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Sensitivity of Commercial Rooftop Photovoltaic Inverters to Grid Voltage Swell

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***Abstract*—The ever-increasing electricity generation from rooftop photovoltaic (PV) systems, also known as distributed PV (DPV), leads to new challenges for transmission and distribution network service providers. DPV lacks visibility and control from system operators, and this issue becomes critical especially during and after grid contingencies. Technical standards applicable to DPV inverters define expected performance and behavior, however they do not always provide clear guidelines under several grid disturbance conditions. On the one hand, inverters are allowed to respond flexibly. However, knowledge of inverters behavior under grid voltage disturbances is necessary to design and tune the parameters of composite load models, used by power system operators in planning the required power reserve. This article investigates through experiments the sensitivity and behavior of 25 off-the-shelf residential DPV inverters under grid voltage swells. Inverters are found to behave in either of these ways: 1) Ride-through, 2) curtail power, and 3) disconnect. Power curtailment or disconnection under such disturbances can have a detrimental impact on power system security. Accordingly, power system operators should schedule enough power reserves or take other appropriate measures.**

***Index Terms*— Composite load model, commercial photovoltaic inverters, grid voltage increase, inverter test benchmark, standards, voltage swell.**

I. Introduction

Installation of rooftop photovoltaic (PV) systems, also known as distributed PV (DPV) inverters, is growing rapidly all over the world, as a result of government support, high electricity costs and improving technology. As an example, the cumulative installed power of DPV systems with rated power smaller than 10 kW is shown in Fig. 1. In 2020, the total installed capacity of DPV systems with rating of less than 10 kW in Australia was around 10 GW, which accounts for approximately 20% of total demand [1]. These PV inverters are mainly installed in residential places, and have the following features:

- The online behavior of majority of DPV inverters is scarcely visible to power system operators and their output active/reactive power cannot be controlled in real time with energy management systems.
- These inverters are from several manufacturers with different hardware/software features.

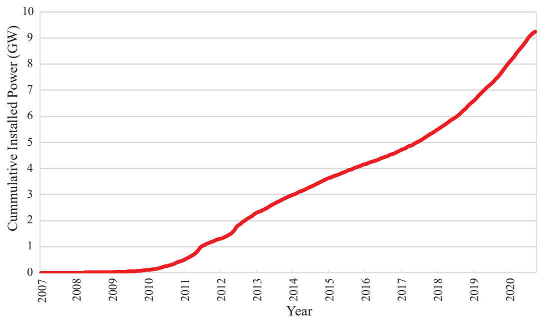


Fig. 1: Cumulative installed power of rooftop photovoltaic inverters with rated power smaller than 10 kW in Australia [1].

- Standards are continuously evolving, while legacy inverters can continue operation with corresponding older versions of standards.
- The installation of each inverter brand and model in the power system changes over time, which means its overall impact on the power system changes overtime.

These features of DPV inverters and their increasing rate of installation lead to new challenges for power system operators regarding the security and reliability of the power system. As an example of such new challenges, some types of grid disturbances can lead to the disconnection of a large amount of DPV inverters. In such a condition, if the amount of DPV disconnecting (which is unknown and often invisible to the grid operator) is larger than the power reserve planned for contingencies, then the disturbance conditions may be exacerbated with detrimental effects on the power system stability/security/operation. As an example, 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 sags in areas with high DER contribution. As illustrated in Fig. 2, a significant load increase was observed in these areas following voltage disturbances, signaling the missing contribution of DER generation [2].

To reduce such adverse effects under high penetration of DPV inverters in the power system, standards and grid codes

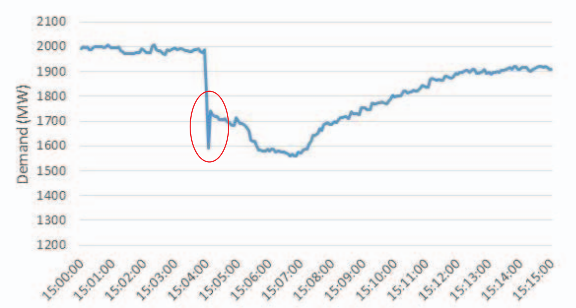
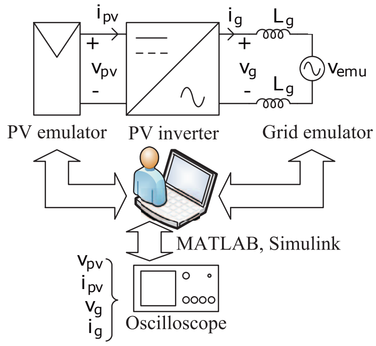


Fig. 2: South Australia demand, coincident with the fault at the Torrens Island switchyard on 3 March 2017 - DPV disconnection, due to the voltage sag, results in an increase of the load demand [2].

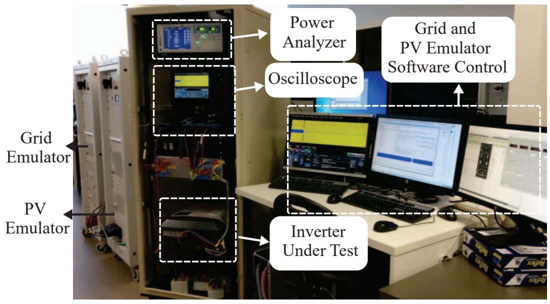
are updated to impose specific operating requirements on these systems [3], [4]. However, there are several operating conditions, like short-duration grid voltage disturbances, for which the current standards do not impose clear requirements on the PV inverters. Accordingly, inverters from different manufacturers exhibit different behaviors under the same grid disturbance condition [5]. Additionally, new standards are not imposed on currently installed PV inverters. Therefore, knowledge of the behavior of PV inverters under various types of grid disturbances is necessary for maintaining power system reliability during ongoing transitions towards renewable energy resources.

Several papers in the literature analyze inverter performance and behavior against grid disturbances. They often perform bench testing to identify various types of behavior of inverters under different grid disturbance conditions [6], [7]. 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 high penetration of DPV connected to their distribution networks, especially from residential and commercial PV. The response of small-scale PV inverters to short-duration voltage sags is investigated, highlighting undesired and inconsistent behaviors, including disconnection from the grid [8], [9].

Voltage swells can occur due to disconnection of large loads or connections of large capacitor banks [10]. In the current version of Australia's standard AS/NZS 4777:2015 [4], if the voltage at the point of common coupling (PCC) is greater than 265 V, the inverter shall disconnect in less than 0.2 s. It is also desirable for the inverter to remain in continuous and uninterrupted operation for voltage variations with a duration shorter than the trip delay time, also specified by the standard. However, in the test procedure defined by the standard, the voltage only increases beyond the trip value and stays at this voltage to record the disconnection time. Accordingly, the behavior of inverters under short duration voltage swells is not examined in the standard. In this way, the inverters may exhibit different types of behavior under shirt duration voltage swells, while still complying with corresponding standards.



(a)



(b)

Fig. 3: Inverter testing setup: (a) Schematic representation, (b) photo of the inverter testing setup [5].

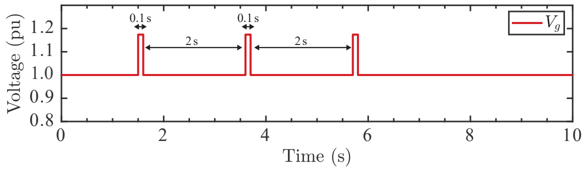


Fig. 4: Profile of the Grid voltage during the voltage swell test.

To investigate different DPV inverter behaviors under voltage swell, empirical tests over a wide range of inverters are required. However, currently no comprehensive experimental study of this type is available in the literature.

To fulfill the lack of knowledge of behavior of commercial PV inverters under grid voltage swell conditions, this paper analyzes the behavior of 25 off-the-shelf commonly installed single-phase DPV inverters in Australia. The inverters are subjected to voltage swells and the behavior of each inverter is recorded. Three types of behavior are identified from the tested inverters in this study: 1) Ride-through, 2) power curtailment, and 3) disconnection. Each of these types of behavior has a different impact on the grid. The details of these types of responses are explained in this paper.

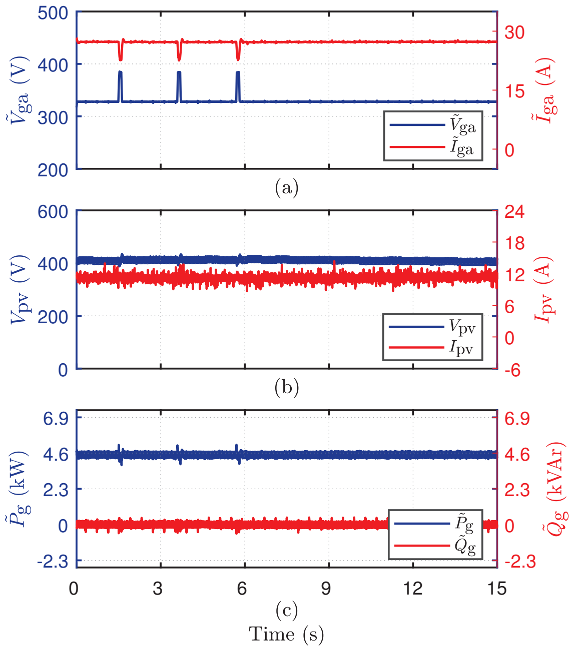


Fig. 5: **Ride-through** behavior of an inverter (inverter 13 - AS/NZS 4777.2:2015) under three consecutive voltage swells with amplitude of 270 $\mathrm{V_{rms}}$: (a) Grid voltage and current, (b) PV voltage and current, and (c) grid active and reactive power.

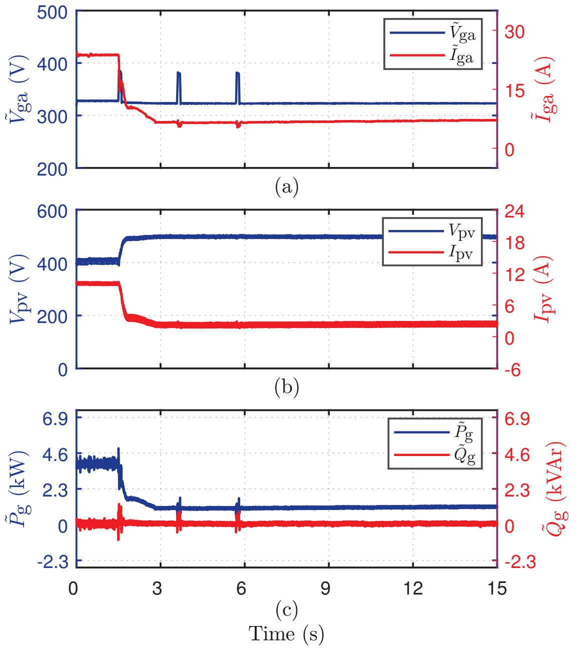


Fig. 6: **Power curtailment** behavior of an inverter (inverter 10 - AS/NZS 4777.2:2015) under three consecutive voltage swells with amplitude of 270 $\mathrm{V_{rms}}$: (a) Grid voltage and current, (b) PV voltage and current, and (c) grid active and reactive power.

II. Inverter Testing Setup

The inverters investigated are rated between 1.5 kW and 5 kW, which mainly are installed in residential places and they comply with Australian standard (9 inverters with AS 4777.3:2005 and 16 inverters with AS/NZS 4777.2:2015). All inverters are single-phase and some of them are with single PV input and some are with double PV input. A schematic representation of the inverter testing setup and a photo are shown in Fig. 3. Inverters are connected to a 50 kVA Regatron TCACS four-quadrant grid emulator, in which the voltage disturbances are emulated. Two Regatron TopCon Quadro programmable dc power supplies are used to emulate the predefined PV curves at the PV input ot the tested inverters. A grid line impedance of $L_g = 0.12 + j0.16\,\Omega$, based on the recommendation of AS/NZS 4777.2:2015, is connected between the grid emulator and the ac terminal of the inverter. The details of the tested inverters can be found in [5], [11], [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

Three consecutive voltage impulses are used at the grid emulator, as shown in Fig. 4. At each voltage step change, the grid voltage changes in such a way that the PCC voltage at the inverter terminal changes from 230 V to 270 V. The voltage remains at 270 V for a duration of 0.1 s and then it

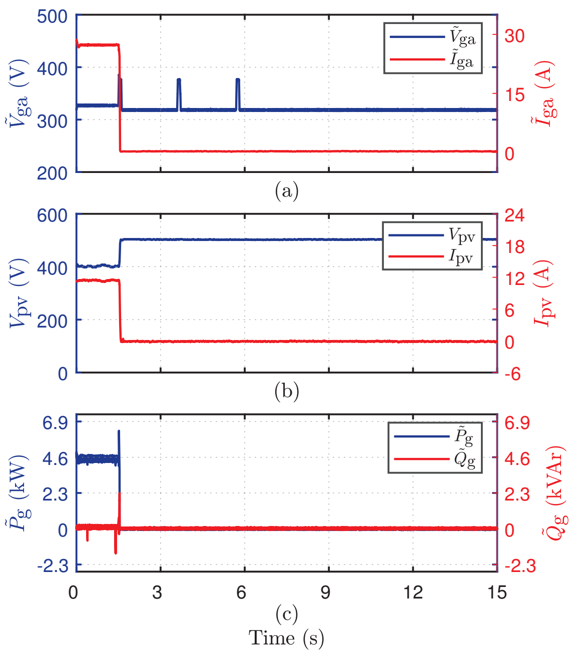


Fig. 7: **Disconnection** behavior of an inverter (inverter 14 - AS 4777.3:2005) under three consecutive voltage swells with amplitude of 270 $\mathrm{V_{rms}}$: (a) Grid voltage and current, (b) PV voltage and current, and (c) grid active and reactive power.

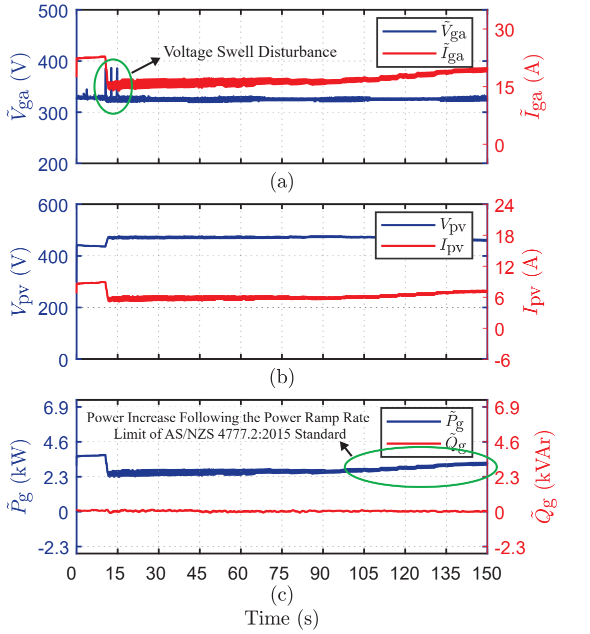


Fig. 8: Reconnection behavior of an inverter (inverter 10 - AS/NZS 4777.2:2015) after **power curtailment** due to the voltage swell disturbance: (a) Grid voltage and current, (b) PV voltage and current, and (c) grid active and reactive power.

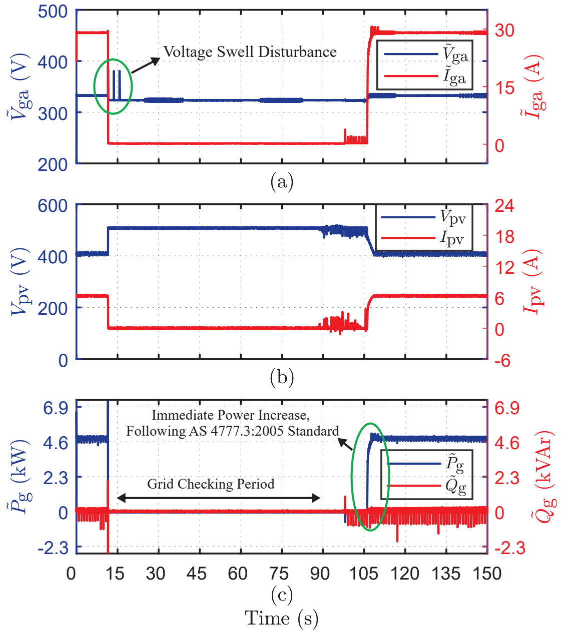


Fig. 9: Reconnection behavior of an inverter (inverter 14 - AS 4777.3:2005) after **disconnection** due to the voltage swell disturbance: (a) Grid voltage and current, (b) PV voltage and current, and (c) grid active and reactive power.

returns to 230 V. The same sequence repeats two more times and the time interval between the ending of one voltage step change and beginning of the consecutive voltage change is 2 s. The waveform of the PCC voltage $\tilde{V}_{ga}$ under this test scenario is shown in Fig. 5(a).

Three types of behavior are recorded from the investigated inverters. The details of each behavior are explained in the following:

Ride-through: In such behavior, the inverter continues its operation at the pre-disturbance conditions. There is no transient or reduction of the output power of the inverter. One example of such behavior (inverter 13) is illustrated in Fig. 5. It is seen that during the period that grid voltage increases to 270 V, the inverter output current reduces as shown in Fig. 5(a). In this condition the PV current and voltage does not change at depicted in Fig. 5(b), which indicates that the output active power of the inverter also remains constant (refer to Fig. 5(c)). This behavior is the most desired behavior based on the standard because the amount of injected power from PV inverters in the power system does not change.

Power curtailment: In this case, the inverter reduces its output power after the disturbance. An example of such behavior is shown in Fig. 6 (inverter 10). The output active power of the inverter reduces from 4.5 kW to 1 kW in approximately 1 s. Note that even though the inverter power is reduced, it remains connected to the grid and after a few minutes, it recovers the output power to the condition before the disturbance.

Disconnect: The last kind of inverter behavior under grid voltage swells is disconnection from the grid. As shown in Fig. 7, an inverter (inverter 14) disconnects from the grid after the disturbance. The disconnection occurs in less than 0.1 s and the PV voltage increases to the open circuit voltage, while the inverter current reduces to zero.

Remark: The main difference between power curtailment and disconnection behavior is the time that is required for the inverter to recover its output power to the pre-disturbance conditions.

- Under a power curtailment, the inverter remains connected and can start to increase its output power based on the corresponding standard power ramp rate. The power increase behavior of the inverter 10 is depicted in Fig. 8. This inverter follows AS/NZS 4777.2:2015, in which a power ramp rate limit is required. It is seen that the inverter increases the power linearly based on the standard requirement.
- After a disconnection, the inverter requires to follow the startup process, in which it is required to remain in standby mode and measure the grid voltage for at least 1 min before the startup. This period is illustrated in Fig. 8(c), in which the inverter 10 increases the power immediately after grid checking period is passed. It is noted that this inverter follows AS 4777.3:2005, in which no power ramp rate limit is imposed.

TABLE I: Summary of inverter behaviors under voltage increase transients

Manufacturer	Inverter ID	AS 4777 version	†Installed power (MW)	Behavior under voltage transient
A	1	2015	56	Ride-through
	1*	2005	167	Ride-through
	6	2015	8	Ride-through
	6*	2005	28	Ride-through
	7	2015	3	Ride-through
	8	2005	2	Ride-through
	19	2015	52	Ride-through
	24	2005	72	Ride-through
B	2	2015	65	Ride-through
	9	2005	4	Ride-through
C	3	2015	136	Ride-through
	13	2015	22	Ride-through
D	4	2015	32	Power curtail
	10	2015	1	Power curtail
	12	2015	12	Power curtail
	16	2015	3	Ride-through
E	5	2015	37	Ride-through
	14	2005	197	Disconnect
F	15	2005	< 1	Ride-through (with transients)
G	17	2015	26	Ride-through
	20	2015	129	Ride-through
H	18	2005	28	Ride-through
	21	2005	60	Ride-through
I	22	2015	91	Ride-through
J	23	2015	70	Ride-through
Total installed power from tested rooftop PV inverters in Australia [5]			**1303**	
Total power of installed rooftop PV inverters with rated power smaller than $6.5\,\mathrm{kW}$ in Australia, estimated as of September 2020 [1].			**6740**	

†Estimate as of April 2019.

*Indicates firmware reconfiguration to AS 4777.3:2005 of inverter certified for AS 4777.2:2015.

IV. Discussion

Table I summarizes the behavior of investigated inverters under voltage swells. The identification number, manufacturer of each inverter and the corresponding standard are also included in the table. The total installed power of the investigated inverters is $1303\,\mathrm{MW}$ which accounts for approximately 20% of overall installed DPV inverters with rated power smaller than $6.5\,\mathrm{kW}$ in Australia. Although most of the inverters ride through the investigated voltage disturbance, there are several cases with power curtailment or disconnection. Theses inverters account for $242\,\mathrm{MW}$ out of $1303\,\mathrm{MW}$, which is approximately 19% of the investigated inverters. By extrapolating the results to all installed PV inverters, more than $1,280\,\mathrm{MW}$ of the installed DPV inverters are at risk of disconnection or power curtailment under such voltage disturbance in the grid. The results show the importance of inclusion of clear guiedelines in new standards for the operation of DPV inverters under short duration voltage swells.

V. Conclusion

The experimental behavior of 25 off-the-shelf DPV inverters under voltage swells has been discussed in this paper. The study shows that inverter exhibit different kinds of behavior under voltage swells, being ride-thorough, power curtailment, and disconnection. The latter two behaviors are not desired for power system operation, because large amount of power generation may disconnect under such grid disturbance. It has been seen that a relatively high portion of the tested inverters show undesired behavior. The results of this study help power system operators to estimate the required power reserve in the system to sustain security and reliability of the power system with high penetration of distributed energy resources.

VI. Acknowledgment

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