Major Technical issues with increased PV penetration on the existing electrical grid.

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Declaration

I declare that this thesis is my own work, based on my own research, except where otherwise referenced. I further declare that this report has not been submitted previously to any other institution.

Signed

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Abstract

In the past decade, the installation of rooftop PV (Photovoltaic) systems has substantially increased in many countries. This increase is anticipated due to government incentives like RECs (Renewable Energy Certificates) and feed-in tariff, to counterbalance the carbon emissions and satisfy local energy needs provided to the customers. The existing electrical grid infrastructure was originally designed to supply power from source to load but now due to such increase of distributed PV generation there is the possibility of reverse power flow which presents some technical challenges when the numbers of such systems increase for the utilities. Out of all the technical issues, to analyse the effects of voltage rise on LV (Low Voltage) distribution side of the grid due to such systems is the main objective of this project. This paper considers data that is collected from 7 different grid connected solar PV systems that are installed in different suburbs of Perth, Western Australia and one outside Perth in Bridgetown, Western Australia in order to show that voltage rise on the feeder is a common effect wherever these systems are installed. The Australian Standards for grid connected PV systems are studied and what effects are caused when a number of such systems are increased on the grid. A number of options are suggested in order to lessen or overcome this effect some of which suggest revising the existing old standards for connection. The conclusion derived will be what are the necessary steps need to be taken in order to integrate future penetration of such distributed generation.

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1.0 Introduction

The increase in the conventional fuel prices and undesired climate change over the past few decades have forced countries across the globe to start switching towards the power generation from renewable resources [7]. Out of different forms, the Photovoltaic power generation is considered one of the most capable methods in producing electricity from solar energy [23]. With 25-35% annual growth rate over past decade, solar PV is one of the fastest growing sources of energy. Also the market for solar PV has shifted from Off-grid applications like water pumping, solar lighting etc. To grid-connected in past decade [10]. The installation of grid connected PV systems all over the world is on the rise. The two main reasons for this rise are the better efficiency of PV systems & inverters, low cost due to different government benefits like rebates, subsidies for the initial cost of the system, feed-in-tariff etc. [30]

The purpose of this thesis is to study various technical issues with increased PV penetration on the existing electrical grid. An attempt is made to describe the impacts through past research in this area. Out of these impacts, the rise in voltage due to PV integration is focused in this paper. This includes desktop study and field measurements of 7 grid connected PV systems in different suburbs and Perth, Western Australia. Also different options are proposed to overcome this effect.

This paper begins with a background on the subject of voltage regulation and the impact of distributed PV generation on the network. This is followed by different suggestions to overcome the voltage impact particularly inverter reactive power. Finally, the field measurements and observations of the grid connected PV systems are described through results and discussion.

1.1 Background:

The Voltage regulation is an essential feature of distribution network and to maintain the voltage within standard range at the PCC is utility's concern in this case. There is a guideline provided for this range from different standards (e.g. Australian standards here) however, the utilities (e.g. Western Power here in WA) can stipulate any changes depending on particular conditions. The main concern for utilities is to sustain the service voltage within a standard range and as long as the wiring of the house is done following the wiring codes (AS 3000), the utilization voltage is maintained automatically. The majority of the utilities indirectly maintain the service voltage, by maintaining the voltage at the feeder primary circuit. The service voltage is proportional to the feeder voltage; bearing in mind same base voltage, the result of difference between the drop in voltage between the secondary circuit point of connection and the service transformer, from the feeder voltage is the service voltage. Hence for all loads, if the parameters for service runs and transformer are consistent, the service voltage can be predicted from the feeder voltage. Based on this fact, the utilities design the strategies for the service transformer and the decision for length and size for the service connection. The conductor sizes are designed on an economic basis, so with the fixed circuit components, only two common methods for voltage control on feeder are: putting switched or fixed capacitors to balance demand for reactive power from load and other is to use OLTC transformers. Bigger conductors have low power loss and voltage drop, however are expensive, hence the utilities trade-off between savings from reducing losses and rise in conductor costs [10].

1.2 Impact of DG (Distributed Generation) on Distribution Networks:

For many years, the distribution networks were designed in a manner was the power flows from single main centralized generation sources to supply load in a radial structure. Now as this traditional method of transmission which tends to depend on the limited fossil fuel energy sources is not proving to be sustainable, the world is now shifting towards the growth of DG which does consist of few alternative sources of energy which are sustainable. In this situation, there are multiple DG sources which are connected to the network and the power flow reverses i.e. from DG units towards main generation source. The main difference in this method is the reverse power flow. [6]

Up until now the existence of DG had not impacted significantly the operation of distribution networks as the number of installed units was small. However, as the amount of such units increase these units could lead to some technical challenges such as:

- Customers supplied with quality power or not e.g. harmonics, voltage fluctuation frequency, etc.
- Power control parameters (power factor, fluctuation in power produced etc.)
- DG units not complying with utility protection rules.
- Islanding operation [33]

2.0 Impact between the network and multiple PV inverters:

2.1 Voltage Rise:

Fig 1 shows the voltage profile on a LV feeder during light load and maximum nominal load conditions under with and without PV introduced power environment. As the off-load tap is already synchronised with approximating drop in voltage at maximum nominal load, hence voltage rise needs to examined only under light loads.[8]

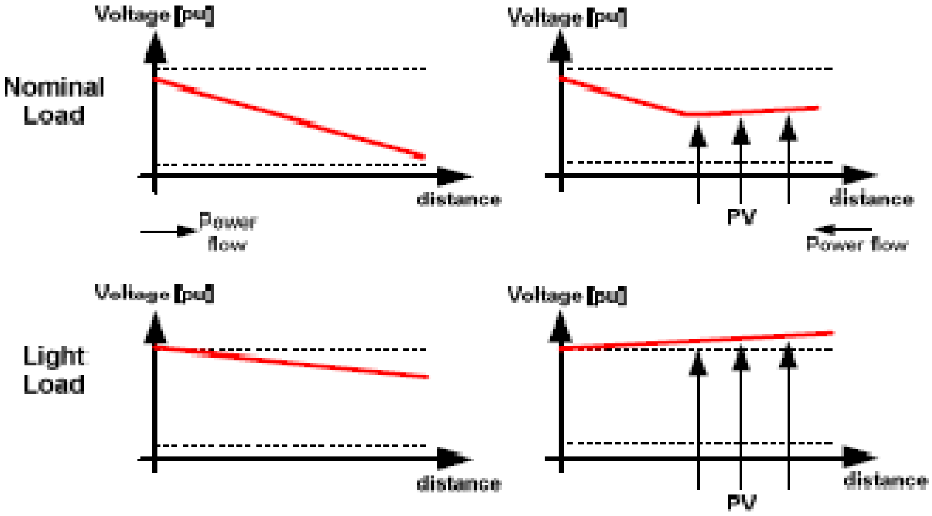


Fig 1. Voltage profile with first column without PV and second column with PV [8]

2.2 Harmonics:

Combined effect of many PV inverters could initiate a parallel resonance because of contact among equal line inductance, introduced harmonic currents and residential units capacitance. The resonance frequency could be reduced to 5th harmonic level based on the capacitance of inverter output filter, total residential units, and line impedance. If there exist voltage distortions in the background of the network and current controller arrangements, grid synchronization of inverters are grid voltage sensitive then, operation of these inverters could be affected. The dispersed inverters could decrease, neutralize or increase the harmonics of the grid voltage based on the phase angle between grid voltage harmonic and the introduced current. [8]

2.3 DC Injection:

The grid-tied magnetic equipment could be saturated, produce pulsating torques, overheating and vibration on electric machines due to circulating DC current in the network. High risk probability with dc current introduction in the LV network is associated with transformerless inverters which are mostly used with grid-connected PV systems around the world. [8]

2.4 Unintentional Islanding:

Due to maintenance after disconnection from a LV network, the inverters continue to inject power in the disconnected part. As the majority of inverters depend on current control, the frequency and voltage stability of the network degrades. [8] However, in Australian context the standards specify the inverters turn off during islanding condition.

2.5 Grid Impedance Variation:

Grid connected inverters need output filters to decrease the high and low frequency harmonic parameters associated to the grid. [8]

3.0 Effect of PV on distribution transformer:

One of the requirements by following AS 4777 is the operation of inverters at high (unity) power factor and is thus just doing the real power support. One problem with this is that its PF at distribution transformer is reduced. This occurs because of the generation of active load current by inverters locally while the entire reactive load current is supplied to the grid upstream resulting in higher ratio of reactive load current to active load current which lower the PF at distribution transformer while passing through it. The benefit of this is the network losses are reduced as transportation of power to a distance is not needed as shown in fig. 2 [40]

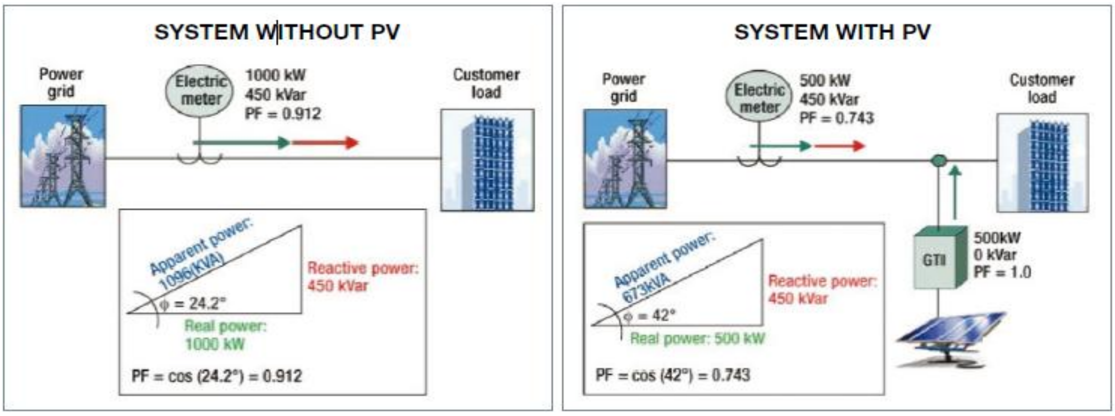


Fig 2. Impact of PV systems on PF at distribution transformer [40].

4.0 Effect of PV on protection device:

The high levels of PV penetration have the capacity to contribute to the fault currents. Without PV, the fault current is normally supplied by the upstream network and passes through their protection equipment. The fault is cleared by the protection device once the fault current is detected. With PV, there will also be a fraction of fault current, and as these systems are fundamentally current limited, under particular fault scenarios, the inverter might not turn off. Fig 3. shows this phenomenon of PV systems contributing to the fault current. [40]

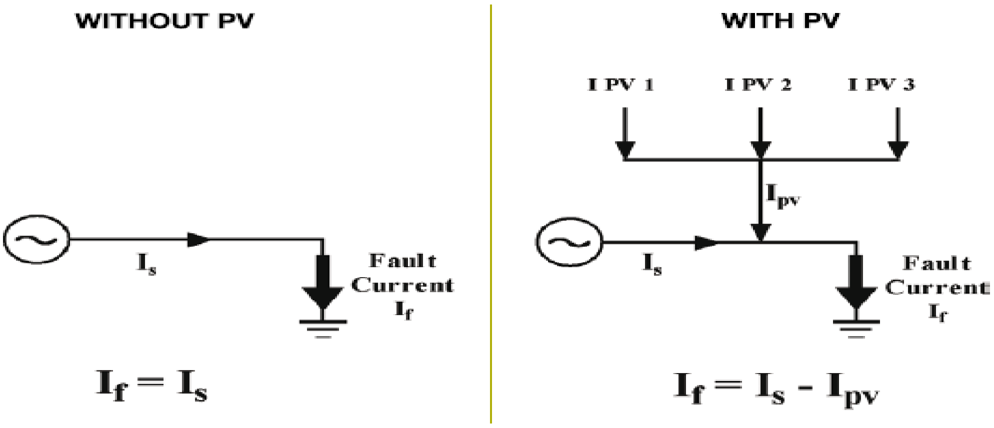
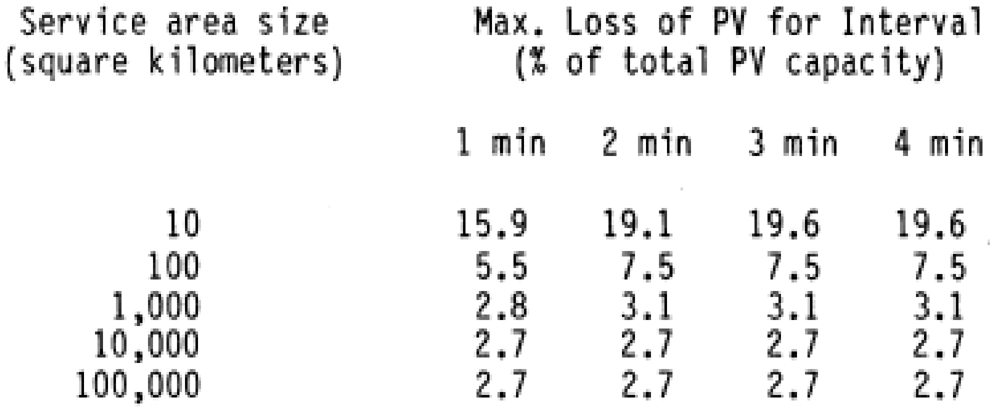


Fig 3. Reduction of fault current due to high PV penetration [40].

Few inverters might not contribute to fault current much, but with high penetration the fault current is reduced to such an extent that it restricts the fault current flowing upstream which makes it insufficient for the operation of the protection device. Thus, in this scenario the PV systems are covering the fault. This could lead to safety risk and also possible destroy the equipment. [40]

5.0 Effects of moving clouds on utilities with dispersed PV:

This study [43] shows how the power output decreases when shadow of clouds passes above a distributed PV system and full generation is resumed once it moves away. To determine this effect, a simulation was done on the cloud patterns and the consequent effect on the PV output in that region. This output is then gathered to analyse its effect on utility. This study was conducted to demonstrate PV generation loss because of cumulus clouds. The possible loss identified in the simulation study for different sizes of area is stated in terms of overall percentage of PV capacity in that area. Time intervals of 1-4 minutes are taken. The Table 1 below shows the loss of PV capacity at each interval in percentage of total PV capacity. Hence, for a $10km^2$ area it demonstrates 15.9% overall PV generation lost in 1 min period which indicates that there will be 159 kW of PV lost in 1 min if there was a 1MW of distributed PV generation in 10 km^2 area. Thus utilities need to have a spinning reserve ready to match the power flow of 15.9% of total power generated from PV in that area in 1 min. Also, there is a possibility of regaining this PV capacity in the next minute. The geographical variety causes the probable loss in PV capacity to reduce as the area increases as evident from the Table 1 where there is 15.9% loss in 1 min in the 10 km^2 area, as opposed to only 5.5% in 100 km2 area. As the size increases the maximum loss is under 3%. [43]



Service area size (square kilometers)	Max. Loss of PV for Interval (% of total PV capacity)			
	1 min	2 min	3 min	4 min
10	15.9	19.1	19.6	19.6
100	5.5	7.5	7.5	7.5
1,000	2.8	3.1	3.1	3.1
10,000	2.7	2.7	2.7	2.7
100,000	2.7	2.7	2.7	2.7

Table 1. Percentage of PV lost with respect to time and area [43].

6.0 Impact of PV on network voltage:

The penetration of grid-connected PV systems tends to raise the voltage at the PCC. The level of increase depends on different network parameters like load variation, power produced from the PV systems and the distribution infrastructure. [6] In the past, the voltage deviations under usual operating situations without DG would occur because of changes in load demand only. This change could be dealt with through voltage regulation in couple of seconds and appropriate feeder design. The existence of PV, whose output is intermittent and changes with meteorological circumstances, makes the normal voltage regulation method ineffective for many utilities. These systems produce a rise in the voltage profile due to the reduction in the total load [33].

6.1 Problem Description:

The effect of voltage rise at the feeder end is completely opposite at the time of peak load on the distribution network, when the load at this point experiences low voltage. Hence, it could be used at such a point where the peak generation meets the peak load, however this is not the case always and so the voltage exceeds the permitted limit. In order to decrease this effect two main suggestions are: one is to restrict the power and second to allow the inverter attached to absorb reactive power. However, IEEE 1547 standard says that operation of Grid connected PV should be at unity power factor and play no role in voltage regulation [7]

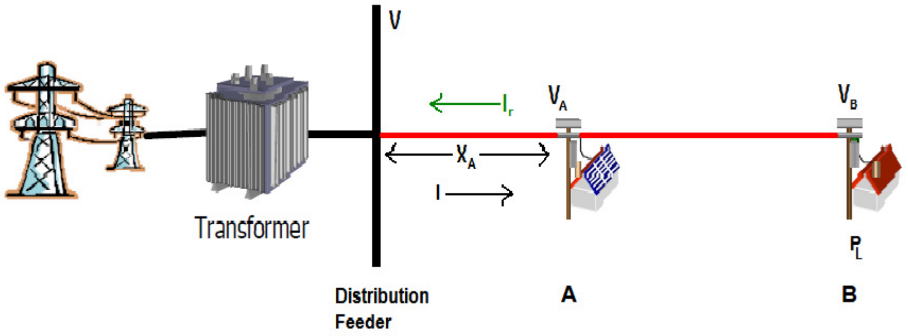


Fig 4. LV distribution network with PV [7]

In the LV distribution network with PV shown in fig 4. DG is at located point "A" and loads after this point are considered lumped together as total loads P_L at point 'B'. Thus at point A voltage is $V_A = V-IX_A$. Where V is the feeder voltage, I is the current between V and 'A' under normal conditions when the DG PV is not generating any power ($P_G = 0$) and

X_A is the impedance between V and ‘A’. When $P_G < P_{L,}$ I is a little less than when it was at $P_G = 0$. But when $P_G > P_L$, the extra power produced is fed back into the feeder. Thus the current flow direction is reversed and now at point A is voltage is $V_A = V+I_rX_A$ where Ir is the reverse current. This shows that the PV generation increases the voltage at the connection point and the power flow reverses when generation exceeds consumption. This feature could reduce losses and deliver voltage support by 3 phase PV generators. But in domestic rooftop systems the voltage could increase at the phase connection as they mostly comprise of single phase converters and thus disturb the equal voltage balance condition for 3 phase balanced power. [7]

6.2 Problem Description in terms of Thevenin equivalent:

In this study the utility power system is represented as shown in fig 5. by its thevenin equivalent where generally the utility series impedance is reasonably low and the drop in voltage is not substantial. But in some places the load current in relation to this impedance could become high enough resulting in too low service voltage (load node voltage). The traditional answer to this would be to raise the voltage at the sending end (Utility_V) in order to keep the service voltage within standard limits. This also means the service voltage under light loads would be rise significantly. Now if a PV unit generates power more than that required by the loads, there will be reverse power flow over the series impedance (Utility_Z) leading to negative voltage drop due to the reverse direction and Now the PV end voltage is the sum of the voltage across the series impedance and the utility voltage. In such a scenario, the service voltage could be pushed above the set limits if the voltage at the utility end is set high enough. [42]

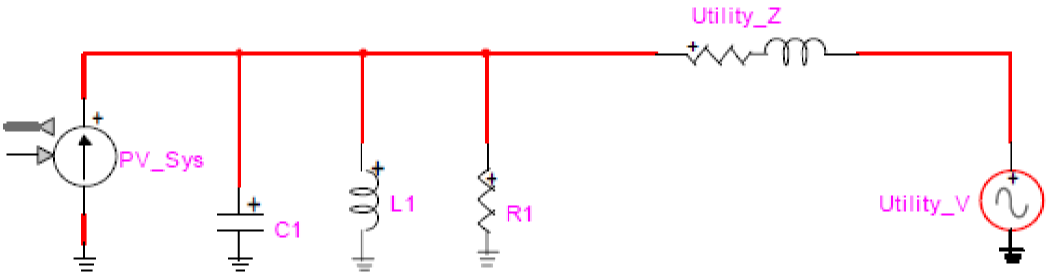


Fig 5. Shows utility source, series impedance, PV system and RLC load [42].

6.3 Techniques to measure voltage unbalance:

Voltage unbalance could be measured mainly by two established methods: one is "Percentage Voltage Unbalance – PVU which is calculated by ration of max. deviation from average voltage to average of three voltages".

%PVU = (max. voltage deviation from the avg. line voltage)/ (avg. line voltage) *100

The second method is "Voltage Unbalance Factor – VUF. It is ratio of negative sequence voltage to positive sequence voltage. It is more precise method. Where phases and magnitude for three phases had to be measured".

%VUF = (negative sequence voltage)/(positive sequence voltage) * 100 [7]

6.4 Traditional methods for Voltage Regulation:

- At MV (Medium Voltage) Distribution level, it is a common practice to achieve automatic voltage regulation via step-up transformers which modify their transformer ratios automatically when their secondary side voltages change. The secondary side voltages can hence fixed close to nominal system voltage by automatic tap changers.

- Other measures would be to install voltage regulators at the line mid-point where the secondary voltage is set higher compared to primary voltage of the regulator.

- The voltage regulation at LV distribution level is performed manually by using the off-load tap changers. The positions of these tap changers are not changed after being set initially unless there are network modification or extension.

- With PV: if voltage regulators are provided on distribution lines, they will operate quite often due to voltage matching arising from changes in the solar irradiation. Hence, their life might be reduced [26].

6.5 Under voltage issue with traditional voltage regulation:

Generally, as the distance from the voltage source and different load types met increases the line voltage decreases. The PV generated power when flowing back in a strong feeder having low impedance is not an issue however; in rural feeder with high impedance it could cause overvoltage. One way to keep this in limits is by controlling the sending end voltage from the transformer bank, This could cause under voltage problems in the other lines with little or no reverse flow connected to the same transformer bank as it is impossible to control sending end voltages for each line individually from the same transformer as shown in fig 6 below. [17]

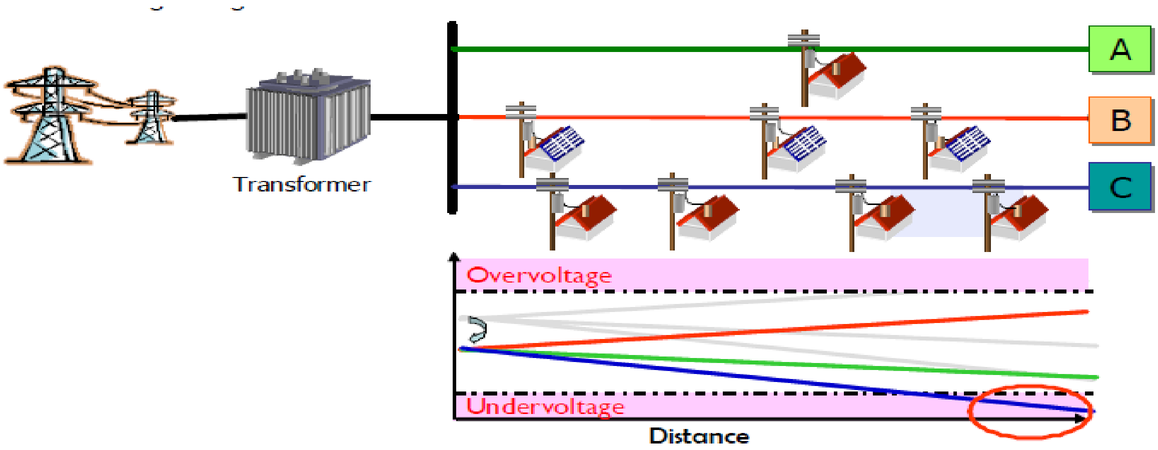


Fig 6. Undervoltage Issue due to elevation of sending end voltage of transformer [17].

7.0 Role of PV in reducing T&D (transmission and distribution) losses

The typical practice for the utilities which are affected by transmission and distribution losses due to overloads is equipment upgrade. A test was conducted in a substation in California, where the data proposed that the T&D rate could surpass the generation rate. Grid-connected PV could benefit the utilities by delaying the upgrades for transmission lines and transformers, improving distribution reliability, decreasing line losses, which all are cost savings. Line losses are caused by current flowing through T&D devices like conductors and transformers etc. The resistance of these devices and the current flow determines value of the losses which could be reduced by decreasing the current or resistance. Decreasing the resistance involves replacing or adding of new equipment, on the other hand decreasing the current involves load reduction or simply meeting this load locally with the help of grid-connected PV. [15]

7.1 Savings from preventing T&D losses.

The two kinds of loss savings defined here are the energy loss and capital loss savings. The capacity loss savings is the amount of savings which is formed due to delaying capital expenditure for a further period. It minimizes the capital requirement for generation, transmission & distribution equipment upgrade by decreasing the peak loads. The energy loss savings is the amount of savings which is formed due to reduction in operation and maintenance cost of prevailing generation plants. [15]

8.0 Strategies to resolve overvoltage issue:

At present due to the increase of grid connected PV systems; the following strategies are proposed here to overcome the impact of overvoltage.

8.1 Japanese rule: Restricting PV output to avoid overvoltage:

In Japan, the utilities have to maintain the LV distribution voltage at 101+/-6 V for single phase and 202+/-10 V for three phase. If the voltage rises beyond the above mentioned limits the PV output is restricted. This will result in PV systems installed at the far end from the substation or distribution transformer to be switched off first as the systems installed here will have frequent overvoltages compared to those installed near to the substation or distribution transformer, This disadvantages those customers at the far end who loose benefit of feed in tariff or cannot compensate their load with PV generation. [13]

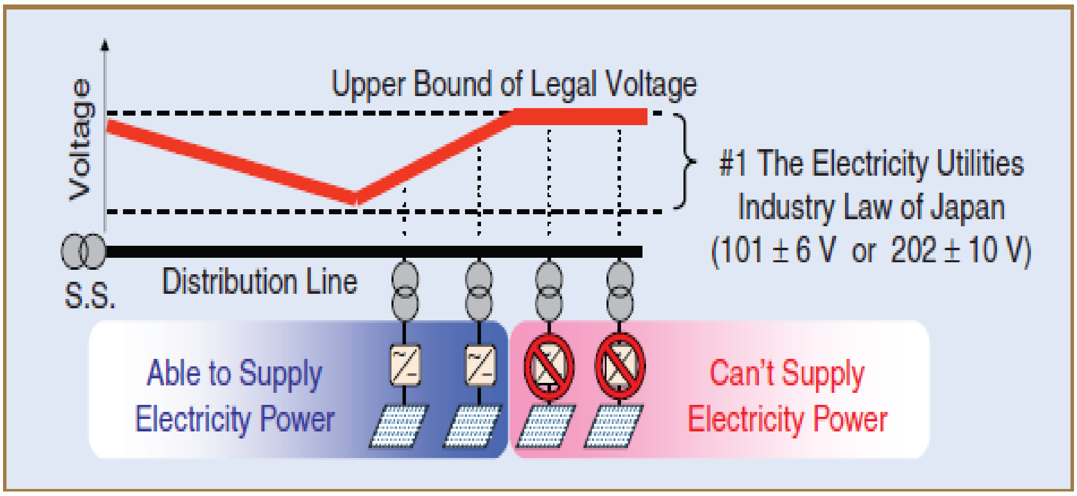


Fig 7. Output power restriction to avoid overvoltage. [13]

8.2 Use of battery to avoid overvoltage.

This study [38] was conducted in Japan, where the distribution line voltage is to be maintained within 202(+/-) 10V or 101(+/-) 6V. The basic model for a PV system incorporated with a battery is shown below in fig 8 [38]

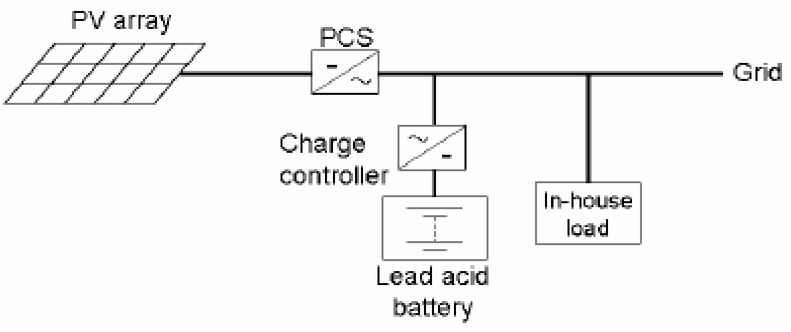


Fig 8. Schematic diagram of PV system incorporated with battery and charge controller [38].

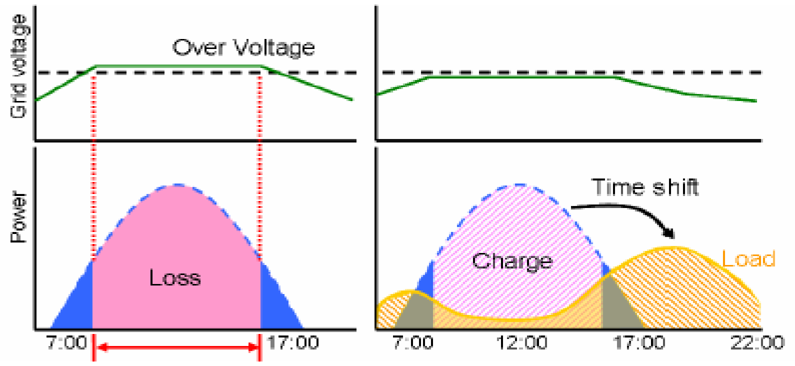


Fig 9. General theory of need for PV incorporated with battery system [38].

Due to reverse power flow from PV systems, when the grid voltage increases to the upper allowed limit, the output power is restricted, this causes energy loss as lot of irradiation is wasted as shown in the left section of fig 9. This loss is a result not only because of a particular system but also due to neighbouring systems on the network. Hence there is a difference of some systems output is zero while others would be still feeding to the grid. This kind of difference intensely relies on PCS type and the line impedance. Those systems experiencing minor overvoltage are connected with low impedance, and the systems have high energy loss which has low value for starting voltage for output restriction. In order to avoid this loss, the PV battery system will charge the battery with excess energy during daytime and use this energy stored at night. [38]

8.3 Three Modes of Battery operation:

A high SOC for (lead-acid) batteries is preferable from the aspect of life time but in order to avoid overvoltage issue the battery needs to have enough capacity to allow charge resulting from reverse power flow situations and this demands lower SOC. In order to fulfil these different needs the battery is shown to be operated in 3 different modes shown in fig 10. Which is 1) “Minimising reverse power” 2) “voltage control” and 3) “schedule” mode?

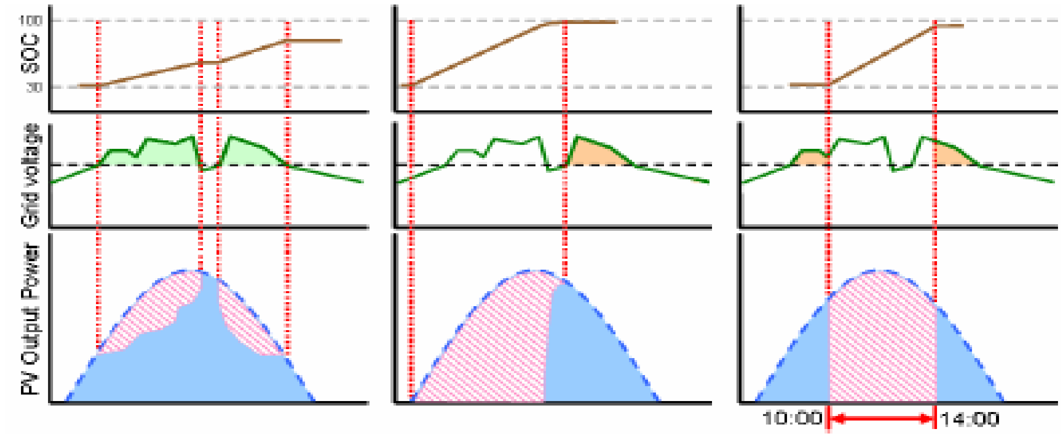


Fig 10. The right chart shows the “Schedule mode”, the middle one the “Minimizing reverse power” and the left one for “Voltage control” [38]

In the “Voltage control” mode when the output terminal voltage of PCS goes beyond the set limit, the battery will start getting charged. The battery will not be charged (apart from the recovery charge) if the voltage is lower then the set limit. This condition is likely to occur during heavy loads and rainy season or prolonged period of low radiation. This mode can decrease the battery capacity although it reduces the losses due to charge and discharge. In the “Minimizing reverse power” mode the battery gets fully charged irrelevant of the time or set limits. Thus, due to the absence of remaining capacity this mode may not be suitable in preventing the afternoon output energy loss. It only helps in keeping the battery state of charge high which avoids battery degradation. In “Schedule” mode , the battery is charged in a certain time period irrelevant of voltage. Suppose as shown in the fig 10. we assume that over voltage generally arises from 10:00 to 14:00, the schedule is set between this time and most of the energy loss can be avoided. [38]

8.4 Reactive power range :

The existing standards for PV-inverter interconnection mandates all inverters in grid-interface mode to function at unity power factor i.e. the inverter is not allowed to regulate voltage by consuming or generating reactive power. Numerous researchers have suggested that, these standards will not be practical for allowing high PV penetration levels on distribution network as the current regulation equipment is insufficient to control two-way power flows and very slow to match the rapidly moving cloud transients. As shown in fig 11. When S (apparent power) is greater than $P^{(g),}$ the reactive power $Q^{(g)}$ can be consumed or supplied by the inverter. Fast voltage regulation can be achieved as the inverter can provide $Q^{(g)}$ rapidly on the cyclic time scale. [20]

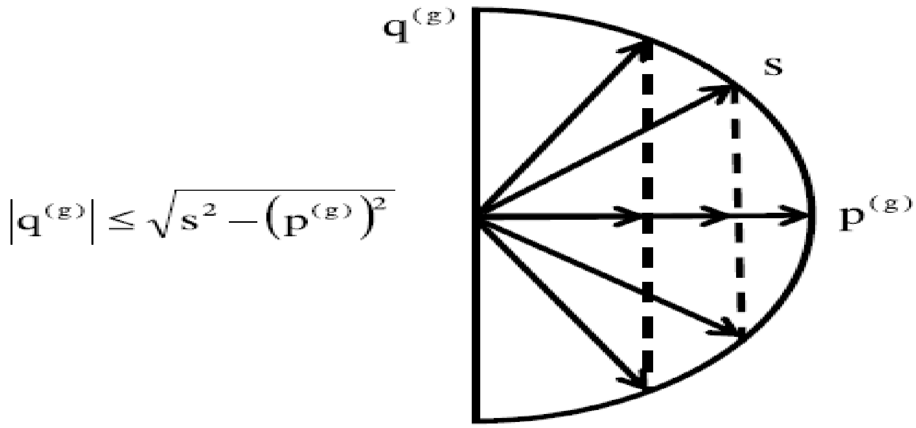


Fig 11. Reactive power absorbed/generated based on apparent power capacity [20]

The comparison between use of reactive power ability of PV inverters with respect to inverters operating at constant power factor mode is analysed in order to improve the voltage quality. The voltage deviation of the PV generator output terminals can be controlled by reactive power flow adjustment from the system however, there is a limit on the amount of reactive power flow that could be absorbed or injected. Let S_{inv} be the apparent power rating of the inverter and P_i is the introduced real power. Assuming the lossless inverter, then the upper and lower limits of reactive power on inverter are:

$$Q_{inv,}\ \text{min} = -\sqrt{Sinv^2 - Pi^2}\ .$$

$$Q_{inv,}\ \text{max} = +\sqrt{Sinv^2 - Pi^2}\ .$$

Hence the reactive power capacity of the system will be $Qinv,min \leq Qi \leq Qinv, max$. [23]

8.5 Inverter capacity for reactive power:

Another example can be shown in fig 12. For reactive power limits available from inverter. Here S indicates the (inverter's ratings or) range of operation by Semi circle for inverter in PQ space. Now, the Power Output is $P_{pv,}$ the inverter operation range decreases to the red line. The Reactive power range is then given by the projecting the point of interaction of the red line with semi-circle on the Q axis. Also inverters function quite fast i.e. switching frequency of microseconds, and they don't create problem of switching transients like capacitors. [10]

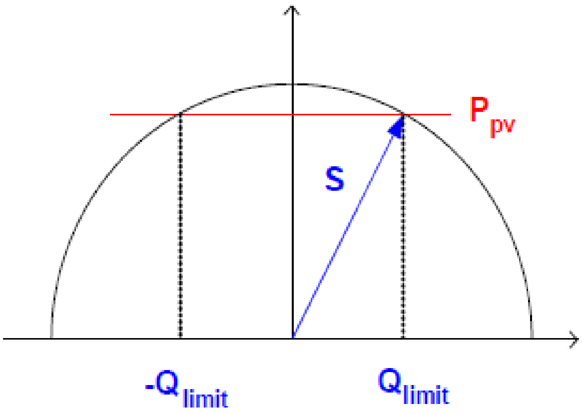


Fig 12. Reactive power limits available from inverter. [10]

The most commonly used solutions to maintain the grid voltage in standard range are use of switching reactor/capacitor banks, storage devices, and LDC (line drop compensator). Nevertheless, PV inverters also can add towards grid voltage support. When a capacity of inverter is raised by 11% of power, it is capable of operating in the power factor range of 0.9 lagging and leading. This surplus capacity could be applied to reduce voltage by reactive power absorption from the grid. This resultant voltage depends on capacity and location of inverter and short circuit power of the grid. Also there is less effect of reactive power compared to active power on voltage regulation of the grid for extremely resistive networks. [9]

9.0 PV Penetration:

"Penetration" is the ratio of capacity of the PV to the overall generating capacity. Two kinds of penetrations are defined here: 1) "Installed penetration" is the proportion of PV capacity installed to the overall capacity of generation installed on utility. It changes when new generation is either removed or installed from service. 2) "Operational penetration" is the proportion of PV capacity installed (currently generating) to the overall capacity at a definite time. It changes continuously with the change in load and insolation. At the penetration level where generation from PV becomes substantial, these systems cannot be considered individual units but their collective impact should be considered. This phenomenon is particularly essential when broken moving clouds cause the output of the PV system to change randomly over time. [43]

9.1 Study on PV penetration level.

From a study [10] done on a distribution feeder to analyse the effect of various PV penetration levels on the voltage regulation where a switched capacitor, (SVR) step voltage regulator is applied in combined form and independently to form different feeder arrangements, the simulation results were as follows:

- The traditional utility equipment can accommodate reverse power flow upto a certain penetration level (Note: here studies were conducted upto 50% penetration only)
- The effect of inverters on feeder's voltage regulation at 5% PV penetration is not significant during peak load.
- The size of traditional voltage support capacitors is decreased by inverters to about 40% at 10% PV penetration.
- The Inverters are sufficient to deliver complete voltage support at 30-50% PV penetration. [10]

9.2 Possible Increase in PV penetration due to lagging power factor:

According to [48], the amount of PV systems that could be operated when feeding at unity power factor is shown in fig 13. Now, it is suggested if the power factor is optimised to 0.9 lagging, the amount of PV on the same feeder could approximately be doubled i.e. from 90 kW to 163 kW of max active power as shown in fig 14. about 80% increase.

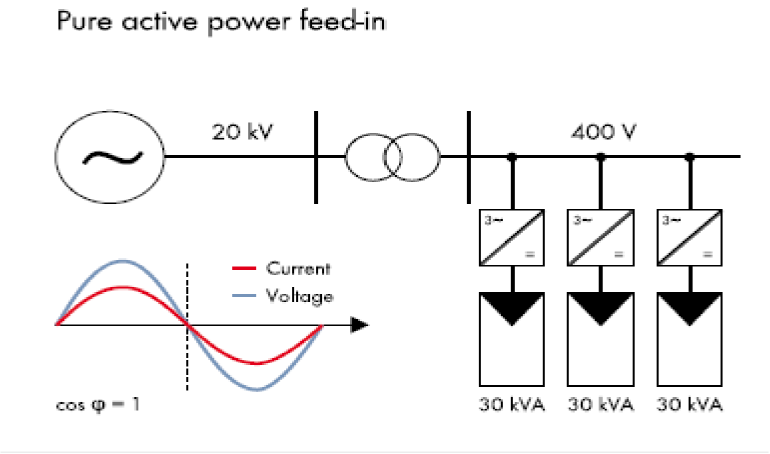


Fig 13. Feed-in power with unity power factor [48].

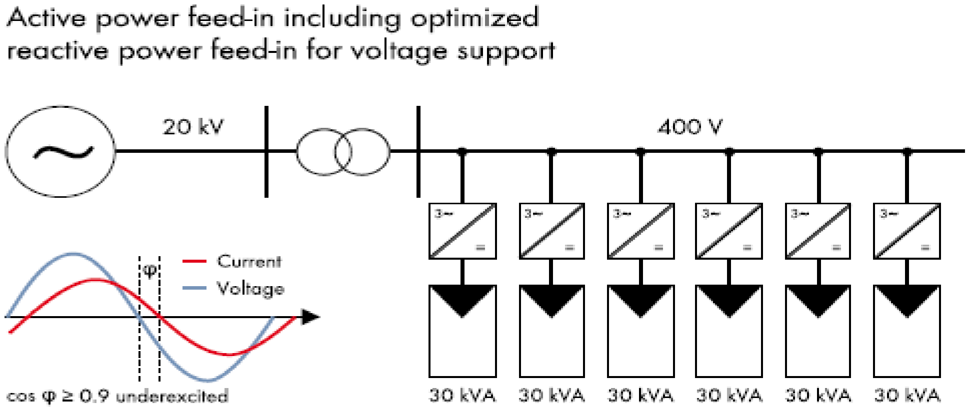


Fig 14. Feed-in of active power with power factor power factor between 0.9 and unity [48].

10.0 Standards and Utility technical rules:

10.1 Review on relevant Australian Standards:

According to Standards Australia clause 5.3 [45], the frequency and voltage limits are as per the following table 3 & 2 respectively. Now, if this range is breached the disconnection device for passive anti-islanding protection will operate in 2 seconds. It also states that the protection device settings should not go beyond the inverter capability.

Voltage	Single – phase system	Three – phase system
Vmin	200 – 230 V	350 – 400 V
Vmax	230 – 270 V	400 – 470 V

Table 2. Voltage limits according to Standards Australia.

Frequency	Range
Fmin	45 – 50 Hz
Fmax	50 – 55 Hz

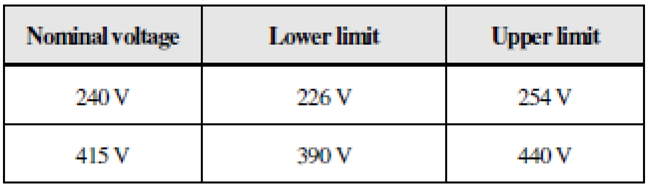
Table 3. Frequency limits according to Standards Australia.

The reconnection of the inverters to the network again (clause 5.6) [45] is done if the above limits for voltage and frequency are sustained for at least 1 min and the inverter is synchronized in-phase with the network. Also there is consideration of graded trip introduction for limiting the continued operation at extreme voltages for extended periods even if it is within limits. [45]

According to Australian standard, (clause 4.4) [46]. the power factor range of the inverter, when regarded as a load from the grid perspective is between 0.8 leading to 0.95 lagging and that is for the range of rated outputs from 20% to 100%. However, the limits are inapplicable if the utility approves the inverter for voltage support purposes. [46]

10.2 Review on relevant WP (Western Power) technical rules:

The voltage limits for LV distribution network is as per table 4 below and the inverter system should remain connected as per this range which is based on average RMS(root mean square) value taken on 5-minute intervals clause 3.7.7.5 [47].



Nominal voltage	Lower limit	Upper limit
240 V	226 V	254 V
415 V	390 V	440 V

Table 4. Voltage range for LV distribution network.

The envelope for LV and HV distribution system temporary over-voltage with respect to time permitted by the utility (here WP) technical rules clause 2.2.10 [47] is given by the following figure 15. Here the percentage voltage level is in reference to the RMS line to line voltage. One important requirement regarding the overvoltage issue added in the revised edition of the WP technical rules is clause 3.2.1 (a) [47] which states that the users who are intending to connect their equipment to the border of the distribution systems where it is not compatible with a particular high voltage connection point shown in fig 15. could request the utility to carry out a study to determine the maximum overvoltage at the desired connection point. The user is responsible for the study requested. [47]

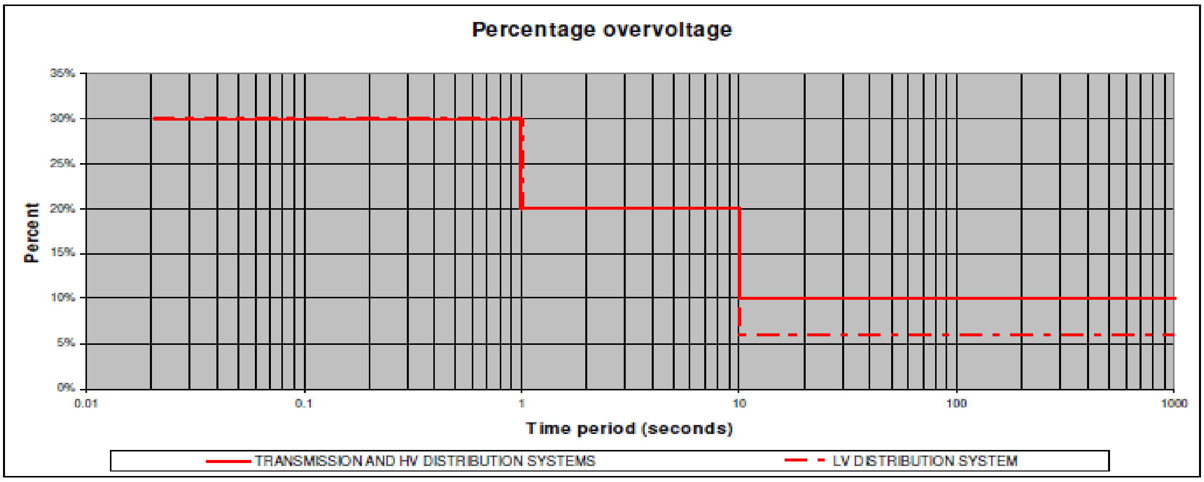


Fig 15. Percentage level vs. time period of temporary AC overvoltage. [47]

The negative phase sequence voltage component limit clause 2.3.5 [47] for system below 10 kV with respect to the positive phase sequence voltage component is 2%. Clause 3.2.1 (d) [47]. The user must balance at the connection point the current drawn from all 3 phases in order to attain a 10 min average negative sequence voltage level mentioned above. [47]

10.3 Important Revisions in the 2011 updated WP Technical rules:

- The revised rule for reactive power capability clause 3.3.3.1 (b) [47] states that all every generating unit should vary the reactive power at point of connection within maximum export and import level. This feature should be continuous and independent of any switched devices except OLTC (Online Tap Changer) which is a component of unit's transformer. Also 3.3.3.1 (e) [47] states that if the generating unit is unable to provide the power factor proficiencies mentioned in clauses 3.3.3.1. (c) [47], an extra reactive power source must be included inside the facility.

- The revised rule for power quality 3.6.8 (c) [47] states that the connection point voltage rise at steady state because of power exported must not result in voltage limits to go beyond those stated in clause 2.2 [47] and not exceed 2% if agreed with the utility. This limit could be waived if the utility contracts the generator for providing voltage control. This waiver is expected to be mandatory at the border of grid locations. [47]

- The revised rule for energy system capacity clause 3.7.2 (a) [47] states that the utility will be responsible for the assessment of connecting the following systems when operated at their full rated capacity should meet the standards stated in clause 2.2 [47]: 1) PV connections for single phase with rated capacity greater than 5kVA, and 2) PV connections for 415 V three phase with imbalance greater than 2.5 kVA between any two phases.

11.0 Observations from voltage measurements on grid connected PV systems:

11.1 Procedure:

Most of the measurements are taken on a sunny day and a cloudy day is avoided in order to get stable readings. The appointment to the system owners is done in advance after looking at Perth weather report for the day. A standard DMM is used to measure the voltage in the house, by connecting it to the nearest plug socket from the PV inverter. The DMM is first turned ON and a stable voltage reading is taken when the PV system is generating. i.e.

phase to neutral voltage. Then the shutdown procedure for PV systems according to Australian standards is followed i.e. Switch OFF the AC isolator, then switch OFF the DC isolator. As soon as the DC isolator is switched OFF another stable voltage reading is taken when the PV is not generating any power. Now, the DC isolator is switched back ON and AC isolator is switched ON after that. The power was measured from the respective inverter units. There are 7 residential readings taken and 1 commercial i.e. in Murdoch ROTA (rise outdoor test area) centre. The readings are as follows:

1) **House A :**	
Location	: Nedlands, 6009.
Rated Power	: 2.2 kW
Distribution System	: Underground
Power Supply	: 3 Phase
Weather	: Partly cloudy day with few showers
Time	: 14:16 PM
Power Output	: 1.525 kW
Voltage when PV ON	: 242.4 V
Voltage when PV OFF	: 240.1 V
Voltage difference	: 2.3 V

Table 5. House A measurements

2) **House B :**
Location : Hammond Park, 6164.
Rated Power : 1.52 kW
Distribution System : Underground
Power Supply : 1 Phase
Weather : Sunny day
Time : 10:32 AM
Power Output : 1.085 kW
Voltage when PV ON : 250.1 V
Voltage when PV OFF : 246.7 V
Voltage difference : 3.4 V

Table 6. House B measurements

3) **House C1 :**
Location : Hilton, 6163.
Rated Power : 5 kW
Distribution System : Overhead
Power Supply : 3 Phase
Weather : Sunny day
Time : 11:50 AM
Power Output : 4.271 kW
Voltage when PV ON : 255.4 V
Voltage when PV OFF : 246.8 V
Voltage difference : 8.6 V

Table 7. House C1 measurement

4) **House C2 : (Neighbour)**	
Location	: Hilton, 6163.
Rated Power	: 5 kW
Distribution System	: Overhead
Power Supply	: 3 Phase
Weather	: Sunny day
Time	: 12:05 AM
Power Output	: 4.290 kW
Voltage when PV ON	: 250.1 V
Voltage when PV OFF	: 243.2 V
Voltage difference	: 6.9 V

Table 8. House C1 measurements

5) **House D : (Rural Feeder)**	
Location	: Bridgetown, 6255.
Rated Power	: 3 kW
Distribution System	: Overhead
Power Supply	: 1 Phase
Weather	: Sunny day
Time	: 15:30 PM
Power Output	: 0.500 kW
Voltage when PV ON	: 249 V
Voltage when PV OFF	: 247 V
Voltage difference	: 2 V

Table 9. House D measurement

6) **House E :**	
Location	: Bull Creek, 6149.
Rated Power	: 3 kW
Distribution System	: Overhead
Power Supply	: 3 Phase
Weather	: Sunny day
Time	: 11:35 AM
Power Output	: 1.681 kW
Voltage when PV ON	: 241.5 V
Voltage when PV OFF	: 238.6 V
Voltage difference	: 2.9 V

Table 10. House E measurements

7) **House F :**	
Location	: Kensington, 6151.
Rated Power	: 3.04 kW
Distribution System	: Overhead
Power Supply	: 3 Phase
Weather	: Sunny day
Time	: 11:46 AM
Power Output	: 1.857 kW
Voltage when PV ON	: 252.5 V
Voltage when PV OFF	: 251.6 V
Voltage difference	: 0.9 V

Table 11. House F measurements

8) **ROTA test centre : (commercial zone)**	
Location	: Murdoch, 6150.
Rated Power	: 1.44 kW
Distribution System	: Underground
Power Supply	: 3 Phase
Weather	: Sunny day
Time	: 12:20 PM
Power Output	: 0.648 kW
Voltage when PV ON	: 242.7 V
Voltage when PV OFF	: 242.4 V
Voltage difference	: 0.3 V

Table 12. ROTA centre measurements

11.2 Results and discussion:

House A: It was a fairly cloudy day with a few showers show less solar irradiation and with an underground distribution system, the grid is considered to be strong with low impedance value so less effect on voltage rise i.e. a voltage difference of just 2.3 Volts (table 5) compared to other test conditions. This shows even though minor but there is an effect of the PV on the LV distribution system.

House B: It was a sunny day. The location of this system was in one of the newly built suburbs of Perth, where most of the houses are given single phase power supply with an underground distribution system. Voltage rise of 3.4 Volts (table 6) is due to the system.

Houses C1 & C2: This was the most interesting observation of this project and also an important example for the adverse impact of high PV penetration level on the existing grid. Both the houses were connected to 3 phase power supply overhead system network which is weak grid having high impedance and quite far from the nearest distribution pole transformer. The effect of 5kW PV system on the House C1 voltage is significant with a voltage rise of 8.6 Volts (table 7) and also on House C2 voltage with a rise of 6.9 Volts (table 8). From the system owner of House C1, it was found that in the past when House C2 did not install the PV system their PV inverter would run smoothly during peak sun hours of the day. However, since their neighbour House C2 also installed a 5kW PV system; the House C1 inverter would trip quite often during peak sun hours. As a consequence of this house C1 contacted the utility (WP) which came to notice that the two systems were on the same phase and after connecting their system on a different phase this issue was resolved. One important point to be noted here is the utility (WP) is supposed to keep a record of the number of systems installed on a particular feeder or a phase before giving approval to houses like house C2 in order to avoid such events. It was noticed that even after changing the phases of the two systems, the upper limit of the voltage is still above the voltage range specified by WP technical rules [47]. Thus, this confirms the fact that the PV penetration level has considerable effect on the voltage if there is phase unbalance and many systems are connected on the same phase or same distribution feeder.

House D: This system was connected to a rural feeder with single phase power supply. The interesting fact about this observation was this system was producing 1/6th of the rated power and still causing a voltage rise of 2Volts (table 9). Hence, if the system was performing at its best the voltage rise could be 12 Volts which is 5 volts higher than the upper limit of WP technical rules. It is found that there is significant effect of PV on the voltage rise on the weak rural network.

House E: It was sunny day. A typical house with PV system facing not completely south with an underground distribution system. The PV system resulting in a voltage rise of 2.9 volts (table 10). It again shows the strong grid system keeping the upper limit of voltage near to the nominal value of the WP technical rules.

House F: This observation was quite different from the previous ones as there was hardly any effect of PV. A voltage rise of 0.9 volts (table 11) only was observed and that also bounced back after a while to the normal value. After discussing with the system owner it was found that there was a pole mounted transformer recently replaced in the street which was less than 100 metres away from the PV system which satisfies above theory of less effect of PV on the voltage if near to the transformer or substation.

ROTA: As expected there was hardly any voltage rise effect due to the PV, the readings were taken for 2 hours with a 20 min interval and the maximum voltage difference observed was of 0.3 volts (table 12). I suspect only one out of two strings is operating (working) from the output power at solar noon. This was due to the fact that the ROTA is located in a commercial zone with strong underground grid distribution network.

Success of the Analysis: The purpose of these measurements was to prove the fact that the voltage rise is not an issue in a certain feeder or particular type (UG/OH) of distribution system, but wherever these grid connected PV systems are installed. Out of 8 systems 7 systems showed a voltage dip after the PV was turn OFF. Thus, this is the success for the analysis.

12.0 Conclusion:

An investigation into the major technical issues associated with PV penetration on the existing electrical grid is presented in this report. The paper starts with the desktop study of past studies done in this area to understand the effect of distributed generation in general and PV in particular on existing network infrastructure. After a brief overview over the different impacts of PV on the grid like the effect of PV generation on distribution transformers, masking of fault currents, the effect of moving clouds on utilities with dispersed PV, the report focuses on the impact of voltage rise due to PV penetration. The level of penetration and loss savings due to PV support is also analysed.

The different strategies proposed to overcome the effect of overvoltage are presented. Japan for example has a policy to restrict the power output if the voltage goes beyond a set limit, battery charging during excess voltage, and the most suitable scheme of providing reactive power support through PV inverters to control the voltage is studied.

Finally, the observation is done for the voltage measurements taken from the 7 residential rooftop grid connected solar PV systems are presented and discussed. The results were quite typical except one or two systems due their location or load distribution. The most interesting observation was from Houses C1 & C2 confirming PV impact in producing extreme voltage levels, the results of which fulfils the basis for this study.

The contribution of PV in overall electricity generation is outstanding; recently on a Saturday Germany produced 22GW/hr. (gigawatts) solar power which fulfilled approximately 50% of midday electricity needs for Germany which is a record breaking amount of electricity production from PV for any country to achieve for the first time. [49]

13.0 Recommendations:

1) Develop a group of recommended strategies for integrating existing techniques for voltage control with High PV penetration on different feeder topologies.

2) To add communication infrastructure for improved distribution system and demand-side management.

3) To develop an analysis software which has a database of recommended strategies with different existing control options which are used for overcoming issues. It will help in solving a particular situation.

4) The utility should approve customer a PV connection to a phase which is well loaded during the course of the day.

5) The utility assessment should be made that the household loads for a three phase supply are evenly distributed by the PV installers/electricians.

6) Demand side management should be encouraged with respect to the PV generation to lower the stress on LV networks.

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Acronyms

AC	Alternating Current
DC	Direct Current
PV	Photovoltaic
RECs	Renewable Energy Certificates
LV	Low Voltage
HV	High Voltage
DG	Distributed Generation
T&D	Transmission & Distribution
AS	Australian Standards
WP	Western Power
PF	Power Factor
RLC	Resistor Inductor Capacitor

ROTA	Rise Outdoor Test Area
PCC	Point of Common Coupling
OLTC	Online Tap changer
SOC	State of Charge
RMS	Root Mean Square
DMM	Digital Multimeter