The impact of DC/AC ratio on short-term variability of utility-scale PV plants

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***Abstract*— The growing concern of frequency regulation resulting from high penetration of large-scale Photovoltaic (PV) power plant leads to the need of understanding the characteristics of short-term PV variability and mitigation approach. This study takes the advantage of the trending PV design which is an oversized DC capacity to the AC capacity of the PV plant to study the impact of this oversizing on the short-term variability of PV output. The term, DC/AC ratio is used to define the ratio of the DC capacity to the AC capacity of the plant. Some countering effects are found between the increasing magnitude of variability due to DC capacity expansion and the limit of the AC capacity. Overall, the variability is bounded by increasing the ratio while the impact is more significant during the peak generation period.**

***Index Terms*—Photovoltaic systems, Solar power integration, Frequency regulation, Large scale integration, Solar variability**

I. Introduction

The increasing penetration of utility-scale photovoltaic (PV) generation in electricity industries around the world introduces a number of challenges for both short-term and long-term power system operation. In particular, the additional short-term variability introduced by PV generation increases the challenge of balancing system demand and supply over short timeframes, requiring additional fast-response resources. However, given their power electronics interface, PV plants are potentially highly controllable and capable of implementing a control strategy to limit fluctuations in power output within the constraints of available solar insolation.

[1] reviewed strategies for mitigating the variability of the PV output, including smoothing by increasing geographical dispersion of the plant, using battery energy storage systems (BESS) to limit output ramping, and curtailing active power output by controlling the operating point of the inverter's maximum power point tracker (MPPT). Not covered in this review, and having received less attention in the literature, this study focuses on mitigation of variability by oversizing the PV array compared to the inverter. A higher DC/AC ratio (ratio of the DC nameplate capacity of the PV array to the AC nameplate capacity of the inverter) has become common as the price of PV panels has declined rapidly [2]. Increasing the capacity on DC side allows the inverter, which has cost per MW higher than PV modules [3], to be operated at high efficiency, and potentially limited network capacity to be better utilized because the plant spends more time at the (AC) rated capacity. This includes times when power clipping occurs due to output of the PV array exceeding the inverter rated capacity.

A number of studies on optimising the DC/AC ratio of PV plants [4]–[6] have assessed trade-offs between maximising the use of AC capacity and the lost value of 'spilled' generation. These studies have focused on economic profitability, maximizing generation yield, and operating the inverter at high efficiency, and found that some level of oversizing results in lower cost per MWh of plant output, depending on the specifics of the plant and electricity market arrangements.

A high PV plant DC/AC ratio and the resultant inverter clipping effect also has the potential to reduce the short-term variability of large-scale PV plant output. Work done by [7] quantified the frequency distribution of output variability at different DC/AC ratios of a 1 MW plant. However, large-scale PV plants have different variability characteristics to smaller systems, due to spatial smoothing as clouds take longer to pass over the field of a large array. Moreover, the impact of growing spatial dispersion was not considered.

In this paper, the effect of utility scale PV plant DC/AC ratio on short-term variability is analysed using 4-second resolution output data from four major (20-100MW) utility PV plants operating in the Australian National Electricity Market (NEM). This work offers new insights into the role of DC/AC ratio and inverter clipping in stabilising PV output during times of high generation and its potential provision of generation

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TABLE I. THE DETAILS OF PV PLANTS CONSIDERED IN THIS STUDY

PV plant (latitude, longitude)	AC Capacity (MW)	DC Capacity (MW)	Original DC/AC Ratio	Mounting Technology	Data Period
Nyngan, NSW (-31.57, 147.08)	102	132.4	1.30	Fixed-tilt	June, 2016 – May 2017
Moree, NSW (-29.57, 149.87)	56	69.5	1.24	Single-axis tracking	
Broken Hill, NSW (-31.99, 141.39)	53	70	1.32	Fixed-tilt	
Royalla, NSW (-35.49, 149.14)	20	24	1.20	Fixed-tilt	

reserve, which could potentially be used to participate in frequency regulation services. It also highlights, the competing influence of DC/AC ratio on variability as high ratios drive more periods of clipping reducing variability, yet also increase variability when the plant is not clipping due to greater PV capacity. The rest of this paper is structured as follows. The study method is presented in Section II including details of data and variability assessment as DC/AC ratio is varied. Results are then presented in Section III, while Section IV provides discussion on these findings, and suggestions for future work.

II. METHODOLOGY

A. Data

4-second resolution data of four utility-scale PV plants registered in the NEM is used. The details of the plants and study period are listed in TABLE I. This data was collected by the Australian Energy Market Operator (AEMO) for the purpose of Ancillary Services Market Causer Pays calculations and is publicly available on the AEMO website [8].

B. DC/AC ratio and variability analysis

To increase the DC/AC ratio for this study, the DC capacity of the plants is scaled up while the AC capacity remains constant as a reference point. This is the most appropriate approach, since the AC capacity has been approved for network connection, is registered with the market operator, and provides the basis of energy dispatch calculations. There is also likely to be flexibility in expanding or modifying the DC side of the PV plant while maintaining the AC capacity for grid compliance.

Five levels of DC/AC ratio are modelled including the existing ratio for each plant, and multiples of 1.3, 1.5, 1.7 and 2.0. The ratio is defined by (1).

$$DC/_{AC}\, ratio = \frac{P_{DC\, nameplate\, capacity}}{P_{AC\, nameplate\, capacity}} \tag{1}$$

Variability in this study is defined as the change in power output over a 4-seconds interval as shown in (2).

$$\Delta P_t = P_t - P_{t-1} \tag{2}$$

Where P_t is the instantaneous power output measured at timestamp t and $t-1$ is the previous timestamp.

C. Limitations

As the DC capacity of a PV plant is increased, we would expect to see smoothing related to inverter clipping, and also spatial smoothing as the plant becomes larger and clouds take some time to move over or off the PV array.

The only available high resolution utility PV plant output data available for this study is the instantaneous 4-seconds output recorded at the grid connection point of the plants. Solar insolation measurements are not available at this time resolution. Therefore, the effects of weather, installed capacity and the geographical coverage of the PV plants are difficult to isolate. Due to different sizes, technologies and climate zones across the PV plants in this study, they are not directly comparable [9]. In particular the variability characteristics from plant to plant will differ. Although several studies [10]–[13] have attempted to quantify the impact of geographical smoothing on reducing PV variability, the impact is weather and system specific. These studies have also tended to focus on the spatial dispersion across distributed PV systems over a large radius of hundreds kilometers [10] which is not relevant to smoothing across an individual plant.

To quantify the effect of geographical smoothing related to DC capacity expansion, the output at inverter level within the plant would be required. Otherwise, knowing meteorological parameters such as cloud speed could be helpful [14]. Since it is not possible to separate spatial smoothing from DC/AC ratio smoothing effects with the data we have available, this study quantifies an upper and lower bound of expected change in underlying variability as DC/AC ratio increases.

1) Worst-case Scenario

Given that the frequency distribution of variability will change and the overall normalised variability will decrease if a PV plant is larger [15], a simple scaling method may result in an overestimation of the magnitude of the output variability as a plant is scaled up, and can be considered the worst-case variability scenario. This approach essentially assumes that the output of the additional capacity and the original are perfectly correlated. The equation to calculate variability of the scaled up plant is shown in (3) – (4).

$$\Delta P_{scaled,correlated} = \Delta P_0 \times N \tag{3}$$

$$N = \frac{DC_{new\, capacity}}{DC_{original\, capacity}} \tag{4}$$

Where ΔP_0 is the variability of the original DC capacity and N is the ratio of new DC capacity to its original capacity.

2) Best-case Scenario

The best-case scenario can be calculated by assuming that the output variability of the additional capacity is entirely uncorrelated with existing output over 4 second intervals. The aggregated variability of uncorrelated PV plants is equal to $1/\sqrt{n}$ of the total variability [16]. Hence, the variability of the new capacity is calculated by (5).

$$\Delta P_{scaled,uncorrelated} = \Delta P_0 \times \sqrt{N} \tag{5}$$

D. Clipping Analysis

This study separately analyses the impact of DC/AC ratio during times of high plant output because this is the period when there is inverter clipping, and therefore reduction in variability. To assess the clipping effect, days with unscaled generation reaching at least 90% of the plant's AC capacity for at least three hours are selected (calculated by aggregating 4 second periods where output was at least 90%). The time period between 10.00 to 14.00 was analysed for fixed-axis plant as this is the time when peak generation usually occurs. For single-axis tracking plants, 8.00 to 16.00 was the period analysed, as high generation levels can be reached across a longer period of the day.

III. Results

A. Characteristics of PV variability

Fig. 1 illustrates probability density function of 4-second variability for each original PV plant before DC upscaling. All four plants have an extremely high probability of very low variability which implies that very short-term fluctuations in PV output over this timescale should not typically be problematic. However, the distributions also exhibit fat tails which contain a small number of large magnitude changes in power output over 4 seconds. The distribution of the variability fits a Laplacian distribution but only when changes in output of zero are excluded. In Fig. 1, the probability density distribution derived from the data includes zero changes but the fitted distribution is calculated by excluding non-zero variability.

Nyngan and Royalla (Fig. 1(a) and 1(d)) show very high insignificant variability with fatter tails while Moree and Broken Hill (Fig. 1(b) and 1(c)) have a considerably narrower range of fluctuation distribution with a number of small fluctuations. This may have an influence on how DC/AC ratio could affect the variability distribution of these plants.

B. Variability with Increasing DC/AC Ratio

Fig. 2 shows the change in the mean of the overall PV output variability under worst-case and best-case scenarios. In the worst-case scenario (additional DC capacity is perfectly correlated with existing), the mean normalized variability of all plants increases as the DC/AC ratio increases, which indicates that the underlying plant variability increase due to larger DC capacity is more important than the clipping effect. However, for most of the plants, the mean variability reaches its maximum point at DC/AC 1.7, except for Royalla which has its maximum at ratio of 1.5. This is because at higher DC/AC ratios, the clipping effect is more significant that the larger variability caused by larger DC plant size. Meanwhile, in the best-case scenarios, mean variability at all sites significantly decreases due to both spatial smoothing and inverter clipping effects.

C. Variability During Clipping Periods

Since, without spatial smoothing, variability increases as DC capacity increases, and is reduced by clipping, the impact of increasing DC/AC ratio on variability during clipping periods are considered separately in this section. Only high output

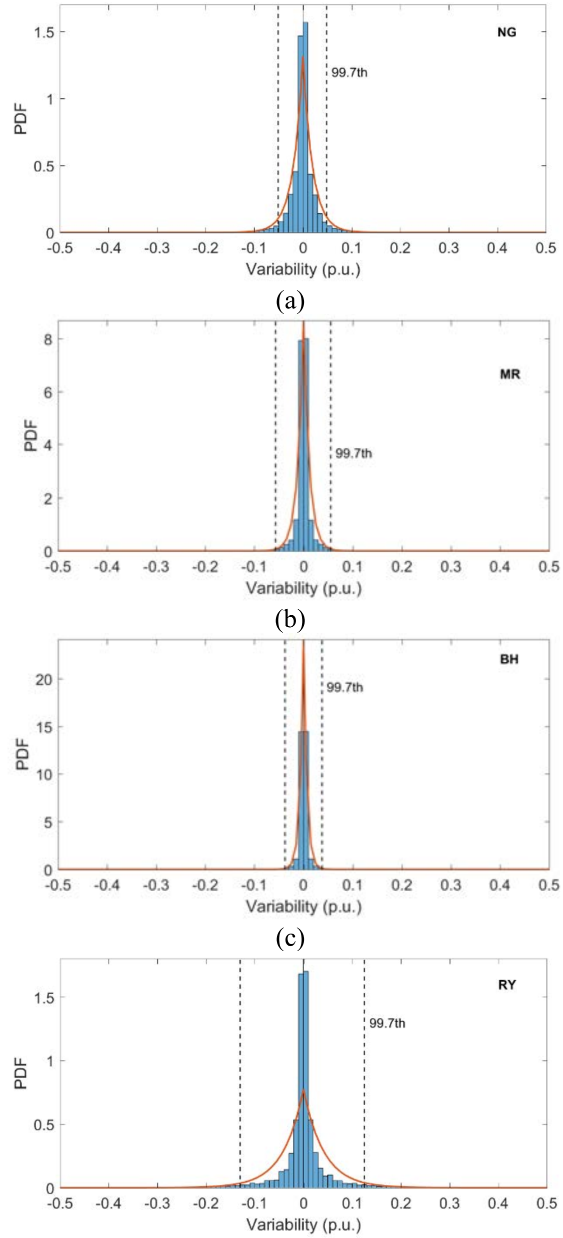

Fig. 1 Probability density distribution derived from 4-sceonds data (true PDF) with Laplacian distribution fit (an estimator) of (a) Nyngan, (b) Moree, (c) Broken Hill and (d) Royalla

periods (as defined in the method) were considered, in order to ensure clipping. Fig. 3 shows a decreasing trend in the mean variability during periods of high output (blue lines) at all four PV plants as the DC/AC ratio increases, while the impact on the means for remaining time periods (red lines) is still similar to the overall pattern (Fig. 2). The reduction in variability is particularly high for Royalla, a plant with originally higher variability.

D. Extreme Fluctuation During Peak Time

Extreme variation in PV output that could not be managed by regulation services are believed to fall in the top 1% of cumulative distribution or the 99.7th percentile value (that is

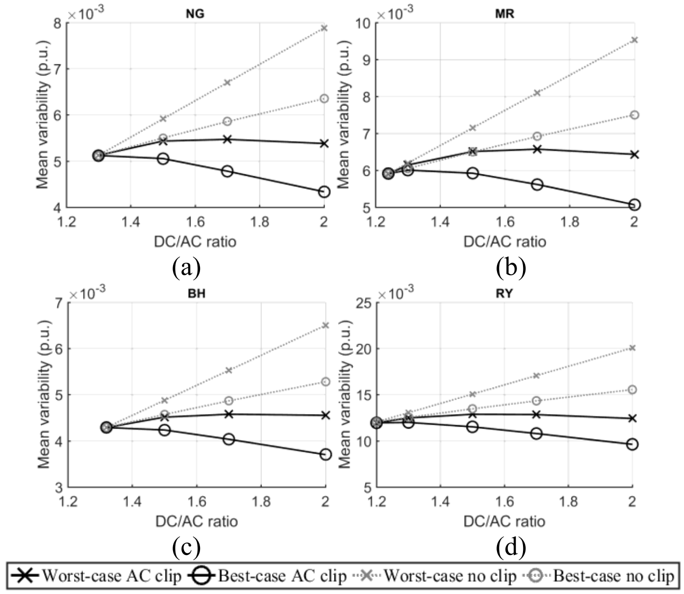

Fig. 2 The mean of output variability at each DC/AC ratio at (a) Nyngan, (b) Moree, (c) Broken Hill and (d) Royalla. The no-clip plots represent expected variability with respect to AC rating if there was no clipping, highlighting the role that clipping plays in reducing variability.

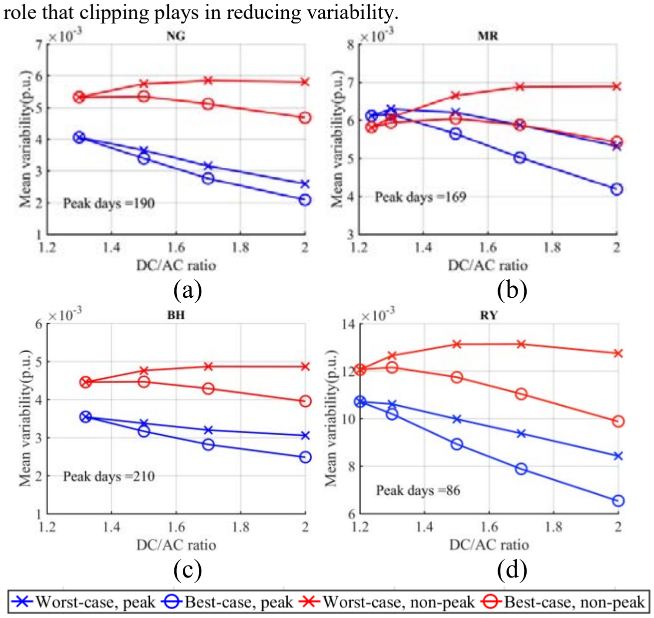

Fig. 3 The mean of output variability considering the peak generation period and other hours out of the peak time at each DC/AC ratio at (a) Nyngan, (b) Moree, (c) Broken Hill and (d) Royalla

equivalent to ~26 hours) [13]. Therefore, the characteristics of the top 1% of output fluctuations are plotted, with 99.7th indicated in Fig. 4. The peak generation period is the focus because the impact of clipping is clear during that period. As demonstrated in Fig. 1, the unscaled characteristics of 4-second variability at all four PV plants do not follow a normal distribution. From Fig. 4(d), variability of Royalla, is reduced by the clipping effect the most. The 99.7th values decrease drastically from 0.11 (p.u.) to 0.02 (p.u.) and zero variability can already be reached within the 1% window at the DC/AC ratio of 1.5. A similar pattern can also be observed for Nyngan, where zero variability occurs within 1% of the cumulative probability. Broken Hill and Moree which originally have few extreme fluctuations are not much affected by the change in DC/AC ratio. The impact of changing DC/AC ratio is very minimal for Moree's variability probability distribution (Fig. 4(b)) which could be because less extreme clipping occurs with the flat generation profile of a single-axis tracking plant where the peak generation can be reached soon after sunrise and the characteristic dip in the generation profile during the day may not be clipped.

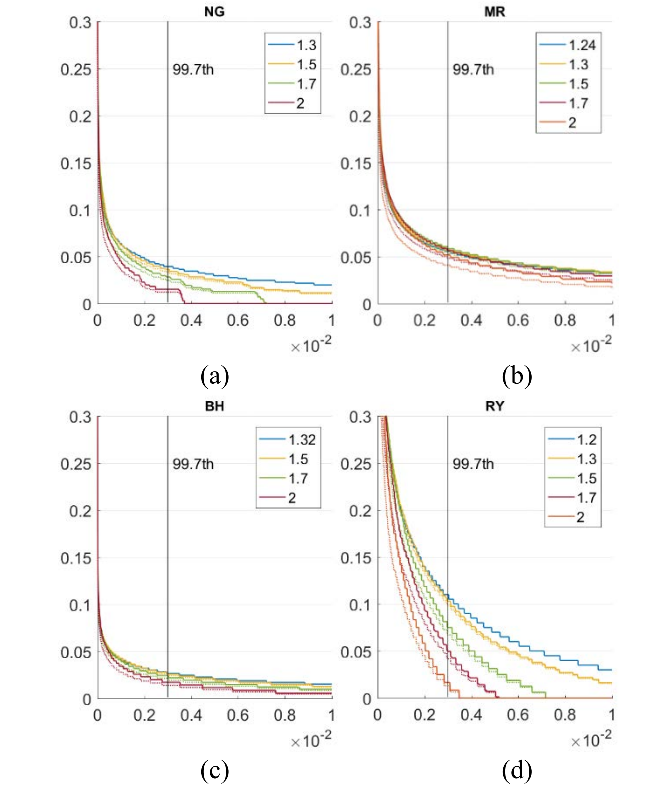

Fig. 4 The top 1% of true cumulative probability distribution of variability for different DC/AC ratios, with 99.7th percentile indicated for (a) Nyngan, (b) Moree, (c) Broken Hill and (d) Royalla during peak generation periods.

E. Clipped generation

The total annual clipped (hence spilled) generation is summarised in Fig. 5. Moree has the highest fraction of clipped generation as DC/AC ratio increases due to the output profile of a single-axis tracking plant. Nonetheless, the fractions of energy spilled for all four plants are similar.

The number of hours that could be required for energy storage and the amount of energy that could be stored daily due to the excess generation are estimated and shown in TABLE II. An analysis on commercial aspect is beyond the scope of this study. However, a review study [1] has already shown that using battery systems to store all the excess generation in PV plants is currently very costly and [17] concludes that the battery-less option is more economical.

IV. Conclusion

This study shows that increasing the DC/AC ratio of utility scale PV plants can reduce short-term output variability. Even though variability may increase, if the variability increase due to DC capacity expansion is larger than the clipping effect, overall variability in the worst-case scenario remains bounded

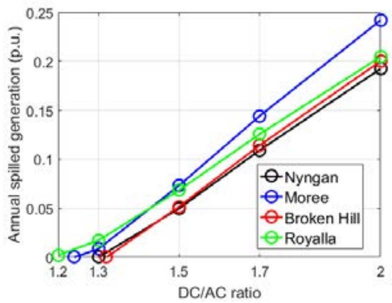

Fig. 5 The total annual spilled generation calculated as per unit of total annual energy generation from the PV plants

TABLE II STORAGE REQUIREMENT FOR SPILLED GENERATION (MEAN DAILY SPILL HOURS / MWH STORAGE)

DC/AC ratio	Nyngan	Moree	Broken Hill	Royalla
1.3	-	2.4 / 3.4	-	1.4 / 1.8
1.5	3.1 / 35.3	4.4 / 34.1	3.5 / 20.0	2.6 / 8.2
1.7	3.9 / 88.0	5.7 / 76.1	4.3 / 50.1	3.2 / 17.2
2	4.8 / 182.4	6.5 / 150.1	5.2 / 103.3	3.9 / 32.8

by the AC capacity of the inverter. The difference in the mean variability of the worst-case and best-case scenarios in all four plants are not significant. This approach therefore provides a reasonably tight range for quantifying the impact of DC/AC ratio on variability.

Analysis of times of high generation shows that clipping due to increasing DC/AC ratio can decrease mean variability. However, the significance of the impact varies from plant to plant depending on the original characteristics of the plant's variability. The results suggest that variability of single-axis tracking plant is reduced less by upscaling the DC/AC ratio while plants with fat tailed variability distributions show a noticeable reduction in the extreme values (99.7th percentile) and relatively steady peak generation can be achieved 99% of the time.

It should be noted that DC/AC ratios also cause clipped (spilled) generation. A study on the potential to use the curtailed generation to assist with frequency regulation services would be a useful extension to this work.

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