticated frequency dithering pattern for single inverters • NDZ almost eliminated for single inverter	• Ineffective for multiple inverters
Sandia frequency shift (SFS)	• One of the smallest NDZ for islanding detection method • Highly effective when coupled with Sandia Voltage Shift	• Slight power quality degradation • Susceptible to noise and harmonics
Sandia voltage shift (SVS)	• Easy to be implemented • Most effective positive feedback method for islanding prevention • Highly effective when coupled with SFS	• Slight power quality degradation • Lower PV inverter operating efficiency
General electric frequency schemes (GEFS)	• Easy to be implemented • Negligible power quality degradation • Low cost • Robust to grid disturbances • No NDZ	• Disturbance signal (frequency and voltage) has to be as small as possible

balance of the system is therefore broken due to this. The available techniques are:

a. Impedance Measurement (IM) [59,60]
In this technique, the changes in systems impedance are monitored which happens when islanding occurs. The changes in voltage at PCC with respect to the inverter's current (dV_{PCC}/dI_{Inv}) represent the impedance value to be monitored. Typically, the value of impedance increases when system is islanded.

b. Harmonic Injection [61,62]
This method is similar to the passive harmonic detection technique in which a specific current harmonic is intentionally injected at the PCC. During normal operation, the harmonic current flows into the grid since the utility impedance are lower than the load impedance at harmonic frequency. However during islanding, the harmonic current will flow into the load which produces a harmonic voltage, which can be detected to obtain the status of the system.

c. Slip-Mode Frequency Shift (SMS) [63–65]
The SMS technique relies on the positive feedback to shift the phase in order to destabilize the inverter when it is islanded. The current–voltage phase angle of the inverter is made to be a function of the frequency of the PCC voltage instead of zero.

d. Active Phase Shift (APS) [66,67]
This technique is a modified form of SMS technique with additional phase shift introduced to break stable operating points during the overfrequency/underfrequency relay tripping window. This additional phase shift will be able to ensure that OFR or UFR trips even if the frequency of the terminal voltage stabilizes at new operating point.

e. Active Frequency Drift (AFD) [48,64,68,69]
The frequency of the output current is varied through positive feedback. A slightly distorted current waveform is injected into the PCC to change the frequency. When phase error occurs between the inverter current and PCC voltage, the islanding event is said to have occurred.

f. Frequency Jump [48,70]
This technique is conceptually similar to the IM method with the distinctive difference being that dead zones are inserted in the output current waveform. The dead zones are not inserted in every cycle but spread according a pre-assigned pattern. The islanding scenario is detected by forcing a deviation in the PCC voltage frequency.

g. Sandia Frequency Shift (SFS) [71–73]
This is another positive feedback method which is used to detect islanding in the system. The positive feedback is applied to the frequency of voltage at PCC. During islanding, the frequency error increases producing phase error. Detecting the error, the inverter will try to compensate it and this process is iterated until the OFR threshold is reached.

h. Sandia Voltage Shift (SVS) [48,49,71]
Positive feedback is also utilized in this method by applying it to the voltage at PCC. If the voltage magnitude decreases, the inverter's output current is reduced as well. This will in turn reduce the inverter's output power. The OVP or UVP will be able to detect this voltage magnitude and trip accordingly.

i. General Electric Frequency Schemes (GEFS) [74,75]

In this method, disturbance is injected into the system and the impact of the disturbance is monitored at the PCC. The disturbance signal is injected to the DQ frame in which the active power is proportional to the *D* axis and the reactive power is proportional to the *Q* axis.

The strength and weakness of each technique is given in Table 1.

i. Hybrid Technique

Hybrid detection methods have garnered much attention from researches due to their advantages in accurately detecting islanding scenarios. This technique comprises the advantages of both the active and passive method. The common techniques used are:

a. Technique based on Positive Feedback (PF) and Voltage Unbalance (VU) [49,70]
The VU (passive) and PF (active) are combined and used to monitor three phase voltage anomalies at the PV terminals. Spikes in the VU are used as an indicator to detect disturbances in the system such as islanding. A threshold is set in order to discriminate the VS spike due to islanding or any other reason.

b. Technique based on covariance and Adaptive Reactive Power Shift (ARPS) [76]
The covariance (passive) is used as indicator to obtain the possibility of islanding in the system. This indicator is then used to activate the ARPS (active) algorithm by shifting the frequency of PCC voltage into the UFP/OFP tripping window.

c. Technique based on local measurements and high frequency component evaluation [49,77].

In this technique, the local measurements (passive) at PCC such as voltage and current are initially obtained. High frequency components injected by the inverter are then evaluated to detect the islanding conditions. The discrete wavelet transform is applied extract features form high frequency component at PCC.

The advantage of using hybrid detection is that the level of perturbation introduced in the system is minimal since the passive method checks the system for possibility of islanding before the active method is implemented. The NDZ is also smaller compared to other local techniques. However, since both the active and passive techniques are used, longer time is taken to detect the islanding event.

7. Standards and guidelines

As discussed above, different issues arise from high penetration of solar power in distribution system. The impact of these has to be carefully analyzed and mitigated in order to prevent these issues from jeopardizing the grid and the power quality in the system. The main issues in the solar penetration in distribution system are voltage related issues, harmonics and islanding detection. These important system elements have to adhere to certain standards and regulations set by international committees or regional based regulatory bodies.

In order to address the voltage related issues, the IEC standard (IEC 60038) in European countries, and the IEC 60038 standard has been commonly used in most of the countries where the distribution voltage level is 230/400 V for standard 3-phase 4-wire. In Low Voltage (LV) system, the voltage at the supply terminals should not be differing from the nominal voltage by more than $\pm 10\%$ [78]. The reason is that the voltage rise or fall in the system might cause damage to the equipment. The fluctuation in distribution system and LV network normally happens due to starting of large electrical motors, X-rays, pumps and refrigerators [79]. The voltage stability issues in in the system which is a subset of the voltage related problems have to be adequately addressed as well. Therefore, the voltage stability with unity PF is improved based on IEEE 1547 standard.

The harmonics in the system which is often observed in the voltage and current signals in the system has to be within permissible level. The acceptable voltage harmonic or current harmonic distortion within the limits has been defined and recommended in standards and guidelines such as IEEE Std. 519 [80] and AS/NZS 61000.3.6 [81] (an adaptation of IEC 61000-3-6). Another guideline is also available which is known as IEEE Std. 929 [82]. International standards such as IEEE 1547, 2003 [40] are also used to detail the harmonic limits in the system.

In the islanding scenario of the RES based DG connected to the distribution system, the two main standards used are IEEE Standard 929 and Standard 1547. The IEEE Standard 1547 is a uniform standard which is defined as IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. These standards define the appropriate anti-islanding features to be used in order to ensure that the proper steps and guidelines have been followed before islanding is carried out. Table 2 shows a summary of expansion of the IEEE 1547 standard.

Table 2
A summary of expansion of the IEEE 1547 standard.

IEEE	Title	Status
1547	IEEE Standard For Interconnecting Distributed Resources With Electric Power Systems	2003
1547.1	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems	2005
1547.2	IEEE Application Guide for IEEE Std. 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems	2008
1547.3	IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems	2007
1547.4	IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems	2011
1547.5	Draft Technical Guidelines for Interconnection of Electric Power Sources Greater than 10MVA to the Power Transmission Grid	Withdrawn 2011
1547.6	IEEE Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks	2011
1547.7	IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection	2013
1547.8	IEEE Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547	2014

8. Technical solution

In order to mitigate the arising issue in PV integration in the distribution network, research work and investigation has been undertaken to address this problem. The primary issue in the PV integration is related to the voltage quality in the system. Various solutions have been proposed to address the corresponding voltage fluctuation issues.

Conventionally, the OLTC, Switched Capacitors (SC) and Step Voltage Regulators (SVR) are used to control the voltage level. In addition communication channels are also established for coordination purposes. In order to further relieve and optimize the performance of the tap changer, a coordinated control of the distributed energy storage system with the tap changer has been proposed in [33]. Simulation results and hardware implementation has further verified the effectiveness of the proposed system in effectively mitigating the voltage rise issue. Voltage control strategies such as power curtailment and reactive power support are employed in systems where no ESS is installed [18]. The choice of active power curtailment has its own advantages as it does not require extensive modification in the PV's inverter and further presents the option for the system operator for the most cost-effective solution [83]. Reactive control approach to mitigate voltage rise introduced by active power generation has also been proposed [84]. The reactive power provide by the DG is able to support the system during emergency conditions as the voltage regulator usually requires longer time to react [85].

To improve voltage unbalance, a system with converter topology and control algorithm based on DVR and DSTATCOM at their PCC has been proposed [86]. For this purpose, the pole-shift system based on a state feedback control has been implemented. The system can control the voltage at the output of DVR and DSTATCOM in a way where the voltage balancing can be reached in the network. With these control techniques, a significant amount of VUF reduction can be achieved in LV feeders with imbalanced distribution for high penetration of rooftop PVs among the three phases. From the numerical analysis of steady-state situation, it is revealed that a DSTATCOM shows better performance in both voltage profile improvement and VU reduction compared to DVR. Consequently, it is found that a DSTATCOM requires much higher rating than a DVR.

In order to solve the harmonic issue in distributed generation, filters are commonly used. Conventionally, series inductors are used for this purpose. However due to its disadvantages in requiring high switching frequency to attenuate harmonics in the system, different configurations of filters are used. Inductor–Capacitor–Inductor (LCL) filters with robust strategy are currently used to mitigate harmonics in the network. Various control schemes and control strategies has been implanted and simulation results proves that the THD in the system can be significantly reduced [87–89]. Active Filters Units (AFU) with discrete tuning has also been investigated and implemented by researchers. Discrete tuning algorithm for the AFU has managed to overcome the weakness of AFU's damping functionality which could lead to unintentional harmonic amplification [90].

9. Conclusion

In this paper, the impact of PV as an RES on the distribution network and the associated penetration issues in the electrical system has been comprehensively presented. The importance of PV as a significant source of power and its generation capability is shown as a prelude in this review. The impact of the PV and the major problem associated with the distribution system is reviewed. The voltage and harmonics issues in PV and the nature of complications that arise in the system are further elaborated and discussed. Pertinent standards and guidelines to ensure the successful operation of the PV system are also given with respect to the nature of problems faced.

The islanding detection technique can be broadly categorized into two main groups; remote and local techniques. In the remote technique, the islanding detection technique is based on the power grid side whereas in the local technique, comprising of passive, active and hybrid technique, the islanding detection technique is on the PV inverter's side. In the former technique, the NDZ can be completely eliminated; however it comes at an expense of complexity and high cost in implementation. In the latter technique, the passive approach is based on measurement of system parameters and the active approach creates perturbation in the system to evaluate the islanding event. The hybrid technique on the other hand incorporates both the active and passive technique in order to overcome their respective drawbacks in order to accurately detect islanding scenario in the system. Finally, the strength and weakness of each method is given to enable researchers and utility engineers to further compare and analyze the feasibility of each method.

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