



An Experimental Study to Investigate PQ Impacts in a Grid Connected PV System

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Abstract: Grid integrations of Renewable Energy (RE) is identified as one of the most prominent energy technologies to meet the growing energy demand and to build a sustainable society for future. RE resources such as rooftop PV and small wind turbines when connected to the grid will have substantial potential supply electricity with negligible impacts in network. On the other hand, grid integrated with large-scale RE resources results in adverse impacts and increases the network utility concerns especially issues involved with power quality of the distribution networks due to the intermittent nature of solar PV and wind. Hence, there is an emergent need to analyse the impacts of grid integrations for reliable power generation and distribution. The main intent of this paper is to investigate and analyse Power Quality (PQ) impacts in a network by an experimental approach. Renewable Energy Integration Facility at Commonwealth Scientific and Industrial Research Organisation (CSIRO), Newcastle, Australia had been used and different experiments were proposed and analysed with various power sources and highly controllable loads. A great deal of attention has been paid in analysing PQ impacts-voltage variations, power variations, Power Factor (PF), voltage unbalance and neutral currents using low voltage mini grid facility.

Keywords: Impact Analysis, Solar PV, Wind, Integration, Power Quality

1. Introduction

In recent years, integration/deployment of RE resources in to grid is identified as the most promising energy technologies, conserving fossil fuels and reducing the flow of greenhouse gases (GHG) that spur global warming due to fuel exhaustion. Among the renewables, solar PV and wind are proved to be the fastest growing energy integration technologies due to their significant potentials with increased reliability during grid integrations. From the literature [1] it is clear that the solar energy will be exploited effectively in modern power generations fulfilling 28% of the world's energy demand by 2040. Reports of International Energy Agency (IEA) on renewables envisage that wind energy contributes up to 18% of world's electricity by 2050 [2]. Among the developing countries, Australia has been identified as one of the world leaders in the initiation and development of research projects investigating the integration of renewable energy on centralized electricity grids. Recent

update from Energy Network Association (ENA) in partnership with Australian Renewable Energy Agency (ARENA) - a major driver of innovation and research in RE enhances this fact effectively [3]. In addition, research analysis from the past five years evince that, Australia is well placed to effectively utilise the wind and solar PV technologies due to the high power consumer electronic applications and there had been a rapid growth in the penetration levels of PV and wind as seen by the grid [4-6]. As per the research estimations, by 2030 distribution generation is predicted to meet 40% of Australia's energy requirements with the main producer to be the grid connected PV due to its extensive feasibility [7]. Report published by Australian Energy Recourse assessment [8] states that the share of wind energy in total electricity generation is projected to increase by 14% by 2030.

Besides the advantages of RE deployment in a network, large scale integration of wind and solar PV is projected as one of the major potential challenges for modern power

system since it adversely effects the Power quality PQ of the system, based on the network design and grid connection characteristics [9]. Hence, there is a greater importance and essentiality to study such networks, especially a phenomenon to analyse and estimate the impacts of solar PV and wind integrations at the distribution side. All over the world, there are many research literatures available on impacts of grid connected PV (GCPV) systems and grid connected wind systems (GCW) analysing Power Quality (PQ) issues. N. Srisaen and A. Sangswang [10] conducted research on grid connected PV system with 10% and 25% PV penetration levels with respective to the load on distribution side. From their analysis it can be clearly seen that there was a rise of voltage level of around 0.996 p.u when the penetration level changes from 10% to 25% regardless of their installation locations. Ali et al [11] research study on impact of high penetrated GCPV system on distribution network in UK portrayed that with 25% and 50% PV penetrations, the voltage at LV nodes are maintained within the statutory limits (+1.1 and -0.94 p.u) whereas with 100% PV integration, the observed voltage levels were above the statutory limits of the nominal voltage. In [12], voltage regulations issues were dealt on a public service company :Oklahoma system, considering the cloud effect over an area with high PV penetration levels. From the authors research study it was concluded that at penetration levels of 15%, cloud transients were found to be significant. However, the observed power swing issues were solvable at the system level, and hence 15% was deemed to be the maximum system penetration level. In [13], Thomson and Infield found that at 50% penetration distribution system losses were reduced below the base-case values, largely due to the of reductions in transformer loading. Voltage dips due to cloud transients might be an issue at 50% penetration, and the authors suggest further study of this issue is required to analyse the further consequences. In [14], a network was modelled in PSCAD using common feeder characteristics and investigated potential voltage rise issues in the network with 0% to 11.25% and up to 75% LV transformer capacity penetration. Results of this research study indicated that the PV penetration level should not adversely impact the voltage on the grid when the distributed PV resources do not exceed an average of 2.5 kW per household on a typical distribution grid. Variations of wind speed results in power variations causing voltage fluctuations and also injection of harmonics in to grid may also create voltage distortions at PCC, was well explained in [15, 16]. Rona and Guler [17] enormously analysed the impacts of wind on Turkey power grid and from their case studies it can be effectively confirmed that the role of reactive power control of the wind turbine in maintaining the voltage levels of the network is crucial to maintain the voltage proportionalities as per the installed capacity of the wind turbine. From [18], it was observed that with a combination of SVC and 24.55% of wind penetration level the observed transient and voltage stability in the network are in stable condition. Results of [19], analysed level of voltage and power variations in grid during solar PV and wind integrations. The influence of wind turbines on consumer

voltage quality is studied [20]. A frequency domain approach to wind turbines for flicker analysis is presented [21].

Literature reviewed from these papers suggests that there is an extensive need to study a system performance to estimate the level of impacts during RE integration to apply and monitor the control measures for grid stability higher RE integrations. For instance, to improve and maintain the voltage profile at distribution side, it is essential to implement voltage-regulating techniques based on the estimation level of voltage variations at LV nodes with a change of solar PV penetrations in the LV network. These voltage variations at LV bus nodes can be estimated through impact analysis study of GCPV considering different penetration levels in a network. From the above literature it can be seen that most of the impacts were analysed on software simulations and very there is a limited research was available using experimental setup. The main contribution of this research paper is an to study and investigate the PQ impacts in grid using experimental analysis at CSIRO[22], Newcastle, Australia. Next sections of this paper is organised as follows: Section 2 details the effects on grid with RE integration, a great deal of attention has been paid to investigate the impacts using experimental setup in section3. Results and discussions were examined in section 4 and finally section 5 concludes the current research study.

2. Effects on Grid with RE Integration-PQ Issues and Network Standards

The uncertainty and variability of wind and solar generation pose certain challenges for grid operators. Hence, to reliably operate a grid connected renewable energy system there is an emergent need to study the power quality issues as it may pose threat to the system due to the intermittent nature of wind and solar PV. Power quality issues include voltage fluctuations/variations, power variations, poor power factor, harmonics, frequency imbalance.

2.1. Voltage Fluctuations

The voltage measured from phase to neutral or phase to phase for electricity that is supplied at a connection point is termed as the supply voltage. Small increase or decrease in steady state voltage supply voltage for short duration due to changes in load and tap changes on network equipment results in voltage fluctuations. Regular occurrence of these voltage fluctuations is termed as flicker, which is a measure of the magnitude of the voltage variation and frequency with which it occurs. The intermitted nature of the wind and solar PV is one of the reasons for voltage fluctuations in grid connected systems. In case of grid connected PV systems, irregular solar irradiance caused by the passing clouds, PV installation area, and the selected angle of incidences/reflections plays a major role in driving the system to instability by means of voltage fluctuations. Similarly, for direct-connected wind turbines voltage

fluctuation is a serious issue as these turbines produce power which is dependent on the variations of the wind speed and inject it without conditioning into the grid [23]. This irregular fluctuations cause flicker noise, overloading issues, line losses and network losses in the distribution network. In addition, excess variation of voltage also creates a negative influence on the quality of energy supply and disturbs performance of sensitive electric and electronic equipment connected to the grid.

2.2. Voltage Raise and Reverse Power Flow

Traditional centralised power networks allow power flow in only one direction whereas with the introduction of distribution generations in modern power networks localised overvoltage can occur, and the voltage at the load end may be greater than the voltage on the normal supply side of the line – resulting in voltage rise and reverse power flow [24].

The most critical impacts of reverse power flow are:

- Activation of network protection devices designed to stop 'upstream' current flow.
- Destabilisation of voltage regulators' control systems.
- Voltage rise can have negative customer equity impacts for system owners towards the end of the line as the voltage rise will be greater at that point.

For instance, the excess power generated by the solar PV during lower demands should export the active power to the grid which could result in voltage rise or reverse power flow affecting the utility grid and household appliances leading to other safety and protection challenges.

2.3. Power Output Fluctuations

Power fluctuations arise due to variations in supply. For instance, when a power plant stops producing output, or due to rigorous variations in demand [25]. Fluctuations in power output are a major concern for distribution generation systems reliant on solar PV and wind. Based on the duration of occurrence, these fluctuations are categorised as follows short term and long term. Short-term fluctuations occurs in seconds and can cause problems with power quality including both voltage and power factor. Short-term fluctuations can also result in tap-changers. Wear and tear of the devices also increases due to the frequent variation in capacitor switches as they attempt to maintain power quality. In addition, number of switching surges also increases due to short-term power variations. On the other hand long- term fluctuations require back-up generation or spinning reserve to maintain power supply [23].

2.4. Power Factor

Power factor is a measure of the phase difference between the voltage and current in an AC power system or it is defined as the ratio of the active power to the apparent power. Supply of reactive power is very important in an AC power system and the amount of reactive power produced must closely match to that which is being consumed to avoid under and over voltage supplies in the network. Grid operated PV

systems normally operate at unity power factor and the power produced by the PV units is 100% active power and 0% reactive power. Hence, when grid is integrated with PV, the grid still has to still supply excess reactive power to maintain the optimum PF as PV does not support any reactive power. During this process, the regular power flow of the system may have the adverse effect due to the insufficient reactive power and may decrease the power implying insufficient transmission [26]. On the other hand wind turbines, especially inductive machines, tend to absorb reactive power from the system and results in a low power factor. If this process continues, the system can become highly unstable. New advancements in the design process of wind generators effectively utilize power electronics and variable-pitch turbines that allow the wind turbine to produce energy at various wind speeds. The same power electronics regulate the turbine's output voltage while maintaining the power factor close to unity [27, 28].

2.5. Unbalance Voltage and Neutral Current

Unbalance voltage and current is referred as one of the main PQ issue in power system network. It is defined as deviation in magnitude of voltage or current of any one or two of the three phases from its rated value with respect to the magnitude and phase angle. Unbalance in LV network may occur due to the following reasons [29, 30]:

- Uneven distribution of single phase loads
- Uneven power generation from single phase type power sources
- Unbalanced three phase loads
- Unequal impedance of three phase distribution network etc.

An unbalance in a network can result in excess drawl of reactive power, mal-operation of protective system, the performance of power metering devices can be de-rated, reduce life span of electrical appliances, increases the power loss etc. Specifically, voltage unbalance creates thermal stress for Variable Speed Drive (VSD) electronic components with the effect of triple harmonic current. During current unbalance, negative sequence component appears and it increases net current in some phase and decreases net current in other phases resulting in unequal loss in phases and unequal heating. Excessive neutral current level due to the effect of unbalance, leads to overloading of the distribution feeder and transformer with addition of creating heat losses. [29-31]. There are two standard methods used to evaluate unbalance voltage and current in network. The IEC (International Electro-technical Commission), which applies the symmetrical components for unbalance factor calculation and the NEMA (National Electrical and Manufacturers Association) method, which applies magnitudes of system voltage or current.

IEC method:

$$VUF = (V_- / V_+) \% \quad (1)$$

$$IUF = (I_- / I_+) \% \quad (2)$$

V_+ and V_- represent the root mean square (RMS) values of the positive and negative sequence components respectively.

As per NEMA, VUF [31] can be calculated using Equation 3.

$$VUF = \frac{V_{mean} - \max(V_{ab}, V_{bc}, V_{ca})}{V_{mean}} \quad (3)$$

where V_{ab} , V_{bc} , and V_{ca} , are the line voltages, and V_{mean} is average values of V_{ab} , V_{bc} , V_{ca} and

I_N is calculated as per Equation 4.

$$I_N = \sqrt{I_a^2 + I_b^2 + I_c^2 - I_a I_b - I_b I_c - I_c I_a} \quad (4)$$

Where I_a , I_b , I_c are the phase currents.

2.6. Harmonics

Harmonics are the alternating components having frequencies other than fundamental present in voltage and current signals. A periodical deviation of frequency for voltage and current wave forms from that of the fundamental frequency causes Harmonics. Within the power plant, there are many components that can resonate with one another and create harmonics. For instance, cables, transformers, shunt switched banks and other reactive elements resonate to produce harmonics within the system. Additionally when system is integrated with PV and wind the impact of harmonics is adverse. In case of GCPV systems, inverters inherently create current harmonics at the collector bus, due to the internal switching of the converter insulated gate bipolar transistor. If this persists for longer durations and if the system is not well tuned, the presence of excessive current harmonics may force solar inverters to trip offline and cause unnecessary heating and losses on cables and transformers. The situation reinforces the impact and worsens the system if there are existent background harmonics on the grid [32]. In addition inverters used for conversion of DC current to AC current, inject voltage harmonics and current harmonics to the system and will result in power harmonics. As the number of inverters increases the system becomes highly unstable and unreliable due to the overheating in capacitor banks and transformers.

2.7. Voltage Standards

Under normal operating conditions, Ausgrid's objective is to maintain a target steady state phase to neutral supply voltage within the range of 216 V to 253 V for electricity that is supplied at connection points. This range is the nominal voltage range of 230 V in Australian standard AS600038 Standard voltages, following a tolerance of +10% /-6% to allow the possible voltage regulation with in the network. However, during abnormal conditions it may not be possible to maintain the target steady state voltage due to system constraints and physical network limitations. Hence Ausgrid's objective is to maintain a steady state voltage of 207 to 262 V maintaining a tolerance of +14% /-10% at all times. In addition, for low voltage networks in AS/NZS 610002.2, Ausgrid's objective is to limit the flicker to less than the compatible levels. For Ausgrid's low voltage

networks, the compatibility level for short term flicker is $Pst=1$ and for long term flicker is $Plt=0.8$ [33].

2.8. Unbalance Voltage

As per Australian standard, the maximum allowable unbalance voltage level for LV network should be around 3%. The allowable range of unbalance voltage level over the average period of 1 minute, 10 minutes, and 30 minutes are 3%, 2.5%, 2% and 2% respectively [33, 34].

2.9. Harmonics Limits

As per AS4777-2005 standard [35], maximum limit of current harmonics injection from grid connected PV inverter should be less than 5 % and from (ref) As per AS/ NZS 61000.2.2 [33], compatibility level of voltage THD in LV network distribution network should be less than 8%.

2.10. Power Factor Standards

The following are the standard power factors considered during this research analysis [36].

Table 1. Standard power factor.

Supply voltage and maximum demand	Up to 100VA	Over 2MVA
< 6.6kV	- 0.75 to +0.8	- 0.85 to + 0.85
6.6Kv, 11kV and 22kV	-0.8 to +0.8	- 0.9 to + 0.9
66kV	- 0.85 to +0.85	- 0.95 to + 0.95

3. Experimental-Setup

To investigate and analyse the network impacts a series of experiments were conducted using REIF at CSIRO, Newcastle, Australia. At CSIRO, a low voltage mini grid facility is available with various power sources and highly controllable load banks. Mini grid facility is comprised with a 50kW rooftop PV system as a primary RE resource. A 300W solar PV micro inverter (ABB Power-One Aurora Micro -0.3.I.OUTD) was used as a single phase inverter. This specification is distributed as 7kW, 7kW and 11kW in phase 1, phase 2 and phase 3 respectively. In addition, two solar PV modules with each 12.5kW is integrated with 15kVA three phase inverter (SMA Sunny (15000TL) Tripower Economic excellence). A 64kVA load bank was effectively operated with both manual commands and with programmed load profile (typical). Distribution boards (DB) are available with Data acquisition units (DAQ) for collecting the required data with respective to grid (DAQ-DB), PV (DAQ-PV), load bank (DAQ-load) and the turbine (DAQ-turbine). Data Acquisition (DAQ) system has the flexibility to collect the power system network data at higher sampling rate (50000 samples/second) effectively.

For continuous performance monitoring and control, effective user interface was also developed at CSIRO using Supervisory Control and Data Acquisition (SCADA) and Lab-view. Considering the robustness and the flexibility of the power devices a series of experiments were conducted

with various PV capacity combinations network using the switching facility available at the inverters to observe the level of impacts. In addition to the solar PV, a 2kW wind turbine is also available at CSIRO. Due to the poor performance of this wind turbine during the day of

experiments, this study is limited to only solar PV. However, a typical wind profile varying in seconds level and the active power set point as per varying typical wind profile was fed to the micro turbine controller to analyse various impacts. Fig. 1 shows the connection layout diagram at CSIRO.

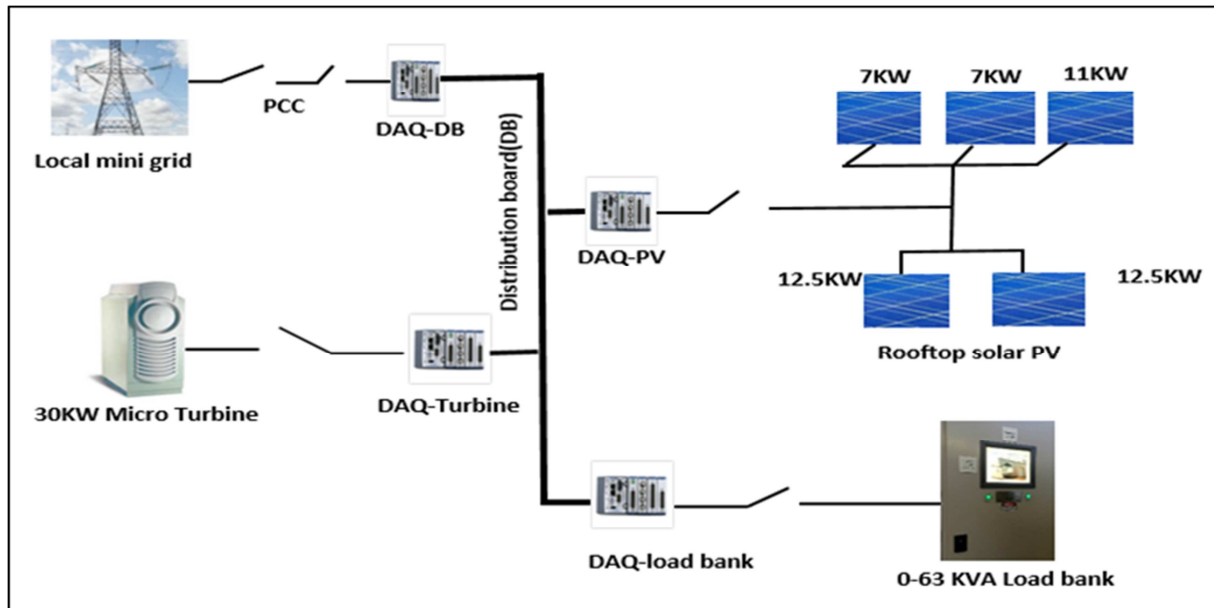


Fig. 1. Network layout at CSIRO using REIF.

4. Results and Discussion

4.1. Experiment 1: Rooftop PV Power Variation and Load Variation

(i) Power-variations

Considering the maximum solar irradiation, a series of experiments were conducted during 9:30 am to 3:00 pm with variations in load and PV. During this analysis, load was varied from a minimum of 0kW to maximum of 40kW and using the switching facility of the inverters different PV

combinations were chosen to vary the power level of PV. The maximum active power of PV was observed to be varied from a minimum of 3kW to maximum of 38kW following different steps and Fig. 2 depicts the variation in power levels of load and solar PV. This complete analysis is performed with in a time frame of 7 min considering the robustness of the devices. With reference to these loads and PV variations, corresponding grid power variations were observed and from the Fig. 3 it can be clearly seen that the maximum and minimum power variation of grid were observed to be 38KW and -39KW respectively.

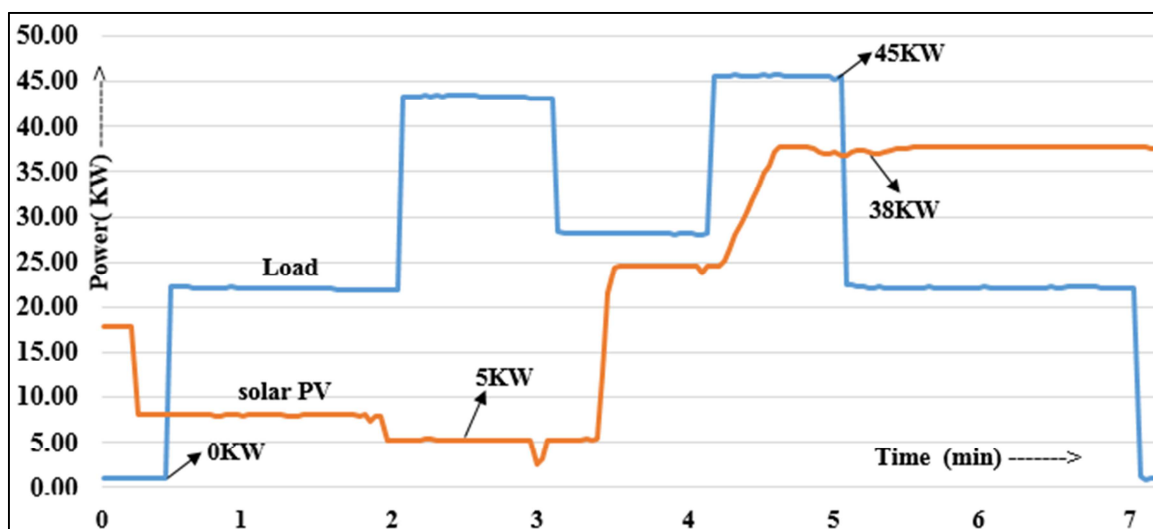


Fig. 2. Power variations-PV and load.

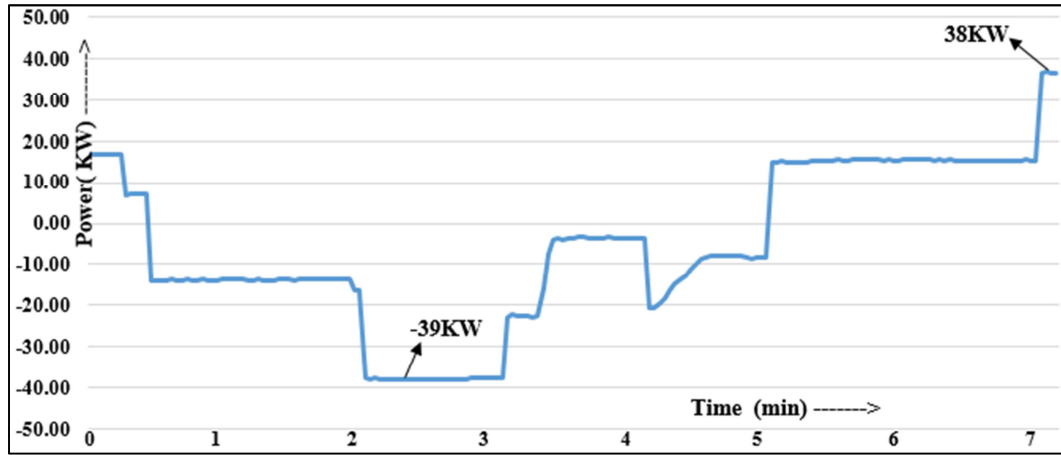


Fig. 3. Grid power variations.

(ii) Voltage variations at PCC

Voltage variations are observed when there is a small increase or decrease in the steady state supply voltage for a short period, caused by changes in load or by tap changes on network equipment. In this scenario, voltage level at PCC was observed to be varied according to the load and the change of level of integration of PV in to the network. The phase voltage variations that were observed with varying load and varying PV are depicted in Fig. 4. From these results, it can be clearly noticed that the observed voltage variations were higher during low load demand and higher PV integration condition. The voltage variations that were noticed from all the three phases are different (out of phase)

due to unbalanced PV distribution from the three phases. However, a standard statutory limit (+10% and -6%) of nominal voltage (240V at CSIRO) is maintained at each phase. For instance, the maximum and minimum voltage variation that was observed in phase 3 were 238.3V and 232.8V respectively. The measured voltage level during high PV integration and low load demand is 0.7% less than the nominal voltage whereas the voltage level during lower PV integration and high load was 3% less than the nominal voltage and maintaining the statutory limit. Considering high PV low load and low PV high load conditions, Table 2 summarizes the voltage variations and deviations with respective to all the three phases.

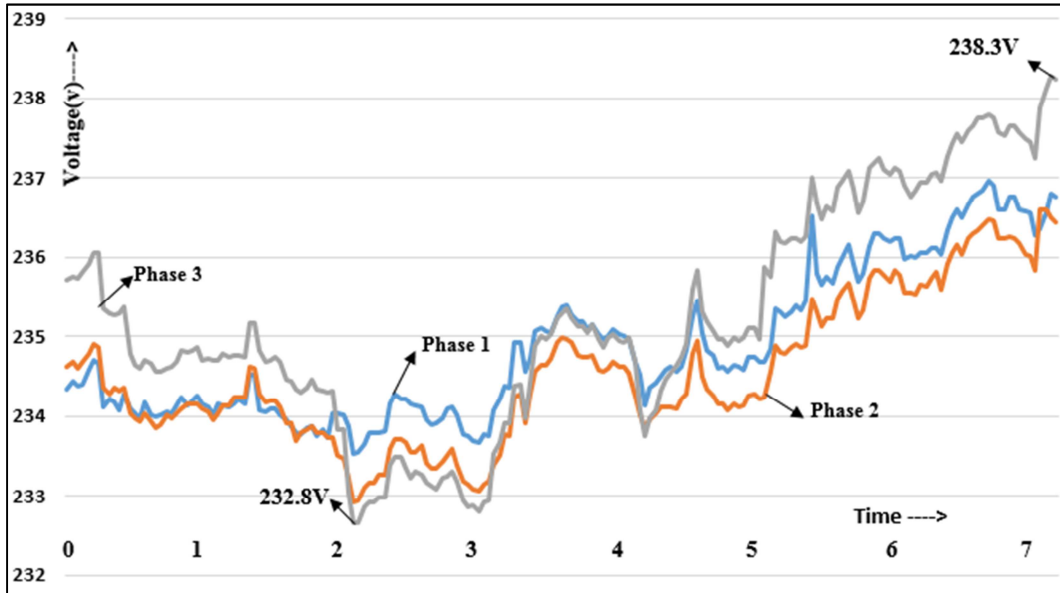


Fig. 4. Voltage variations at PCC.

Table 2. Voltage variations and deviations at PCC.

Phases	Voltage variation(v)		Voltage deviation (%)	
	Max	Min	Max	Min
Phase 1	236.9	233.8	-1.29	-2.58
Phase 2	236.7	233.0	-1.3	-2.9
Phase 3	238.3	232.8	-0.7	-3.0

4.2. Experiment 2: Micro Turbine with Varying Typical Solar Profile

To investigate the level of voltage and power variations in the network with the change of level of solar irradiance and load, a typical solar profile with 7 minutes duration was fed

to the micro turbine. Fig. 5 shows the typical solar profile the maximum and minimum step variations in load levels were deemed

(i) *Power variations:*

In this experiment, power variations at grid side were analysed by considering minimum and maximum step variations in load levels. From Fig. 6, it can be clearly depicted that during the first five minutes of analysis the load is varied from 10kW to 15kW to maintain the minimum step variation in load level. After 5 minutes, loads are randomly varied from 5kW to 22kW to maintain the maximum load

variation limit. As per the minute level variation of typical solar profile, the power variation from the turbine side was considered to be 9kW to 25kW during the minimum step load varying condition and 8kW to 23 kW during the maximum step variation of the load. These power variations from the turbine side create corresponding power flow variations in the grid side as depicted in Fig. 7. Power flow variation in grid side during minimum and maximum step load varying condition was observed to be varied from -1 (grid import) to a 15kW and -15kW to 17kW respectively.

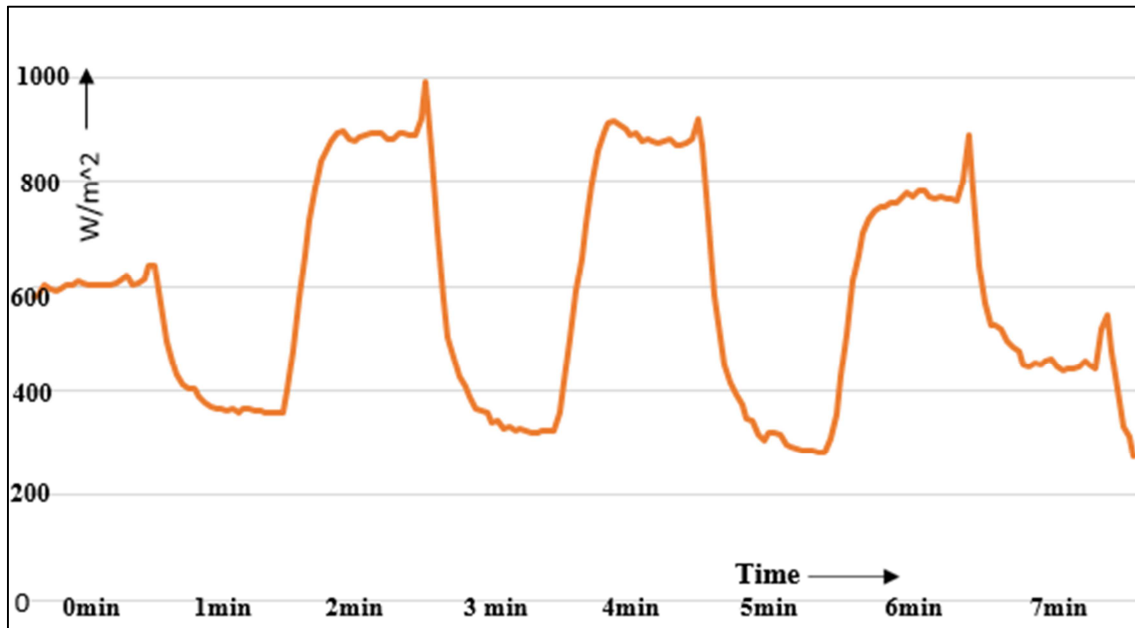


Fig. 5. Typical solar profile.

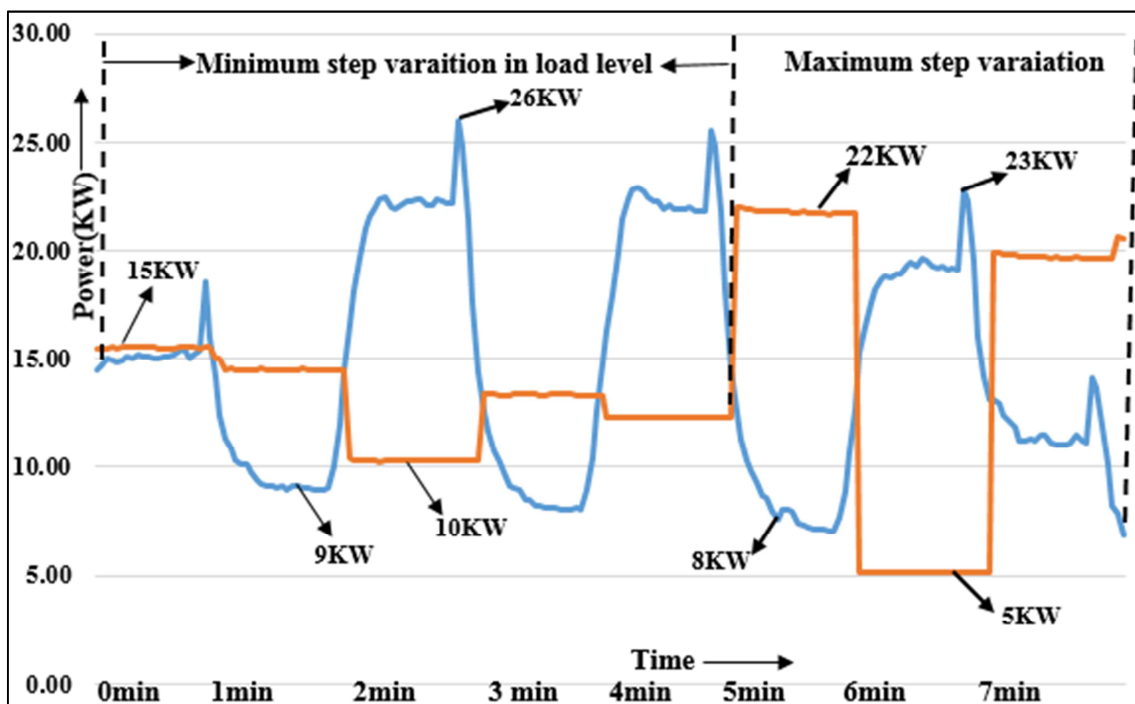


Fig. 6. Load variations in steps and PV power variations.

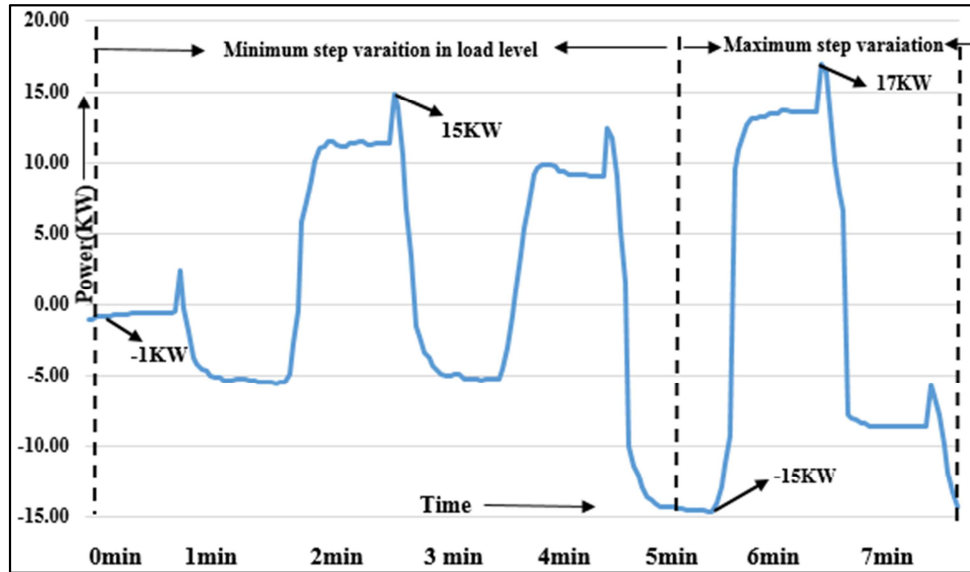


Fig. 7. Grid power variations.

(ii) Voltages at PCC

Considering micro turbine with varying solar profile, the maximum and minimum voltage variations that were observed at PCC are plotted in figure 8. From this analysis it is clear that the voltage variations at PCC are higher during minimum step variation in load level compared to the maximum step variations in load level condition. This is due to the turbine power variations as per the considered variations in typical solar profile during minimum and

maximum step variations in load level. From Fig. 8, the observed maximum voltage variation in line 3 was around 238V whereas the minimum voltage variation in line 1 was around 234.5V. Table 2 summarizes the voltage variations and deviations with respect to all the three phases. From this analysis it can be clearly seen that the observed voltage deviations are higher during maximum step variation in load level condition than the minimum step variation.

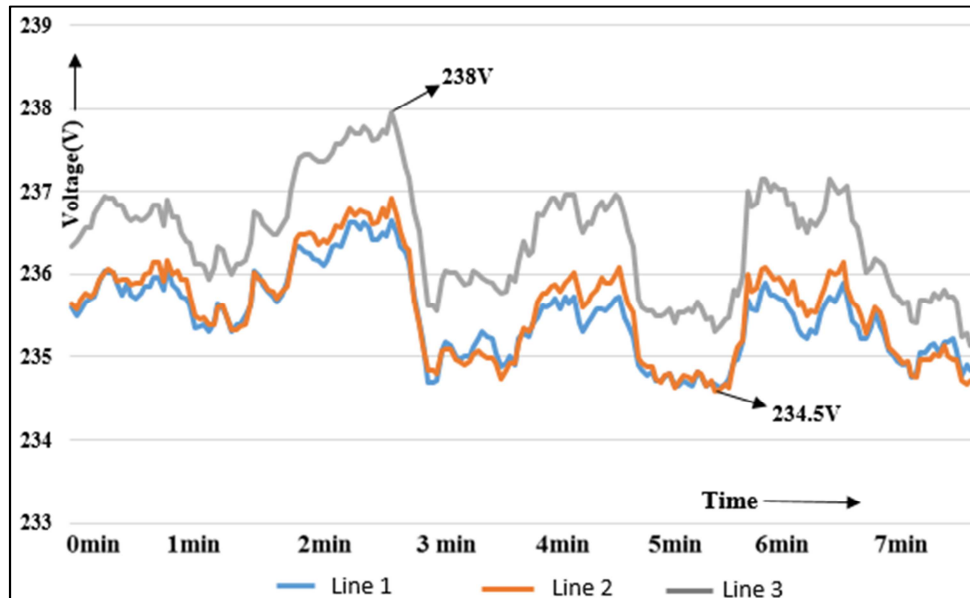


Fig. 8. Voltage variations.

Table 3. Voltage variations and deviations at PCC.

	Minimum step variation in load level				Maximum step variation in load level			
	V variation		V deviation		V variation		V deviation	
	Max	Min	Max	Min	Max	Min	Max	Min
Phase 1	236.7	234.7	-1.37	-2.2	235.9	234.7	-1.7	-2.2
Phase 2	236.9	234.7	-1.3	-2.2	236.1	234.5	-1.6	-2.3
Phase 3	238	235.7	-0.8	-1.8	237.1	235.3	-1.2	-1.9

4.3. Experiment 3: Rooftop PV and Micro Turbine with Typical Wind Profile

To further investigate and analyse the level of impacts in the network, a typical wind profile with second's level variations was considered in addition to the available roof top PV integration in the network. Fig. 9 shows the considered typical wind profile during this analysis. The active power set point as per varying typical wind profile was fed to the micro turbine controller and apparently a varying power point command was given to load bank controller as per the varying typical load. Following four cases were considered and the level of voltage and power variations was further explored in the network.

Case 1: Constant load +No PV

Case 2: Constant load + constant PV

Case 3: Constant load + varying PV

Case 4: Varying load + varying PV

(i) Power variation

From Fig. 10, it can be clearly seen that during “constant load and no PV” condition, the active power generated from the turbine is varied as per the typical wind profile. Based on the considered load variations, level of rooftop PV integration and the variations in wind profile, the corresponding grid power variations were observed in the network. Fig. 11 clearly depicts that during low load and high PV generation conditions the observed grid power is maximum in the network due to the excess power generations- PV active power and the turbine power as per the wind profile. Excess power generated by the solar PV should be properly accommodated by the grid for consistent power flow to avoid the worst case scenarios like power outage. A complete analysis has been done for all the four cases and the amount of power variation with respect to the grid were summarized in Table 4 corresponding to the load, rooftop PV and wind profile variations in the network.

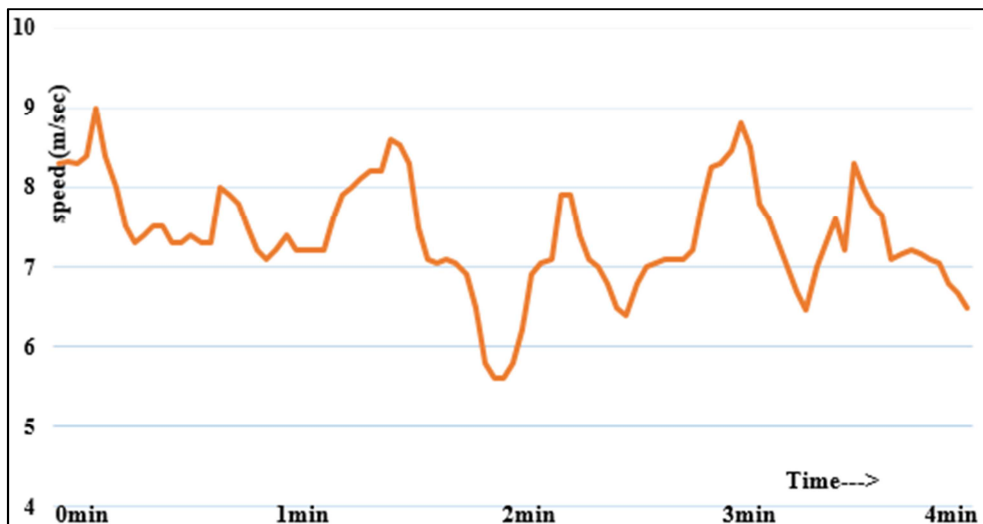


Fig. 9. Typical Wind profile.

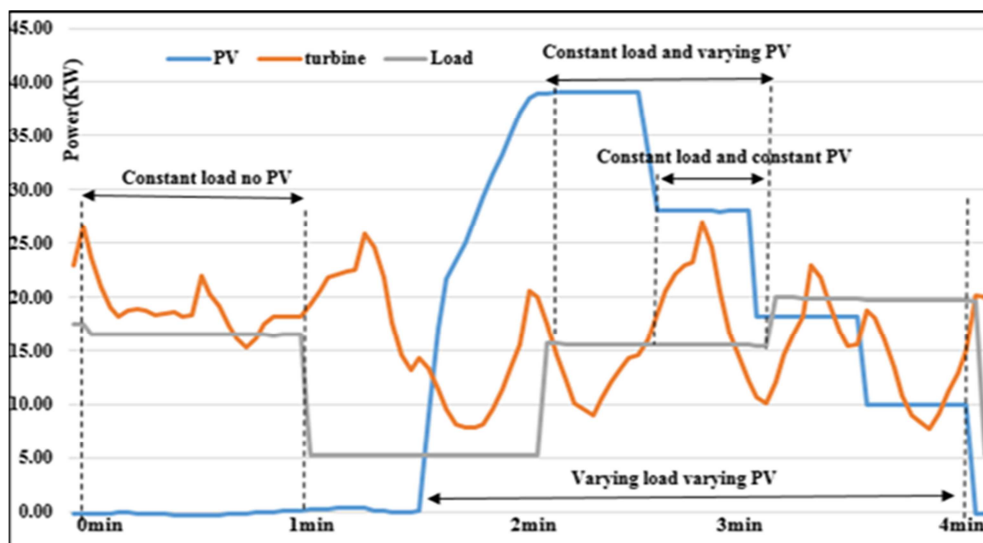


Fig. 10. Load, PV and turbine power variations.

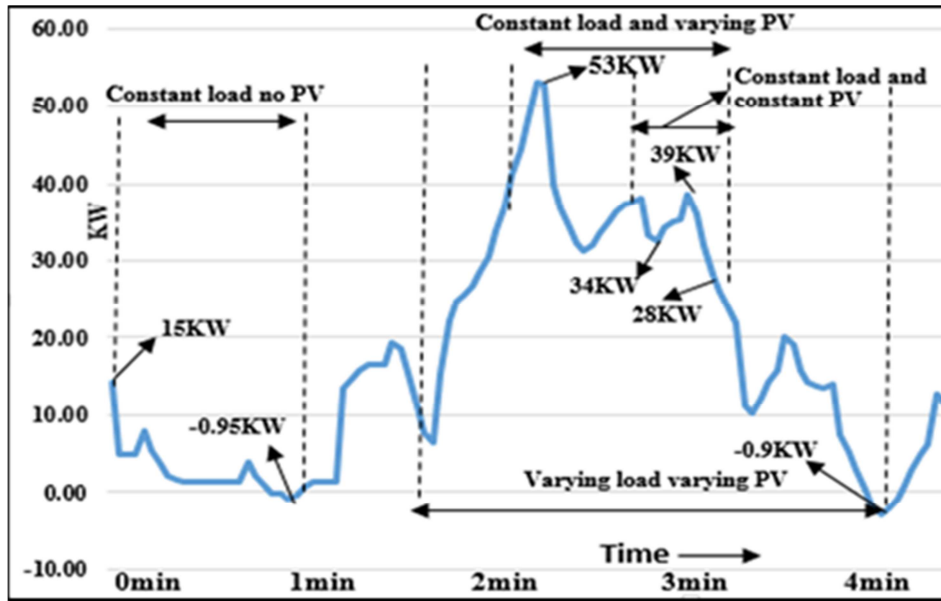


Fig. 11. Grid power variations.

Table 4. Power variations.

Case	Active power (KW)			
	Load	Turbine	PV	Grid
Constant load+No PV	17	15 to 27	-	-0.95 to 15
Constant load+constant PV	15	11 to 27	28	34 to 39
Constant load+varying PV	15	9 to 27	18 to 39	28 to 53
Varying load+varying PV	5 - 20	8 to 27	5 to 39	-0.9 to 53

(ii) Voltage variations

Voltage variations with regards to phase1, phase 2 and phase 3 are shown in Fig. 12. During 2nd and 3rd minutes the variation in voltage levels are quite high compared to the next the other intervals and this is due to the low load demand and the combined impact of high PV generations and the turbine power due to the varying wind profile. Table 5 summarizes the voltage variations and deviations for the four cases.

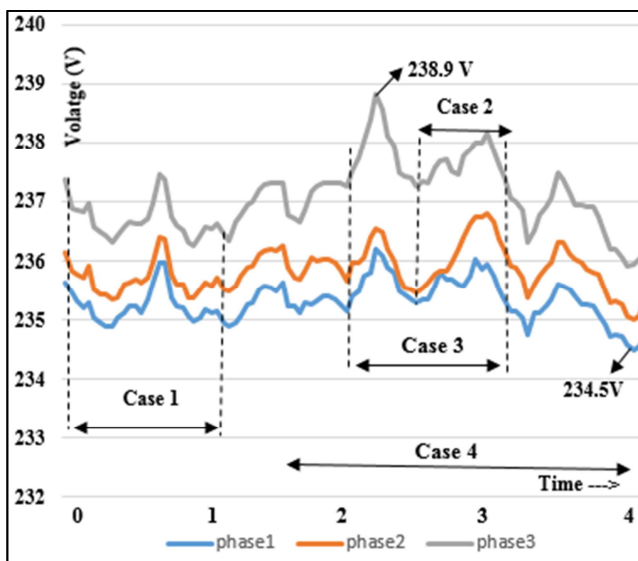


Fig. 12. Voltage variations.

Table 5. Voltage variations and deviations.

case	Voltage variation(v)		Voltage deviation (%)	
	Max	Min	Max	Min
1	237.4	236.4	-0.41	-1.5
2	238.1	237.5	-0.79	-1.0
3	238.9	237.3	-0.45	-1.1
4	238.9	236	-0.45	-1.6

4.4. Experiment 4: Power Factor Analysis

This experiment was aimed to analyse the PF variations in the network with the change of load and the whole analysis was undertaken with in the duration of 4 minutes. A load variation of 22kW to 47kW was deemed to estimate the level of PF variations at PCC during this analysis. The reactive power variations in the considered load are observed to be varied from -5kVAR to 17kVAR. Erratic variations in reactive power demands lead to fluctuating voltage drops across the impedance of a distribution system resulting in voltage flicker. During this scenario, PV power variations were recorded to be a minimum of 9kW to a maximum of 39kW as shown in Fig. 13. Corresponding to these variations, grid supports a maximum of 38kW to minimum of 4kW active power variation. Fig. 14 summarizes the active and reactive power variations of grid as per the load and PV power variations in Fig. 13. Following this, at PCC, system maintains almost unity power factor during the first two end half minutes of the total interval. On the other hand, a huge variation is deduced in PF profile after 2.75 minutes resulting in poor PF as depicted in Fig. 15. A PF variation of 0.48 to

0.5 is recorded after 2.75 minutes and this is maintained around a minute and gradually the PF reaches to a higher value for a fraction of time and then set to decline as per the load and PV variations. During these respective intervals, supply of reactive power from grid source is in higher proportion when compared to active power contribution as PV only contributes active power in higher proportions. Due to this phenomenon, PF is fairly reduced and hence deteriorates PF profile.

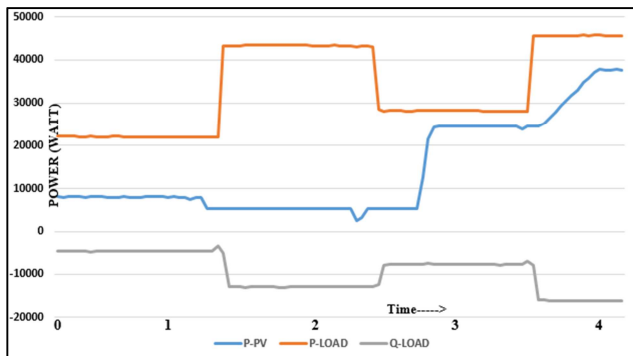


Fig. 13. Power variation of load and PV.

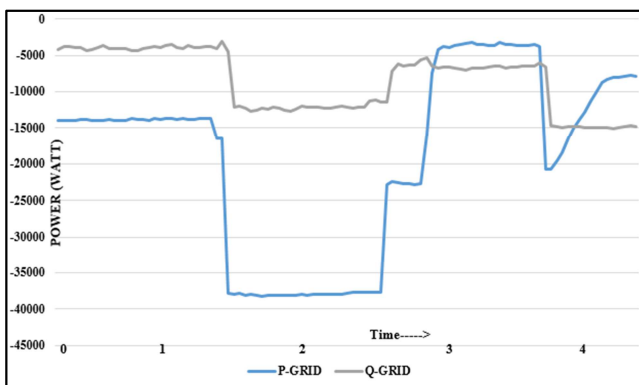


Fig. 14. Power variations of load and PV.

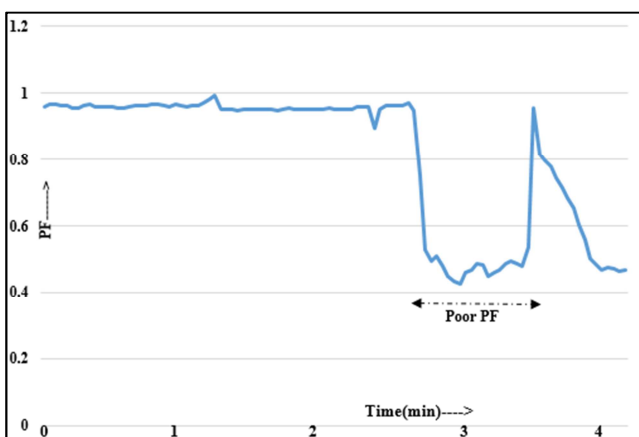


Fig. 15. PF variations.

4.5. Experiment 5: Unbalance Voltage (VUF) and Neutral Current (I_N)

To analyse unbalance voltage and the neutral current, a case study with unbalanced PV generations in each phase and

uneven distribution of load from three phases is monitored continuously. Over a period of 1 minute, this analysis is performed and as per the equations defined in section 2, VUF and I_N are calculated. Following figures summarize PV power variations, load variations, current variations, neutral current, voltage variations and changes in VUF that were observed during this analysis. In this analysis, it was observed that the variation in neutral current levels had been increased randomly from 2 amps to 22amps. If this uneven distribution continues for larger duration probabilities for an increase in excessive neutral current level may increase and may result in overloading of the distribution feeder and may degrade the system performance or electronic appliances connected at LV side. Unbalance voltage variations were depicted in Fig. 21 and from this analysis it can be seen that variation in the VUF is maintained as per the mentioned standard.

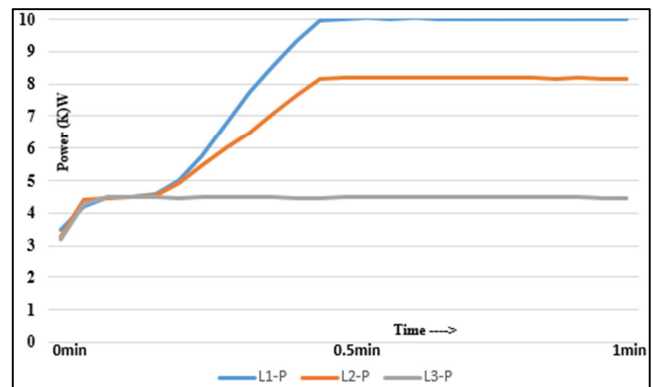


Fig. 16. Uneven PV power distributions.

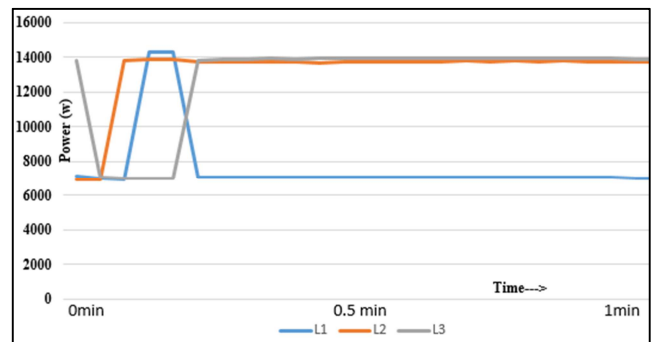


Fig. 17. Un-even load variations.

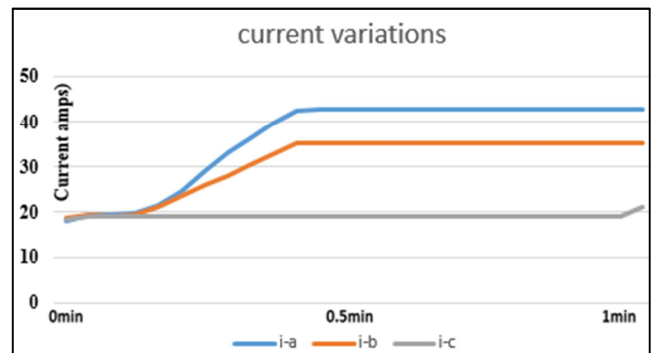


Fig. 18. Uneven PV power distribution.

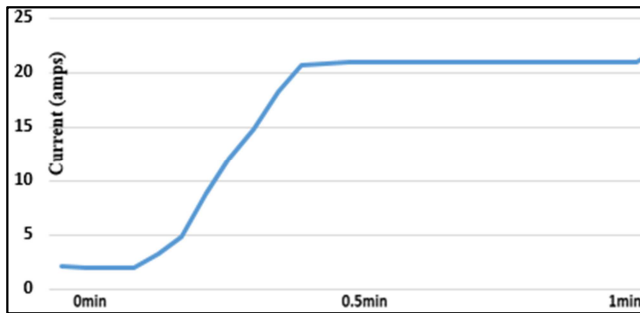


Fig. 19. Neutral current variations.

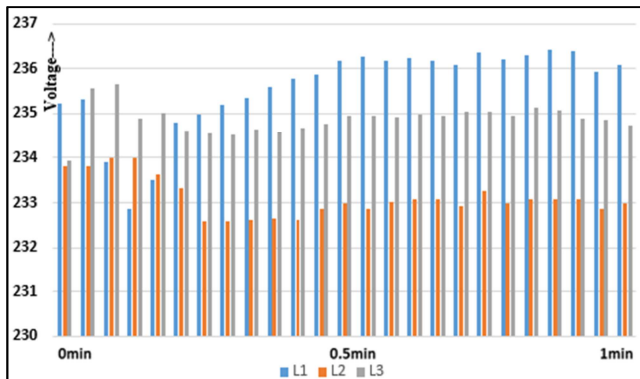


Fig. 20. Voltage variations.

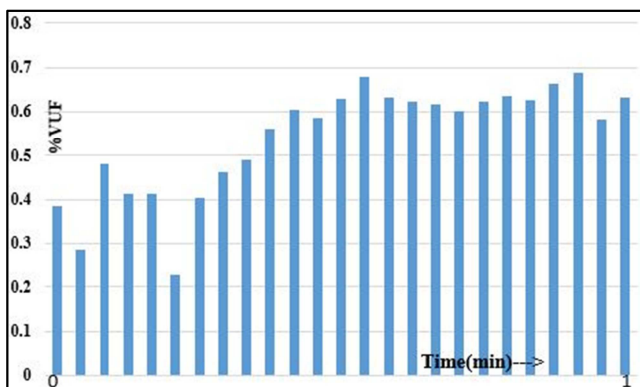


Fig. 21. VUF variations.

5. Conclusion

To investigate and analyse network impacts, REIF facility at CSIRO had been used in this research study. A series of experiments were conducted based on the flexibility and the robustness of the devices and variations in active power and the corresponding voltages at PCC are recorded. Initially with the available rooftop PV integration, voltage and power variations were analysed considering different scenarios and from the results it can be concluded that the level of voltage and power variations increases with the increase in RE integration during low load demand. To further investigate the level of impacts on network, a varying solar profile was considered in experiment 2. In addition to this analysis, a varying wind profile with rooftop PV integration is also considered in experiment 3 and further impact levels were analysed. From the results, it is clearly evident that power

variation depends on the level of integrations of RE into the network causing voltage variations at PCC. High voltage variations were observed in phase 1 compared to phase 2 and phase 3 due to the unbalanced PV generation from the three phases from the first three experiments. In practical, the level of RE integrations in to the network depends on the weather conditions of PV integration and installation sites of wind turbine if considered. PF analysis was conducted in experiment 4 and from the results it can be seen that system maintains almost unity power factor during the first two end half minutes of the total interval during the analysis and gradually PF deteriorates for few seconds and reaches the actual point due to the excess active power production from PV with respective to the load demand.

In addition, VUF and I_N were estimated and verified in the network as per the mentioned standards. This study is primarily focused on the impacts considering the actual roof PV system and the micro turbine with typical wind profile and solar profile due to the limited resource availability during this research analysis. A real wind turbine can be used to further investigate and analyse the possible impacts in the network along with the available PV integration facility. However, results of this research study can be used as guidelines for utility grid to provide regulated and improved quality of energy supply by implementing appropriate planning of generation reserve and other control measures in the network.

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References

- [1] Hossain, M. K. and M. H. Ali, Transient stability augmentation of PV/DFIG/SG-based hybrid power system by parallel-resonance bridge fault current limiter. *Electric Power Systems Research*, 2016. 130: p. 89-102.
- [2] Online Available from: <http://www.iea.org/topics/renewables/subtopics/wind/>.
- [3] (ENA), E. N. A., ARENA, A. R. E. Agency, Editor 2016, Energy Network Association (ENA): Australia.
- [4] Mills, D., Renewable energy in Australia. *Energy & Environment*, 2000. 11(4): p. 479-509.
- [5] Jackson, T. M., G. R. Walker, and N. Mithulananthan. Integrating PV systems in to distribution networks with battery energy storage systems. in *Power Engineering Conference (AUPEC), 2014 Australasian Universities*. 2014. IEEE.
- [6] Ackermann, T., Wind power in power systems. Vol. 140. 2005: Wiley Online Library.
- [7] Lewis, S. Analysis and management of the impacts of a high penetration of photovoltaic systems in an electricity distribution network. in *Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES*. 2011. IEEE.

- [8] Geoscience Australia, A., Australian Energy Resource Assessment, E.a.T. Department of Resources, Editor 2010. p. 253-274.
- [9] KSV Swarna, A. V., Sui Yang Khoo, Alex Stojcevski Impacts of integration of wind and solar PV in a typical Power Network, in International Conference on Sustainable Energy and Environmental Engineering(SEE2015),2015, Atlantis press: Bangkok,Thailand.
- [10] Srisaen, N. and A. Sangswang. Effects of PV grid-connected system location on a distribution system. in Circuits and Systems, 2006. APCCAS 2006. IEEE Asia Pacific Conference on. 2006. IEEE.
- [11] Ali, S., N. Pearsall, and G. Putrus. Impact of high penetration level of grid-connected photovoltaic systems on the UK low voltage distribution network. in International Conference on Renewable Energies and Power Quality. 2012.
- [12] Eltawil, M. A. and Z. Zhao, Grid-connected photovoltaic power systems: Technical and potential problems—A review. Renewable and Sustainable Energy Reviews, 2010. 14(1): p. 112-129.
- [13] Thomson, M. and D. Infield, Impact of widespread photovoltaics generation on distribution systems. Renewable Power Generation, IET, 2007. 1(1): p. 33-40.
- [14] Tonkoski, R., D. Turcotte, and T. H. El-Fouly, Impact of high PV penetration on voltage profiles in residential neighborhoods. Sustainable Energy, IEEE Transactions on, 2012. 3(3): p. 518-527.
- [15] Haque, M., A novel method of evaluating performance characteristics of a self-excited induction generator. Energy Conversion, IEEE Transactions on, 2009. 24(2): p. 358-365.
- [16] Khadem, S. K., M. Basu, and M. Conlon, Power quality in grid connected renewable energy systems: role of custom power devices. 2010.
- [17] Rona, B. and Ö. Güler, Power system integration of wind farms and analysis of grid code requirements. Renewable and Sustainable Energy Reviews, 2015. 49: p. 100-107.
- [18] El-Shimy, M., M. Badr, and O. Rassem. Impact of large scale wind power on power system stability. in Power System Conference, 2008. MEPCON 2008. 12th International Middle-East. 2008. IEEE
- [19] Swarna KSV, A. V., Sui yang Khoo, Alex Stojcevski. Impacts of integration of wind and solar PV in a typical network. in SEE2015. 20. Thailand, Bangkok: Atlantis.
- [20] Tande, J. O. G., Applying power quality characteristics of wind turbines for assessing impact on voltage quality. Wind energy, 2002. 5(1): p. 37-52.
- [21] Vilar, C., J. Usaola, and H. Amarís, A frequency domain approach to wind turbines for flicker analysis. Energy Conversion, IEEE Transactions on, 2003. 18(2): p. 335-341.
- [22] CSIRO Energy Transformed Flagship Available from: <http://www.csiro.au/org/EnergyTransformedFlagship>.
- [23] El-Tamaly, H. H., M. A. Wahab, and A. H. Kasem, Simulation of Directly Grid-Connected Wind Turbines for Voltage Fluctuation Evaluation. International Journal of Applied Engineering Research, 2007. 2(1).
- [24] Australia, I. P., ADDRESSING GRID-INTERCONNECTION ISSUES WITH VARIABLE RENEWABLE ENERGY SOURCES, in Repoer for Asia pacific Economic Cooperation (APEC)2010, itp. p. 6-14.
- [25] Leavey, S., Mitigating Power Fluctuations from Renewable Energy Sources 2012.
- [26] Swarna Kumary, S., et al. Modelling and power quality analysis of a grid-connected solar PV system. in Power Engineering Conference (AUPEC), 2014 Australasian Universities. 2014. IEEE.
- [27] Georgilakis, P. S., Technical challenges associated with the integration of wind power into power systems. Renewable and Sustainable Energy Reviews, 2008. 12(3): p. 852-863.
- [28] Kanellos, F. D. and N. D. Hatziaargyriou, The effect of variable-speed wind turbines on the operation of weak distribution networks. Energy Conversion, IEEE Transactions on, 2002. 17(4): p. 543-548.
- [29] Chattopadhyay, S., M. Mitra, and S. Sengupta, Electric power quality. 2011: Springer.
- [30] Baghini, A. B., Handbook of power quality. 2008: Wiley Online Library.
- [31] Gosbell, V., Volatge Unbalance.
- [32] Facchini, K., How to Manage Grid Impact As Solar Deployment Increases, 2012.
- [33] Ausgrid, NS238 Supply Quality, 2015.
- [34] Energy, E., Network Power Quality Limits and Levels, 2015.
- [35] energy, e., grid connection of embedded generation through inverters by endeavour energy, 2014.
- [36] Guide to connecting a distributor generator in Victoria, S. Victoria, Editor, State Government Victoria: Victoria.