FROM INVERTER STANDARDS TO UNDERSTANDING INVERTER BEHAVIOUR FOR SMALL-SCALE DISTRIBUTED GENERATION

Addressing barriers to efficient renewable integration

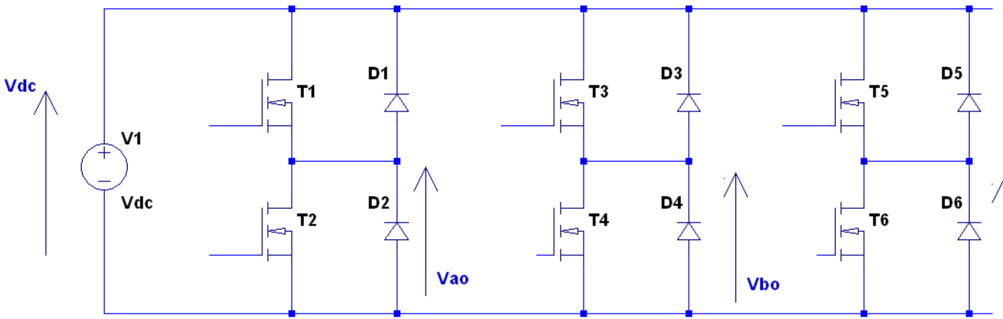
What is this talk about?

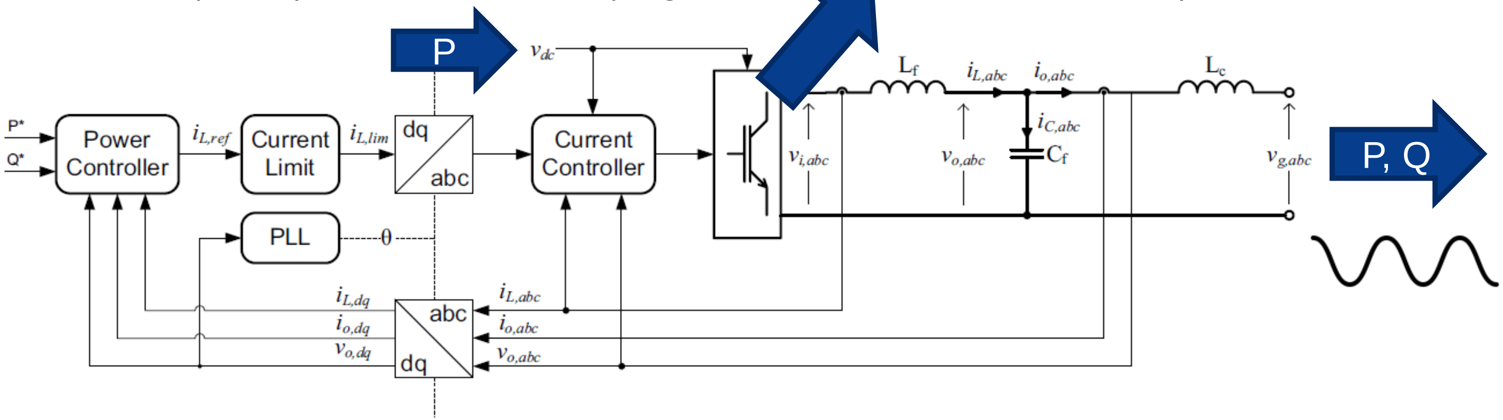
- There is currently around 7 GW of residential inverters connected to the distribution network, typical sizes are 2-5 kVA, mainly single-phase
- That is in a system with a peak demand ~40 GW
- Some states are ‘running entirely’ on inverter connected renewables
- There are two ‘versions’ of AS4777 – 2005 and 2015 with a revision in process
- There are portfolios of small-scale inverter makes and models that add to >250 MW
- How vulnerable are they to disconnecting or reducing their output power in response to grid disturbances? **This question is becoming of increasing importance.**

https://www.youtube.com/watch?v=qurQdewERD8&list=PLHSIfioizVW0A4mPU7S52qU-8zjEdYa-h&index=64&t=0s

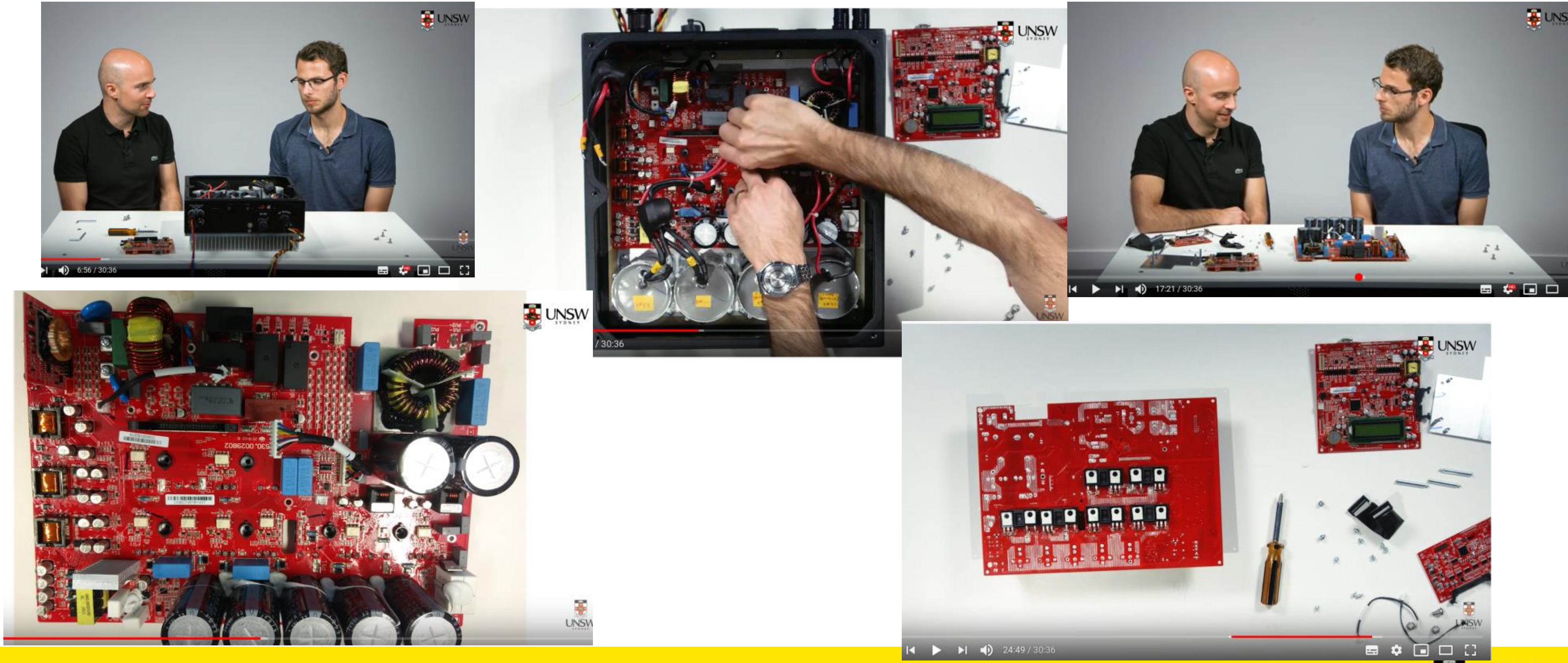
Inverter Control Scheme for Grid Connection

- One of many examples of grid connection con
- The VSI is fed from a dc link, v_{dc}, from which tl
- The three-phase output ac waveforms are fed
- The filter removes high-frequency components
- The current controller (in *abc* phase reference frame) regulates ac current to deliver set-point P^* and Q^* values.





Inside a PV Inverter



System components

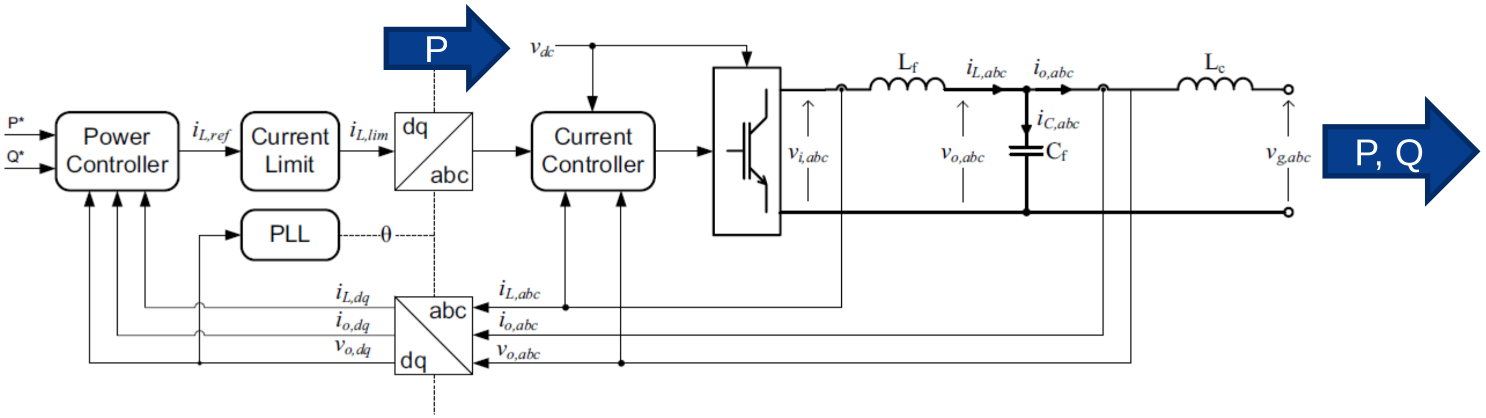
PLL: Determines the phase angle of the positive sequence fundamental component of the grid voltage, $V_{g,abc}$.

Lc: Interfacing inductance. Used to control $I_{o,abc}$.

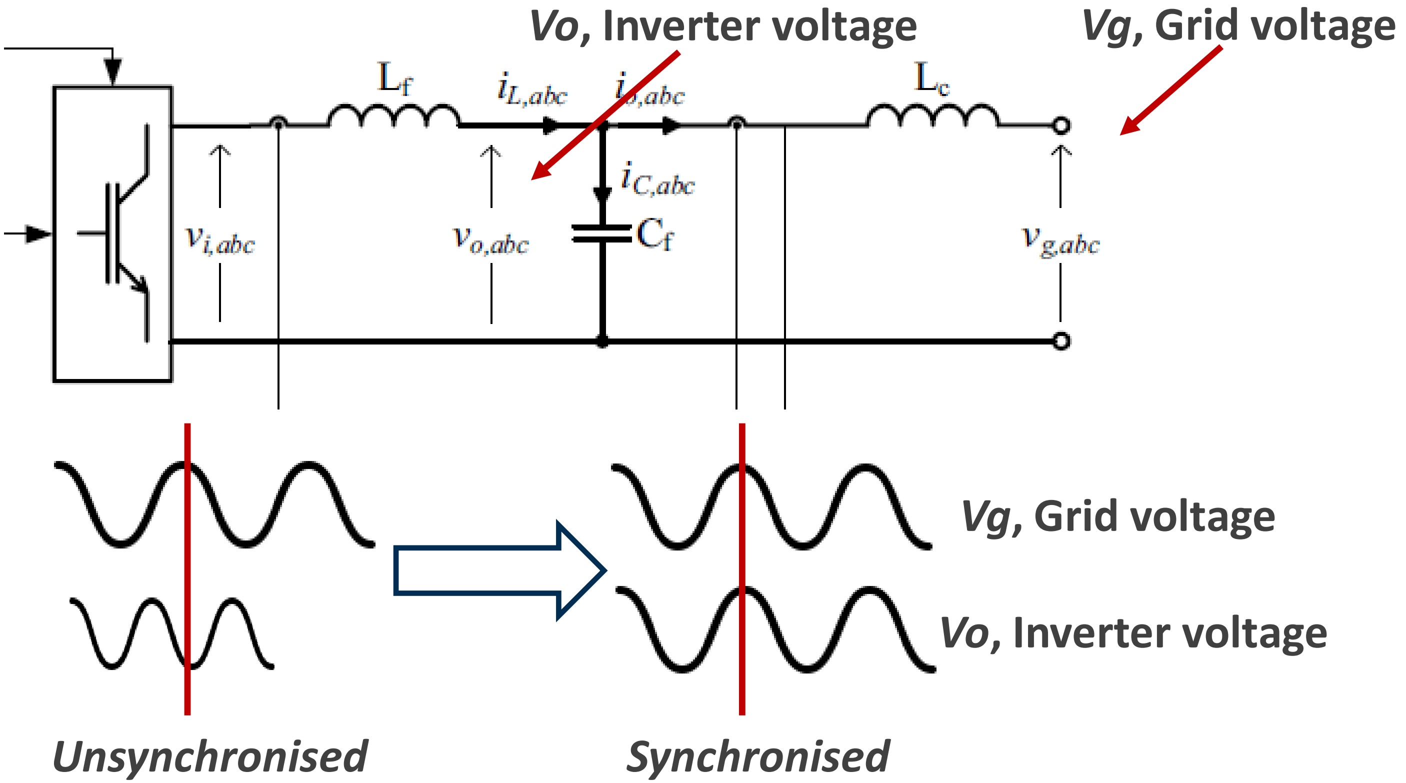
Lf, Cf: Low-pass filter which generates sine wave voltage $V_{o,abc}$ from switched output $V_{i,abc}$.

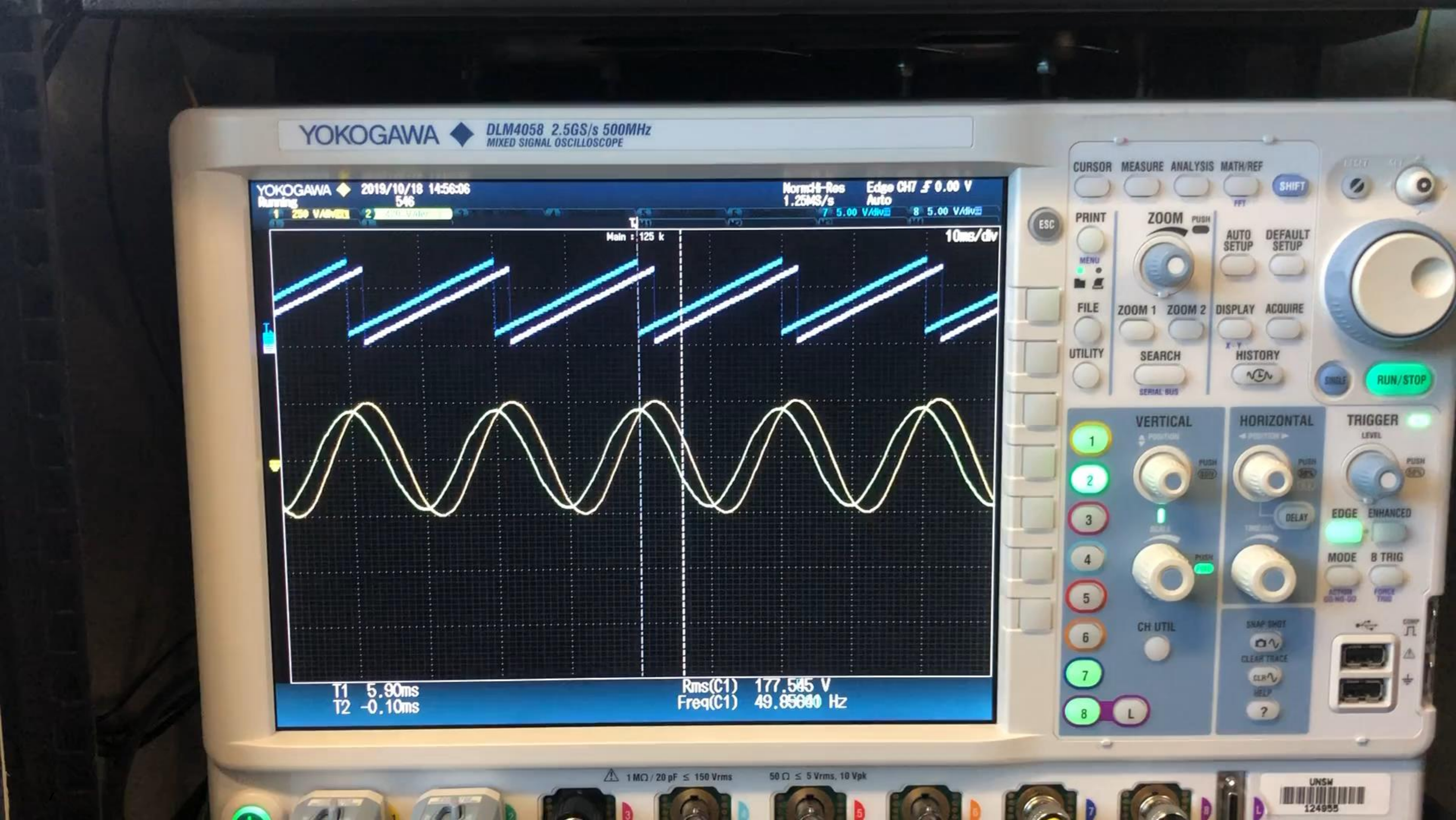
In the power path

abc/*dq* blocks: Reference frame transformations from stationary *abc* to rotating *dq* and vice-versa. Uses angle output from PLL.



Grid Synchronisation




YOKOGAWA
DLM4058 2.5GS/s 500MHz
MIXED SIGNAL OSCILLOSCOPE
2019/10/18 14:56:06
Running
10ms/div
T1 5.90ms
T2 -0.10ms
Rms(C1) 177.545 V
Freq(C1) 49.85000 Hz
CURSOR
MEASURE
ANALYSIS
MATH/REF
SHIFT
PRINT
ZOOM
AUTO SETUP
DEFAULT SETUP
FILE
ZOOM 1
ZOOM 2
DISPLAY
ACQUIRE
UTILITY
SEARCH
HISTORY
RUN/STOP
VERTICAL
HORIZONTAL
TRIGGER
EDGE
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B TRIG
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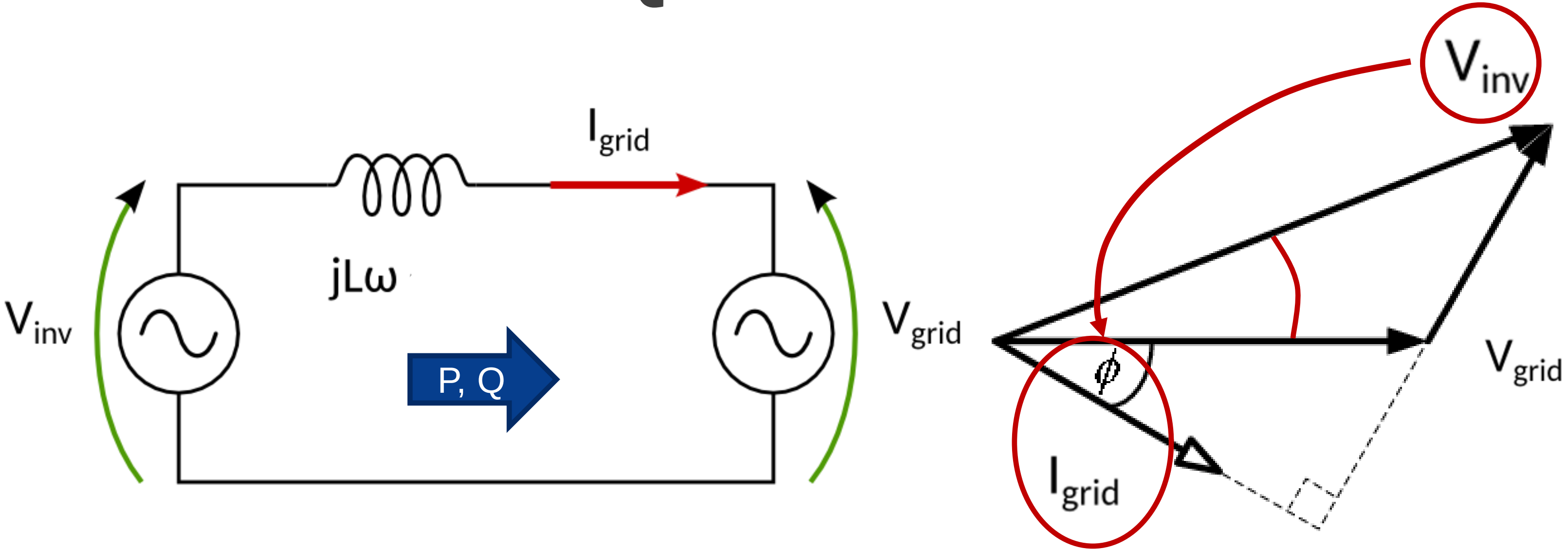
Control of P & Q



Once V_{inv} and V_{grid} are synchronized it is possible to control I_{grid} in magnitude and phase such that P and Q are independently controlled by the inverter control system.

Current Controller

Current controller: Adjusts $V_{i,abc}$ in order to meet $i_{L,abc,ref}$.

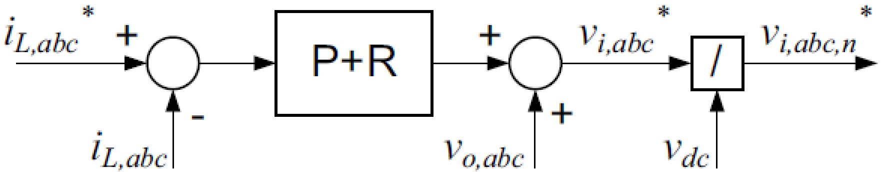
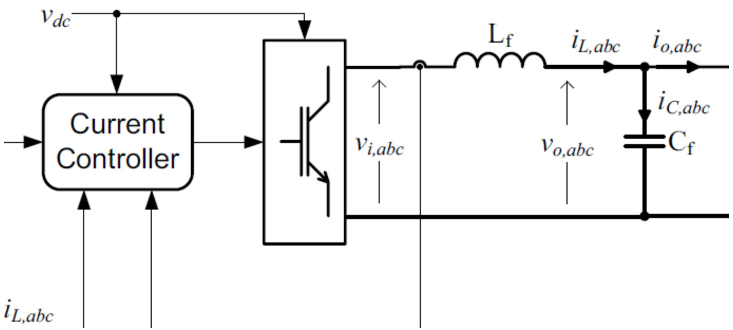
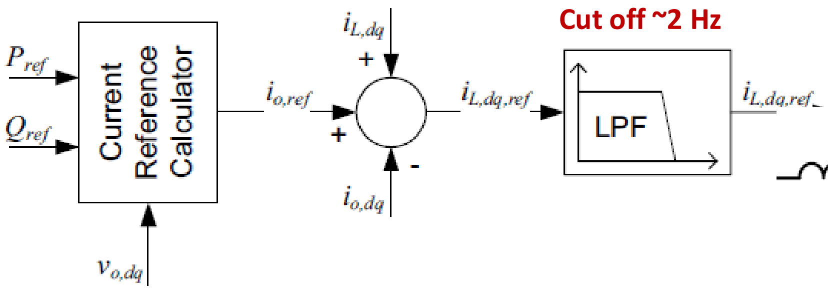


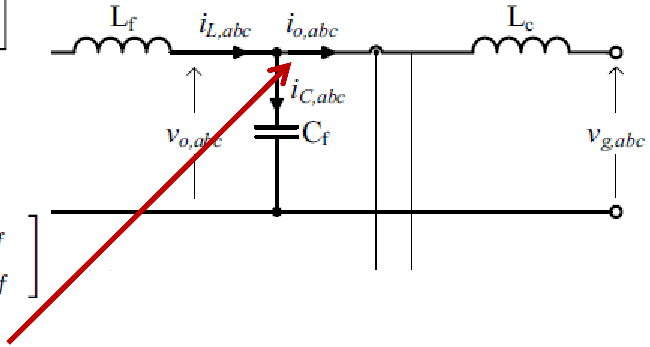
Figure 2. Current Controller



Power controller

Power controller: generates $i_{L,dq,ref}$ command to generate *P** and *Q**.





$$\begin{bmatrix} i_{od,\mathrm{ref}} \\ i_{oq,\mathrm{ref}} \end{bmatrix} = \frac{1}{v_{od}^2 + v_{oq}^2} \cdot \begin{bmatrix} v_{od} & v_{oq} \\ v_{oq} & -v_{od} \end{bmatrix} \cdot \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix}$$

Given that $i_C = i_L - i_o$, and $i_{L,\mathrm{ref}} = i_{o,\mathrm{ref}} + i_C$ the inductor reference currents can be found from

$$i_{L,\mathrm{ref}} = i_{o,\mathrm{ref}} + i_L - i_o$$

Inverter Response to Faults

Example: Voltage sag to 1/3 pu

- Inverter attempts to increase output current to maintain P and Q. (Would naturally reach 3 pu in these circumstances.)
- At time *td*, current reaches a threshold at which the control system decides there is a fault.
- Immediately steps current reference to 2 pu in order to support the network with fault current.
- Note the difference in response compared to the synchronous generator

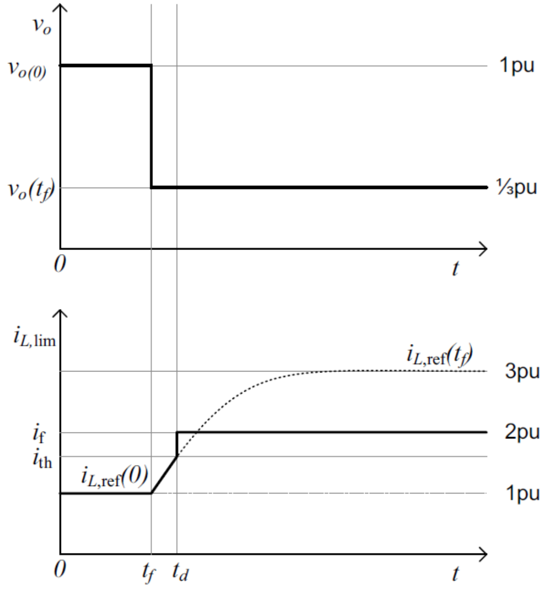
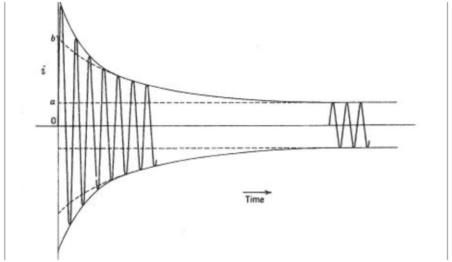
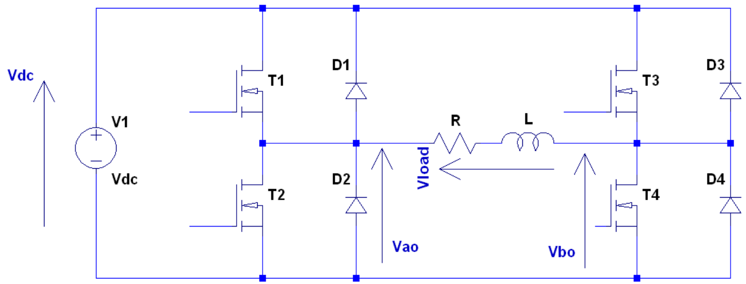


Figure 4. Single inverter fault response



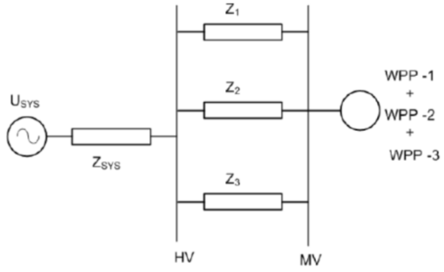
What can a VSI do?

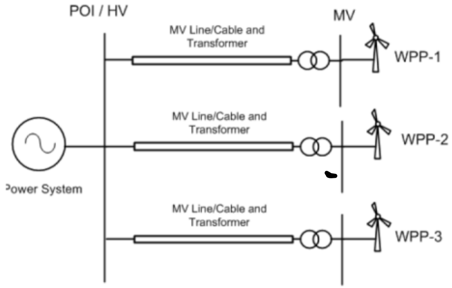


- Source single- and three-phase voltages.
- They can be controlled to deliver a certain voltage at its terminals.
- Control of voltage allows control of the output current magnitude and phase.
- Hence control of the real power and reactive power to/from the grid.
- During faults emphasis is typically on injecting reactive power. Reactive power is important as the transmission network voltages are depressed during a fault. The reactive elements (*L*s and *C*s) of the transmission network need to be 'recharged'.
- This energy is delivered by supplying reactive power.
- Remember that real power requires voltage and current to be present. During a severe fault, zero voltage conditions may be experienced.

What can a VSI do?

- In a stiff network, the connection between the VSI and the rest of the grid is low impedance. The VSI output voltages are then almost exactly the same as the network. Injecting real and/or reactive power will not influence the network voltages so less likely to cause instability.
- In a weak network, the connection between the VSI and the rest of the network has ‘significant’ impedance. The VSI output power (*P* and *Q*) can influence the local voltages – indeed they can alter voltages so much that the VSI control system can become unstable.





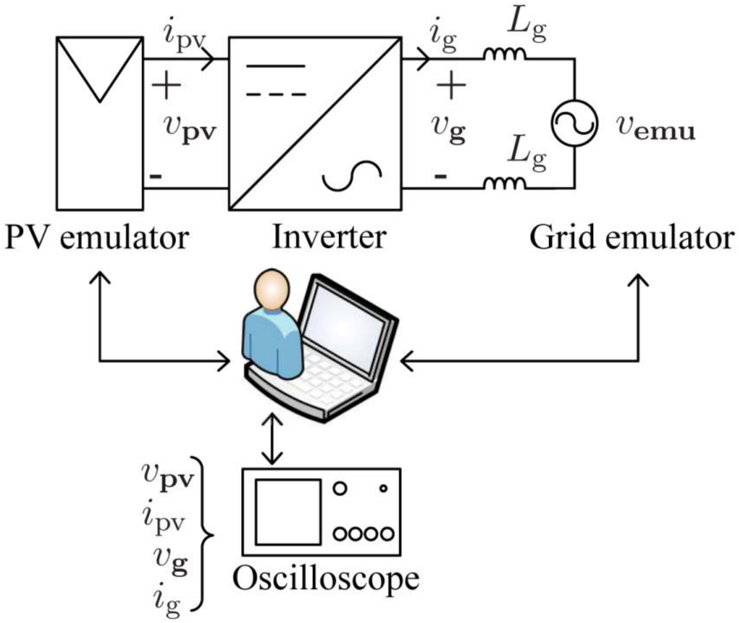
- If during the fault the impedance changes significantly then the required output voltages from the VSI have to change quickly to maintain the same output conditions.

PV Inverters Testing: Progress

How vulnerable are inverters to disconnecting or reducing their output power in response to grid disturbances?

This question is becoming of increasing importance.

Inverter bench testing setup



- PV emulator (*P* up to 16 kW) simulates characteristic of PV array, with non-linear power curve, solar irradiation can be varied.
- Grid emulator (*S* up to 50 kVA) emulates single phase grid voltage; provides ability to change frequency, phase angle, voltage amplitude.
- Data are sampled at 50 kHz on digital oscilloscope and post processed using MATLAB/SIMULINK.

Tests on PV inverters

Progress since project start

Tested 22 inverters

Tests executed reveal unexpected inverter behaviours with respect to:

- Changes in the grid voltage particularly short duration voltage sags
- Steps in the grid voltage-phase angle
- Changes in the grid frequency (RoCoF)

The aim is to observe inverter responses to grid disturbances which are not necessarily defined in the current version of the AS 4777.2:2015, in order to:

- Identify risk of inverters suddenly disconnecting or curtailing power, unexpectedly
- Provide inputs for discussion and improvement of AS 4777.2:2015

Main results from inverter bench testing

- Keypoint 1: Inverter disconnection due to fast voltage sag
  - » Approximately half of the inverters tested reduce power. When scaled, using CER figures, this set of inverters represents 140MW of inverter connected PV generation that may curtail generation. (There is likely to be many more inverters displaying this behaviour.)
- Keypoint 2: Inverter disconnection and curtailment due to grid phase angle jumps
  - » Equivalent to 175MW of inverter connected generation that is vulnerable to phase jumps <45^{o} in both directions.
- Keypoint 3: Inverter disconnection due to grid voltage rate of change of frequency
  - » Equivalent to 240MW to ROCOF > 1Hz/s. (From one make and model of inverter.)

http://pvinverters.ee.unsw.edu.au/

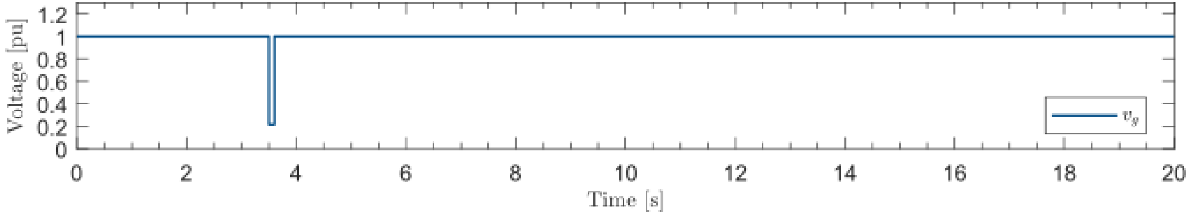
PV Inverters Testing: Results

Note from AS 4777.2:2015

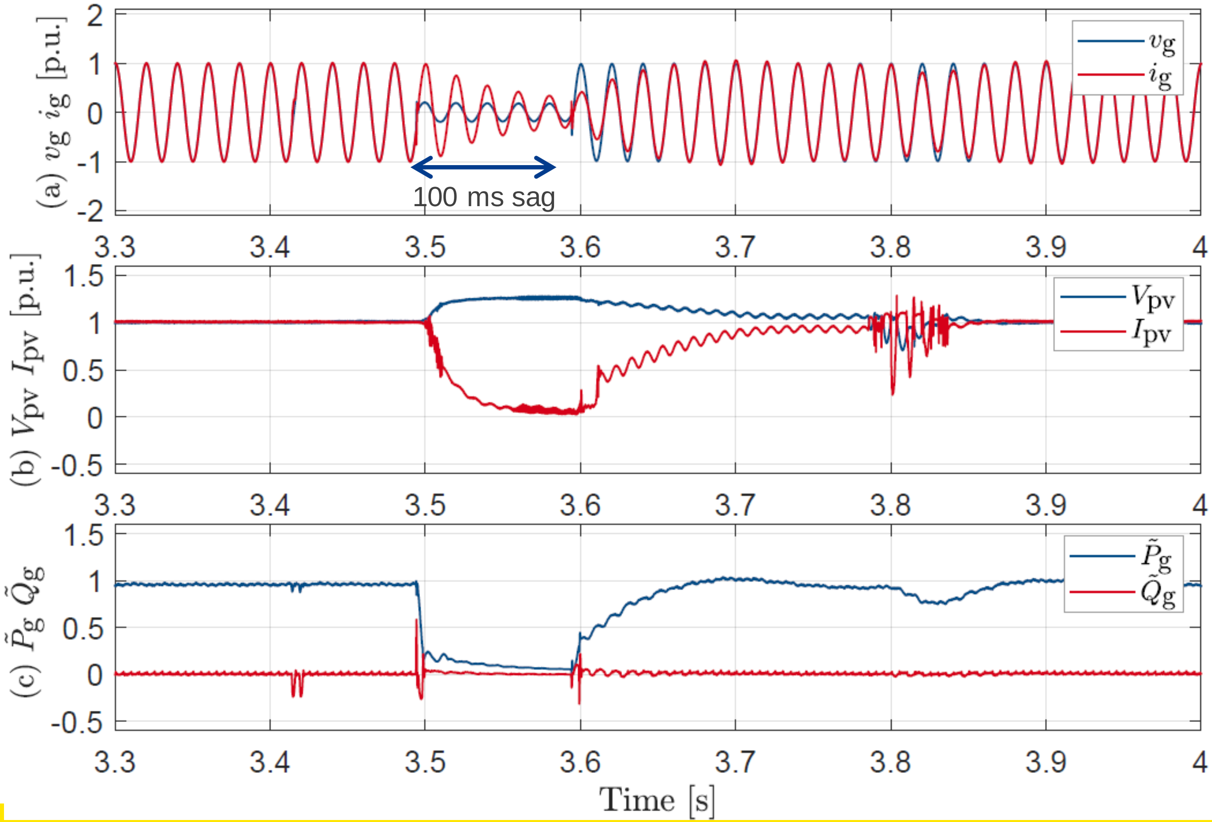
Table 13 in AS 4777.2 2015

Protective function	Protective function limit	Trip delay time	Maximum disconnection time
Undervoltage (V<)	180 V	1 s	2 s
Overvoltage 1 (V>)	260 V	1 s	2 s
Overvoltage 2 (V>>)	265 V	—	0.2 s
Under-frequency (F<)	47 Hz (Australia) 45 Hz (New Zealand)	1 s	2 s
Over-frequency (F>)	52 Hz	—	0.2 s

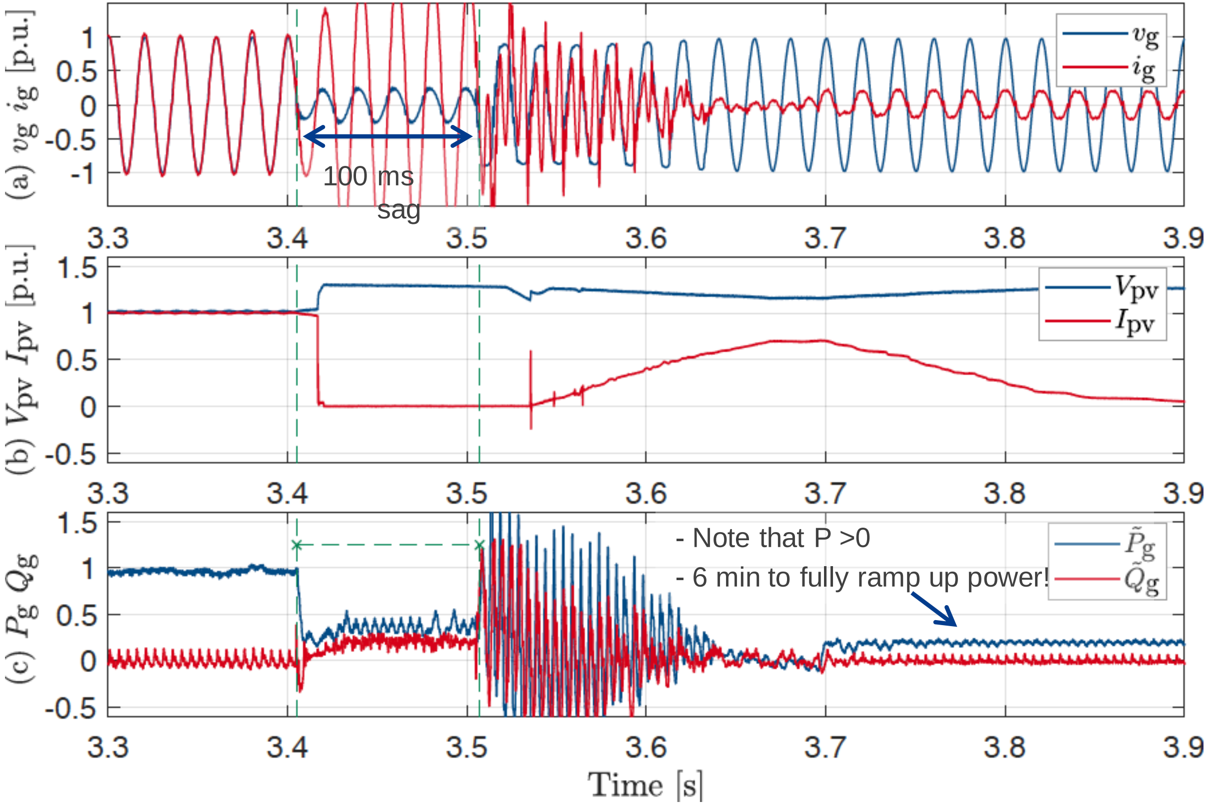
There is no guideline in the appendix of AS 4777.2: 2015 specifying tests procedures for an under-voltage that is cleared before the trip delay time is elapsed



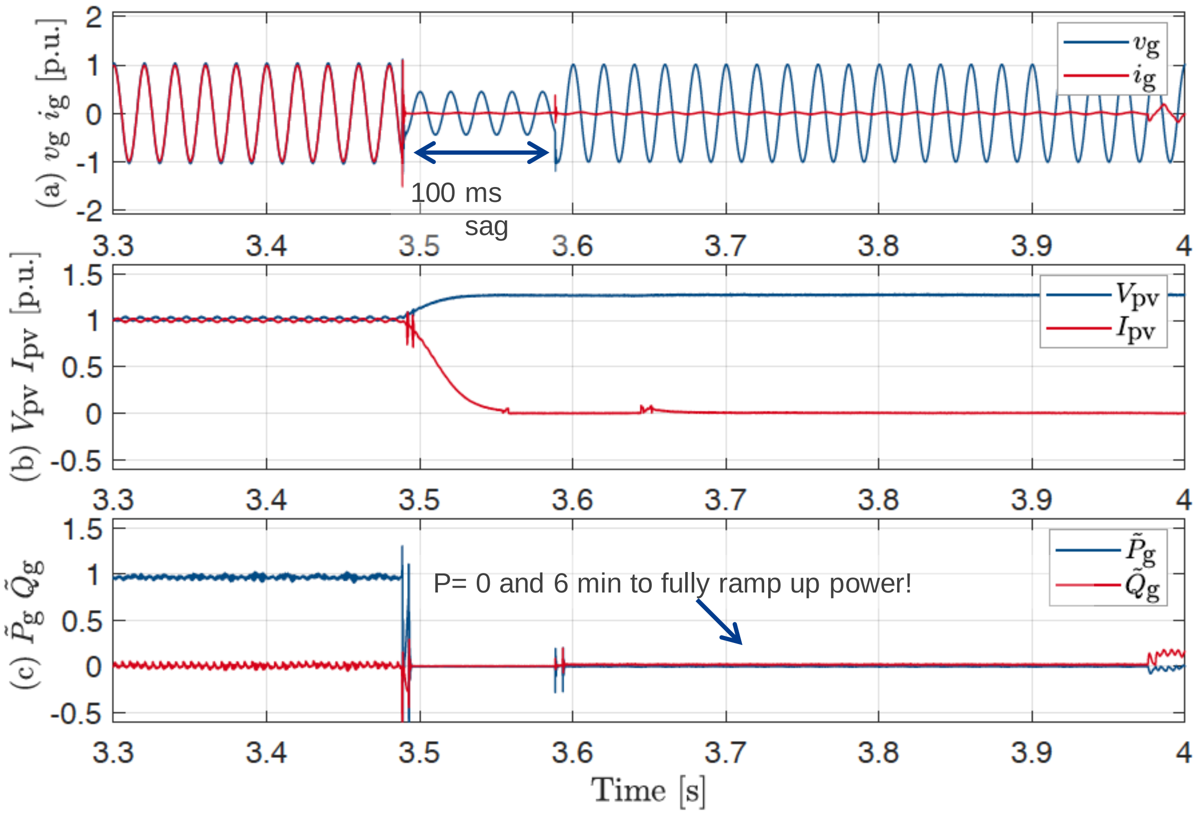
Fast voltage sag: 2015 inverter riding through



Keypoint 1: Fast voltage sag 2015 inverter curtailing



Keypoint 1: Fast voltage sag 2015 inverter curtailing



Keypoint 1: Fast voltage sag summary

	2005 inverters			2015 inverters		
	Inv.	Brand	Total	Inv.	Brand	Total
Nºof inv. riding through	14	E	1	1, 6, 7/3, 13/5/17	A/C/E/G	7
Nºof inv. disconnecting	8/15	A/F	2	11	F	1
Nºof inv. curtailing ($P > 0$)	-	-	-	2/16	B/D	2
Nºof inv. curtailing ($P = 0$)	-	-	-	4, 10, 12	D	3
Nºof inv. with other behavior	6/9	A/B	2	-	-	-
Total Nºof inv. tested			5			13

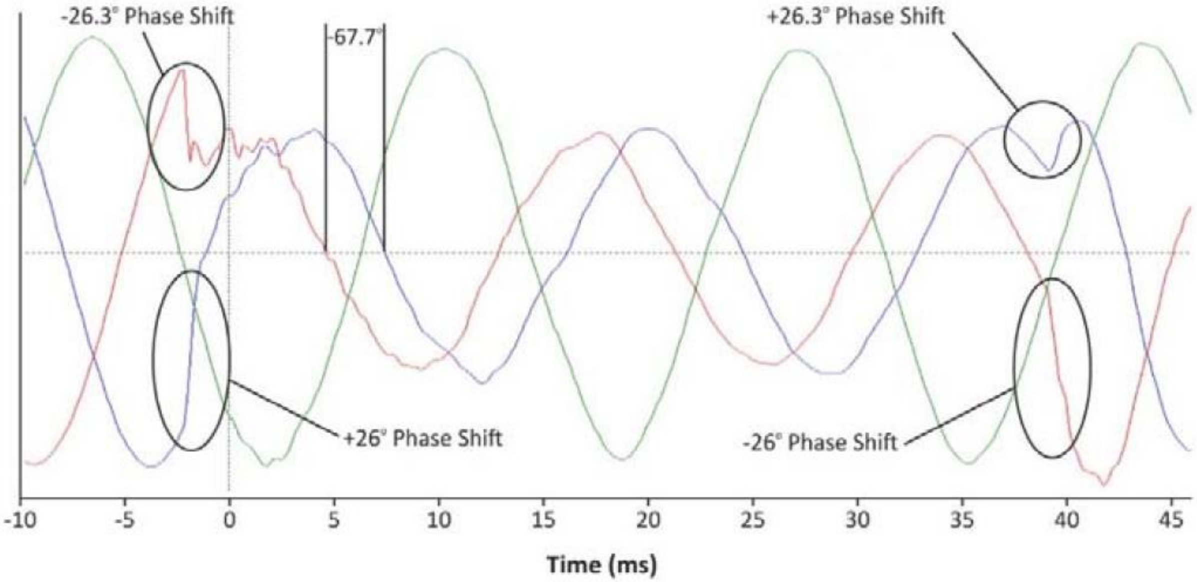
- Inverter disconnections and power curtailment on fast voltage sag is a risk for the power system (sudden loss of generation)
- 2015 inverters remain connected but half of the inverters tested curtail power (some to zero) and take 6 – 7 min to reach operation at pre-disturbance power levels
- From the inverters tested (which represents 10% of the 6.8GW of inverter connected systems <5kVA) the potential loss of power per state and in the NEM is:

	NSW	VIC	QLD	SA	WA	TAS	NT	NEM
MW	24.01	36.82	42.59	16.23	14.67	2.48	0.93	137.72
%	1.60	2.86	2.03	2.05	1.56	2.22	1.74	2.03

UNSW SYDNEY

Grid voltage phase angle jump

Example of phase angle jump on a 500 kV transmission line, due to a fault in Southern California (Blue Cut Fire event 2016) [2]

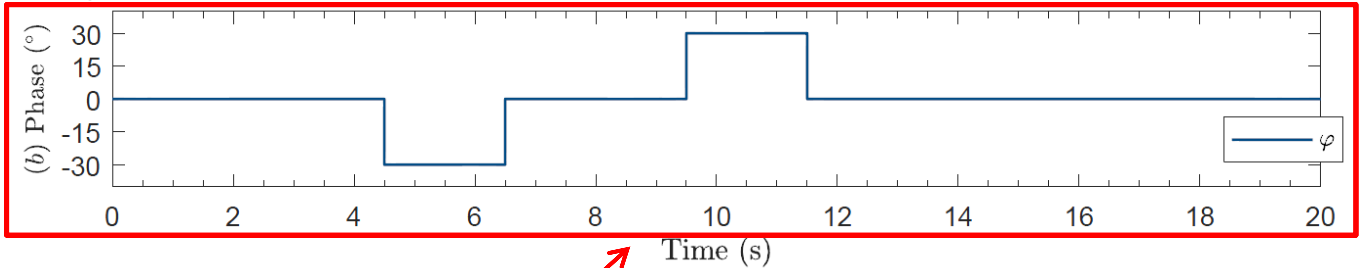


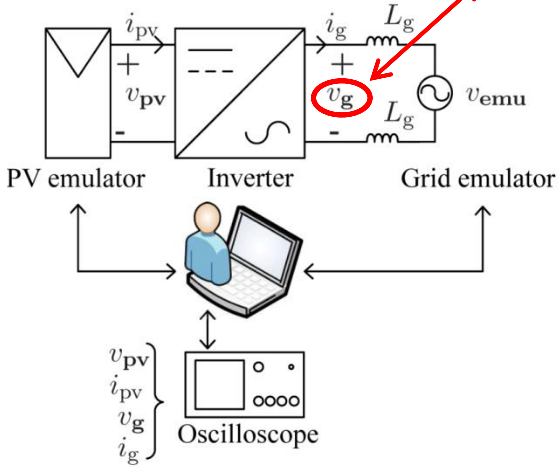
Phase jumps permeate through the network to the ac port of the inverter, challenging its normal operation

[2] IEEE PES, "Impact of IEEE 1547 Standard on Smart Inverters," Technical Report PES -R67, May 2018

Grid voltage phase angle jump test

Test profile:

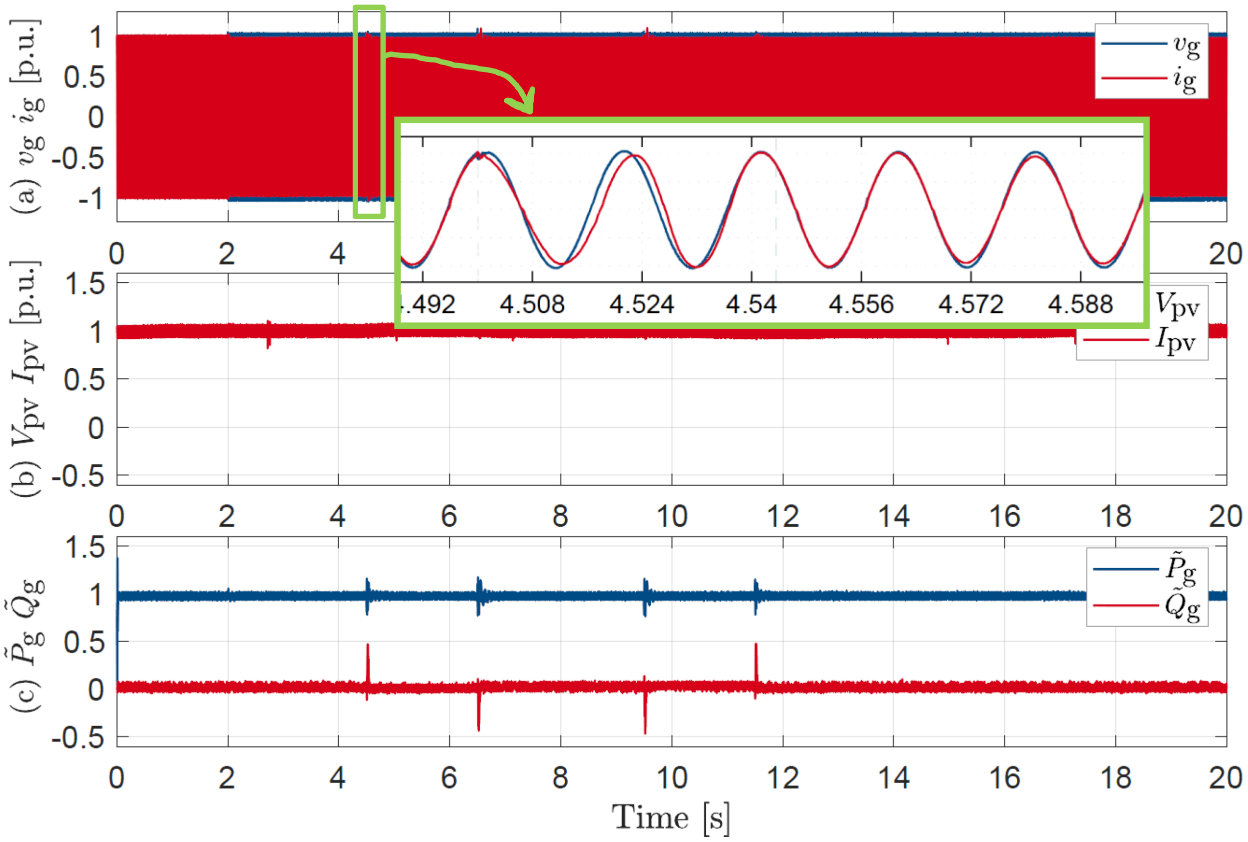




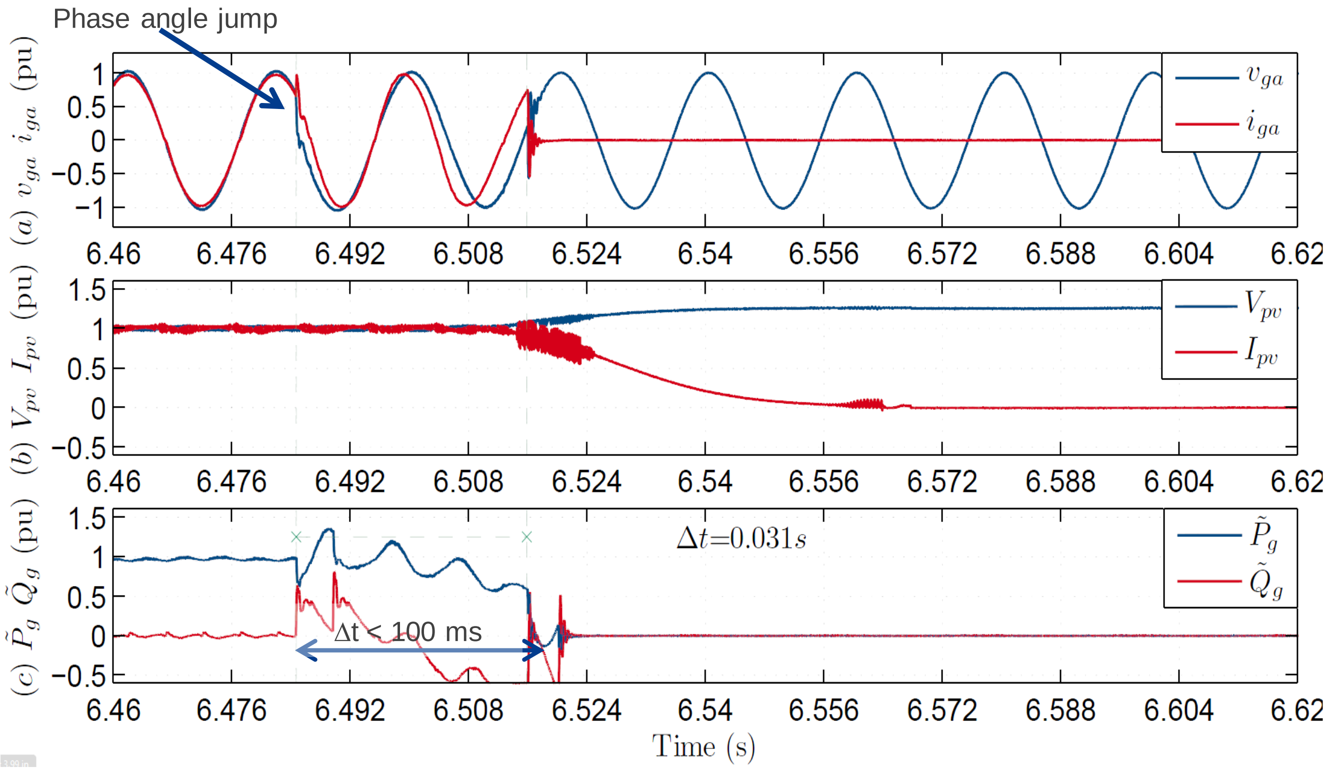
Possible inverter behaviour:

- **Ride through**
- **Power curtailing**
- **Disconnection**

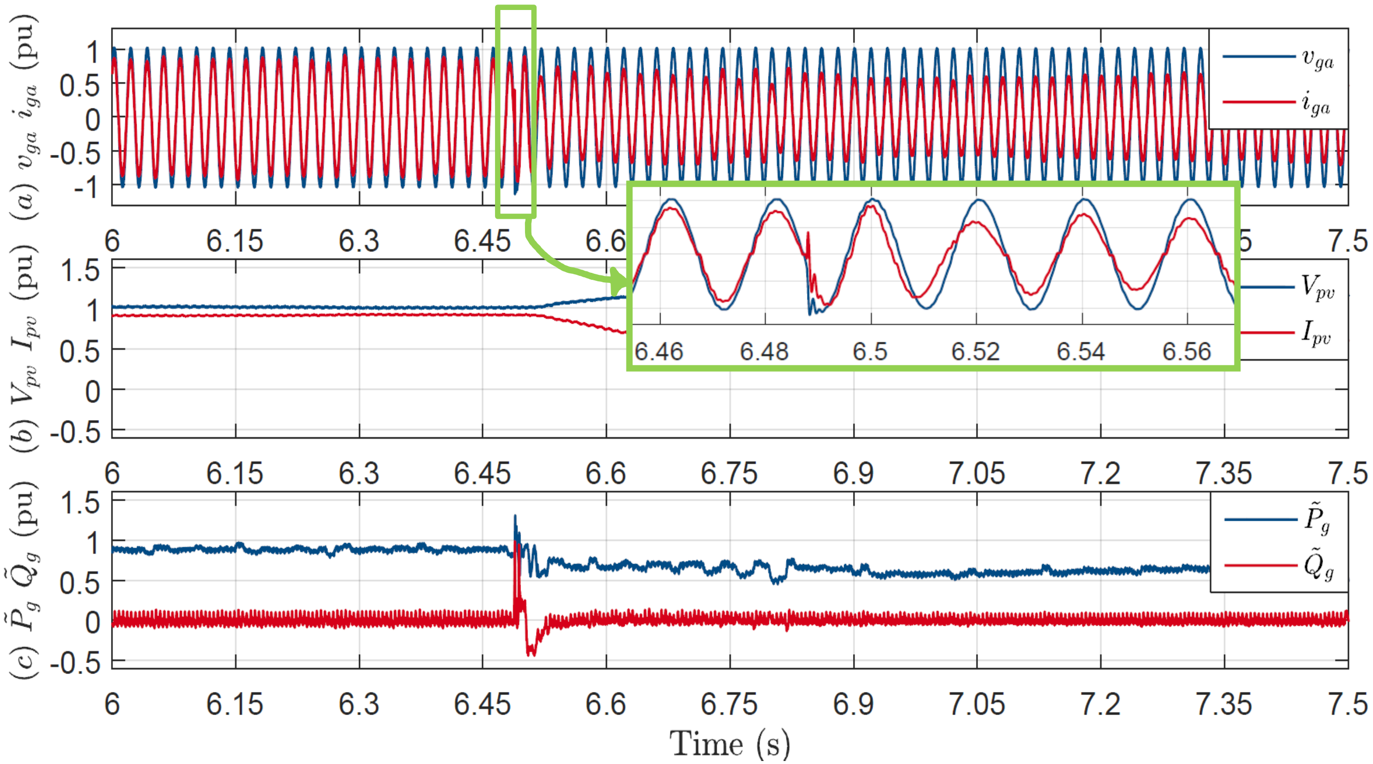
Phase jump 15°: 2015 inverter riding through



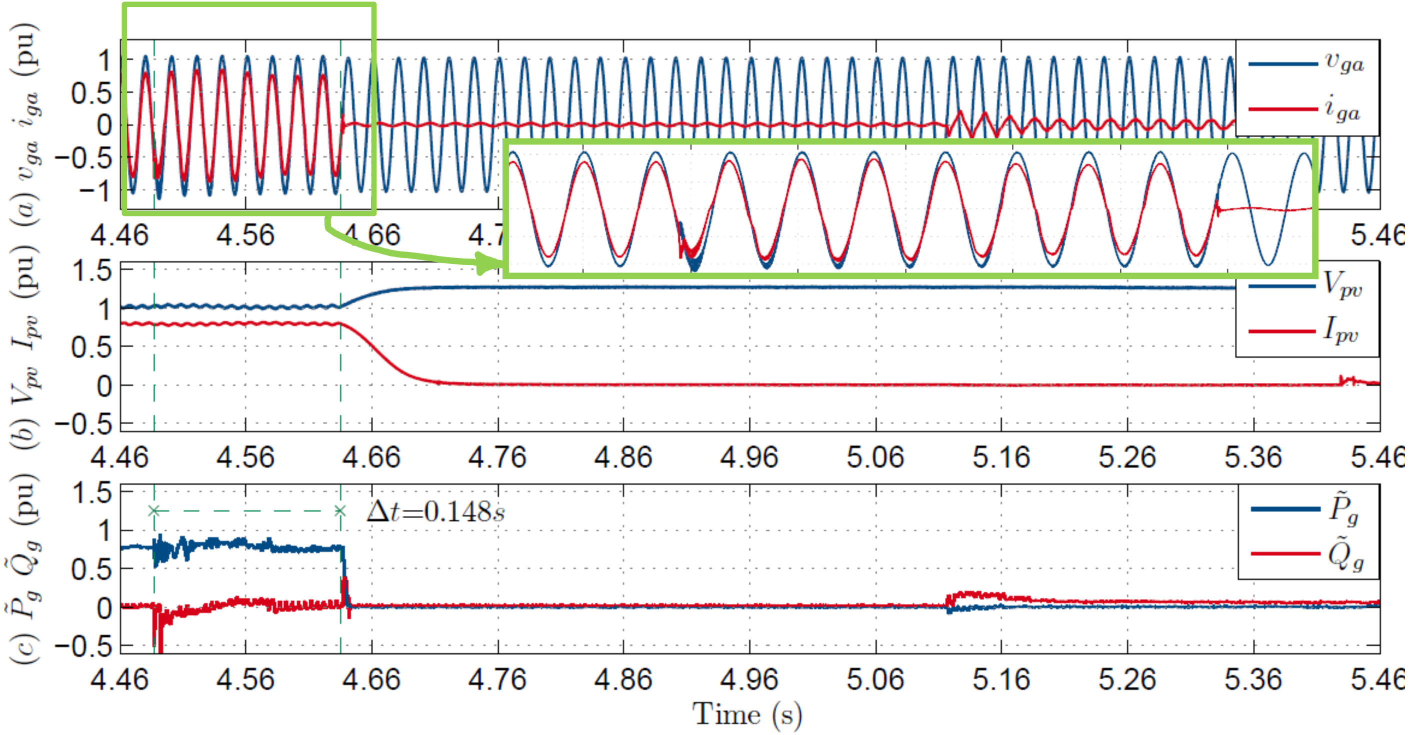
Keypoint 2: Phase jump 30°, same 2015 inverter disconnecting



Keypoint 2: Phase jump 30° 2015 inverter curtailing power



Keypoint 2: Phase jump 30° 2015 inverter reducing power to zero



Phase angle jump: results from inverter bench testing

2005 inverters

	Brand	15°	30°	45°	90°
Inv. 6	A	✓	✓	✓	✓
Inv. 8	A	✓	✓	✓	disc.
Inv. 9	B	✓	✓	disc.	disc.
Inv. 14	E	✓	✓	✓	disc.
Inv. 15	G	✓	disc.	disc.	disc.

disc.: disconnection
curtail: P curtailment
P = 0: P curtailment 0 W, but remains connected
✓: no change in operation

2015 inverters

	Brand	15°	30°	45°	90°
Inv. 1	A	✓	disc.	-	-
Inv. 2	B	disc.	curtail	disc.	disc.
Inv. 3	C	✓	✓	✓	✓
Inv. 4	D	P=0 (?)	curtail	P=0	P=0
Inv. 5	E	✓	✓	✓	✓
Inv. 6	A	✓	disc.	disc.	disc.
Inv. 7	A	✓	curtail	P=0	P=0
Inv. 10	D	P=0	P=0	P=0	P=0
Inv. 11	F	disc.	disc.	-	-
Inv. 12	D	P=0	P=0	P=0	P=0
Inv. 13	C	✓	✓	✓	✓
Inv. 16	D	✓	✓	✓	curtail
Inv. 17	G	✓	✓	✓	✓

Keypoint 2: Phase angle jump summary

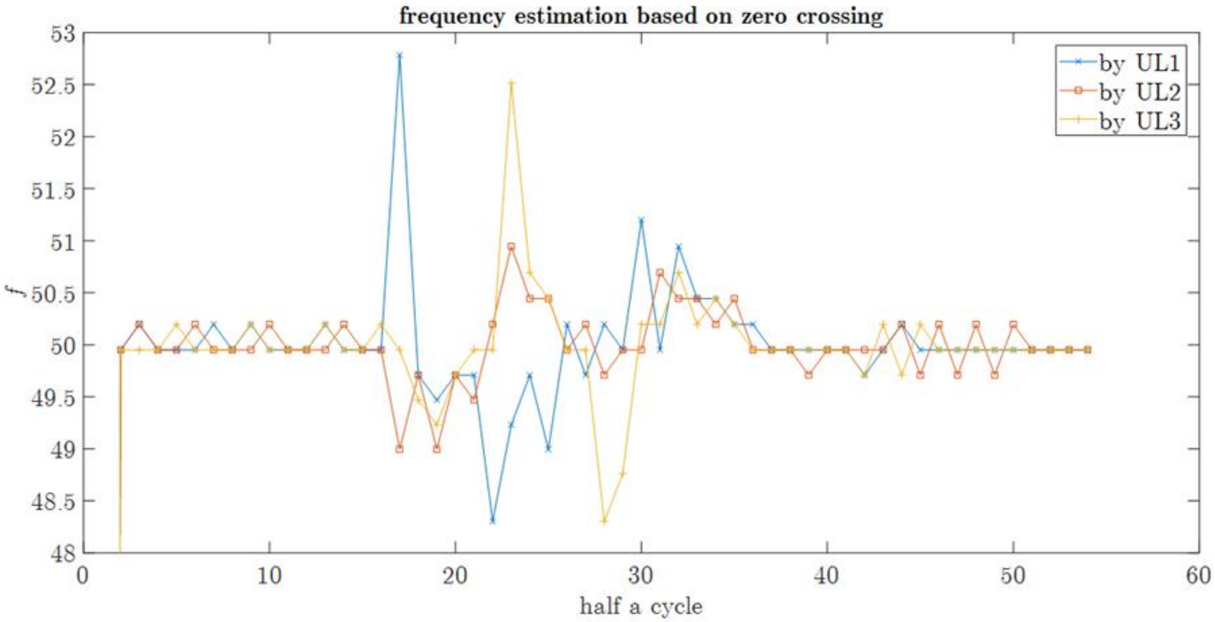
- The impact of phase angle jump disconnection is significant and increases with the value of angle jump

Not riding through PAJ		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
15°	MW	4.71	13.15	10.59	3.18	3.77	1.05	0.00	36.44
	%	0.31	1.02	0.51	0.40	0.40	0.94	0.00	0.54
30°	MW	20.44	32.27	34.33	11.39	11.43	1.87	0.88	112.61
	%	1.36	2.51	1.64	1.44	1.22	1.68	1.64	1.66
45°	MW	34.32	39.02	53.68	21.65	17.43	2.55	4.46	173.11
	%	2.29	3.04	2.56	2.73	1.85	2.29	8.32	2.55
90°	MW	42.57	50.44	144.59	28.17	22.75	6.16	4.59	299.28
	%	2.84	3.92	6.90	3.55	2.42	5.53	8.57	4.42

- In the US, IEEE 1547 2018 mandates phase angle jump ride through up to 60°

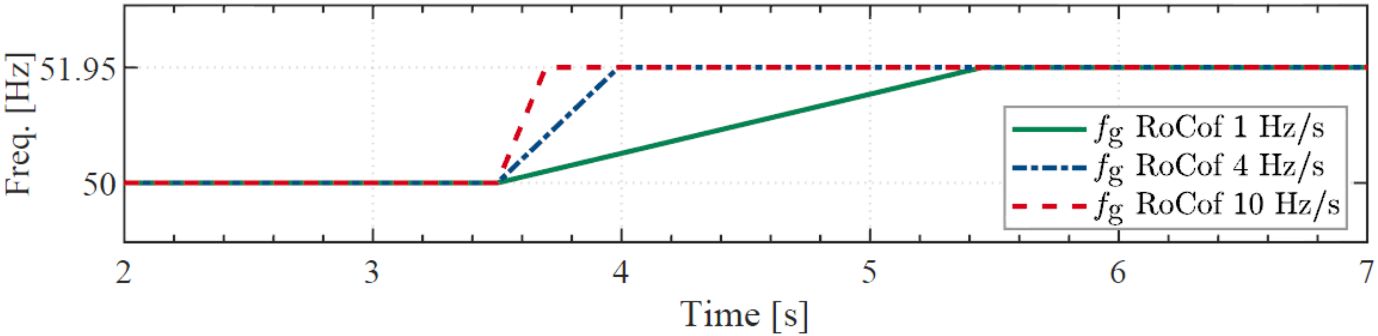
Further observations

Zero-crossing detection using 10,240Hz data

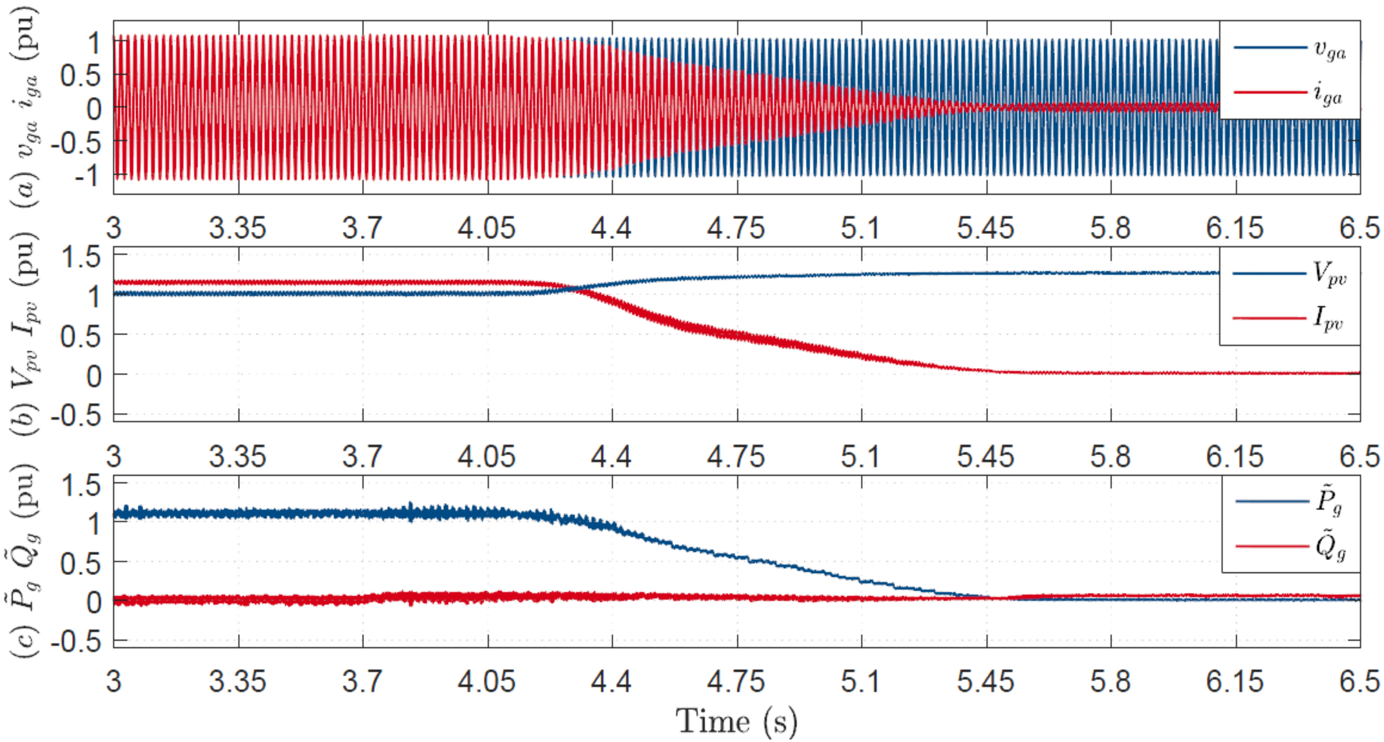


Keypoint 3: Rate of Change of Frequency (RoCoF) in the grid voltage

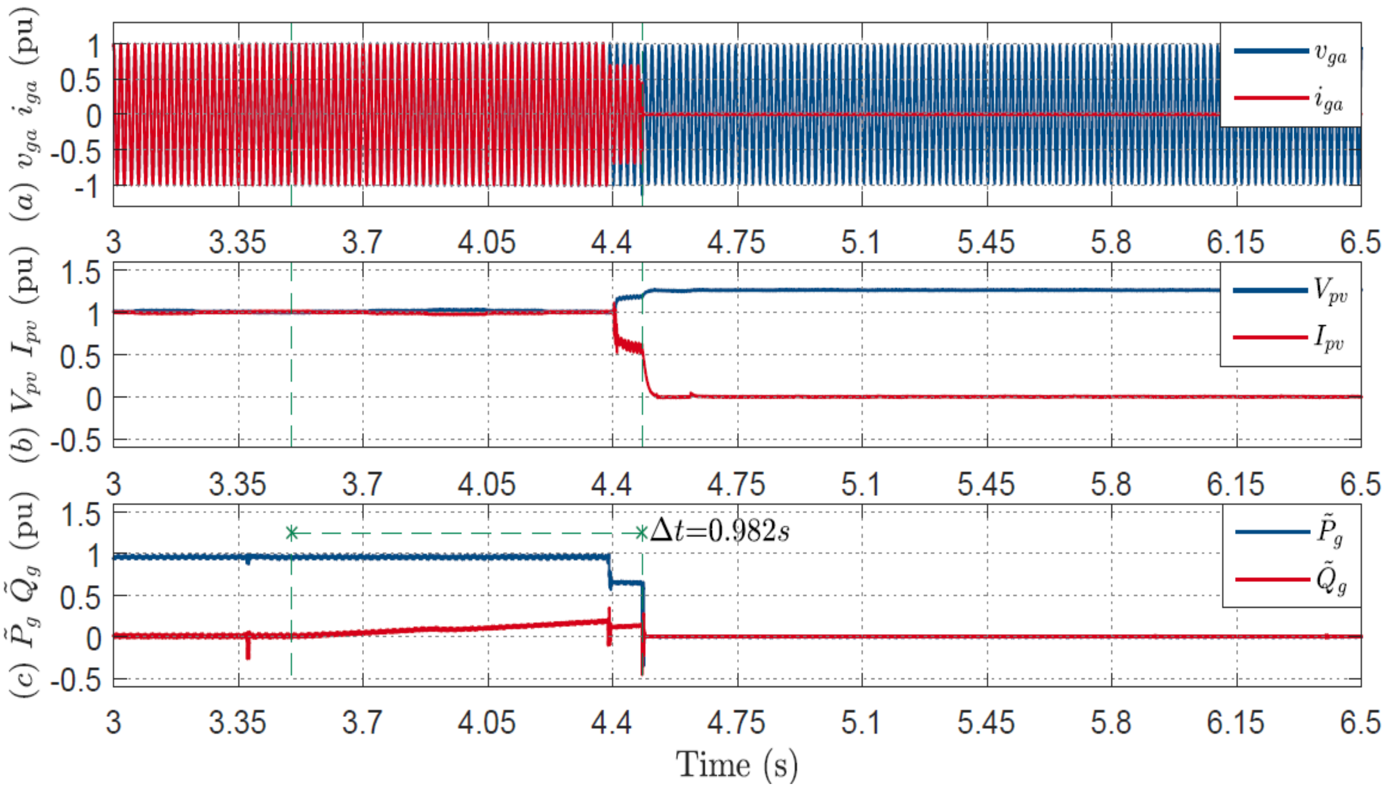
- Caused by a significant mismatch between generation and demand in the grid
- RoCoF profiles tested on PV inverters



1 Hz/s RoCoF: 2015 inverter riding through and displaying desired operation



Keypoint 3: 1 Hz/s RoCoF 2015 inverter disconnecting



Keypoint 3: RoCoF summary

- Few inverter models disconnect due to RoCoF

	2005 inverters			2015 inverters		
	Inv.	**Brand**	**Total**	**Inv.**	**Brand**	**Total**
N°of inv. disconnecting @ 10 Hz/s	-	-	-	4	D	1
N°of inv. disconnecting @ 1, 4, 10 Hz/s	14	E	1	5	E	1
N°of inv. riding through @ 1, 4, 10 Hz/s	all others		4	all others		11
Total N°of inv. tested			5			13

- However, due to the large numbers of this particular inverter connected to the grid, the risk of disconnecting on RoCoF in the NEM is significant

Not riding through 1 Hz/s RoCoF		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
Inv. 5 and Inv. 14	MW	21.54	21.05	164.93	12.08	8.61	5.15	0.43	233.78
	%	1.44	1.64	7.87	1.52	0.92	4.62	0.80	3.45

NEM Risks

Fast voltage sag

	NSW	VIC	QLD	SA	WA	TAS	NT	NEM
MW	24	37	43	16	15	2	1	138
%	2	3	2	2.0	2	2	2	2

	NSW	VIC	QLD	SA	WA	TAS	NT	NEM
MW	361	527	292	278	303	29	9	1549
%	24	41	14	35	32	26	16	23

Phase angle jump 45°

Not riding through PAJ		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
45°	MW	34	39	54	22	17	3	4	173
	%	2	3	3	3	2	2	8	3

Not riding through PAJ		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
45°	MW	515	558	368	371	360	30	42	1947
	%	34	43	18	47	38	27	78	29

ROCOF

Not riding through 1 Hz/s RoCoF		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
Inv. 5 & Inv. 14	MW	22	21	165	12	9	5	0	234
	%	1	2	8	2	1	5	1	3

Not riding through 1 Hz/s RoCoF		NSW	VIC	QLD	SA	WA	TAS	NT	NEM
Inv. 5 & Inv. 14	MW	323	301	1129	207	178	61	4	2629
	%	22	23	54	26	19	55	7	39

Power evaluated based on number of inverters tested installed in the field

Power estimated if all inverters installed in the field behave like the ones tested