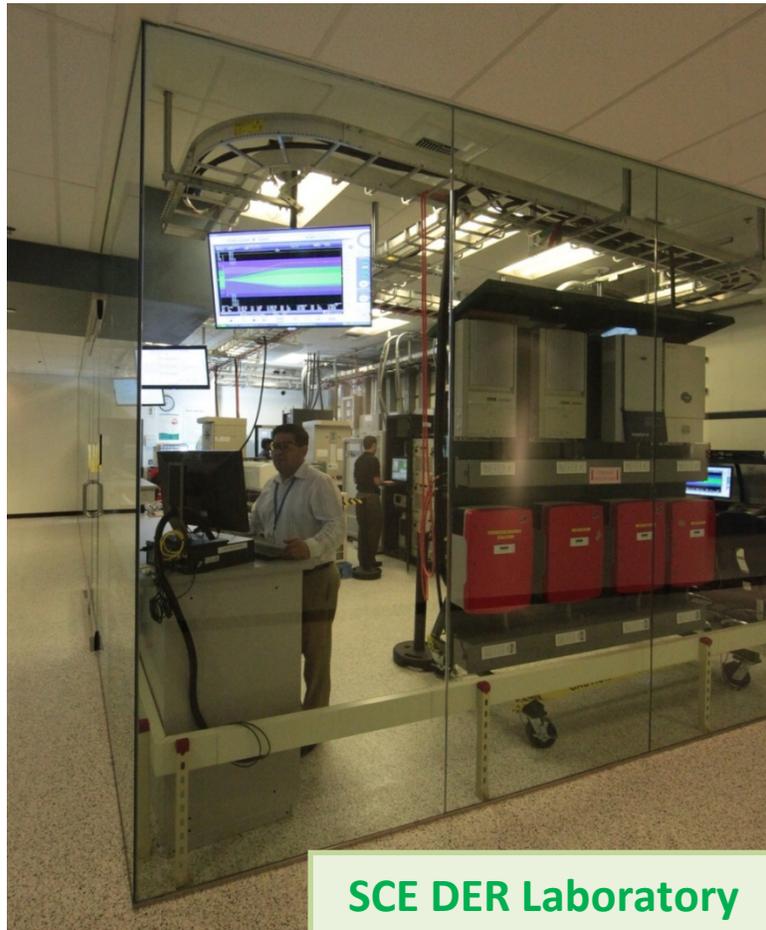


# Three-Phase German Solar PV Inverter Test Report



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## German Commercial Solar PV Inverter Test Report

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**1.0 EXECUTIVE SUMMARY**

This report will evaluate the dynamic performance of a three-phase commercial solar PV inverter designed to operate according to German grid code standards. Grid Advancement had previously tested various U.S. standard inverters as well as German residential inverters with advanced features. The testing for this inverter will be using a similar test methodology. The incentive for testing German grid code inverters is to evaluate the advanced features (voltage ride through, power curtailment, ramp rate, watts/over-frequency, voltage support, and communications) not currently available for inverters that follow U.S. standards. All tests were performed with the inverter advanced features enabled. The following steady-state, transient, and harmonic test results will be used to support SCE Field Engineering’s assessment of the advanced inverter characteristics and uncover any potential impacts or benefits from this inverter. As with the previous testing, the data will be used to:

- Influence the standards revisions such as UL1741, IEEE 1547, and California Rule 21, in order to ensure that these devices support the reliability of the grid
- Develop and/or validate solar PV models for distribution system impact studies
- Review and revise, if necessary, SCE internal standards (interconnection or working practices)

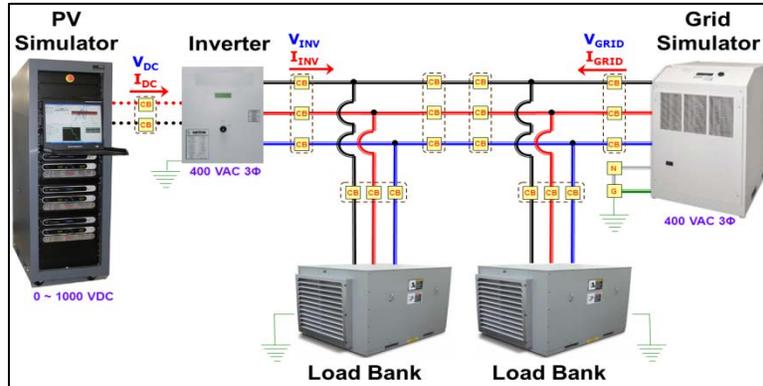
Table 1.0.1 has the specifications of the tested inverter. The inverter was tested in the Distributed Energy Resources (DER) Lab at SCE’s Fenwick facility in Westminster, California.

Inverter #	Ratings						Topology
	V <sub>AC</sub> (L-L)	Φ	P <sub>GEN</sub> (kW)	Freq. (Hz)	PF	V <sub>DC</sub> (MPPT)	
206	400	3	17.0	50 - 60	± 0.8	400 - 800	Transformerless

Table 1.0.1 German Commercial Solar PV Inverter Tested in Southern California Edison

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Figure 1.0.1 shows the test setup used in this testing. A test procedure for this purpose was created and has been shared with other organizations including manufacturers, national laboratories, and other utilities.



### Test Layout

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## 2.0 GRID DISCONNECTION TEST

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The inverter was islanded with varying amounts of load to better understand the temporary over-voltages (TOV) generated when it is disconnected from the grid. Table 2.0.1 summarizes the inverters behavior during these different islanding conditions. The detailed phase to ground TOV performance is shown Figure 2.0.1.

### Key findings:

- Temporary over-voltage behavior is typically reduced when the inverter is isolating from the grid with larger amounts of load. Additionally, the cases with load make the inverter shutdown faster than with no load.
- Highest temporary overvoltage is 145% of nominal voltage and occurs when islanding with no load
- The maximum time when the voltage goes above 100% is less than 3.2 cycles
- When islanded, the inverter will trip off within 27 cycles (within IEEE 1547 anti-islanding protection of 2 seconds)
- When islanding with load that matched the rated output, the inverter would typically take slightly longer to trip off
- Only islanding in the 0% load case generates Temporary Over Voltages (TOVs) outside the CBEMA or ITIC curve (tolerance envelope for voltage sensitive loads) into the prohibited region as shown in Figure 2.0.2
- The dynamic behavior is repeatable when performing multiple grid disconnection tests
- When disconnecting the inverter with no load, voltage across the switch goes up to 230% of nominal and have similar behavior of a discharging capacitor
  - Switch voltage is above nominal for more than 24 cycles

## German Commercial Solar PV Inverter Test Report

Inverter #	Inverter Manuf.	Rating (kW)	Load (kW)	% Load	Max. Instantaneous Over-Voltage (%)	Max. t(cycles) for V > 100%	Max. t(cycles) for V > 10%
206	Manuf. #4	17.00	0.00	0%	145	3.2	26.1
			4.18	25%	141	0.3	1.8
			8.35	49%	126	0.6	0.8
			12.49	73%	127	1.1	1.9
			16.66	98%	105	0.1	3.6

Table 2.0.1 Temporary Over-voltage Performance

# German Commercial Solar PV Inverter Test Report

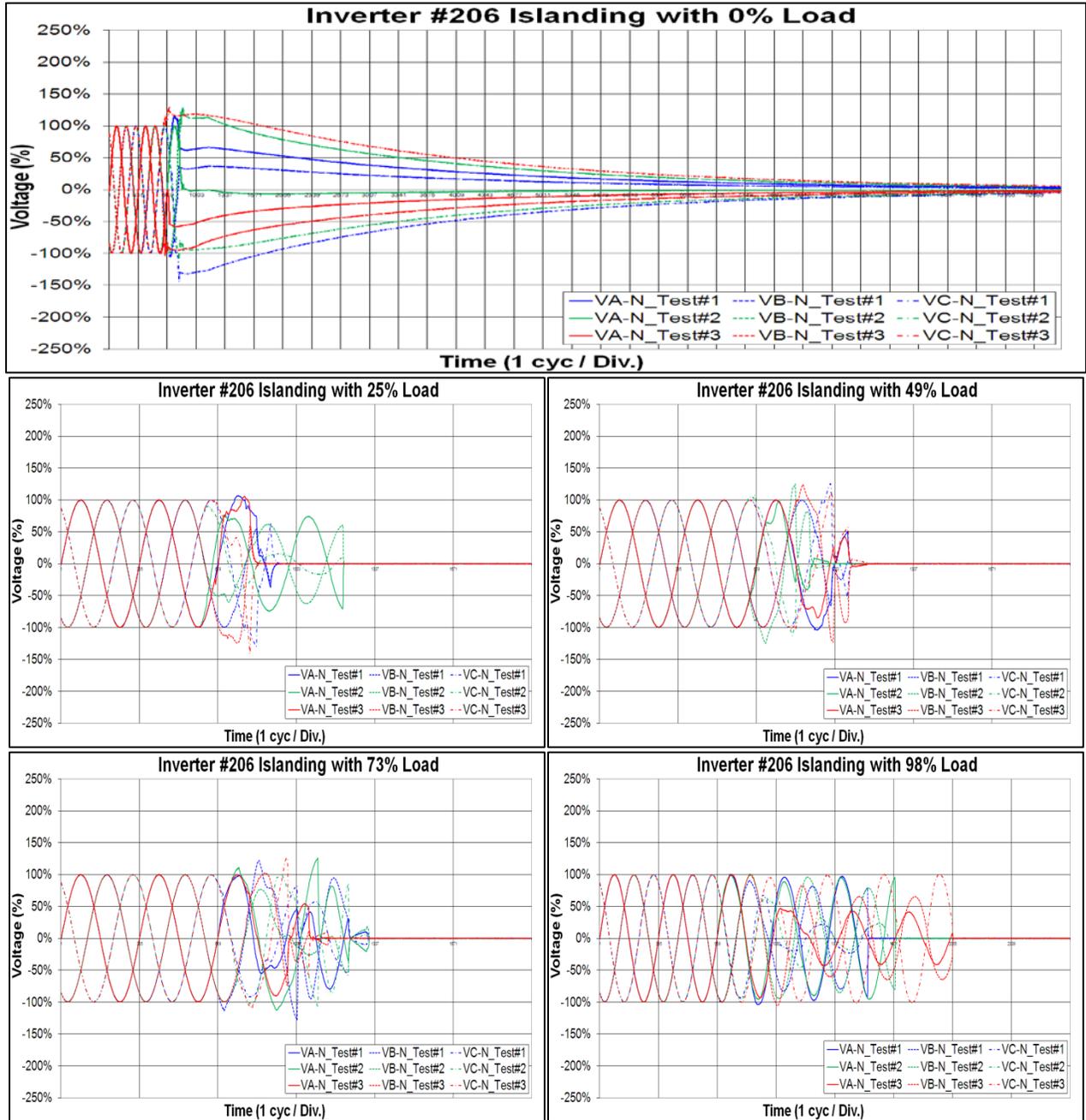


Figure 2.0.1 Temporary Over-voltages During Grid Disconnection with Different Loads

## German Commercial Solar PV Inverter Test Report

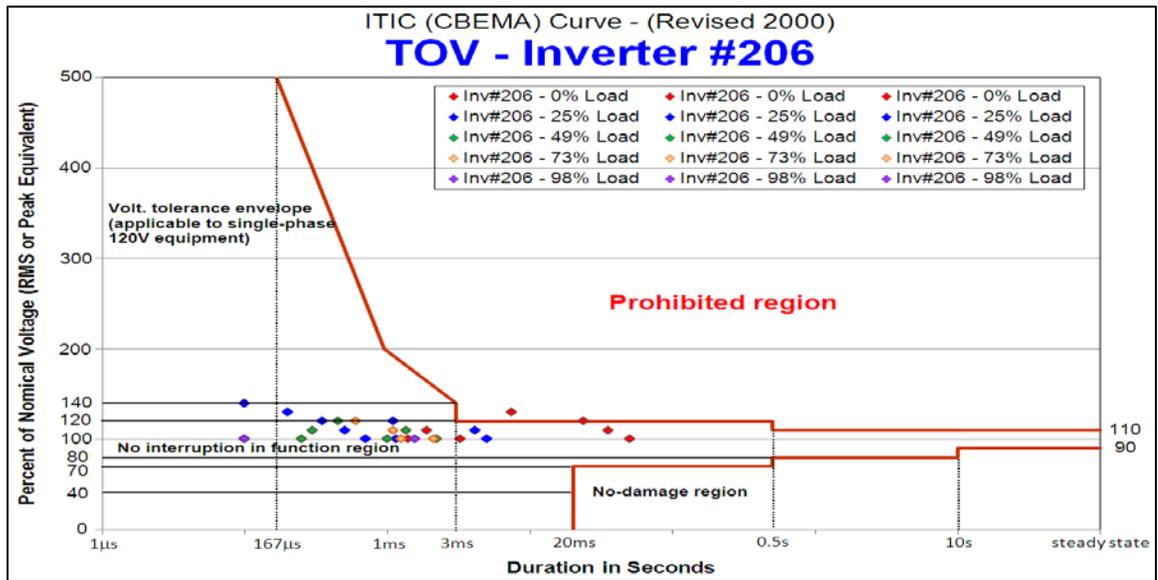


Figure 2.0.2 Temporary Over-voltages on ITIC (CBEMA)

Table 2.0.2 summarizes the inverters TOV across the switch during these different islanding conditions. The detailed phase to ground TOV performance is shown Figure 2.0.3.

Inverter #	Inverter Manuf.	Rating (kW)	Load (kW)	% Load	$V_{ACROSS-SWITCH}$ (%)	$t_{MAXIMUM}$ (cycles) for $V > 100\%$	$t_{MAXIMUM}$ (cycles) for $V > 150\%$
206	Manuf. #4	17.00	0.00	0%	230	24.3	9.2
			4.18	25%	116	0.1	0.0
			8.35	49%	109	0.1	0.0
			12.49	73%	148	1.7	0.0
			16.66	98%	120	0.6	0.0

Table 2.0.2 Voltage Across the Switch Over-voltage Performance

# German Commercial Solar PV Inverter Test Report

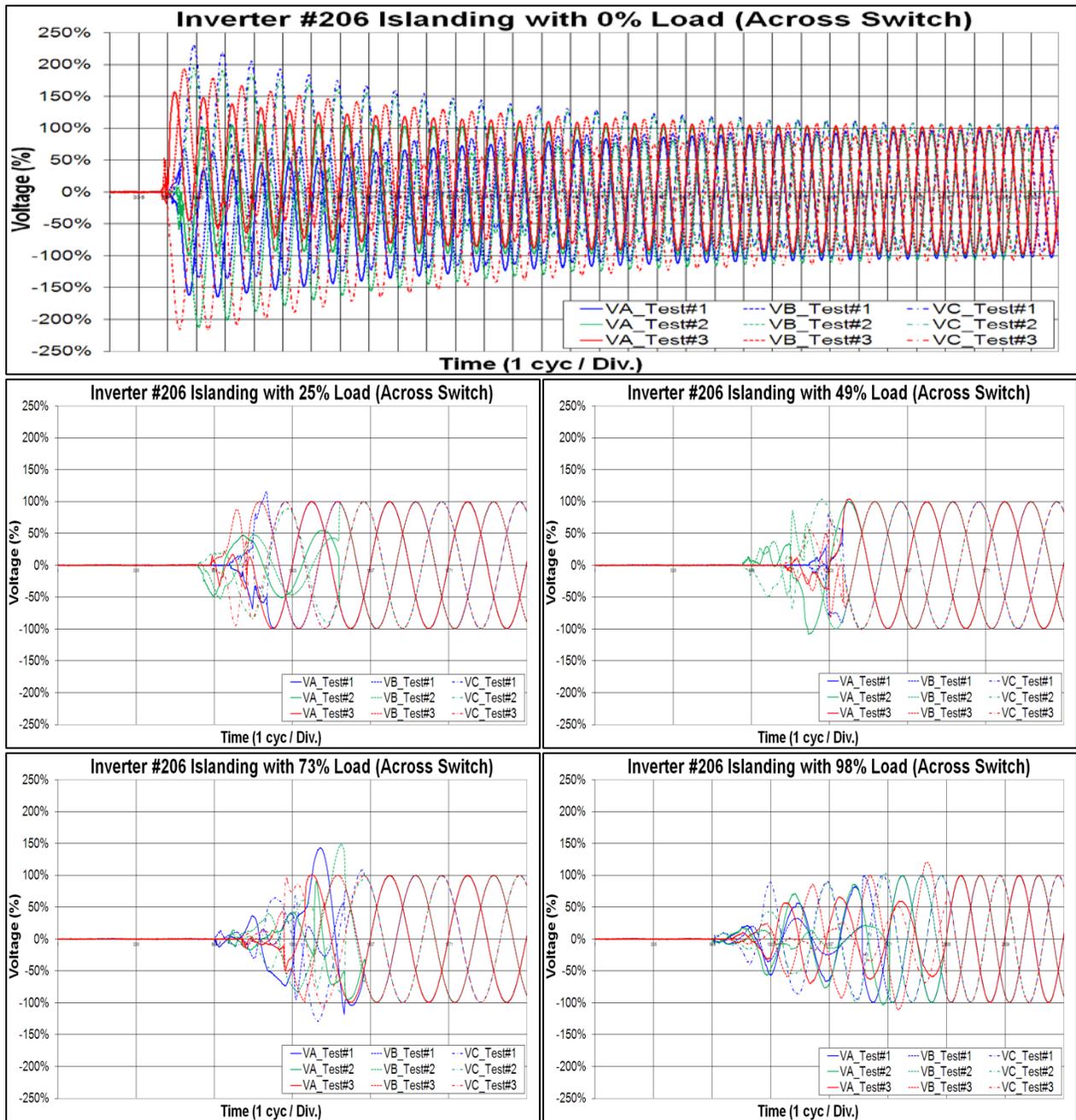


Figure 2.0.3 Voltage Across the Switch Over-voltages During Grid Disconnection with Different Loads

### 3.0 FAULT CURRENT CONTRIBUTION

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During these tests, the German commercial inverter was physically shorted in order to assess its short circuit current contribution. Table 3.0.1 summarizes the fault current parameter values for the inverter during the different types of fault tests. Figure 3.0.1 shows the detail performance of the inverter during various short circuit conditions.

#### Key findings:

- Maximum instantaneous fault current contribution ranges from 139% to 295% of nominal current within the first cycle during fault condition
- The maximum instantaneous short circuit current contribution is 295% (for < 1ms) during a three-phase to ground fault
- The longest short circuit current time above 100% is 7.9 cycles
- Instantaneous short circuit current less than 256% of the nominal current
- Maximum time to stop producing current (shutdown) ranges from 1.8 to 8.2 cycles
  - Shortest disconnection times occur for faults that include ground (1.8 ~ 2.1 cycles)
  - Longer disconnection times occur for phase-to-phase faults (7.8 ~ 8.2 cycles)
- Instantaneous fault current contributions (spikes) can vary for the same fault type
- Fault current duration times remained consistent for the same fault type

## German Commercial Solar PV Inverter Test Report

Inverter #	Inverter Manuf.	Fault	$I_{\text{MAXIMUM-INSTANTANEOUS}}$ (%)	$t_{\text{MAXIMUM}}$ (cycles) for $I > 100\%$	$t_{\text{MAXIMUM}}$ (cycles) to trip off
206	Manuf. #4	3Ph-Gnd	295%	1.8	1.8
		PhA-PhB-PhC	267%	2.9	7.8
		PhA-PhB-Gnd	225%	1.6	2.0
		PhB-PhC-Gnd	288%	1.9	1.9
		PhC-PhA-Gnd	193%	1.6	1.9
		PhA-PhB	253%	7.4	7.9
		PhB-PhC	256%	7.9	8.2
		PhC-PhA	247%	7.7	8.2
		PhA-Gnd	166%	1.7	1.9
		PhB-Gnd	186%	1.7	2.1
		PhC-Gnd	139%	1.4	1.9

Table 3.0.1 Short Circuit Performance

# German Commercial Solar PV Inverter Test Report

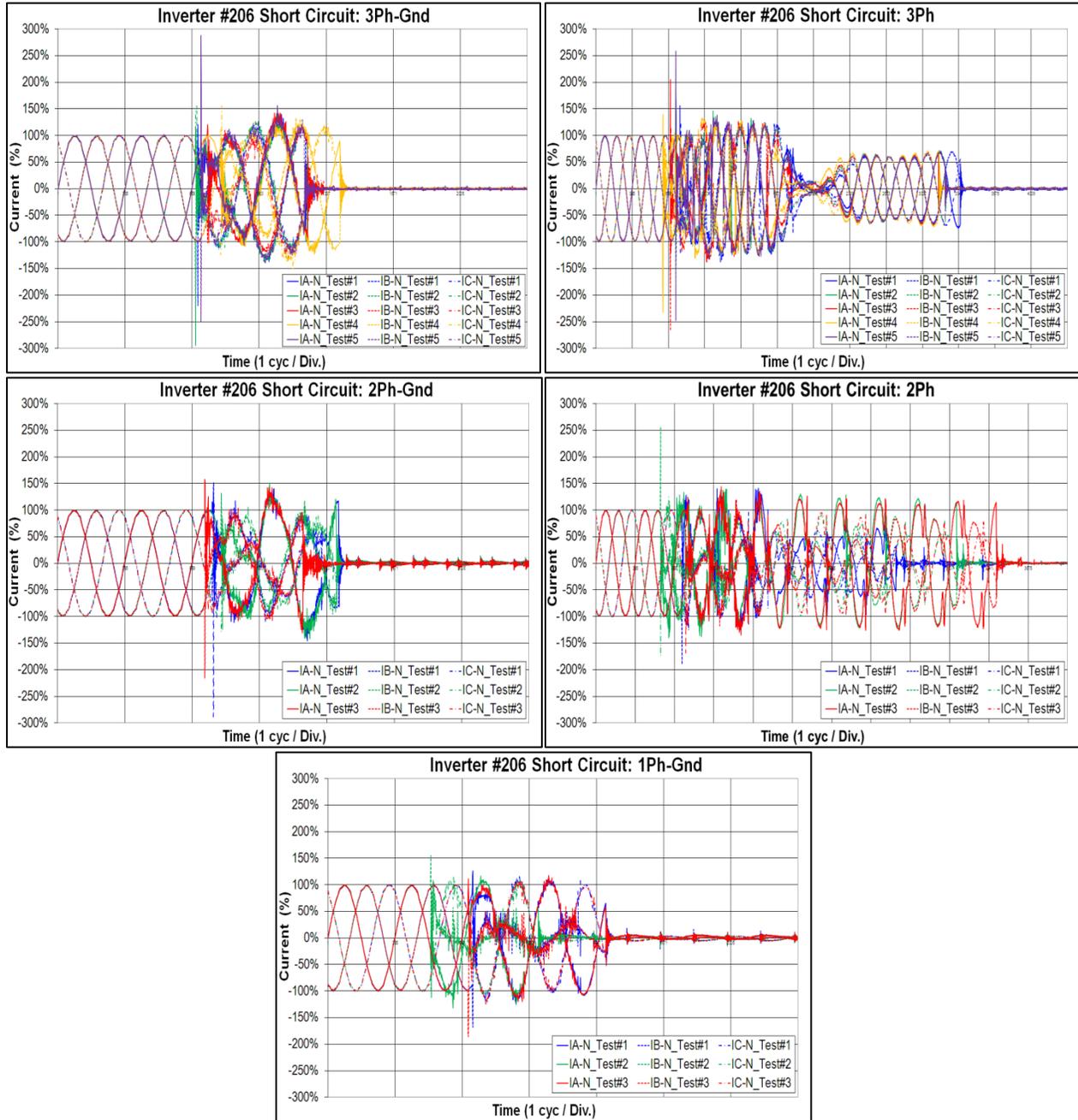


Figure 3.0.1 Fault Current Contribution

## 4.0 HARMONICS GENERATION

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The purpose of this test was to assess the inverter harmonics contribution. In this test, a high sampling voltage and current sinusoidal waveform data (1 million samples per second) was captured at the output of the inverter to calculate its harmonics contribution. Table 4.0.1 summarizes the harmonics contribution for this inverter and how it compares to U.S. standards. In addition, Figure 4.0.1 and Figure 4.0.2 display the individual harmonics values as well as the total harmonic distortion (THD). It is important to mention that the grid simulator have some harmonics and can be found in section 4.1.

- All harmonics are within the IEEE 1547 recommendations
- The inverter THD is less than half of IEEE 1547 maximum recommendations
- The inverter showed an increase in voltage and current THD when calculating up to the 700<sup>th</sup> harmonic as opposed to calculating up to the 100<sup>th</sup> harmonic
- Individual voltage harmonics are less than 0.05% of the fundamental
  - $H_3$  is the highest of the lower order harmonics (0.0469%)
  - $H_{419}$  is the highest of the high order harmonics (0.0386%)
- Individual current harmonics are less than 0.6% of the fundamental
  - $H_{11}$  is the highest of the lower order harmonics (0.5623%)
  - $H_{431}$  is the highest of the high order harmonics (0.2116%)

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Inv. #	Current Harmonics (% of Fundamental)						THD (up to 100 <sup>th</sup> harm.)		THD (up to 700 <sup>th</sup> harm.)	
	3rd	5th	7th	9th	11th	13th	%V	%I	%V	%I
201	1.51	0.33	0.25	0.23	0.18	0.15	0.09	2.00	0.15	2.02
202	0.71	0.24	0.16	0.15	0.16	0.16	0.11	1.41	0.44	2.47
203	0.72	0.19	0.12	0.08	0.11	0.10	0.10	1.35	0.35	1.57
205	0.22	0.20	0.16	0.15	0.10	1.08	0.19	1.28	0.19	1.28
206	0.18	0.44	0.40	0.05	0.56	0.25	0.11	1.16	0.16	1.24
<b>IEEE1547</b>	<b>4.00</b>	<b>4.00</b>	<b>4.00</b>	<b>4.00</b>	<b>2.00</b>	<b>2.00</b>		<b>5.00</b>		<b>5.00</b>

Table 4.0.1 Harmonic Contribution from German Inverters

# German Commercial Solar PV Inverter Test Report

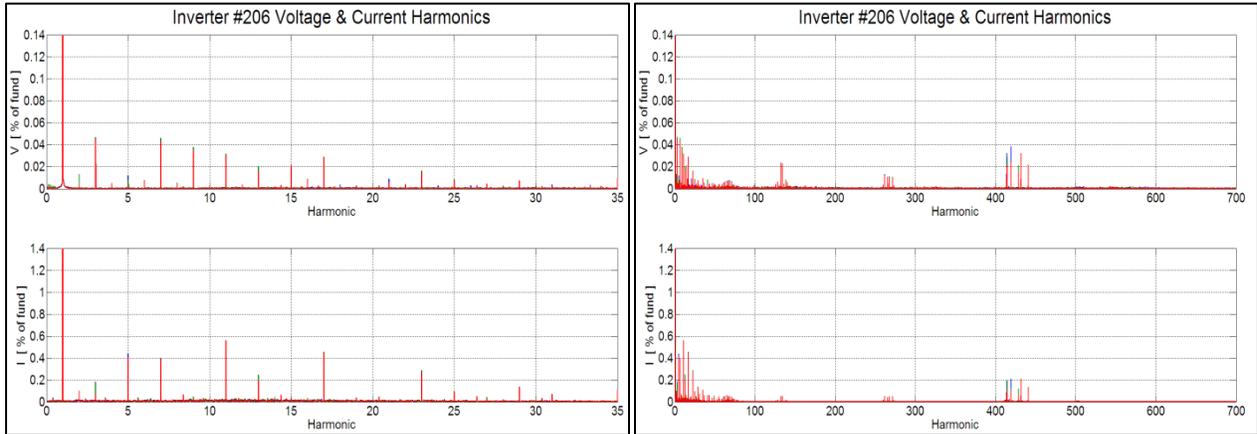


Figure 4.0.1 Voltage & Current Harmonics (1<sup>st</sup> - 35<sup>th</sup> and 1<sup>st</sup> - 700<sup>th</sup>)

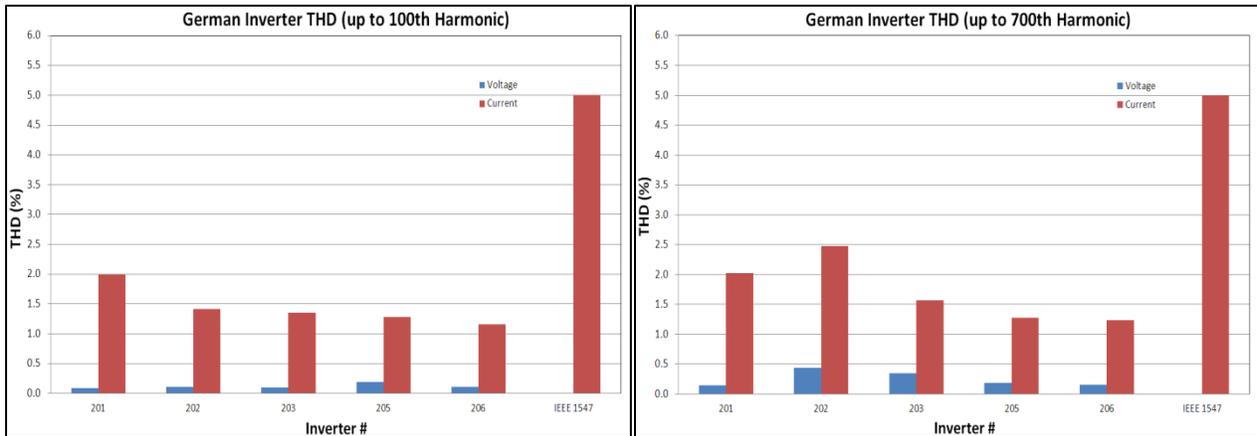


Figure 4.0.2 Total Harmonics Distortion (up to 100<sup>th</sup> and 700<sup>th</sup> Harmonic)

## 4.1 Grid Simulator

The grid simulator harmonics contributions are shown in Figure 4.1.1 as a percentage of the fundamental. The grid simulator was operating with a light resistive load, no inverter, to assess its worst harmonics generation.

- Individual voltage harmonics are less than 0.05% of the fundamental
  - $H_3$  is the highest of the lower order harmonics (0.0199%)
  - $H_{420}$  is the highest of the high order harmonics (0.0486%)
- Individual current harmonics are less than 0.6% of the fundamental
  - $H_3$  is the highest of the lower order harmonics (0.53%)
  - $H_{414}$  is the highest of the high order harmonics (0.15%)
- The grid simulator has both voltage and current harmonic contribution specially in the high order levels of about the 420<sup>th</sup> harmonic

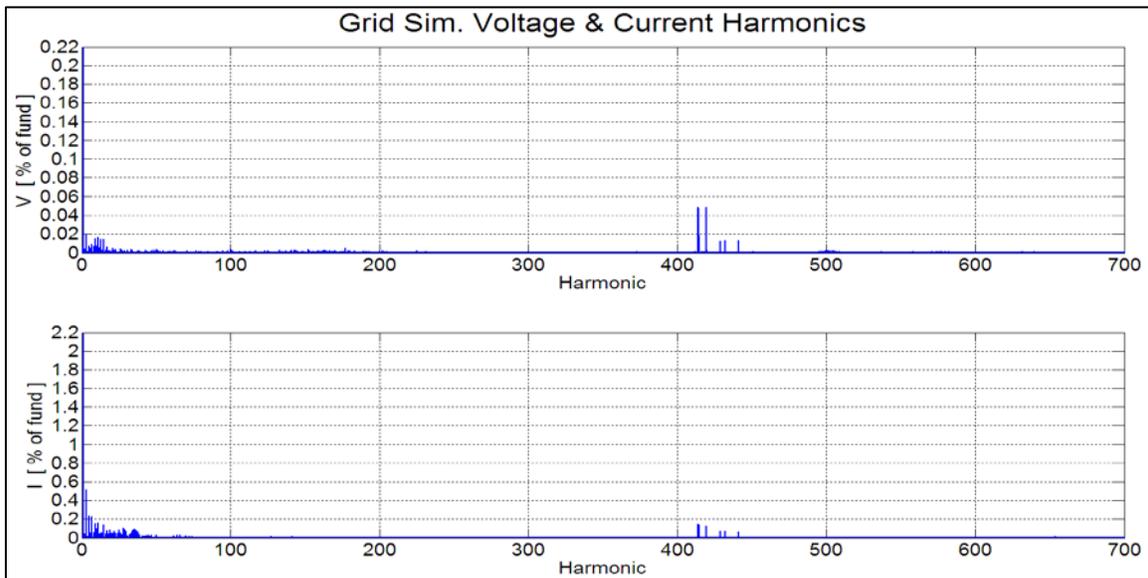


Figure 4.1.1 Harmonics Contribution (Grid Simulator)

## 5.0 VOLTAGE RAMP

The purpose of this test is to find the dynamic performance of the inverter during various voltages within 10% of steady state. For this test, the grid voltages were ramped down and up while maintaining constant load. The inverters advanced features, such as voltage support, were enabled during testing, as indicated in the results. Table 5.0.1 summarizes the deviation in current and power caused by the voltage ramping.

- Inverter initially attempts to maintain constant real power (P) during lower or higher voltages if current is within the appropriate limits
- When maximum current limit is reached, the inverter reduces its real power output to generate the necessary reactive power
  - Voltage/VAR support tests will be performed at 80% rated power to avoid this issue
  - Inverter should be designed with an additional 10% kVA capacity or the inverter should be designed like conventional generation; deliver rated power while operating over a range of 0.9 PF lag to 0.95 PF lead

Inverter #	Manuf. #	V <sub>DEVIATION</sub> (± %)	t <sub>RAMP</sub> (sec)	I <sub>DEVIATION</sub> (± %)	P <sub>DEVIATION</sub> (± %)	Q <sub>DEVIATION</sub> (± %)	Comments
206	Manuf. #4	-10%	4	+7%	-16%	+50%	
			8	+7%	-17%	+52%	
		+10%	4	-9%	-17%	-46%	
			8	-10%	-17%	-46%	

Table 5.0.1 Voltage Ramp Response

## 5.1 Voltage Ramps Down 10%

Figure 5.1.1 below indicates the behavior for Inverter 206 during voltage ramp-down tests.

- The inverters voltage support feature triggers and generates reactive power in response to under-voltage. The grid simulator voltage is very strong (90KVA) compared to the inverter (17KVA) so the system voltage cannot be changed
- The inverter current initially ramps up until it reaches its maximum output limit, 104% of its nominal rating
- Real power (P) drops down to approximately 80% nominal power after current is limited

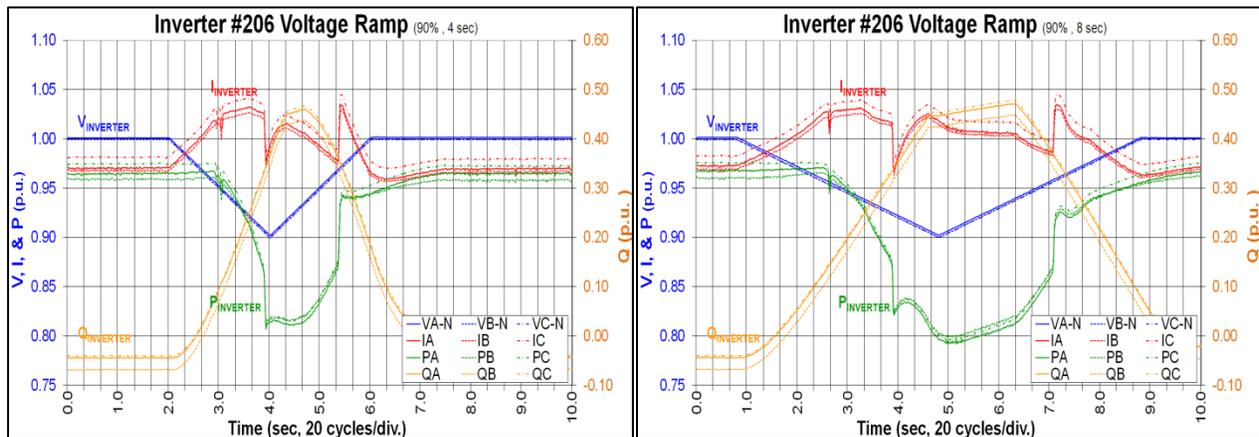


Figure 5.1.1 Voltage Ramp Down Response (4 sec. and 8 sec.)

## 5.2 Voltage Ramps Up 10%

Figure 5.2.1 below indicates the behavior for Inverter 206 during voltage ramp-up tests.

- The inverters voltage support feature triggers and absorbs reactive power in response to over-voltage. The grid simulator voltage is very strong (90KVA) compared to the inverter (17KVA) so the system voltage cannot be changed
- Current initially declines in order to maintain constant real power (P)
- Real power (P) falls below 80% nominal power at the peak of the voltage ramp

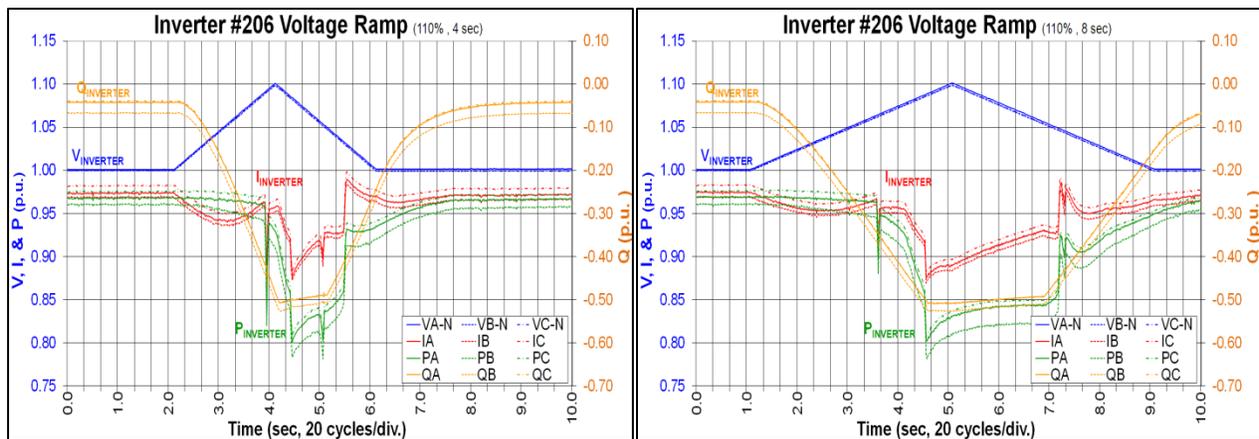


Figure 5.2.1 Voltage Ramp Up Response (4 sec. and 8 sec.)

## 6.0 FREQUENCY RAMP

The purpose of this test is to find out the inverters performance during various frequency deviations, specifically the response of the current and active power. For this test, the grid frequency was ramped down and up while maintaining constant load. Table 6.0.1 summarizes the deviation in current and active power and Figure 6.0.1 shows the detailed performance of inverter behavior during frequency ramping.

- Frequency ramped down to 59.4 Hz and back to 60 Hz in 8 and 4 second intervals
- Under-frequency protection did not trip off the tested inverter
- Negligible changes in current and power output (within 1% of steady state condition)

Inverter #	Manuf. #	t <sub>RAMP</sub> (sec)	F <sub>DEVIATION</sub> (Hz)	I <sub>DEVIATION</sub> (± %)	P <sub>DEVIATION</sub> (± %)	Q <sub>DEVIATION</sub> (± %)	Comments
206	4	4	59.4	+1% , - 0%	+1% , - 1%	+0% , - 0%	Negligible Current/Power Deviation
		8	59.4	+1% , - 0%	+1% , - 1%	+0% , - 0%	Negligible Current/Power Deviation

Table 6.0.1 Frequency Ramp Response

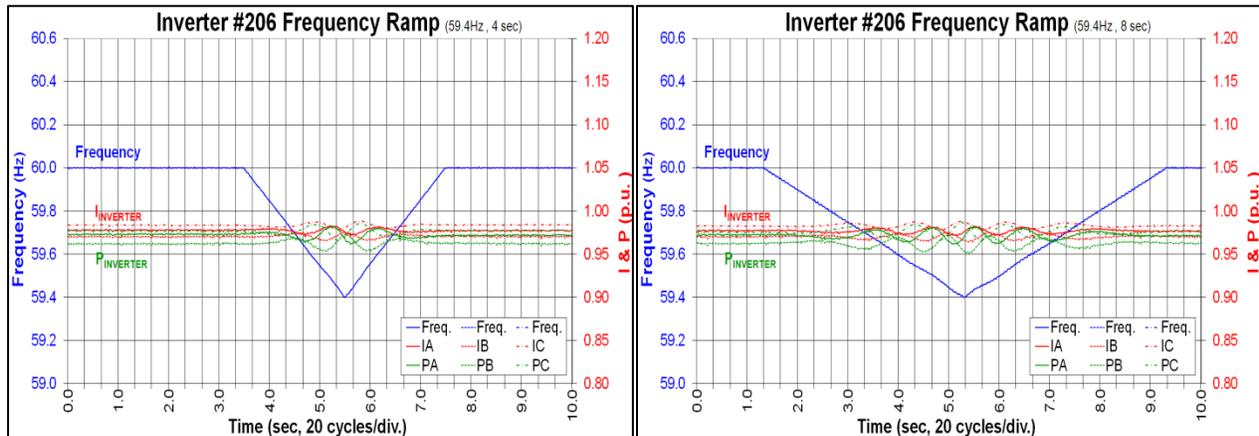


Figure 6.0.1 Frequency Ramp Response (4 sec. and 8 sec.)

## 7.0 VOLTAGE OSCILLATION

This test was performed to assess the inverter performance during voltage oscillations. For this test, the grid voltage was oscillated between 100% and 90% to create voltage oscillations with swing frequencies of 0.25 Hz, 1 Hz, and 2 Hz. Table 7.0.1 summarizes the inverter performance during voltage oscillations. Figure 7.0.1 displays the detailed performance of the inverter during voltage oscillations.

- The inverter generates reactive power that oscillates opposite of the programmed voltage
- Maximum current output is limited to 104% nominal, making it difficult to maintain a constant real power
- Real power ramps down as low as 80% of the inverters nameplate rating
- Current and real power deviations typically decrease at higher swing frequencies such as 1 Hz and 2 Hz because there is less impact from the Volt/VAR support due to its delayed response

Inverter #	Manuf. #	$f_{\text{swing}}$	$I_{\text{DEVIATION}} (\pm \%)$	$P_{\text{DEVIATION}} (\pm \%)$	$Q_{\text{DEVIATION}} (\pm \%)$	Comments
206	4	0.25 Hz	+7% , - 0%	+0% , - 16%	+50% , +15%	Current oscillates opp. of volt. (limited to 103% current) / Power oscillates with volt.
		1.0 Hz	+6% , - 1%	-1% , - 8%	+38% , +26%	Current oscillates opp. of volt. (limited to 103% current) / Power oscillates with volt.
		2.0 Hz	+6% , - 0%	-4% , - 7%	+36% , +28%	Current oscillates opp. of volt. (limited to 103% current) / Power oscillates with volt.

Table 7.0.1 Voltage Oscillation Response ( $f_{\text{swing}} = 0.25, 1.0, 2.0 \text{ Hz}$ )

# German Commercial Solar PV Inverter Test Report

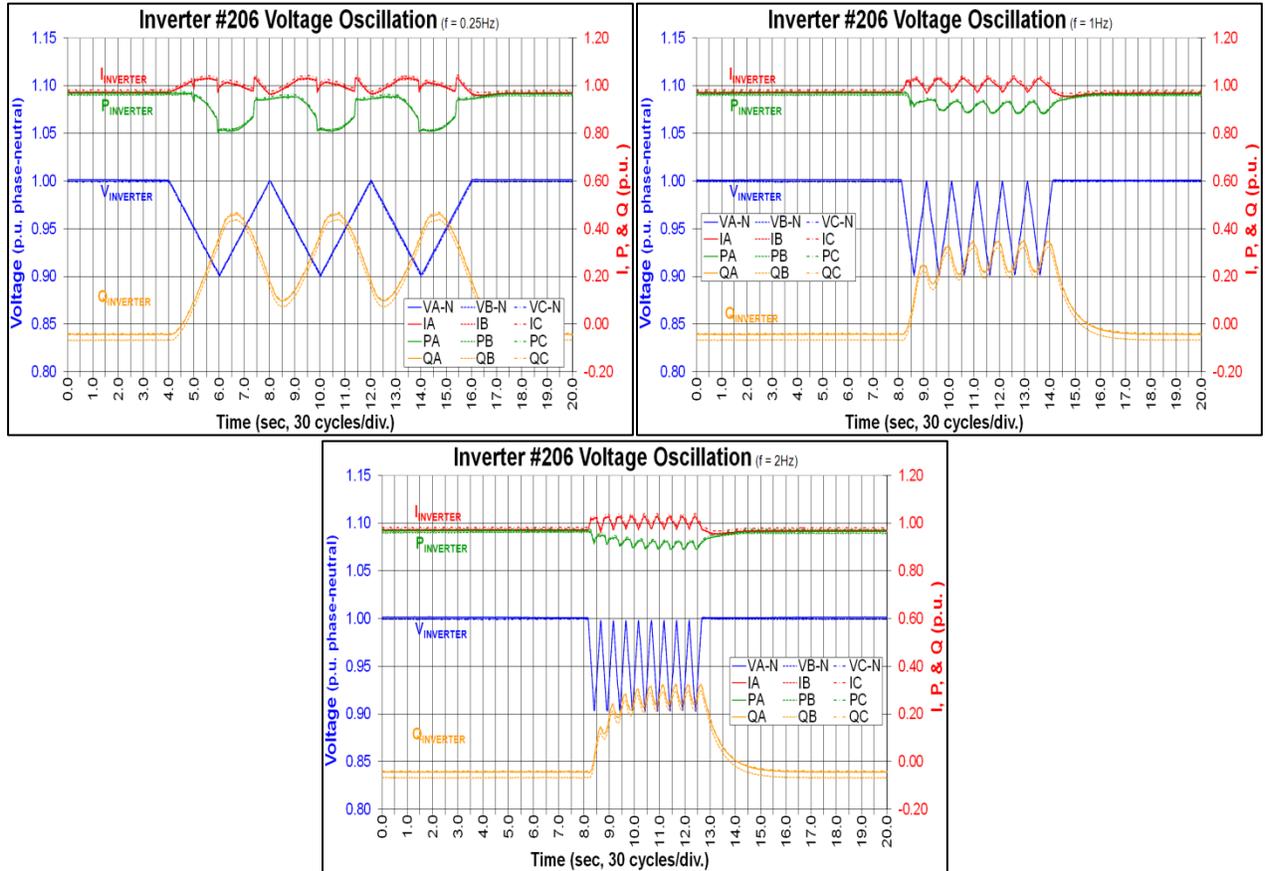


Figure 7.0.1 Voltage Oscillation Response (0.25Hz, 1 Hz, and 2 Hz)

## 8.0 FREQUENCY OSCILLATION

This test was performed to assess the inverter performance during frequency oscillations. For this test, the grid frequency was shifted between 59.4Hz and 60.4Hz. Frequency oscillations were performed at different rates, with swing frequencies of 0.25 Hz, 1 Hz, and 2 Hz. Table 8.0.1 shows the performance of the inverter during frequency oscillations and Figure 8.0.1 provides the detailed performance of the inverter during frequency oscillation tests.

- Frequency protection did not trigger, inverter rode through all frequency oscillations
- Inverter power curtailment feature reduces real power output linearly in response to the over-frequency
- Higher swing frequencies (1 and 2 Hz) result in a delayed response of the power curtailment feature

Inverter #	Manuf. #	$f_{\text{swing}}$	$I_{\text{DEVIATION}} (\pm \%)$	$P_{\text{DEVIATION}} (\pm \%)$	$Q_{\text{DEVIATION}} (\pm \%)$	Comments
206	4	0.25 Hz	+0% , -8%	+0% , -8%	+0% , -0%	Current/Power deviate during over-frequency
		1.0 Hz	-1% , -9%	-1% , -9%	+0% , -0%	Current/Power deviate during over-frequency (delayed response results in step-down behavior)
		2.0 Hz	-1% , -9%	-1% , -9%	+0% , -0%	Current/Power deviate during over-frequency (delayed response results in step-down behavior)

Table 8.0.1 Frequency Oscillation Response ( $f_{\text{swing}} = 0.25, 1.0, \text{ and } 2.0 \text{ Hz}$ )

# German Commercial Solar PV Inverter Test Report

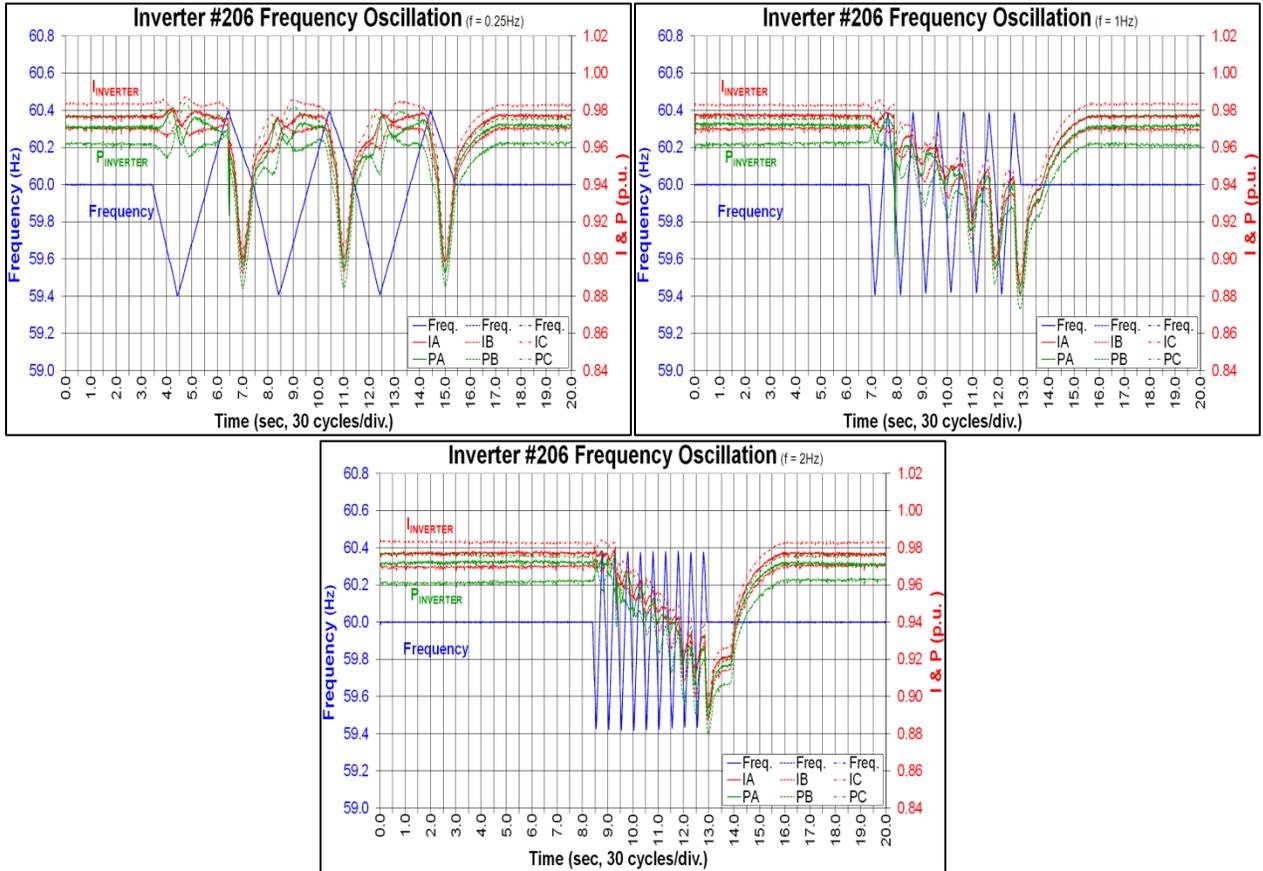


Figure 8.0.1 Frequency Oscillation Response (Inverter #201)

## 9.0 CONSERVATION VOLTAGE REDUCTION

The purpose of this test was to find out the inverter performance during 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 over longer periods in the cases where the system undergoes CVR. Figure 9.0.1 provides the detailed performance of the inverter during CVR tests.

- Inverter maintains nearly constant active power (P) until the maximum output current limit is reached
  - Current becomes clipped just below 102% of the inverters current nameplate rating
- Prior to the output current limit, current increases about 1% for every 1% decrease in voltage
- Inverters voltage support feature results in the generation of reactive power for each voltage step
- Real power (P) drops as far as 91% of the inverters nameplate rating

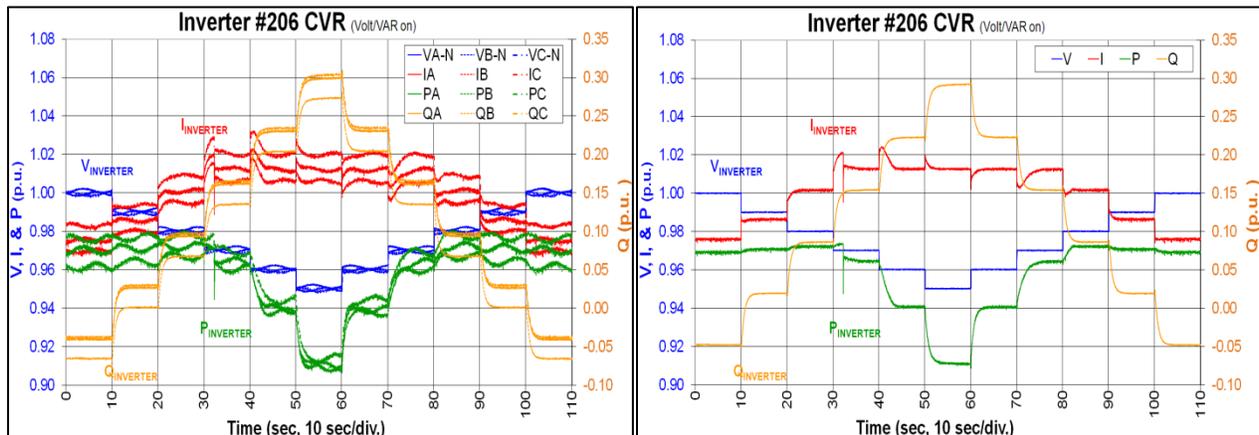


Figure 9.0.1 Conservation Voltage Reduction

# ADVANCED FEATURES TESTING

## 10.0 ADJUSTABLE START-UP POWER RAMP RATES

---

The inverter was energized at the output AC terminals with the grid simulator and then fed power into its DC terminals with the PV simulator. This was performed in order to assess the start-up or restarting performance of the inverter. The power ramp function can be used to slowly increase the inverter output power at an adjustable ramp-up rate when starting up or on reconnection. The test results are shown in Figure 10.0.1.

### Adjustable Settings:

- **WGra:** is the power ramp rate. It can be set from 1 to 1000%  $P_{MAX}$  per second; the default setting is 20%  $P_{MAX}$  per second

### Tests performed:

- Slope A = 20%  $P_{MAX}$  per second (ramp duration of 5 seconds)
- Slope B = 2%  $P_{MAX}$  per second (ramp duration of 50 seconds)

### Results:

- The inverter followed the expected slope behavior based on the setting
- No unexpected issues involving the system voltage upon start-up

### Benefits:

- Mitigate distribution circuit voltage fluctuations during start-up conditions at high solar PV penetrations

# German Commercial Solar PV Inverter Test Report

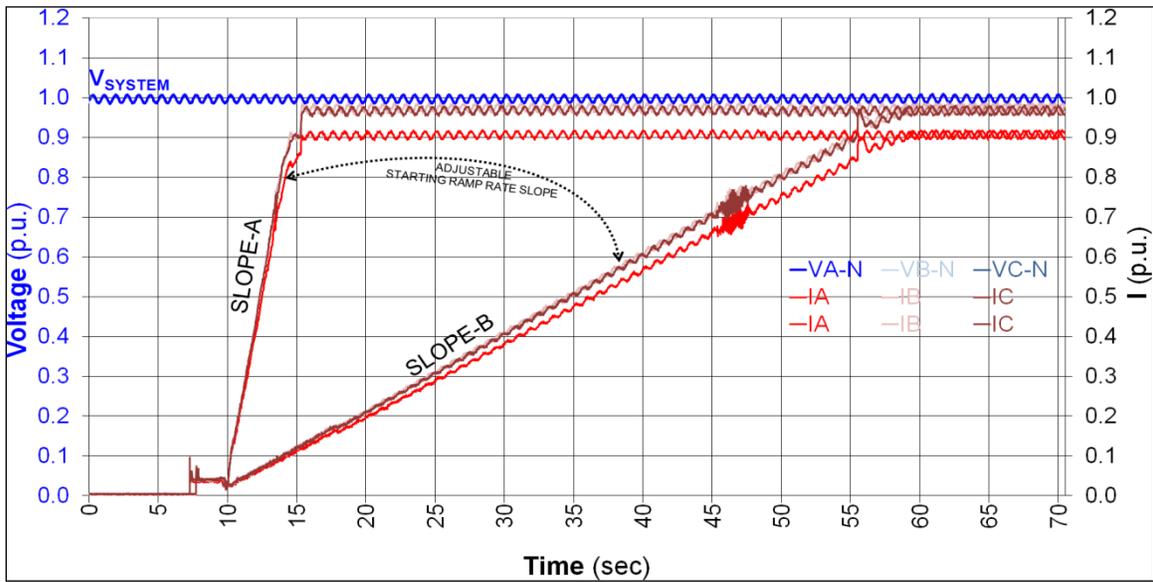


Figure 10.0.1 Adjustable Start-up Power Performance

## 11.0 LOW VOLTAGE RIDE THROUGH

---

Fault Induced Delayed Voltage Recovery, or FIDVR, is a grid event where system voltage remains at significantly reduced levels for several seconds after a fault has been cleared. Significant load loss due to motor protective device action can result, as can significant loss of generation, with a potential secondary effect of high system voltage due to the load loss. The grid simulator voltage was programmed to output a FIDVR event profile, as shown in Figure 11.0.1, in order to assess the inverter's ride through behavior, specifically the response of the current and active power to the reduced voltage. Voltage falls to 45% and takes approximately 16 seconds to recover followed by a system over-voltage.

### Adjustable Settings:

- Adjustable voltage protection thresholds and corresponding clearing times
  - **Vac-Min:** is the slow voltage protection set point
  - **Vac-Min-Tm:** is the timer for the slow voltage protection set point
  - **Vac-Min-Fast:** is the fast voltage protection set point
  - **Vac-Min-Fast-Tm:** is the timer for the fast voltage protection set point
- **DGS-PWMVoINom:** is the Low Voltage Threshold. The inverter will cease generating power to the grid when voltage falls below this value
- **DGS-HystVoINom:** is the restart Hysteresis. The inverter begins generating again when voltage exceeds the sum of this value and the cease generation voltage threshold

### Tests Performed:

- LVRT during FIDVR event without triggering cease generation feature (passive)
- LVRT during FIDVR event using cease generation feature (active)

Benefits:

- Support the grid during contingencies such as FIDVR events and prevent unnecessary tripping for large penetrations of solar PV generation

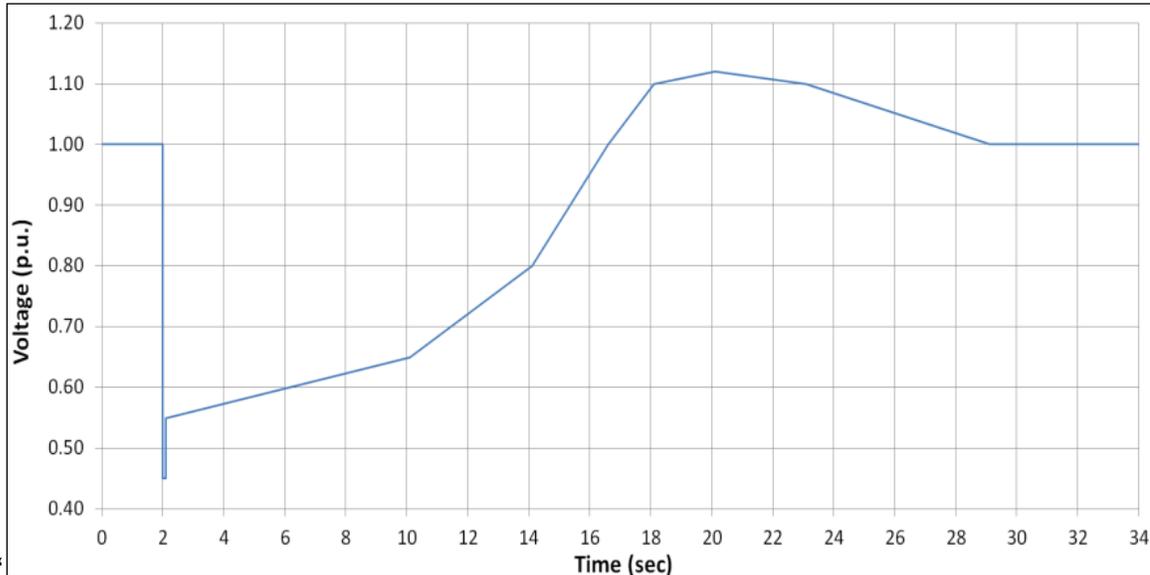


Figure 11.0.1 SCE Distribution FIDVR Profile

One of the inverters had different names and additional protection settings, as shown in Table 11.0.1.

- **VolCtl.hhLim:** is the fast high voltage protection set point
- **VolCtl.hhLimTms:** is the timer for the fast high voltage protection set point
- **VolCtl.hLim:** is the slow high voltage protection set point
- **VolCtl.hLimTms:** is the timer for the slow high voltage protection set point
- **VolCtl.iLim:** is the fast low voltage protection set point
- **VolCtl.iLimTms:** is the timer for the fast low voltage protection set point
- **VolCtl.iLim:** is the slow low voltage protection set point

## German Commercial Solar PV Inverter Test Report

- **VolCtl.IILimTms:** is the timer for the slow low voltage protection set point
- **DGS-PWMVolNom:** is the Low Voltage Threshold. The inverter will cease generating power to the grid when voltage falls below this value
- **DGS-HystVolNom:** is the restart Hysteresis. The inverter begins generating again when voltage exceeds the sum of this value and the cease generation voltage threshold

Name	Min. Value	Max. Value	Default Value	Unit
VolCtl.hhLim	100	300	-	V
VolCtl.hhLimTms	0	60	-	s
VolCtl.hLim	100	280	-	V
VolCtl.hLimTms	0	60	-	s
VolCtl.ILim	45	230	-	V
VolCtl.ILimTms	0	10	-	s
VolCtl.IILim	45	230	-	V
VolCtl.IILimTms	0	10	-	s
DGS-HystVolNom	0	100	5	%
DGS-PWMVolNom	0	100	70	%

Table 11.0.1 Voltage Protection Parameters

### 11.1 LVRT when Voltage above Threshold

Figure 11.1.1 shows the inverter behavior during a FIDVR event when the voltage is not low enough (above the setting “**DGS-PWMVoINom**”) for the inverter to cease generating power into the grid. Only the voltage protection parameters were changed.

#### Test Settings:

- Low Voltage Threshold = 40%
- Restart Hysteresis = 5%

#### Test Results:

- Inverter stays online and continues generating power for the entire FIDVR event
- Voltage support feature enables the inverter to generate/absorb reactive power during the under-voltage and over-voltage conditions
- During under-voltage condition, inverter produces maximum output current to support generation
  - Current clipped at nearly 100% nameplate rating for most of voltage recovery
  - Available current is used to generate reactive power before real power
- During over-voltage condition, the inverter reduces current in an attempt to maintain constant power
  - Real power reduced to 80% of inverter nameplate rating
  - Reactive power is absorbed in an attempt to reduce the overvoltage condition

# German Commercial Solar PV Inverter Test Report

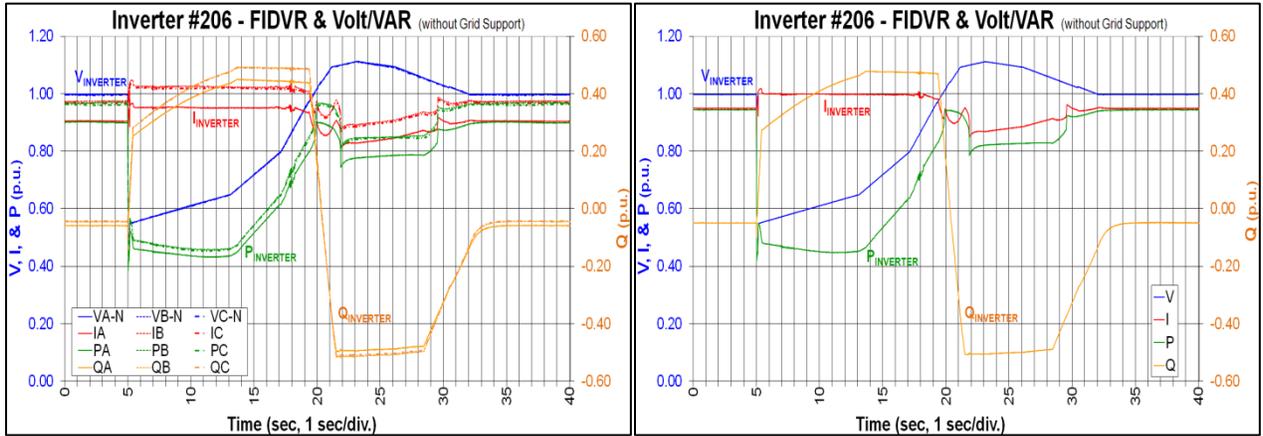


Figure 11.1.1 Passive LVVRT Performance (Individual phases and total)

## 11.2 LVRT when Voltage below Threshold

Figure 11.2.1 below indicates the inverters' behavior during a FIDVR event when the voltage is too low (below this setting “**DGS-PWMVoINom**”) and the inverters cease generating power into the grid until the voltage goes above the programmed threshold.

### Test Settings:

- Low Voltage Threshold = 47%
- Restart Hysteresis = 3%

### Test Results:

- Inverter stops generating power once voltage falls below 47% and begins generating again once voltage recovers to 50% after a short delay (approx. 1 ~ 2 seconds)
- After generation begins again, current rises almost immediately to its maximum value
- Voltage support feature allows the inverter to generate/absorb reactive power during the under-voltage and over-voltage conditions
- Just as the previous test, reactive power is prioritized over real power during the high and low voltages

# German Commercial Solar PV Inverter Test Report

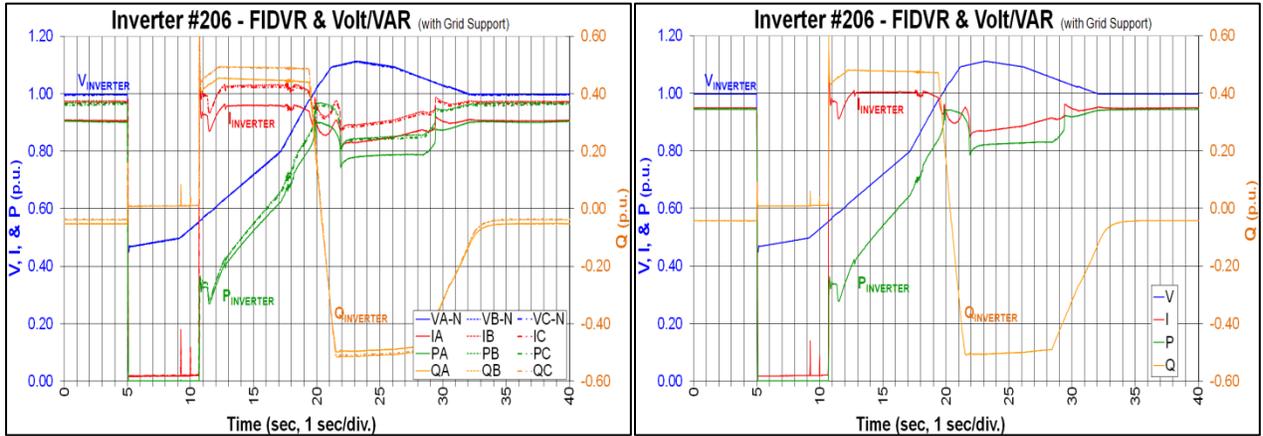


Figure 11.2.1 Active LVRT Performance (Individual phases and total)

## 12.0 POWER CURTAILMENT DURING OVER-FREQUENCIES

---

The grid frequency was ramped up and down while maintaining constant load in order to assess the inverters power reduction behavior during over-frequency conditions. Over-frequency conditions are typically produced during instances of over-generation on a circuit.

Adjustable Settings: are shown in Table 12.0.1

- **P-HzStr:** is the over-frequency threshold. The inverter limits its output power when frequency goes above this value
- **P-WGra:** is the power limit slope. Defines the relationship between the active power limitation and over-frequency values
- **P-HystEna:** It is the power limit at maximum over-frequency. The inverter continuously limits its output power during the maximum over-frequency condition until being reset
- **P-HzStop:** is the power-reset frequency threshold. The power output resets when frequency falls below this value
- **P-HzStopWGra:** is the power-reset ramp rate. Is the speed at which power recovers to nominal after being reset

Tests Performed:

- **P-HystEna:** is the over-frequency ramp. For these tests it was disabled (Linear Power Curtailment with Over-frequency)
- **P-HystEna:** is the over- frequency ramp. For these tests it was enabled (Constant Power Curtailment at Max Over-frequency)

Benefits:

- Prevent unnecessary tripping of generation during over-frequency events
- Support the system during cases of over-generation

## German Commercial Solar PV Inverter Test Report

Name	Min. Value	Max. Value	Default Value	Unit
P-HzStr	0	5	0.2	Hz
P-WGra	10	130	40	%/Hz
P-HystEna	Off	On	Off	
P-HzStop	0	5	0.2/0.05	Hz
P-HzStopWGra	1	10000	10000	%/min

Table 12.0.1 Power Curtailment Parameters

## 12.1 Linear Power Curtailment with Over-frequency

Figure 12.1.1 below indicates the inverters behavior during a frequency ramp where the power limitation has a linear relationship with over-frequency.

### Test Settings:

- Over-frequency Threshold = 50.2 Hz
- Power Limit Slope = 50%  $P_{MAX}$  / Hz
- Power Limit at Max. Over-frequency = Off

### Test Results:

- Power begins ramping down, shortly after the system frequency goes above the 50.2 set threshold, according to the limit slope (reduces power by 10% for every increase of 0.2 Hz)
- Active power also begins ramping up as system frequency returns to steady state (50Hz)
  - For 51 Hz over-frequency ramp, inverter experiences delay in performance as power recovers/ramps up
  - For 50.6 Hz over-frequency ramp, there are no delays as power recovers/ramps up

# German Commercial Solar PV Inverter Test Report

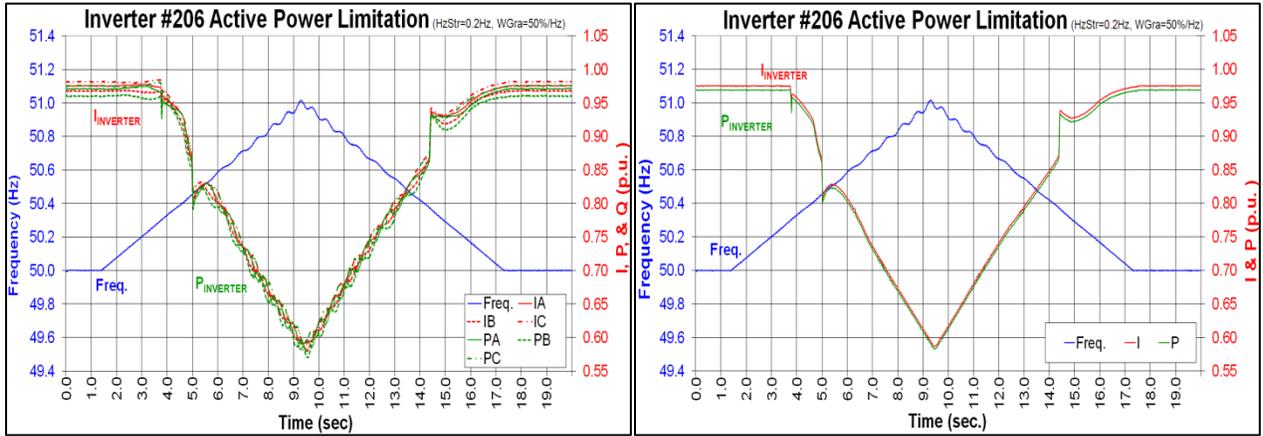


Figure 12.1.1 Linear Power Curtailment with Over-frequency Performance (Individual phases and total)

## 12.2 Constant Power Curtailment at Max Over-frequency

Figure 12.2.1 below indicates the inverters behavior during over-frequency event when its over-frequency power limiter feature is enabled.

### Test Settings:

- Over- frequency Threshold = 50.2 Hz
- Power Limit Slope = 50%  $P_{MAX}$  / Hz
- Power Limit at Max. Over-frequency = On
- Power-Reset Frequency Threshold = 50.2 Hz
- Power-Reset Ramp Rate = 10,000%  $P_{MAX}$  / min

### Test Results:

- Power begins ramping down, shortly after the system frequency goes above the threshold (50.2 Hz), according to the limit slope (reduces power by 10% for every increase of 0.2 Hz)
- The inverter limits its output power generation once the active power (P) reaches its minimum set point (60%), which in this case occurs at max over-frequency. The inverter will remain at 60% output power no matter if the frequency goes up or low. If it goes too high the high frequency protection will disconnect the inverter
- When the frequency falls below 50.2 the output power resets and the inverter immediately starts ramping up its output power to steady state

# German Commercial Solar PV Inverter Test Report

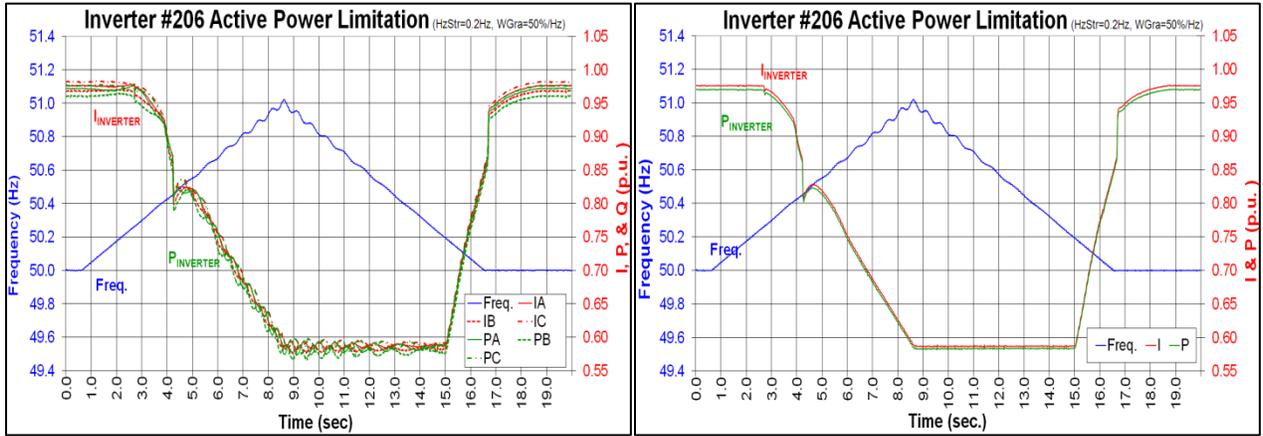


Figure 12.2.1 Constant Power Curtailment at Max Over-frequency Performance (Individual phases and total)

### 13.0 AUTONOMOUS VOLTAGE SUPPORT (POWER FACTOR ADJUSTMENT)

---

The PV simulator was programmed to ramp up its power output, as shown in Figure 13.0.1, in order to assess the inverters ability to autonomously adjust its power factor. The PV simulator's irradiance value was ramped from 60% to 100% to ramp up the inverter power output from 20 to 80%.

Adjustable Settings: are shown in Table 13.0.1

- **PF-WNomStr:** is the active power start point. The inverter linearly adjusts PF when power goes above this value
- **PF-PFStr:** is the PF start point. The inverter PF when output power is less than or equal to "Active Power Start Point"
- **PF-PFExtStr:** is the excitation start point. The excitation type of "PF Start Point", either leading or lagging
- **PF-WNomStop:** is the active power stop point. The inverter linearly adjusts PF when power goes up to this value
- **PF-PFStop:** is the PF stop point. The inverter PF when output power  $\geq$  "Active Power Stop Point"
- **PF-PFExtStop:** Excitation stop point. The excitation type of "PF Stop Point", either leading or lagging

Tests Performed:

- Ramp up PV simulator irradiance with PF set to change from unity to leading/lagging
- Ramp up PV simulator irradiance with PF set to change from leading/lagging to unity

## German Commercial Solar PV Inverter Test Report

### Benefits:

- Feature could be used to implement power factor scheduling to mitigate mild voltage fluctuations on distribution circuits with large penetrations of solar PV generation

Name	Min. Value	Max. Value	Default Value	Unit
PF-WNomStr	0	100	50	%
PF-PFStr	0.8	1	1	
PF-PFExtStr	Underexcited	Overexcited	Overexcited	
PF-WNomStop	0	100	100	%
PF-PFStop	0.8	1	1/0.95/0.9	
PF-PFExtStop	Underexcited	Overexcited	Underexcited	

Table 13.0.1 Autonomous Power Factor Parameters

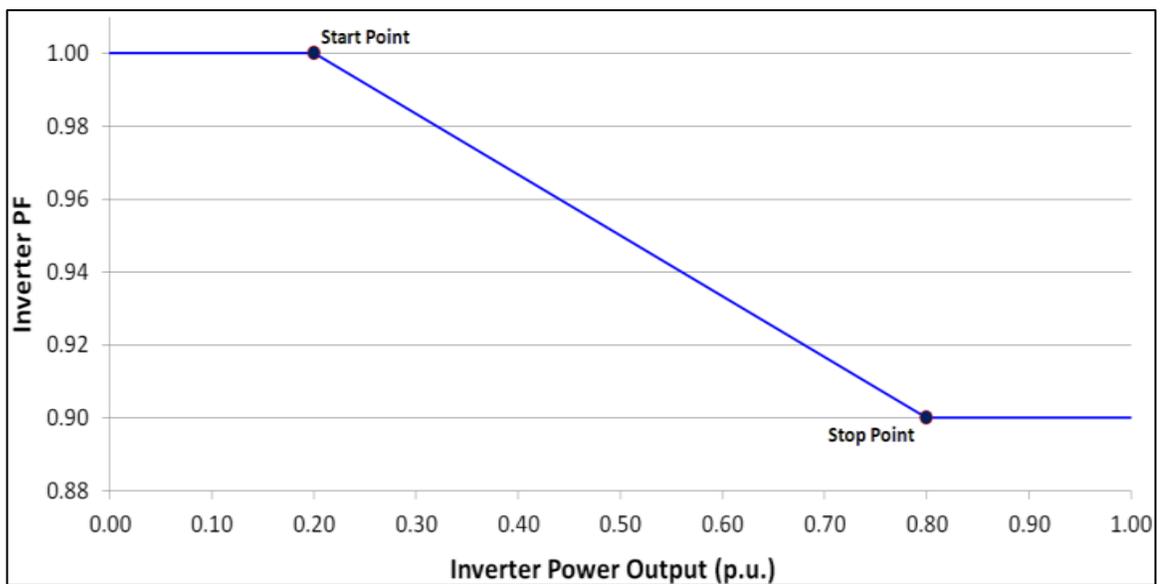


Figure 13.0.1 Sample Autonomous Power Factor Setup

### 13.1 Unity PF to Leading/Lagging PF

Figure 13.1.1 below shows the inverters autonomous power factor performance as generation increases.

#### Test Settings:

- Active Power Start Point = 70%
- PF Start Point = 1.0
- Excitation Start Point = Overexcited (irrelevant at unity PF)
- Active Power Stop Point = 90%
- PF Stop Point = 0.9
- Excitation Stop Point = Underexcited/Overexcited

#### Test Results:

- Inverter initially operates at unity PF until real power output goes above 70% of nominal
- Power factor linearly ramps down to approximately 0.9 leading/lagging
- Inverter continues operating at 0.9 leading/lagging after power nears 90% of the nameplate rating
- Test data suggests an imbalance in power between the individual phases

## German Commercial Solar PV Inverter Test Report

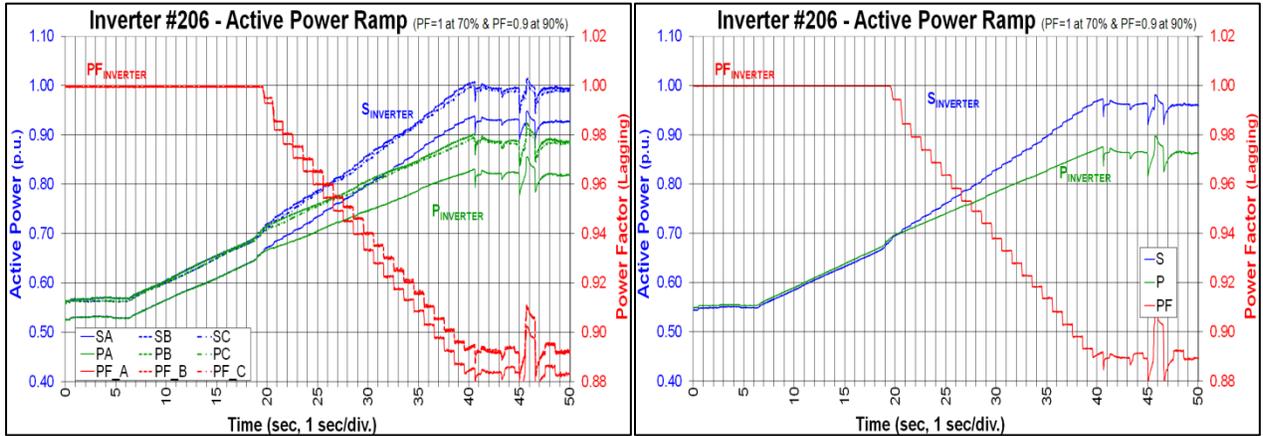


Figure 13.1.1 Unity PF to Leading/Lagging PF Performance (Individual phases and total)

## 13.2 Leading/Lagging PF to Unity PF

Figure 13.2.1 below indicates the inverters autonomous power factor performance as generation increases.

### Test Settings:

- Active Power Start Point = 70%
- PF Start Point = 0.9
- Excitation Start Point = Underexcited/Overexcited
- Active Power Stop Point = 90%
- PF Stop Point = 1.0
- Excitation Stop Point = Overexcited (irrelevant at unity PF)

### Test Results:

- Inverter initially operates near 0.9 power factor until generation increases above 70% of nominal
- Power factor begins to linearly ramp up to unity once generation is above 70% of nominal
- Inverter continues operating at unity PF while total generation is above 90% of the nameplate rating
- Data suggests an imbalance in power between the individual phases during testing

# German Commercial Solar PV Inverter Test Report

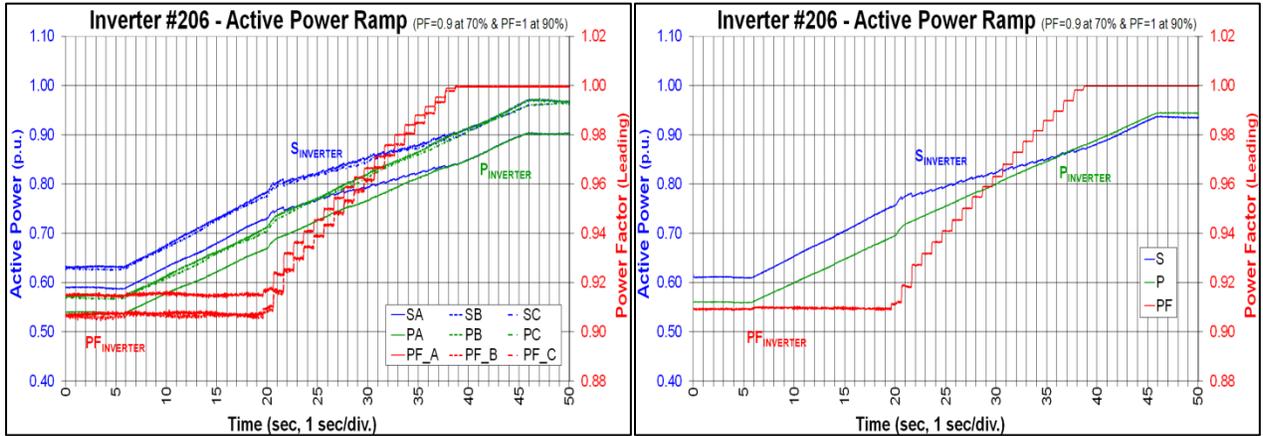


Figure 13.2.1 Leading/Lagging PF to Unity PF Performance (Individual phases and total)

## 14.0 AUTONOMOUS VOLTAGE (VAR) SUPPORT

---

This inverter has the ability to provide autonomous VARs support during voltage deviations to maintain the voltage at its nominal value, 100%. The purpose of the following tests was to assess this particular feature on this inverter. The grid simulator was programmed as a weak source where its output current was manually limited in approximately 5 second intervals. This system current limitation (weak source) will adjust the test setup generation-to-load ratio to either sag or swell the system voltage in order to assess the inverters voltage support functions.

Adjustable Settings: are shown in Table 14.0.1

- **Q-VArMaxNom:** is the maximum Q limit. The maximum amount of reactive power that can be provided, percentage is based on the inverters nominal power rating or  $P_{MAX}$
- **Q-VArGraNom:** is the Q/V gradient. The slope of reactive power/voltage characteristic curve
- **Q-VArTms:** is the adjustment time. The adjustment time for the operating point of the characteristic curve
- **Q-VolWidNom:** voltage spread. The voltage region where voltage support is disabled ( $\pm X\%$  voltage deviation)

Tests Performed:

- System voltage lowered in steps for multiple Volt/VAR feature settings
- System voltage increased in steps for multiple Volt/VAR feature settings

Benefits:

- Support the voltage (boost or buck) autonomously by injecting or absorbing reactive power

## German Commercial Solar PV Inverter Test Report

Name	Min. Value	Max. Value	Default Value	Unit
Q-VArMaxNom	0	50	0	%
Q-VArGraNom	0	10	0	%
Q-VArTms	2	60	10	s
Q-VolWidNom	0	20	0	%

Table 14.0.1 Voltage Support Parameters

### 14.1 Voltage/VAR Support During Under-voltage

Figure 14.1.1 shows the inverter behavior with and without the autonomous voltage support feature enabled. At steady state voltage, the grid simulator's current was limited in 5 second intervals. After decreasing the setup's generation-to-load ratio, the system voltage sags as a result.

#### Test Settings:

- Maximum Q Limit = 50%
- Q/V Gradient = 0% (VAR-OFF), 1%, 3%
- Adjustment Time = 2 seconds
- Voltage Spread = 0%

#### Test Results:

- When the Volt/VAR feature is off (Q-0%), the inverter does not inject any VARs into the system
  - Voltage drops in 5% increments down to 80% of nominal
- When the Volt/VAR feature is on, the inverter increases its VAR output shortly after voltage drops below 98% of nominal and boosts the system voltage accordingly
  - At Q/V = 1%, the inverter prevents the system voltage from falling below 92% of nominal
  - At Q/V = 3%, the inverter prevents the system voltage from falling below 96% of nominal

# German Commercial Solar PV Inverter Test Report

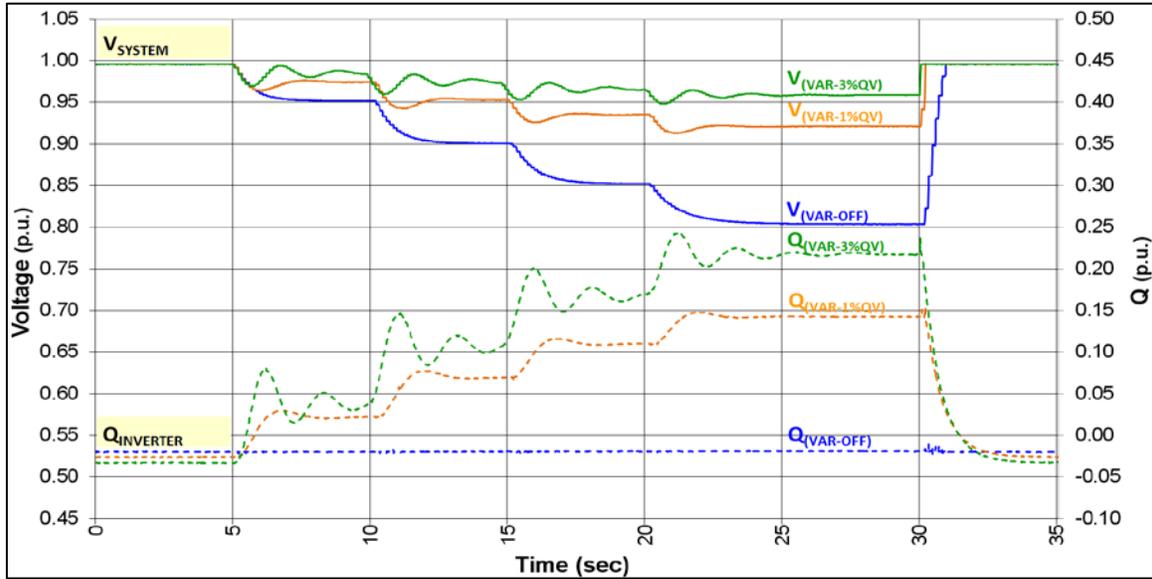


Figure 14.1.1 Voltage Support during Under-voltage

### 14.2 Voltage/VAR Support During Over-voltage

Figure 14.2.1 shows the inverter behavior with and without the autonomous voltage support feature enabled. At steady state voltage, the grid simulator's current limit is increased in 5 second intervals. By increasing the setup's generation-to-load ratio, the system voltage swells as a result.

#### Test Settings:

- Maximum Q Limit = 50%
- Q/V Gradient = 0% (VAR-OFF), 1%, 3%
- Adjustment Time = 2 seconds
- Voltage Spread = 0%

#### Test Results:

- When the Volt/VAR feature is off, the inverter does not absorb any VARs from the system
  - Voltage is increased in 5% increments up to 120% of nominal
- When the Volt/VAR feature is on, the inverter begins drawing VARs shortly after voltage goes above 102% of nominal and bucks the system voltage accordingly
  - At Q/V = 1%, the inverter prevents the system voltage from going above 111% of nominal
  - At Q/V = 3%, the inverter prevents the system voltage from going above 106% of nominal

# German Commercial Solar PV Inverter Test Report

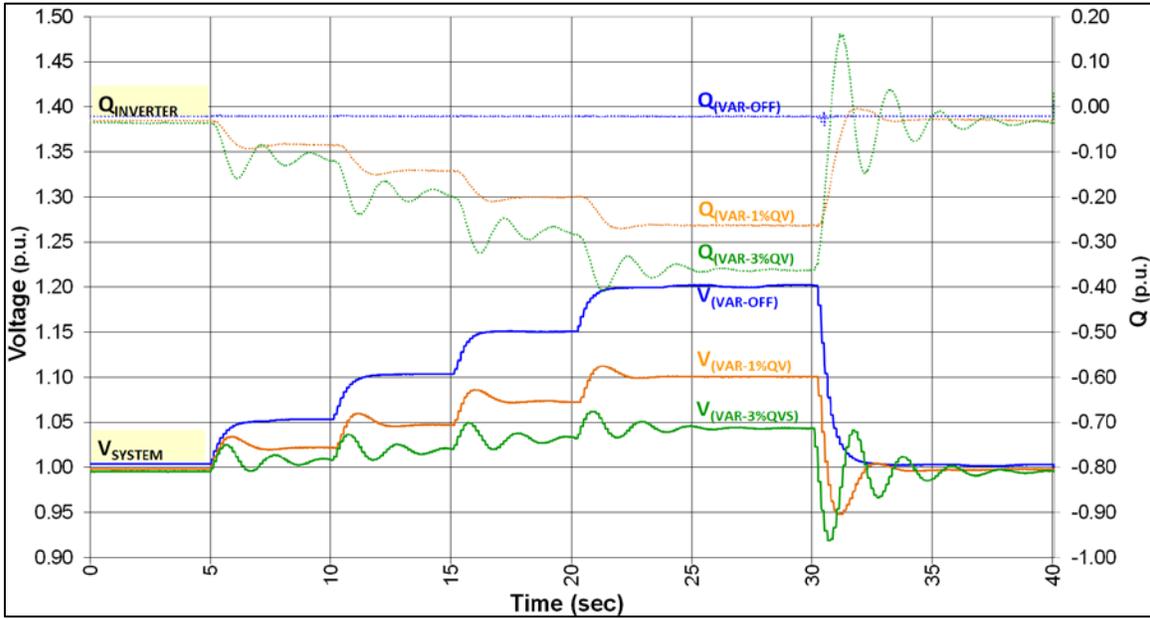


Figure 14.2.1 Voltage Support during Over-voltage

# POTENTIAL IMPACTS on ANTI-ISLANDING

## 15.0 POTENTIAL IMPACTS ON ANTI-ISLANDING

---

There is a concern that inverter advanced features may compromise the device's anti-islanding protection. This concern is shared by many utilities that want to ensure the safety of field personnel by preventing self-sustaining islands from occurring on the grid.

### 15.1 Islanding Potential with Adjusted Protection Settings

This inverter has a remote possibility of being islanded if someone were to enter the wrong settings. All of the following settings must be changed in order for the inverter to remain generating power to an island: wider frequency protection beyond IEEE 1547, match load and generation, anti-islanding protection disabled, and volt/var feature disabled. The inverter was islanded indefinitely to prove this very point and we have captured at least 1 hour of data during the islanding condition. Figure 15.1.1 shows the detailed performance of the inverter during this test.

#### Island Settings:

- Disabled the inverters anti-islanding detection setting (“status of islanding detection unbalance detection”)
- Real and reactive load reasonably matched inverter generation
- Under-frequency protection was set low ( < 55 Hz)
- Disabled inverter volt/var control features

#### Test Results:

- Inverter immediately begins operating at approximately 56 Hz while successfully islanded
  - U.S. frequency protection standards would have resulted in the inverter tripping

## German Commercial Solar PV Inverter Test Report

- With constant load, inverter remains islanded for over an hour when it was manually disconnected
- A static PF of 0.9 leading was used to maintain consistent generation values
  - Previous attempts with dynamic generation settings (i.e. Volt/VAR controls) resulted in tripping

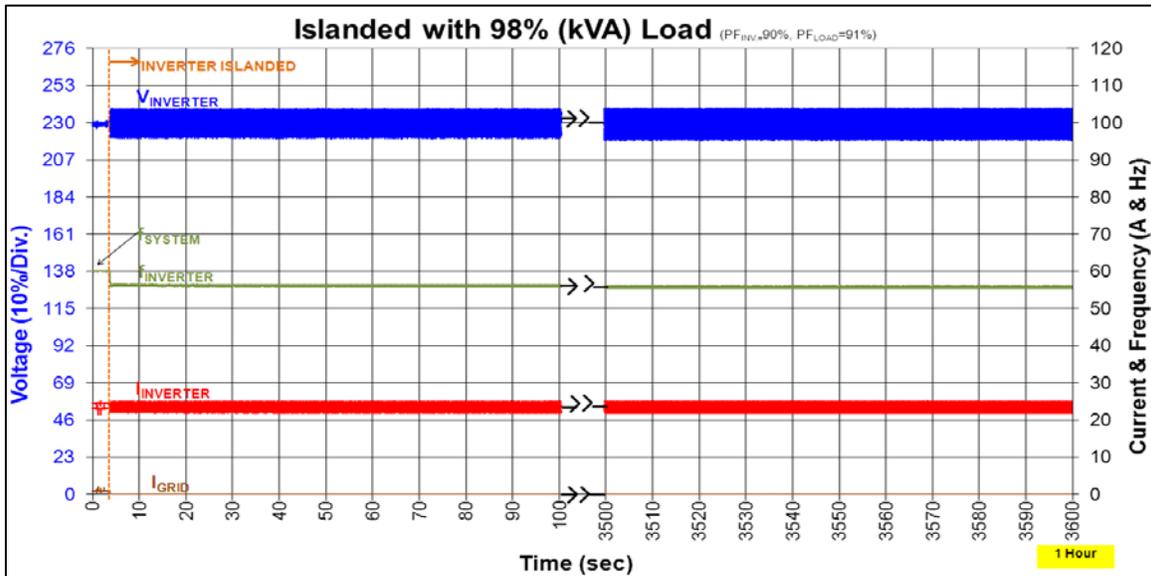


Figure 15.1.1 Inverter Islanded

## 15.2 Islanding Potential with Volt/VAR Controls

This test was performed to investigate a concern of engineers that the volt/var features will be able to override the anti-islanding protection allowing the device to continue operating during off-grid conditions. Therefore, the commercial inverter was disconnected from the grid with matched load to evaluate its performance. The tests conducted reveal no evidence that the inverters volt/var features will result in an islanded condition.

### Island Settings #1:

- Enabled inverter volt/var control features
- Real and reactive load reasonably matched inverter generation

### Test Results #1: details are shown in Figure 15.2.1

- Inverter phase voltages become unbalanced upon disconnection from the grid
- Voltages fluctuate as high as 115% nominal voltage
- Inverter shuts down within 8.5 cycles after being disconnected

## German Commercial Solar PV Inverter Test Report

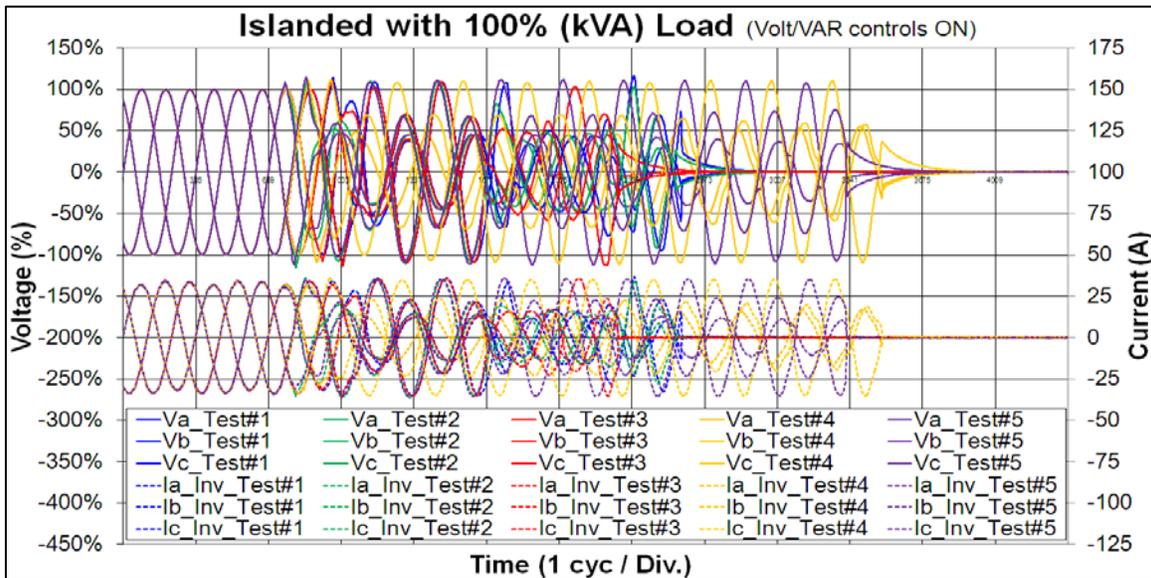


Figure 15.2.1 Inverter Disconnected with Volt/VAR

### Island Settings #2:

- Enabled inverter volt/var control features
- Real and reactive load reasonably matched inverter generation
- Disabled the inverters anti-islanding detection setting ("status of islanding detection unbalance detection")
- Under-frequency protection was set low (< 55 Hz)

### Test Results #2: are shown in Figure 15.2.2

- Even with similar protection settings as Section 15.1, the inverter still trips off relatively quickly
- Voltages fluctuate as high as 112% nominal voltage
- Inverter shuts down within 11 cycles after being disconnected

# German Commercial Solar PV Inverter Test Report

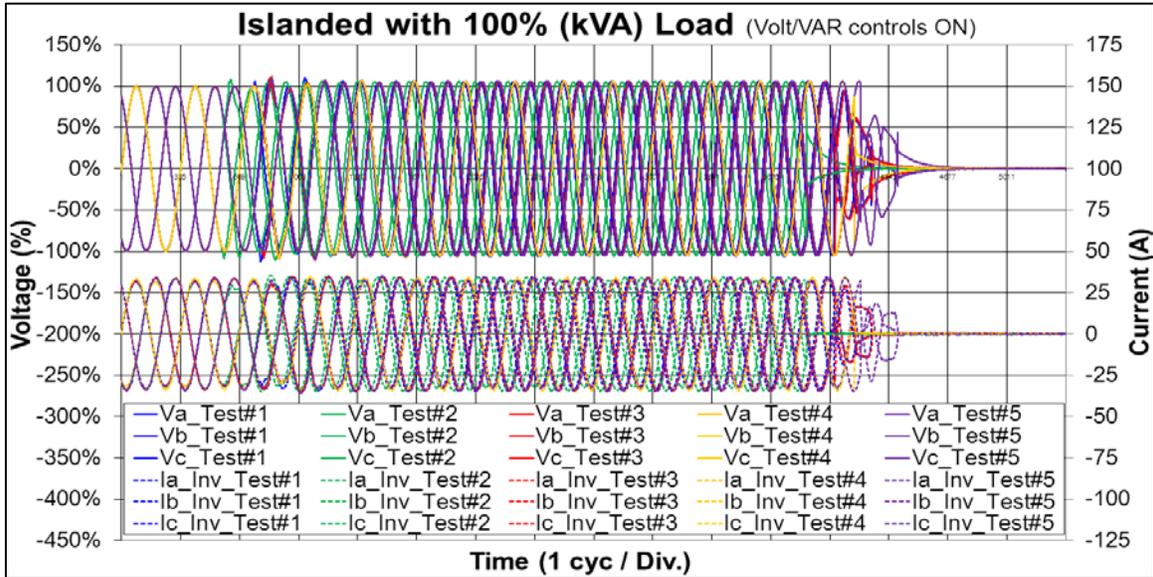


Figure 15.2.2 Inverter Disconnected with Volt/VAR and Disabled Protection

### 15.3 Islanding Potential during Voltage Ride Through

Another concern regarding advanced features is effects of volt/var controls when disconnecting from the grid during low voltage conditions. Hence the inverter was disconnected from the grid with matched load during the low voltage region of a fault induced delayed voltage recovery (FIDVR) profile. The tests revealed no evidence that the inverters volt/var features will compromise anti-islanding protection during a low voltage ride through event.

#### Island Settings:

- Enabled inverter volt/var control features
- Real and reactive load reasonably matched inverter generation

#### Test Results: test results details are shown in Figure 15.3.1

- Before grid disconnection, the inverter begins riding through the low voltage event
  - Current increases to its maximum value to power generation
  - Real power is still being generated at a reduced output
  - Reactive power is increased per the Volt/VAR support features
- During grid disconnection, the inverter almost immediately shuts down
  - Inverter current, real, and reactive power begin decreasing within several cycles
  - Inverter voltage appears to increase from 55% to 103% nominal voltage before shutdown

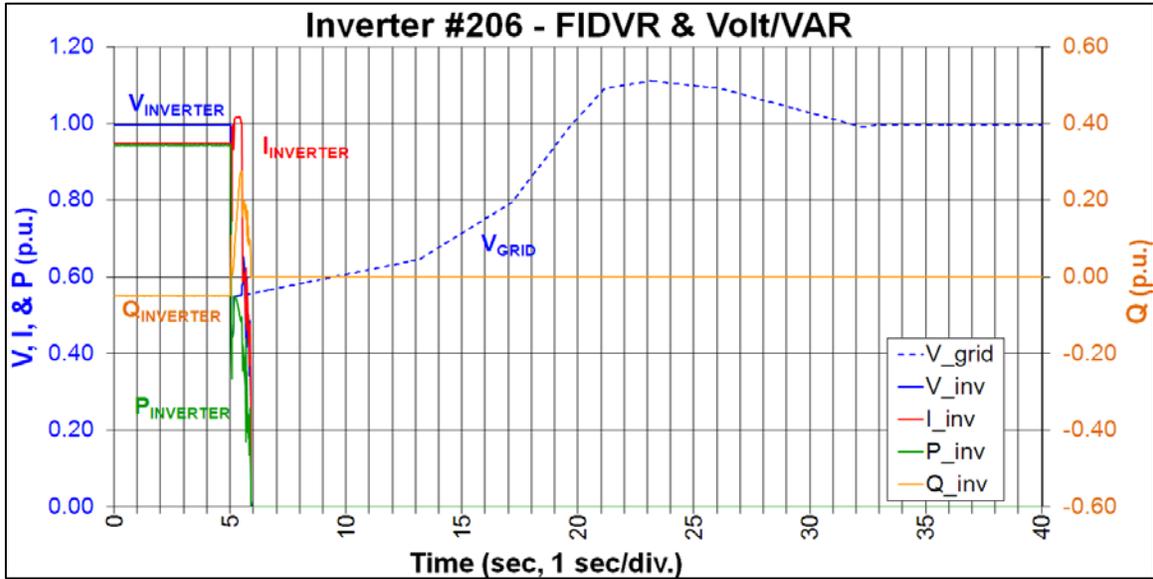


Figure 15.3.1 Inverter with Volt/VAR Disconnected during LVRT