# Addressing Barriers to Efficient Renewable Integration

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# Analysis on the Behavior of Grid-Connected Single-Phase Photovoltaic Inverters Under Voltage Phase-Angle Jumps

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***Abstract*—There is increasing interest in understanding residential inverter behavior, particularly due to the growth of roof-top photovoltaic (PV) system installations and the impact behavior has on the distribution system. The response of a single PV inverter or a simulated model does not represent the actual behavior of several inverters integrated with the distribution network. In this research, 28 off-the-shelf residential PV inverters experimental responses to voltage phase angle jumps are analyzed. Statistical analysis is performed to demonstrate the impact of the behavior of the installed roof-top PV inverters under such disturbances on the Australian National Electricity Market. Undesired curtailment and disconnections were observed, threatening the power system's stability where a high penetration of solar PV generation exists. The main objective of this study is to provide a statistical analysis method to identify the potential power system response under massive disconnection and power curtailment of inverters. Another aim is to assist in future Standards development and a proper contextual investigation for high penetrated areas of roof-top PV systems.**

***Index Terms*—Distributed energy resource (DER), inverters, photovoltaic (PV), ride-through, standard, volatge phase angle jump (VPAJ),**

## I. Introduction

The growing demand for electricity in the world requires sustainable and reliable sources to overcome power shortfall. Renewables are a promising solution to overcome the power demand and reduce the carbon footprint from conventional power generation sources. Renewable energy production is becoming the major contributor of power in the grid worldwide, and with the increasing power demand, more and more renewables are connecting to the grid to fulfill that demand. The total power generated by renewables in 2019 is $2532\,\mathrm{GW}$, with $578.5\,\mathrm{GW}$ is contributed by photovoltaic energy [1]. Such an example of roof-top PV system's contribution in Australia is about $22.3\%$ in 2019, with a significant contribution of more than $52.5\%$ renewable energy in South Australia. The data in Fig. 1 presents the growing trend of the installed PV system in Australia over the past ten years. These combined distributed energy resources (DER's) can be seen as the centralized power system, but this system is not controlled or monitored by any centralized grid operators. This will make things very complicated under grid disturbances that are not controlled by any centralized system to overcome system failure. This presents a significant threat to the power system's operation, which needs to remain stable after integrating millions of PV systems. [2]. Small-scale PV systems' growth poses a significant challenge to the power system operators because they are invisible compared to large systems. It is crucial to study the response under different grid conditions to understand these challenges posed by small-scale PV systems.

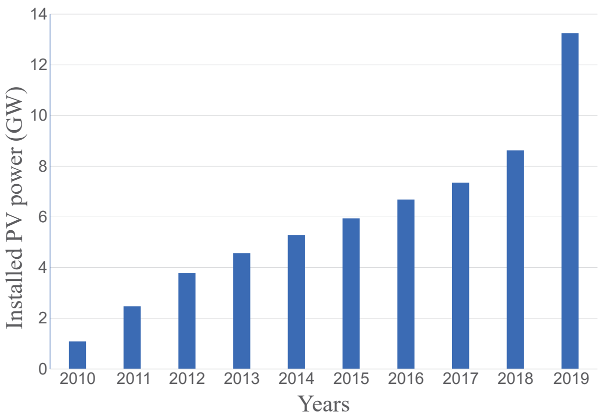


Fig. 1. Cumulative solar energy generation in Australia in the last decade [1].

A sudden change in reactive load, balance, and unbalance faults in the power system are not only the cause of voltage sag but also the voltage phase angle jump (VPAJ) in the power system. In the case of balance faults in the transmission system, and if the source and the feeder's impedance is equal X/R ratio, VPAJ does not occur at the point of common coupling but not in the case of a distribution system. There will be a small VPAJ in the distribution system. In case of unbalance faults, single-phase load experience a phase jump even the X/R ratio is equal between the source and feeder impedance. The phase of the voltage at the point of common coupling (PCC) may experience an instantaneous change, known as voltage phase angle jump (VPAJ). This VPAJ may be seen as a frequency change in the system by the inverters. This phenomenon may trigger fault condition

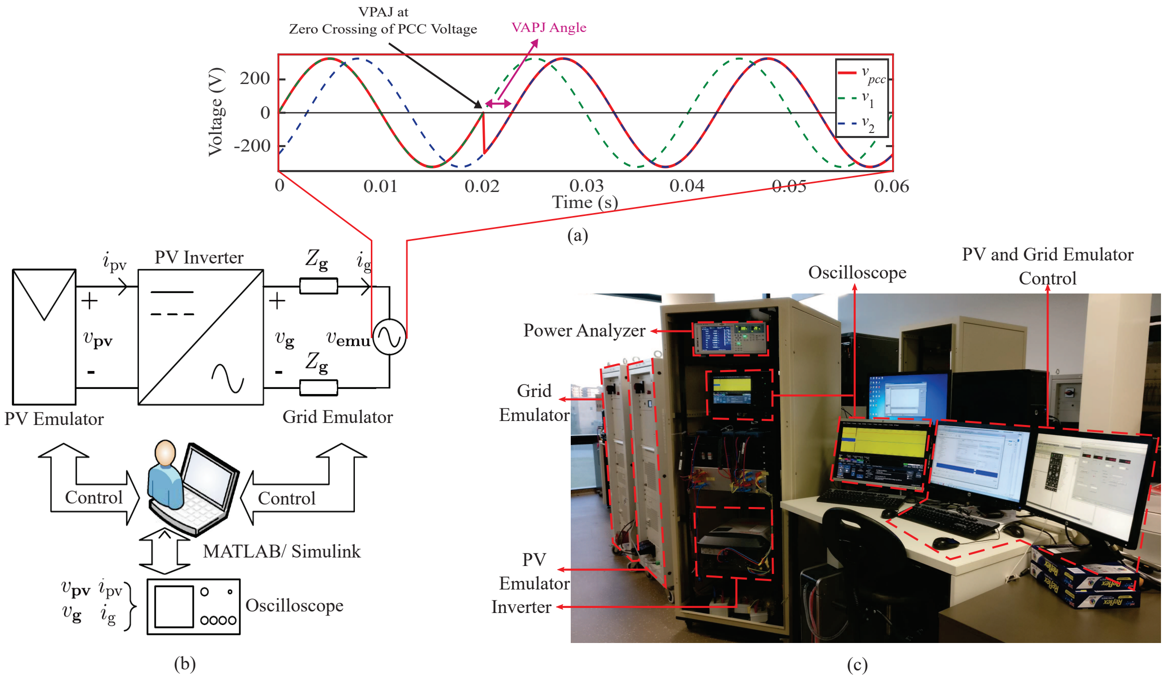


Fig. 2. (a) Voltage phase angle jump waveform, (b) schematics of testing setup, and (c) photo of experimental testing setup [3].

in inverters because of miscalculation of the disturbance as frequency deviation during the transient period of VPAJ, even though there is no frequency deviation in the grid [4]. In August 2016, such an event happened in Southern California, where 1.2 GW solar PV generation was disconnected due to misinterpretation of phase jump as frequency disturbance by inverters. A fault in the transmission level created a VPAJ that translate into a large instantaneous frequency deviation. Inverter instantaneous frequency calculation suggested a sudden change in the frequency and caused a cascading effect tripping off multiple small scale PV generation plants. The X/R ratio change occurs by any fault on the system through this event widespread effect, seen as a VPAJ by nearby distributed energy resources (DERs) [5]. Another example of such an event was reported in January 2017 in the UK, where a fault in 400 kV line caused the VPAJ measured by the phasor measurement units (PMUs) even though no frequency change was reported. The fault was cleared in 120 ms but PMUs recorded 20° VPAJ with a measuring frame of 2-3 cycles ($40 - 60$ ms). The rate of change of frequency (RoCoF) observed was outside of the normal system bounds of RoCoF. This indicates that if inverters are programmed based on the calculation of instantaneous frequency change in the system may seriously impact the distributed generation system tripping off multiple inverters [6]. One example of blackout in Europe caused due to transmission line disconnection in Germany which aggregated inverters disconnection. This loss of DERs caused a cascading effect and made a large area of the grid unstable.

The inverters response varies according to the manufacturers' embedded control, which complies with different countries' technical standards. The purpose of these standards is to maintain grid support during the fault through grid supporting functions as prescribed in standard to sustain the system's power quality. Standards define these grid supporting functions after a long investigation on the grid disturbance, which causes damage to the economy if PV penetration increases and the power system collapses. The Australian standard AS 4777.2 (2015) [7] does not specify any particular action against this disturbance type. Inverter ride-through capability for VPAJ is required in IEEE 1547 (2018) [8] for PV inverters connected to the low voltage grid. Newer standards such as IEEE 1547.1 (2020) [9] requires inverter to stay connected for VPAJ up to 60°.

Several researchers analyze inverters behavior under grid disruptions by historical, experimental, and bench-testing data in the literature. The driving force behind is changing grid conditions and standards essential for grid support; with increasing DER penetration, it is essential to understand the impact of commercial and residential PV systems on the grid. In [5], two commercial inverters were tested for the IEEE 1547.1-2020 VPAJ protocol to understand the behavior and validate compliance with the standard. The results demonstrated that one inverter complies with standard while the other does not. A commercial PV inverter was tested for grid disturbances in [10], exploring miscalculation of frequency due to VPAJ, preventing inverter from activating fault ride-through settings. Multiple inverters were subjected to different grid disturbances in [3] to understand the inverters aggregated

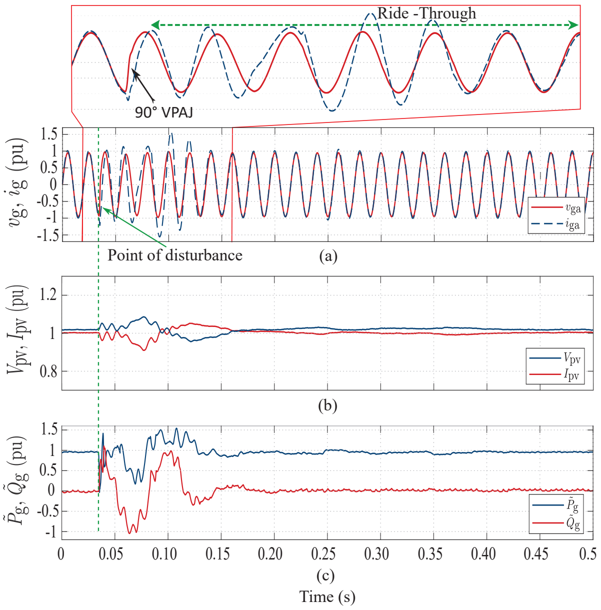


Fig. 3. Inverter riding-through behavior for 90° VPAJ: (a) Grid voltage and inverter output current, (b) PV voltage and current, and (c) inverter output active and reactive power.

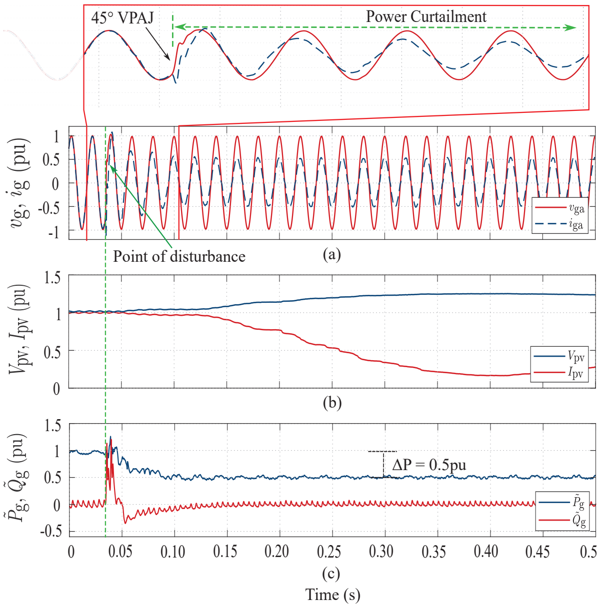


Fig. 4. Inverter power curtailment behavior for 45° VPAJ: (a) Grid voltage and inverter output current, (b) PV voltage and current, and (c) inverter output active and reactive power.

response. Previously only two inverters were investigated for grid disturbances, but here, 28 off-the-shelf most common commercial inverters were tested to see the wider effect on inverters by the grid disturbances.

This paper analyzes and categorizes the behavior of grid-connected roof-top commercially available PV inverters under sudden VPAJ incidents. Accordingly, comprehensive experimental tests are performed on 28 off-the-shelf most common commercial inverters in the Australian National Electricity Market (NEM). Even though all inverters comply with the current Australian Standards, they show different responses to similar VPAJ incidents. This work aims to provide statistical information about inverter behavior and inform utilities, DNSPs, and companies about the performance of PV inverters currently available in the market.

The next section of this article gives detail about the experimental inverter testing setup with the behavior of VPAJ disturbance from the system. Bench testing results for different VPAJ are presented in section III. Section IV critically analyzed the bench testing results and providing statistical evidence for VPAJ behavior.

## II. Inverter Bench Testing Setup

The testing setup contains off-the-shelf single phase PV inverters rated between $1.5\,\mathrm{kW} - 5\,\mathrm{kW}$ following AS 4777.2:2015 [7] or AS 4777.3:2005 standard. Inverters are selected based on the most commonly installed inverter types across Australian NEM from market analysis. Inverters are connected to a bidirectional Regatron grid emulator. The voltage parameters can be varied at the point of connection, including voltage magnitude, the frequency, and phase angle, representing a controllable voltage source through a small impedance of $L_g = 0.12 + j0.16\,\Omega$ recommended in [7], indicating the typical line impedance between grid and inverter. The inverter dc side is connected to the PV emulator, and the PV curve is generated to act as a solar array producing nonlinear voltage versus current attributes. The grid voltage profile during VPAJ test, experimental testing setup schematic and photo is shown in Fig. 2 (a), (b) and (c) respectively. The details of the tested inverters can be found in [11] and [12]. Furthermore, all the detailed results of the tests in this paper and other voltage/frequency disturbance tests are available in [13].

## III. Inverter Testing Results Under VPAJ

This section analyzes inverters behavior under various grid VPAJ incidents; however, there is no specific requirement for inverter response under VPAJ specified in the standard. Therefore, carrying out these tests is useful for analyzing and understanding the grid disturbance's aggregated effect on the inverters. Different VPAJ tests are carried out on the inverters to identify the percentage of inverters, presenting undesired responses under such grid disturbances. The inverters are subjected to VPAJ of 15°, 30°, 45°, and 90° from grid emulator at zero crossing, as shown in Fig. 2(a). During the bench-testing of VPAJ, three distinct inverter responses were observed, i.e., i) ride-through, ii) power curtailment, and iii) disconnection.

*Ride-Through*: Ride-through is the inverter capability to sustain the grid disturbance without any major disruption in

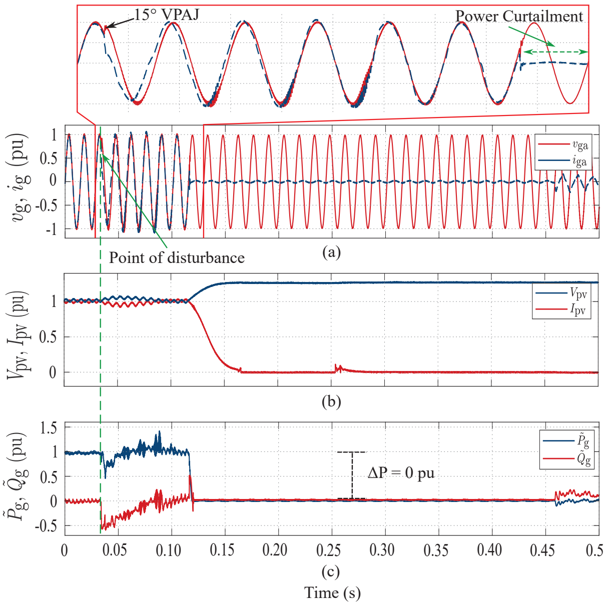


Fig. 5. Inverter disconnection behavior for 15° VPAJ: (a) Grid voltage and inverter output current, (b) PV voltage and current, and (c) inverter output active and reactive power

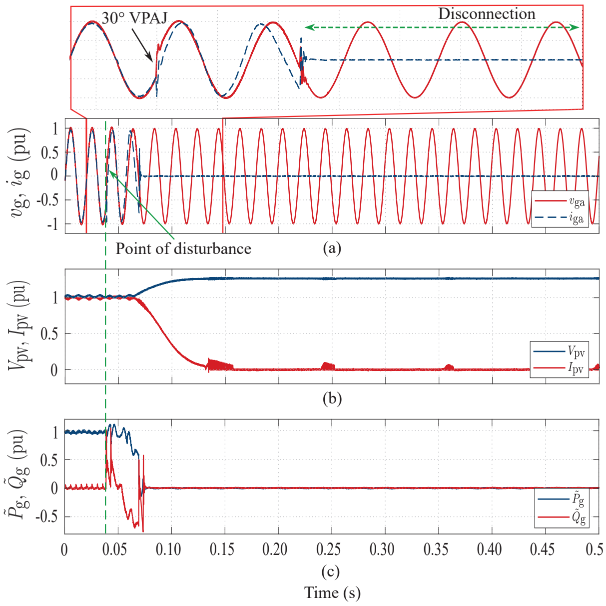


Fig. 6. Inverter disconnection behavior for 30° VPAJ: (a) Grid voltage and inverter output current, (b) PV voltage and current, and (c) inverter output active and reactive power

the inverter's output. There is no noticeable change in the inverter's active and reactive power in this condition, and most of the investigated inverters ride through a 15° VPAJ. Under this condition, there is a relatively small phase angle difference at PCC between the output voltage and current of the inverter after the beginning of disturbance, but this phase difference vanishes after two or three cycles. The desirable condition for VPAJ is up to 60° based on IEEE Std. 1547:2018 [8]. The ride-through capability of inverters starts to decrease with an increase in the level of VPAJ. The statistical analysis shows that only half of the inverters installed in the grid could ride through up-to 45° without any major disruption in the power system. Most of the inverters could ride through 15° VPAJ except 5-6 inverters. A 90° VPAJ inverter response is shown in Fig. 3, which is the maximum VPAJ investigated on inverters where the inverter rode-through without significant disruption. Because of the phase shift between the voltage and current, second harmonic ripples exist in the inverter output active and reactive power for several cycles after the disturbance shown in Fig. 3 (c).

*Power-Curtailment*: The inverter output power is reduced for several minutes and returns to pre-fault level following the ramp rate as required by the standard [7]. Power curtailment is different for different inverters based on the inverter firmware. For example, inverter 25 have seen the VPAJ as a frequency change in the grid, which activates the inverter grid supporting function by decreasing the active power injection to the grid with different VPAJ. In some inverters, i.e., inverter 10 and 12 power is curtailed to zero without disconnection from the grid as seen in the Fig. 5, where power of the inverter decreases to zero without disconnecting the inverter with 15° VPAJ. In Fig. 5 (a) after the VPAJ inverter remains connected for 5-6 cycles and then decreases the power to zero which shows that some inverter takes time to interpret the grid disturbance to perform certain actions. A case of 45° VPAJ in inverter 25 is shown in Fig. 4 where power is curtailed to 50% in Fig. 4 (c). These inverters power curtailment behaviors are undesirable, and the inverter takes several minutes to reach maximum power.

TABLE I
SUMMERY OF INVERTER RESPONSE TO VPAJ

| Behavior \ VPAJ | 15° | 30° | 45° | 90° |
|---|---|---|---|---|
| | No of Inverters | | | |
| Ride-Through | 23 | 18 | 15 | 10 |
| Power Curtailment | 4 | 6 | 7 | 6 |
| Disconnection | 2 | 5 | 7 | 13 |

*Disconnection*: The disconnection of several inverters for VPAJ is highly undesirable; Fig. 6 shows the inverter disconnection for 30° VPAJ. Instead of clearing the fault in 1 s inverter goes into reconnection procedure and takes several minutes to start delivering maximum power again. The inverter disconnection starts to increase with the increase in VPAJ value. Such disconnections may cause substantial loss of generation in the distribution system, leading to blackouts.

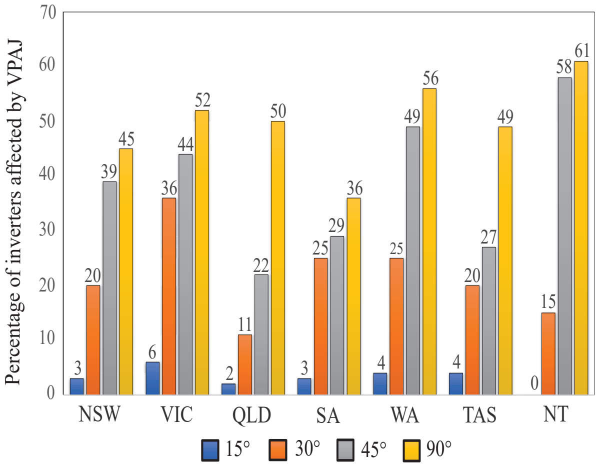


Fig. 7. Projected percentage of PV inverters vulnerable to VPAJ across Australia.

## IV. Bench Testing Discussion

As mentioned in Section III, a relatively high proportion of the installed inverters in NEM show undesirable behavior under various VPAJ conditions, power curtailment, and disconnection. With changing international standards, IEEE 1547(2018) [8] and continuously changing grid conditions, inverters are required to be more resilient under such grid disturbances. This article presents the inverters responses leading to accumulated loss of DERs and load fluctuations of the roof-top PV systems with statistical evidence gathered from the industry. Thus it is crucial to examine facts and figures collected from bench-testing of inverters, If extrapolated at the same time to a hundred or thousands of inverters can undoubtedly cause a large part of DERs loss discussed previously in Section II. The inverters sensitivity to VPAJ varies across the board depending upon the grid synchronization and fault detection strategies. More research efforts are needed to get a better understanding of these aspects of inverters. Besides, multiple fault types and grid transformer vectors may cause voltage sag simultaneously with VPAJ [14], increasing the loss of DERs during grid fault. Table I shows the summary of all the inverters response to each VPAJ for all the inverters under bench-testing, giving statistics for deriving aggregated response of inverters for different VPAJ.

Fig. 7 projects the percentage of PV inverters vulnerable to VPAJ across Australia, extrapolating the results from the tested inverters to all the inverters in the grid. The data reported in the figure provide information about the unexpected disconnection of DERs in different states and territories. NEM presents the same trend of increasing inverters disconnection with increasing VPAJ. A VPAJ of 30° disconnect 1010 MW, making it 19% and VPAJ of 45° VPAJ disconnects 2224 MW of installed PV capacity. This shows that with 45° VPAJ, makes almost one third of the installed PV capacity is at risk. It is clear from the Fig. 7 that most of the inverters are vulnerable to 45° and 90° VPAJ. Large amount of inverters installed in Victoria are sensitive to 30° VPAJ, which poses a big challenge for the operators to compensate for power during grid VPAJ disturbance to avoid blackouts. The results of this paper can be used to tune the parameters of load composite model with power system operators. It leads to a more accurate estimation of the power loss from PV inverters, in response to a VPAJ.

## V. Conclusion

The response of 28 off-the-shelf most popular inverters across Australia has been studied with inverter bench testing. The experimental tests show that various inverters have four different behavior types under the same voltage phase angle jump conditions: ride-through, power curtailment, and disconnection. The results show that a relatively high proportion of inverters presents undesired behavior under various voltage phase angle jump. This data shows that a high proportion of installed inverters could present undesirable behavior to VPAJ, impacting the power systems operation and stability. A statistical analysis has been presented in the paper providing evidence for vulnerability to voltage phase angle jump. The results can be used to provide more accurate models for estimation of PV inverter loss due to different values of VPAJ.

## VI. Acknowledgment

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