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Testing Evidence and Analysis of Rooftop PV Inverters Response to Grid Disturbances

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***Abstract*— With ever-increasing rooftop photovoltaic (PV) penetrations in the bulk power system, comes the growing interest in understanding the behavior of PV inverters during grid disturbances. Providing a wealth of experimental evidence, this paper presents results from testing twenty-five off-the-shelf residential PV inverters subjected to voltage and frequency perturbations. Notwithstanding compliance with Australian standards, test results demonstrate that the inverter operation can be jeopardized by grid disturbances such as frequency variations, rapid voltage sags and phase-angle jumps. It is shown that inverters may abruptly disconnect or undesirably curtail their output power, potentially disrupting the security of systems with high power contribution from rooftop PV. The findings of this work ultimately contribute to explain aggregate behavior of rooftop PV during grid events recently experienced in Australia, and compel key points to consider in the development of future standards, forming a worthwhile case study for any region of the world with high PV penetration.**

***Index Terms*—Photovoltaic power systems, Standards, Inverters, Power distribution, Grid connection**

I. Introduction

ABUNDANCE of solar irradiation, favorable climate conditions and economic incentives have propelled the take-off of photovoltaic (PV) energy in Australia, at utility and residential scale. With an overall capacity of about 11 GW, Australia ranks third in the world for PV power installed per capita. In a typical sunny day for PV production, the percentage of daily energy demand satisfied by PV systems reaches 30% to 40% in certain regions (Fig. 1). Rooftop PV systems are installed on average in 20% of all residential dwellings, with peaks of 70% in some areas [1]. This very high PV penetration translates into almost 60% of the total PV capacity installed in Australia coming from rooftop PV systems rated at less than 10 kW [1], [2], known as distributed energy resources (DER). Although their aggregate contribution in the bulk power system is now comparable to that of centralized power plants, DER are not usually monitored or controlled by grid operators, raising concerns on their behavior during grid disturbances.

As DER are connected to the grid via off-the-shelf inverters, their response to grid disturbances is decided by embedded firmware, which is designed to pass compliance testing defined by technical standards of individual countries. These standards prescribe intelligent functions, enabling inverters to support grid stability and power quality, as well as to provide ancillary services. Smart inverter functions are the result of years of investigation, often following widespread economic damages caused by grid disturbances. In the past decade, it was in fact understood that inverter grid supporting modes were essential to prevent large scale collapse of power systems with high DER penetration. A notorious example is the 2006 European blackout [3], triggered after an unscheduled disconnection of a major transmission line in Germany. Consequent frequency disturbances were exacerbated by a large and sudden loss of distributed PV generation, set to disconnect at 50.2 Hz. As the loss of DER was much greater than the available power reserved for frequency regulation [4], further frequency disturbances propagated and caused instabilities across wide areas of the European grid [5]. After this event, the inverter 'frequency-watt' [6] response appeared in many technical standards, mandating inverter output power droop at increased frequencies, rather than disconnection at a fixed threshold, widening DER's operating frequency range.

In Australia, performance requirements for PV inverters connected to the low voltage (LV) distribution grid, whose nominal voltage is 230/400 V and nominal frequency 50 Hz, are currently specified by AS 4777.2:2015 [7]. The standard specifies inverter functionalities and testing to ensure the desired operation during nominal and abnormal grid con-

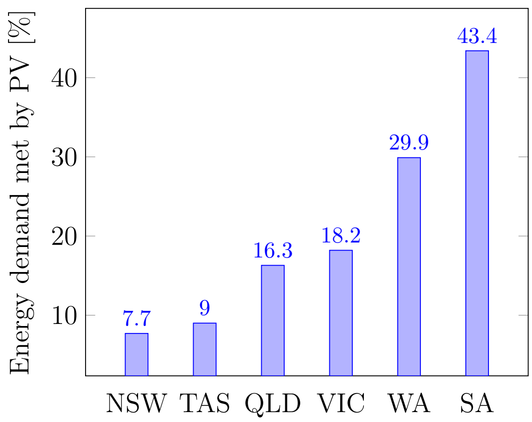

Fig. 1. Sunny day (17 Feb. 2020) percentage of energy demand satisfied by PV production across Australian states. Data sourced from [2], ACT is together with NSW, NT data unavailable.

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ditions. Nonetheless, its purpose is contradicted by recent field experience, where hundreds of residential PV inverters were being monitored, as the following examples suggest [8]–[12]. In March 2017, the explosive failure of a capacitor voltage transformer connected to the largest gas generator in South Australia (SA), triggered widespread faults and voltage depressions in areas with high DER contribution. A significant load increase was observed in these areas following voltage disturbances, signaling the missing contribution of DER generation [8], deemed to have disconnected due to under-voltage [9], [10]. In August 2018, lightning strikes on a 330 kV infrastructure supporting the interconnecting lines between Queensland (QLD) and New South Wales (NSW), caused a series of cascading failures, eventually leading to loss of synchronism and islanding of the QLD region [11]. At the same time, data analysis carried out on hundreds of rooftop PV inverters monitored at that time, inferred that up to 30% of them did not respond to over-frequency conditions in accordance with the frequency-watt droop characteristic specified in AS 4777.2:2015 [12, pp. 42-43]. In short, [9]–[12] report instances of grid disturbances where a significant and unexpected loss of DER generation was experienced, raising the necessity to revisit the current standard and to perform additional inverter testing. These tests, involving voltage and frequency perturbations, aim to improve understanding of PV inverters response to grid disturbances, as is the objective of this paper.

A growing body of literature analyzes inverter performance and behavior against grid disturbances, often by means of bench testing. Research in these areas has been driven by evolving technical standards and by the need of transmission and distribution system operators to understand the impact of so much DER connected to their distribution networks, especially from residential and commercial PV. In [13]–[15], the response of small-scale PV inverters to short-duration voltage sags is investigated, highlighting undesired and inconsistent behaviors, including disconnection from the grid. [16] and [17] utilized bench testing results to validate inverter models for power system dynamic studies. Bench testing is also used in [18], [19] to study PV inverter short-circuit fault-current contribution. Performance of inverter grid supporting functions such as volt-var, volt-watt and constant power factor operation, among others, are tested in [20]–[22], whereas [23], [24] examine interactions of inverter grid support functions with voltage regulation in the power system. While some of these works are dated, most of them tested a few inverters only, often rated at tens or hundreds of kW, highlighting a need to perform more testing on typical few kW-rated residential PV inverters. The literature also gives attention to PV inverter related overvoltage caused by load-rejection [25] and ground faults [26]. Last, [27] reports field experience regarding harmonic instability [28] of large inverters in utility-scale PV plants, but these topics are out of the scope of this work.

This paper presents critical bench testing results of twenty-five PV inverters commercially available in Australia, and complying with AS 4777.2:2015 [7] or its legacy version AS 4777.3:2005 [29]. The inverters tested are from well-known international manufacturers and were chosen accordingly with the most common models installed in the Australian National Electricity Market (NEM); they represent close to 20% of the approximately 7 GW of DER contribution from rooftop PV systems [2], as detailed in Table I. Experimental results reveal that although all inverters comply with the local standards, the performance of each inverter is diverse across different inverter makes and models. Yet these results support rational conclusions regarding inverter behaviors during grid disturbances, potentially justifying the loss of DER generation mentioned in [9], [10], [12]. In detail, it is shown that some PV inverters are vulnerable to grid disturbances such as voltage sag, rate of change of frequency (RoCoF) or phase-angle jump, which can cause unintended power curtailment or even disconnection from the grid.

TABLE I
RATINGS OF THE 25 RESIDENTIAL SINGLE-PHASE PV INVERTERS TESTED

Manufacturer	Inverter ID	AS 4777 version	Rating [kW]	P_{inst} † [MW]
A	1	2015	4.6	56
	1*	2005	5	167
	6	2015	3	8
	6*	2005	3	28
	7	2015	4	3
	8	2005	5	2
	19	2015	5	52
	24	2005	4	72
B	2	2015	4.6	65
	9	2005	5	1
C	3	2015	4.99	136
	13	2015	4.99	22.4
D	4	2015	5	31
	10	2015	4.2	1
	12	2015	5.5	11
	16	2015	3	3
E	5	2015	5	37
	14	2005	5	197
F	15	2005	3	< 1
G	17	2015	5	26
	20	2015	5	119
H	18	2005	1.5	28
	21	2005	3	55
I	22	2015	5	91
J	23	2015	5	74
Total power from rooftop PV inverters tested				**1,290**
Total power from rooftop PV inverters installed in Australia [2]				**6,788**

† Estimate as of March 2020.
* Indicates firmware reconfiguration to AS 4777.3:2005 of inverter certified for AS 4777.2:2015.

The next section of this paper describes the experimental inverter testing setup and comments on the chosen inverters. Section III presents results from inverter bench testing. Attention is given to frequency variations, short-duration ac voltage sags and phase-angle jumps. Section IV critically reviews the observed test results and provides recommendations for improving future standards. The Conclusion section summarizes the merits of the manuscript and future directions.

II. Bench-Testing Setup

The power rating of the inverters chosen for bench testing is displayed in Table I. All inverters are single-phase, and are

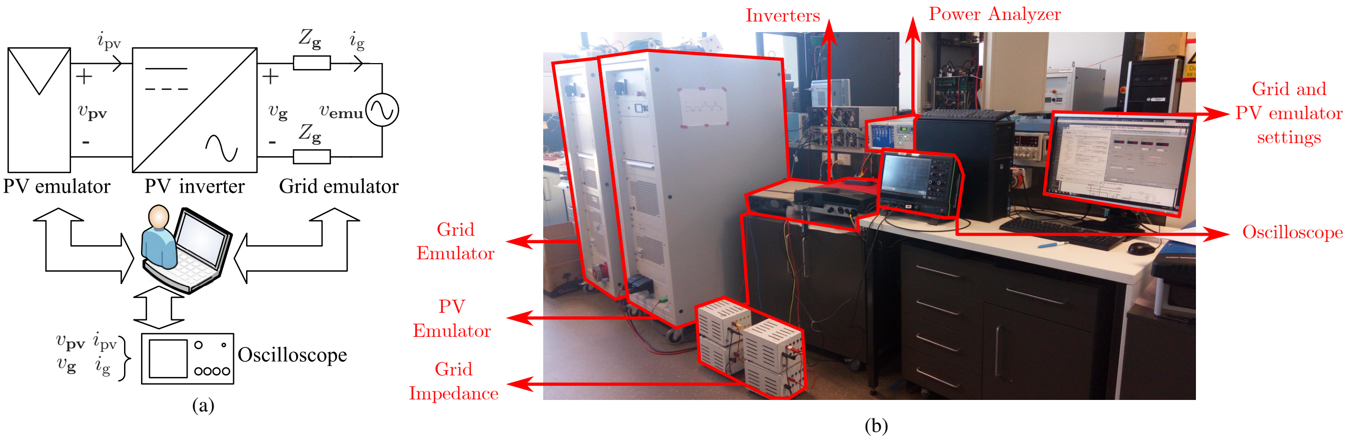

Fig. 2. Inverter bench testing setup. (a) Schematic representation. (b) Photo showing from left to right: bidirectional 50 kVA/305 $V_{rms\,(L\text{-}N)}$/72 A grid emulator (Regatron TC.ACS.50.528.4WR.S.LC), PV emulator 16 kVA/600 V/32 A (Regatron TC.P.16.600.400.S, with linear high dynamic solar post-processor TC.LIN.SER.26.1000.26), off-the-shelf inverters, grid impedance $Z_g = 0.12\ \Omega + j0.16\ \Omega$, control and measuring instrumentation.

rated up to 5.5 kW. These features were carefully selected upon analyzing data of the most commonly installed inverters across Australian electricity networks. At the time of writing, the 4.6 kW and 5 kW single-phase inverters are the most common inverter sizes installed in Australia [30].

The bench testing setup schematic is represented in Fig. 2a, translating into the laboratory arrangement of Fig. 2b. The single-phase PV inverter is connected to a PV emulator, reproducing the nonlinear current vs. voltage characteristic of the solar array, hence deciding the inverter input current. The PV inverter output is connected to a grid emulator, acting like a controllable voltage source, effectively permitting to vary the parameters of the voltage at the connection point of the inverter, such as frequency, amplitude and phase-angle. The inverter is connected to the grid emulator via an interfacing impedance Z_g, approximately of the value recommended in [7], representing a typical LV line impedance between the point of connection of the inverter and the distribution grid. A digital oscilloscope records the measured values of ac and dc voltage and current at the input and the output side of the inverter at 50 kHz sampling rate. The objective is to record the instantaneous behavior of voltages and currents, as well as active and reactive power injected by the inverter into the grid emulator, when the grid voltage experiences variations in magnitude, frequency or phase-angle.

III. Bench Testing Results

Although dozens of tests were carried out on each of the 25 inverters, this section focuses on those tests displaying critical outcomes on selected inverter samples complying with AS 4777.2:2015 [7]. At the same time, the tests are representative of disturbances which may actually occur in the grid; hence the results are meaningful to understand aggregate inverter behaviors during grid events [31, p. 39]. The types of disturbances assessed are: ramp increase in grid frequency (Section III-A), short-duration grid voltage sag (Section III-B) and grid voltage phase-angle jump (Section III-C).

The graphs displayed in the following paragraphs are in per unit (p.u.), unless otherwise indicated. Whenever grid voltage

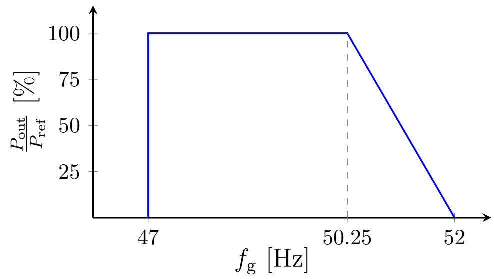

Fig. 3. PV inverter frequency-watt droop response [7].

and current are plotted as RMS values, this is signaled by a tilde subscript such as $\tilde{V}_g$ and $\tilde{I}_g$. In those tests enforcing a change in the grid frequency, the latter variable is plotted as $\tilde{f}_g$. For the graphs presented in this paper, the waveforms for ac voltage and current have been normalized with base values of 230 V and 20 A RMS, respectively. The base active and reactive power are 4.6 kW and 4.6 kvar, respectively.

A. Inverter Response to a Ramp Increase in Grid Frequency

In the event of a grid over-frequency, [7] mandates the execution of a frequency-watt droop response, where the inverter is required to linearly reduce its active output power according to Fig. 3 [7]. Reduction of the inverter active output power following an increase in the grid frequency is a grid supporting function, aiming to revert the over-frequency by decreasing the amount of active power in the system. This function emulates the primary frequency regulation of synchronous generators.

As over-frequency events occur due to the surplus of generation over load, the frequency is likely to deviate from its nominal value following a ramp pattern, whose slope is known as or rate of change of frequency (RoCoF). In the South Australia blackout event of Sept. 2016 [32], there were RoCoF up to 6 Hz/s. In the more recent separation event between Queensland and South Australia [11], the highest RoCoF experienced was 0.65 Hz/s. Whilst [7] specifies the desired inverter output power at frequencies other than the nominal one, it does not prescribe tests to verify RoCoF

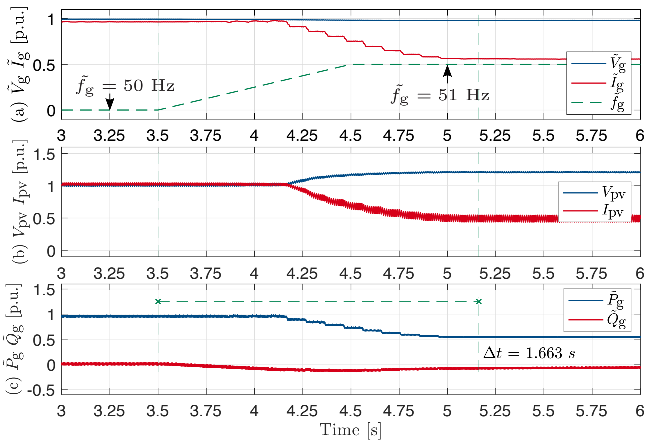

Fig. 4. RoCoF ride-through behavior: inverter outputs reduced active power at the new steady-state frequency, after 1 Hz/s RoCoF is elapsed.

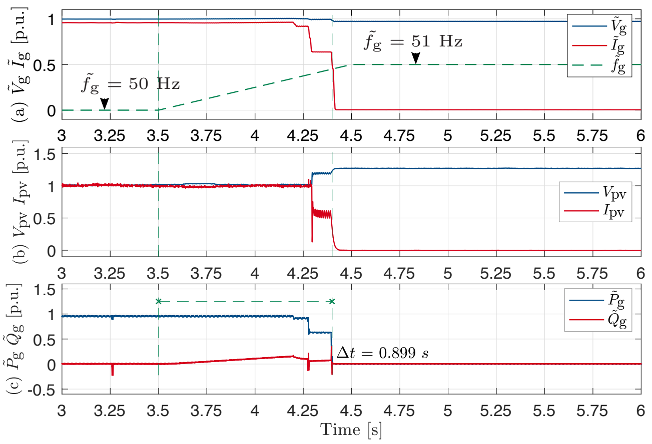

Fig. 5. Undesired disconnection due to 1 Hz/s RoCoF: inverter abruptly interrupts delivery of output power.

withstand, nor does it specify the speed at which the inverter output power shall reduce following a frequency increase. Exploiting the ramifications of this missing guideline, a test where the grid frequency was increased from 50 Hz to 51 Hz with a RoCoF of 1 Hz/s was performed, exposing a range of inverter behaviors otherwise invisible under the current testing procedures of [7].

Most of the inverters tested displayed the desired behavior, riding-through the RoCoF event. This means that they remained in operation at the increased frequency, giving a reduced output power. An example of desired behavior is portrayed in the test result of Fig. 4, where at 51 Hz the inverter is injecting the target power $P_{\text{out}} \approx 0.57$ p.u. with $P_{\text{ref}} = 1$ p.u. in accordance with Fig. 3. In contrast, two of the inverters tested disconnected from the grid due to the 1 Hz/s RoCoF, as displayed in the plots of Fig. 5, where at 4.4 s the output power abruptly drops to zero, flagging the undesired disconnection. At last, the 1 Hz/s RoCoF test highlighted that two inverters, while correctly reducing their output power in response to the over-frequency, did so in a sluggish fashion, which would provide little support to the grid [12, p. 43], as displayed in the test result of Fig. 6. Note that the time to curtail the power is about 16 s in Fig. 6, whereas the majority of inverters tested completed the over-frequency power curtailment similarly to Fig. 4, i.e. in a time interval between 1 and 2 s.

B. Inverter Response to Short Duration Grid Voltage Sags

Another area of concern, as it is scarcely covered in [7], regards the behavior of residential PV inverters in response to short-duration sags of the grid voltage. Short-duration voltage sags are known to cause spurious tripping of power electronic-interfaced equipment, such as adjustable speed drives [33], process control apparatus and computers [34, p. 139]. Therefore, to prevent the aggregate loss of inverter-based DER generation, it is important to ensure that PV inverters are immune to this type of disturbance.

On the one hand, [7] includes test procedures to verify that an inverter disconnects if the under-voltage duration is

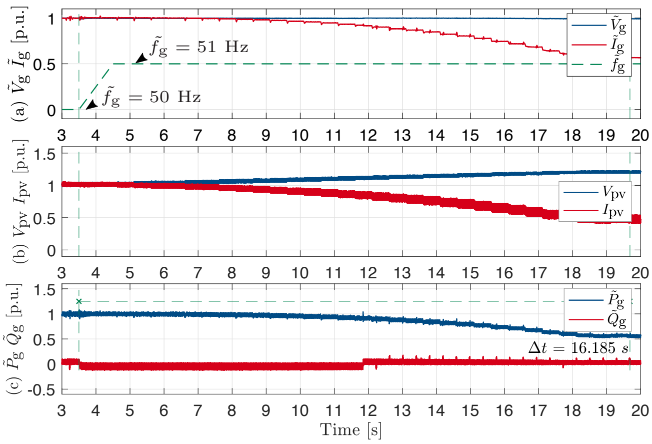

Fig. 6. Undesired response: inverter rides-through 1 Hz/s RoCoF, however exhibiting sluggish power curtailment.

longer than 1 s (referred to as *trip delay time*), but on the other hand this standard does not specify a test procedure to verify the inverter ability to withstand and immediately recover from an under-voltage with duration *shorter* than 1 s. This gap arises a variety of outcomes when PV inverters are subjected to short-duration voltage sags, as exposed by the tests outlined here. The test consisted in applying a voltage sag at the inverter output terminals, bringing the RMS voltage from 230 V down to 50 V for 100 ms, a reduction by about 80% for a typical fault clearance time. The results of this test unveiled considerably different inverter behaviors, some of which may constitute a threat to the power system operation, namely:

- *Ride-through (desired):* without grid current injection for the duration of the under-voltage (Fig. 7); with increased grid current injection for the duration of the under-voltage (Fig. 8); with decreasing grid current injection for the duration of the under-voltage (Fig. 9).
- *Power curtailment (undesired):* where the inverter remains connected to the grid, however the output power injected after the under-voltage disturbance is greatly reduced,

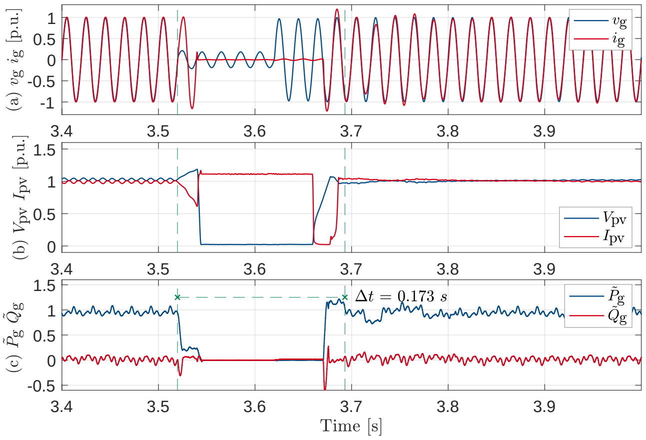

Fig. 7. Ride-through behavior towards 100 ms 0.78 p.u. ac voltage sag, no ac current is injected during the voltage sag.

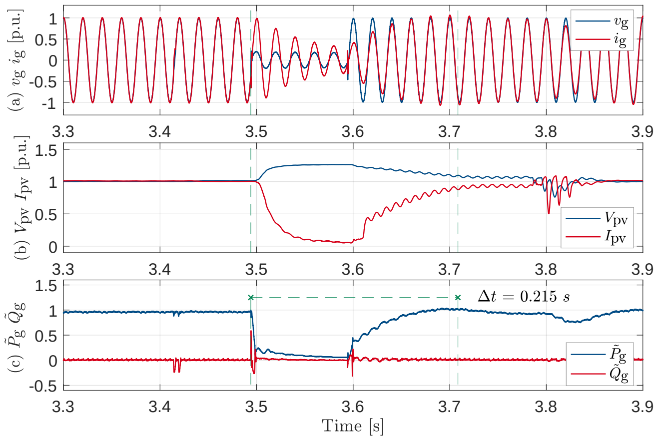

Fig. 9. Ride-through behavior to 100 ms 0.78 p.u. ac voltage sag, showing desirable decrease of ac current injection during the ac voltage sag.

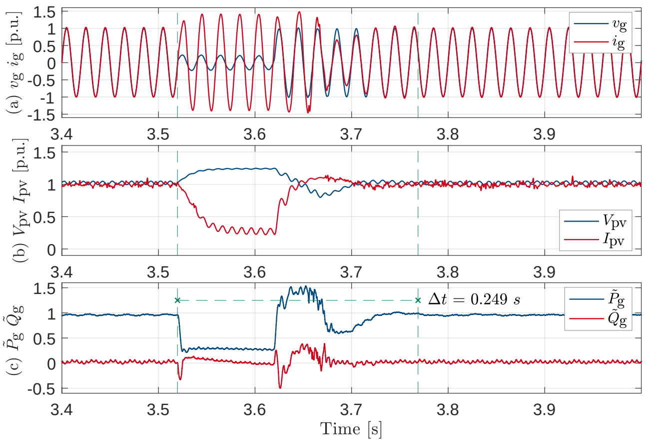

Fig. 8. Ride-through behavior to 100 ms 0.78 p.u. ac voltage sag, with undesired increase in ac current injected during the voltage sag.

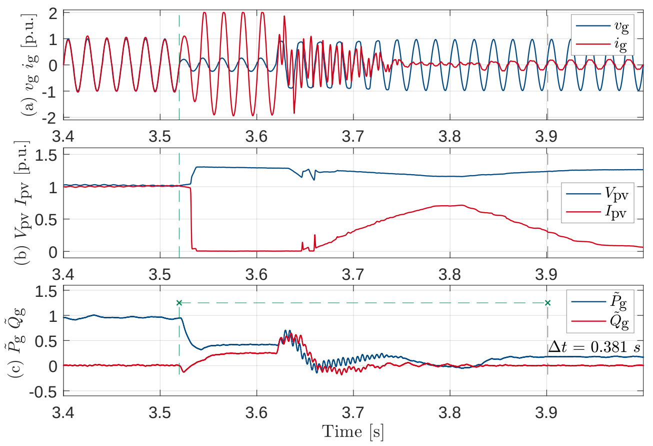

Fig. 10. Undesired power curtailment by 85% following the 100 ms 0.78 p.u. ac voltage sag.

as seen in Fig. 10: inverter output power reduced by 85%, and Fig. 11: inverter output power reduced by 100%. In these cases, the inverter takes several minutes before gradually resuming operation at the pre-disturbance power level. Such responses should not occur following an under-voltage event cleared within 1 s.

• *Disconnection (undesired):* where the inverter abruptly ceases to inject any power into the grid, raises an alarm, and restarts the reconnection procedure, taking several minutes before redelivering the pre-disturbance output power. While the reconnection procedure carried out by the inverter is performed correctly according to [7], it is worth emphasizing that the inverter should *not* have disconnected from the grid, given that the voltage disturbance was cleared before 1 s.

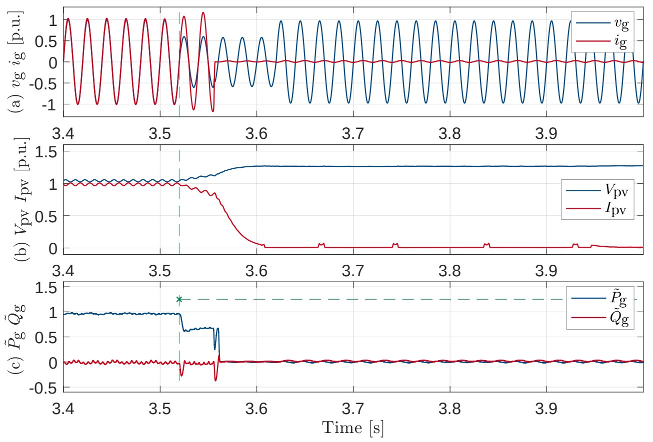

Fig. 11. Undesired power curtailment by 100% following the 100 ms 0.78 p.u. ac voltage sag.

C. Inverter Response to Grid Voltage Phase-Angle Jumps

The ac voltage in a distribution feeder may experience phase-angle jumps due to faults in the transmission network propagating through power transformers, where their vector group influences the phase-angle relationship between primary and secondary voltages. Technical standards around the world are starting to introduce the requirement for LV connected PV inverters to ride-through grid voltage phase-angle jumps. For instance, the IEEE Std 1547:2018 [35], [36] requires single-

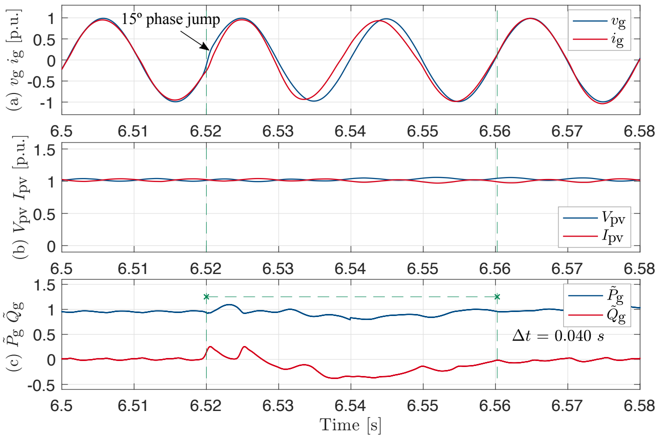

Fig. 12. Ride-through behavior to 15° phase jump disturbance.

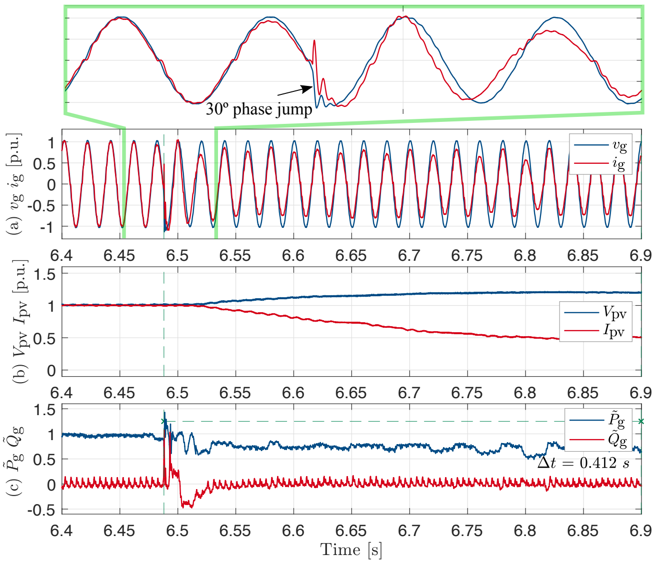

Fig. 13. Power curtailment following 30° phase jump disturbance (undesired behavior).

phase inverters the capability to ride-through 60° phase-angle jumps. AS 4777.2:2015 [7] does not require the ride-through capability of inverters against ac voltage phase-angle jumps. Therefore, this section presents the results of phase-angle jump tests performed on PV inverters complying with [7], but whose control system is not necessarily designed to ride-through this disturbance. In the tests, the phase-angle of the grid voltage was given steps of 15° and 30°. For these values of phase-angle jump the inverter should have maintained continuous and uninterrupted operation, without variation in the amount of active power injected to the grid. However, a contrasting scenario emerged from bench testing, where once again multiple behaviors were observed, as reported below.

• *Ride-through (desired):* as represented in Fig. 12, where the 15° phase-angle jump causes the momentarily phase shift of the grid current from the grid voltage. These two variables return to be in phase within about one ac cycle, and the power delivery to the grid is not affected by significant variations.

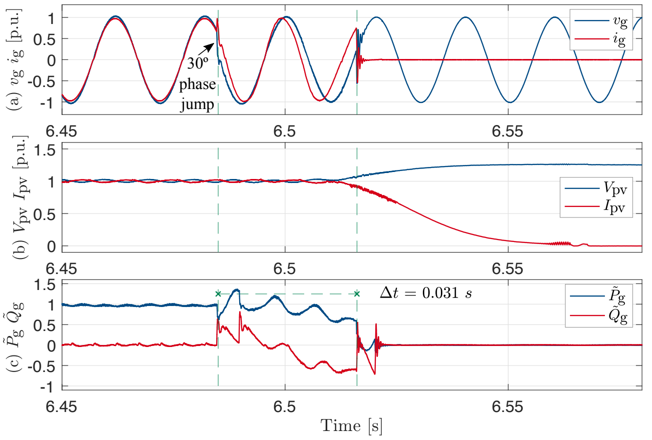

Fig. 14. Disconnection due to 30° phase jump disturbance (undesired behavior).

• *Power curtailment (undesired):* as depicted in Fig. 13, some inverters curtailed their output power due to the phase-angle jump, taking several minutes to deliver the pre-disturbance output power, since the power after the disturbance rises following the 16%/min ramp up-rate mandated in [7].

• *Disconnection (undesired):* as portrayed in Fig. 14, where a 30° phase-angle jump causes the immediate disconnection of the inverter from the grid. The inverter takes about 7 min before resuming operation at the pre-disturbance power level.

IV. Discussion

A. *Critical Evaluation of Bench-Testing Results*

Section III highlighted undesired inverter behaviors such as sudden disconnection from the grid or power curtailment, due to disturbances such as RoCoF, short-duration ac voltage sags and phase-angle jumps. These undesired behaviors occurred notwithstanding inverters compliance to the latest standard, which therefore failed to ensure appropriate resilience towards certain grid disturbances. The results reported in this paper unveil potential reasons for the aggregate loss of DER and unmanaged fluctuations in load demand triggered by grid events in areas with high rooftop PV penetration, as documented in recent research [9], [10], [12, pp. 42-43], and energy market operator reports [11], [32]. Thus, it is worthwhile to critically review the insights gained from the inverter bench testing process, for each of the grid disturbances tested.

a) RoCoF: these tests demonstrated that certain inverters can abruptly disconnect for RoCoF events of 1 Hz/s, as summarized in Table II. Inverters installed in Australia are not tested to withstand RoCoF, and those models failing the 1 Hz/s test described here cover a large market share, with an overall DER capacity of more than 200 MW (Table I). It is highly likely that these inverter models were those deemed to have disconnected, or not having performed according to the standards during the frequency events discussed in [11] and [12, p. 43].

TABLE II
SUMMARY OF INVERTER RESPONSES TO 1 Hz/s RoCoF DISTURBANCE

	2005 inverters			2015 inverters		
	Inv. ID	**Manuf.**	**Tot.**	**Inv. ID**	**Manuf.**	**Tot.**
disconnect	14	E	1	5	E	1
ride-through	all others		8	all others		15
tested			9			16

TABLE III
SUMMARY OF INVERTER RESPONSES TO SHORT-DURATION VOLTAGE SAG

	2005 inverters			2015 inverters		
Behavior	**Inv. ID**	**Manuf.**	**Tot.**	**Inv. ID**	**Manuf.**	**Tot.**
disconnect	8 / 15 18,21	A / F H	4	20	G	1
curtail	-	-	-	2 / 16 4,10,12	B / D D	5
other	6,24 9	A B	3	-	-	-
ride-through	1 / 14	A / E	2	all others		10
tested			9			16

TABLE IV
SUMMARY OF INVERTER RESPONSES TO 30° PHASE-ANGLE JUMP

	2005 inverters			2015 inverters		
Behavior	**Inv. ID**	**Manuf.**	**Tot.**	**Inv. ID**	**Manuf.**	**Tot.**
disconnect	15	F	1	1,6	A	2
curtail	-	-	-	2 4,10,12	B D	5
other	-	-	-	7 / 23	A / J	2
ride-through	all others		8	all others		7
tested			9			16

b) Short duration grid voltage sag: these tests demonstrated that certain inverters contribute to making the power system vulnerable by curtailing, or ceasing, the delivery of output power for minutes following a short-duration ac voltage sag. A summary of the voltage sag test results for the inverters tested is reported in Table III. Overall, 12 out of 25 inverters rode-through the short-duration voltage sag, without affecting their post-disturbance output power, i.e. delivering the same output power before and immediately after the disturbance, when the voltage recovered to its nominal value. The remaining inverters displayed undesired behaviors, curtailing their output power for minutes or, in the worst case, disconnecting from the grid. These undesired behaviors, replicated by thousands of inverters at the same time, certainly form a basis to explain some of the aggregate loss of DER power experienced in the recent under-voltage events discussed in [9], [10] and [12, pp. 42-43]. This is partly a consequence of missing strict specifications in [7], and previously [29], with respect to inverter performance and testing against undervoltage disturbances shorter than 1 s.

c) Phase-Angle Jump: these tests demonstrated that certain inverters undesirably disconnect from the grid, or curtail their output power for minutes upon phase-angle jump disturbances, further increasing vulnerability of the power system. A summary of inverter responses to a 30° phase-angle jump in the grid voltage is reported in Table IV. While some inverters may be more sensitive than others to phase-

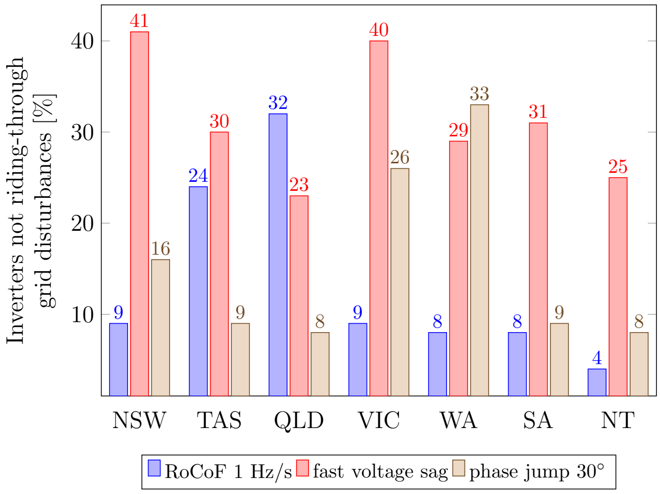

Fig. 15. Estimated percentage of rooftop PV capacity vulnerable to grid disturbances across Australian states and territories.

angle jumps depending on their grid synchronization strategy, specific research efforts in the area of grid synchronization are needed to gain a better understanding of these aspects. Besides, variety of fault-types and transformer vector groups in the grid also mean that phase-angle jumps may occur simultaneously with ac voltage sags [34], aggravating the risks of DER loss during grid faults.

Finally, under the assumption that the distribution of inverters tested for this work is representative of all rooftop PV inverters installed in Australia, an estimate on the percentage of inverters vulnerable to each disturbance in every state and territory is displayed in Fig. 15. Data reported in this figure inform the investigation on unexpected mass DER disconnection and power curtailment reported in [8]–[12]. These data were obtained from a campaign testing 25 residential PV inverters on an individual basis, disregarding eventual mutual interactions among DER. This assumption is reasonable for frequency disturbances, as the frequency is a global variable across a network, or for voltage disturbances where voltage deviates substantially from DER tripping set-points. Further research is required to understand whether fleets of DER interconnected on actual low voltage grids display the same behaviors against grid disturbances.

B. Need for Enhanced Standard Compliance Testing

The compliance test specified in [7, Appendix H] to derive the frequency-watt droop curve (in Fig. 3) recommends varying the frequency in steps of 0.1 Hz every 30 s: a very low rate of change of frequency. Nevertheless, should the grid frequency increase at a faster rate, as per the 1 Hz/s tests shown in this paper, some of the inverters tested improperly tripped and disconnected. Even among those inverters riding-through the RoCoF test, it was found that the time to reduce the power output could be one order of magnitude apart among different inverters. A short power settling time, ideally less than 1 s [6] and at most 2 s [37, p. 207], is arguably required for the inverter to provide effective grid support during over-frequency events. Hence, compliance to [7] does not imply that a prompt power response to frequency variations is achieved, nor does it entail ride-through of frequency events. In this regard, leading examples can be found in [38], [39], serving to test and certify inverters for grid supporting functions. In UL 1741-SA the frequency-watt characteristic is verified by means of step variations in frequency, to observe the inverter control time-constant, and slower frequency ramps, to validate the frequency-watt droop profile [40]. Future improvements of current standards should therefore consider the example of [38], as well as [35], [37], [39], [41] which already demand ride-through of RoCoF disturbances.

Short duration grid voltage sags are taken into account by recent standards, such as [35], [37], [41], which also specify inverter low voltage ride-through behavior. In the case of [35], it is suggested that PV inverters adopt 'momentary cessation' of their output power (i.e. inject no ac current) during a short-duration voltage sag, and resume operation at full power immediately following the ac voltage recovery [35], [42]. In [37], the inverter behavior during the sag is not prescribed; however, it is required that the output power is returned at the pre-fault level immediately after the sag. The future version of the Australian standard [7] must also define a ride-through behavior against short-duration ac voltage sags, together with appropriate testing procedures. Similar remarks can be applied to phase-angle jump ride-through requirements, which are already integrated in [35]. Priority of functions should be specified, defining the hierarchy of inverter responses as in [35, p. 32]. Importantly, the recently updated IEEE 1547.1 [39] is a valuable reference, as it includes test procedures to verify ride-through behavior against disturbances such as RoCoF, phase-angle jump and undervoltage, among others.

Finally, key points on existing and proposed passive anti-islanding protections to consider in future versions of AS 4777.2 [7] are summarized in Table V. Based on this study and on the recent development of DER connection standard worldwide [35], [37]–[39], [41], addition of RoCoF and phase-angle jump protections seems highly reasonable. New protective function limits are proposed based on [35], however, further dialogue among standard development stakeholders is necessary to tailor these limits to the Australian grid conditions. Prospective enhancements deriving from the evidence of this study are also commented in Table V; these recommendations improve DER performance against voltage disturbances shorter than 1 s and frequency-watt dynamic response.

V. Conclusion

This paper provided evidence demonstrating some limitations of residential single-phase rooftop PV inverters complying with Australian standards. In spite of this compliance, it was highlighted that residential PV inverters might be vulnerable to certain grid disturbances, resulting in undesired disconnection and output power curtailment. Taking into account the extraordinary amount of inverter-interfaced generation installed in Australia, these undesired power curtailments and disconnections can pose a serious threat to the secure operation and stability of the bulk power system. Disturbances such as RoCoF, short-duration voltage sags and phase-angle jumps in the grid voltage have demonstrated to produce the documented undesired behaviors. In conclusion, the findings presented in this paper serve two purposes. Firstly, they underpin the urgent necessity for a revision of AS 4777.2:2015. Secondly, they provide a baseline to interpret the undesired aggregate behavior of inverter-connected DER observed during grid events recently occurred in Australia, forming a worthwhile case study for any region of the world with high rooftop PV penetration.

TABLE V
Proposed AS 4777.2 Enhancements Resulting From This Study

Protective function [limit]	**Trip delay [max trip] time**	**Proposed enhancement**
Undervoltage [V_L: 180 V]	1 s [2 s]	If voltage disturbance is cleared in Δt <1 s • specify DER behavior during Δt, and up to 1 s after Δt • power after Δt to match pre-disturbance power [35], [41]
Overvoltage 1 [V_{H1}: 260 V]	1 s [2 s]	
Overvoltage 2 [V_{H2}: 265 V]	- [0.2 s]	
Under-freq. [f_L: 47 Hz]	1 s [2 s]	Complete freq.-watt response within 2 s when f_L<freq.<f_H, in alignment with [35], [37]–[39]
Over-freq. [f_H: 52 Hz]	- [0.2 s]	
RoCoF* [$\dot{f}_g$: 3 Hz/s]	- [0.2 s]	RoCoF ride-through when f_L<freq.<f_H, in alignment with [35], [37], [41]
Phase jump* [$\Delta\phi$: 60°]	- [0.2 s]	Phase-angle jump ride-through in alignment with [35], [39]

* New protective function

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