NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Experimental Evaluation of Load Rejection Over-Voltage from Grid-Tied Solar Inverters

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Outline

- Introduction and Background
- Experimental Test Setup
- Test Results
- Conclusions

Introduction and Background

- **Two type of temporary over-voltage (TOV) events are of immediate concern to utilities:**
  - Ground fault over-voltage (GFO)
  - Load rejection over-voltage (LRO)

- **LRO occurs when a portion of a feeder containing significant PV resources and equal or smaller amount of load becomes disconnected**
  - Generation to load ratio (GLR) exceeds unity

- **Theoretical max *LRO* = $\sqrt{GLR}$, for balanced active and reactive power in the island**

- **Theory/simulation poorly predict LRO due to many factors, including:**
  - Inverters more complex than constant current sources
  - Inverters are not a voltage-behind-impedance
  - Models can fail to factor in over-modulation

- **Great need for experimental data to evaluate the magnitude/duration of LRO**

Test Setup and Procedures

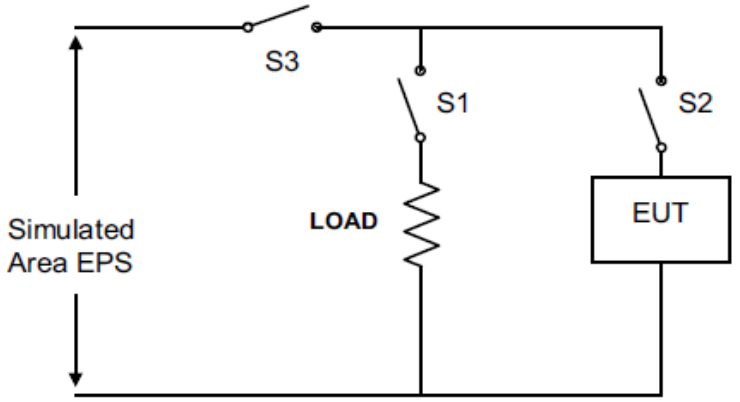
Test Inverter Types

	Voltage Configuration	Nominal Power	Details
Inverter 1	240V Split Phase	6.0 kW	Dual stage, transformerless
Inverter 2	240V Split Phase	6.0 kW	Single stage, transformerless
Inverter 3	240V Split Phase	3.0 kW	Single stage, 60 Hz transformer
Inverter 4	480V Three Phase	12.0 kW	Dual stage, transformerless
Inverter 5	208V Three Phase	4.5 kW	18 x 250 W microinverters

Test Settings

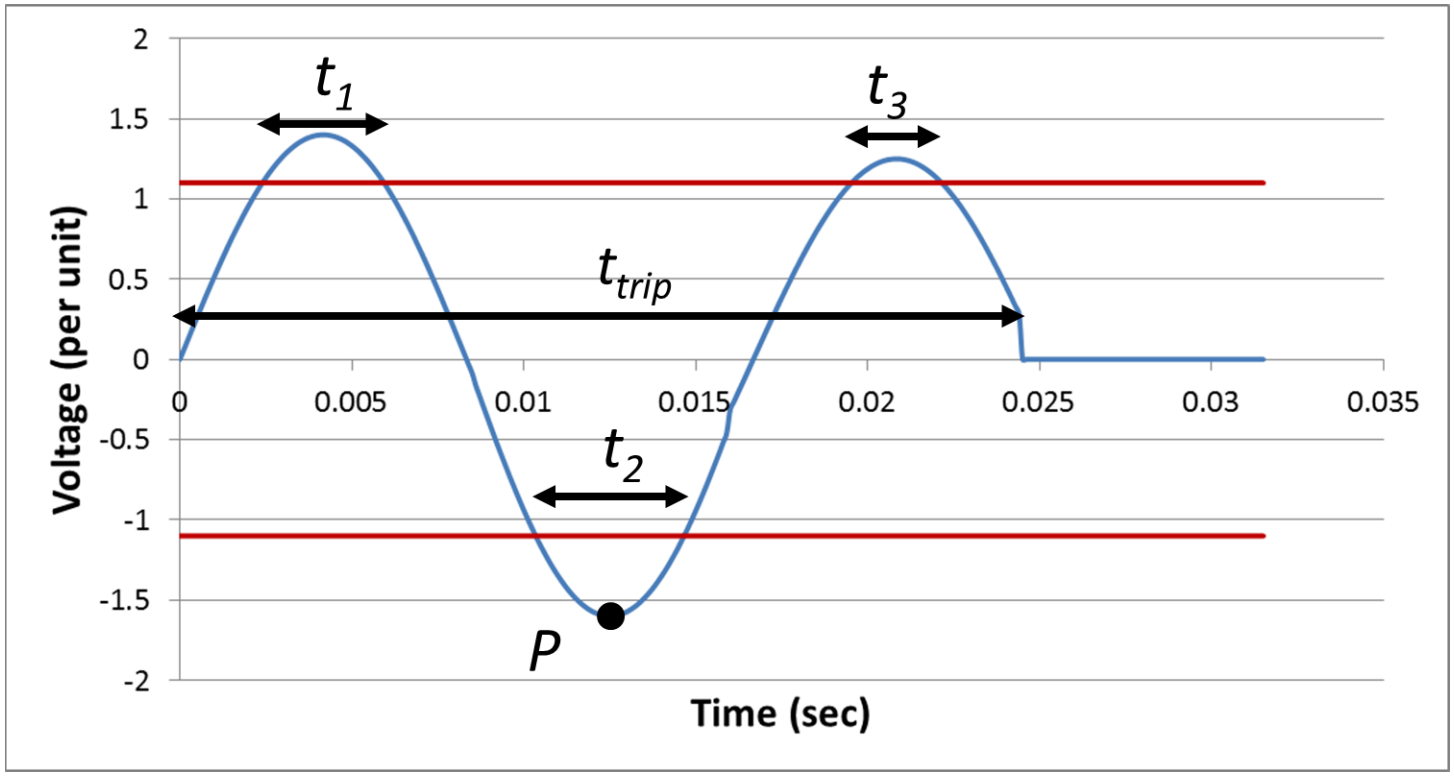
Load power (% of EUT rated power)► EUT output▼	100%	66%	50%	33%	10%
100%	Yes	Yes	Yes	Yes	Yes
66%	No	Yes	Yes	Yes	Yes
33%	No	No	No	Yes	Yes

Test Schematic

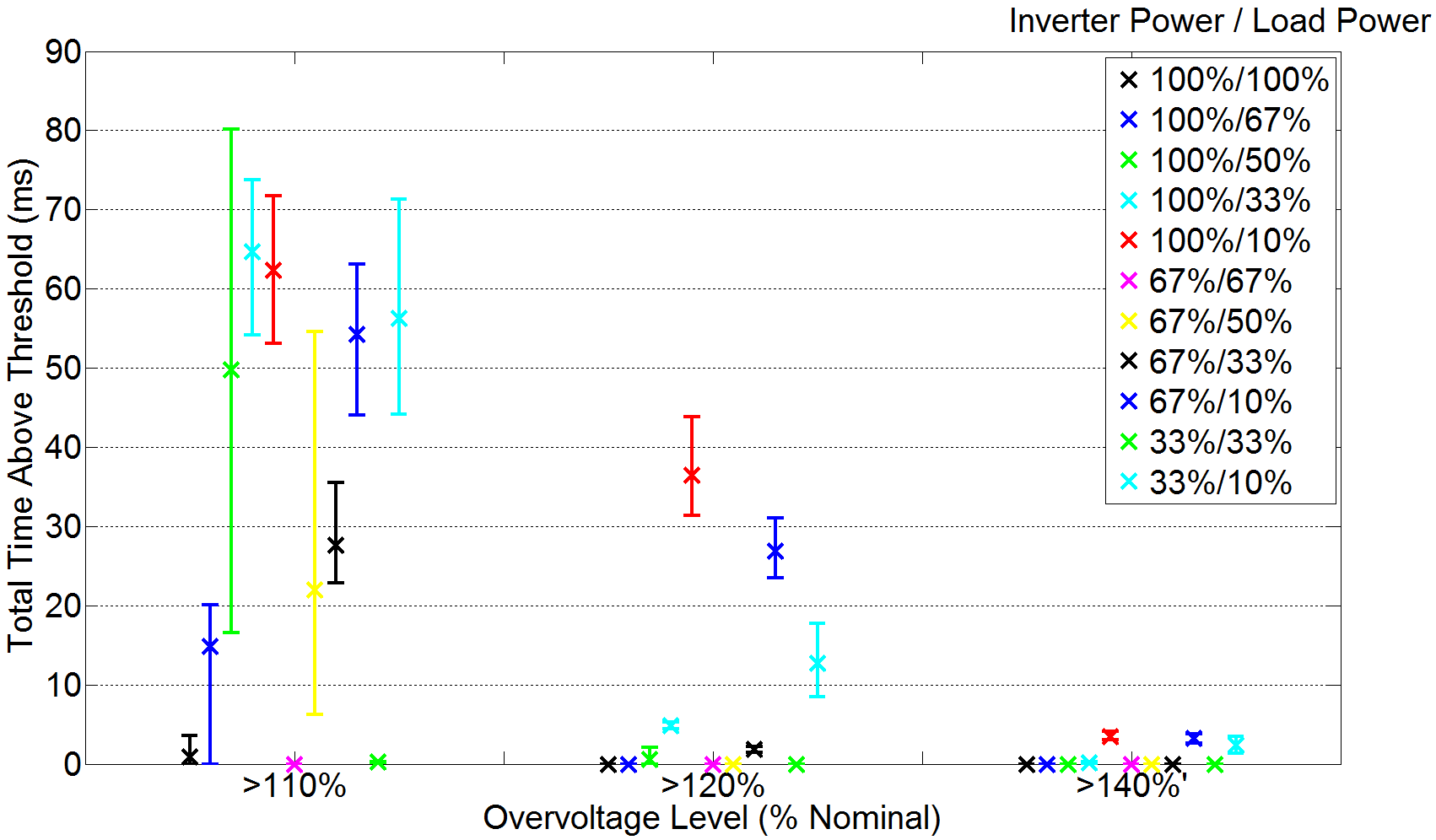


Data Reporting

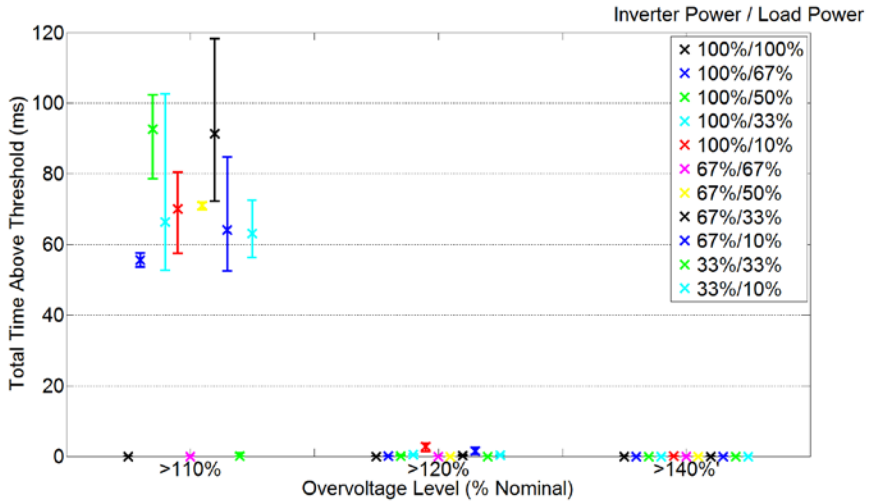
- **Time above voltage thresholds**
  - 110%/120%/140%/200% of nominal
  - Total vs. continuous
- **Time to disconnect (t_{trip})**
- **Maximum peak overvoltage (point P)**
- **Effect of DC input voltage**



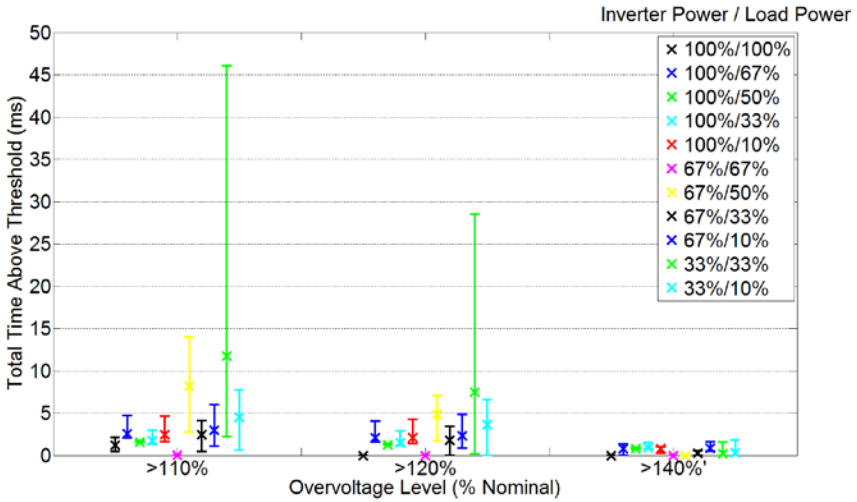
Over-voltage Duration Time for Inverter 1



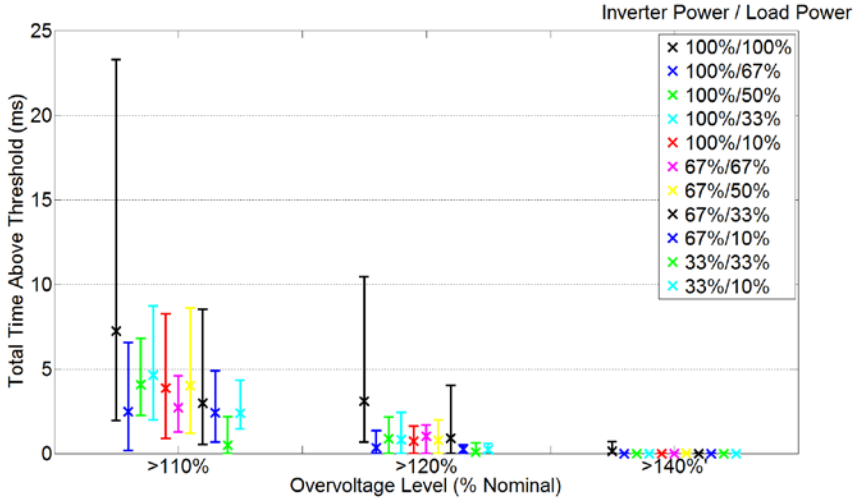
Over-voltage Duration Times for Inverters 2 - 5



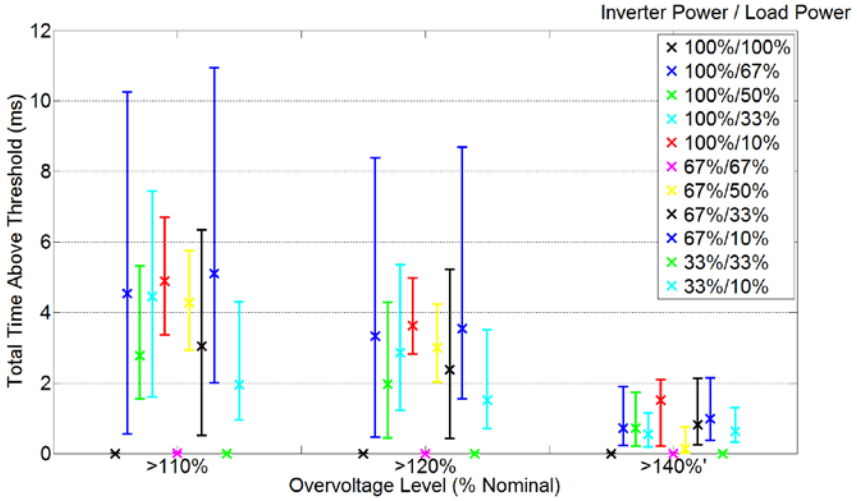
Inverter 2



Inverter 3



Inverter 4

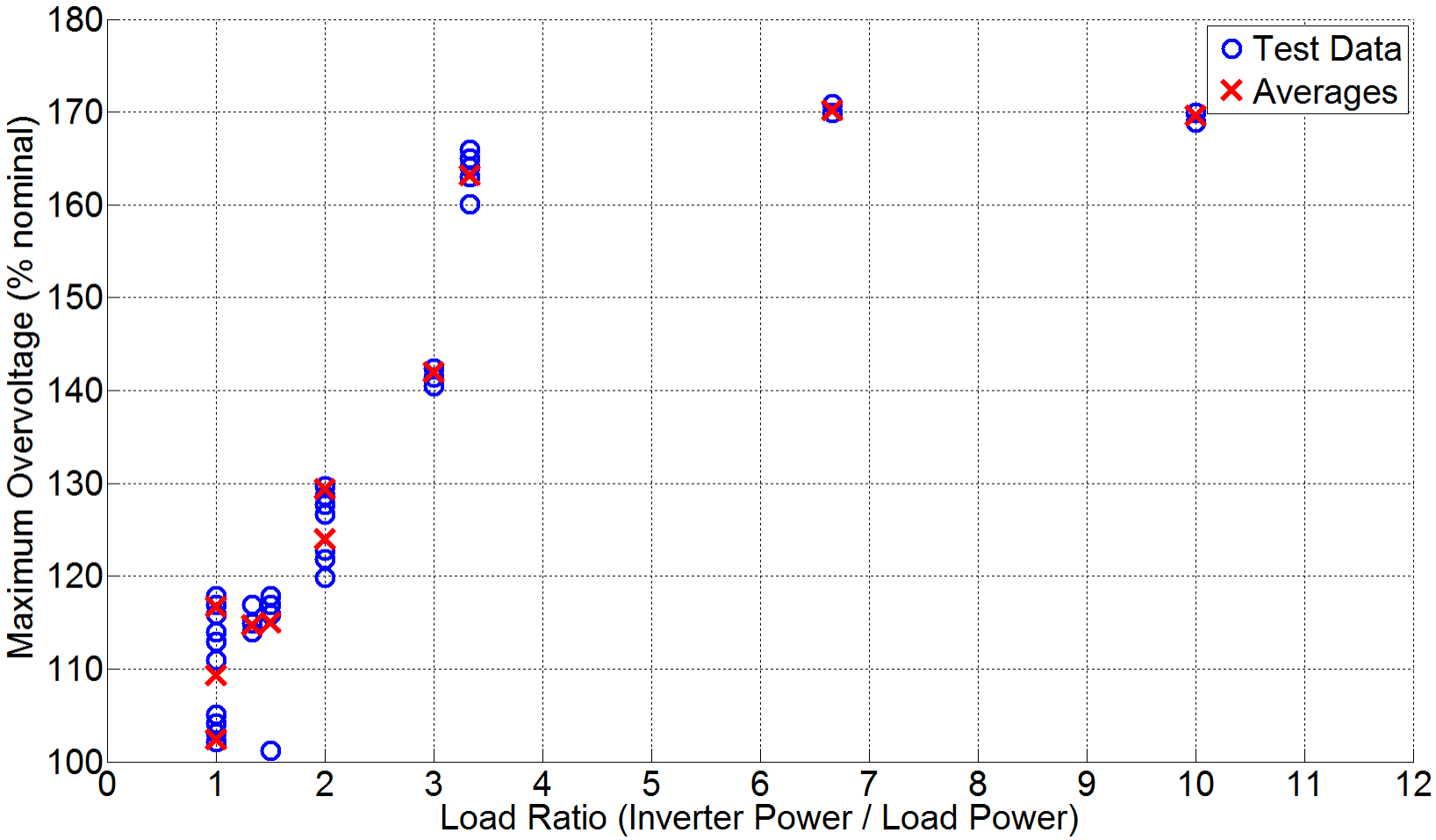


Inverter 5

Maximum Instantaneous Voltage Measurements for all Test Inverters

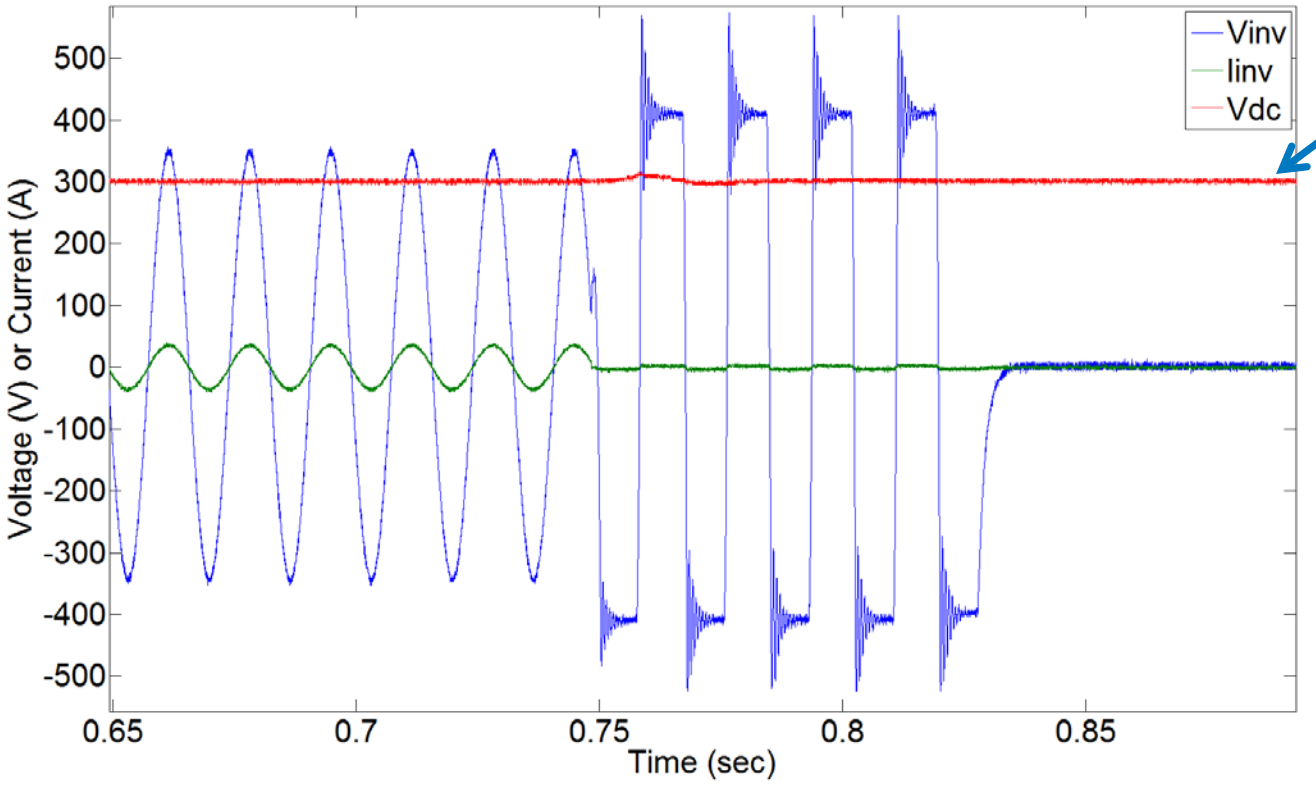
Power (% EUT Rating)		Inverter				
EUT	**Load**	**1**	**2**	**3**	**4**	**5**
100	100	113.9	106.9	113.1	149.7	109.9
100	67	117.9	120.2	154.0	136.9	151.1
100	50	127.7	126.9	159.1	131.0	163.9
100	33	142.4	133.6	170.9	132.3	156.0
100	10	169.9	151.6	190.5	128.4	196.3
67	67	103.1	106.1	110.8	132.7	111.9
67	50	116.9	116.3	131.6	140.3	145.2
67	33	129.6	126.1	152.0	134.4	160.9
67	10	170.9	136.7	167.0	125.9	184.5
33	33	117.9	111.6	162.2	126.7	109.9
33	10	166.0	124.1	175.6	128.4	161.9

Maximum Over-voltage Magnitude vs. GLR for Inverter 1



Typical Waveform Characteristics – Inverter 1

Load = 10% Power, EUT = 100% Power

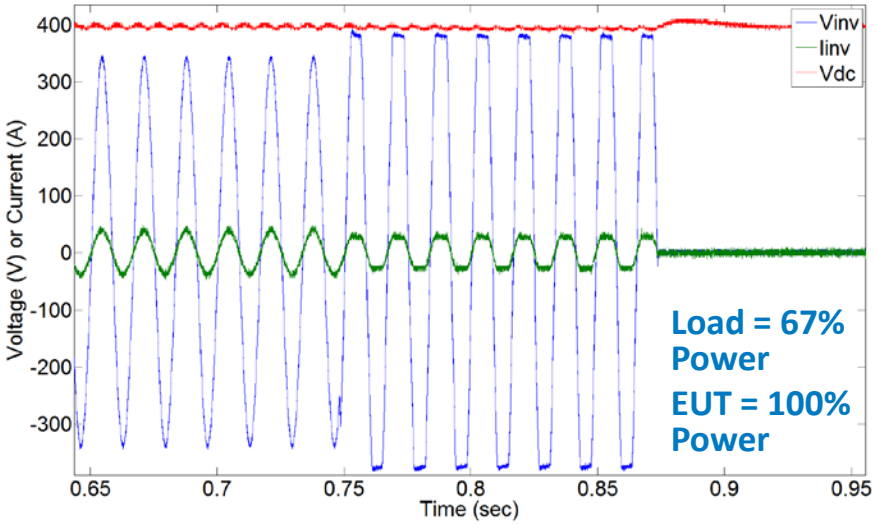


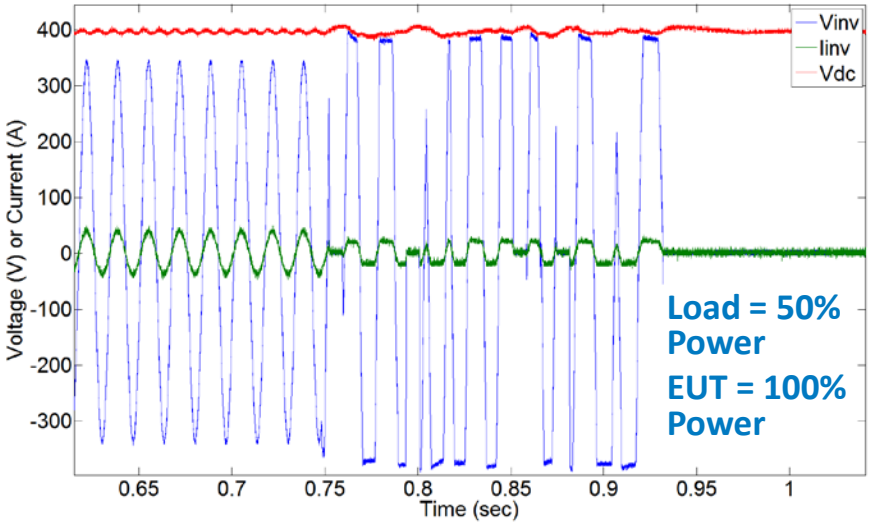
Showing PV input voltage not DC bus voltage – two-stage inverter

- At unity or low GLR, output was sinusoidal with varying magnitude near nominal
- At medium to high GLR, waveform clipped at DC bus voltage (not shown here), following the AC half cycle

Typical Waveform Characteristics – Inverter 2

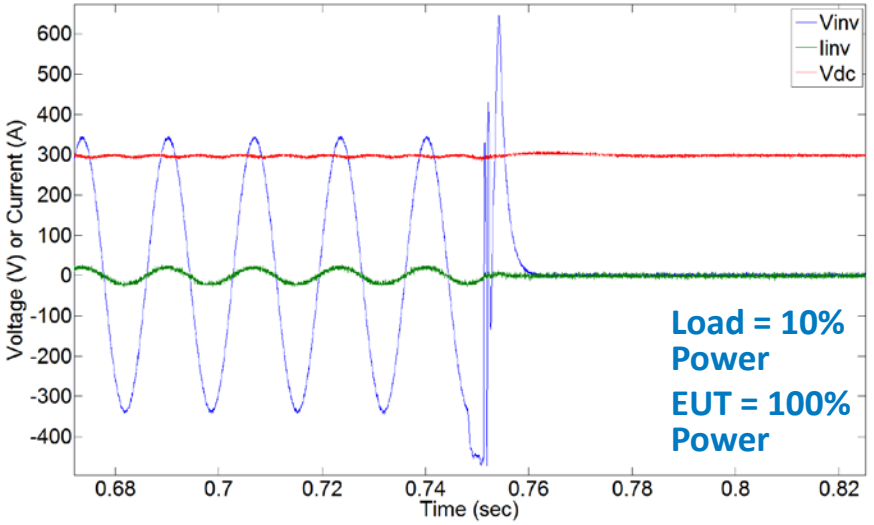
- **Unity or low GLR: sinusoidal, slightly above nominal**
- **Medium GLR: Clipped sinusoid near DC bus voltage, following AC half cycle (top)**
  - Led to additional investigation into effect of DC bus voltage on LRO
- **Medium or high GLR: Irregular output, clipped at DC bus voltage (bottom)**



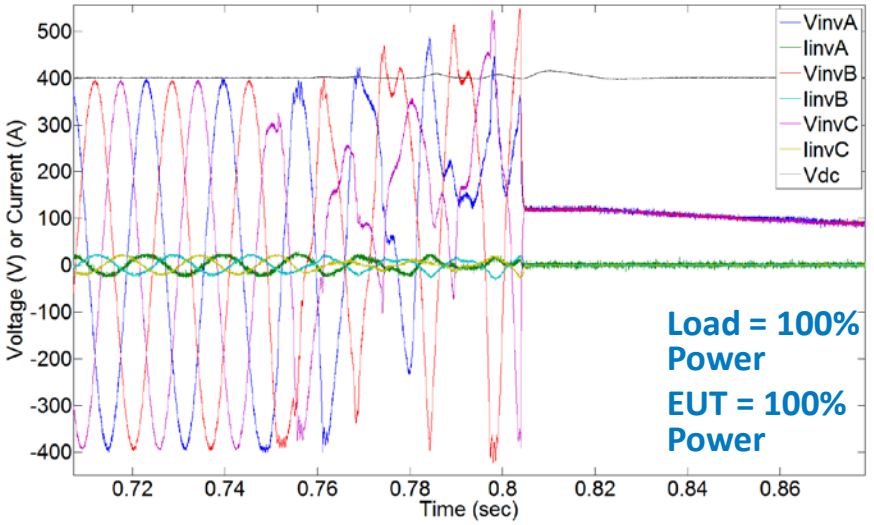


Typical Waveform Characteristics – Inverters 3 and 4

- **Inverter 3:**
  - Unity GLR: Sinusoidal near nominal voltage for several cycles
  - Medium or high GLR: Rapid shutdown after one brief OV spike (top)

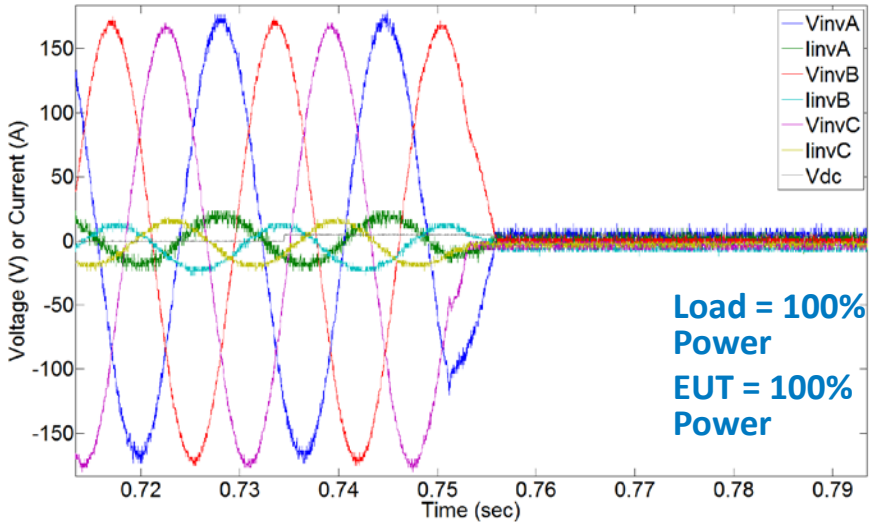


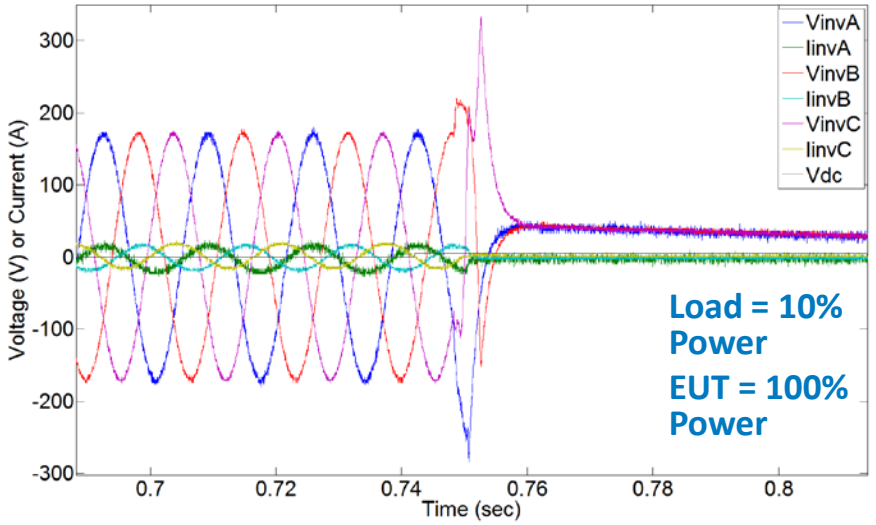
- **Inverter 4:**
  - Similar response across the range of GLR
  - Irregular three-phase output for several AC cycles, quick shutdown (bottom)



Typical Waveform Characteristics – Inverter 5

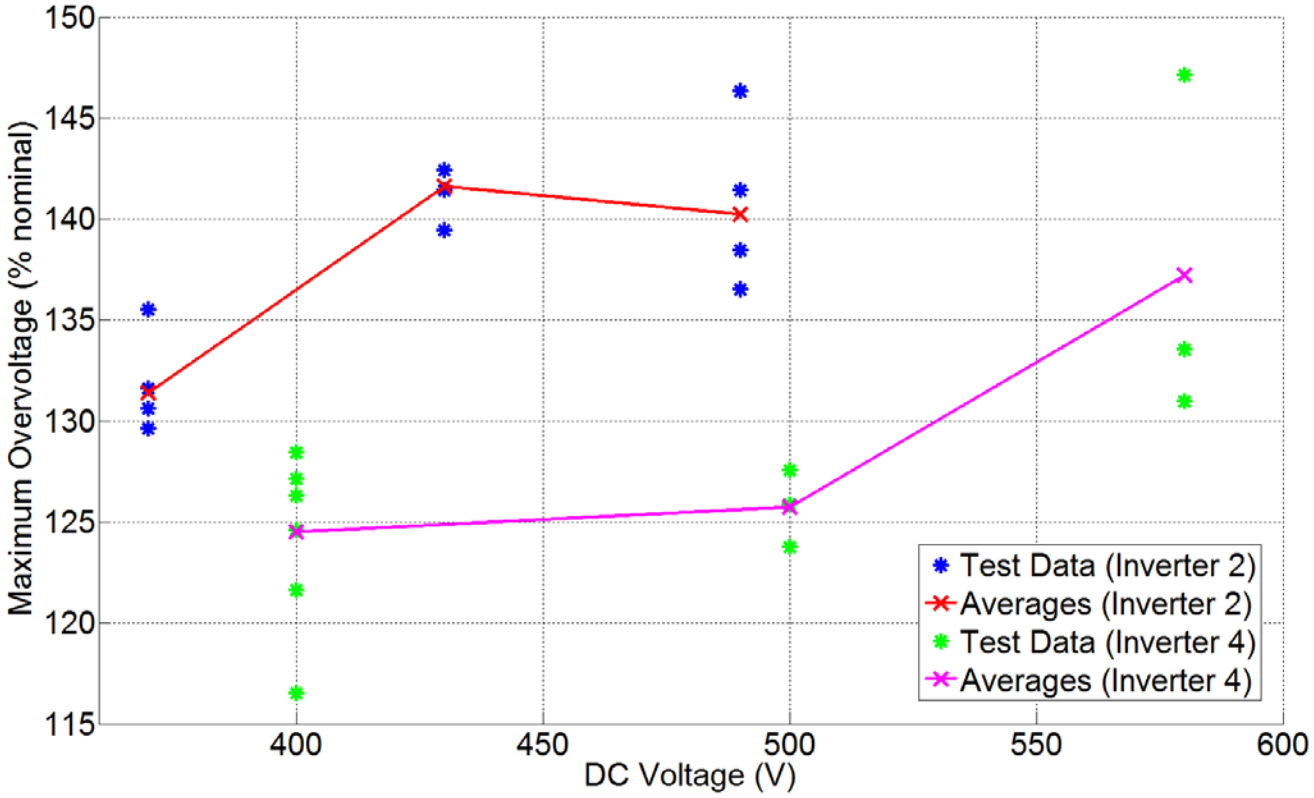
- **Unity or low GLR: sinusoidal, quick disconnect (top)**
- **Medium or high GLR: Single OV spike, rapid shutdown (bottom)**





Effect of DC Bus Voltage on LRO Magnitude

- **Inverter 2 test results motivated this study**
  - Single stage, transformerless inverter clipped AC output at the DC bus voltage
- **Inverter 4 tested as well**
- **Possible positive correlation, but test results are inconclusive**



Conclusions

- **Magnitude and duration of LRO measured for five commercially available PV inverters**
  - LRO poorly predicted by simulation
  - Typical OV responses on the order of microseconds to milliseconds
- **Maximum instantaneous voltage measurement = 196.3% nominal; average OV level was 132.3% for all tests**
- **Future work: Build more detailed inverter models and link to experimental test results**

Comprehensive NREL technical report available at:
http://www.nrel.gov/docs/fy15osti/63510.pdf

Acknowledgements

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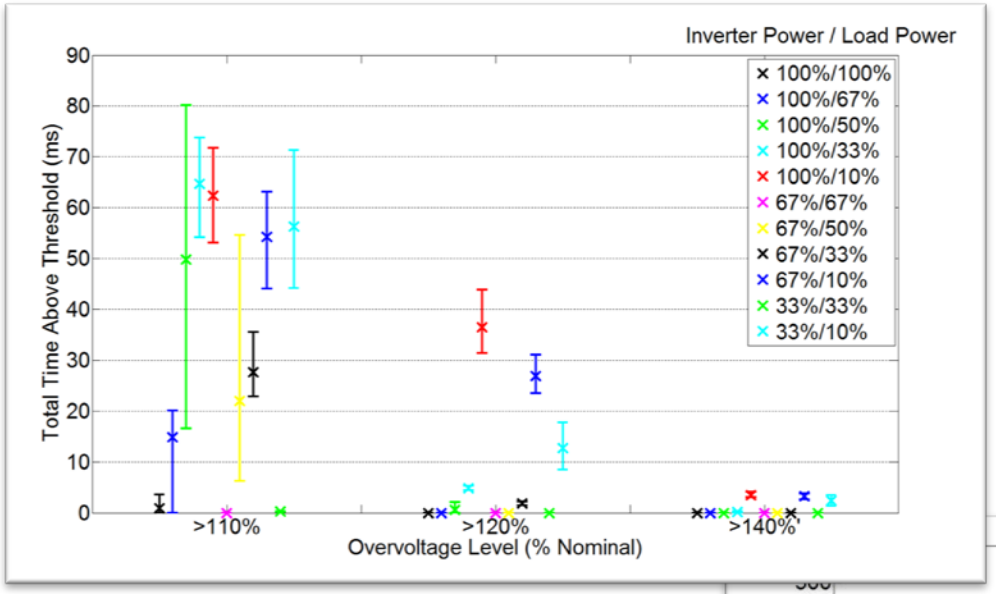
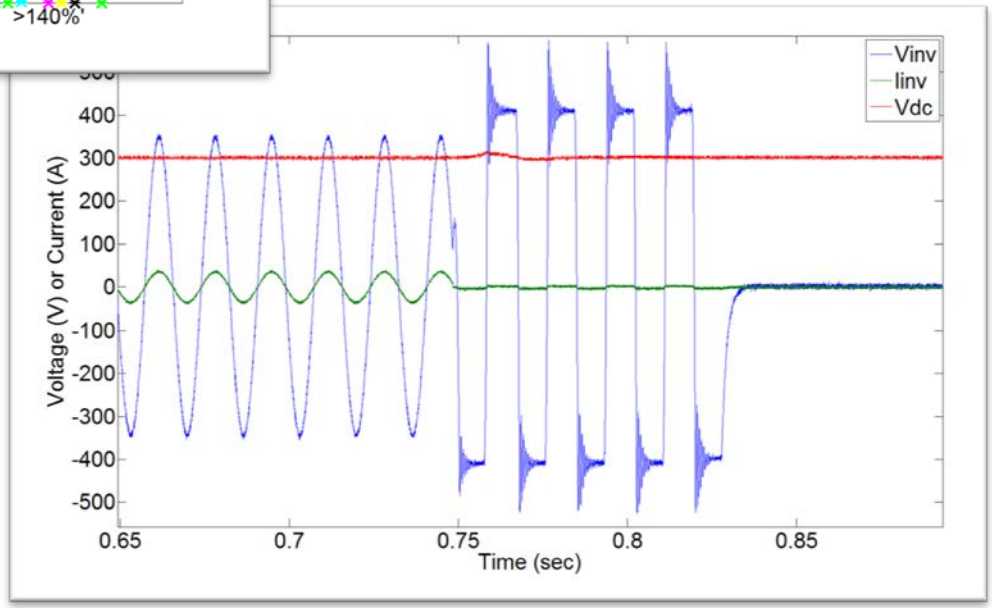
Q & A


Inverter Power / Load Power
Total Time Above Threshold (ms)
90
80
70
60
50
40
30
20
10
0
100%/100%
100%/67%
100%/50%
100%/33%
100%/10%
67%/67%
67%/50%
67%/33%
67%/10%
33%/33%
33%/10%
>110%
>120%
>140%
Overvoltage Level (% Nominal)


Vinv
Iinv
Vdc
Voltage (V) or Current (A)
400
300
200
100
0
-100
-200
-300
-400
-500
0.65
0.7
0.75
0.8
0.85
Time (sec)