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Megawatt-Scale Solar Variability Study: An Experience from a 1.2MWp Photovoltaic System in Australia over Three Years

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Abstract: With more photovoltaic (PV) systems being integrated into distribution networks, power utilities are facing many challenges in both planning and operation. Network operators are concerned with PV variability and associated necessity of voltage regulation, control coordination, reserve adequacy and dispatch constraints. While to address the obligatory connection agreement, it is vital for PV farm owners to accurately estimate PV variability and then provide the most cost-effective compensation method. In the literature, PV variability of different scales has been investigated over the last 20 years. However, little has focused on output fluctuations of PV systems with long-term and high-resolution recorded data at a low-voltage distribution feeder level where voltage regulation has become a serious issue. This is particularly true in Australia, where PV penetration is growing in many states and is expected to grow further in the near future. This paper utilizes the data of a distributed 1.2MWp PV system in the University of Queensland recorded over the last 3 years with 1-min resolution to analyse the statistical characteristics of PV power variability. The results from this study will provide very useful information for both power utilities and solar farm owners regarding network operation and future PV system development.

Keywords: PV output variability, PV integration, large-scale PV, PV data processing.

1. Introduction

Grid tied solar photovoltaic (PV) installation has substantially increased over the last decade in Australia, from around 10MWp in 2006 to 4,177MWp by March 2015 [1]. In the sunshine state – Queensland, the installed PV capacity has risen from less than 500kWp in 2006 [2] to 1,325MWp by March 2015 [1]. This generally accounts for nearly 15% of the total demand in Queensland [1]. As PV becomes a significant generation source, power system operators are considering its power output variability and subsequent impacts on network management and security. At the same time, PV owners (especially large-scale PV system owners) also express their concerns on PV power variation and its resultant compensation requirement for meeting their connection agreement.

Firstly the owners of PV farms with more than 30kWp normally need to negotiate with local utilities for terms and conditions of the connection agreement according to the Australia Standard – AS 4777 [3]. Typically, distribution utilities require a PV farm to comply with a certain voltage band, ramp rate limits, and reverse power flow constraints regarding the time of a day; otherwise the PV farm can be disconnected and may be penalized. Therefore, the owners need to know PV output variability in order to select the correct type and sufficient size of reactive power compensation devices while considering cost and benefit [4, 5]. For example, if a power variation of 90% PV system rating statistically only occurs once every 3 years, the owner will first weigh the cost of compensation devices and the penalty of voltage violation. Then a decision can be made to fully compensate PV variability of 90% or a lower level with less cost for voltage regulation.

Secondly, for distribution utilities, it is also crucial to understand PV power variability of small PV systems collectively in a feeder or a large PV farm at a single location in order to plan for the required additional compensation devices [4-6]. Moreover, necessary control coordination between network compensators, PV plants and loads can be accordingly designed [5]. This will help to avoid negative interactions between different controllers and undesirable impacts on network security.

Lastly, for independent system operators (ISOs), it is essential to comprehend PV output variability of a single large PV farm and all PV plants in a region or in a state or in the whole network. This will provide useful information for a better ancillary service plan and power dispatch, and it is also helpful for improving network operation stability and reliability.

Therefore, PV power variability is of a particular interest of PV farm owners, distribution utilities and ISOs. The related studies have been conducted over more than two decades with some early attempts starting from late 1980s. The paper presented by Jewell in 1987 [7] is one of the earliest studies on PV variability over the areas with different sizes – from 10km^2 to 100,000km^2. This research concluded the tendency of declination in the percentage of PV power fluctuations as a result of geographic diversity – as known as the smoothing effect. Because of availability of data at that time, it could only use simulated solar irradiance data instead of measured data. After Jewell, many papers [8-19] had addressed the PV variability modelling and the smoothing effect for a number of locations in different countries. Based on the suggestions from Suehrcke in 1989 [20] and Gansler in 1995 [21], researchers had a tendency of using instantaneously measured high resolution data (normally from 10s to 5min) rather than the average hourly data. Many of them had utilized both irradiance and PV power measurement. However, due to the different data recording resolutions, area sizes and weather patterns, a variety of PV variability had been reported ranging from a few percent to several tens of percent per minute (or per hour).

Murata in 2009 [22] investigated the geographic correlation between PV output fluctuations in different places in Japan and found PV variability depends on data recording interval and physical distance between PV units. Larger space with higher data resolution will result in lower variability correlation. Hoff [23] and Mills [24] in 2010 expanded the relationship developed by Murata [22] by including the number of PV systems and dispersion factor, and formulated them into equations for PV output variability prediction.

At the same time, the purposes of the PV variability studies have never been left behind – power engineers are concerned about the implications of PV generation uncertainty on the related cost associated to additional regulation necessity, power ramping requirement, and reserve adequacy [15, 25]. Many papers had explored these issues since 1980s [12, 17, 24-32]. The main finding was that the rise of PV penetration requires increase of extra compensation, ramp rate and capacity of dispatchable generators while the subsequent cost and constraints may limit further PV development.

In the literature, there is a lack of studies focusing on a relatively small area which is close to the size of a residential feeder with PV generation data recorded in high resolution for multiple years. Especially in Australia, such research has not yet been reported. In this paper, the University of Queensland (UQ) 1.2MWp PV system with 1-min data resolution over the last three years is utilized for PV power variability analysis. The output of different PV sites is recorded with synchronized instantaneous measurement. The whole system is situated in an approximate 700m × 150m area which is similar to a range of a typical residential feeder. With more PV being connected to distribution networks, this study will certainly provide valuable statistical information to both distribution utilities and PV owners for coordinating regulation and determining compensation for either large-scale or distributed small-scale PV system development.

2. UQ 1.2MWp PV System

The UQ 1.2MWp PV system is installed on the rooftop of 4 buildings across the UQ St. Lucia Campus (Brisbane, Australia) – Multilevel Car Parks (98A and 98B), Sir LIew Edward (14) and UQ Center (27A) [33]. It consists of 5,004 polycrystalline PV panels (TSM-PC05, 240Wp [34]). The PV systems of two Car Parks (98A and 98B) are identical – 338.9kWp (1412 panels) each. Building 14 has a much smaller PV capacity of 89.9kWp (374 panels), and the largest system is on Building 27A with 433.4kWp (1806 panels).

The four PV sites are distributed over an area around 700m x 150m as shown in Figure 1. This dimension is comparable to a long low-voltage residential feeder with high PV penetration or a several MW level solar facility situated at one location (such as the UQ Gatton campus 3.4MWp PV system to be presented in Section 5); therefore, the percentage variability of this PV system should reasonably represent power fluctuation of distributed PV at a residential feeder level as well as output variability of a multi-MW solar farm. This is the main reason why the UQ PV system can provide meaningful statistical information to both solar farm owners and distribution utilities for tackling PV induced voltage regulation issues.

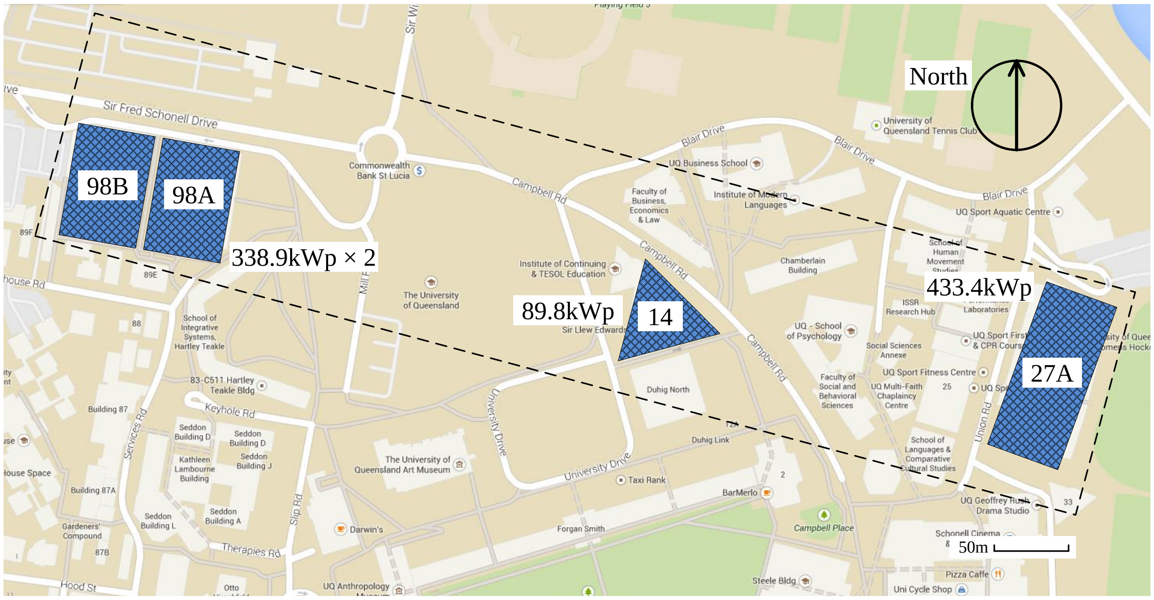


Figure 1 Dimension and capacity of UQ 1.2MWp PV system [35]

All PV sites were brought to normal operation by the end of July 2011, and this study covers a 3-year period from August 2011 to July 2014. The data logging system synchronizes the clock of all sites and instantaneously collects measured data with 1-min resolution (PV power).

3. Overview of PV Generation and Analysis

3.1 Overall PV Power Generation

The overall PV power output over the 3-year period is illustrated in Figure 2(a). The seasonal effect can be clearly observed. The whole system generated more power which was close to the 1.2MW rating during the summer (December to February in Australia), and produced much less during the winter (June to August). Therefore, it is evident that the majority of the most severe cloud induced PV power fluctuations should occur between late spring to early autumn. However, it is hard to visualize PV output variability from Figure 2(a). To give a clear picture of PV power variation, a sample week in January 2013 is demonstrated in Figure 2(b). It can be seen that the PV system in six out of seven days was heavily affected by cloud movement.

The monthly energy yield over three years is depicted in Figure 2(c), which provides useful information to solar PV plant owners. The PV energy generation in winter months can be as low as a half of energy production in summer months. It can be seen that the tendency of the overall energy profile coincides with that of the power profile in Figure 2(a).

3.2 Definitions and Approaches for PV Power Variability

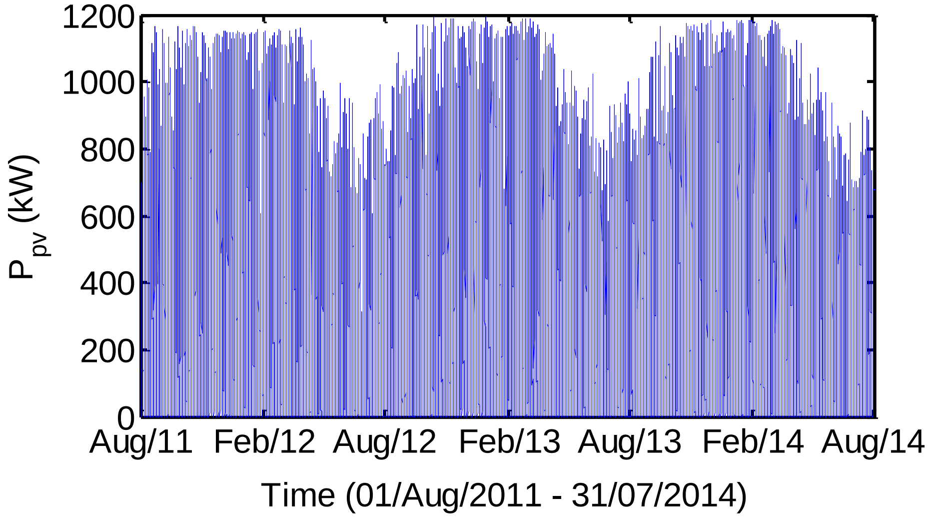
Eq. (1) calculates variations in PV power over 'x' minute (x-min) intervals, where x-min may be 1-min, 2-min or 5-min in this study. $P_{pv}(t)$ is the instantaneous power generation from the UQ PV system at time t, measured at a resolution of once per minute.

For each time interval (1-min, 2-min or 5-min), Eq. (1) is evaluated at every reading. Application of this method has the advantages of providing all possible PV variations $[\Delta P_{pv\,x-min}(t)]$ within each interval, better representing extreme changes in PV power, and providing a uniform base for each of the time resolutions studied in this research.

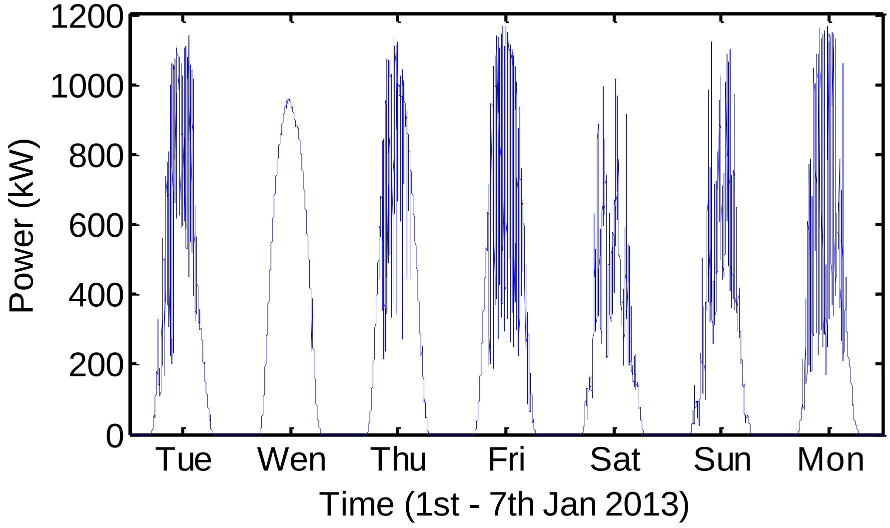
$$\Delta P_{pv\,x-min}(t) = P_{pv}(t) - P_{pv}(t-x) \quad (1)$$

Based on the definition by Eq. (1), $\Delta P_{pv} > 0$ means power rise, while $\Delta P_{pv} < 0$ means power drop. To better present the scale of changes, per unit system (equivalent to percentage) is utilized. For PV power, the UQ PV system ratings of overall and individual sites are chosen as bases for per unit (pu) calculation.

(a) UQ PV power recorded over three years with 1-min resolution



(b) UQ PV power – a sample week in summer (1st – 7th Jan, 2013)



(c) UQ PV monthly energy generation recorded over three years

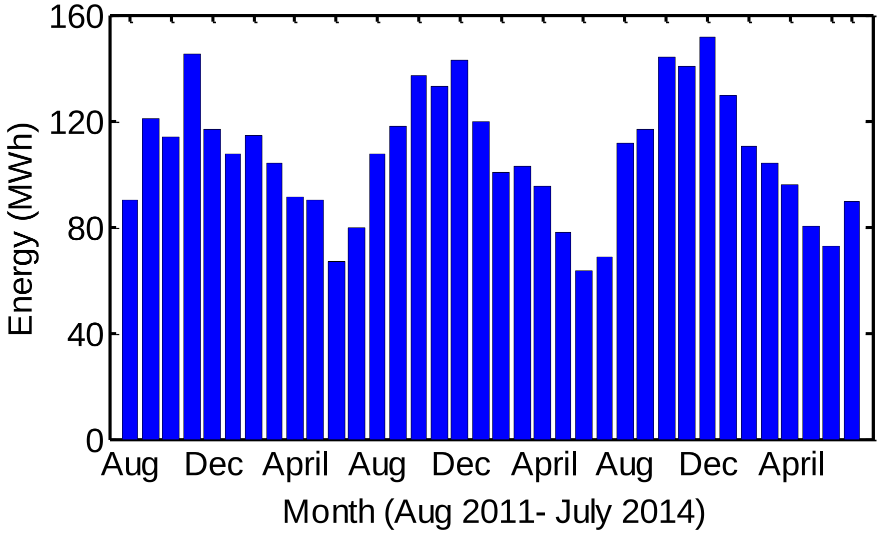


Figure 2 PV Power output and Energy generation

In order to study PV power variability in a statistical sense, a number of methods are applied for examining the tendency of PV output fluctuations, including distribution of the number of events, Quantile-Quantile Plot, Cumulative Distribution and variation correlation. These techniques and their analyses are presented in the next section.

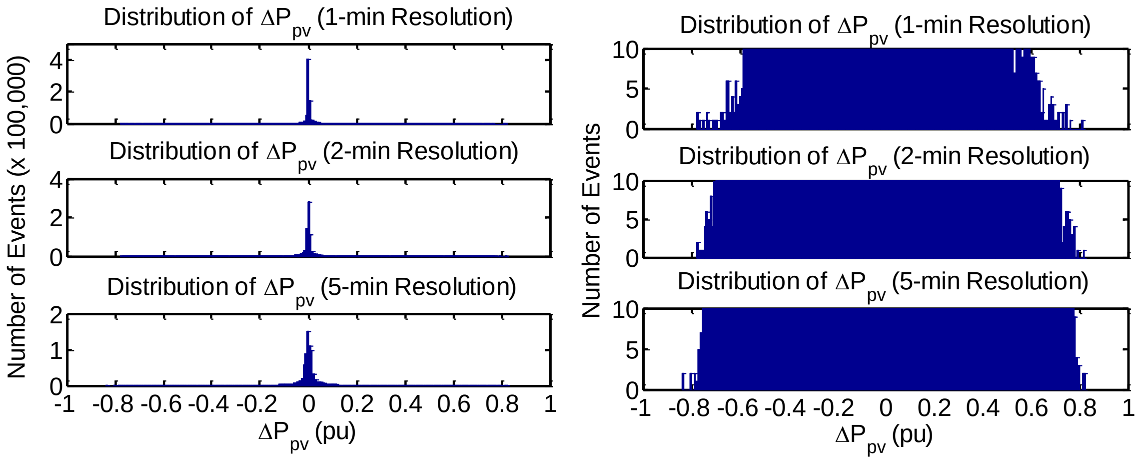
4. PV Power Output Variability

4.1 Distribution of the Number of Events

4.1.1 Overall System

Distribution of the number of events (all ΔP_{pv} calculation) for the overall PV system is shown in Figure 3(a). It can be noted that the majority of variations are centred on 0 with a very small standard deviation, and the deviations get a little bit larger (a wider base) for longer observation intervals. This means PV power variations are mainly slow and smooth in nature. However, occasionally they can become very significant, sometimes more than 80% of the rated power, due to movement of fast and thick clouds over the area [Figure 3(b)].

Table 1 has listed all events in which PV output has changed more than 80% of its rating. For both 1-min and 2-min intervals, $\Delta P_{pv} \geq 80\%$ has only happened once each in the same day (2012-10-23 late spring), however, there were more chances for such event in a 5-min scale (8 incidents). This is mainly due to the smoothing effect of the geographically distributed PV systems. It really requires rare and special (thick and fast) clouds to cover the area within 1-min or 2-min, however, in the 5-min scale a total coverage by thick clouds becomes more probable. It can be noted that most of these events happened during later spring, summer and early autumn (except two incidents in one particular day in winter – 2011-08-23), and all of them occurred during the peak solar radiation window from 10:30am to 14:30pm. It can also be seen that the power fluctuation for the overall PV system over the 3-year period has never been greater than 85%.



(a) All events (b) Focusing on the large variation events

Figure 3 Distribution of the number of events for the overall system over three years

Table 1 Significant PV Power Variation Events for Overall System – $|\Delta P_{pv}| \geq 80\%$

Time Interval	Date (yyyy-mm-dd)	Time (hh:mm)	ΔP_{pv} (%)
1-min	2012-10-23	10:44	81.5
2-min	2012-10-23	10:50	82.2
5-min	2011-08-23	11:41	-80.6
	2011-08-23	11:42	-84.0
	2012-10-23	10:45	-83.5
	2012-10-23	10:50	81.4
	2013-01-30	10:54	82.5
	2013-11-24	14:13	81.4
	2013-11-24	14:14	82.7
	2014-03-13	12:22	-80.3

4.1.2 Summary of the Number of Significant Events for All Sites

Very detailed information can be presented using the approaches such as Figure 3 and Table 1 in the last sub-section; however, this will become very complicated when comparing between different locations. Since the significant events (large PV fluctuations) should be the focus, a summary of the number of such events over a 3-year period is listed in Table 2. The following are the observations made from this table.

(1) The event of $75\% < \Delta P_{pv} < 80\%$ happened far more frequently than that of $\Delta P_{pv} \geq 80\%$ at all time-resolution levels

(2) Due to the smoothing effect, there were more incidents for significant power variations in a longer time-resolution scale than a shorter one.

(3) For the individual sites (27A, 98A, 98B and 14), although the PV area coverage of building 14 is the smallest (Figure 1), it does not mean more severe incidents could be observed than others. On the contrary, the statistics show that most of them are more or less at the same level. This is potentially due to the relatively small-scale of each site, and 1-min resolution may be too long for such a scale, which makes little difference in terms of full cloud coverage.

Table 2 Summary of the Number of Significant Events Over Three Years

PV Site	**ΔP_{pv}**	**Time Interval**	**Power Drop $\Delta P_{pv} < 0$**	**Power Rise $\Delta P_{pv} > 0$**
27A	≥ 80%	1-min	1	7
		2-min	4	15
		5-min	19	43
	75%-80%	1-min	32	59
		2-min	74	144
		5-min	159	257
98A	≥ 80%	1-min	2	8
		2-min	3	18
		5-min	28	37
	75%-80%	1-min	29	89
		2-min	73	169
		5-min	187	334
98B	≥ 80%	1-min	2	9
		2-min	2	18
		5-min	25	23
	75%-80%	1-min	27	69
		2-min	55	137

		5-min	167	298
14	≥ 80%	1-min	4	6
		2-min	7	11
		5-min	23	32
	75%-80%	1-min	41	64
		2-min	79	139
		5-min	159	244
Overall	≥ 80%	1-min	0	1
		2-min	0	1
		5-min	4	4
	75%-80%	1-min	4	2
		2-min	4	19
		5-min	24	77

(4) The overall system had considerably fewer events at all time-resolution levels than the individual sites. This has further supported the spatial smoothing effect and the appropriateness of applying 1-min resolution to such an area for investigating the smoothing effect.

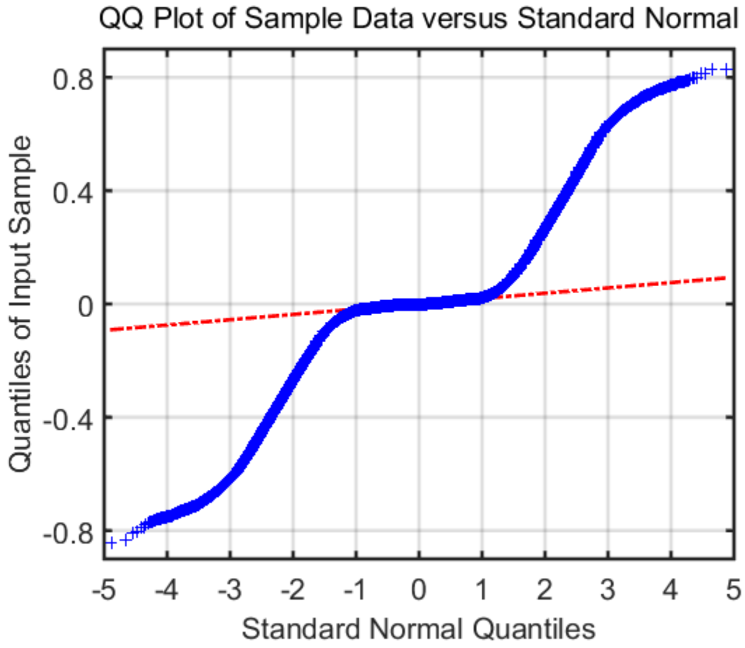
(5) More significant power rise ($\Delta P_{pv} > 0$) events have been observed than the power drop ($\Delta P_{pv} < 0$) ones for almost all sites and the overall system at any time-resolution levels. This may be due to the characteristics of PV panels.

- PV temperature effect: When clouds cover a PV system, the PV power will decrease. During this period, with less sunlight radiation and power generation, the PV array temperature will decline, which makes the PV panels more efficient. Therefore, after the clouds move away, for the same solar irradiance the PV system will be able to produce more power than that of before the cloud coverage.

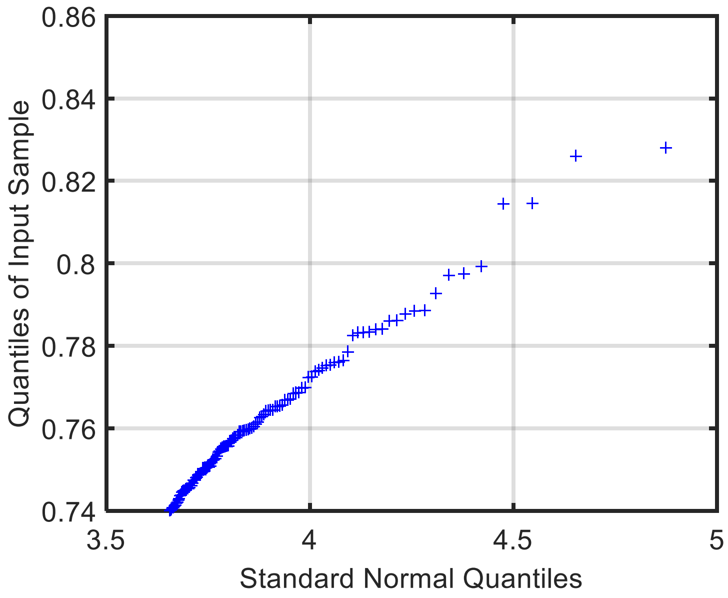
4.2 Probability Density Distribution

The distribution of PV power variations visually looks like a normal distribution by observing Figure 3(a). However, it is actually very different from the normal distribution. This can be best analyzed by Quantile-Quantile Plot (Q-Q Plot) of PV output variations over 3 years with 5-min resolution as shown in Figure 4(a).

(a) Quantile-Quantile Plot of ΔP_{pv}



(b) Occurrence of $\Delta P_{pv} > 75\%$



(c) Occurrence of $\Delta P_{pv} < -75\%$

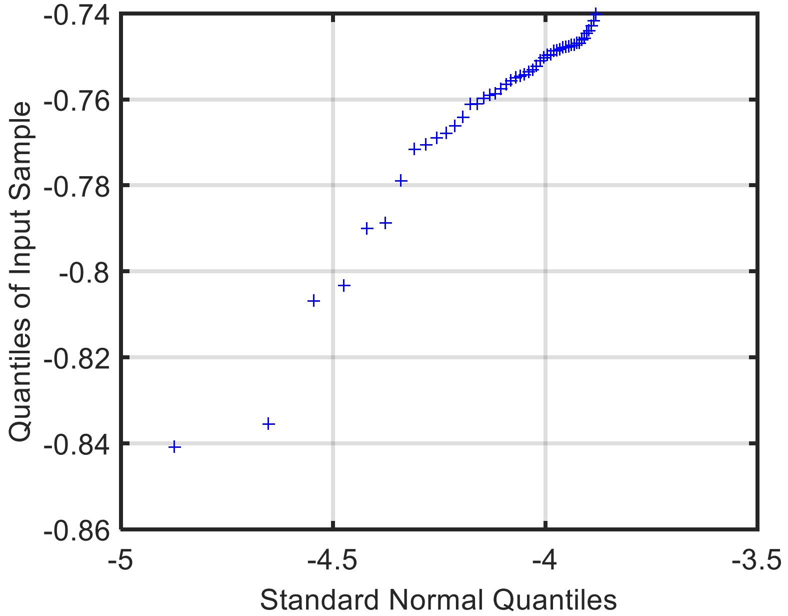


Figure 4 Quantile-Quantile Plot of PV output variations over 3 years (5-min resolution)

Firstly, the probability of occurrence of PV power drop ($\Delta P_{pv} < 0$) is almost 0.5, which clearly indicates the overall numbers of PV power drops and rises are approximately the same. Secondly, the region of low power variations does resemble the normal distribution as this part of the contour (blue "+") closely coincides with the normal distribution curve (red dash-dot). Thirdly, the tendency of the medium to high PV power variations has significantly deviated from the normal distribution. This is illustrated as a heavy-tailed distribution suggesting that the probability for an incident occurring far away from the mean value is much more than that in a normal distribution. Such a distribution curve tends to have large value of standard deviation. Finally, a close observation around the tail part on each end also shows the number of significant power rises is far more than that of the PV power drops and clearly the most significant PV power fluctuation has never been greater than 85% [Figures 4 (b-c)].

4.3 Cumulative Distribution

4.3.1 Individual Sites and Overall System

Cumulative Distribution (CD) is another great tool that can be utilized for analyzing the tendency of PV power variability with statistical confidence. The CDs of the individual PV sites and the overall system are calculated and compared in Figures 5 and 6. If a cumulative distribution curve (say Curve CD-1) shifts toward the left-hand side or lies on top of another cumulative distribution curve (say Curve CD-2), it means the realizations of the PV power variations that are below a certain value (say $\Delta P_{pv} \leq 0.4pu$) from CD-1 are more likely than those from the Curve CD-2. In another word, the realizations of the high PV power variations (e.g. $\Delta P_{pv} > 0.4pu$) from the Curve CD-2 are more probable than those from the Curve CD-1. From Figures 5 and 6, the observations from Section 4.1.2 can be further evidenced, and the conclusions are made as follows:

(1) All three graphs in Figure 5 show that a shorter time-resolution curve is located on the left/top position of a longer time-resolution curve, which provides evidence that PV power variations over a longer time intervals are more likely to exceed those over a shorter time intervals – Observations (1) and (2) in Section 4.1.2.

(2) Figures 5 (b) and (c) illustrate despite the size of the individual PV sites their CD curves show very similar ΔP_{pv} distributions at each time-resolution level, which is aligned with Observation (3) in Section 4.1.2.

(3) All CD curves of the overall system in Figure 5 (a) are on the left/top place of those of the individual sites in Figures 5 (b) and (c), and this further supports Observation (4) in Section 4.1.2 – the smoothing effect.

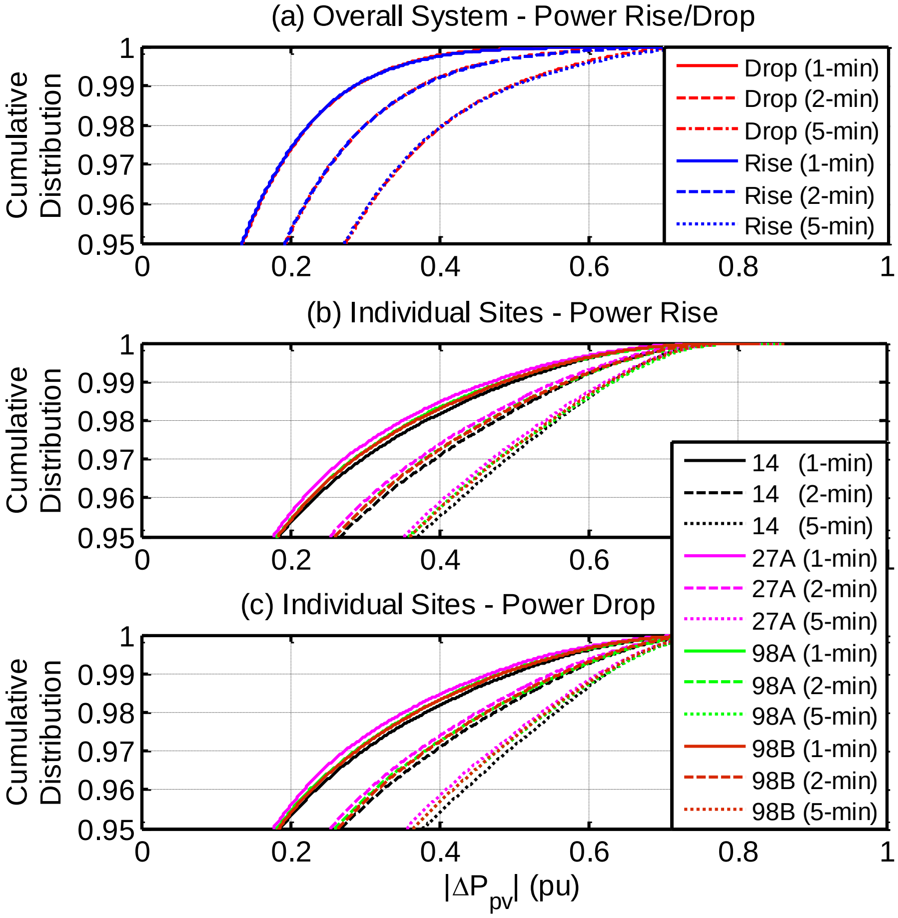


Figure 5 Cumulative distributions (95th-100th percentiles) of PV power changes of individual sites and the overall system over three years

(4) When CD curves of the power drop and power rise in all individual sites and the overall system are compared in Figure 6 (a), it is found that the power drop CD curves are situated to the right/bottom position of the power rise CD curves for the low to medium PV power variation range (approximately $|\Delta P_{pv}| < 40\%$). However, the reverse is true for the medium to high variation range based on Figure 6 (b), which supports Observation (5) in Section 4.1.2. The reasons are explained in the last section as the PV temperature effect. Since the total power drop and rise incidents were almost equal, a relatively larger number of power rising events in the medium to high variation range certainly lead to marginally

fewer power rising events in the low to medium variation range. However, it should be pointed out that the difference between power rise and power drop is very small. Whether it is statistically significant will be up to further observations and justification in the future.

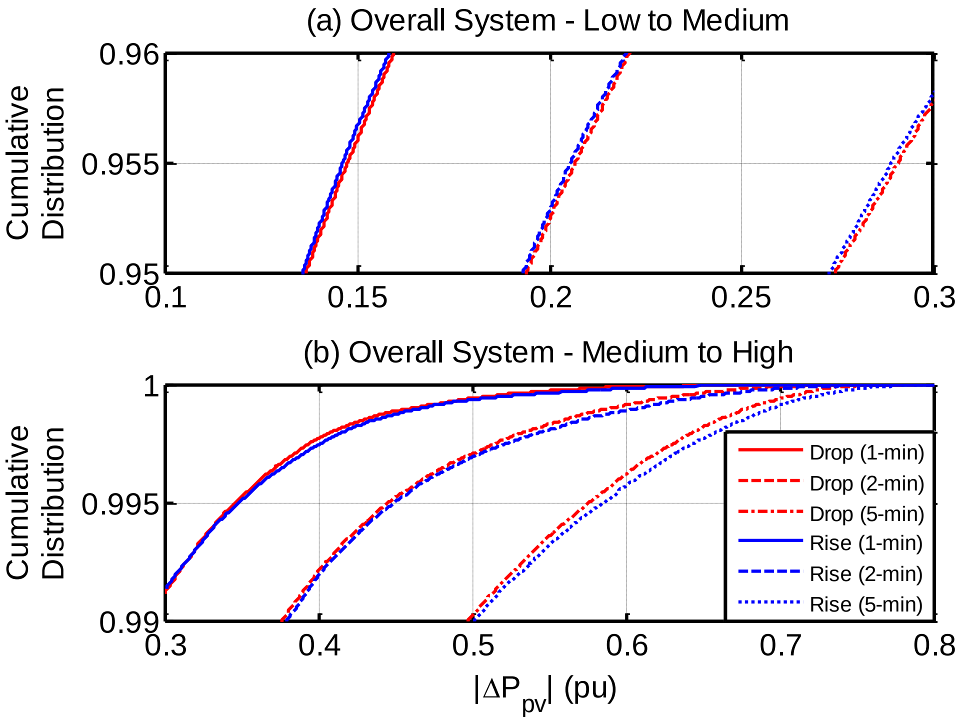


Figure 6 Cumulative distributions (99th-100th percentiles) of PV power changes of individual sites and the overall system over three years

4.3.2 Yearly Comparison

Annual cumulative distributions of PV power variations are shown in Figure 7(a). There is no substantial difference between the yearly tendencies of the CD curves for each time-resolution scale. It can also be noted that from 2011-2012 to 2013-2014, the CD curves were slightly moving toward the right/bottom position. This means there were more significant PV power variation incidents in 2013-2014 than those in 2011-2012. Moreover, Figure 7(a) also indicates the yearly statistical results are very close at all time-resolution levels, so annual statistics should be able to provide a fairly good overview of the studied PV system.

The yearly PV power variability can also be evaluated based on the Smoothing Factor – an index for measuring PV power fluctuations. The Smoothing Factor (S) can be calculated by (2) [36].

$$S = \frac{\sigma_{98A}+\sigma_{98B}+\sigma_{27A}+\sigma_{14}}{\sigma_{overall}} \tag{2}$$

where "σ" represents the standard deviation of the daily PV output changes for a particular PV site or the overall site. For a perfectly sunny day or a totally overcast day when PV power variations of all sites are slow and occur at the same time, there is nearly no smoothing effect for the overall system. In this case, the common Smoothing Factor is around 1.0~1.2. While for a partially cloudy day when the smoothing effect is observed, the typical Smoothing Factor is generally above 1.2. Therefore, a higher value of the Smoothing Factor means a greater smoothing effect.

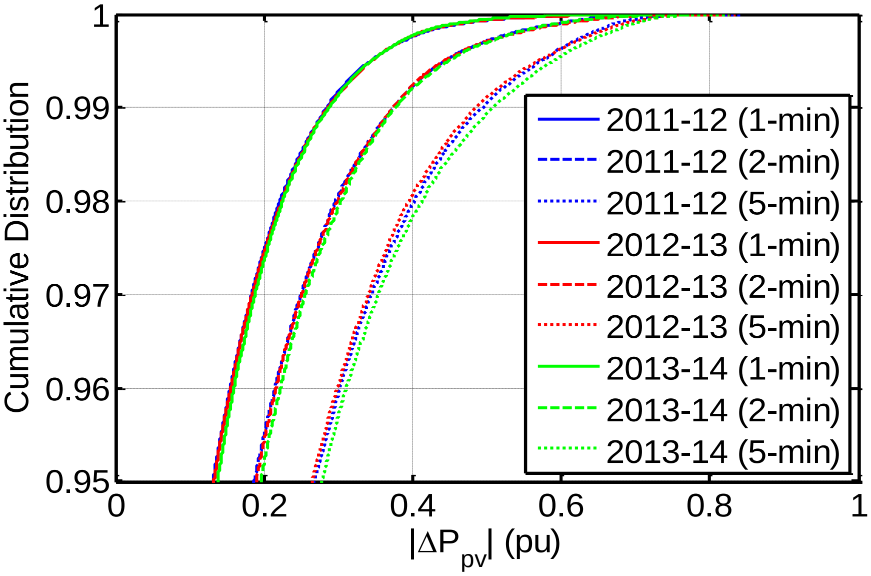
Figure 7(b) shows the frequency of occurrence of the Smoothing Factor during the years 2011-12, 2012-13 and 2013-14. It can be observed that the frequency of occurrence has a very similar profile for each year, which is in agreement with the results of the cumulative distribution analysis as in Figure 7(a). Further, it can also be seen that a noticeable dip of the Smoothing Factor occurred for the year 2013-14 in the range of 1.1~1.2, which implies relatively fewer incidents with low smoothing effect have happened. While the Smoothing Factor of the year 2013-14 in higher ranges (1.3-1.7) is marginally larger than that of the previous years. This potentially indicates there were more significant PV power variations in this year, which also aligns with the observation from Figure 7(a).

4.4 Correlation of PV Power Output Variation

Correlation coefficient is a measure of strength and direction of the linear relationship between two variables [37]. A superior positive coefficient of correlation between two variables indicates that if the value of one of the variables is changed then the probability of change in the same direction for the second variable is greater. In this research, correlation coefficient has been utilized to investigate the relationship between two different PV sites. A larger correlation between the output variations of the two PV generators implies that if one of them is affected by the cloud movement, then the probability of the other one which is also influenced by the same factor becomes higher.

In this paper, the correlation coefficient between two PV sites (27A and 98A) on power fluctuations is examined at three different time resolution levels, and the results are listed in Table 3. It can be seen that the correlation coefficients increase with time resolution intervals, and this means the two PV sites are more correlated with a longer period of time. It is due to the fact that the clouds are more likely to shade or clear the area coverage of these PV sites at the 5-min resolution level rather than at the 1-min level, which again is an indication of the smoothing effect.

(a) Cumulative Distribution of PV power output change



(b) Smoothing Factor for all 3 years

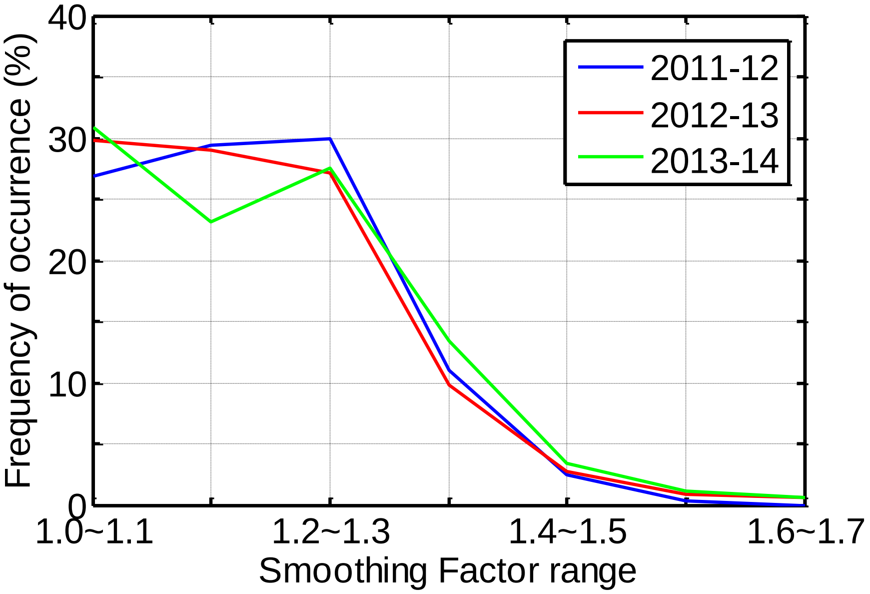


Figure 7 Comparison of yearly variability

Table 3 Mean value of correlation coefficient for three different time resolutions

Time Resolution	Annual mean of correlation coefficient		
	2011-12	2012-13	2013-14
1-min	0.41	0.42	0.41
2-min	0.49	0.50	0.49
5-min	0.59	0.60	0.59

The correlation is also examined with respect to cloudiness, which is classified to four different levels – clear-sky, partly-cloudy (with infrequent transient clouds), extremely-cloudy (with frequent transient clouds) and overcast (totally cloudy or rainy without transient clouds). The mean values of correlation coefficients for different cloudiness are summarized in Table 4. Surely, the smoothing effect can again be observed from the tendency of the correlation values with different time intervals. However, more importantly the correlation in the horizontal direction shows an increasing trend with a sequence of extremely-cloudy, partly-cloudy, clear-sky and overcast. This indicates that when there are more frequent transient clouds, the correlation between two distanced PV sites becomes weaker, which is in turn also an evidence of the smoothing effect. It should be pointed out that the differences in correlation between clear-sky and overcast categories are probably due to small PV variability from low PV power generation in overcast days when comparing to that in clear-sky days. Therefore, the overcast set has the highest correlation coefficient.

Table 4 Mean value of correlation coefficient for different cloudiness

Time Resolution	Mean of correlation coefficient for different cloudiness			
	Clear-sky	Partly-cloudy	Extremely-cloudy	Overcast
1-min	0.46	0.41	0.28	0.70
2-min	0.59	0.48	0.36	0.77
5-min	0.75	0.58	0.46	0.86

5. An Application Example

To further demonstrate the value of the statistical analysis provided in this paper, an example of its application is presented in this section. In late 2013, the University of Queensland was granted to complete a 3.4MWp PV plant in UQ Gatton campus, which has an approximate area of 700m × 300m (slightly bigger than that in Figure 1). The local power network structure is shown in Figure 8 [38]. The Gatton substation transforms grid voltage from 33kV to 11kV, and then the 11kV network stretches around 7.5km to serve UQ campus load, which normally ranges from 1MW to 3MW [39]. The line voltage is traditionally supported by a step voltage regulator (SVR), which has an action time delay of 2-min according to the regulation rules. The PV system, which is formed by 5 identical 684kWp array blocks in parallel, was planned to be connected to the 11kV level. Based on the connection agreement [40], the voltage fluctuation limits are summarized in Table 5.

The focus was once to determine the size of the inverter (e.g. SMA 630kVA/720kVA/760kVA/800kVA … [41]) that can guarantee there is enough reactive power capacity to quickly compensate PV real power variations, therefore, the corresponding voltage fluctuations can be controlled well within the limits in Table 5. According to the connection agreement with the local distributor, the number of 4% (0.04pu) voltage fluctuations cannot be more than once per hour, and 3% (0.03pu) voltage fluctuations cannot be more than 10 times per hour. Surely, such estimation was conducted before the construction of the Gatton PV plant, and only the sunlight radiation data from a single station was available over a limited period. As a result, it is assumed that PV power generation proportionally varies with sunlight radiation, which also implies a linear relationship between PV power variations and radiation changes Next, the emission evaluation of voltage fluctuation is conducted. Without any knowledge of PV variability of such a scale, 90%/min power variation of the rated PV capacity was concluded based on the recorded radiation profile at a single spot. However, 80%/min is found to be more realistic for the dimension of this PV system as evidenced in previous sections, and a comparison study will be presented next to show the importance of the knowledge of PV variability. The quasi-static time-series method [39] was applied with reactive power control suppressing voltage fluctuations [42] during investigation as shown in Figure 9.

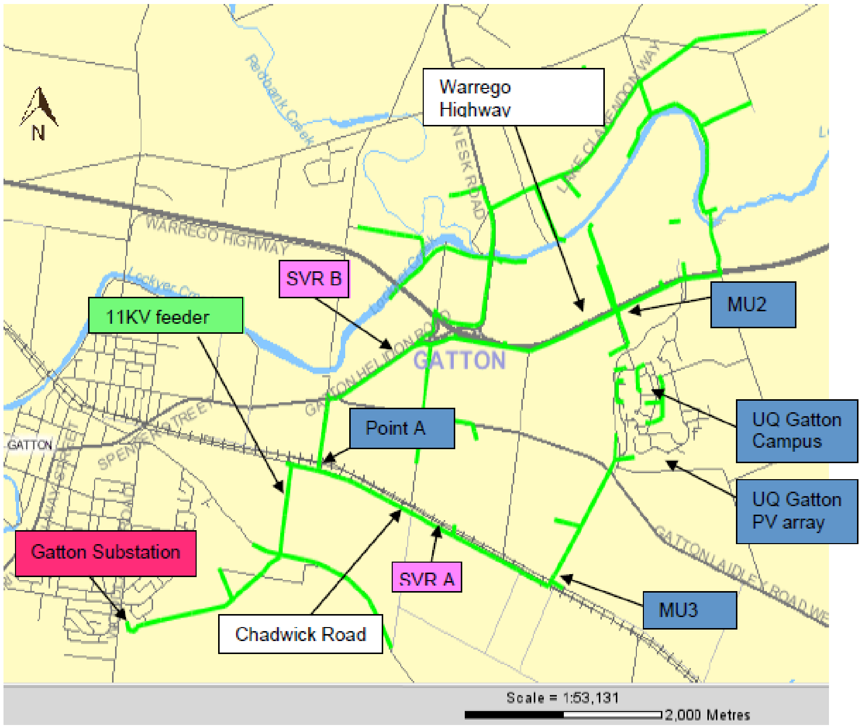


Figure 8 UQ Gatton power network and PV connection map [38]

Table 5 Emission limits of voltage fluctuations [40]

Repetition frequency r (hour^{-1})	**$\Delta V/V_N$ (%)**
	MV (11/33kV)
$r \leq 1$	4
$1 < r \leq 10$	3

The overall results are summarized in Table 6. Firstly, without any reactive power compensation (2nd and 3rd columns), the voltage fluctuations will become a serious concern for UQ to fulfill the connection agreement. Secondly, if such evaluation is conducted with an assumption of maximum 90%/min for ΔP_{pv}, the more expensive SMA 760kVA inverter would have been chosen rather than the SMA 720kVA inverter when considering to leave a certain safety margin. However, with certain knowledge of PV variability of such a dimension (around 80%/min), the SMA 720kVA inverter was found to be sufficient for this application, which reduces the cost of the project.

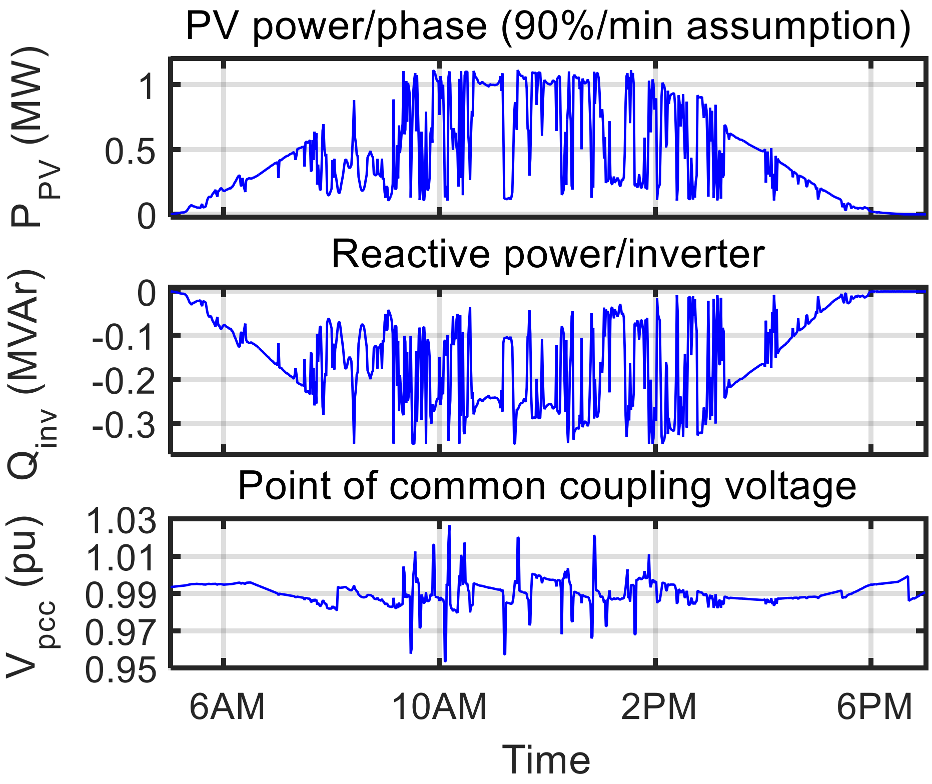


Figure 9 Simulation results with Quasi-Static Time-Series method (720kVA inverter)

Table 6 Evaluation results

	Repetition frequency (maximum times per hour)				
ΔP_{pv_max}	**80%**	**90%**	**80%**	**90%**	**90%**
$S_{inverter}$	**No Q**	**No Q**	**720kVA**	**720kVA**	**760kVA**
ΔV > 4%	1	4	0	1	0
ΔV = 3-4%	4	3	0	2	0
ΔV = 2-3%	6	6	1	3	0

6. Conclusions

This paper utilizes the recorded data over a 3-year period of a distributed PV system in the University of Queensland in Brisbane and performs statistical analyses for PV power variability. It has been observed that PV power variation in the studied time-resolution scale (1-min, 2-min and 5-min) has never exceeded 85% from August 2011 to July 2014. The smoothing effect has a significant impact on the dispersed PV system of the studied scale (a 700m × 150m area), and this effect has been evidenced via different approaches, such as distribution of the number of events, cumulative distribution and correlation coefficient. Moreover, the results suggest that PV power rise has happened more frequently than power drop for significant power fluctuation events (approximately $|\Delta P_{pv}| > 50\%$) due to potential PV temperature effect. This has been supported through a few methods including distribution of the number of events, Quantile-Quantile Plot and cumulative distribution. An application example has been presented to show the value of statistical analysis. The information in this study will provide valuable statistics to current and potential PV farm owners and power utilities for evaluating voltage regulation requirement, determining compensation devices, and developing future network plans.

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