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Distributed Photovoltaic Inverters' Response to Voltage Phase-Angle Jump

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***Abstract*—The rapid increase in the installation of distributed photovoltaic (DPV) systems has led to an increased interest in modeling and analyzing residential inverters to understand their behavior and thereby understand the corresponding challenges to the distribution system. This article provides extensive experimental evidence on the behavior of 31 off-the-shelf residential DPV inverters under different voltage phase-angle jump disturbance conditions. The undesirable behavior from DPV inverters is classified into disconnection and power curtailment. Such types of behavior potentially threaten the operation of highly penetrated systems because a large portfolio of generation can suddenly disconnect, leaving a large contingency to be satisfied. The reasons behind these undesirable behaviors are explored in this article and are based on the experimental inverter responses. The outcomes from this research have been far-reaching, including a necessary update to the Australian standard for grid-connected inverters, the emergency voltage disturbance ride-through tests enforced in the state of South Australia, and provided essential behaviors and data for a load-PV composite model for the market operator (Australian Energy Market Operators) in Australia. Additionally, with 22 inverters demonstrating low or no tolerance to voltage phase-angle jump, this work provides insights to guide inverter responses and protection requirements and standards development for networks with high penetration of DPVs, making a valuable case study for the international audience who may face the high penetration of DPV inverters as in Australian states.**

***Index Terms*—Distributed energy resource (DER), distributed photovoltaic (DPV) inverters, ride-through, standard, voltage phase-angle jump (VPAJ).**

I. Introduction

THE quality of power delivered to consumers is constantly evolving in multiple dimensions because of the advancements in grid technology and public awareness of the energy challenges faced. The increasing penetration of distributed photovoltaic (DPV) generation in electrical grids around the world and Australia (Fig. 1) makes the power system more susceptible to power quality issues, and the responses of DPV inverters are crucial in understanding power system security and reliability. Although renewables reduce the carbon footprint and decrease fossil fuel consumption, they can cause complications in the power system. Previously, a continuous supply of electricity without any interruption was considered enough, but constantly increasing DPV in the system introduces additional power quality issues. Several significant issues such as voltage phase-angle jumps (VPAJs), voltage sags, frequency variation, temporary or permanent power fluctuations, harmonics, and interruptions are all considered new factors that threaten power quality [1]. The increased integration of power electronic inverters into the power system is perceived to contribute to power quality issues requiring more attention from power system operators [2], [3].

The grid response is fundamentally a combined response from all loads and sources as well as necessary in the delivery. Power system operators lack visibility and control over small-scale DPVs unlike large-scale systems. These DPV inverters are not monitored or controlled by a centralized system, causing further complications during grid disturbance [4]. Although regional standards may guide the response of DPV inverters to particular grid disturbances, the control strategy implementation is still flexible. This leads to a portfolio of DPV inverters that respond differently to the same grid disturbances, and the uncertainty in responses of DPV inverters leads to power system vulnerability. Therefore, it is imperative to first understand the behavior of the DPV inverters under different types of grid disturbances in order to model the behavior of the DPV inverters.

Detailed and accurate DPV and load modeling that better represent distribution feeders are crucial for power system operators. In addition, it is important to comprehend the response of these devices under normal or grid disturbance conditions as they respond differently according to their internal settings. With increasing DPV inverter integration, the problem is exacerbated for power system operators managing the system without jeopardizing grid stability. A study by the US Western Interconnection was conducted from the large system perspective, maintaining the system's transient stability while integrating renewables in large quantities [6]. It emphasized the importance of the continuous enhancement of the system modeling based on the systems changing distributed energy resource (DER) concentration. A

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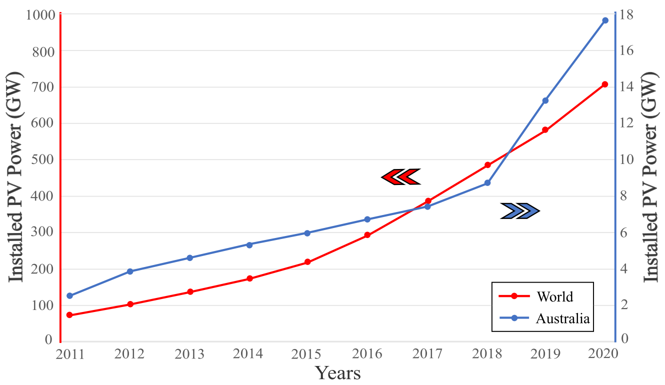


Fig. 1. Cumulative solar energy generation of world and Australia in the last decade [5].

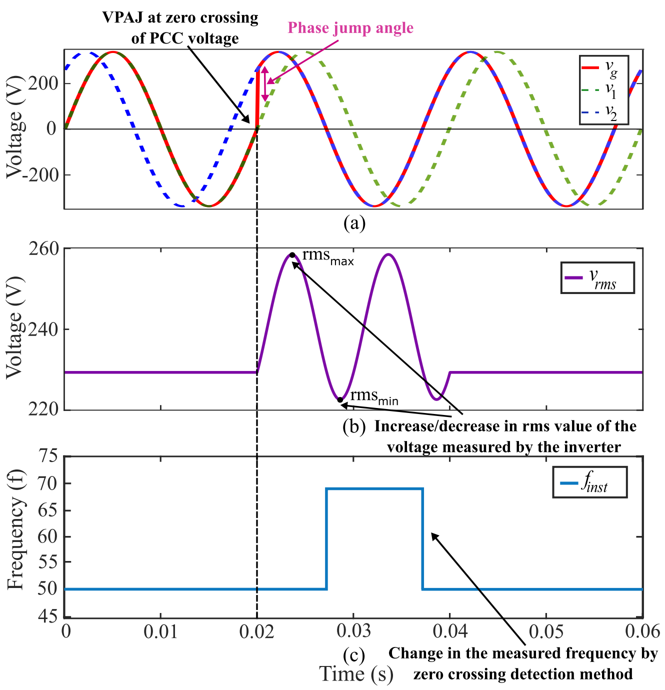


Fig. 2. (a) VPAJ waveform, (b) calculated RMS voltage by the inverter, and (c) calculated instantaneous frequency using zero crossing by the inverter.

similar outcome was suggested in [7], focusing on the impact of DER's reliability from a large power system perspective. Constant power injection and ZIP load models [4] are sufficient for the low penetration areas. However, high DER penetration must be precisely modeled to avoid issues in the power system.

One of the common types of grid voltage disturbance is VPAJ, which is a near instantaneous change in the voltage phase experienced at the point of common coupling [8]. Fig. 2(a) shows a representation of VPAJ, where a 30° VPAJ that occurs at the zero crossing is shown as v_g. VPAJs occur in power systems as a result of multiple reasons such as the following:

1) short circuits;
2) sudden changes of the load;
3) turning on generators or motors;
4) transformer energization;
5) difference between source and the faulted feeder X/R ratio in a three-phase system;
6) transfer of a nonsymmetrical voltage sag through transformers to the low voltage network [9, p. 175].

DPV inverters may interpret the VPAJ as a change in the grid voltage such as amplitude (rms) or frequency, even though these parameters are not actually changed other than during the cycle where the disturbance occurs [8]. Two events are discussed here, in which VPAJ was misinterpreted as change of frequency from DPV inverters: 1) Southern California, "Blue Cut Fire" event in 2016, where 1.2-GW generation from DPV was disconnected because of a line-to-line fault. The fault that occurred at the transmission line created a VPAJ in the system that was interpreted by the DPV inverters as a significant frequency deviation. This misinterpretation by DPV inverters led to disconnection of multiple PV plants, producing a cascading effect in DPV inverters [10].

2) A fault on the 400-kV line was reported in the United Kingdom (2017), where a VPAJ of 20° that occurred during the shorter window of 40–60 ms was observed and reversed back quickly after the fault was clear [11]. No change in underlying frequency or rate of change of frequency (RoCoF) occurred, but with such a small measurement window of 40–60 ms, a RoCoF was observed by P-class phasor measurement unit (PMS). The RoCoF observed was beyond the usual limit of the system RoCoF threshold. The decision made by DPV inverters based on such algorithms of PMUs can cause misinterpretations and have a severe impact on the power system by tripping off multiple DPV inverters [12].

The changing operational conditions of the grid and standards for DPV inverters require attention in understanding the behavior of the inverters during grid disturbances. Several studies were conducted to validate standard bench testing and experimentally analyze the behavior of the inverter under grid disturbances [13]–[18]. Most studies focused on compliance of inverters to the standards without analyzing the reasons of such responses, and some of the studies have a minimal data set to comprehend the wide variety of inverters integrated into the network and the diversity of their responses. It is essential to understand the reasons for inverter responses in order to make revisions to standards and inverter firmware. This article presents an experimental study of DPV inverter behavior under VPAJ. The main contributions of this article are as follows:

1) to propose and experimentally verify a test procedure to analyze the undesired behavior of inverters under VPAJ;
2) to identify possible reasons for DPV's undesirable responses under VPAJ;
3) to provide information about the DPV's output power reduction during VPAJ for load modeling purposes;
4) to analyze a wider range of inverters as compared with previous studies in the literature.

The testing is performed on 31 commercially available off-the-shelf PV inverters complying with the Australian Standards AS 4777.2:2015 and AS4777.3:2005 [19], [20]. All models of inverters are commonly installed in the Australian National Electricity Market (NEM). Although all follow Australian standards, the testing illustrates a wide range of responses from inverters exposed to the same grid disturbances. The potential of DER disconnection discussed in [7], [11], [18], and[21] becomes a plausible event according to the experimental results and analysis presented in this study. This work aims to provide detailed information about the possible reasons for inverters' responses and informs system designers, developers, utilities, and companies on the performance of PV inverters currently installed and their expected responses.

The rest of this article is organized as follows. Section II details two reasons for undesirable responses from the inverters. Details of the experimental setup and test procedure are provided in Section III. Experimental results from inverter testing for the VPAJ disturbances are illustrated in Section IV. A discussion on the results in Section V that provides evidence to support the outcome of the article is provided. Section VI concludes this article.

II. Various Responses of DPV Inverters to VPAJ

There are two quantities, the amplitude (rms) and the frequency which are monitored by DPV inverters to activate their protection during serious disturbances. The VPAJ shown in Fig. 2(a) could be misinterpreted by inverters in two ways. The rms voltage is plotted in Fig. 2(b) using a window that is a fundamental period and shows that the rms value varies during the cycle that the VPAJ occurs in. This variation in rms voltage can result in the inverter misinterpreting the disturbance as an overvoltage or undervoltage condition. Fig. 2(c) presents the estimated frequency estimate in the system after the VPAJ using a rudimentary, zero-crossing detection to calculate the frequency of the voltage. Clearly, this technique would misinterpret the disturbance as a gross change in frequency during the cycle that has VPAJ. Further details about VPAJ misinterpretation are discussed in Sections II-A and II-B.

A. RMS Voltage Misinterpretation

IEEE 1564:2014 [22] standard defines a method for calculating rms voltage as a function of time. A sliding window of one cycle of system frequency is used to measure the rms of the voltage and the calculation is repeated every half cycle. A voltage disturbance caused in the power system is discussed in [23, p. 754], where a VPAJ caused by a voltage sag is analyzed. The rms voltage measurement disclosed the sudden change in the rms voltage as shown in Fig. 2(b), indicating the effect of VPAJ on the rms voltage of the system. The change in the rms voltage beyond the limits specified by the standards through VPAJ disturbance causes inverters to misinterpret and activate the overvoltage or undervoltage protection against the disturbance.

B. Frequency Misinterpretation

When the VPAJ appears in the power system, the period of the voltage cycle in which the phase jump occurs is changed cause an increase or decreasae in frequency depending upon the magnitude and direction of the VPAJ. Therefore, the frequency calculated by the device in a particular cycle is changed, even though there is no frequency deviation in the system [8]. The zero-crossing method is commonly used for the frequency measurement as shown in Fig. 2(b) [23, p. 166]; some use full cycle while others use half cycle to avoid harmonic distortion in the waveform. The DPV inverters' behavior in [11] and [12] indicates instantaneous frequency calculation over a short duration caused a significant deviation in the frequency disconnecting several DERs.

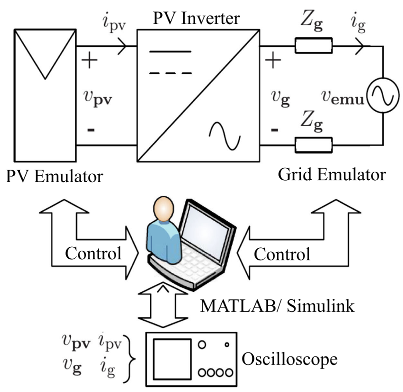
III. Experimental Setup

The testing setup uses off-the-shelf single-phase PV inverters rated between 1.5 and 5 kW following AS 4777.2:2015 [19] 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 anonymized in order to avoid any negative impacts on any one vendor. Inverters are connected to a bidirectional Regatron ac grid emulator. The voltage parameters can be varied at the point of connection, including the voltage magnitude, frequency, and phase angle, representing a controllable voltage source through an impedance of $Z = 0.12 + j0.16\,\Omega$ to present a typical line impedance as recommended in [19]. The inverter dc input is connected to the PV emulator, and the PV curve is generated to act as a solar array producing nonlinear voltage versus current characteristic. The experimental test setup schematics and laboratory setup are shown in Fig. 3(a) and (b), respectively.

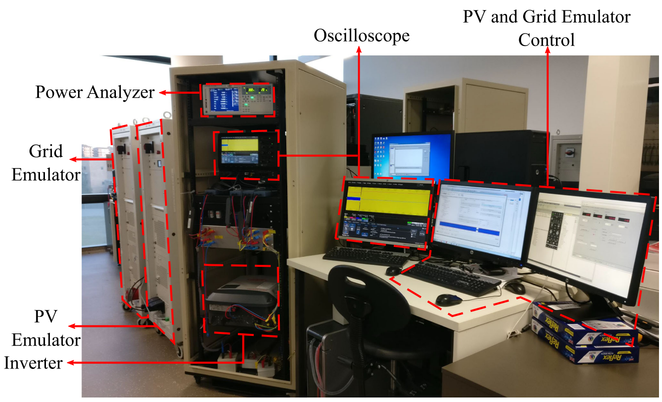
IV. Experimental Results

This section analyzes 31 inverters tested for the VPAJ disturbance to categorize the inverters' response. The tested PV inverters represent almost 20% of Australia's installed rooftop PV capacity as of 2020, and these inverters significantly contribute to the power generation in some states. The complication of the grid is further increased by the two different fleets of inverters following two different standards. The inverters following the AS4777.2:2005 standard [20] represent 4.7 GW while almost 9.2 GW follows the AS4777.3:2015 standard [19].

Based on the grid parameters, the protection of inverters is activated on one of the following parameters: 1) measured rms value of the voltage; 2) measured frequency; and 3) injected current. Of course, there might be some internal parameters of the inverter, like the dc-link voltage, etc., that can trigger the protection. From the parameters mentioned, VPAJ can affect the measured voltage or measured frequency. There is no overcurrent observed in VPAJ tests; so the grid current might not be the reason for triggering the protection in these inverters. Based on the tested inverters' response to VPAJ disturbance presented in [24], two undesirable behaviors were observed, described as 1) power curtailment and 2) disconnection. The VPAJ shown in Fig. 2(a) generated from the grid emulator could be interpreted by inverters in two ways. First, the rms value varies for a short time after the VPAJ and causes the inverter disconnection. Second, the sudden change in the frequency calculated by the inverters is the reason for power curtailment by the inverters. This may happen to the inverter if either the volt–watt setting or frequency–watt mode, AS4777.3:2015 standard [19], is enabled.



(a)



(b)

Fig. 3. Inverter bench testing experimental setup. (a) Schematic diagram of the circuit. (b) Experimental setup in laboratory.

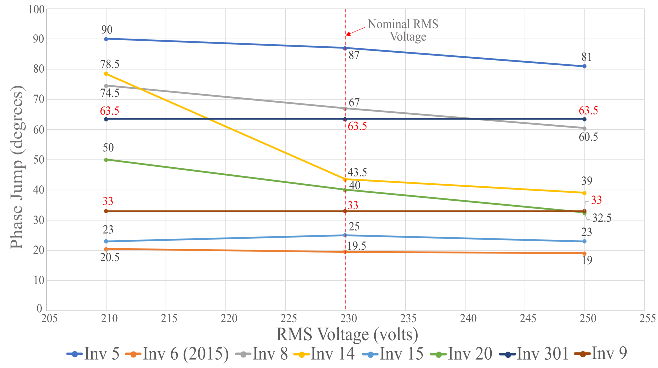


Fig. 4. Misinterpretation of VPAJ as rms voltage change response, results for inverters that are affected by relatively low VPAJ values.

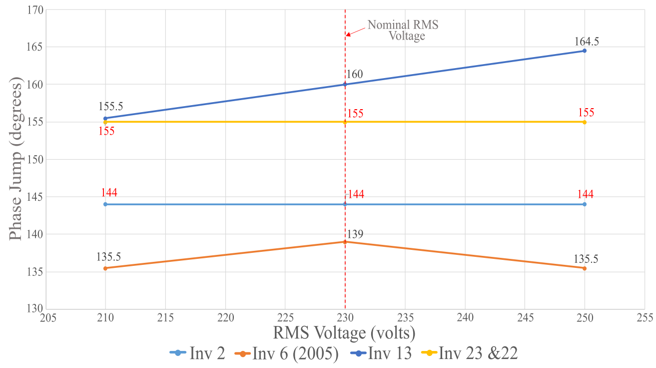


Fig. 5. Misinterpretation of VPAJ as rms voltage change response, results for inverters that are affected by relatively high VPAJ values.

In these tests, only the frequency–watt setting was enabled; hence, a curtailment in power demonstrates activation of the frequency–watt response. Additionally, none of the inverters following AS4777.2:2005 standard [20] presented power curtailment behavior which further supports the power curtailment being frequency or rms voltage misinterpretation under phase jumps. Furthermore, the tested inverters with a display (16 from 31) show an error related to the voltage or frequency after a phase jump. The activation of these two errors occurs based on the specified limitation on rms voltage and frequency posed by AS4777.3:2015 and AS4777.2:2005 [19], [20].

The above-mentioned reasons justify that inverters either misinterpret the phase jump as an rms voltage change or as a frequency change in the system. In order to classify the inverters' behavior as misinterpreting rms voltage or frequency, two sets of tests are performed in this article.

A. Test 1: VPAJ Misinterpretation as RMS Voltage Change

This test is to verify whether an inverter misinterpreted the VPAJ as an rms voltage excursion. The grid rms voltage is set to 210, 230, and 250 V one at a time. Under each of these rms voltage levels, VPAJ increases from zero to an angle at which the inverter changes behavior from ride-through to disconnection. The VPAJ at which the inverter disconnects is recorded. If an inverter does not misinterpret the VPAJ as rms voltage change, the recorded value for inverter disconnection under all different voltage levels of the grid remains exactly the same. However, if the inverter misinterprets the VPAJ as rms voltage change of the grid, there is a considerable change in the VPAJ at different levels of rms voltage. Out of all tested inverters, eight are classified under this category. It is noted that seven inverters in this category display an rms voltage-related error massage.

Fig. 4 presents the response of six inverters misinterpreting VPAJ as rms voltage error, and it can be seen in the figure that different inverters disconnect at different VPAJ when the nominal grid rms voltage is changed before the jump. A noticeable change can be seen in the VPAJ disconnection angle for inverters 5, 8, 14, and 20 as the rms voltage is changed. The trend followed by these inverters is that as the prefault rms grid voltage decreases, the VPAJ disconnection angle increases. In some cases like inverter 6 (2015), the change in the VPAJ angle is only 1° with different grid rms voltages which is not significant, and inverter 15 shows the same disconnection VPAJ angle above and below the nominal grid rms voltage. As mentioned before, the inverters that do not misinterpret VPAJ as rms voltage change in the grid will maintain the same disconnection VPAJ angle as shown in inverter 9 and 301.

Fig. 5 presents five more inverter responses but with impractically high VPAJ. Nonetheless, the tests still identify the inverters misinterpreting the VPAJ as an rms voltage change in the grid. The same response could be seen from inverter 6 (2015) as seen in inverter 15 in Fig. 4. The behavior of inverter 13 is opposite to that of inverters 5, 8, 14, and 20 of Fig. 4.

B. Test 2: VPAJ Misinterpretation as a Frequency Change

Due to the VPAJ, the measured value of grid frequency changes for at least one cycle; either the inverter measures it on the basis of zero-crossing times or uses a phase-locked loop (PLL)-based algorithm or equivalent. Accordingly, because the inverter reads a frequency larger or smaller than the nominal, it may trigger protection. Furthermore, if it reads the frequency during phase jump as a larger value than the nominal, it reduces the output power based on the frequency–watt requirement of AS4777.3:2015 standard [19].

Under this test, the frequency of the voltage between the two consecutive zero crossings is calculated for different values of phase jump. The inverter is tested under these two conditions: 1) VPAJ of 15°, 30°, 45°, and 60° and 2) the frequency of the voltage changes in one cycle, based on the frequency corresponding to the period between the two zero-crossing points during the phase jump referred to as "frequency map." If the reduction in the output power is similar under these two tests, it can be concluded that the inverter misinterprets the phase jump as frequency change. Furthermore, two more responses are captured under these tests to confirm how inverters translate the VPAJ into frequency. The first one identifies frequency for one cycle that reduces the same power as VPAJ, referred to as "frequency one cycle." The second one is the constant frequency at which the power drop from the inverter is the same as that with VPAJ and is denoted by "steady state." It is also verified that out of ten inverters classified under this category, eight of them with display show an error relating to frequency change in the grid.

The response from inverter 25 is shown in Fig. 6, where a 15° degree VPAJ disturbance generated from the grid emulator caused power curtailment from the inverter. Fig. 6(a) shows the grid voltage and current in per unit, and Fig. 6(c) presents the power drop of the inverter due to VPAJ. It is clear from Fig. 6(c) that the power drop from each of the four tests discussed above is the same. The power drop from VPAJ of 30°, 45°, and 60° is shown in Fig. 7. The difference between the "phase jump" and the "frequency map" is increased as the VPAJ angle is increased, but the response of the inverter to all other tests remain the same. Additionally, a comparison of all four tests is shown in Fig. 8, where the power curtailed from tests follow each other very closely. This is done to confirm that the inverter curtails the power according to AS4777.3:2015 standard [19] following the "frequency–watt" curve, although the VPAJ curtailed power is beyond the recommended power curtailment, but it is following the pattern.

A similar case of VPAJ misinterpretation as the frequency for inverter 7 is presented in Fig. 9. The power curtailment is 50% of the rated power with a maximum VPAJ of 60° as shown in Fig. 10. The comparison of tests is presented in Fig. 11. All

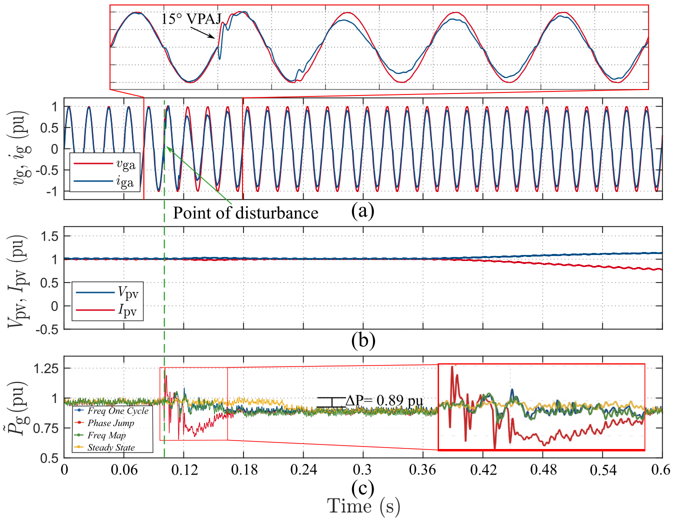


Fig. 6. Inverter power curtailment behavior for 15° VPAJ. (a) Grid voltage and inverter output current. (b) PV voltage and current. (c) Inverter output active power.

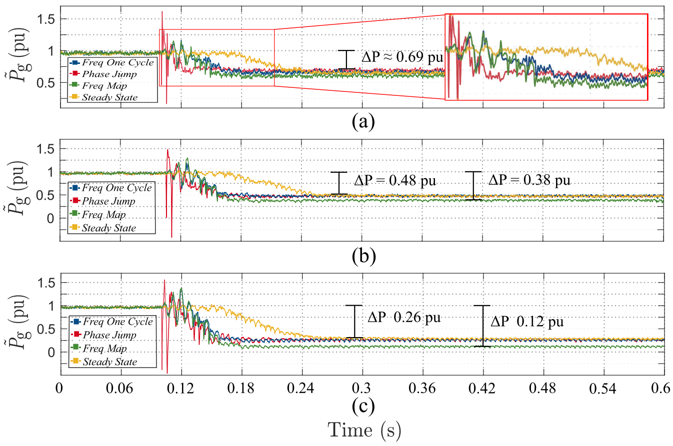


Fig. 7. Power curtailment for different VPAJ. (a) 30°. (b) 45°. (c) 60°.

responses follow the "Frequency–watt" curve not as closely as those shown in Fig. 8. The purpose of this test is to verify whether the inverter is following the same curve for the VPAJ disturbance as it does for the frequency disturbance in the grid. The above results demonstrated that the inverters misinterpret the VPAJ and translate it into the frequency deviation of the grid. The response from inverters for the VPAJ follows the same characteristics as the inverters do for a frequency deviation of the grid.

There are some inverters, which cannot be classified in either of the two mentioned categories. They either remain connected or disconnected under all tested phase jumps (neither misinterpret it as frequency nor rms voltage); no precise reason was identified.

V. Discussion

Section II highlighted the two significant misinterpretations of VPAJ by the inverters, which were further experimentally

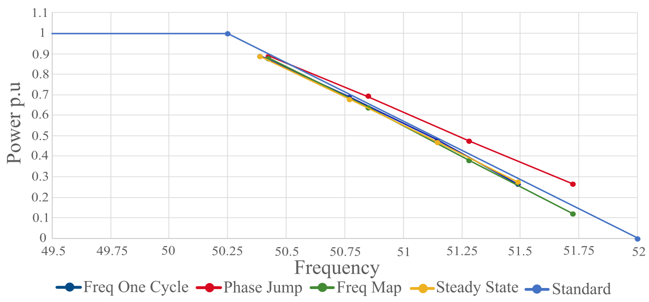


Fig. 8. Comparison of VPAJ response with frequency response of inverter through frequency–watt characteristic specified by AS4777.3:2015 standard [19].

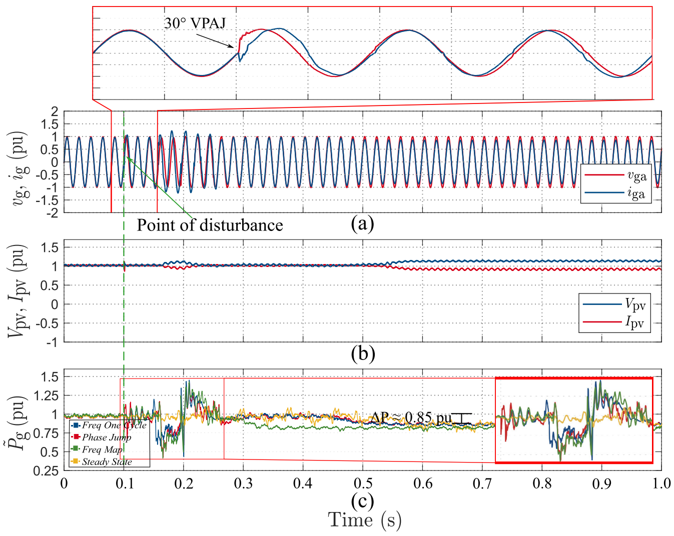


Fig. 9. Inverter power curtailment behavior for 30° VPAJ. (a) Grid voltage and inverter output current. (b) PV voltage and current. (c) Inverter output active power.

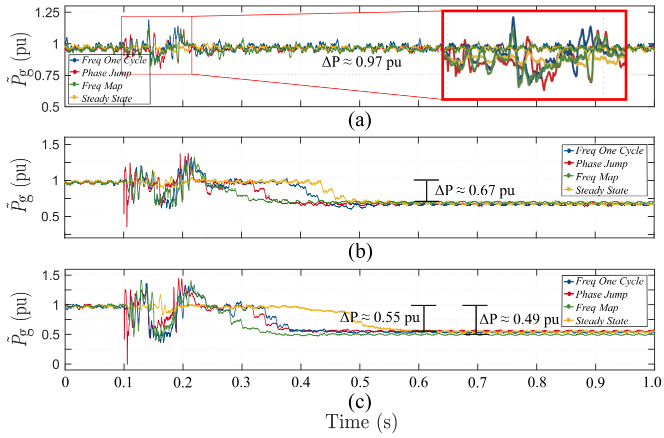


Fig. 10. Power curtailment for different VPAJs. (a) 15°. (b) 45°. (c) 60°.

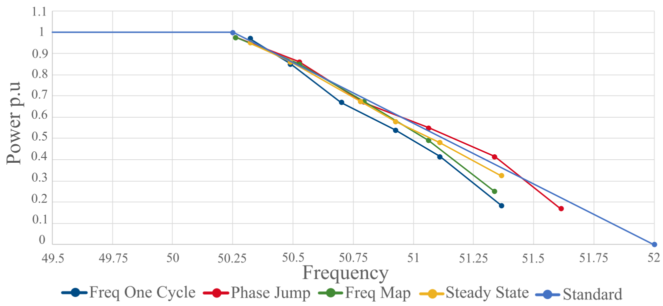


Fig. 11. Comparison of VPAJ response with frequency response of inverter through frequency–watt characteristic specified by AS4777.3:2015 standard [19].

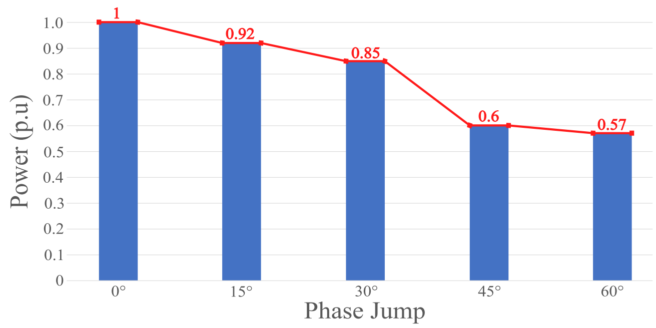


Fig. 12. Power drop of installed PV inverters due to VPAJ.

investigated in Section IV. Therefore, the undesirable behaviors of the inverters cannot meet the latest standards, as they misinterpret the VPAJ disturbance from the grid. The results from this article give an insight into the potential causes of inverter behaviors contributing toward the loss of DER in high PV penetration areas reported in [10]–[12] and [25]. The strict requirements missing in [19] and [20] are among the reasons for such behavior of inverters. The aggregated response of inverters to such behavior is crucial for better representation of distributed PV models in the system. Thus, it is essential to investigate the root cause of inverter responses to such grid disturbances. The grid synchronization components plays an integral part in enhancing inverter sensitivity to VPAJ, requiring more attention and understanding of these aspects.

The behavior of inverters is summarized in Table I for VPAJ disturbance in the grid. Manufacturer, inverter ID (both anonymized), corresponding standard, and installed power of each inverter in Australia are also presented in the table. The response of each inverter for VPAJ with displayed errors on the inverters is included to verify the response. The 31 tested inverters present 21 % of the total DPV generation from inverters rated less than 6.5 kW. This represents that a total of 1402 MW of installed inverters are tested for the VPAJ disturbance out of 6740 MW. The impact of this disturbance is more on undesirable inverter behavior, as investigated in the previous sections. Almost 75 % of the total tested inverters demonstrate undesirable behavior either by power curtailment or disconnection as presented in Table I. The total power of tested inverters is taken as 1 p.u. in Fig. 12 and the power curtailed or reduced due to disconnection is presented by power drop is calculated for each VPAJ, with a maximum power drop of 60° VPAJ is 0.57 p.u. There is a significant drop in power after 30° VPAJ as shown in

TABLE I
SUMMARY OF INVERTER BEHAVIORS UNDER VPAJ TRANSIENTS

Manufacturer	$^{\Pi}$Inverter ID	AS 4777 version	†Installed power (MW)	Misinterpretation of VPAJ as	Inverter massage display
A	1	2015	56	Frequency change	Grid frequency disturbance
	$1^{\star}$	2005	167	Frequency change	Grid frequency disturbance
	6	2015	8	RMS voltage change	Error Overvoltage
	$6^{\star}$	2005	28	RMS voltage change	Error Overvoltage
	7	2015	3	Frequency change	N/A
	$8^{\wp}$	2005	2	Frequency change	Error Frequency Fault
	19	2015	52	Frequency change	N/A
	24	2005	72	N/A	N/A
	302	2015	24	Frequency change	N/A
B	2	2015	65	Frequency change	Error Grid frequency become high
	9	2005	4	Frequency change	STATE: AC frequency is too high
	25	2015	–	Frequency change	Error Grid frequency become high
	301	2015	48	Frequency change	Error Grid frequency become high
C	3	2015	136	N/A	N/A
	13	2015	22	RMS voltage change	Error Bus voltage is high
	27	2015	–	N/A	N/A
D	4	2015	32	N/A	N/A
	10	2015	1	RMS voltage change	Error Bus voltage out of range
	12	2015	12	N/A	N/A
	16	2015	3	Frequency change	N/A
E	5	2015	37	RMS voltage change	Error Grid voltage outside range
	14	2005	197	RMS voltage change	Error Grid voltage outside range
F	$15^{\wp}$	2005	1	RMS voltage change	N/A
G	17	2015	26	N/A	N/A
	20	2015	129	RMS voltage change	Grid voltage fault
H	$18^{\wp}$	2005	28	N/A	N/A
	$21^{\wp}$	2005	60	N/A	N/A
	$26^{\wp}$	2015	<1	N/A	N/A
I	22	2015	91	Frequency change	Error Frequency Fault
J	23	2015	70	Frequency change	Error Frequency Fault
K	28	2015	27	RMS voltage change	Error Grid voltage outside range
Total tested rooftop PV inverters power installed in Australia [18]			**1402**		
Total rooftop PV inverters power with rated power less than 6.5 kW installed in Australia estimated as of September 2020 [17].			**6740**		

1) All two-stage conversion, 2) All transformer-less except A8, 3) 30X: three-phase inverters.
*Firmware reconfiguration to AS 4777.3:2005 of inverter certified for AS 4777.2:2015.
†Estimate as of March 2020.
$^{\Pi}$Input dc range: 70–550 V and 245–800 V.
$^{\wp}$No reactive power control.

Fig. 12. If extrapolated to the total installed inverter power of up to 2898 MW there would be a risk of disconnection or a power curtailment under this disturbance.

Based on the data collected through testing 31 off-the-shelf residential PV inverters, it is crucial to identify the proper behavior of inverters under VPAJ. Although [2] and [3] specify the ride-through capability of the inverter for 60° VPAJ, the response of inverters reflected through this study demonstrates the need for a strict requirement for inverters to avoid undesirable behavior. The work reported in this study and recent standard updates around the world is the reason for the recent enhancement in Australian standards. Also, the undesirable behavior of inverters presented in this article is implemented in the load composite model by Australian Energy Market Operators (AEMO) to study power systems under large-scale DPV disconnection. Emergency measures introduced in South Australia for short-duration disturbances are derived after the evidence presented in this study. Further analysis is required to identify the response of interconnected inverters under such disturbance. This research provides a clear picture for power system operators to properly tune the load models during the grid disturbance and update the DPV models based on the power reduction during VPAJ.

VI. Conclusion

This article experimentally determined the responses of 31 off-the-shelf residential PV inverters to VPAJ that comply with the relevant Australian standard. Many of the inverters respond undesirably by curtailing the power or disconnecting from the grid. The aim was to identify the reasons behind these undesirable behaviors during the VPAJ test. The misbehavior can be change in power or a disconnection. The inverter misinterprets VPAJ as rms voltage beyond maximum or minimum disconnection setting; otherwise, it interprets the high rms voltage change, which leads to a volts–watt constraint from the inverter causing an interrupt in injected power. The inverter misinterpreting VPAJ as frequency changes beyond the limits, causing disconnection. However, power curtailment occurs because of the enabled frequency–watt constraint from the inverter. In conclusion, the findings have allowed an estimation of generation loss and inverter behavior during VPAJ disturbances to update the model of distributed PV inverters. An aggregated response can be derived from individual inverter behaviors, hence making a valuable contribution to the overall modeling of power systems with high PV penetrations.

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