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Effects of high solar photovoltaic penetration on distribution feeders and the economic impact

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ABSTRACT

Significant growth in PV penetration worldwide has introduced intriguing challenges for power utilities and consumers alike. This include financial losses resulting from overvoltage-induced PV curtailment during times of high PV generation. This paper examines these issues by first developing a methodical approach to quantify the impacts of PV penetration in terms of reverse power flow, overvoltage and undervoltage events. A real distribution feeder in South Australia is analysed against various PV penetration levels. The simulation model developed utilises residential load profile of South Australia and voltage regulation limits of the feeder and the inverter as set by the Australian standard. Results show that increase in PV penetration reduces the instances of undervoltage, however the instances of overvoltage increase substantially. The latter leads to inverter shutdowns when the voltage exceeds the nominal maximum voltage of the inverters. Maximum possible PV generation loss due to inverter shutdown is evaluated and some recommended solutions are presented. The financial loss due to PV curtailment has been estimated from different perspectives, namely, using feed-in-tariff, retail price and the pool price (market price). In the context of rapidly evolving regulatory frameworks and financial models for renewable energy, power utilities will need to take these financial losses into account when conducting cost-benefit analysis for possible network upgrades for increasing the PV hosting capacity of the network.

1. Introduction

Growing energy demand, depleting fossil fuel reserves and the global concern for increasing greenhouse gas emissions have encouraged the use of renewable energy sources such as solar photovoltaic (PV) and wind for electricity production. The falling price of PVs and its suitability for residential application have made it the prime choice as green energy solution. Globally, PV systems are the fastest growing power generation source [1]. In Australia, more than 20% of homes have installed rooftop solar PV systems and are expected to increase in future [2]. Capacity wise, more than 8.48 GW of small-scale PV systems have been installed cumulatively by March 2019, which is 2.3 times the total cumulative PV installation up to the year 2014 [3,4]. State wise, South Australia (SA) has a good proportion of rooftop solar, which has increased from a negligible penetration level of less than 20 MW in 2009 to an installed capacity of 989 MW at the end of 2018 as depicted in Fig. 1 [5–7]. The average installation size of a rooftop PV system in SA has increased significantly (see Fig. 2). More than 31.2% of dwellings in SA now have rooftop PV systems installed [8]. The reason for this high penetration at low voltage side (distribution side) is the initial generous government subsidies in the form of rebates on the cost of PV system installation, Renewable Energy Certificates that can be sold for cash, attractive distributor feed-in-tariffs and increasing electricity retail prices [9–11]. According to the Commonwealth Scientific and Industrial Research Organization (CSIRO), this uptake is expected to increase massively in the future [12].

Abbreviations: AS, Australian Standard; AS/NZS, Australian Standard/New Zealand Standard; B, Susceptance; BESS, Battery Energy Storage Systems; CSIRO, Commonwealth Scientific and Industrial Research Organization; DER, Distributed Energy Resources; DSTATCOM, Distribution Static Synchronous Compensator; DVR, Dynamic Voltage Restorer; FIT, Feed-in-Tariff; HV, High Voltage; IEEE, Institute of Electrical and Electronics Engineers; LV, Low Voltage; OH, Overhead; OLTC, On-Load Tap Changers; PCC, Point of Common Coupling; P/Q, Active/Reactive power; p.u, Per Unit; PV, Photo-Voltaic; RPF, Reverse Power Flow; RP, Retail Price; RRP, Regional Reference Price; R/X, Resistance to reactance ratio; SA, South Australia; SAPN, SA Power Networks; UG, Underground; UL, Underwriters Laboratories; V/I, Voltage/Current; X, Reactance; Z, Impedance.

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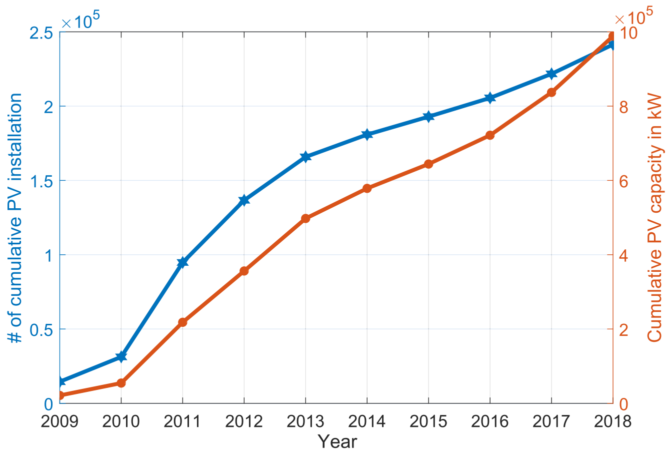

Fig. 1. Number of small-scale PV installations in SA and cumulative capacity [3,6].

With the numerous advantages of solar PV systems listed above, there are some challenges. For example, too much export of PV energy to the grid during low demand periods can cause some operational issues in the power system [13]. These include reverse power flow, increase in power loss, voltage fluctuations and frequent operation of protective devices [14,15]. In particular, overvoltage is a serious problem in small residential areas sharing a distribution transformer [16]. Prolonged periods of overvoltage can decrease the life span of household electronic appliances [17]. It may cause frequent operation of on-load tap changers (OLTC) and line voltage regulators, which can shorten the life expectancy of these equipment [4]. If overvoltage persists for a long time, there are high chances of violating the regulatory voltage rise limits, which can result in inverter output reduction or disconnection and thus loss of PV generation (PV curtailment) [18]. Moreover, the overvoltage issue decreases the PV system efficiency by limiting its active power injection into the low voltage (LV) lines. To mitigate the issues arising from high PV penetration, many utilities have implemented export limits and reduced feed-in-tariffs (FIT) to much lower levels. Despite these restrictions, as per [19], PV system sizes have continued to increase and are likely to impact distribution systems significantly. Understanding these impacts will be critical for the operation, control and management of distribution systems with high PV penetration. A few studies have been reported on the impact of PV penetration. From these studies three definitions of PV penetration are found based on (1) available generation (dwelling penetration) [20,21], (2) system peak load [22] and (3) amount of energy served [23]. The study presented in this paper has used the latter definition of PV penetration (also known as energy penetration). Very few research work have been reported so far based on energy penetration. The work presented in Ref. [23] analysed the IEEE 13-node test feeder under Brazilian electricity regulation. It has considered power factor control through PV inverters to limit the voltage at the point of common coupling (PCC). However, this type of control can result in the loss of active power, put stress on the inverters and consequently warrant larger inverter size [24]. In addition, power factor control is not very effective for regulating voltage on distribution feeders with high R/X ratio branches [25,26]. While PV inverters have the ability to supply or absorb reactive power, the Australian Standard (AS4777.2) that governs grid connection of energy systems via inverters [27] has required reactive power modes to be disabled by default. Consequently, this mode is disabled in the majority of the inverters installed in South Australia. Some power utilities have commenced enabling this mode in inverters installed only since December 2017 [28]. However, the number of such inverters is still very low. Therefore, PV inverter-based reactive power control is not considered in this study.

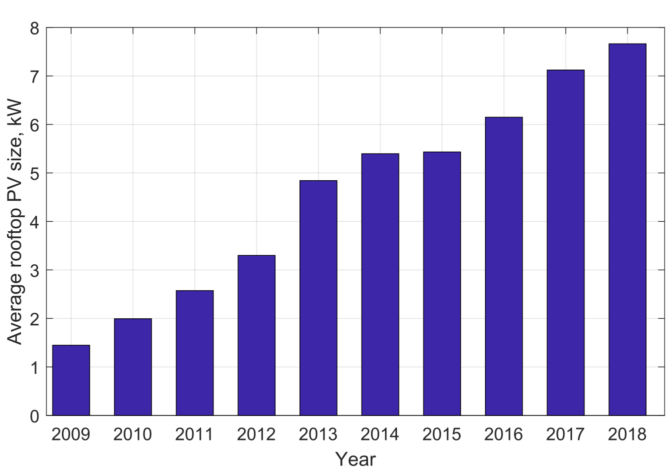

Fig. 2. Average rooftop PV size in South Australia [3,6].

As for studies on real LV feeders, a few research were conducted previously to find out the impacts of high PV penetration. Most of these studies are focussed on the influence of high PV penetration on voltage profile and distribution loss [29,30]. They have highlighted the need for a smarter grid to effectively monitor these effects across the network so that mitigation strategies can be implemented [11]. In another study [31], the roles of feeder impedance, feeder length and transformer short circuit resistance in the determination of voltage rise were quantified. However, none of these works have studied the extent of voltage violations on real distribution feeders and the consequent PV generation loss and economic impact. Other literature [32–34] have discussed how OLTC, PV inverters and battery could control voltage by changing taps, varying power factor and storing energy respectively. The technical benefits of these strategies are listed; however, the financial benefits have not been determined. A cost-benefit analysis using voltage control strategies (OLTC and PV inverters) was carried out for few German low voltage grid [35–37]. This study is based on the local Renewable Energy Act according to which the export of power from residential-scale PV systems to the grid is restricted to 70% of their installed module capacity. Other reasons which make the studies carried out in Europe and USA not directly applicable to the Australian context [38] include the following:

- Australia has very different geographical conditions with less densely populated areas [39] and has different weather patterns.
- It has higher solar generation than any other country due to its higher radiation levels [40].
- Australian rural and remote distribution feeders have different characteristics such as higher impedance than the European feeders [40,41].

Limited researches are available on the impacts of high PV penetration in the Australian context [42–44]. They are conducted on grid-connected as well as isolated LV feeders, however none of them have discussed the techno-economic analysis of the PV generation loss due to inverter shutdowns. The Australian power utilities need to know the extent of PV generation loss and consequent economic impact due to high PV penetration to assist with planning and network capacity upgrades. As stated in SA Power Networks' latest "Regulatory Proposal 2020–2025" [45], cost-benefit analysis need to be performed when planning network upgrades to support additional PV hosting capacity. Currently, comprehensive information on voltage violations and PV generation loss aren't available from the network as it does not have automatic network-wide measurement provisions, i.e. a smart grid. To the best of our knowledge, detailed study on the extent of PV curtailment in Australian grids due to overvoltages and its economic impact have not been reported in literature either. These are vital information for the utilities to make decisions about costly network upgrades to accommodate more PV systems in the grid.

This study aims to fill the above gaps by studying the impacts of high PV penetration on an actual distribution feeder in South Australia. To the best of our knowledge, this is the first time a study of PV generation loss and consequent economic cost due to overvoltage has been performed on an Australian distribution feeder. The study models and analyses the distribution feeder to quantify impacts such as reverse power flow, overvoltage and voltage violation instances. This research proposes methods to determine the maximum possible PV generation loss (PV curtailment) and the consequent financial loss due to high PV penetration. Potential solutions to address the overvoltage problem are briefly discussed in the last section. As previously stated, cost-benefit analysis is performed when planning network upgrades to support additional PV hosting capacity [45]. The work presented in this paper will further enhance the process by enabling the estimation of costs associated with PV generation loss.

2. Distribution feeder

An actual 11 kV distribution feeder in South Australia, operated by the SA Power Networks, is analysed. The feeder is supplied by a 66/11 kV substation transformer. The single line diagram of the feeder is given in Fig. 3. It comprises of six buses (0–5) and 5 line/cable sections in between the buses. Bus 0 is the 11 kV root or source bus. The other buses supply consumer loads via step-down transformers which transfer the 11 kV feeder voltage to the distribution voltage of 250 V (1.087 p.u on a 230 V base). There are 2 overhead (OH) lines, one between buses 1 & 2 and the second between buses 3 & 4. All the remaining lines are made up of underground (UG) cables. For UG cables, shunt admittance is included in the power flow analysis.

The load distribution of the feeder is shown in Fig. 4. Clearly, most of the load is served by buses 3 and 4. At present, the feeder has a total of 2570 kW of PV systems connected and the measured annual net energy consumption of the feeder is 16.11 GWh. The mean, maximum and minimum real load at the source node of the feeder is 1.84 MW, 6.97 MW and −0.50 MW respectively. Note that the negative load is a consequence of power injection into the grid from PV generation. An on-load tap changer (OLTC) and a shunt capacitor are installed on the high voltage (HV) side of the substation transformer to maintain the voltage of bus 0 at 1.087 p.u. Half-hourly load data of each bus for the year 2018 is used during the analysis. Uniform PV penetration is assumed along with the prevailing regulatory limits imposed on the feeder and inverter voltages.

2.1. Load profile

The measured load profile obtained at the feeding node (sending end) of the feeder is not an actual load profile of the system but is a net system load profile due to the presence of PV systems. Mathematically, it can be expressed as:

$$E_L^N = E_L^A - E_P \quad (1)$$

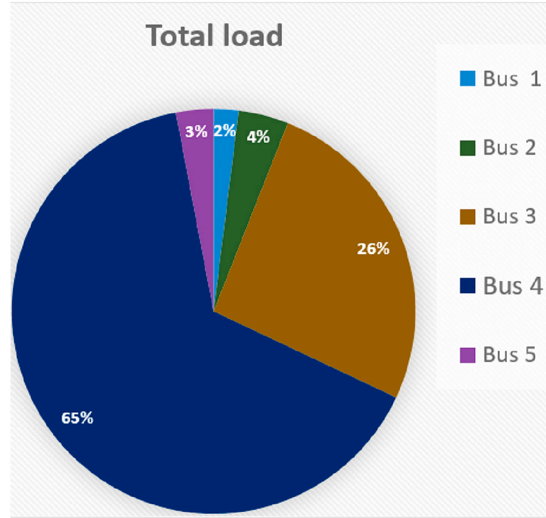

Fig. 4. Load distribution of the 11 kV feeder.

where, E_L^N and E_L^A represent the annual net and actual load energy of the system respectively. E_P is the annual energy produced by the PV systems. For a given annual net load energy and PV generated energy, the actual annual load energy of the system can be calculated using (1).

Hourly PV generation data are available from the Renewables ninja website [46]. To match the half-hourly interval of the load profile data given for the feeder, half-hourly PV generation data was calculated from the hourly data by taking the average of consecutive hourly values. Fig. 5 shows the half-hourly PV generation profile of a 1 kW$_p$ PV system for a region of South Australia (SA) in the year 2018. 5% inverter loss and 35° tilt angle are considered in this output.

The estimated average PV generation of a 1 kW$_p$ PV system in SA is

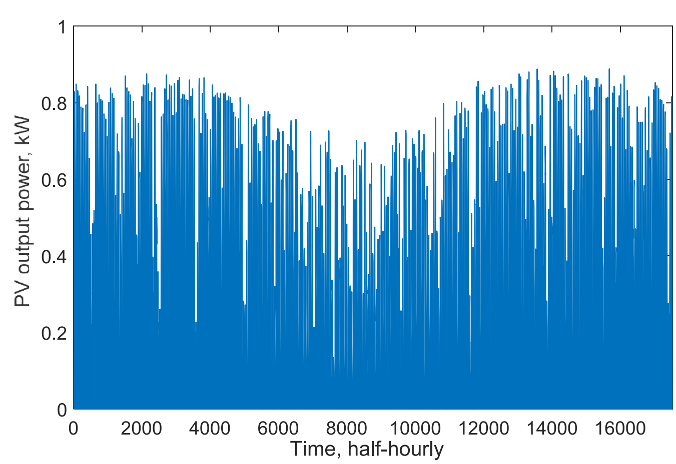

Fig. 5. Half-hourly power generation of 1 kW$_p$ PV system in 2018 [46].

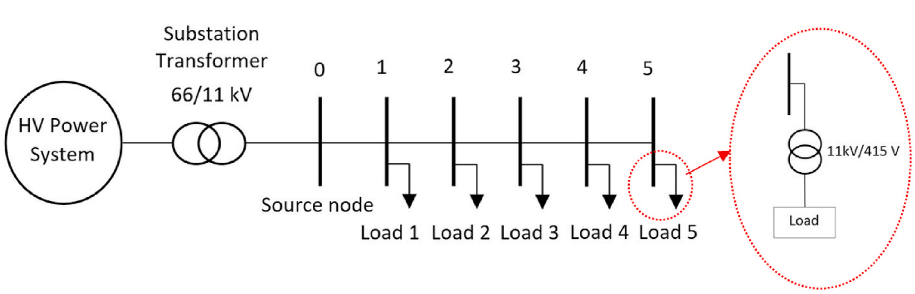

Fig. 3. Single line diagram of the 11 kV distribution feeder.

4.77 kWh/day which remains more or less constant every year. According to this estimation, the annual PV generation of the studied network is equivalent to 4.47 GWh. As mentioned earlier, the annual net load energy of the selected feeder is 16.11 GWh. Using (1), the actual annual load energy of the network is 20.58 GWh.

2.2. PV penetration

The term PV penetration (PV_{pen}) used in this study defines the fraction of annual load energy served by the PV systems. Mathematically, it can be expressed as:

$$PV_{pen} = \frac{E_P}{E_L^A} \tag{2}$$

Based on (1) and (2), the PV penetration of the feeder is 21.72%. It means that currently 21.72% of the load energy of the feeder is served by the existing PV systems. It is assumed that the PV penetration distribution is uniform i.e. PV energy are uniformly distributed among the various buses in proportion to their load energy. For example, if a feeder has 10% PV penetration, every bus on the feeder has PV energy to serve 10% of the respective bus load energy. Random PV penetration can also be considered for the analysis, however, it will influence the results because of different PV distributions among the various buses.

2.3. Feeder and inverter voltage limits

In Australia, low voltage (LV) lines normally operate at 230 V with +10% and −6% voltage regulation limits [47]. The voltage at the point of common coupling (PCC) is generally set to 250 V to cater for the voltage drop along the feeder, which is more prominent during the peak load demand in the evening [48]. Table 1 shows the nominal voltage limits of LV lines both in Volts and in per units (p.u) [27].

To avoid exceeding the upper voltage limit, voltage regulation limits are set in the PV inverters. Consequently, the inverter will disconnect the PV supply whenever the upper voltage limit is exceeded. However, depending on the inverter settings, initially, the PV output power may be reduced and if the overvoltage problem is not remedied then the PV generated power may be completely cut-off by inverter disconnection. As mandated by AS/NZS 4777.2:2015, the automatic disconnection device of the PV inverter should operate when the feeder voltage exceeds pre-set limits as shown in Table 2 [27]. It shows that if the average voltage during a 10-min period is above the maximum nominal voltage of 255 V as set by the Australian Standard then the inverter should trip within 3.0 s. However, the inverter trips quicker if higher voltages are reached, i.e. within 2 s or 0.2 s if the voltage is above 260 V or 265 V respectively.

In the PV inverters available in Australia after 2015, maximum nominal voltage can be set between 244 V and 258 V, and the factory default setting is 255 V. However, for high PV penetration areas such as SA, 258 V is the default set point recommended by SA Power Networks [28] to allow minimum inverter disconnection due to high voltage. After an instance of inverter disconnection, it is able to reconnect to the grid if the voltage returns to the normal range for a 1-min continuous period [27]. Considering the above voltage constraints and the half-hourly load and PV generation patterns, an algorithm based on power flow equations is proposed to perform power flow analysis. First, the power flow equations are presented in the next section followed by the proposed algorithm in Section 4.

Table 1
Voltage limits of LV lines in Australia.

Normal Voltage	230 V	1.000 p.u
Upper limit	253 V	1.100 p.u
Lower limit	216 V	0.939 p.u
PCC voltage	250 V	1.087 p.u

Table 2
Inverter disconnection limits as per Australian standards.

Overvoltage condition	Per unit voltage	Inverter mode of operation	Time to operate
>255 V sustained for 10 min	1.1086	Trip	3.0 s
>260 V	1.130	Slow Trip	2.0 s
>265 V	1.152	Fast Trip	0.2 s

3. Methodology

To examine the impact of high PV penetration on voltage profile, power flow analysis can be used to determine the steady-state operating condition of the system [49]. Traditionally, the power flow equations of transmission and distribution networks are solved separately using different algorithms. However, with high penetration of rooftop solar PV, distribution networks are becoming more active. In order to analyse the effects of high PV penetration, treating it as a global or integrated power flow problem (combined transmission and distribution networks) would make sense. References [50–52] solved the global power flow problem by decomposing it into two subproblems and solving them simultaneously using master-slave iterative technique. The above methods can provide the actual voltage and power at the boundary buses in addition to the normal power flow solutions. However, in South Australia, the voltage at the boundary buses (or sending end of the distribution feeders) is kept more or less constant at 1.087 pu using local shunt compensation and/or on-load tap changer to maintain adequate voltage at far end of the feeder, especially during peak load condition. Thus, inclusion of the effects of transmission network to determine the voltage at the boundary bus may not be needed in this investigation for the South Australian context.

Given the above, the power flow problem of the given distribution system can be solved using a modified backward-forward sweep method by properly incorporating the effect of PV generation and load demand at the respective buses [49]. Well known numerical methods such as Gauss-Siedal method, Newton Raphson method and Fast-decoupled method have been used in literature. However, the Gauss-Seidel method has poor convergence [53], Newton-Raphson method is versatile but complex and may not be needed for simple radial systems, and the Fast-decoupled method may not be suitable for distribution networks which normally have high R/X ratio branches [54,55]. A backward-forward sweep method is generally used for distribution systems to analyse voltage levels [56]. The backward sweep includes branch power calculation from the far end of the feeder to the sending end and forward sweep includes node voltage calculation from sending end to the far end. Maximum active and reactive power mismatch at the source node or node voltage magnitude between two successive iterations are used as the convergence criteria [57]. In this paper, the backward-forward sweep method is applied with the maximum power mismatch at the source end being used as the convergence criteria.

3.1. Power flow equations

A general π-circuit model of a branch of the given feeder is shown in Fig. 6. It is considered that branch i is connected between buses i-1 and i. The series impedance and total shunt admittance of the branch are $(R_i + jX_i)$ and jB_i respectively.

In this study, the PV generation is considered as negative load. Thus, the net active (P_i^N) and reactive (Q_i^N) load power at bus i can be written as:

$$P_i^N(t) = P_i^A(t) - P_i^P(t) \tag{3}$$

$$Q_i^N(t) = Q_i^A(t) - Q_i^P(t) \tag{4}$$

where, $P_i^A(t)$ and $Q_i^A(t)$ are the actual active and reactive load power

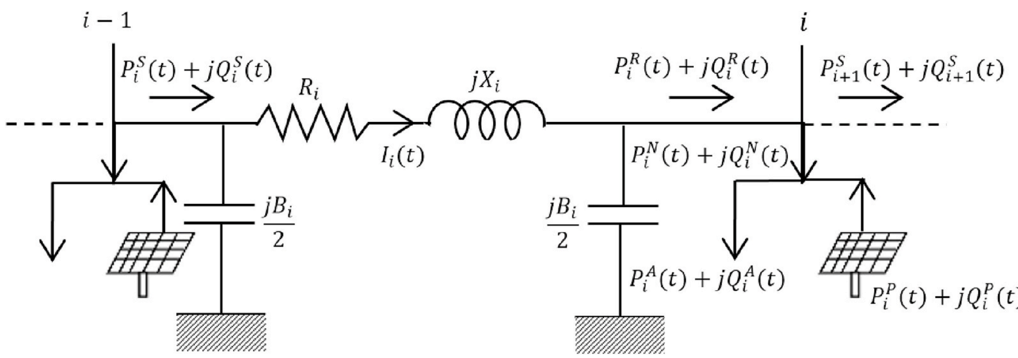

Fig. 6. A general π circuit model of a branch.

respectively at time t. $P_i^P(t)$ and $Q_i^P(t)$ represent the active and reactive power generation by the PV system.

The power at the receiving end of branch i is the sum of net load power at bus i and the power at the sending end of the downstream branch i+1. Therefore, the active (P_i^R) and reactive (Q_i^R) power at the receiving-end of the branch i are

$$P_i^R(t) = P_i^N(t) + P_{i+1}^S(t) \tag{5}$$

$$Q_i^R(t) = Q_i^N(t) + Q_{i+1}^S(t) \tag{6}$$

where, $P_{i+1}^S(t)$ and $Q_{i+1}^S(t)$ are the active and reactive power flow to the next branch i+1.

By including the losses of the branch to the receiving-end power, the active (P_i^S) and reactive (Q_i^S) power at the sending-end of the branch i can be obtained as [49]

$$P_i^S(t) = P_i^R(t) + \frac{\left(P_i^R(t)\right)^2 + \left(Q_i^R(t) - V_i^2(t).B_i/2\right)^2}{V_i^2} R_i \tag{7}$$

$$Q_i^S(t) = Q_i^R(t) + \frac{\left(P_i^R(t)\right)^2 + \left(Q_i^R(t) - V_i^2(t).B_i/2\right)^2}{V_i^2} X_i - \frac{V_{i-1}^2(t).B_i}{2} \tag{8}$$

The phasor voltage at bus i can be written as

$$\boldsymbol{V}_i(t) = \boldsymbol{V}_{i-1}(t) - \boldsymbol{I}_i(t).(R_i + jX_i) \tag{9}$$

Here, $\boldsymbol{I}_i$ is

$$\boldsymbol{I}_i(t) = \frac{P_i^S(t) - \mathrm{j}\left(Q_i^S(t) + V_{i-1}^2(t).B_i/2\right)}{\boldsymbol{V}_{i-1}^*(t)} = I_{iR}(t) + jI_{iQ}(t) \tag{10}$$

$\boldsymbol{V}_{i-1}(t)$ is a reference voltage. $I_{iR}(t)$ and $I_{iQ}(t)$ are the real and imaginary part of the phasor current $\boldsymbol{I}_i(t)$ at any time t. Using equations (9) and (10), the voltage magnitude at the bus i at any time t can be written as:

$$V_i(t) = \sqrt{V_{i-1}^2(t) + Z_i^2\left(I_{iR}^2(t) + I_{iQ}^2(t)\right) - 2V_{i-1}(t).(I_{iR}(t).R_i - I_{iQ}(t).X_i)} \tag{11}$$

Here, $Z_i = \sqrt{R_i^2 + X_i^2}$, $I_{iR}(t) = \frac{P_i^S(t)}{V_{i-1}(t)}$ and $I_{iQ}(t) = -\frac{(Q_i^S(t) + V_{i-1}^2(t).B_i/2)}{V_{i-1}(t)}$

Equations (3)–(11) can be used to obtain the power flow solution of the radial distribution system.

4. Proposed algorithm

The high-level computational steps for the proposed algorithm are provided in the flowchart shown in Fig. 7. The details of those steps are given below.

(i) Read the line and load data of the distribution feeder. Select network information such as voltage limits, voltage at the source node and PV penetration level of the feeder.
(ii) Calculate the PV generation profile of each bus assuming uniform PV penetration and using the PV profile of a 1 kW$_p$ PV system (shown in Fig. 5 without adding any uncertainty).
(iii) Set the initial time ('t = 1') and the time duration (Δt = ½ hr in this case).
(iv) Perform power flow analysis as described in following steps and store the results.
   a) Initialise the voltage of all buses except the source bus.
   b) Moving from last branch to first branch, compute active and reactive power flow using (7-8).
   c) Moving from first branch to last branch, compute voltage using (11).
   d) Repeat step b)-c) until the method converges with an acceptable tolerance.
(v) Move to the next time instance (t = t+1) and repeat step (iv) for the entire year (t ≤ T).
(vi) Check the number of voltage violations.

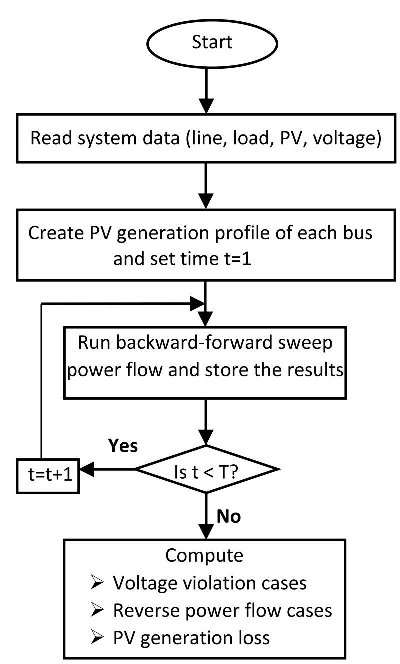

Fig. 7. Flowchart of the proposed algorithm.

(vii) Compute maximum possible PV generation loss based on inverter disconnection limits (see Table 2).

This algorithm has been implemented in MATLAB for balanced operating condition of the network.

5. Results and discussion

The above technique was tested with real data from the 11 kV distribution feeder in South Australia (SA) as described in Section 2 (see Fig. 3). It was stated in Section 2 that every load bus has a transformer which steps down the 11 kV feeder voltage to 250 V (phase voltage). However, precise voltage data on the low-voltage side was not available, therefore it was assumed that the per unit voltage is the same on both sides of the transformer. All buses of the distribution system were analysed using the methodology proposed in Sections 3 and 4. As mentioned in the Introduction, the majority of PV inverters in SA are set not to deliver reactive power, therefore, $Q_i^P(t)$ in (4) is considered as zero. For various PV penetration scenarios, three major events are investigated: (1) undervoltage, (2) reverse power flow, and (3) overvoltage. Table 3 summarises these events when there is no PV penetration.

As mentioned in Section 2, the feeder already has 2570 kW of PV systems connected. All three events are evaluated next for the existing PV penetration as well as additional levels of PV penetration.

5.1. Undervoltage events

Only bus 5 was found to have undervoltage problem. This finding is consistent with the fact that it is the farthest load bus from the source node. Fig. 8 shows the undervoltage events at bus 5 during the year 2018 against various levels of PV penetration. A '0' on the x-axis represents the current level of PV penetration while other values represent additional PV penetrations (this also applies to Figs. 9 and 10). Clearly, at the current PV penetration, the number of undervoltage events reduced to 25 from the 'no PV penetration' value of 58 events. Fig. 8 demonstrates that increasing PV penetration above the current level would further reduce the number of undervoltage events. However, there is not much reduction in undervoltage events above 30% penetration. This is due to the fact that the undervoltage events at 30% penetration occur at times of day when there is not enough PV generation to mitigate those events. The time frame of the observation is half-an-hour, which means 25 undervoltage events observed for the current PV penetration is equivalent to 12.5 h of undervoltage in the year 2018. For 40% additional PV, the number of undervoltage events reduces to 15, a 40% reduction from that for the existing penetration level.

Undervoltage events occur during the evening high demand period, when PV generation is mostly unavailable, especially during the winter months when the sun sets at around 5 p.m. Still, the annual reductions in undervoltage events depicted in Fig. 8 for increasing PV penetrations are indicative of the PV power generated during the evenings of the South Australian summer months when the sun sets near or after 8:30 p.m.

5.2. Reverse power flow events

Reverse power flow (RPF) occur when the PV power generation exceeds the local load demand. When this excess PV generation is exported to the grid, the voltage on the power line (low voltage lines in this case) rises, causing overvoltage. Apart from the overvoltage problem, RPF

Table 3
Summary of events for zero PV penetration.

Event	Number of instances
Undervoltage	58
Reverse power flow	0
Overvoltage	0

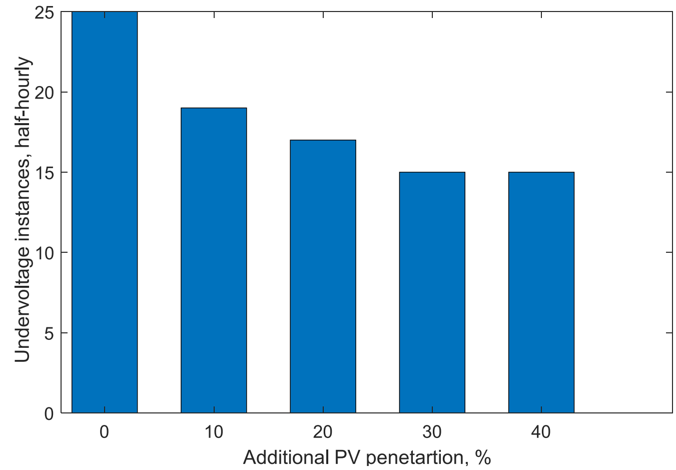

Fig. 8. Half-hourly undervoltage events at bus 5 for various PV penetration levels.

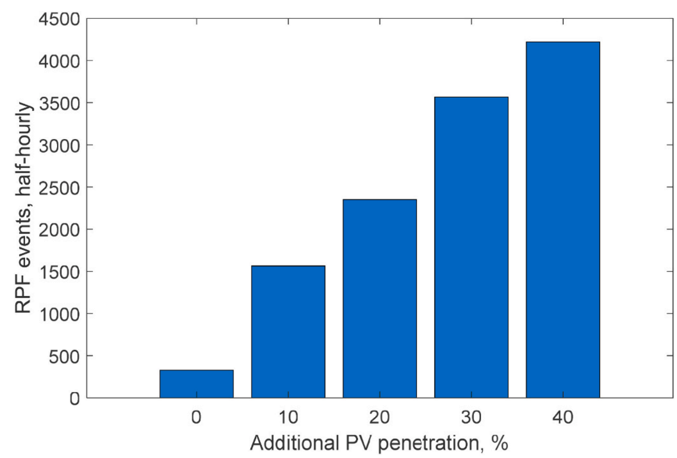

Fig. 9. Reverse power flow events for various PV penetration levels.

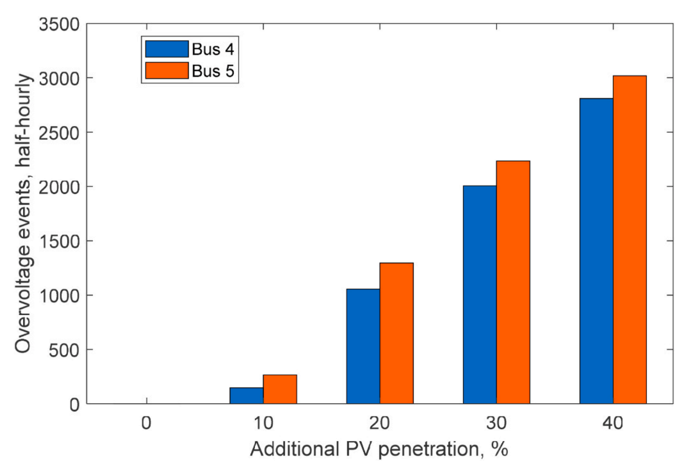

Fig. 10. Overvoltage events for various PV penetration levels.

may also cause mal-operation of the protection devices [58]. Fig. 9 shows the number of reverse power flow events in a year against various levels of PV penetration. It indicates that for a given load, increase in PV penetration will increase the number of RPF events. For example, there are only 327 half-hourly RPF instances with current level of PV penetration. This number rises to 4303 with 40% additional PV. Overvoltage is the most critical consequence of reverse power flow, which is discussed in the next sub-section.

5.3. Overvoltage events

The analysis revealed that only bus 4 and 5 experienced overvoltage problem with increasing PV penetration. Fig. 10 shows the overvoltage instances in these two buses against penetration levels. At the current penetration level ('0'), there is no overvoltage event. Overvoltage events start at bus 5 with 3.7% additional PV and continues to increase significantly with increasing PV penetration. For 40% additional PV penetration, the total number of overvoltage events on buses 4 and 5 rise to 5827. All overvoltage events are caused by reverse power flow (due to excess PV generation) during sunny afternoons when the demand is low. The expected future proliferation of PV systems will surely make the number of occurrences and severity of overvoltage events far greater unless action is taken to mitigate them. Detailed analysis of the bus voltage profiles for various PV penetration levels are presented next.

5.4. Voltage profiles under various PV penetration scenarios

In the analysis of the voltage profile of the distribution feeder both undervoltage and overvoltage events were observed. Overvoltage can have adverse effects such as inverter disconnection, therefore, in addition to the number of overvoltage events, the location of the buses suffering from overvoltage and the instances of voltage limit violation are assessed. Furthermore, based on the maximum nominal voltage of the inverter, the shutdown events of the inverter and maximum possible PV curtailment are evaluated. For simplicity, only shutdown mode of the inverter is considered in this study, i.e. reducing the power output of the inverter to tackle overvoltage problem is not considered.

5.4.1. 0% additional PV penetration (existing PV penetration)

The simulation results on bus voltages for the current PV penetration level are presented as a box plot in Fig. 11. As was shown in Fig. 3, bus 0 represents the voltage source (low voltage side of the substation transformer) and the other buses (1–5) represent loads. Fig. 11 shows that undervoltage events are observed only at bus 5 (when voltage reduces below 0.94 p.u). It also shows that for current PV penetration level there are no overvoltage events (exceeding 1.1 p.u) at any bus, which confirms the results presented in Fig. 10.

5.4.2. 10% additional PV penetration

Considering the same level of PV growth as seen up to 2018 (see Fig. 1), the system should have had 10% additional PV growth by August of 2019. For this penetration level, Fig. 12 shows the voltage profiles of buses 4 and 5 against half-hourly time intervals throughout the year 2018. Undervoltage events in bus 5 are now reduced by 12% compared to that for the existing PV penetration (instances can be seen below the bottom red line). Reverse power flow events increase to 4.8 times compared to that for the current PV penetration. The RPF events raise the number of overvoltage events at buses 4 and 5 combined to 413 when the voltage exceeds 1.10 p.u (instances can be seen above the top red line). However, the voltage levels during these overvoltage events still remain below the maximum nominal voltage of the inverter and therefore keeps the inverter running. The analysis has demonstrated that the 10% additional PV penetration increases the overall voltage profile of the network, however no PV generation loss or curtailment occurs.

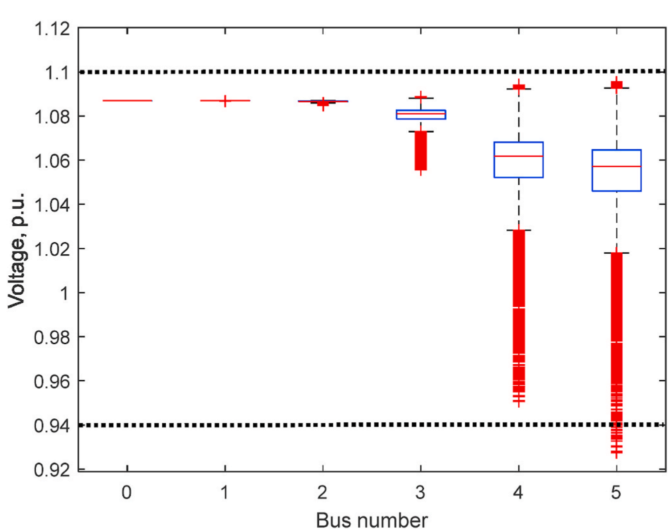

Fig. 11. Voltage profiles of the distribution feeder at current penetration level.

5.4.3. 30% additional PV penetration

Additional 30% PV penetration is expected in South Australia (SA) by the end of 2020. Analysis shows that this would significantly increase the overvoltage instances in buses 4 and 5 as shown in Fig. 13 (above the top red lines). In total 4242 overvoltage instances were observed which included 537 voltage violation cases (see the instances above 1.1 p.u in Fig. 14). If the overvoltage events shown in Fig. 13 persist for 10 min continuously, it will curtail up to 101.1 MWh of PV generated energy during the whole year due to 268.5 h of inverter shutdown. The financial loss for this would be at least Australian $17,187 considering a feed-in-tariff (FIT) of $0.17/kWh (see Table 4). However, if this energy was available for consumption then it would save the cost of buying this energy at a much higher retail price (RP) of $0.48/kWh. This means the actual financial loss could be much higher ($48,528) than estimated above. However, from the market operator's perspective, if the PV isn't able to generate because of curtailment, another non-zero cost generator is required to meet the shortfall. A simple way to estimate this cost is to use the pool price at the time of curtailment (also referred to as regional reference price – RRP [59]). As shown in Table 4, the estimated financial loss using this method is $13,538.

Assuming that a 1 kW_p PV system produces 1742 kWh of energy per annum, Table 4 summarises the amount of PV generation loss and financial loss for various PV penetration levels along with the corresponding overvoltage period and voltage violation period. In practice, due to sub-optimal tilt and orientation of the PV panels, cable and ac-dc conversion losses as well as dirt on the panels, a 1 kW_p PV would produce 4.1 kWh of energy per day or 1500 kWh per annum (presenting 18% system loss). For this scenario, Table 4 summarises the PV generation loss and financial loss for various PV penetration levels. The results are based on half-hourly PV generation and load data. For higher resolution data, the PV generation loss may change slightly. As was stated in Section 2.3, in South Australia, the maximum nominal voltage is 258 V [28]. However, older inverters have a default setting of 255 V, which means these inverters would shut down at a lower voltage than considered in the above analysis. Hence, for the older inverters, possible PV generation loss could be as high as 806.5 MWh with a corresponding financial loss of at least $137,105. Such huge loss demonstrates the need for changing the default setting of the inverter in high PV penetration areas such as South Australia (SA).

Apart from financial losses, other consequences of overvoltage include increased power consumption and possible damage to domestic appliances and decreased life expectancy. Around 75% of the residential load contain motors, for example air-conditioners, refrigerators and ceiling fans [60]. The amount of magnetic flux required to magnetise the core of the motors is directly proportional to the voltage to frequency ratio. During the overvoltage events, this ratio increases which increases the amount of flux required to magnetise the core. This results in increased losses, and higher power consumption and lower efficiency. 25% of the residential load is resistive in nature and includes ovens, heaters, kettles, incandescent and some fluorescent lamps. The effects of overvoltage on various lamps are summarised in Table 5. It is clear that

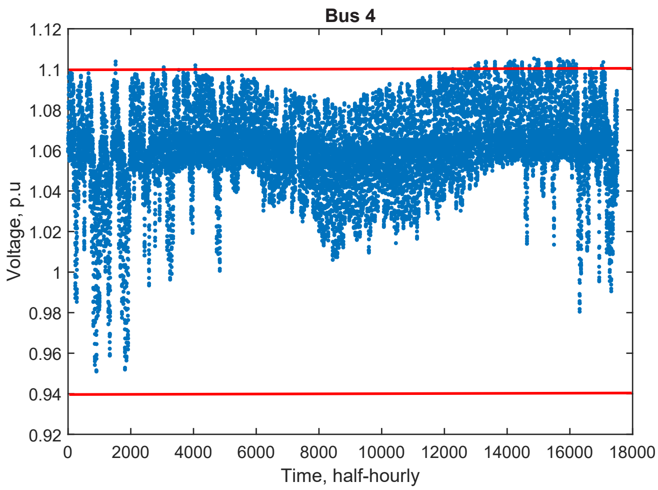

Fig. 12. Voltage profiles of bus 4 and 5 at additional 10% PV penetration.

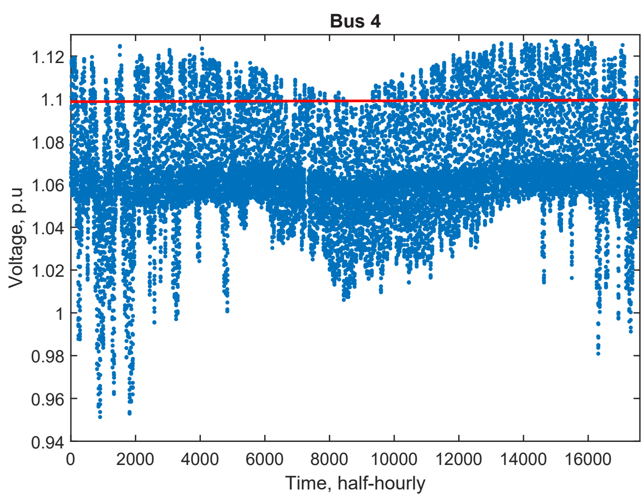

Fig. 13. Voltage profiles of bus 4 and 5 at additional 30% PV penetration.

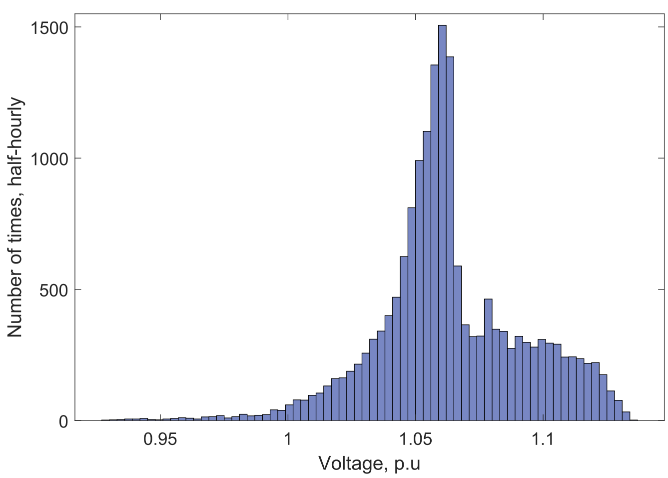

Fig. 14. Voltage distribution of bus 5 at additional 30% PV penetration.

overvoltage decreases the life span of the lamps and increases their power consumption. Some schemes to reduce the loss of PV generation due to voltage limit violations caused by increasing PV penetrations are briefly discussed in the next section.

Considering all the above scenarios, it can be summarised that increasing PV penetration not only increases overvoltage events but also the number of customers experiencing voltage violations. These violations result in inverter shutdown and consequently PV generation loss (PV curtailment) and financial loss. To avoid this loss, some preventive actions can be taken as recommended in the next section. Note that the reported results are conservative as they are calculated at the low-voltage side of the 66/11 kV substation transformer. The actual voltage profile of the feeder would be higher at the downstream side than reported in the paper. It means, in reality there will be more voltage violation cases and therefore more PV generation loss and financial loss. The number of undervoltage instances would also be higher due to the distance of the houses from the 11/415 kV distribution transformer.

6. Schemes to address the overvoltage problem

Conventional techniques to maintain the voltage of the system within regulatory limits include using on-load tap changers (OLTC) and shunt reactors [17]. These solutions are less effective for PV induced overvoltages due to the intermittency of PV generation. To address this problem, a few other schemes can be used in conjunction with the existing solutions. These include battery energy storage system, solar inverter, DSTATCOM, export limit, reconductoring, reconfiguration of lines, and DVR.

Table 4
Consequences of high PV penetration.

Annual PV generation of a 1 kW_p PV system (kWh)	Additional PV penetration	Overvoltage (Hours)	Voltage violation (Hours)	Maximum PV generation loss (MWh)	Financial loss ($)		
					Due to loss of export revenue at FIT of $0.17/kWh	When buying this energy from grid at RP of $0.48/kWh	Pool price loss
1742	0%	0	0	0	0	0	0
	10%	206.5	0	0	0	0	0
	20%	1175.5	0	0	0	0	0
	30%	2121.0	268.5	101.1	17,187	48,528	13,538
	40%	2913.5	994.5	796.1	135,337	382,128	111,318
1500	0%	0	0	0	0	0	0
	10%	177.5	0	0	0	0	0
	20%	1056	0	0	0	0	0
	30%	2040.5	200.5	68.3	11,611	32,784	9566
	40%	2856.5	837.5	624.9	106,233	299,952	87,785

Table 5
Effect of overvoltage on lifespan and power consumption of resistive devices [61].

Resistive Device	Overvoltage %	Life span	Power consumption
Incandescent lamp	10%	Reduces by 60%	Increases by 16%
Fluorescent lamp	10%	Reduces by 17%	Increases by 16%

6.1. Battery energy storage system

Battery energy storage systems (BESS) are mainly used to increase the self-consumption of solar energy to reduce the consumer's overall electricity cost [62]. If proper sizing, siting and energy management (charging/discharging) strategy are used, it can help mitigate voltage rise and thus PV curtailment problem [63]. Storing PV generated energy can prevent reverse power flow and thus voltage rise, which reduce the instances of inverter output reduction and disconnections. The main drawback of this solution is the relatively high cost of BESS. However, recent trends show a reduction in battery cost and this trend is expected to continue, which can make BESS a potential solution to mitigate the PV induced overvoltage problem.

6.2. Solar inverters

Initially voltage regulation using distributed energy resources (DER) such as PV inverters was not allowed due to IEEE 1547 and UL 1741 [64–66], which state that solar inverters should not actively regulate the voltage at the connection point. In Australia, all versions of AS4777 (the Australian standard which governs grid connection of energy systems via inverters) to date have required reactive power modes to be disabled by default. Therefore, the solar inverters have been mostly used as source of active power, not as source of reactive power. However, within the last few years, countries such as Germany and Australia have initiated practices to allow DER contribution for voltage regulation. Consequently, the solar inverters now have the option to enable the Volt-VAr mode to provide reactive power support [48,67]. However, enabling this mode either reduces active power generation or increases the size of the inverter. Solar inverters are a very effective option in networks with relatively low R/X ratios [68], for example, medium voltage networks. However, it proves less effective in low voltage (LV) networks due to high R/X ratios where variations in reactive power have a smaller influence on voltage than variations in active power [69]. Therefore, solar inverters aren't highly effective in reducing the PV curtailment issue. They can still prove beneficial in reducing PV curtailment when used in conjunction with battery energy storage systems [70].

6.3. Export limit

To mitigate issues arising from large PV penetration, some utilities such as SA Power Networks (SAPN) and Western Power have already applied export limits to restrict excessive reverse power flow. For houses with single-phase LV supply, Western Power applies a 5-kVA limit on the single-phase inverter [71]. In SA, the export limit was previously 10-kVA on single phase, which is now reduced to 5-kVA after the enforcement of Australian Standard (AS) 4777.2:2015 [27]. Reference [72] provide the method to find the adequate export limit that can be used to resolve operational issues with minimum PV curtailment.

6.4. DSTATCOM

Distribution static synchronous compensators (DSTATCOM) can provide reactive power compensation during high PV generation times [42]. Traditional shunt capacitors or reactors are discrete elements, which cannot provide continuous reactive power support like DSTATCOM. In addition, DSTATCOM can provide both inductive and capacitive reactive power support. However, due to the high R/X ratio of LV lines, reactive power compensation is not a very effective solution. Recently, a utility named ERGON Energy has used STATCOM in distribution lines to deal with overvoltage problems caused by reverse power flows [73].

6.5. Reconductoring

Replacing old conductors in existing networks with larger conductors (to carry more current) can enhance the network's capacity to accommodate larger number of PV systems without voltage fluctuations. Increasing the cross-sectional area of the conductors can reduce the voltage drops. However, this solution is costly. To defer the costly replacement of conductors for a certain time period, other solutions such as battery energy storage system has been used by some utilities such as SAPN. It has deferred the network upgrade by 10 years using distributed battery energy storage systems [74].

6.6. Reconfiguration

Rearranging the load and PV power among different phases can improve voltage profiles. It will allow utilizing the network infrastructure more effectively without much additional infrastructure cost. However, this approach would require more research and planning for it to become a potential solution [4].

6.7. DVR

Dynamic Voltage Restorer (DVR) is another effective way to mitigate overvoltage issues due to its small size and low capital and operating costs [75]. DVR is a custom power device i.e. a power electronic controller having a voltage source inverter, a filter and capacitor as a storage unit. It is basically a series compensator whose output is connected in series with the distribution feeder. It can regulate the voltage by injecting a voltage of required magnitude and phase angle into the feeder. The success of DVR depends on the choice of appropriate filter capacitor [4]. If a battery (sourced by the PV system) can be used as the storage unit then the DVR will be able to inject or absorb both active and reactive power to compensate for the voltage variations (overvoltage and voltage drop) [76]. This would make DVR more versatile for resolving voltage fluctuation issues. With the use of the battery the size of the DVR can also be reduced. The declining trend in battery cost is likely to make the combination of battery and DVR a viable solution in the near future. Relatively shorter life span of DVR compared to transformers can introduce additional maintenance and cost for DVR replacement.

7. Conclusion

Using data from an 11 kV distribution feeder in South Australia, this study has demonstrated that reverse power flow (RPF) and consequent overvoltage are the most critical impacts of high PV penetration. For the South Australian feeder analysed in this paper, the number of RPF events increases from 327 half-hourly events at current level of PV penetration (21.72%) to a massive 4303 events at 40% additional penetration. At this level of penetration, the overvoltage events cause nearly a thousand 'nominal voltage violation' instances at the inverters leading to at least 625 MWh of PV generation loss due to inverter disconnections. For the customers, this represents an annual financial loss of over $106,000 due to the loss of energy export revenue. If the same energy is to be purchased from the grid, it would cost approximately $300,000. From the power utility's perspective, the lost PV energy would represent a loss of approximately $88,000 at the pool price, which is a significant financial loss for one distribution feeder. Clearly, the total loss of PV generated energy and the associated financial loss for the whole state of South Australia are expected to be much higher. The methodology presented in this paper for estimation of PV generation and financial losses is expected to allow for greater clarity on the potential benefits or otherwise of network upgrades to host additional PV capacity.

Clearly, with increasing levels of PV penetration, it is important to deploy strategies so that large amount of PV generated energy isn't lost due to overvoltage-induced inverter disconnections. A few strategies which can be deployed have been summarised in this paper. Among these strategies, the use of battery energy storage seems to be very logical and cost-effective way to deal with the overvoltage issue, because increasing number of PV systems being installed in Australia and around the world today have battery storage systems associated with them. Nonetheless, this study has highlighted the importance of conducting thorough evaluation of the alternative strategies and their suitability to provide the level of dynamic control required to deal with reverse power flow and overvoltage issues efficiently.

Credit author statement

Vanika Sharma: Conceptualization, Methodology, Software, Validation, Writing - original draft. Syed Mahfuzul Aziz: Conceptualization, Visualization, Writing- Reviewing and Editing, Validation. Mohammed H. Haque: Conceptualization, Validation, Writing- Reviewing and Editing, Visualization. Travis Kauschke: Resources, Data curation, Reviewing.

Declaration of competing interest

The authors declare that they have no known financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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