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Transformerless Solar PV Inverters Test Report

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1.0 INTRODUCTION

This report will provide the performance of five (5) transformerless solar PV inverters, from three different manufacturers, during voltage and frequency events typically found on the grid. Grid Advancement had previously tested various transformer-based residential inverters, and used the same test methodology to evaluate the transformerless inverters. The test results will be used to support SCE Field Engineering's assessment of residential transformerless inverter characteristics and uncover any potential negative impacts. As with the previous testing, the data will also be used to:

- Influence the proper standards revisions, including UL1741 and IEEE 1547, in order to ensure that these are grid friendly devices
- Develop and validate solar PV models for distribution system impact studies
- Review and revise if necessary SCE internal standards (interconnection or working practices)

2.0 TEST SETUP

Five transformerless inverters were installed as illustrated in Figure 2.0.1 and then tested to assess their performance during typical voltage and frequency deviations. Each inverter is supplied by a unique I-V curve from the independent photovoltaic (PV) simulator output channels.

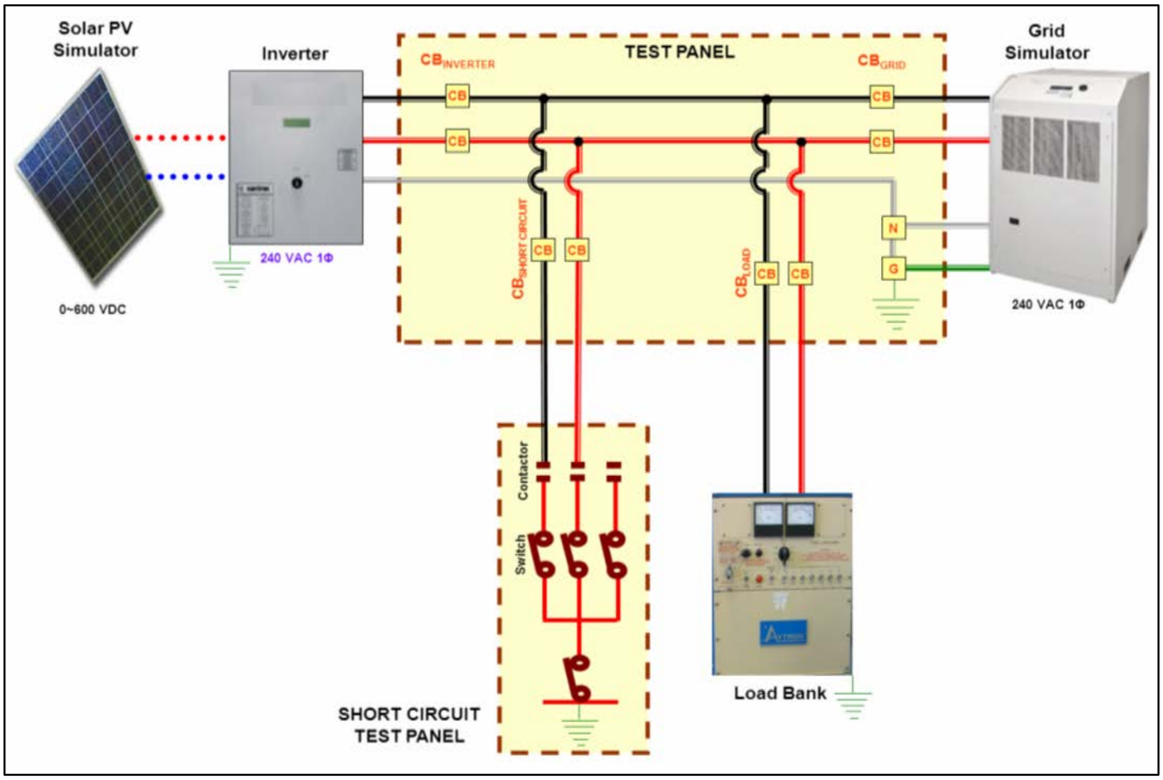

Figure 2.0.1 Paralleled Residential Inverters Test Setup

3.0 EQUIPMENT UNDER TEST

The five transformerless solar PV inverters tested are from three different manufacturers. Engineers at Southern California Edison's (SCE) DER Laboratory tested these inverters individually. Table 3.0.1 lists the specifications for all the tested residential inverters with those transformerless in blue.

Inverter #	Manuf.	Ratings				Comments
		V_{AC}	Φ	P_{GEN} (KW)	V_{DC}	
1	1	240	1	4.0	235 - 550	Transformer-based
2	1	240	1	5.0	235 - 550	Transformer-based
3	2	240	1	5.1	150 - 400	Transformer-based
4	3	240	1	3.9	200 - 550	Transformer-based
5	3	240	1	5.3	200 - 550	Transformer-based
6	4	240	1	5.0	250 - 600	Transformer-based
7	4	240	1	7.0	250 - 600	Transformer-based
8	2	240	1	3.8	230 - 500	Transformer-based
10	6	240	1	1.5	125 - 400	Transformer-based
11	2	240	1	3.0	150 - 400	Transformer-based
12	4	240	1	4.0	250 - 600	Transformer-based
13	6	240	1	3.5	200 - 510	Transformer-based
14	6	240	1	5.0	200 - 510	Transformer-based
16	7	240	1	5.2	240 - 450	Transformer-based
101	8	240	1	3.3	325 - 500	Transformerless
102	8	240	1	5.0	325 - 500	Transformerless
103	9	240	1	3.0	200 - 530	Transformerless
104	9	240	1	6.0	200 - 530	Transformerless
105	4	208	1	10.0	300 - 480	Transformerless

Table 3.0.1 Residential Solar PV Inverters Tested by Southern California Edison

4.0 GRID DISCONNECTION

The transformerless inverters were islanded with varying amounts of resistive load shown in Figure 4.0.1 to better understand the temporary over-voltages produced when disconnected from the grid. Table 4.0.1 below summarizes the different inverters behavior during islanding conditions.

Key findings:

- All inverters create temporary over-voltages (>100%) for more than one cycle
- The inverter temporary over-voltages are greatest when inverter is islanded with NO load (over-voltages can be reduced by increasing the load)
- Inverters 103 and 104 do not comply with IEEE1547 recommendations to shut down the inverter within 2 seconds of islanding with no load (both maintain voltage on AC side). Both inverters have 16Vdc output for infinite time at their output terminals as long DC input voltage is present.
- Dynamic behavior is repeatable on all inverters

Inverter #	Inverter Manuf.	Rating (kW)	Load (kW)	% Load	Max. Instantaneous Over-Voltage (%)	Max. t(cycles) for V > 100%	Max. t(cycles) for V > 10%
101	8	3.30	0.00	0%	222	1.7	13.2
			0.79	24%	139	2.5	2.8
			1.54	47%	118	2.8	3.0
			2.57	78%	111	5.7	6.0
			3.43	104%	102	0.1	9.1
102		5.00	0.00	0%	264	2.3	14.0
			1.16	23%	143	2.1	2.1
			2.67	53%	112	4.3	4.5
			3.81	76%	105	5.7	6.1
			4.98	100%	103	8.0	8.2
103	9	3.00	0.00	0%	271	4.1	21.3
			0.78	26%	130	3.8	4.3
			1.54	51%	128	5.3	5.5
			2.29	76%	117	31.0	31.2
			3.05	102%	103	26.7	40.0
104		6.00	0.00	0%	173	7.4	23.0
			1.54	26%	129	3.8	4.0
			3.05	51%	116	3.7	4.1
			4.58	76%	113	7.2	7.6
			6.10	102%	103	42.7	63.5
105	4	10.00	0.00	0%	181	1.7	129.7
			2.60	26%	126	1.0	1.0
			5.06	51%	126	4.2	5.1
			7.69	77%	111	0.1	6.3
			9.94	99%	101	0.0	5.6

Table 4.0.1 Temporary Over-Voltages During Islanding Condition with Varying Loads

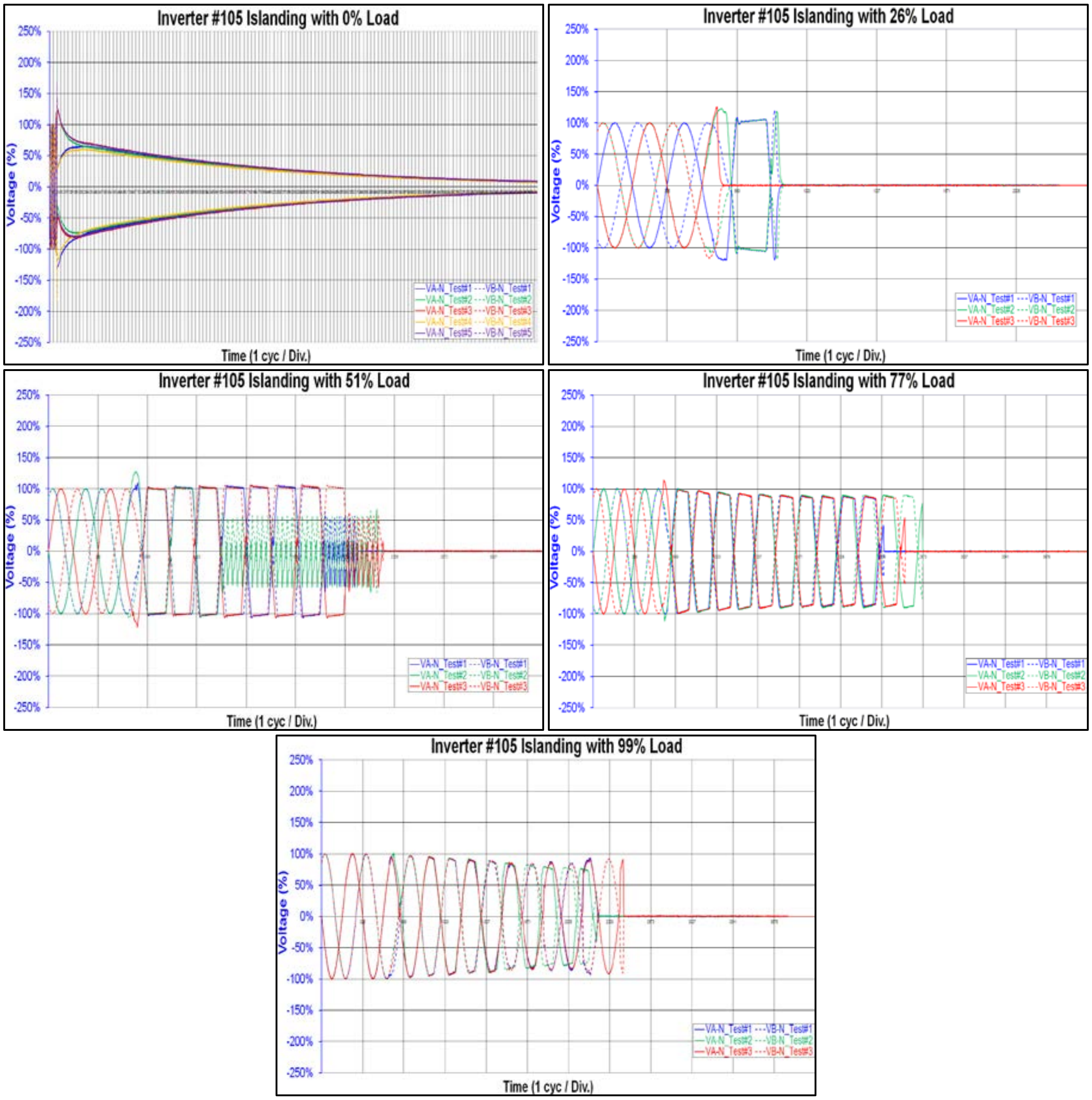

Figure 4.0.1 Temporary Over-voltages During Islanding Condition with Varying Loads

4.1 Inverter Manufacturer #4

Figure 4.1.1 and Figure 4.1.2 below indicate the behavior for Inverter 105 when disconnected from the grid with different amounts of load. Each test was performed several times.

- Highest temporary overvoltage is 181% of nominal voltage and occurs when islanding with no load
- The maximum time when the voltage goes above 100% is less than 4.2 cycles (at 51% rated load)
- Trips off within IEEE 1547 standard anti-islanding protection ---- 2 seconds
- The longest shutdown time (129.7 cycles) occurs at the 0% load case, where voltage discharges
- Inverter voltages falls outside the CBEMA curve when disconnected with 0% load

Figure 4.1.1 shows the transformerless inverter temporary over-voltages with different load conditions on CBEMA curve. Figure 4.1.2shows the inverters temporary over-voltages with different islanded load conditions.

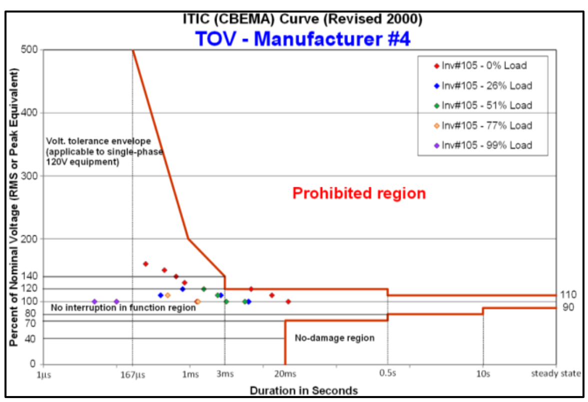

Figure 4.1.1 CBEMA Plot of Temporary Over-Voltages (Manufacturer #4)

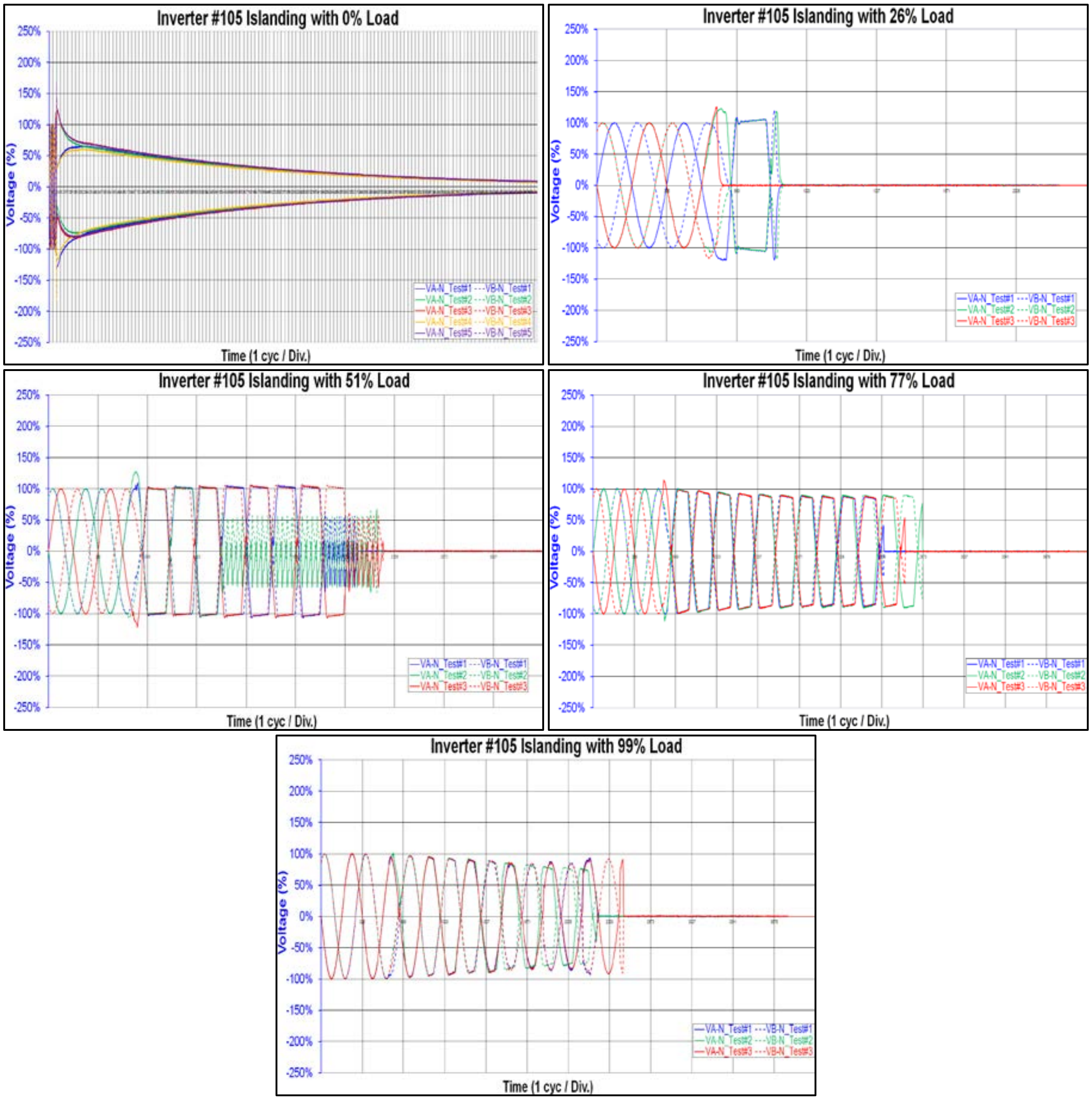

Figure 4.1.2 Temporary Over-voltages During Islanding Condition (Manufacturer #4)

4.2 Inverter Manufacturer #8

Figure 4.2.1 and Figure 4.2.2 below indicate the behavior for Inverters 101 and 102 when disconnected from the grid with different amounts of load. Each test was performed several times.

- Highest temporary overvoltage is 264% (instantaneous impulse)of nominal voltage and occurs when islanding with no load
- The maximum time when the voltage goes above 100% is less than 8 cycles (at 100% rated load)
- Trips off within IEEE 1547 standard anti-islanding protection ---- 2 seconds
- Shutdown times are mixed with respect to magnitude of inverter load – a higher load generally meant a longer time to trip off. The 0% load case was much more scattered. Inverter 102 falls outside the CBEMA curve when disconnected with 0% load

Figure 4.2.1 shows the transformerless inverter temporary over-voltages with different load conditions on CBEMA curve. Figure 4.2.2 shows the inverters temporary over-voltages with different islanded load conditions.

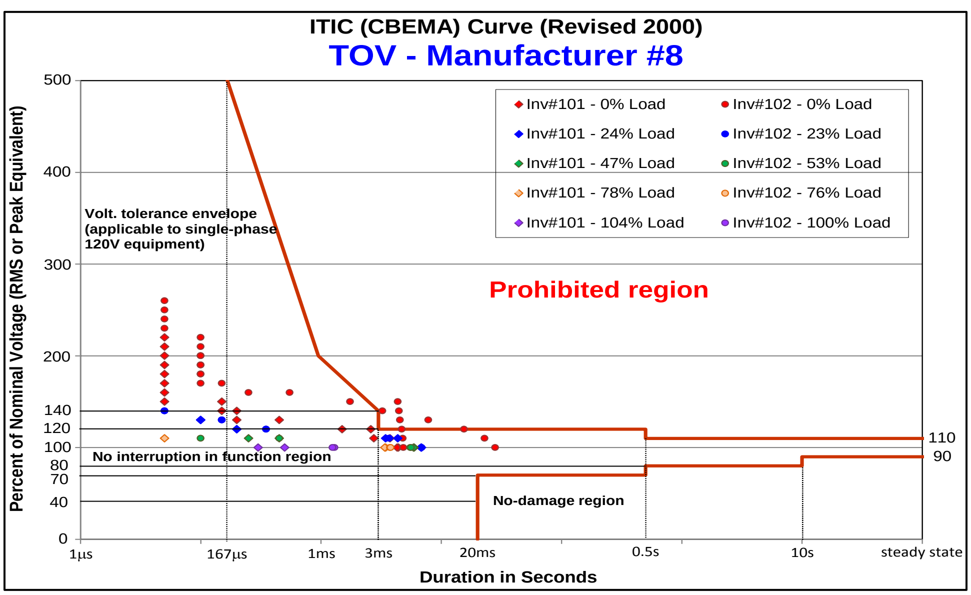

Figure 4.2.1 Transient Over-Voltages (TOV) During Islanding (Manufacturer 8)

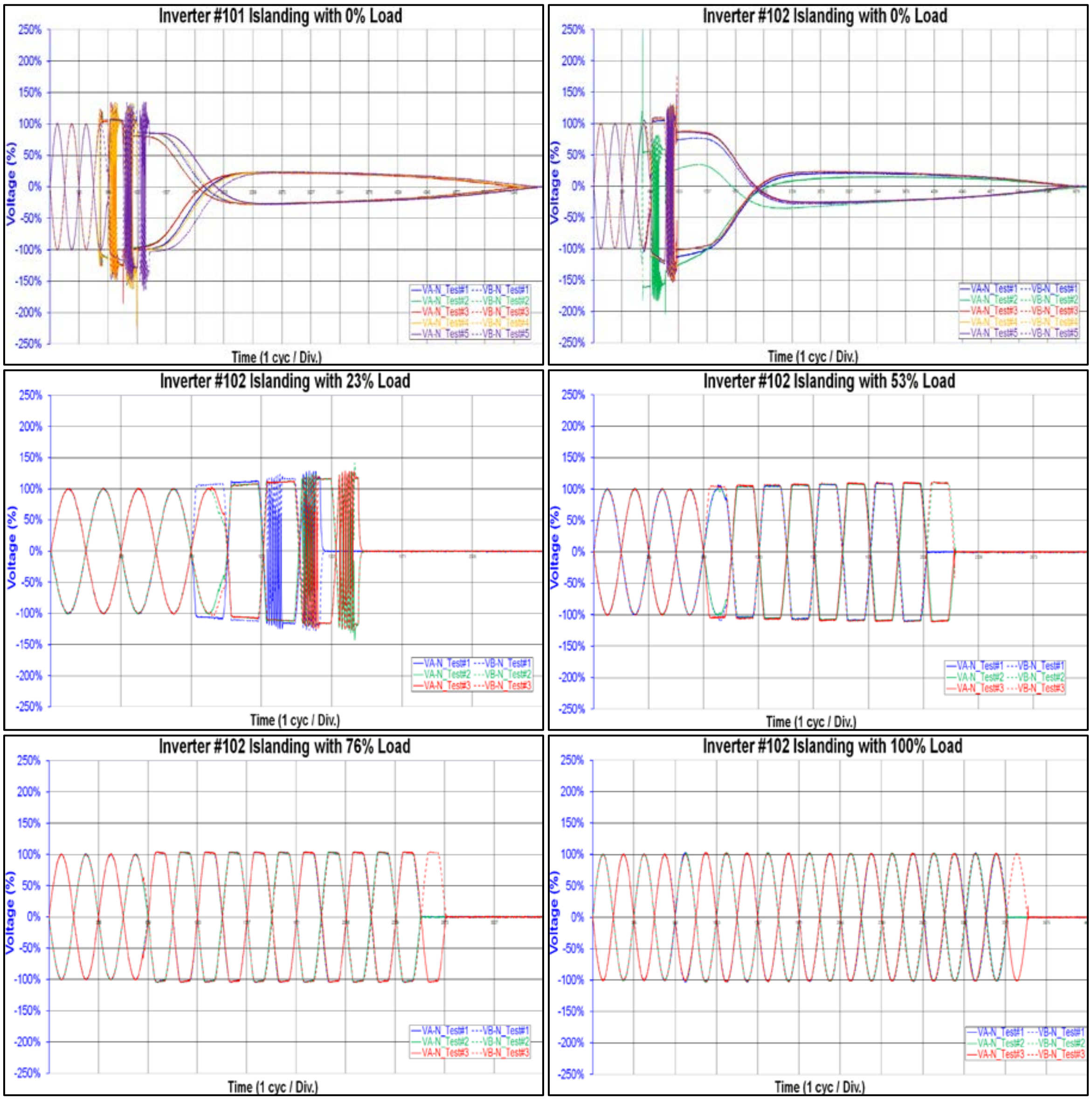

Figure 4.2.2 Temporary Over-voltages During Islanding Condition (Manufacturer #8)

4.3 Inverter Manufacturer #9

Figure 4.3.1 and Figure 4.3.2 below indicate the behavior for Inverters 103 and 104 when disconnected from the grid with different amounts of load. Each test was performed several times as shown in the graphs below.

- Highest temporary overvoltage is 271% (instantaneous impulse)of nominal voltage and occurs when islanding with no load
- The maximum time when the voltage goes above 100% is less than 42.7 cycles (at 102% rated load)
- Does **not** trip off within IEEE 1547 standard anti-islanding protection (2 seconds) at 0% load due to a 16VDC offset
- Shutdown times are generally proportional to magnitude of inverter load; the times in the 0% load case were more scattered
- Both inverters falls outside the CBEMA curve when disconnected with 0% load

Figure 4.3.1 shows the transformerless inverter temporary over-voltages with different load conditions on CBEMA curve. Figure 4.3.2 shows the inverters temporary over-voltages with different islanded load conditions.

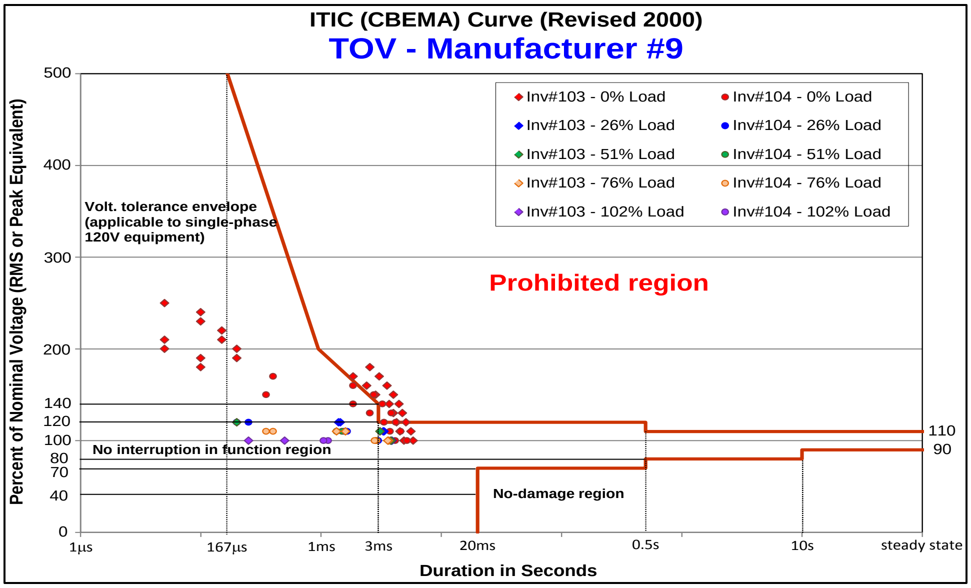

Figure 4.3.1 Transient Over-Voltages (TOV) During Islanding (Manufacturer #9)

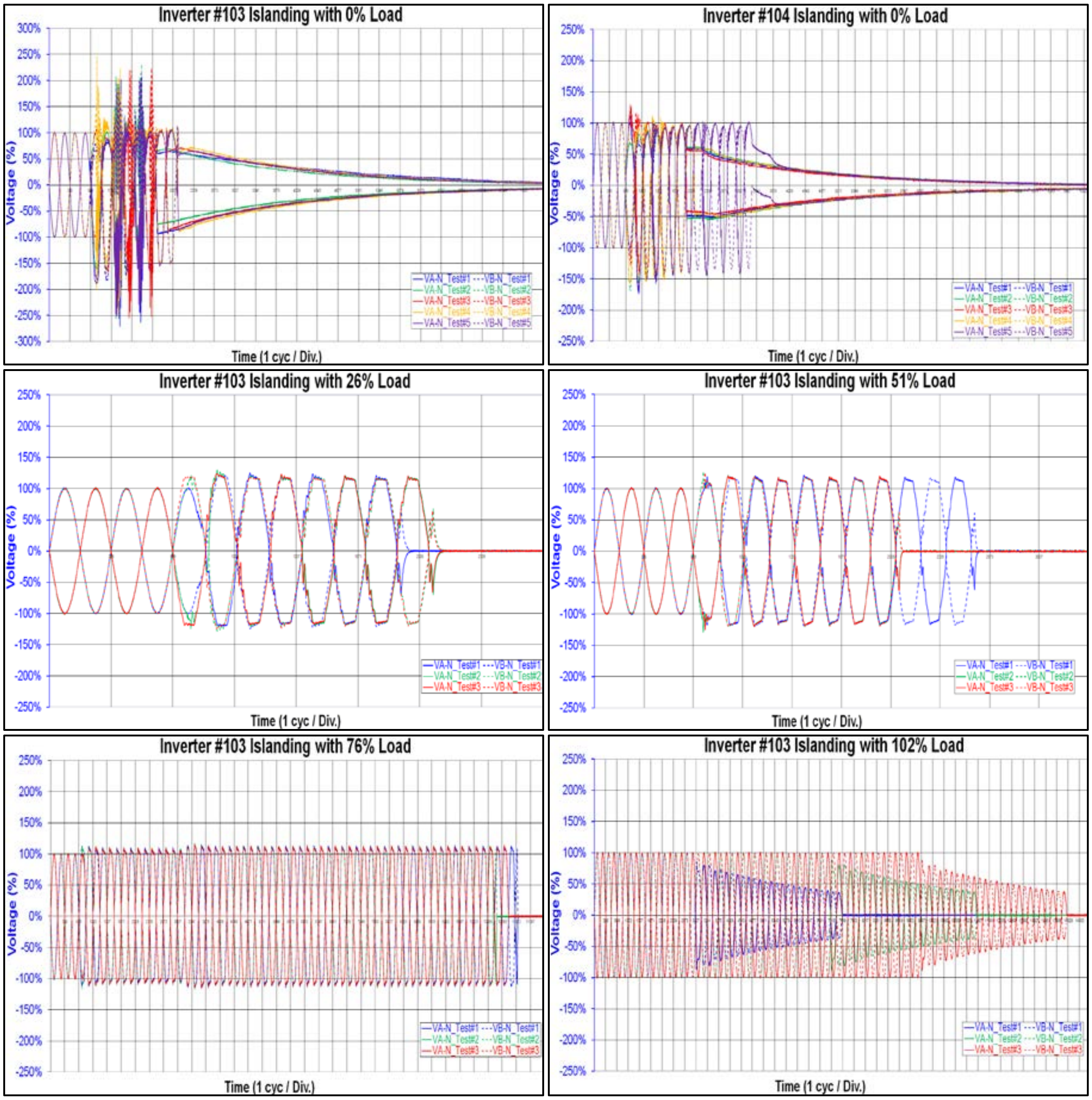

Figure 4.3.2 Temporary Over-voltages During Islanding Condition (Manufacturer #9)

5.0 FAULT CURRENT CONTRIBUTION

In order to assess their fault current contribution during system faults, the inverters were physically shorted when performing the following tests.

Key findings:

- Maximum fault current contribution ranges from 133% to 521% of nominal current within the first cycle of being shorted
- Maximum amount of time to stop producing current (shutdown) ranges from 5.1 to 8.2 cycles
- Manufacturer #8 inverters continue producing over-current until the inverter completely trips off
- Manufacturer #9 inverters only produce instantaneous over-current and then current steadily drops until inverter completely shuts down

Table 5.0.1 provides the various fault current contribution readings during short circuit for the tested inverters.

Inverter #	Inverter Manuf.	Fault	Max. Instantaneous Over-Current (%)	Max. t(cycles) for I > 100%	Max. t(cycles) to trip off
1	1	2Ph-Gnd	525%	0.04	0.95
2		2Ph-Gnd	423%	0.05	0.97
3	2 (a)	2Ph-Gnd	423%	1.10	1.37
11		2Ph-Gnd	688%	3.47	3.68
8	2 (b)	2Ph-Gnd	555%	7.37	7.68
4	3	2Ph-Gnd	525%	0.19	0.47
5		2Ph-Gnd	406%	13.32	13.75
6	4	2Ph-Gnd	423%	0.11	0.15
7		2Ph-Gnd	310%	0.78	0.81
12		2Ph-Gnd	529%	0.95	1.21
10	6	2Ph-Gnd	600%	2.39	2.39
13		2Ph-Gnd	324%	0.06	0.86
14		2Ph-Gnd	355%	0.03	0.61
16	7	2Ph-Gnd	326%	13.52	13.75
101	8	2Ph-Gnd	255%	5.7	6.2
		PhA-PhB	401%	6.1	6.2
		PhA-Gnd	156%	5.8	6.2
		PhB-Gnd	186%	6.1	6.2
102		2Ph-Gnd	227%	5.6	5.8
		PhA-PhB	129%	5.8	6.2
		PhA-Gnd	140%	5.5	5.8
		PhB-Gnd	133%	5.7	6.3
103	9	2Ph-Gnd	521%	0.5	7.7
		PhA-PhB	487%	0.6	7.7
		PhA-Gnd	207%	1.9	7.5
		PhB-Gnd	207%	1.7	7.6
104		2Ph-Gnd	265%	0.1	8.0
		PhA-PhB	260%	0.1	7.7
		PhA-Gnd	191%	1.4	8.0
		PhB-Gnd	153%	1.6	8.2
105	4	2Ph-Gnd	256%	4.7	5.1
		PhA-PhB	303%	4.0	5.5
		PhA-Gnd	175%	1.5	6.6
		PhB-Gnd	150%	1.3	6.5

Table 5.0.1 Fault Current Contribution During Short Circuit

5.1 Inverter Manufacturer #4

Figure 5.1.1 below indicates the behavior for Inverter 105 during various types of short circuit configurations. Each test was performed several times as shown in the graphs below.

- The maximum instantaneous short circuit current is 303% for less than 1ms
- The longest short circuit current time above 100% is 4.7 cycles
- Maximum trip off time is 6.6 cycles
- Fault current remains relatively constant until the inverter completely trips offline
- Inverter contactors appear to open and reclose shortly after phase-to-phase and 2 phase-to-ground faults

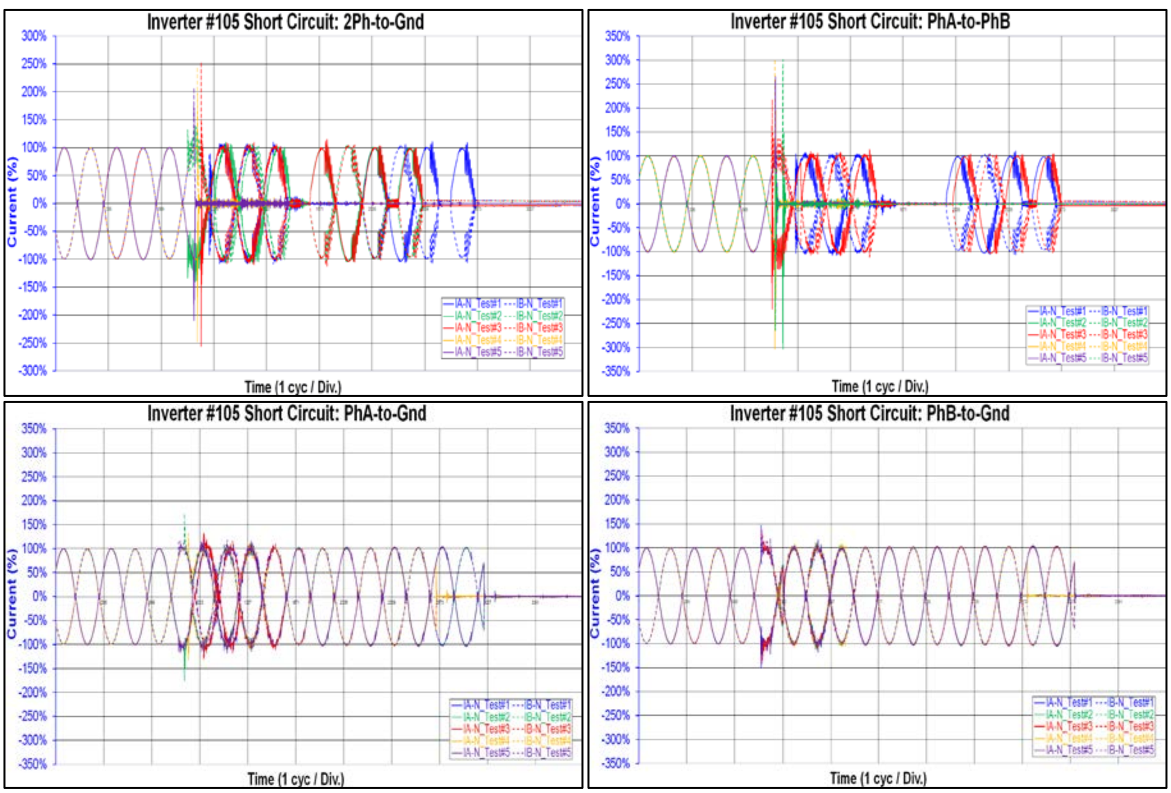

Figure 5.1.1 Fault Current Contribution (Manufacturer #4)

5.2 Inverter Manufacturer #8

Figure 5.2.1 below indicates the behavior for Inverters 101 and 102 during various types of short circuit configurations.

- The maximum instantaneous short circuit current is 401% for less than 1ms
- The longest short circuit current time above 100% is 6.1 cycles
- Maximum trip off time is 6.3 cycles
- Fault current gradually increases after inverter is shorted
- Fault current eventually shifts out of phase for phase-to-phase and 2 phase-to-ground faults
- The inverters produce a high noise current waveform for approximately 1.5 cycles after shorting

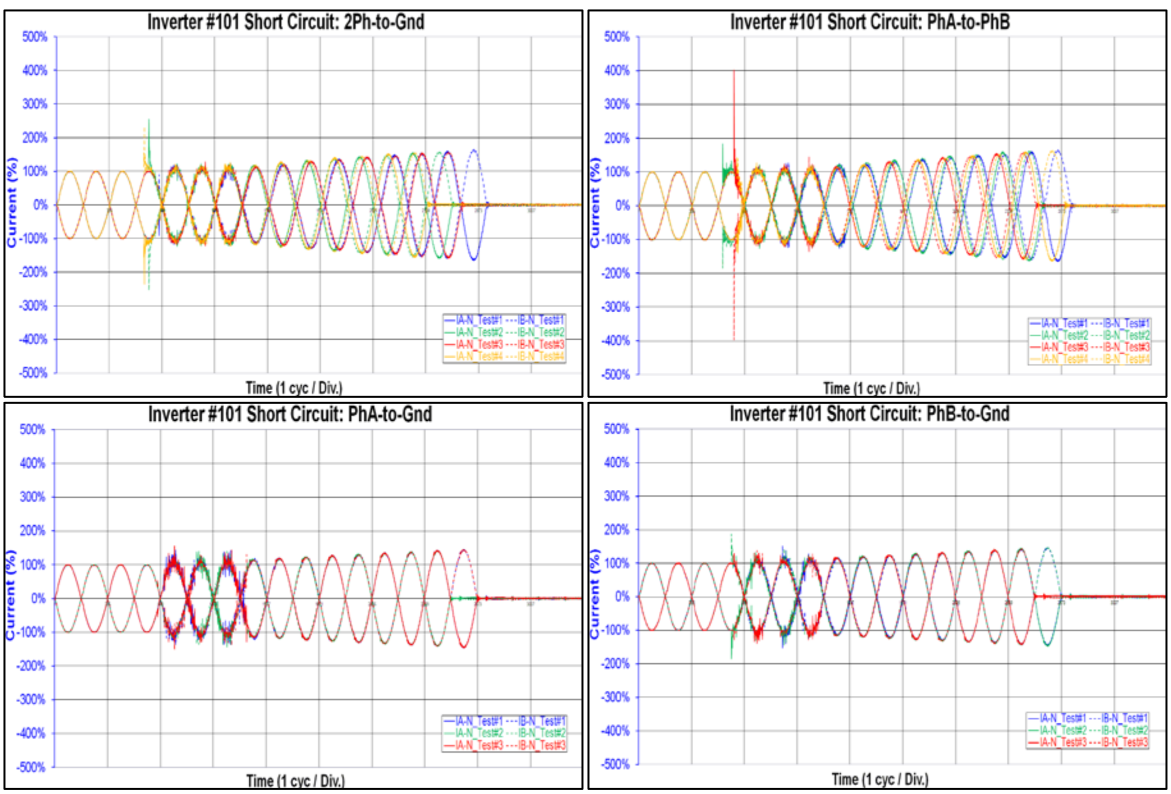

Figure 5.2.1 Fault Current Contribution (Manufacturer #8)

5.3 Inverter Manufacturer #9

Figure 5.3.1 indicates the behavior for Inverters 103 and 104 during various types of short circuit configurations.

- The maximum instantaneous short circuit current is 521% for less than 1ms
- The longest short circuit current time above 100% is 1.9 cycles
- Maximum trip off time is 8.2 cycles
- Fault current gradually increases after inverter is shorted
- Single phase-to-ground faults contribute less instantaneous current, but provide greater continuous current than phase-to-phase and 2 phase-to-ground faults
- Inherent high frequency (380 Hz) cycle every 60.4 cycles at steady state. This high frequency is observed at PhaseA-to-Gnd test plot below before the fault happens.

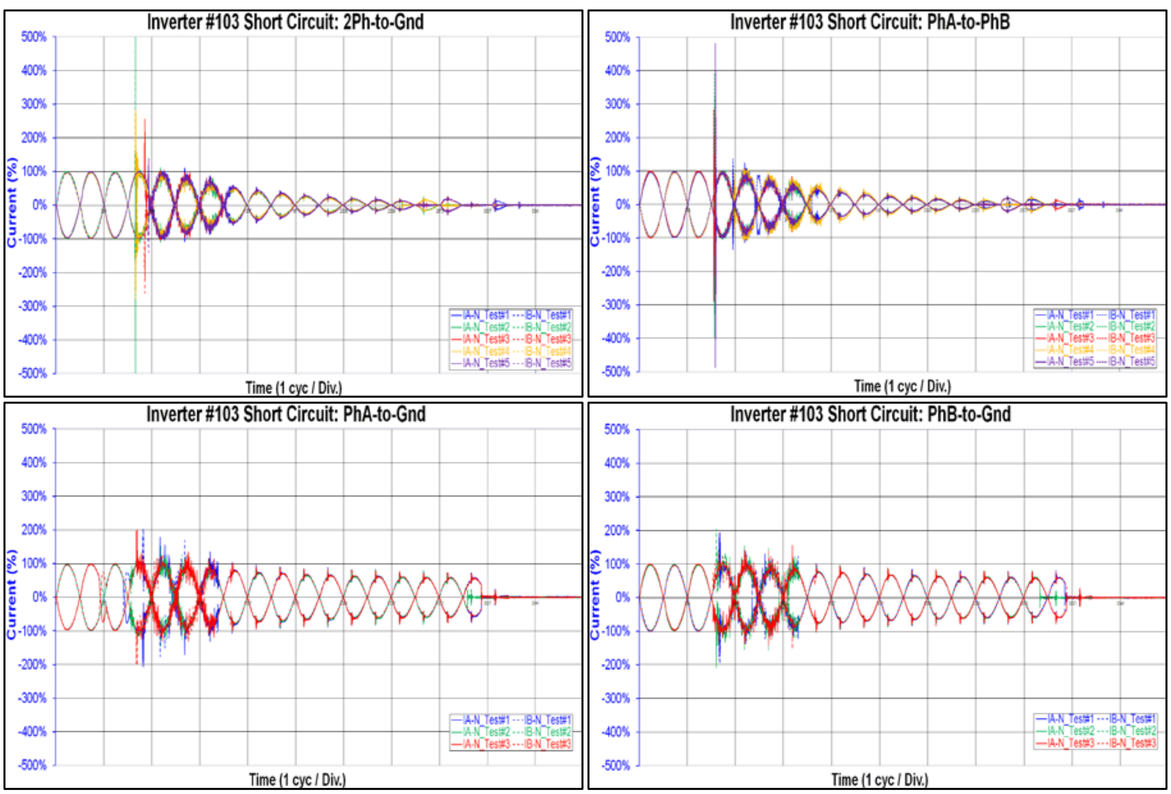

Figure 5.3.1 Fault Current Contribution (Manufacturer #9)

6.0 HARMONICS GENERATION

High sampling sinusoidal waveform data (1 million samples per second) was captured at the output of the inverters to assess their harmonics contribution.

Key findings:

- Transformerless inverters have lower harmonics than IEEE 1547 recommendations for harmonics lower than the 35th
- All transformerless inverters have higher harmonics than the IEEE 1547 recommendations for harmonics above the 35th (greater than 0.30% of the fundamental)
- THD is within IEEE 1547 recommendations for transformerless inverters
- Transformerless inverters voltage harmonics are lower because the powers supply (grid simulator) used for their test was different than the one used for inverters 1 to 16

Table 6.0.1 and Figure 6.0.1 provides the harmonics for the tested inverters.

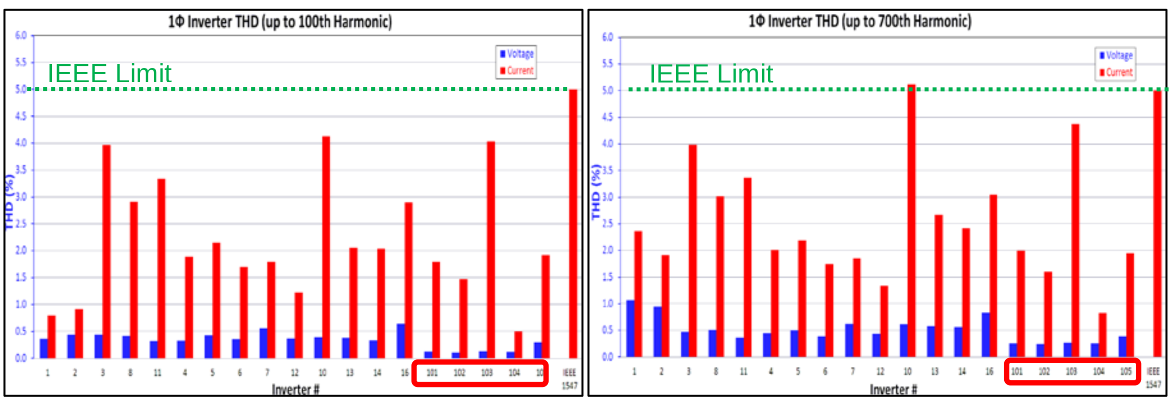

Figure 6.0.1 Inverters Total Harmonic Distortion

Inverter #	Inverter Manuf.	Voltage Harmonics (% of Fundamental)						Current Harmonics (% of Fundamental)						% THD (up to 100th harm.)		% THD (up to 700th harm.)	
		3rd	5th	7th	9th	11th	13th	3rd	5th	7th	9th	11th	13th	Voltage	Current	Voltage	Current
1	1	0.05	0.17	0.11	0.03	0.07	0.04	0.37	0.23	0.06	0.10	0.16	0.16	**0.36**	**0.80**	**1.07**	**2.36**
2		0.11	0.17	0.06	0.03	0.06	0.10	0.29	0.14	0.16	0.17	0.19	0.20	**0.44**	**0.92**	**0.95**	**1.91**
3	2	0.33	0.19	0.02	0.02	0.06	0.06	2.93	0.53	0.19	0.08	0.04	0.02	0.44	3.97	0.48	3.98
8		0.13	0.12	0.12	0.10	0.06	0.06	1.55	0.60	0.35	0.33	0.35	0.32	0.41	2.91	0.51	3.02
11		0.11	0.10	0.11	0.11	0.09	0.05	2.35	0.47	0.37	0.27	0.16	0.06	0.32	3.34	0.36	3.37
4	3	0.04	0.13	0.08	0.08	0.12	0.09	1.03	0.74	0.67	0.50	0.34	0.27	0.33	1.89	0.45	2.01
5		0.17	0.12	0.19	0.12	0.10	0.10	1.24	0.94	0.71	0.54	0.42	0.31	0.43	2.15	0.50	2.19
6	4	0.17	0.12	0.09	0.08	0.09	0.07	1.24	0.66	0.43	0.31	0.31	0.25	0.36	1.70	0.39	1.75
7		0.18	0.11	0.10	0.15	0.17	0.16	1.16	0.48	0.43	0.51	0.48	0.42	0.55	1.79	0.62	1.86
12		0.02	0.15	0.09	0.03	0.08	0.06	0.72	0.32	0.26	0.29	0.20	0.14	0.37	1.22	0.43	1.33
10	6	0.29	0.11	0.05	0.02	0.09	0.06	1.50	0.25	1.43	1.09	0.59	0.56	**0.39**	**4.13**	**0.61**	**5.12**
13		0.13	0.10	0.14	0.02	0.06	0.12	1.35	0.30	0.39	0.39	0.21	0.34	**0.38**	**2.05**	**0.58**	**2.67**
14		0.07	0.13	0.06	0.11	0.06	0.04	1.43	0.32	0.27	0.38	0.17	0.19	**0.34**	**2.04**	**0.56**	**2.41**
16	7	0.04	0.25	0.28	0.27	0.24	0.22	1.03	1.65	1.22	1.06	0.82	0.65	0.64	2.90	0.83	3.05
101	8	0.03	0.02	0.04	0.04	0.04	0.04	1.29	0.60	0.30	0.53	0.44	0.35	0.12	1.79	0.25	1.99
102		0.03	0.01	0.04	0.04	0.04	0.03	1.26	0.34	0.08	0.31	0.20	0.24	0.11	1.48	0.24	1.60
103	9	0.03	0.02	0.04	0.04	0.05	0.04	3.82	0.78	0.64	0.52	0.36	0.25	0.13	4.03	0.27	4.38
104		0.02	0.02	0.04	0.04	0.04	0.03	0.32	0.16	0.15	0.10	0.11	0.10	0.11	0.50	0.25	0.83
105	4	0.05	0.06	0.02	0.05	0.02	0.03	0.80	0.23	0.32	0.31	0.37	0.34	0.29	1.92	0.39	1.95
IEEE 1547								**4.00**	**4.00**	**4.00**	**4.00**	**2.00**	**2.00**		**5.00**		**5.00**

Table 6.0.1 Inverter Harmonics Contribution

6.1 Inverter Manufacturer #4

Figure 6.1.1 shows the harmonics contribution from Inverter 105 measured as a percentage of the fundamental. The inverter was operating at full power output during testing with a purely resistive, linear load.

- Individual lower order voltage harmonics are less than 0.1% of the fundamental
  - H_5 is the highest of the lower order voltage harmonics (0.06%)
- Individual lower order current harmonics are within IEEE 1547 recommendations
  - H_3 is the highest of the lower order current harmonics (0.8%)
  - The largest THD measurement (1.95%) is within IEEE 1547 recommendations

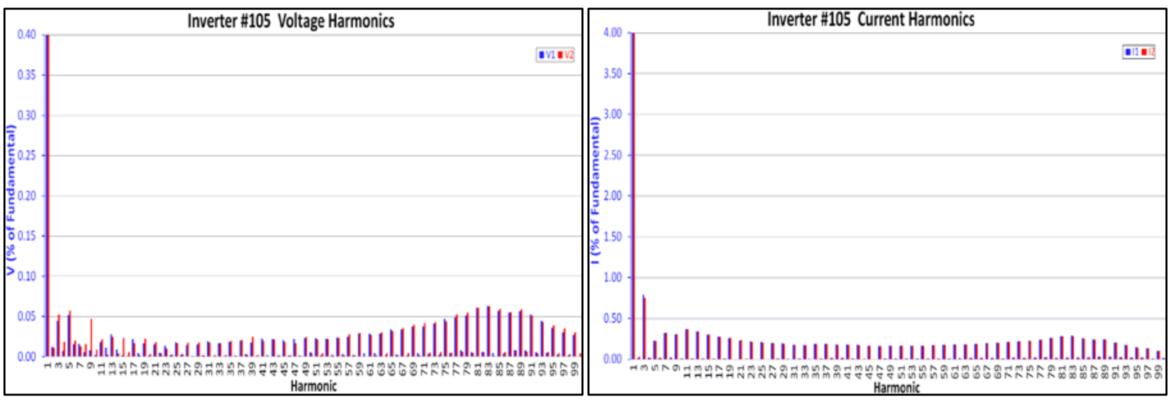

Figure 6.1.1 Harmonic Contribution (Manufacturer #4)

6.2 Inverter Manufacturer #8

Figure 6.2.1 represents the harmonics contribution from Inverters 101 and 102 measured as a percentage of the fundamental. Each of these residential inverters was operating at full power output with a purely resistive, linear load.

- Individual lower order voltage harmonics are within 0.1% of the fundamental
  - H_9 is the highest of the lower order voltage harmonics (0.04%)
- Individual lower order current harmonics are within IEEE 1547 recommendations
  - H_3 is the highest of the lower order current harmonics (1.29%)
  - The largest THD measurement (1.99%) is within IEEE 1547 recommendations

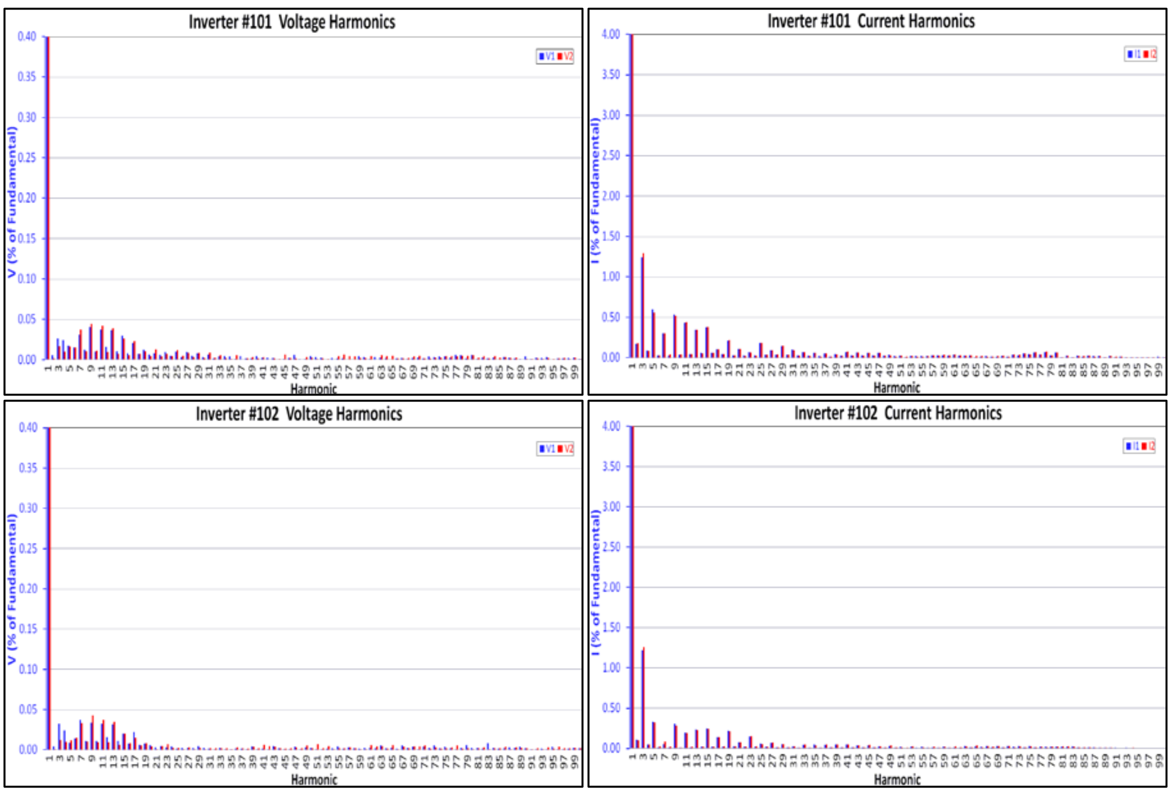

Figure 6.2.1 Harmonic Contribution (Manufacturer #8)

6.3 INVERTER MANUFACTURER #9

Figure 6.3.1 represents the harmonics contribution from Inverters 103 and 104 measured as a percentage of the fundamental. Each of these residential inverters was operating at full power output with a purely resistive, linear load.

- Individual lower order voltage harmonics are less than 0.1% of the fundamental
  - H_9 is the highest of the lower order voltage harmonics (0.05%)
- Individual lower order current harmonics are within IEEE 1547 recommendations
  - H_3 is the highest of the lower order current harmonics (3.82%)
  - The largest THD measurement (4.38%) is within IEEE 1547 recommendations

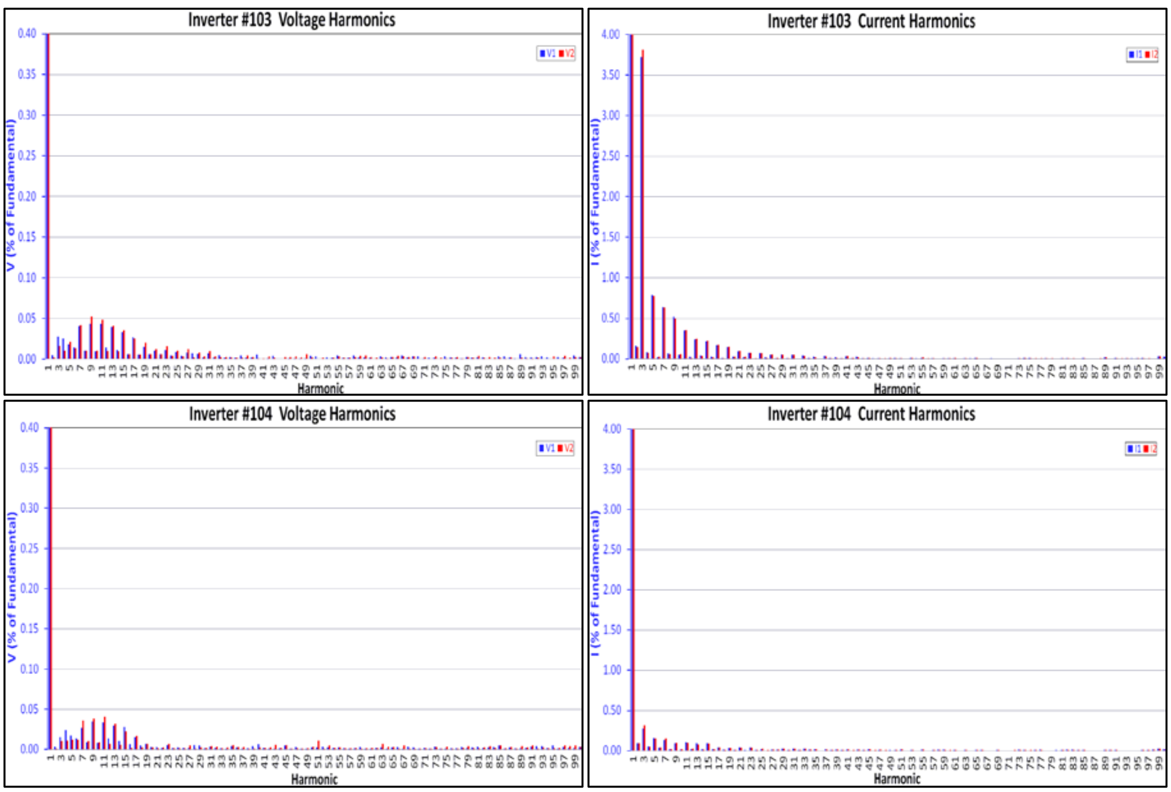

Figure 6.3.1 Harmonic Contribution (Manufacturer #9)

7.0 FREQUENCY TRANSIENTS

A series of frequency sags and swells of varying durations were implemented using the grid simulator in order to assess the transformerless inverters behavior during frequency transients. The table below summarizes the frequency transient tests performed and the resulting inverter behavior.

Key findings:

- All four transformerless inverters tripped off within the IEEE 1547 standards
- All inverters did not trip during frequency deviations within ±0.1Hz of 60Hz
- Some tests indicate tripping after the frequency recovers to steady-state rather than during the transient (typically in the case of the shorter transients)

Table 7.0.1 provides the overall performance of the tested inverters during frequency transients. The area crossed "X" are the tests where the inverter did not shutdown.

Test Description			Inverter #101		Inverter #102		Inverter #103		Inverter #104		Inverter #105	
Type	**Frequency Range**	**Trans. Dur. (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
Under-Frequency	60Hz - 58Hz	130	59.8	13.98	59.8	13	59.2	4.2	59.2	4.2	59.2	5.4
		12	59.6	8.4	59.6	7.98	NA	NA	NA	NA	NA	NA
		6	59.4	6	59.4	5	NA	NA	NA	NA	NA	NA
		3	59	3.6	59.2	4.8	58	3	58.4	3	59.0	1.7
Over-Frequency	60Hz - 62Hz	130	60.2	12.96	60.2	12.96	60.6	4.2	60.6	3.6	60.6	4.8
		12	60.4	8.04	60.4	7.8	NA	NA	NA	NA	NA	NA
		6	60.6	6	60.4	7.8	NA	NA	NA	NA	NA	NA
		3	61	3.6	60.8	6	61.6	3	61	3	61.0	1.8

Table 7.0.1 Frequency Transient Test Results

7.1 Inverter Manufacturer #4

Figure 7.1.1 below indicates the tripping and ride through behavior for Inverter 105 during frequency transient tests.

- Inverter operates continuously between 59.4Hz and 60.4Hz
- The inverter protection remains within recommendations set by IEEE 1547

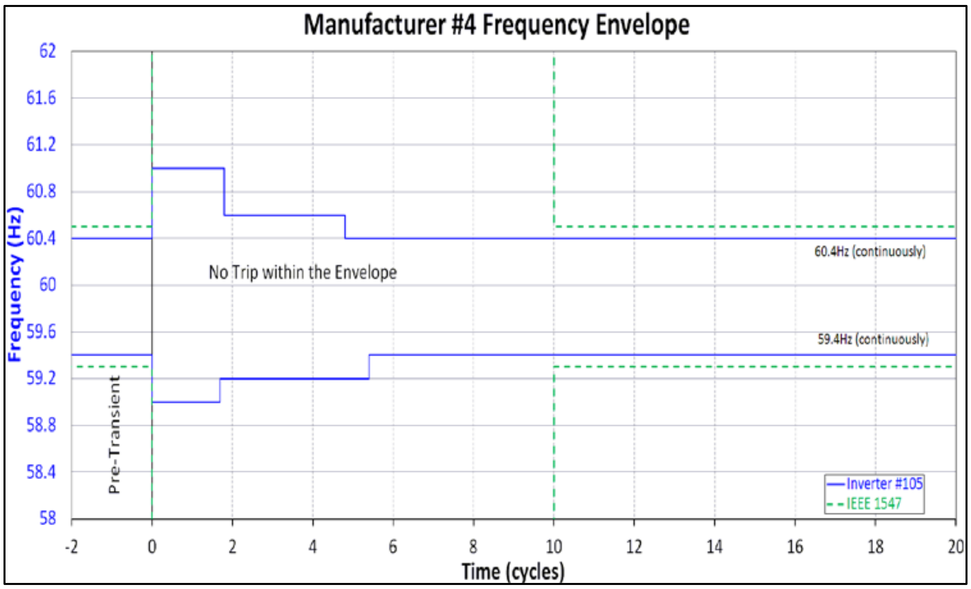

Figure 7.1.1 Frequency Envelope (Manufacturer #4)

7.2 Inverter Manufacturer #8

Figure 7.2.1 below indicates the tripping and ride through behavior for Inverters 101 and 102 during frequency transient tests.

- The lower rated inverter (101) permits a larger frequency envelope than the higher rated inverter
- Inverters are sensitive to frequency deviation (operate continuously only within + 0.1Hz)
- Both inverters remain within recommendations set by IEEE 1547

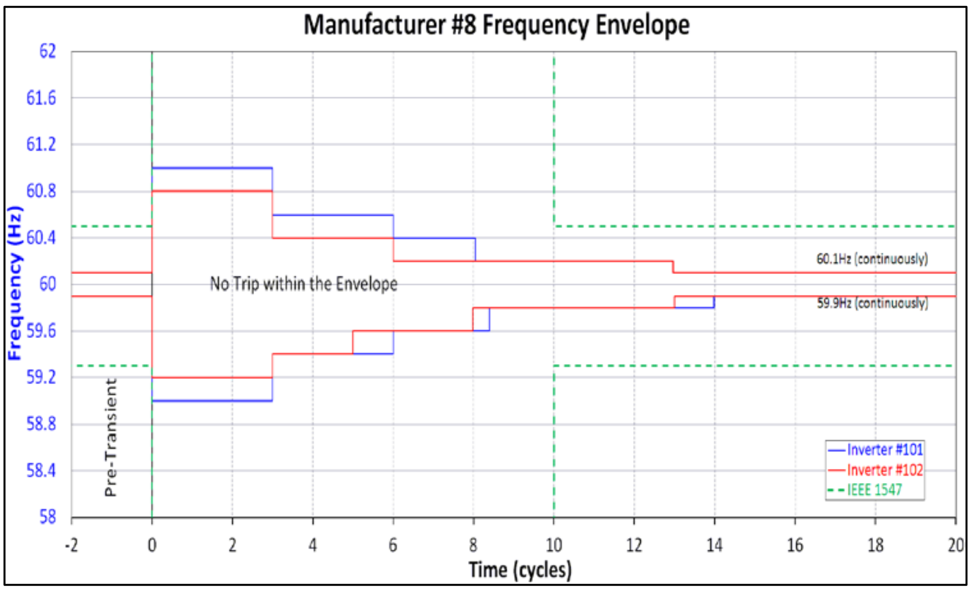

Figure 7.2.1 Frequency Envelope (Manufacturer #8)

7.3 Inverter Manufacturer #9

Figure 7.3.1 below indicates the tripping and ride through behavior for Inverters 103 and 104 during frequency transient tests.

- Frequency trip points are almost identical for Inverters 103 and 104
- Inverters operates continuously between 59.4Hz and 60.4Hz
- Both inverters remain within recommendations set by IEEE 1547

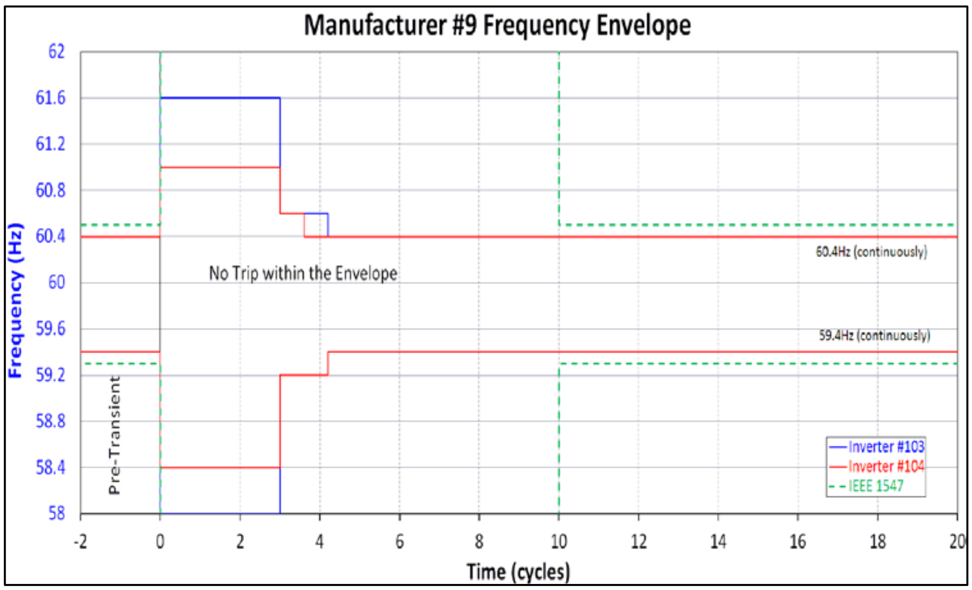

Figure 7.3.1 Frequency Envelope (Manufacturer #9)

8.0 VOLTAGE RAMP

The grid voltages were ramped down and up while maintaining constant load in order to assess the inverters behavior at various voltage levels, specifically the response of the current and active power.

Key findings:

- Four of the transformerless inverters maintain constant active power (P) during lower or higher voltages, the current increases or decreases
- Most inverters provide a fast current response in order to maintain constant active power (P)
- Transformerless inverters from Manufacturers 8 and 9 operate at a unity power factor and contribute little reactive power (Q)
- Inverter #105 maintains constant current for -10% voltage ramp, but maintains constant power for +5% voltage ramp

Table 8.0.1 and Table 8.0.2 provide the overall performance of the tested inverters during frequency transients.

Inverter #	Manuf. #	Ramp Time (sec)	$V_{DEVIATION}$ (± %)	$I_{DEVIATION}$ (± %)	$P_{DEVIATION}$ (± %)	$Q_{DEVIATION}$ (± %)	Comments
101	8	4	-10%	+10%	-3% , +0%	NA	Constant Power
		8	-10%	+8%	-4% , +0%	NA	Constant Power
102		4	-10%	+9%	-3% , +0%	NA	Constant Power
		8	-10%	+8%	-5% , +0%	NA	Constant Power
103	9	4	-10%	+11%	-4% , +3%	NA	Constant Power
		8	-10%	+11%	-3% , +2%	NA	Constant Power
104		4	-10%	+11%	-9% , +3%	NA	Distorted/slow current response
		8	-10%	+12%	-5% , +2%	NA	Constant Power
105	4	4	-10%	-0% , +1%	-10%	NA	Constant Current
		8	-10%	-1% , +1%	-9%	NA	Constant Current

Table 8.0.1 Voltage Ramp Response (-10% Deviation)

Inverter #	Manuf. #	Ramp Time (sec)	$V_{DEVIATION}$ (± %)	$I_{DEVIATION}$ (± %)	$P_{DEVIATION}$ (± %)	$Q_{DEVIATION}$ (± %)	Comments
101	8	4	+5%	-4%	+1% , -0%	NA	Constant Power
		8	+5%	-5%	+0% , -0%	NA	Constant Power
102		4	+5%	-5%	+0% , -0%	NA	Constant Power
		8	+5%	-5%	+0% , -0%	NA	Constant Power
103	9	4	+5%	-5%	+2% , -2%	NA	Constant Power
		8	+5%	-6%	+2% , -4%	NA	Constant Power
104		4	+5%	-7%	+2% , -4%	NA	Distorted/slow current response
		8	+5%	-7%	+1% , -4%	NA	Constant Power
105	4	4	+5%	-5%	+1% , -1%	NA	Constant Power
		8	+5%	-5%	+1% , -1%	NA	Constant Power

Table 8.0.2 Voltage Ramp Response (+5% Deviation)

8.1 Inverter Manufacturer #4

Figure 8.1.1 and Figure 8.1.2 below indicate the behavior for Inverter 105 during voltage ramping tests.

Voltage Ramps Down 10%

- Current remains constant, within +1% of nominal, during voltage ramp
- Active (P) and reactive (Q) power ramps down approximately 10% of nominal
- Reactive power (Q) is noisy and varies even during steady state

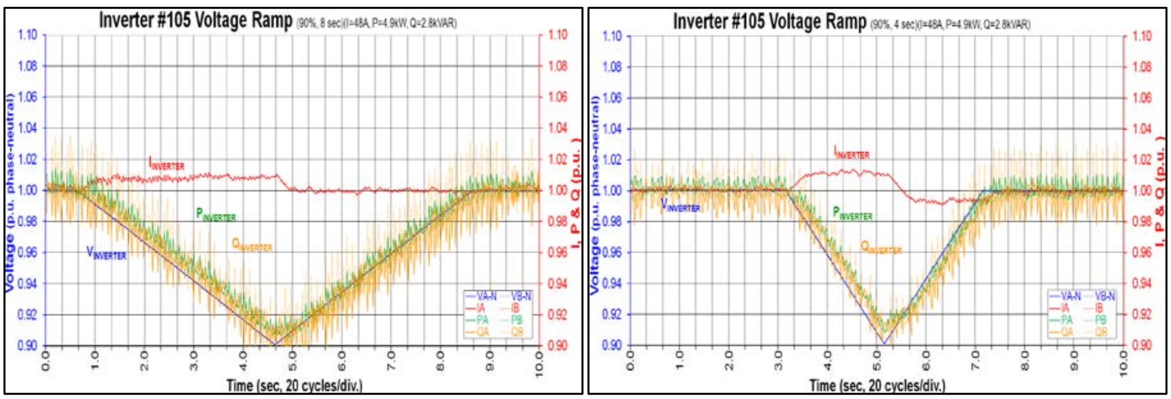

Figure 8.1.1 Voltage Ramp Down & Up (Manufacturer #4)

Voltage Ramps Up 5%

- Current uniformly ramps down 5% of nominal to maintain constant active power (P)
- Active power (P) only deviates up to 1% of its nominal value

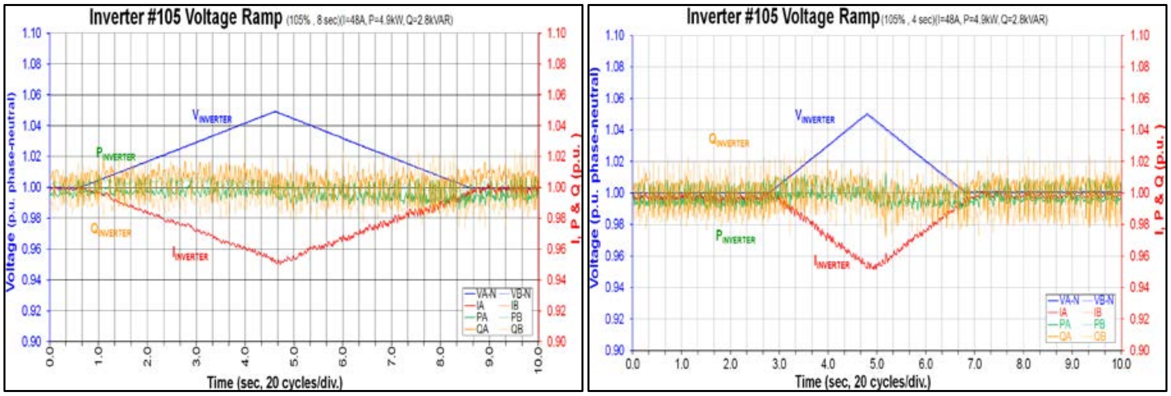

Figure 8.1.2 Voltage Ramp Up & Down (Manufacturer #4)

8.2 Inverter Manufacturer #8

Figure 8.2.1 and Figure 8.2.2 below indicate the behavior for Inverters 101 and 102 during voltage ramping tests.

Voltage Ramps Down 10%

- Current ramps up uniformly 8% to 10% of nominal to maintain constant active power (P)
- Current ramps down too quickly causing the output power to deviate
- Active power (P) only deviates up to 5% of the nominal

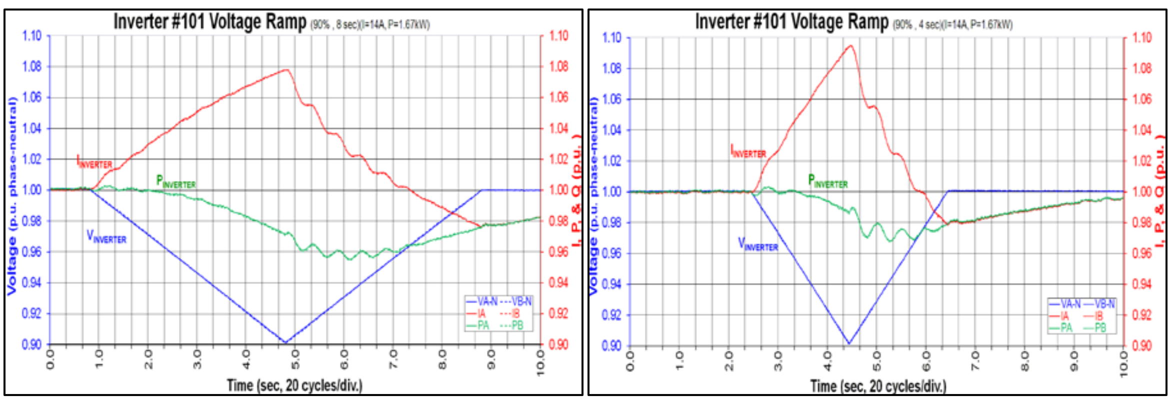

Figure 8.2.1 Voltage Ramp Down & Up (Manufacturer #4)

Voltage Ramps Up 5%

- Current ramps down and up uniformly 4% to 5% of nominal to maintain constant active power (P)
- Active power (P) deviation is minimal, within 1% of its nominal value

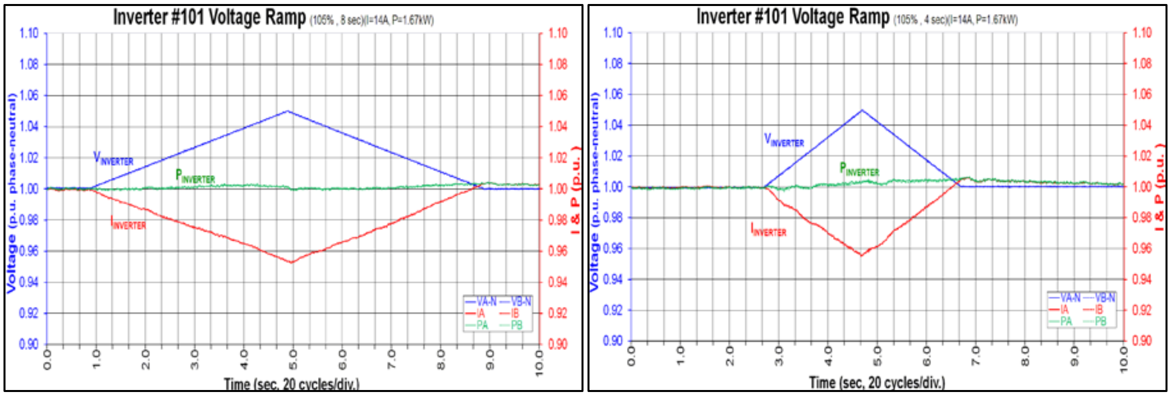

Figure 8.2.2 Voltage Ramp Down & Up (Manufacturer #8)

8.3 Inverter Manufacturer #9

Figure 8.3.1 and Figure 8.3.2 below indicate the behavior for Inverters 103 and 104 during voltage ramping tests. Note: these inverters have inherent current blips approximately every 1 second.

Voltage Ramps Down 10%

- Current ramps up 11% to 12% of nominal to maintain constant active power (P)
- Current response becomes distorted or delayed as voltage ramps down
- Active power (P) deviates up to 5% of the nominal power

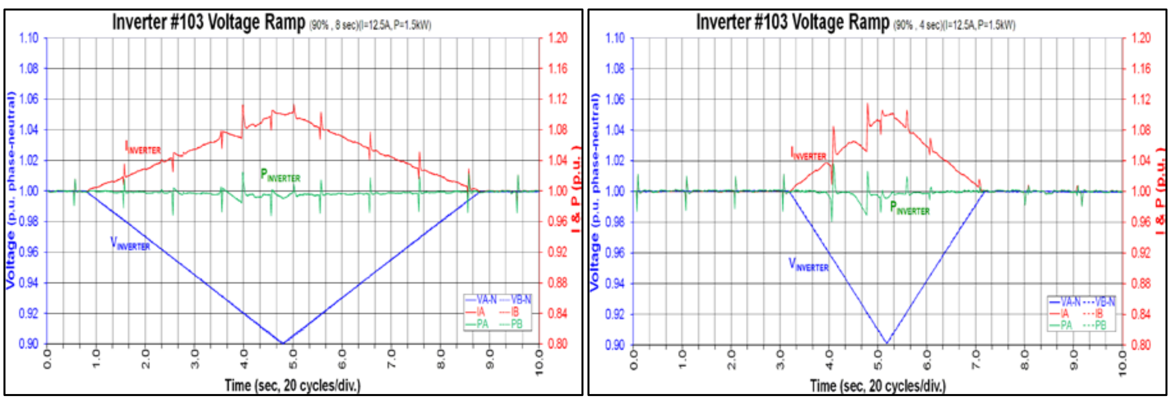

Figure 8.3.1 Voltage Ramp Down & Up (Manufacturer #9)

Voltage Ramps Up 5%

- Current uniformly ramps down 5% to 7% of nominal to maintain constant active power (P)
- Active power (P) deviates up to 4% of its nominal value

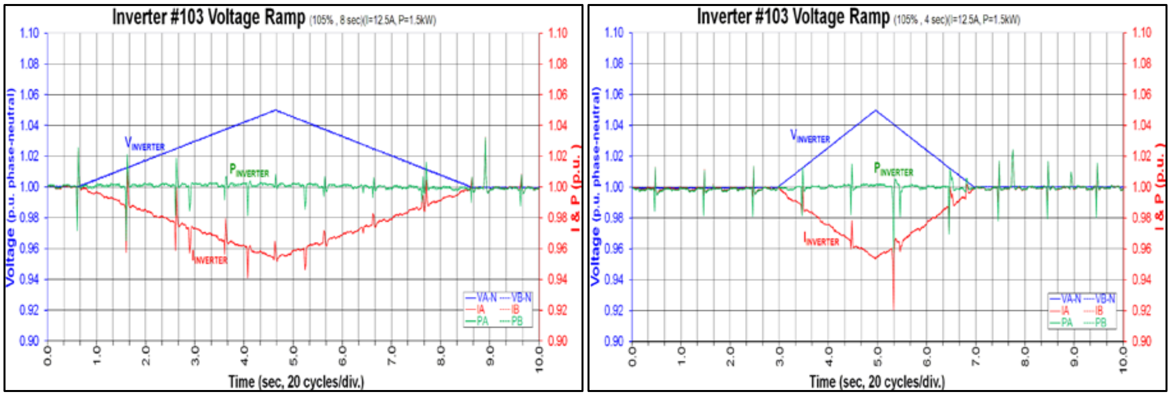

Figure 8.3.2 Voltage Ramp Up & Down (Manufacturer #9)

9.0 FREQEUNCY RAMP TEST

The grid frequency was ramped down and up while maintaining constant load in order to assess the inverters behavior at various frequency levels, specifically the response of the current and active power (P).

Key findings:

- Four of the transformerless inverters respond by maintaining constant current and power when the frequency is between 60Hz and 59.8Hz
- Manufacturer #8 inverters trip off due to frequency protection when ramped below 59.8Hz
- Manufacturer #9 inverters produce current and active power (P) deviations that occur as a “step-shaped” profile
- Manufacturer #4 inverter results in ramping of the active (P) and reactive (Q) power

Table 9.0.1 and Table 9.0.2 provide the overall performance of the tested inverters during frequency ramping.

Inverter #	Manuf. #	Ramp Time (sec)	$F_{DEVIATION}$ (± %)	$I_{DEVIATION}$ (± %)	$P_{DEVIATION}$ (± %)	Comments
101	8	4	59.8	±0%	±0%	Negligible Current/Power Deviation
			59.6	NA	NA	Inverter Tripped Off
			59.4	NA	NA	Inverter Tripped Off
102			59.8	±0%	±0%	Negligible Current/Power Deviation
			59.6	NA	NA	Inverter Tripped Off
			59.4	NA	NA	Inverter Tripped Off
103	9	4	59.8	±2%	±2%	Negligible Current/Power Deviation
			59.6	-17% , +3%	-17% , +3%	Current/Power step down & recover
			59.4	-34% , +5%	-34% , +5%	Current/Power step down & recover
104			59.8	±2%	±2%	Negligible Current/Power Deviation
			59.6	-22% , +2%	-22% , +2%	Current/Power step down & recover
			59.4	-22% , +2%	-22% , +2%	Current/Power step down & recover
105	4	4	59.8	-1%	±4%	P(W) & Q(Var) ramp opposite of each other
			59.6	±1%	±8%	P(W) & Q(Var) ramp opposite of each other
			59.4	±2%	±12%	P(W) & Q(Var) ramp opposite of each other

Table 9.0.1 Frequency Ramp Response (4 sec.)

Inverter #	Manuf. #	Ramp Time (sec)	$F_{DEVIATION}$ (± %)	$I_{DEVIATION}$ (± %)	$P_{DEVIATION}$ (± %)	Comments
101	8	8	59.8	±0%	±0%	Negligible Current/Power Deviation
			59.6	NA	NA	Inverter Tripped Off
			59.4	NA	NA	Inverter Tripped Off
102			59.8	±0%	±0%	Negligible Current/Power Deviation
			59.6	NA	NA	Inverter Tripped Off
			59.4	NA	NA	Inverter Tripped Off
103	9	8	59.8	±2%	±2%	Negligible Current/Power Deviation
			59.6	-35% , +5%	-35% , +5%	Current/Power step down & recover
			59.4	-70% , +4%	-70% , +4%	Current/Power step down & recover
104			59.8	±2%	±2%	Negligible Current/Power Deviation
			59.6	±2%	±2%	Negligible Current/Power Deviation
			59.4	-22% , +2%	-22% , +2%	Current/Power step down & recover
105	4	8	59.8	±1%	-3% , +4%	P(W) & Q(Var) ramp opposite of each other
			59.6	±1%	±6%	P(W) & Q(Var) ramp opposite of each other
			59.4	±2%	±11%	P(W) & Q(Var) ramp opposite of each other

Table 9.0.2 Frequency Ramp Response (8 sec.)

9.1 Inverter Manufacturer #4

Figure 9.1.1 below indicates the behavior for Inverter 105 during frequency ramping tests.

- Current remains constant during frequency ramps
- Active power (P) on Line 1 ramps up while active power (P) on Line 2 ramps down
- Reactive power (Q) on each line ramps the opposite direction of the active power (P)

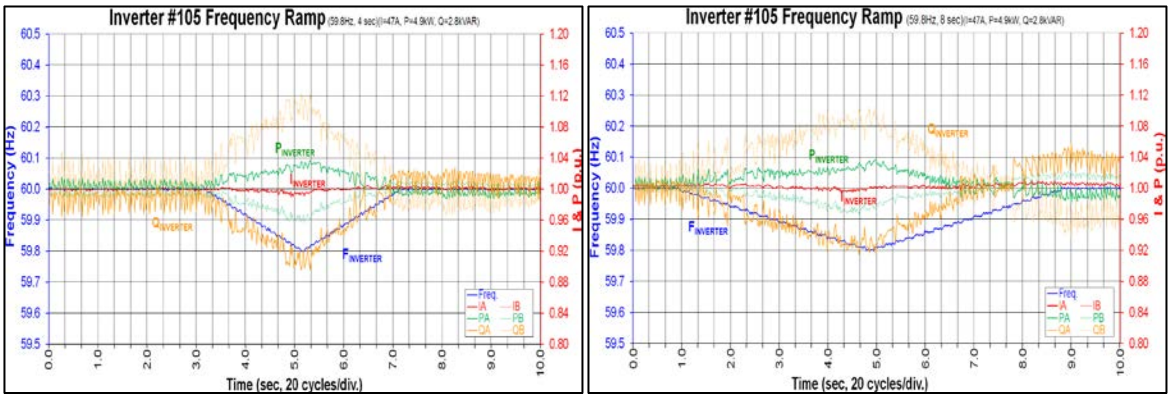

Figure 9.1.1 Frequency Ramp (60 to 59.8Hz; 4 and 8 sec.)

9.2 Inverter Manufacturer #8

Figure 9.2.1 below indicates the behavior for Inverters 101 and 102 during frequency ramping tests.

- Negligible changes in current and active power (P) due to frequency ramps
- Inverter frequency protection is sensitive to low frequencies lasting longer than 10 cycles
    - Inverter tripped during ramp tests below 59.8Hz

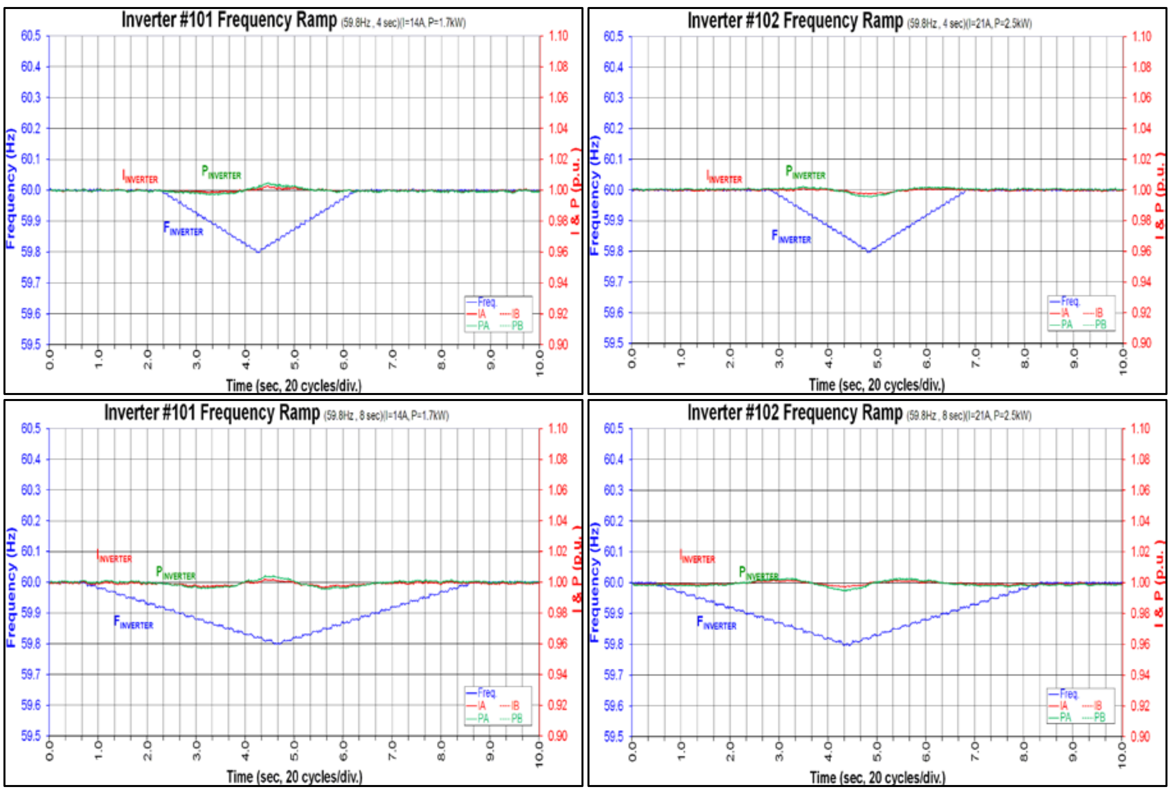

Figure 9.2.1 Frequency Ramp (60 to 59.8Hz; 4 and 8 sec.)

9.3 Inverter Manufacturer #9

Figure 9.3.1 below indicates the behavior for Inverters 103 and 104 during frequency ramping tests.

- Current and power responds slowly (only deviating as frequency recovers)
- Current and power deviations appear to occur in "steps"
- Inverter allows frequency ramping down to 59.4Hz without tripping
- Inverter current and power deviate to as low as:
  - 30% of nominal rating for 8 second ramp test
  - 66% of nominal rating for 4 second ramp test

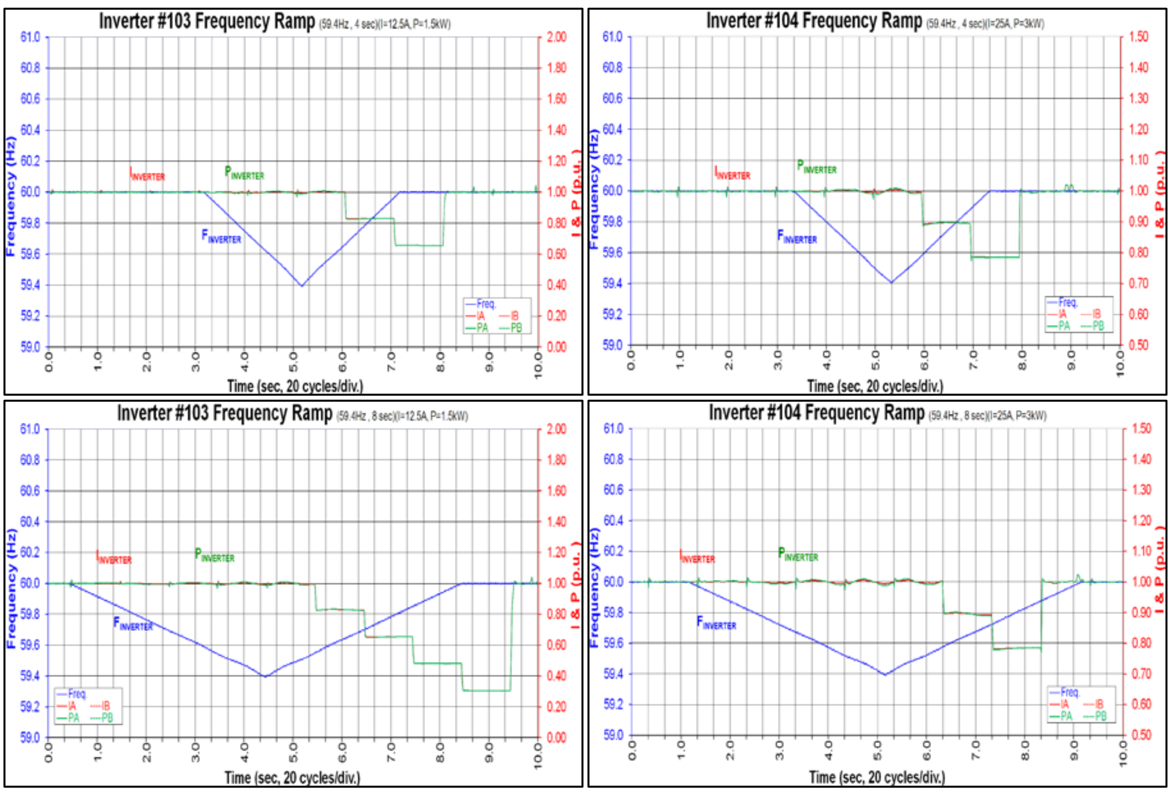

Figure 9.3.1 Frequency Ramp (60 to 59.4Hz; 4 and 8 sec.)

10.0 VOLTAGE OSCILLATION

The grid voltage was shifted between 100% and 90% to create voltage oscillations with swing frequencies of 0.25 Hz, 1 Hz, and 2 Hz. The test will be used to assess the behavior of the inverters during these voltage oscillations.

Key findings:

- Four of the transformerless inverters attempt to dampen power oscillations at 0.25 Hz swing frequency while Inverter #105 maintains constant current
- Current and power deviations typically increase at higher swing frequencies such as 1 Hz and 2 Hz
- Transformerless inverters from Manufacturers 8 and 9 operate at a unity power factor and therefore contribute little reactive power

Table 10.0.1, Table 10.0.2, and Table 10.0.3 provides the overall performance of the tested inverters during frequency transients.

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	8	0.25 Hz	9%	-3%	0%	-4%	Current oscillates opp. of volt. / minimal Power oscillations
102			9%	-3%	0%	-4%	Current oscillates opp. of volt. / minimal Power oscillations
103	9	0.25 Hz	12%	0%	2%	-8%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
104			12%	-2%	4%	-10%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
105	4	0.25 Hz	1%	-1%	0%	-9%	Nearly constant current / Real & reactive power oscillate with voltage

Table 10.0.1 Inverter Response to Voltage Oscillations with f_{swing} = 0.25 Hz

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	8	1.0 Hz	11%	-3%	1%	-5%	Current oscillates opp. of volt. / Power oscillates opp. of volt.
102			11%	-3%	1%	-5%	Current oscillates opp. of volt. / Power oscillates opp. of volt.
103	9	1.0 Hz	11%	-2%	2%	-12%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
104			10%	-6%	3%	-14%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
105	4	1.0 Hz	2%	-1%	1%	-9%	Nearly constant current / Real & reactive power oscillate with voltage

Table 10.0.2 Inverter Response to Voltage Oscillations with f_{swing} = 1.0 Hz

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	8	2.0 Hz	13%	-3%	6%	-8%	Current oscillates opp. of volt. / delayed Power oscillation
102			13%	-5%	6%	-8%	Current oscillates opp. of volt. / delayed Power oscillation
103	9	2.0 Hz	11%	-2%	3%	-11%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
104			9%	-6%	5%	-15%	Current oscillates opp. of volt. / Power oscillations result from distorted current profile
105	4	2.0 Hz	3%	-3%	1%	-9%	Nearly constant current / Real & reactive power oscillate with voltage

Table 10.0.3 Inverter Response to Voltage Oscillations with f_{swing} = 2.0 Hz

10.1 Inverter Manufacturer #4

Figure 10.1.1 below indicates the behavior for Inverter 105 during voltage oscillations at different swing frequencies (0.25 Hz, 1 Hz, 2 Hz).

- Current remains nearly constant at 0.25 Hz, only deviating by 1% of nominal
- Current response is less constant at 1 Hz and 2 Hz causing slightly larger power deviations
- Active power (P) deviates up to 10% from the nominal power
- Inverter returns to steady-state after the event passes

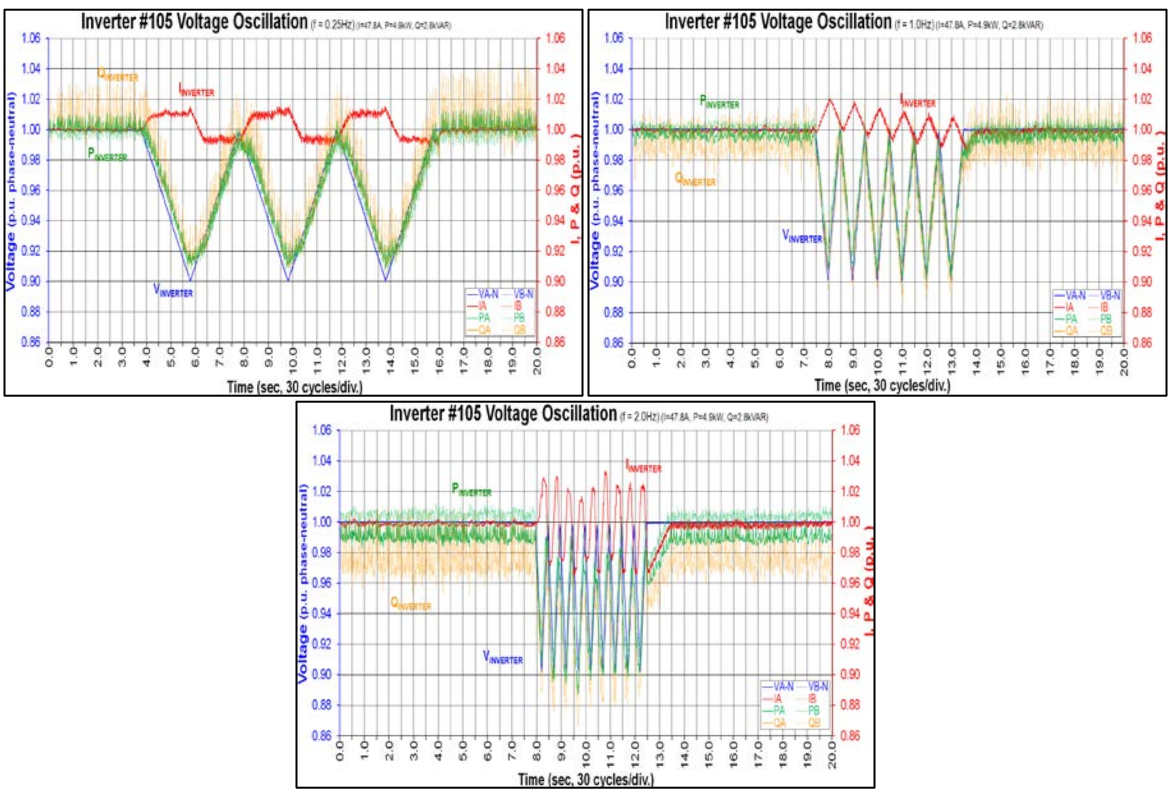

Figure 10.1.1 Voltage Oscillation (Manufacturer #4)

10.2 Inverter Manufacturer #8

Figure 10.2.1 below indicates the behavior for Inverters 101 and 102 during voltage oscillations at different swing frequencies (0.25 Hz, 1 Hz, 2 Hz).

- Current responds faster at 0.25 Hz to reduce changes in active power (P)
- Current response is slower at 1 Hz resulting in larger active power (P) deviations
- Current response is very slow at 2 Hz resulting in larger active power (P) oscillations
- Active power (P) deviates up to 8% from the nominal power
- Both inverters return to steady-state after the event passes

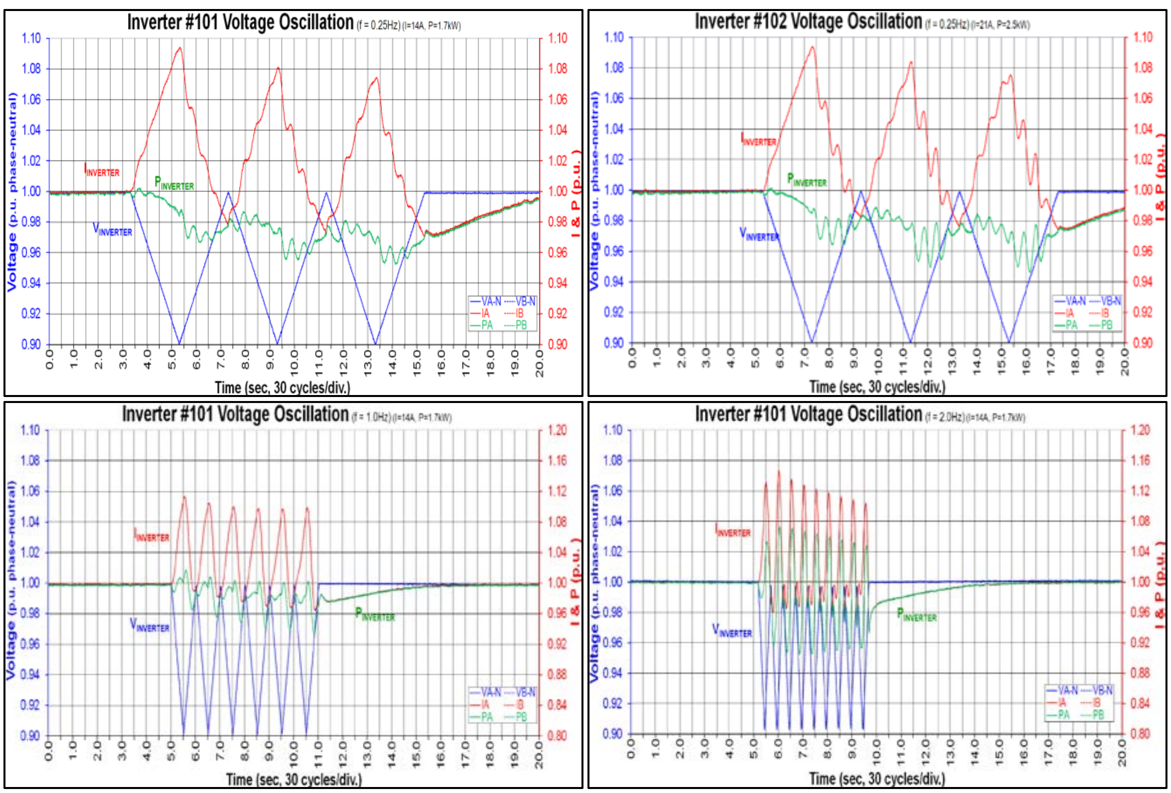

Figure 10.2.1 Voltage Oscillation (Manufacturer #8)

10.3 Inverter Manufacturer #9

Figure 10.3.1 below indicates the behavior for Inverters 103 and 104 during voltage oscillations at different swing frequencies (0.25 Hz, 1 Hz, 2 Hz).

- Current responds faster at 0.25 Hz, but suffers from irregular profile changes
- Current response is slower and less responsive at 1 Hz and 2 Hz causing larger power deviations
- Active power (P) deviates up to 15% from the nominal power
- Both inverters return to steady-state after the event passes

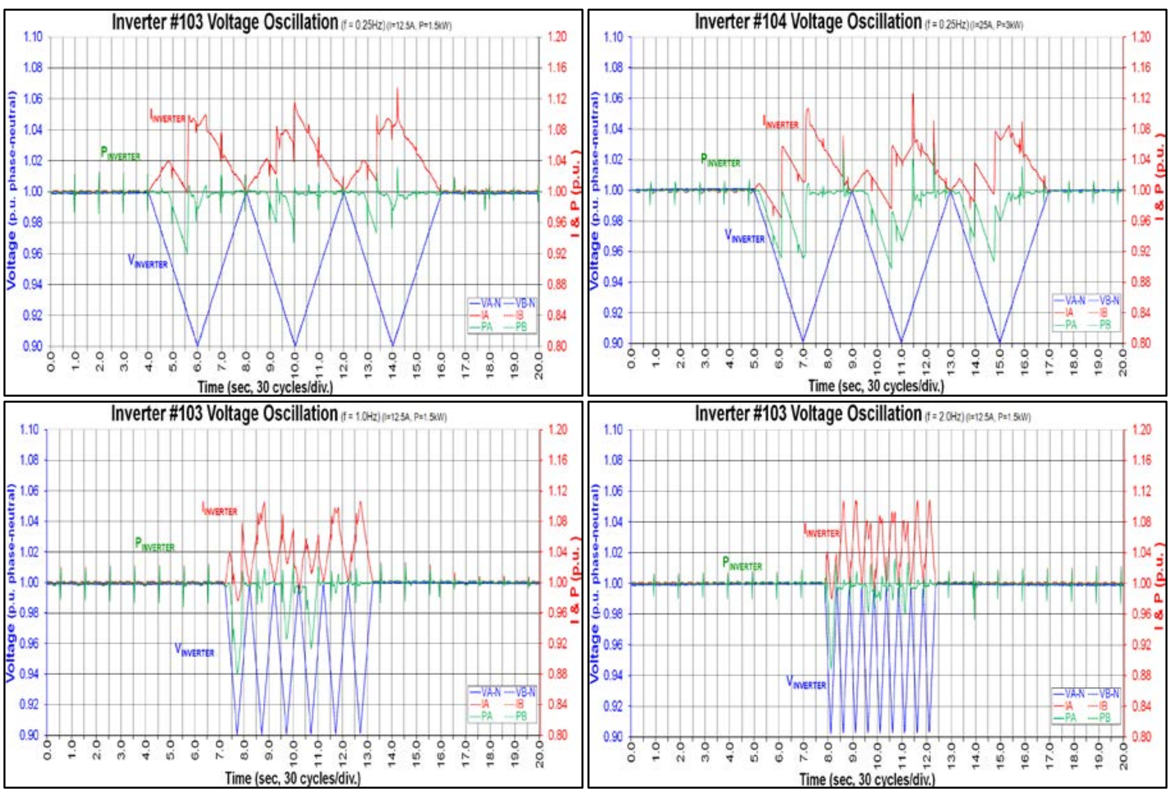

Figure 10.3.1 Voltage Oscillation (Manufacturer #9)

11.0 FREQUENCY OSCILLATION

The grid frequency was shifted between 59.4Hz and 60.4Hz to create frequency oscillations in order to assess the behavior of the inverters during these frequency variations. Frequency oscillations were performed at different rates, with swing frequencies of 0.25 Hz, 1 Hz, and 2 Hz. The inverters were operating in parallel at unity power factor with a resistive load, linear load.

Key findings:

- Inverters from Manufacturer #8 trip off during frequency oscillations due to their protection
- Inverters from Manufacturer #9 produce current and power deviations in a “step-shaped” profile
- Some changes in current and power occur as a delayed response, after frequency recovers to nominal
- Inverter #105 produces active (P) and reactive (Q) power oscillations

Table 11.0.1, Table 11.0.2, and Table 11.0.3 provides the overall performance of the tested inverters during frequency transients.

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	8	0.25 Hz	NA	NA	NA	NA	Inverter Tripped
102			NA	NA	NA	NA	Inverter Tripped
103	9	0.25 Hz	2%	-20%	2%	-20%	Current and Power step down during frequency oscillations
104			2%	-24%	2%	-24%	Current and Power step down during frequency oscillations
105	4	0.25 Hz	2%	-2%	14%	-16%	Real & React. Power oscillate opposite of each other (for both lines)

Table 11.0.1 Inverter Response to Frequency Oscillations with f_{swing} = 0.25 Hz

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	#8	1.0 Hz	NA	NA	NA	NA	Inverter Tripped
102			NA	NA	NA	NA	Inverter Tripped
103	#9	1.0 Hz	2%	-100%	2%	-100%	Current and Power step down after frequency returns to steady-state
104			2%	-36%	2%	-36%	Current and Power step down during frequency oscillations
105	#4	1.0 Hz	3%	-2%	14%	-18%	Real & React. Power oscillate opposite of each other (for both lines)

Table 11.0.2 Inverter Response to Frequency Oscillations with f_{swing} = 1.0 Hz

Inverter #	Manuf. #	f_{swing}	$I_{DEVIATION}$ (± %)		$P_{DEVIATION}$ (± %)		Comments
101	#8	2.0 Hz	NA	NA	NA	NA	Inverter Tripped
102			NA	NA	NA	NA	Inverter Tripped
103	#9	2.0 Hz	2%	-100%	2%	-100%	Current and Power step down after frequency returns to steady-state
104			2%	-11%	2%	-11%	Current and Power step down after frequency returns to steady-state
105	#4	2.0 Hz	3%	-3%	15%	-13%	Real & React. Power oscillate opposite of each other (for both lines)

Table 11.0.3 Inverter Response to Frequency Oscillations with f_{swing} = 2.0 Hz

11.1 Inverter Manufacturer #4

Figure 11.1.1 below indicates the behavior for Inverter 105 during frequency oscillations.

- Current remains constant during frequency oscillations
- Active power (P) on Line 1 and Line 2 oscillate in opposite of each other
- Active power (P) deviates as much as 18% of nominal during frequency oscillations
- Reactive power (Q) on each line oscillates the opposite direction of the corresponding active power

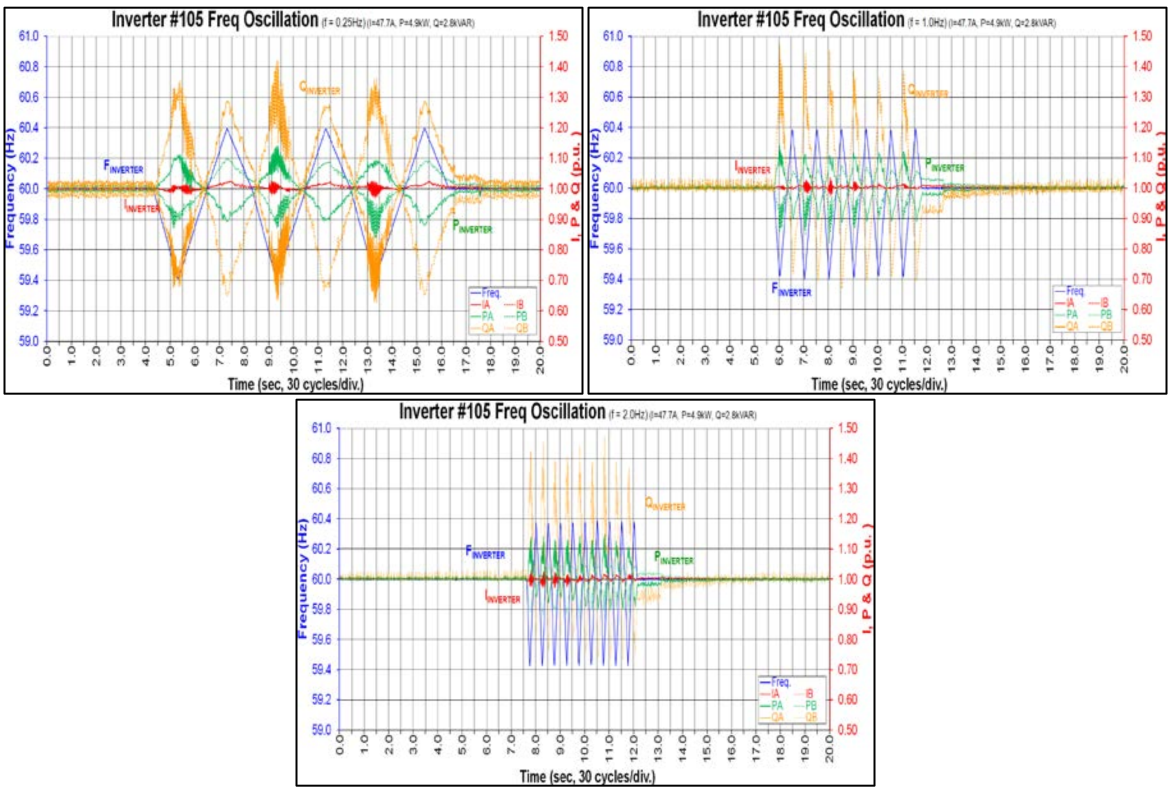

Figure 11.1.1 Frequency Oscillation (Manufacturer #4)

11.2 Inverter Manufacturer #8

Figure 11.2.1 below indicates the behavior for Inverters 101 and 102 during frequency oscillations.

- Inverters are very sensitive to changes in frequency
- Inverters tripped off immediately as a result of frequency oscillations

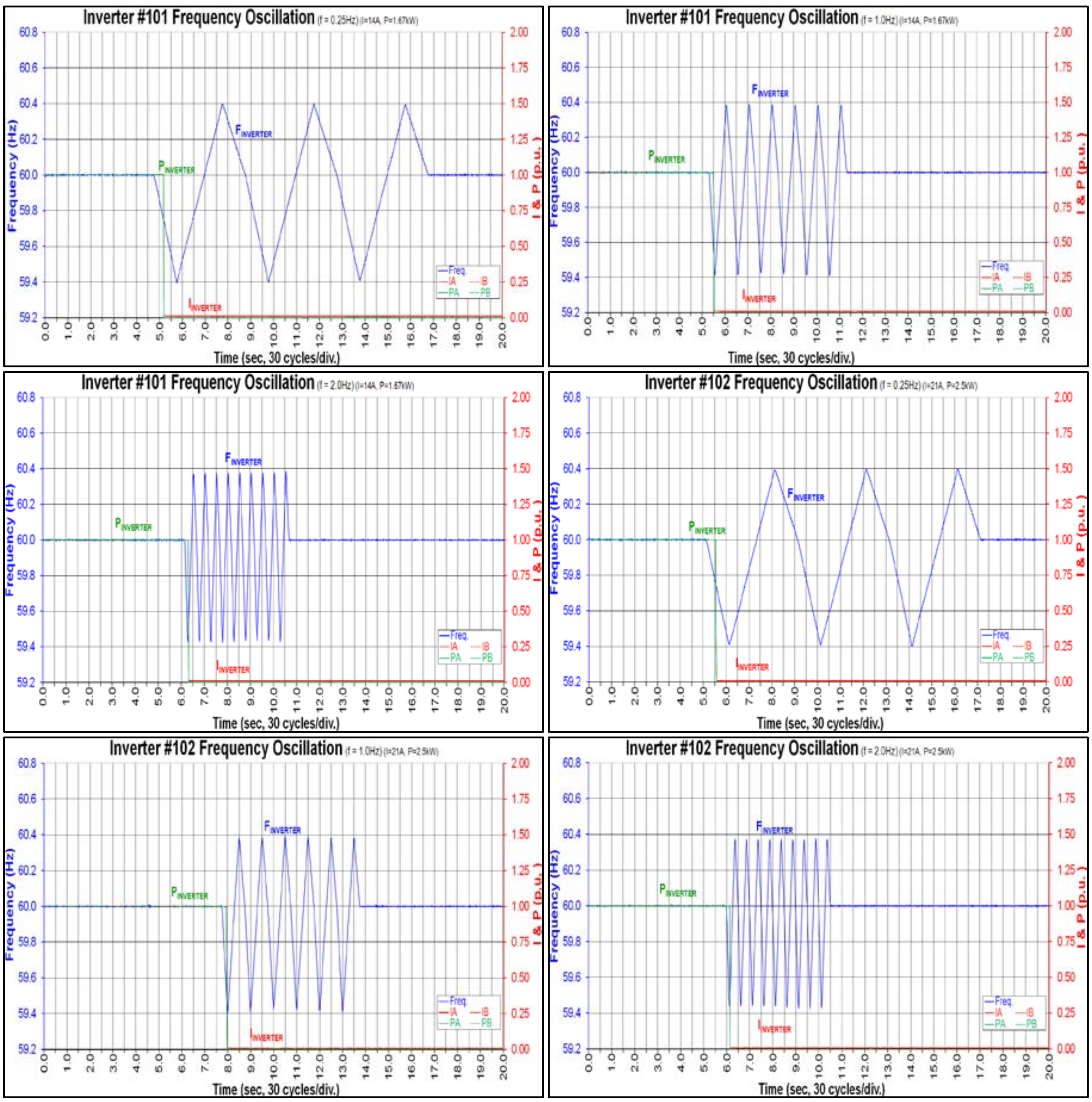

Figure 11.2.1 Frequency Oscillation (Manufacturer #8)

11.3 Inverter Manufacturer #9

Figure 11.3.1 indicates Inverters 103 and 104 behaviors during frequency oscillations.

- Current and active power (P) deviations appear to occur in “steps”
- Current and active power (P) deviated to as low as 0% and did not shutdown in the 1Hz test
- Current response is especially slow with swing frequencies of 1 Hz and 2 Hz, sometimes occurring after frequency has returned to its nominal value

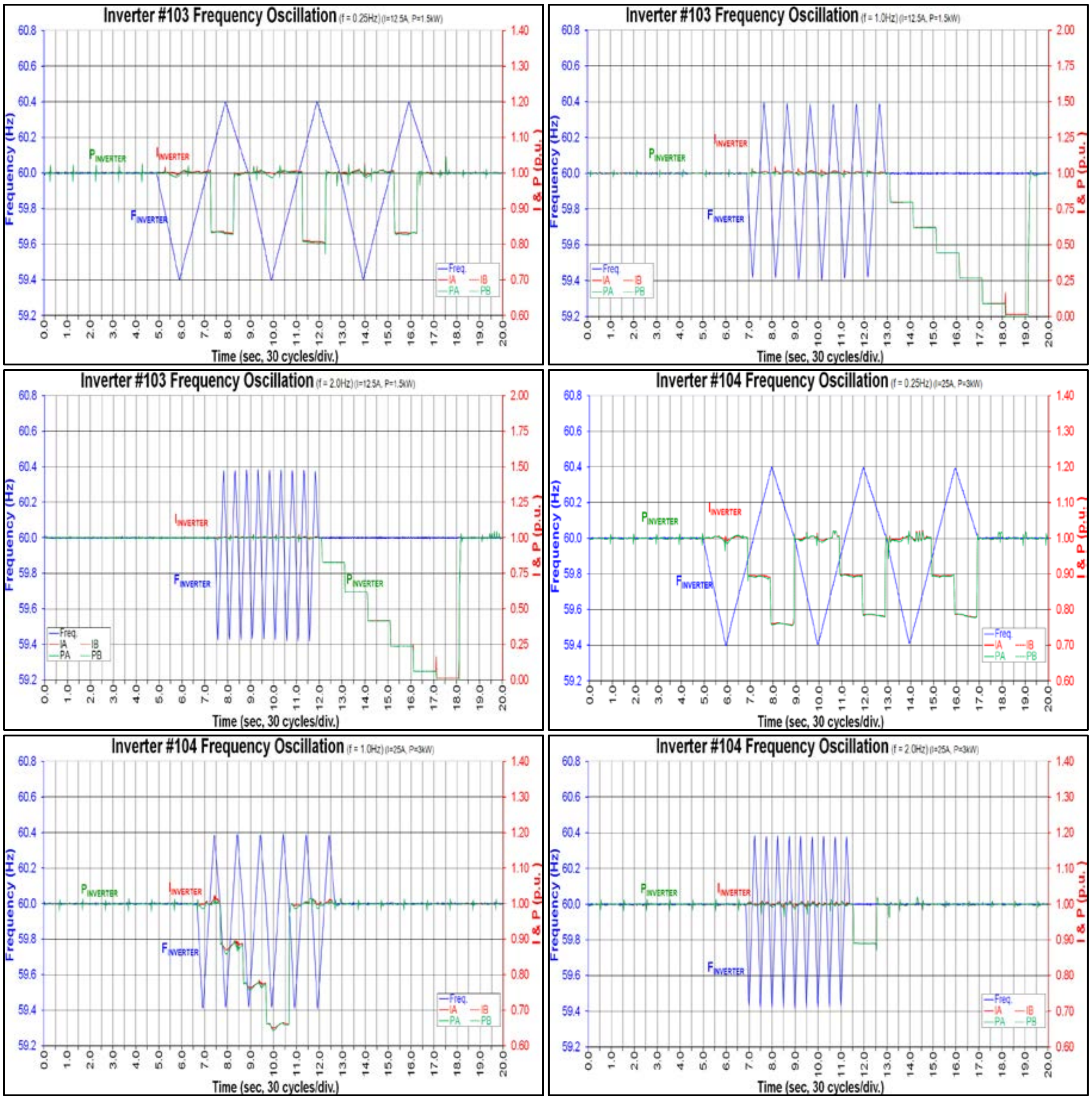

Figure 11.3.1Frequency Oscillation (Manufacturer #9)

12.0 CONSERVATION VOLTAGE REDUCTION (CVR)

The grid voltage was reduced from steady-state in increments of 1% to understand the inverters response and ability to maintain constant power. The inverters were operating at unity power factor and were in parallel with a resistive load.

Key findings:

- Most inverters provide a fast current response to support active power (P)
- Manufacturer #9 inverters prevent active power (P) loss than Manufacturer #8 inverters
- Manufacturer # 4 inverter does not prevent power loss, maintains constant current

12.1 Inverter Manufacturer #4

Figure 12.1.1 below indicates the behavior for Inverter 105 during the conservation voltage reduction test.

- Inverter maintains constant current during voltage reduction
  - Active (P) and reactive (Q) power decreases roughly by 1% for every 1% decrease in voltage
  - Current varies less than 1% of its nominal value
- Inverter does not prevent power loss

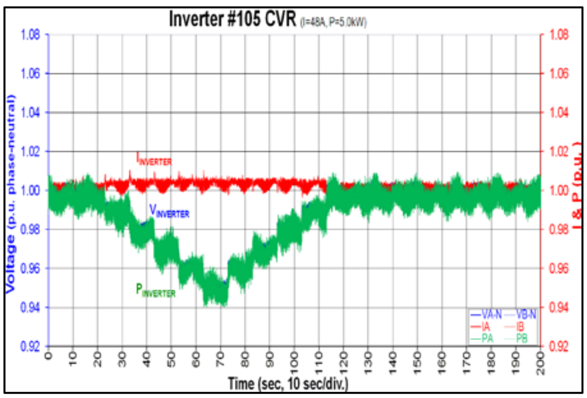

Figure 12.1.1 Conservation Voltage Reduction (Manufacturer #4)

12.2 INVERTER MANUFACTURER #8

Figure 12.2.1 below indicates the behavior for Inverters 101 and 102 during the conservation voltage reduction test.

- Inverters produce less active power (P) as voltage is reduced
- Inverters prevent some power loss by increasing the current
  - Current overshoots and then settles with each voltage step
  - Current increases roughly by 0.5% for every 1% decrease in voltage
- Inverters operate at a unity power factor and therefore contribute little reactive power (Q)

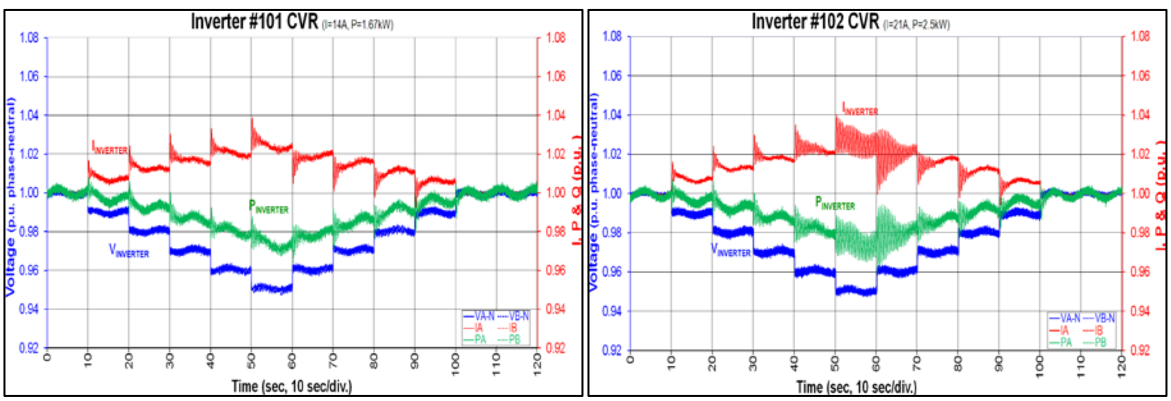

Figure 12.2.1 Conservation Voltage Reduction (Manufacturer #8)

12.3 INVERTER MANUFACTURER #9

Figure 12.3.1 below indicates the behavior for Inverters 103 and 104 during the conservation voltage reduction test.

- Inverters maintain constant active power (P) during voltage reduction
  - Current increases roughly by 1% for every 1% decrease in voltage
  - Current responds fairly quickly to support voltage
- Inverters operate at a unity power factor and therefore contribute little reactive power (Q)

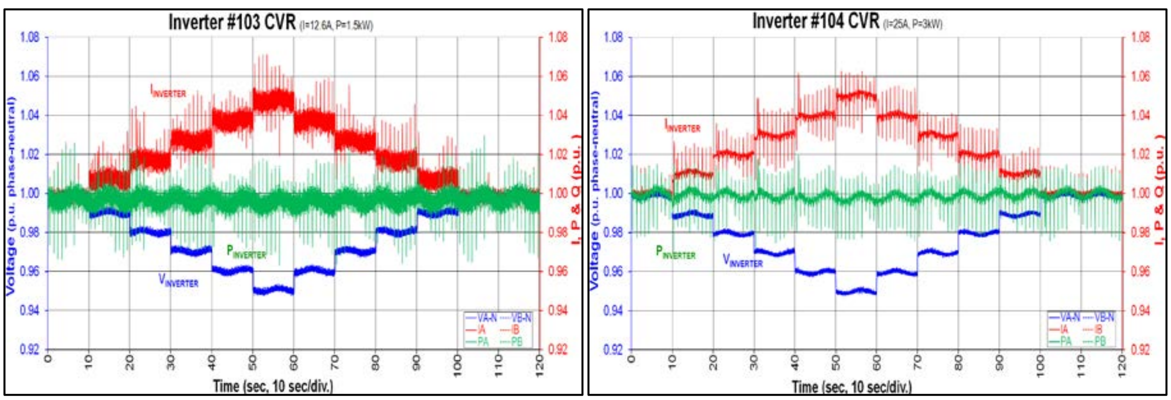

Figure 12.3.1 Conservation Voltage Reduction (Manufacturer #9)