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Data driven exploration of voltage conditions in the Low Voltage network for sites with distributed solar PV

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Abstract

Consumers in Australia have made substantial investment into Distributed Energy Resources (DERs) and in particular, rooftop solar PV. However, there remains limited visibility of the technical conditions experienced by these technologies in the LV network. An improved understanding of these technical conditions has the potential to support more transparent, technically and economically appropriate investment and operational decision making by both consumers and network utilities. In this study, a suitably anonymised data set of voltage measurements at 2,010 sites across Australia with distributed PV provided by Solar Analytics is analysed. Our assessment highlights that, generally, voltage conditions on the low voltage networks at sites with distributed PV are high; the great majority of measurements are greater than the nominal voltage for each network region with some potential for non-compliance. Voltage conditions were also found to vary significantly over the course of the day for different regions and seasons, in accordance with varying net demand and, presumably, network voltage control actions. Importantly, a wide range of voltages are observed during solar generation periods as well as times of lowest load, with low voltage conditions seen at peak load periods in some jurisdictions. These variations have implications for the performance of distributed PV including questions of voltage 'headroom' for PV generation, the challenges of managing low voltage excursions at times of peak demand, as well as for network voltage management more generally. The study highlights the benefits of improved visibility regarding power quality conditions on the low voltage network.

1. Introduction

There has been unprecedented uptake of rooftop solar photovoltaics (PV) across Australia over the past six years, increasing from 133MW at the start of 2010 to over 6.2GW in July 2017 (APVI 2017). As result, in 2016 16% of dwellings in Australia had installed solar PV, a higher penetration than any other country in the world, including Hawaii at 15% and Belgium at 7% (International Energy Agency 2017). The level of uptake varies significantly between states and territories, and even more significantly between local regions. The majority of

systems are small (under 10kW capacity) and are generally installed in the distribution network on residential rooftops (Haghdadi, Copper et al. 2016). To date, their direct impacts have been largely invisible to network businesses and the Australian Energy Market Operator, their presence seen mainly as a reduction in demand during daylight hours. However, as distributed PV capacity grows it is becoming apparent that installation of generating capacity in the Low Voltage (LV) network is entirely nontrivial, with technical, social and economic implications for stakeholders across the electricity supply chain.

One challenge regarding the integration of inverter connected PV is the interaction between PV generation and local grid voltage conditions. This interaction results in a number of impacts, including voltage rise and a widening of the range of voltages observed due to solar PV variability, which are two of the more prominent challenges for Distribution Network Service Providers (DNSPs) with regards to integrating high levels of solar PV (Passey, Spooner et al. 2011, Seguin, Woyak et al. 2016, International Energy Agency 2017). Both excessively low and high voltages can cause damage to energy user equipment and have other safety implications.

Historically, LV network voltage has decreased along the length of each radial feeder due to the current flow through the line impedance and consumer loads along the line. The major challenge for DNSPs has therefore been managing low voltage excursions at consumer connections towards the end of the line during periods of peak demand. Typically, this has been achieved by setting the distribution substation transformer taps so that the feeder head voltage is above the nominal voltage, and therefore voltage at the furthest point on the feeder remains within the allowable range during high demand periods. Where PV injects current into the grid, however, the voltage can rise and may move outside the acceptable range, particularly at times of light load, when current may flow in reverse all the way back to the transformer as illustrated in Figure 1.

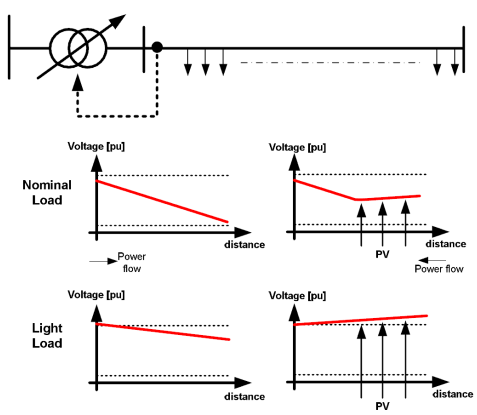

Figure 1 Impact of solar PV on local network voltage (Demirok, Sera et al. 2009)

There are a range of technical options for controlling voltage in the LV network including, particularly, tap changing transformers at feeder level. For more local voltage control, there are options including reconductoring to reduce line impedance, or installation of network equipment such as static Var compensators to manage reactive power and thereby voltage (Demirok, Sera et al. 2009, Alexander, Wyndham et al. 2017). However, such options have associated costs. This study does not assess methods of voltage management – although this is an important area of work. Instead, it addresses the underlying question of voltage behaviour

in the distribution network. Perhaps surprisingly, this behaviour is only poorly understood in many networks. There is limited - if any - direct monitoring by network operators of voltage at the lowest voltage level feeding residential and other small energy users. While interval meters at energy consumer premises can provide voltage information, many small energy users have only accumulation meters. Even with interval meters, voltage information may not be available. This is despite its potential importance for consumers in terms of safety and equipment performance. For small energy consumers with PV, there can also be a direct financial interest given that their system is required to disconnect at times of excessive voltage, reducing the energy generated and hence revenue the system provides.

The study reported in this paper aims to contribute to a better understanding of voltage and PV system operation by analysing a data set containing detailed and very frequent voltage, PV generation and consumer demand measurements for thousands of consumers across Australia. This data is provided by Solar Analytics, a company that provides a performance analytics service to a growing number of energy consumers with PV systems across Australia and internationally. The structure of this paper is as follows; Section 2 presents a review of relevant prior work, Section 3 describes the data set examined in this study, Section 4 presents results of analysis and Section 5 sets out discussion and conclusions.

2. Literature review

Voltage management in the context of integration of distributed PV is a well established challenge for DNSPs, and considerable work has been done to model how solar PV impacts voltage as well as how this can be managed (Demirok, Sera et al. 2009). However, as noted above, there has been limited assessment of actual operational LV network voltage due primarily to the limited data collection undertaken by network businesses. DNSPs are increasingly interested in improving visibility of voltage conditions across their networks and Victorian DNSPs in particular are utilising the fleet of smart meters present on their networks to map voltage conditions. Further, United Energy is investigating the use of voltage reduction to provide demand response (United Energy 2017).

A number of previous studies have also examined operational solar PV generation data, including an assessment of generation compared with expectations across Australia (Haghdadi, Copper et al. 2016) and examination of 10 second operational data to assess short-term generation variability in the Hunter Region (Heslop and MacGill 2011). However, scarcity of voltage and generation data has limited operational analysis of voltage conditions as seen by solar PV inverters.

Several studies completed and currently underway focus specifically on the interaction between solar PV and local network voltage, however differ from this work in two key respects. Firstly, the studies focus on development of mechanisms for managing voltage, rather than characterising existing conditions, and secondly, have utilised less geographically diverse data sets compared with the data set analysed in this work. For instance, an American study developed a voltage management method based on 15 second data, with test results provided using ‘a sample of days’ for a ‘feeder located in Northern Virginia’ (Shibani Ghosh, Saifur Rahman et al. 2017). Similarly, the current Australia-based Networks Renewed project is trialing the use of solar PV inverter power quality capabilities to respond to and manage network voltage (Alexander, Wyndham et al. 2017). The trials will be run in two locations; the mid North coast of NSW and suburban Melbourne.

This study uses geographically diverse and high temporal resolution operational data to assess high level trends and characterise LV network voltage conditions, in the context of network standards. In this context, the value of undertaking analysis of actual voltage conditions at sites with distributed PV is clear.

3. Data set description

The results presented in this paper are a preliminary assessment of a suitably anonymised data set, which is a subset of the Solar Analytics database. Key parameters of the data set are listed in Table 1, and the coverage of this data is indicated in Figure 2 which shows the postcodes included in the data set. Figure 3 shows the number of sites per state and territory at the end of the period covered by the study. Almost all of the sites are residential and have PV systems installed.

Table 1. Data base overview

Data set	Period	Time increments	Number of sites*	Parameters captured	Completeness (*not quality*)**
Subset of Australia	1 January to 30 June 2017	5 minutes	2,010	• Maximum voltage • Minimum voltage • Solar PV generation • Net load	69.18%

* The number of sites listed is the number over the entire period, noting that the number of sites is increasing over time.
** Completeness is defined as the fraction of time periods for which data points exists (given the total number of sites in the data set). Note that some sites begin measurements part way through the six month period and therefore completeness is significantly reduced. However this is *not* an indication of data quality. There are 1,057 sites which span the entirety of the six month period, and for these sites there are measurements for 99.01% of the maximum possible number of data points.

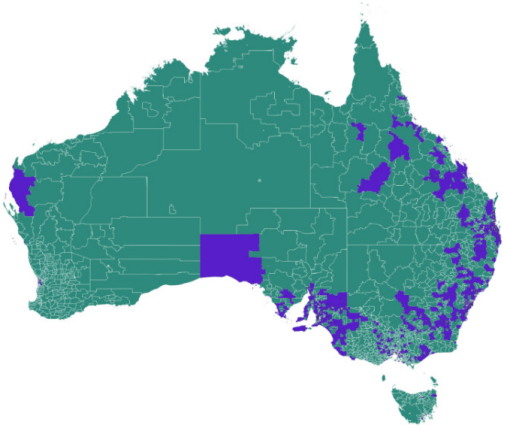

Figure 2 – Data set 1 coverage by postcode

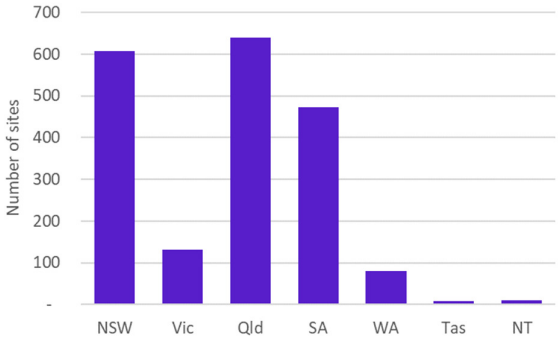

Figure 3 – Data set breakdown of sites by state and territory

4. Assessment of LV network voltage conditions

4.1. Standards and compliance requirements

DNSPs are required under the Australian National Electricity Rules to maintain LV network voltage within +/-10% of the normal voltage (AEMC 2017). AS 60038(2012) (Australian

Standards 2012) specifies a nominal voltage of 230V +10/-6% (216V – 253V), which is the standard most widely adopted by DNSPs as shown in Table 2. The standard for steady-state voltage limits in public networks - AS 61000.3.100-2011 (Australian Standards 2011) - lists the nominal steady-state voltage preferred performance as 225-244V for distribution networks, as well as the nominal steady-state voltage limits. Figure 4 is an illustrative example provided in AS 61000.3.100-2011, which shows an example voltage distribution against the voltage limits and preferred operating zone

Table 2. DNSP nominal network voltages

State	DNSP	Nominal voltage[1]	Nominal range	Reference
Qld	Energex	240V	+/- 6%	(Energex 2017)
	Ergon	240V	+/- 6%	(Ergon 2017)
NSW	Ausgrid	230V	+ 10% / -6%	(Ausgrid 2016)
	Endeavour	230V	+ 10% / -6% *'for most customers most of the time'* + 14% / -6% *'under certain network conditions'*	(Endeavour Energy 2016)
	Essential	230V	+10% / -2% for 95% of the time +10% / -6% for 99% of the time	Section 3.3 of Essential Energy Supply Standards (Essential Energy 2014, Essential Energy 2016)
Victoria	United Energy	230V	Steady state: + 10% / -6% Less than one minute: +14% / -10% Phase to earth for less than 10 seconds: +50% / - 100%	As per Energy Distribution Code section 4.2.2 (Essential Services Commission Victoria 2015)
	Powercor	230V		
	CitiPower	230V		
	Jemena	230V		
	Ausnet Services (SP Ausnet)	230V		
SA	SAPN	230V	+ 10% / -6%	(SA Power Networks 2016)
Tas	TasNetworks	230V	+ 10% / -6%	(TasNetworks 2014)
ACT	ActewAGL	230V	+ 10% / -6%	(ActewAGL Distribution 2016)

[1] AS61000.3.100(2011) states that "the measurement of steady state voltage at a site shall be based on consecutive 10 minute r.m.s. voltage measurements in accordance with AS/NZS 61000.4.30 over a one week period." (Australian Standards 2011)

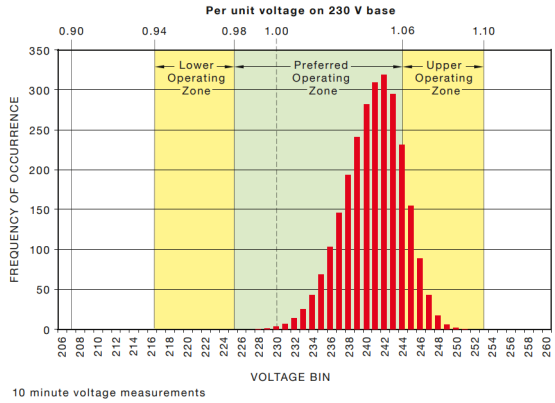

Figure 4 Illustrated example of voltage limits and preferred operating range (informative), Appendix B of AS 61000.3.100-2011 (Australian Standards 2011)

Historically, the standard nominal LV network voltage has been 240V across Australia, in contrast to the international standard of 230V (Ergon Energy 2017), which was developed by the International Electrotechnical Commission under a project initiated in 1983 (Essential Energy 2014). The transition to a nominal voltage of 230V is ongoing across several Australian distribution networks. In the Ausgrid network this predominantly involves adjustment of *'zone substation voltage and regulation setting to lower the 11kV distribution supply'* which is *'substantially complete'*, as well as the resetting of distribution transformer tap settings, which is ongoing and *'not expected to be completed until the next regulatory period'* (Ausgrid 2016). The nominal voltage remains at 240V in Queensland (Queensland Government 2006), however a Regulatory Impact Statement released in September 2017 recommends that the Queensland legislation is amended to require a nominal voltage of 230V (+10% / -6%) in line with *'Australian and international best practice'* (Queensland Government 2017).

4.2. Operational voltage distributions

The analysis presented in this paper compares observed operational data with the nominal voltage ranges set out above. This preliminary analysis is limited by the fact that the data available is 5 minute maximum and minimum $V_{r.m.s}$ measurements[1] rather than 10 minute $V_{r.m.s}$ values as required for assessment of distribution network voltage compliance under the relevant standard. The mid-point-10-minute-average (Equations 1 and 2) has been calculated for each site as a proxy for the 10 minute $V_{r.m.s.}$ value. The mid-point-10-minute-average is the average of the mid point of the minimum and maximum $V_{r.m.s}$ measurements for two consecutive 5 minute time intervals, to give an approximate 10 minute average:

$$V_{mid-pt}(t) = \frac{V_{min}(t)+V_{max}(t)}{2} \qquad \text{(Equation 1)}$$

$$V_{mid-pt-10min-average}(t) = \frac{V_{mid-pt}(t-1)+V_{mid-pt}(t)}{2} \qquad \text{(Equation 2)}$$

[1] Data is collected via Watt Watchers devices, which measure $V_{r.m.s.}$ over 100 milliseconds at the end of each five second period. The five minute data set provided for this study contains a voltage maximum value equal to the maximum five second $V_{r.m.s.}$ value recorded during that five minute period, and a voltage minimum value equal to the minimum five second $V_{r.m.s.}$ value recorded in that five minute period.

Figure 6 - Figure 9 below show the distribution of voltage measurements taken across the entirety of the data set for NSW, Queensland, South Australia and Victoria (using the mid-point-10-minute-average) for sites with solar PV. Note that the other states are not shown since there are only a small number of sites located in these regions. Each figure shows two distributions; one during approximate 'daylight hours' (7am-7pm AEST) and the second for approximate 'non-daylight' hours (7pm-7am AEST). It can be seen that generally the voltages are high, with the majority of measurements above the nominal voltage. Further, there is a slight narrowing of the distribution during non-daylight hours; which is to be expected, given that the majority of variation in load occurs during the day. These figures suggest that generally the distribution tap transformer settings are high, and hence there is a clear potential for restrictions to PV export due to a lack of head room as discussed above. The re-tapping of distribution transformers is proposed by the Queensland government as a low cost option for managing voltage on the distribution network, including to support increased penetration of solar PV in the Queensland networks (Queensland Government 2017).

Figure 5 shows the proportion of dwellings with solar PV installed by state/territory. Queensland has the highest level of PV penetration, and examination of Figure 8 shows that Queensland also exhibits the greatest variation between night and day voltage. However, South Australia has a similar PV penetration whereas the voltage distribution shown in Figure 9 shows minimal change between the day and night voltages, and indeed shows the most narrow voltage distribution of the four states (during both the day and night).

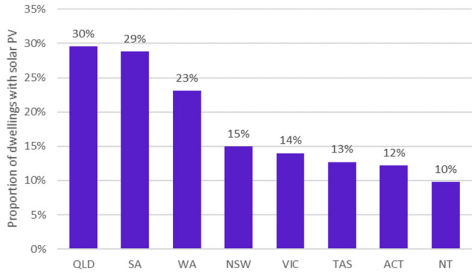

Figure 5 Solar PV penetration by state as at 5 Sep 2017 (APVI 2017)

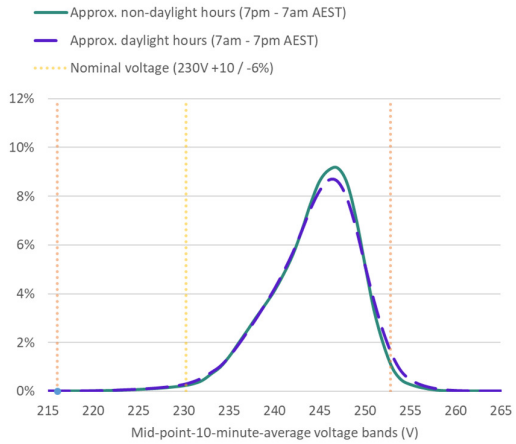

Figure 6 NSW voltage distribution

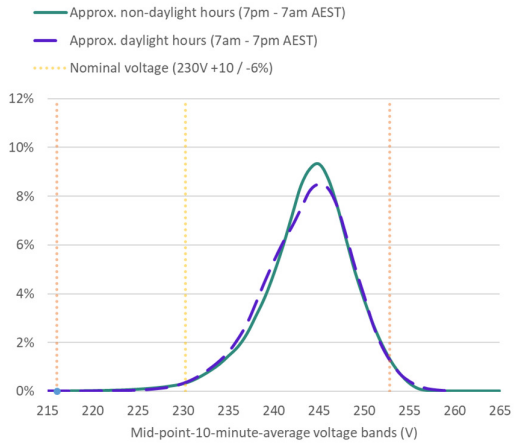

Figure 7 Victoria voltage distribution

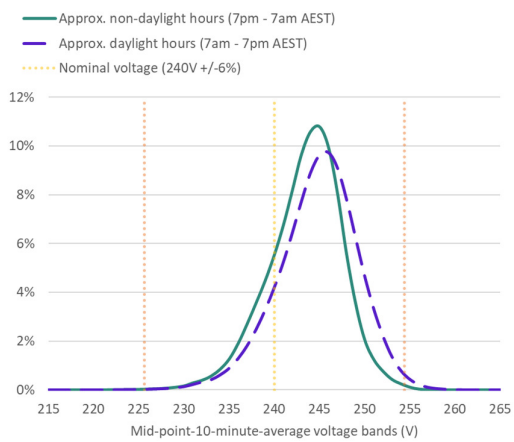

Figure 8 Qld voltage distribution

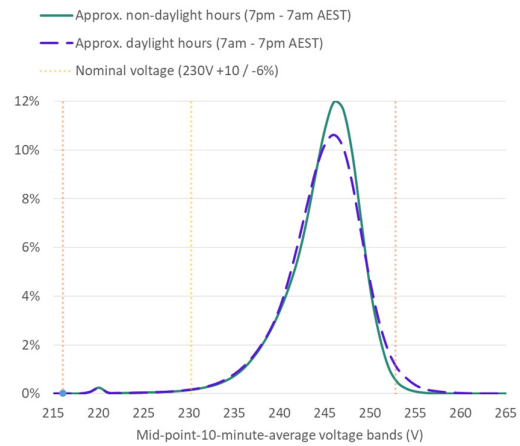

Figure 9 SA voltage distribution

These figures, coupled with the $V_{1\%}$ and $V_{99\%}$ values shown in Table 3 suggest some non-compliance and supports the need for further investigation, preferably utilising a data set with smaller time intervals and $V_{r.m.s.}$ measurements rather than minimum and maximum $V_{r.m.s}$ values. The values in Table 3 also show that the $V_{1\%}$ values are high, and that reducing distribution transformer voltage set points would be unlikely to result in non-compliance issues related to voltages being too low (whilst noting that this may not be the case for specific sections of the network).

Table 3 Upper and lower voltages observed
(based on mid-point-10-minute-average voltage distributions)

	NSW		Vic		Qld		SA	
	Day	Night	Day	Night	Day	Night	Day	Night
$V_{1\%}$	229.4	230.0	230.0	229.2	232.0	231.5	230.2	230.3
$V_{99\%}$	254.7	253.6	253.9	253.6	253.9	251.9	253.9	252.0

4.3. Operational voltage variation across the day

Voltage variation on the LV network throughout the course of a day is largely a function of the balance between generation and demand. The voltage at a given site within the LV network varies with the voltage at the distribution transformer (which is in turn, dependent on the generation and demand across the broader energy system), the net load on the network between the distribution transformer and the site, and the net load at the site itself. As result, voltage may vary significantly across the day at specific sites. Hourly voltage distributions are shown for June and January in Figure 10 - Figure 15[2] to provide an indication of voltage variation spread across the day (shown for all sites in each NSW, Queensland, South Australia and Victoria).

[2] The centre of the box plots indicate the median value, the limits of the box indicate the first and third quartile and the whiskers indicate 1.5 times the inter-quartile range from the edge of the box. The points marked in grey outside the whiskers are considered outliers.

Overall, the voltage profiles are unsurprising and reflect typical summer and winter load profiles. They show that low voltage tends to occur during peak demand periods (during the evening in summer and during the morning and evening in winter). However, it is surprising that there appears to be a narrower overall voltage spread (indicated by a narrower box plot interquartile range) in South Australia and Queensland, despite these states having comparatively higher PV penetrations.

Overall, the median voltage in NSW is relatively consistent, particularly in January (Figure 10). It is of note that the median voltages in NSW during January (Figure 10) are highest outside solar generation hours (for instance in hour 5). While the voltage spread increases during the solar generation period, it peaks during the evening hours, reflecting evening load. In comparison, Figure 11 shows that somewhat higher median voltages occur in June than January during the midday period, despite solar generation being lower in winter. This is likely due to the presence of air conditioning during summer, which acts to reduce voltage during the midday and afternoon period. Consistent with the distributions examined in section 4.2, voltages are generally high with a large proportion of observations between 240 – 250V over the day.

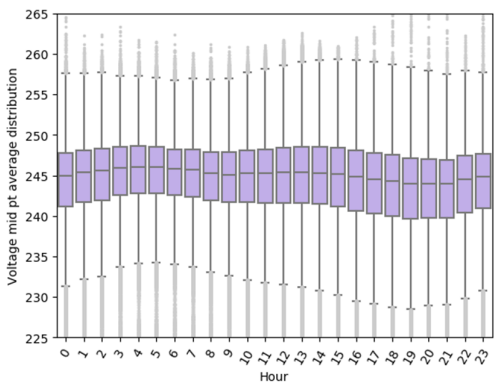

Figure 10 – NSW January daily profile

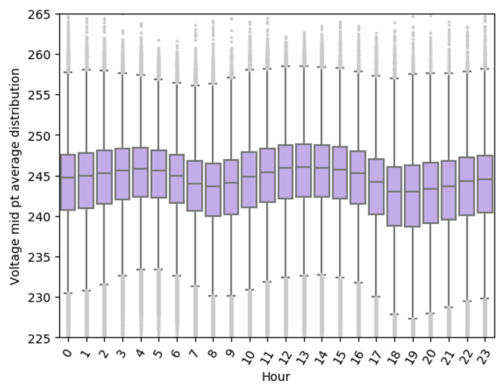

Figure 11 – NSW June daily profile

The same overall pattern is present for Queensland, where the voltage profiles reflect typical load patterns. During January (Figure 12) an increased spread is present during solar generation hours (compared with non solar hours), however while the high voltages decline during the evening when solar generation is minimal, the interquartile spread increases due to low voltages potentially resulting from use of air conditioning. Similarly to the NSW case, winter median daytime voltages are slightly above the night time levels. It is worth noting that a significant number of data points are shown as ‘outliers’, which are generally lower values.

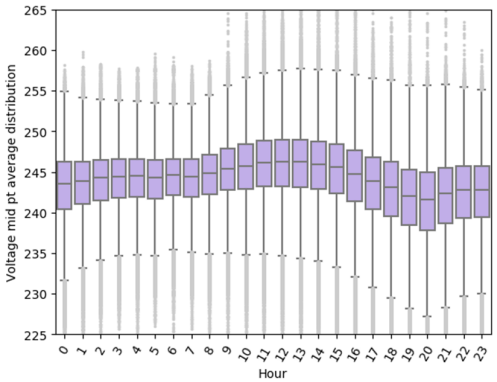

Figure 12 – Qld January daily profile

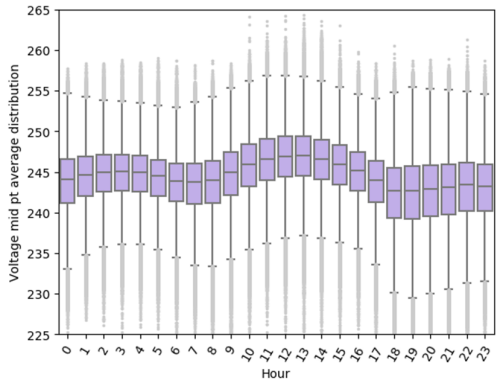

Figure 13 – Qld June daily profile

Figure 14 and Figure 15 show the voltage profiles for South Australia in January and June respectively. In June, Figure 15 indicates a clear increase in median voltage during the day, as well as a clear voltage reduction in the morning and evening, possibly due to significant heating load. In comparison, during January there is some voltage rise during the midday period, however similarly to NSW, the median values observed are lower than some of the overnight or early morning values. Although South Australia follows a similar pattern for both January and June to the other states examined, the median voltage variation during June is comparatively more extreme. However, a narrower interquartile voltage range is observed in comparison with other states, which is surprising given the high PV penetration.

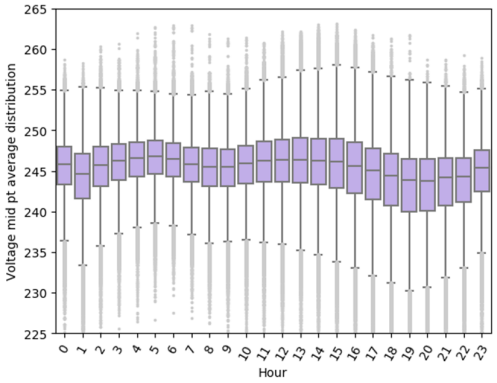

Figure 14 – SA January daily profile

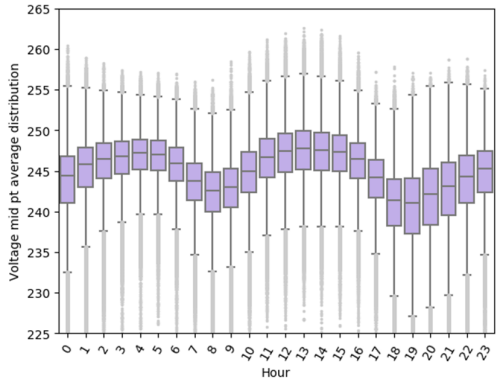

Figure 15 – SA June daily profile

Examination of Victorian sites shows a similar pattern to those observed in other states, with Victoria most closely resembling NSW. This is unsurprising as these states have similar climates and comparatively low solar PV penetration. However it is important to note that the data set examined in this study contains significantly fewer sites in Victoria compared with NSW, Qld and SA and therefore examination of aggregate conditions (such as in Figure 16 and Figure 17) is less representative of the conditions compared with the other states.

Similarly to NSW, the median voltages observed for Vic are fairly consistent across the day in January, with increased variability in June. Interquartile voltage spread is also relatively consistent, apart from some increase during the day and into the evening in January. There is a clear morning and evening voltage drop in June which is likely due to heating load.

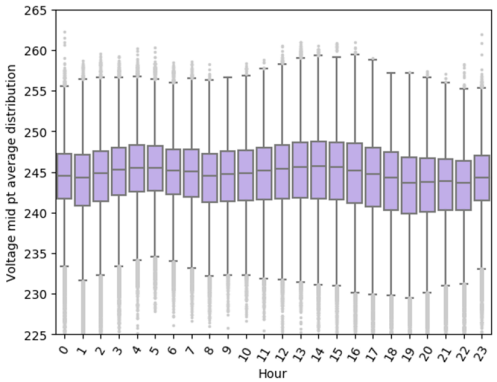

Figure 16 – Victoria January daily profile

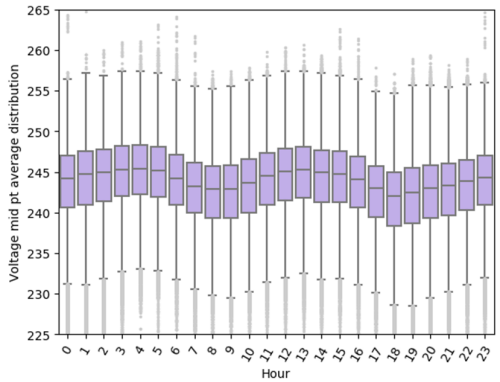

Figure 17 – Victoria June daily profile

5. Discussion and Conclusions

This assessment of voltage conditions on the LV network shows that the bulk of voltages on the LV network are greater than the nominal voltage with some possible non-compliance present, particularly during low load and high solar generation periods. Whilst this is to be expected (given the historic 240V nominal voltage and need to manage low voltages caused by peak demand), this phenomenon has not previously been shown using a comparatively geographically diverse and temporally granular data set. The implications are significant for solar PV integration as it shows that there is limited headroom in most jurisdictions for solar PV to increase voltages during the low-load and high-sunshine periods. The exception is South Australia where voltage spread is minimal and it appears that distribution transformer voltages are set lower, increasing available headroom. This is despite that South Australia has the second highest penetration of solar PV in Australia (by state/territory).

As the uptake of solar PV increases, it is likely that more active means of voltage management and DER coordination will be required in order to maintain voltage within acceptable bands. This may have implications such as increased cross subsidisation between consumers with and without solar PV.

The setting of distribution voltage set points will continue to be a primary factor in determining the degree of headroom and ability for PV to export. The voltage distributions found in this study suggest that distribution transformer voltages could be reduced without causing noncompliance due to under voltage conditions. This highlights the need for a discussion regarding network access rights for PV and fairness, which is an area of ongoing regulatory reform by the AEMC as flagged in its Distribution Market Model review (AEMC 2017).

Regardless of the means of voltage management, it is likely that increased regulatory oversight, for instance through requiring DNSPs to report on LV power quality conditions in a transparent and accessible manner, could improve the discussion of solar PV integration options and may support more efficient and equitable outcomes.

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