Title:

Small-scale PV inverters - New equipment standards versus actual performance

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1. Introduction:

With significant reductions in the cost of solar panels and grid-tie inverters, small-scale grid-connected Photovoltaic (PV) installations are becoming more widespread both here in NZ and worldwide [1, 2]. There are some potential power quality and safety issues that could occur across distribution networks as the number of installations increases.

Power quality concerns include voltage rise caused by reverse current flow from Installation Control Point (ICP) to sub-station and harmonic distortion caused by the imperfect current waveforms produced by power electronic inverters, as well as other issues.

Safety concerns include the possibility of islanding, where the PV inverter continues to inject current into the network when other generators have tripped due to system voltage or frequency excursions beyond agreed limits. This results in sub-networks being livened even when isolated by a circuit-breaker.

AS/NZS 4777.2:2015 [3], published in October 2015, is the standard defining the requirements for inverters to be used with grid connection in Australia and New Zealand. It represents a substantial revision of the earlier AS 4777.2-2005 [4] and AS4777.3-2005 [5] which it will fully replace by October 2016. Among the major new additions are the provision of network voltage support modes, such as Volt-Watt and Volt-VAr, in which the real and reactive output power of the inverter can be programmed to vary with voltage, and demand response modes (DRM), in which the inverter responds to digital signals received from a demand response enabling device (DRED). Some of the requirements, such as active and passive anti-islanding and DRM 0 (operate disconnection device) are mandatory, while others, such as Volt-VAr response are voluntary, but highly desirable.

The present study investigates the performance of several single phase models available on the NZ market, ranging from 215W micro-inverters to 5kW string inverters, against all aspects of the new standard. It identifies that many models do not yet support some of the new requirements and indicates the relative ease with which various units can be commissioned, according to draft small-scale distributed generation (SSDG) connection guidelines being developed by the EPECentre under the GREEN Grid programme.

2. Test Procedure and Test Set-up:

In order to test the inverters repeatably to AS/NZS 4777.2:2015 (referred to as “the standard”), with a few additional tests suggested by GREEN Grid Network Analysis Group (NAG) members, it was necessary to develop a well-structured test procedure and data filing system. The test procedure represents the EPECentre’s interpretation of the standard, which, like most standards, includes some grey areas.

The test circuit is shown in Figure 1.

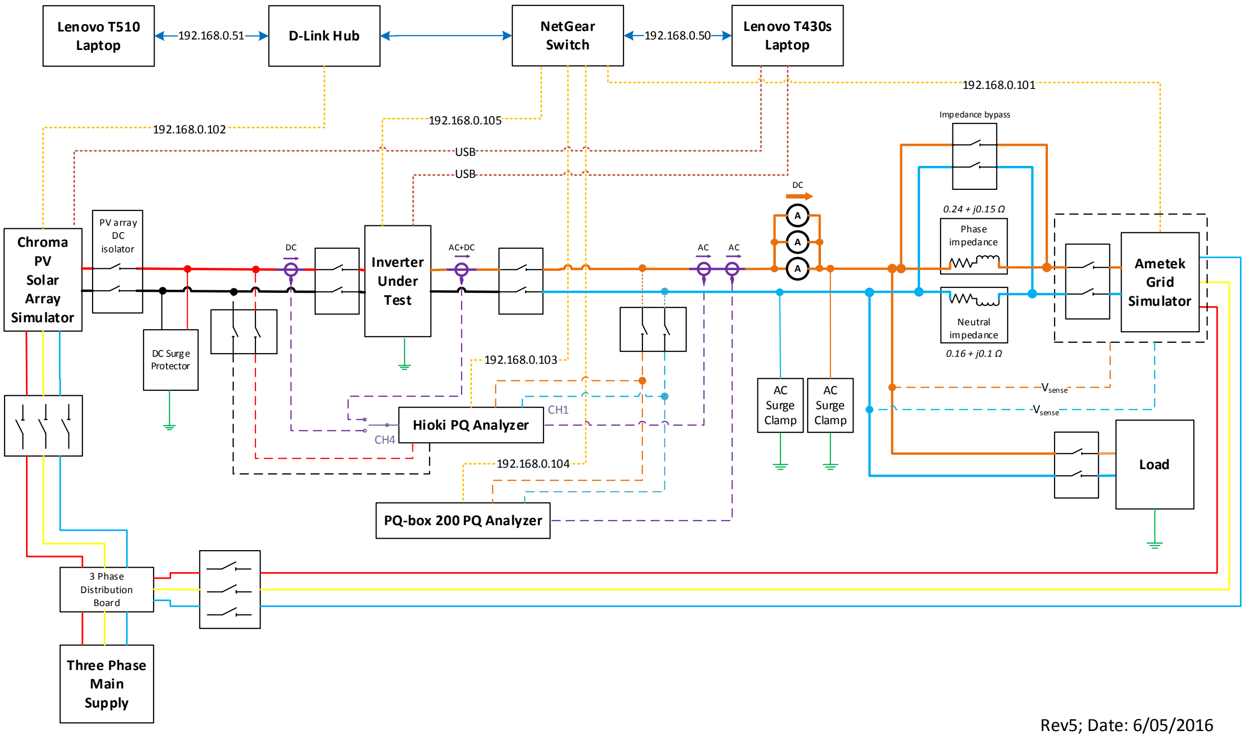

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Figure 1. Test Circuit Schematic

The test circuit is built around a 15kW DC PV Solar Array Simulator (SAS) (Chroma 62150H-600S) and a 45kVA AC Grid Simulator (GS) (Ametek MX45). The SAS can simulate any likely PV array up to 15kW, while the Grid simulator, when employed in single-phase mode, can source or sink up to 50Arms at 230V (0 – 300V range).

Two Power Quality Analyzers (PQAs) are employed to capture and record data during the tests (Hioki PW3198 and A-Eberle PQ-Box 200). The Hioki unit is used to measure the DC side parameters and also the inverter current on the AC side with DC-coupling. The PQ-Box is used only for AC-coupled AC side measurements, but has superior performance in measuring high order signal components.

All of the above devices are connected to an Ethernet Local Area Network (LAN), comprising an Ethernet switch and hub, to which two laptop computers are also attached. One computer typically controls the DC and AC Simulators, while the other interfaces with the PQAs and is used to store measured data.

DC ammeters are incorporated in the AC circuit to measure the DC component of the inverter output. This is because it is very difficult to obtain satisfactory performance from a Hall-effect AC/DC current probe when attempting to read a few milliamps of DC on top of several amps of AC.

The GS has an extremely low output impedance (approximately 1mΩ in series with 15uH). However (in its Appendix A) the standard specifies well-defined separate phase and neutral source impedances. For inverters up to 5kVA these are 0.24Ω + j0.15Ω and 0.16Ω + j0.10Ω respectively (at 50Hz). These were achieved by winding suitable air-cored inductors, placing these in series with resistive shunts and measuring the 50Hz impedance with an HP4192A impedance analyzer.

The effect of this added loop impedance on the inverter terminal voltage is shown diagrammatically in Figure 2.

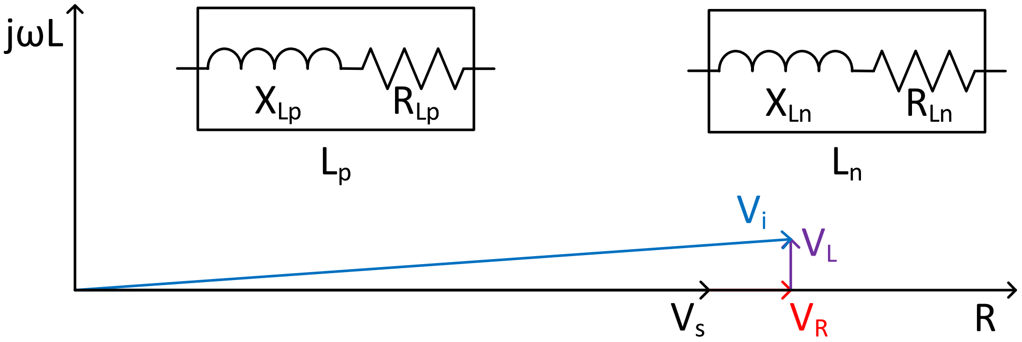

Figure 2. Phase and Neutral source impedances and their effect on inverter voltage

The phasor diagram shows the effect of the loop impedance on the inverter voltage, V_i, which is the phasor sum of the grid supply voltage, V_s, and the resistive and inductive voltage rises across the source impedance resistive (V_R) and reactive (V_L) components.

e.g. 5kVA inverter supplying 21.7A (i.e. maximum allowable for single phase):

$V_s =$ 230V
$V_R = 21.7 \text{ x } 0.4 =$ 8.68V
$V_L = 21.7 \text{ x } 100\pi j \text{ x } 800 \text{ x } 10\text{-}6 =$ j5.45V
$\mathbf{V_i} = \sqrt{}(238.68^2 + 5.45^2) =$ **238.74V**

Since this voltage rise interferes with carrying out some of the tests in the standard (e.g. overvoltage limit testing), the test circuit incorporates a switch for bypassing the source impedances, as well as using remote voltage sensing on the GS to hold the inverter terminals at grid voltage. However, wherever possible the source impedances have been left in circuit.

3. Classification and selection of inverters:

The inverters were classified according to their power rating, as shown in Table 1.

At least one popular inverter of each of the four classifications was chosen for testing, based on the small-scale PV connections lists supplied by four lines companies around New Zealand.

Table 1. Classification of small-scale single-phase inverters

Type	**Code**	**Rated AC Power, VA**
1: Micro-inverter	A215	215
1: Micro-inverter	B500	500
2: 2kVA string inverter	C2000	1950
2: 2kVA string inverter	D2000	2000
2: 2kVA string inverter	E2000	2000
2: 2kVA string inverter	F2000	2000
3: 3kVA string inverter	C3000	3000
3: 3kVA string inverter	G3000	3000
3: 3kVA string inverter	H3000	3000
4: 4-5kVA string inverter	F4000	4000
4: 4-5kVA string inverter	F5000	5000

4. The tests:

The tests carried out cover four overall areas[1]:

i. Basic AC side performance, comprising:
    a. Displacement Power Factor (DPF) measurement
    b. Harmonic measurement with pure sine and flat-topped 4% V_{THD} supply
    c. Ripple voltage injection susceptibility
    d. Incremental impedance with increased 5th & 7th voltage harmonic
    e. DC injection
    f. Flicker
    g. Transient Voltage Limit

ii. Operational Modes – Demand Response Modes (DRM), comprising:
    a. DRM0
    b. DRM1-8

iii. Power Quality (PQ) Response Modes, comprising:
    a. Volt Response Modes (Volt-Watt & Volt-VAr)
    b. Fixed cosφ Mode and Fixed Reactive Power (VAr) Mode
    c. Cosφ (P) Mode and soft ramp-up and ramp-down

iv. Protective Functions, comprising:
    a. Active anti-islanding with varying local load conditions
    b. Passive anti-islanding with varying grid voltage and frequency
    c. Grid under-frequency transient ride-through
    d. Sustained operation limits for grid voltage and frequency

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[1] Underlined tests are additional NAG-suggested tests. Tests in italics have not been conducted yet.

5. A selection of results:

i. Basic Performance

All inverters tested satisfy the standard's requirement of DPF being between 0.95 lead (defined here as positive) and 0.95 lag (defined here as negative) between 25 and 100% rated power. A selection of results is shown in Table 2. (With the SAS the A215 does not achieve continuous steady-state operation with lower power levels, but "hunts" around).

Table 2. DPF at 15, 25, 50 and 100% power, 230V pure sine supply for various inverters

Inverter Code	**A215**	**C2000**	**F2000**	**C3000**	**F5000**
15% Power	Unstable	0.996	0.940	0.999	0.998
25% Power	Unstable	0.999	0.980	1.000	1.000
50% Power	0.992	1.000	0.999	1.000	1.000
100% Power	0.999	1.000	1.000	-1.000	0.999

With a substantially undistorted supply voltage, some inverters easily meet the harmonic current requirements of the standard at both 50% and 100% of rated power. Figure 3 shows the spectra of four inverters, from two manufacturers, including those with the lowest (C3000, 0.92%) and highest (F2000, 4.82%) measured current THD_F, at full rated power. The C3000 is well within the standard's limits, while the F2000 is marginal for 3rd, 17th, 19th & 21st.

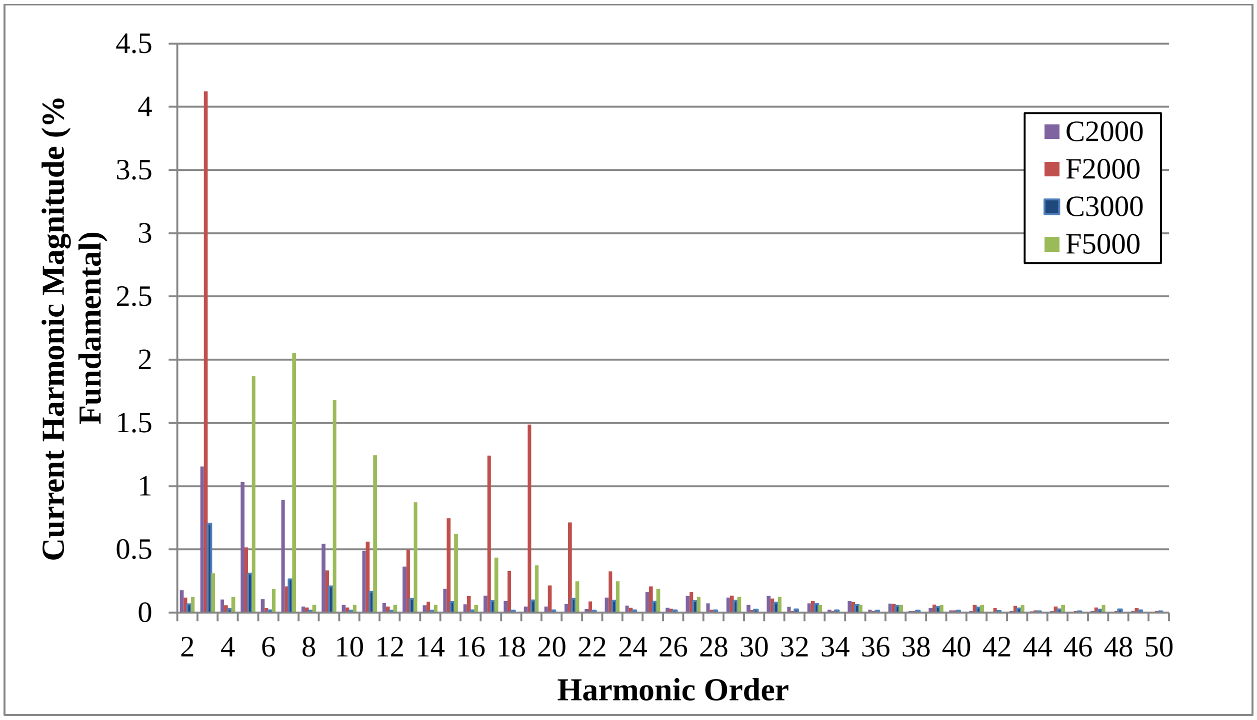

Figure 3. Current harmonic spectra at full power, 230V pure sine supply

When some voltage distortion exists on the supply the current harmonics can be substantially higher, as shown in Figure 4, in which the grid simulator produces a flat-topped voltage waveform with 4% THD_F.

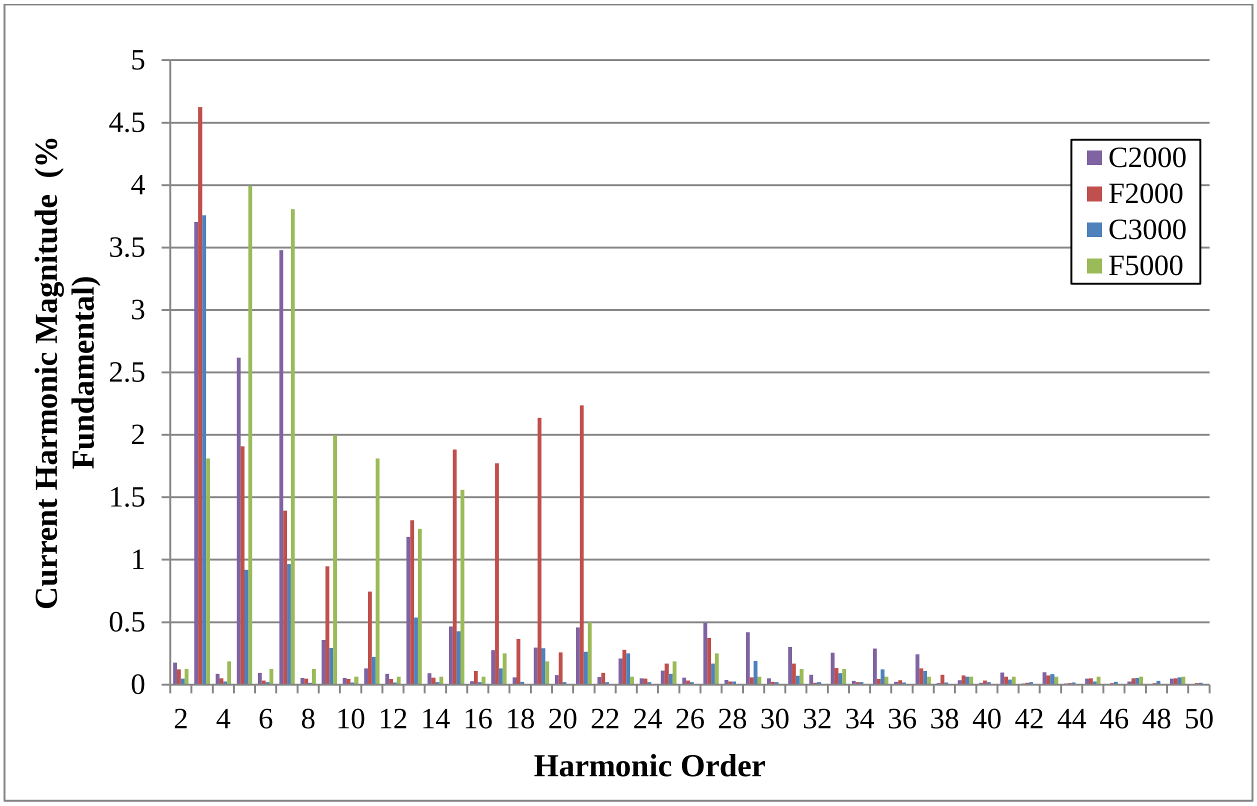

Figure 4. Current harmonic spectra at full power, 230V flat-topped 4% V_{THD} supply

All the inverters were tested with added voltage ripple (1.8% of fundamental at the grid simulator) at the popular ripple control frequencies of 283 and 317Hz. The relevant local inverter voltage inter-harmonic was measured and it was found in all cases that there was no significant amplification or attenuation of the ripple signal (varying between 1.72% and 1.85% at the inverter terminals).

However when some higher frequency ripple signals were imposed, some significant interactions were observed. For instance, with a ripple frequency of 1050Hz, as employed by several distribution companies, significant 21st harmonic current flows causing significant increase in ripple voltage amplitude at the inverter terminals. In the case of inverter C3000, a very large 1050Hz current flows more-or-less doubling the grid-imposed ripple voltage, as shown in Figure 5.

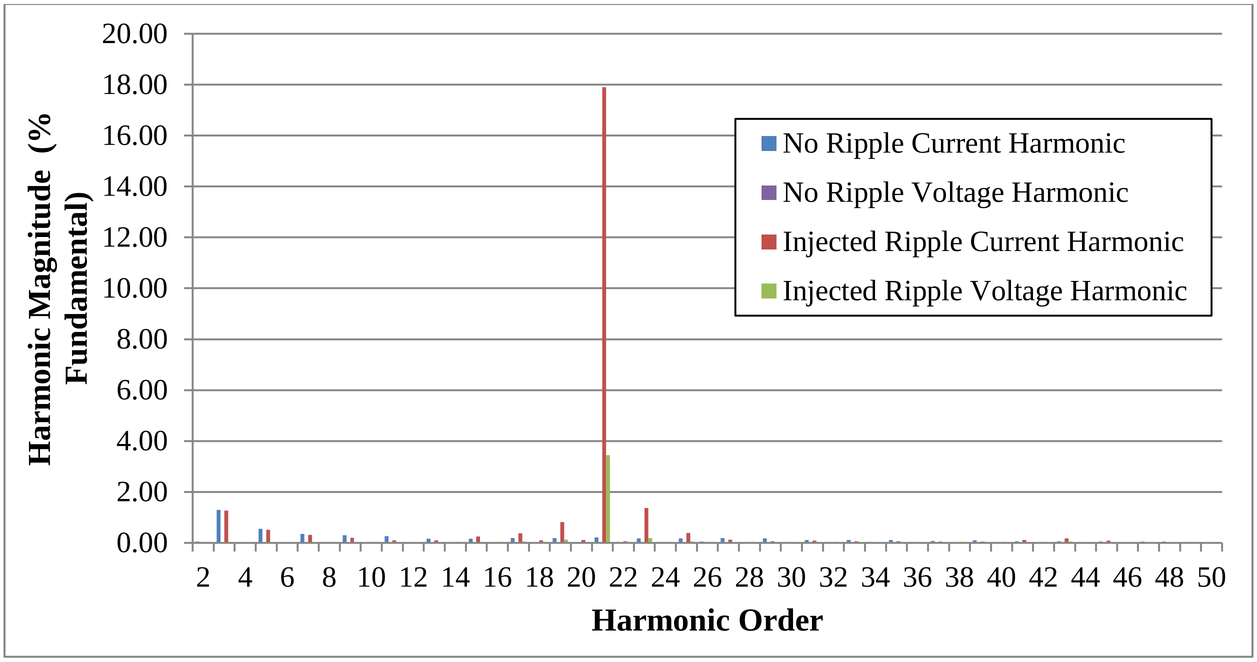

Figure 5. Current and voltage harmonic magnitudes, at C3000 inverter terminals, at 50% rated power, with and without 1050Hz ripple injection of 1.8% of fundamental at grid terminals.

ii. Demand Response Modes

No demand response capability is fitted to any of the inverters tested so far. From October 2016 DRM0 (remote shut-down/start-up) will be mandatory. DRM1-8 (remote control of level of real power generation and reactive power sourcing and sinking) will be desirable, but not mandatory.

It should be noted that no DRMs were specified in the previous version of the standard (before October 2015), so these findings are not surprising.

iii. PQ Response Modes

Provision of these modes is not mandatory in the standard [3] and they were not even mentioned in the previous standard [4]. However, if they are provided they must meet the requirements of the standard.

It was found that most of the inverters rated at 3kVA and above allowed implementation of at least some of the specified modes. The most desirable of these modes for the NZ system have been identified as Volt-VAr and Volt-Watt respectively, with both ideally being implemented according to Figure 6 [6]. If only one mode can be implemented, it is suggested to implement the Volt-VAr response in which the inverter sources reactive power to the network when the voltage is low, sinks reactive power when the voltage is high and operates at unity DPF when voltage is close to nominal.

Unit C3000, for example, has been found to be very flexible in its installer-configurable settings and can provide the response of Fig. 6 almost exactly. However a word of caution is due here:

The configuration is quite complex and requires an intelligent and well-trained installer. Since different inverter manufacturers employ different conventions for specifying leading and lagging power factors, it would be very easy to inadvertently set the Volt-VAr response backwards, thus providing network voltage degradation rather than support. In a laboratory setting it is possible to control the grid simulator voltage to ensure the response is correct, a luxury that is not available to the installer.

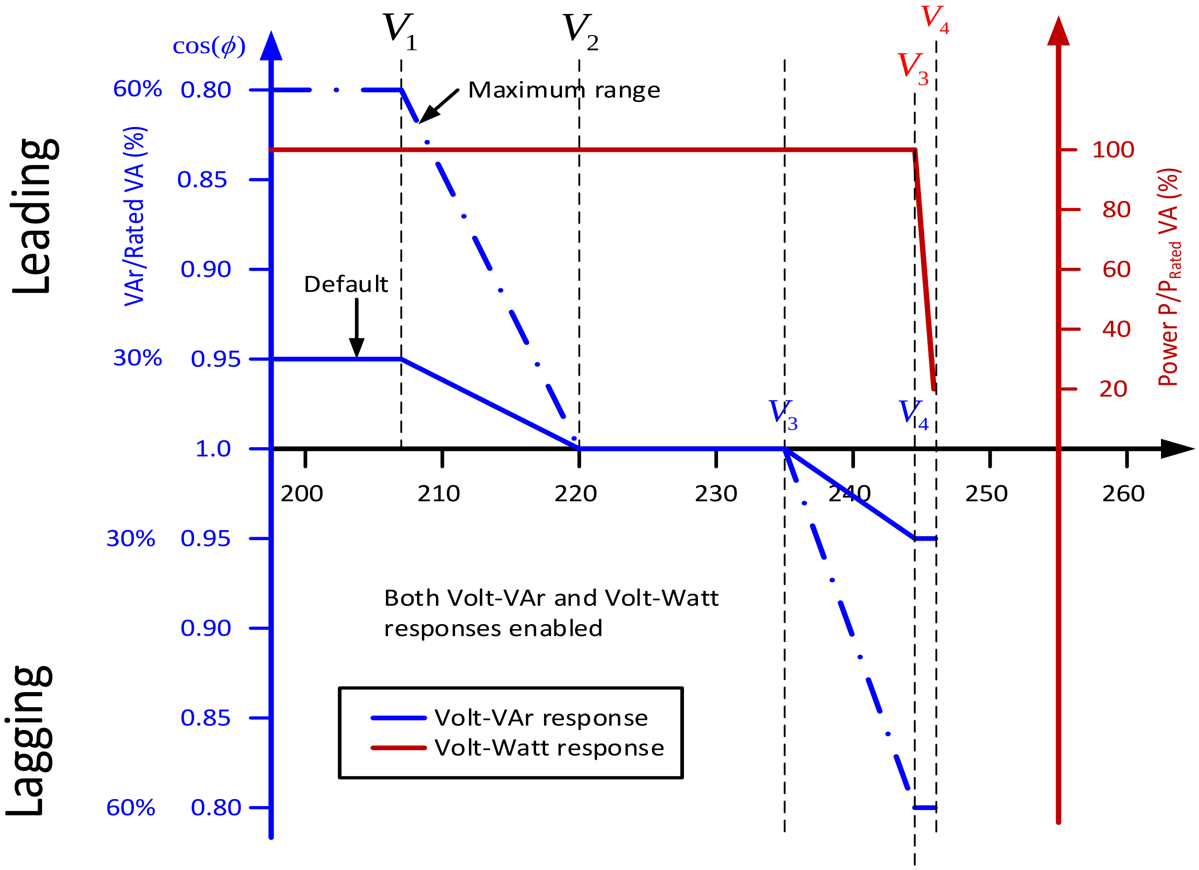

Figure 6. Control Response for New Zealand (N.R. Watson)

iv. Protective Functions

Disconnection of the inverter when the system voltage or frequency goes outside acceptable limits, or if the feeder is disconnected by the opening of a system breaker, is vital to ensure safety. Active and passive anti-islanding performance for all inverters tested to date has been in conformance with the standard, although some inverters have been supplied with incorrect voltage or frequency thresholds for the NZ requirements; thus the installer must check these and alter them as necessary. An additional test, suggested by a Transpower engineer [7], to investigate whether the inverters would ride through the standard under-frequency event shown in Figure 7, was conducted. All the inverters except C2000 successfully rode through the transient. This is because the frequency thresholds are incorrectly set on the C2000 unit and the unit was supplied without the means (optional Bluetooth module) to alter the settings.

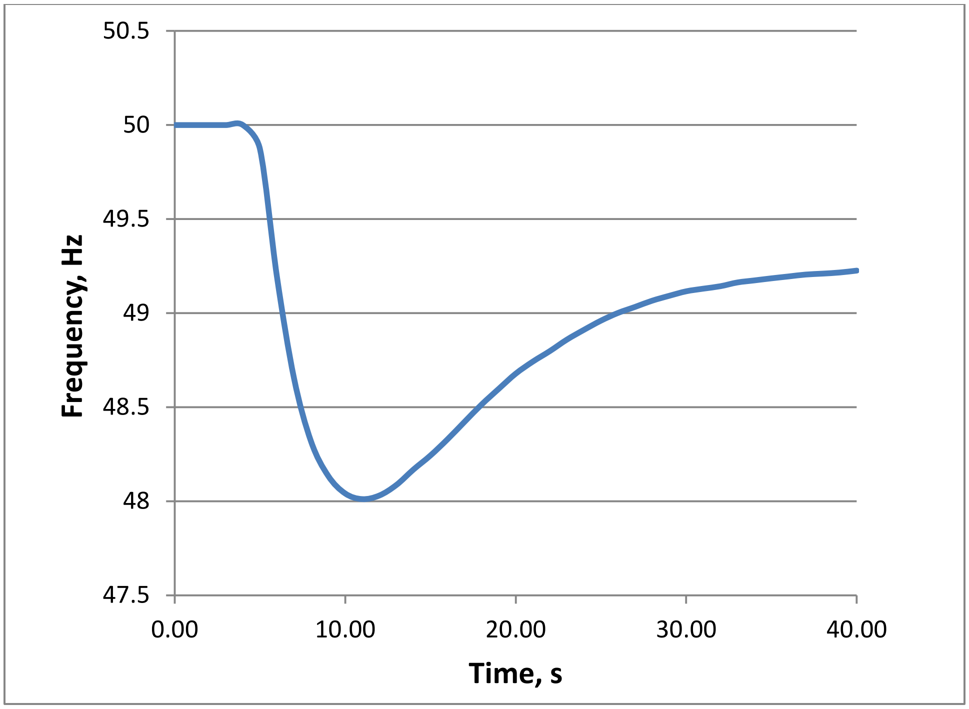

Figure 7. Actual under-frequency transient (according to Transpower), generated by Ametek MX-45, measured by A-Eberle PQ200. (Frequency follows an exponential function from t=5s to t=50s, then returns linearly to 50Hz from t=50s to t=795s).

6. Discussion and Conclusions:

There is a large variety of single phase inverters available on the NZ market, ranging from 200VA micro-inverters to 5kVA string inverters. Few of these are yet fully compliant with the standard, due primarily to the absence of DRM capabilities, but this should change by October 2016.

In general all the protective function requirements are met by all the inverters tested so far, although default voltage and frequency settings may be incorrect and need to be confirmed by the installer.

Some of the units tested are able to fully implement the voltage support response recommended by the GREEN Grid programme [6]; however this requires considerable ability on the part of the installer. It is hoped that new or updated inverter models fully compliant with the standard will be easier to set up (e.g. by having a pre-installed AS/NZS4777.2:2015 NZ parameters option).

Some models have current harmonics that fall well inside the standard limits, while others are quite marginal. In particular, the requirement to have 7th harmonic <= 4% of half load fundamental current and the additional NZ requirement to have 7th harmonic <= 2% of full load fundamental current [8] is barely met in some cases. The DC injection limits were met by all inverters, albeit by a very narrow margin in some cases.

One area of concern is the effect of certain ripple control frequencies on the current harmonics of some models and the resultant change in inverter terminal ripple voltage amplitude. In certain cases this could lead to failure of ripple signals to activate controlled load relays correctly.

7. Acknowledgements:

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8. References:

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[5] AS 4777.3-2005: 'Grid connection of energy systems via inverters, Part 3: Grid protection requirements' (Standards Australia)

[6] EPECentre draught document, 'Guideline for the connection of small-scale inverter based distributed generation', GREEN Grid Programme, 2016

[7] Transpower NZ Ltd, 'Companion Guide for Testing of Assets', 2012

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