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HIGH-PENETRATION PV MODELING, MONITORING, AND ANALYSIS WITH ADVANCED POWER ELECTRONICS

High Penetration 2013
Feb 13-14, San Diego, CA

Focus Areas

Modeling and Simulation

- Solar PV modeling
- Grid Integration analysis
- Smart inverters
- Solar PV monitoring
- PV ramp rate
- PV variability assessments
- Open-source utility modeling tool

Power Electronics

- PV inverter testing
- Cost effectiveness study of PV power conditioning systems
- Development of advanced power conditioners
- Field demonstration with advanced power conditioners

Key Deliverables

Modeling and Simulation

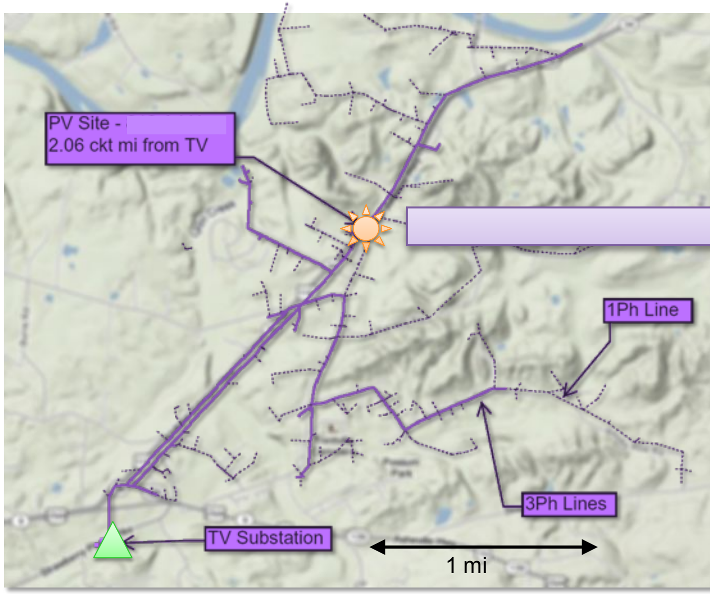
- Evaluation of smart inverters for increasing feeder hosting capacity
- Website hosting measurement data and feeder models (open-source)
- Statistical analysis of PV variability at distribution level
- Hosting capacity results considering % boundary limits
- Comparison of single-point vs multi-point cloud models for distribution analysis

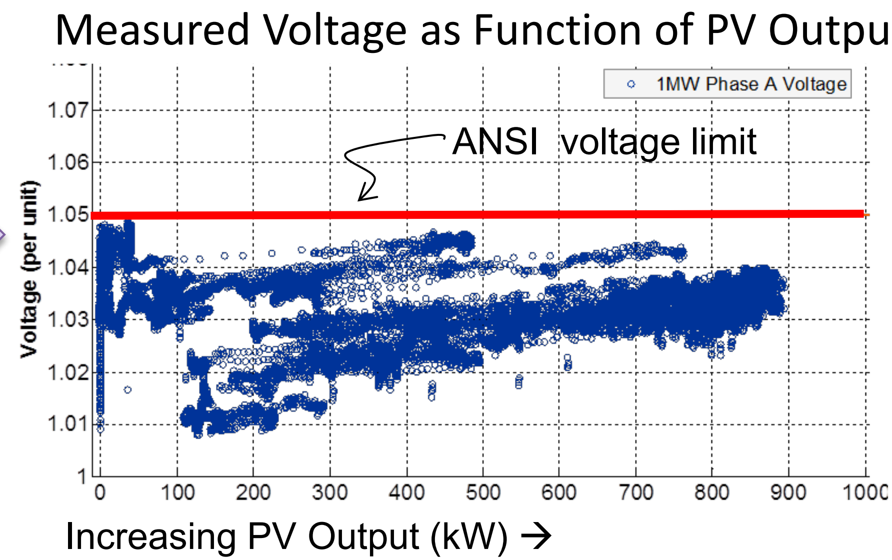
Power Electronics

- Micro-converter (DC optimizer) design with isolation
- Micro-inverter design without electrolytic capacitors
- String/centralized inverter design without cooling fans
- Hardware-in-the-loop simulation

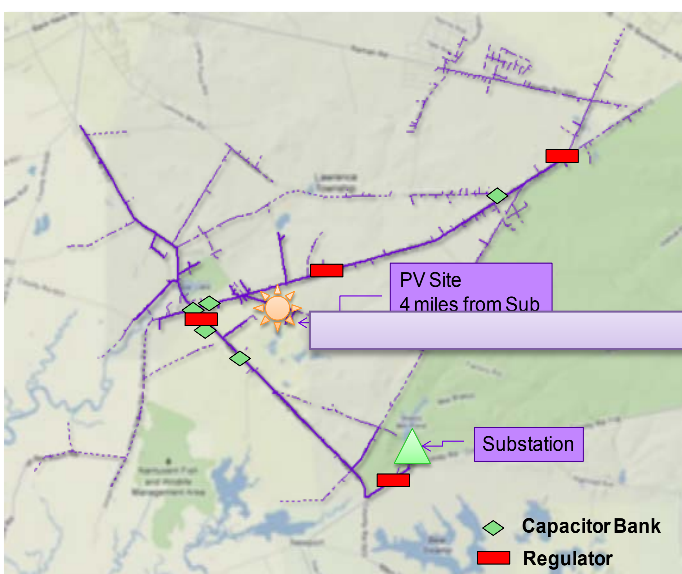
Feeder Comparison

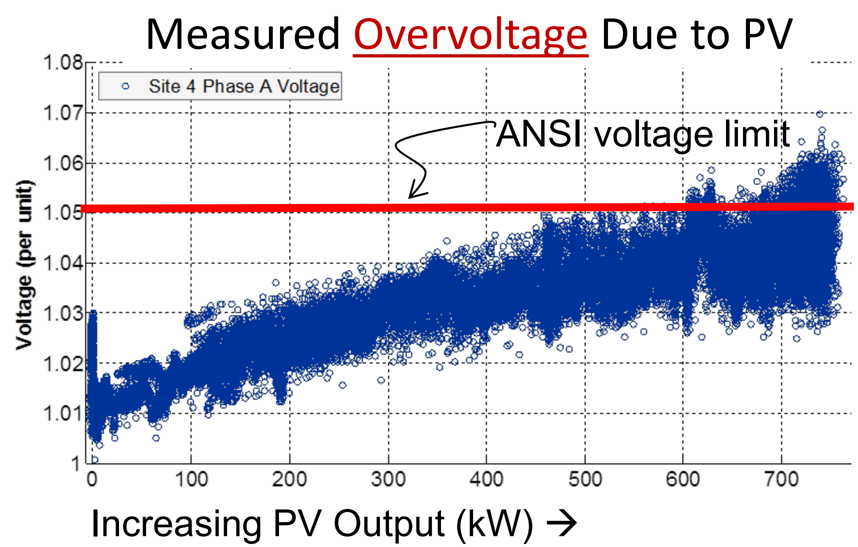
Feeder A





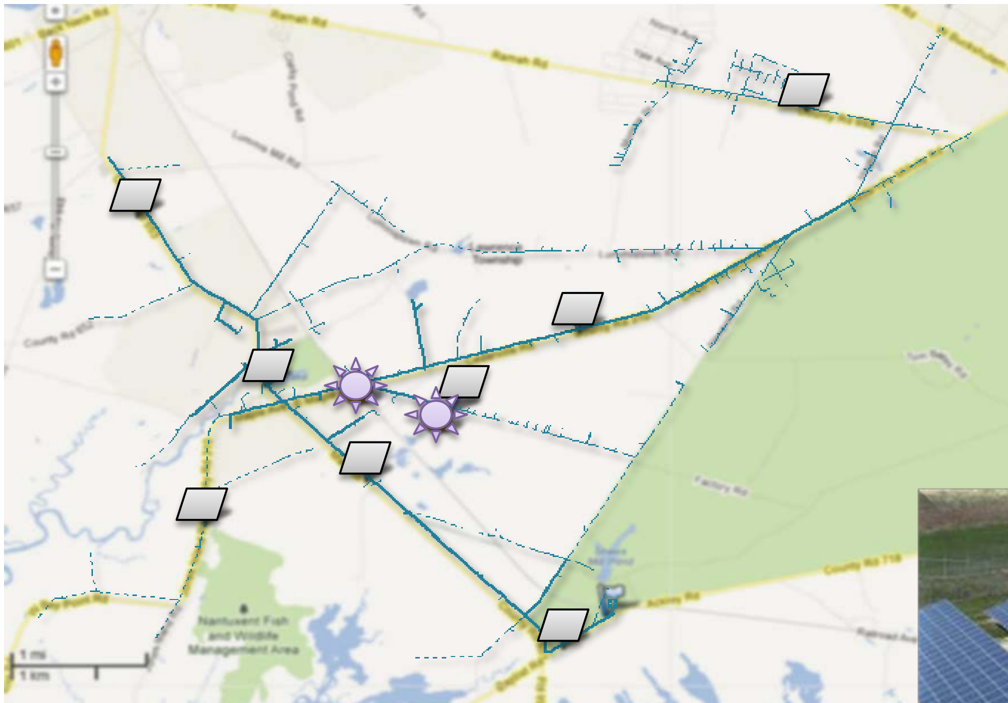
Feeder B





Measurement Data

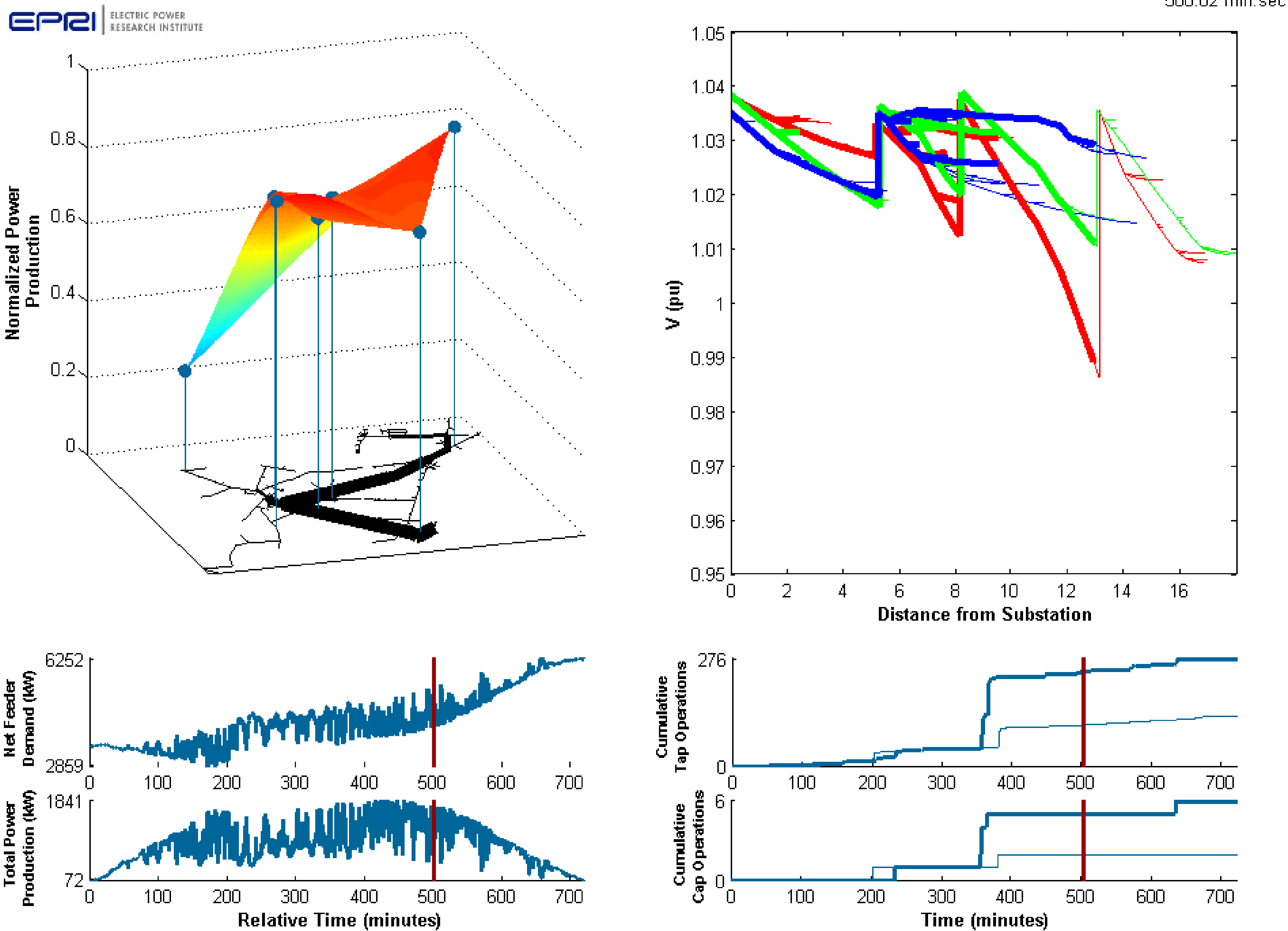
Solar Monitoring



DPV Pole-Mount Panels

Metered Large-Scale PV

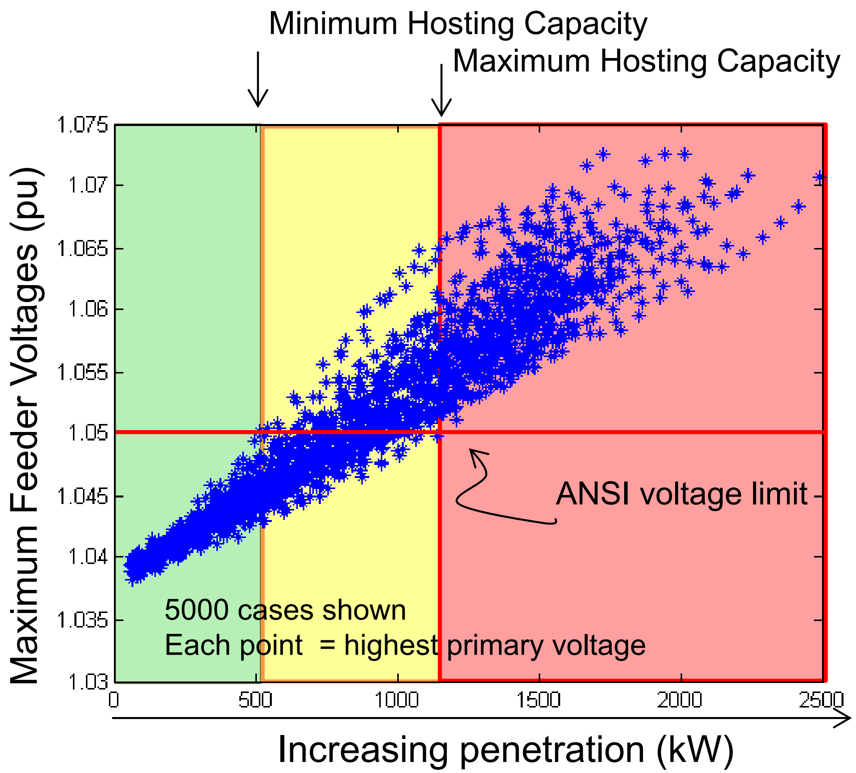
Time Series Response with Existing PV



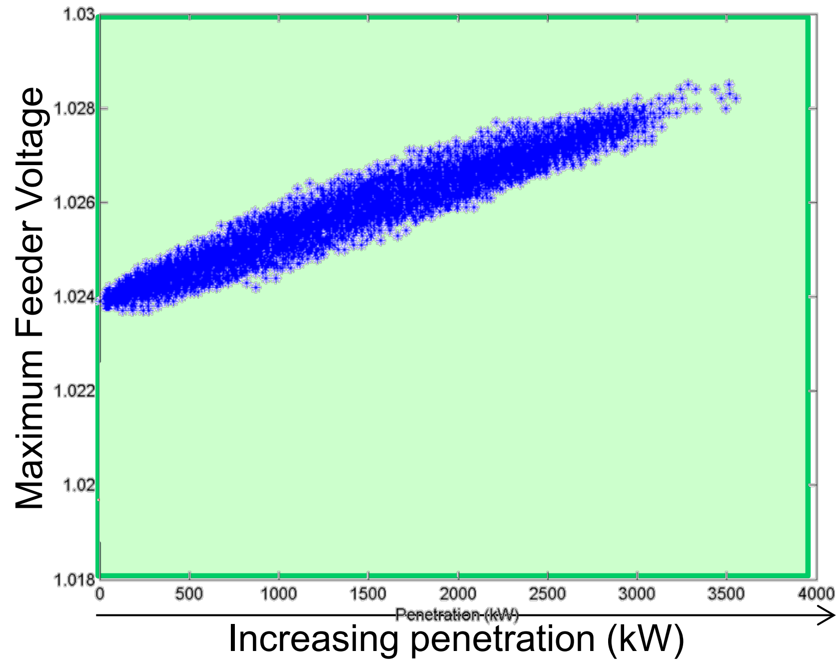
Hosting Capacity Comparison

Quick Look at Overvoltage Impacts

Feeder B



Feeder A



No observable violations regardless of size/location

Possible violations based upon size/location

Observable violations occur regardless of size/location

Hosting Capacity Comparison

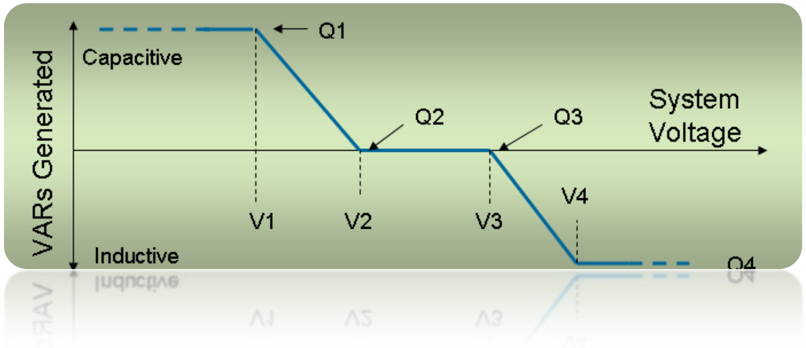
Feeder Comparison			
		Feeder A	Feeder B
Feeder Characteristics	Voltage (kV)	13.2	12.47
	Peak Load	5 MW	6 MW
	Minimum Load	0.8 MW	0.7 MW
	Min Daytime Load	1.1 MW	0.7 MW
	Existing PV (MW)	1.0	1.7
	Total Circuit Miles	28	58
Minimum Hosting Capacity (kW)			
Voltage	Primary Overvoltage	>3500	420
	Regulator Deviation	>3500	250
Protection	Total Fault Contribution	>3500	1685
	Sympathetic Tripping	1478	1426
	Reduction of Reach	>3500	1489
	Fuse Saving	1771	1426
	Anti-Islanding – Breaker	400	390

Customer-based
PV results shown

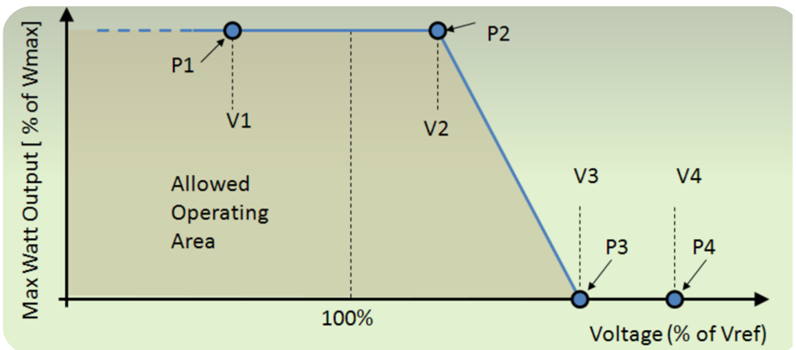
What About PV With Smart Inverters?

Use of Smart Inverters for Increasing Hosting Capacity

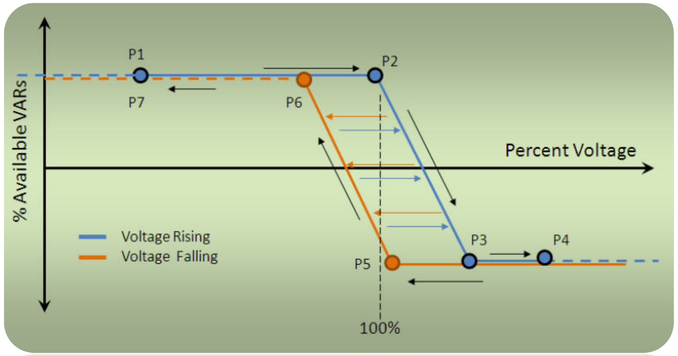
Volt-Var Control*



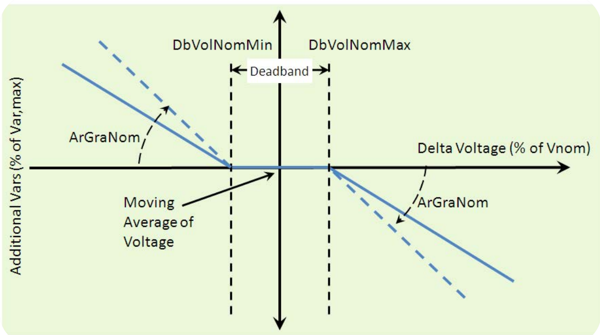
Volt-Watt Control**



Volt-Var w/ Hysteresis**



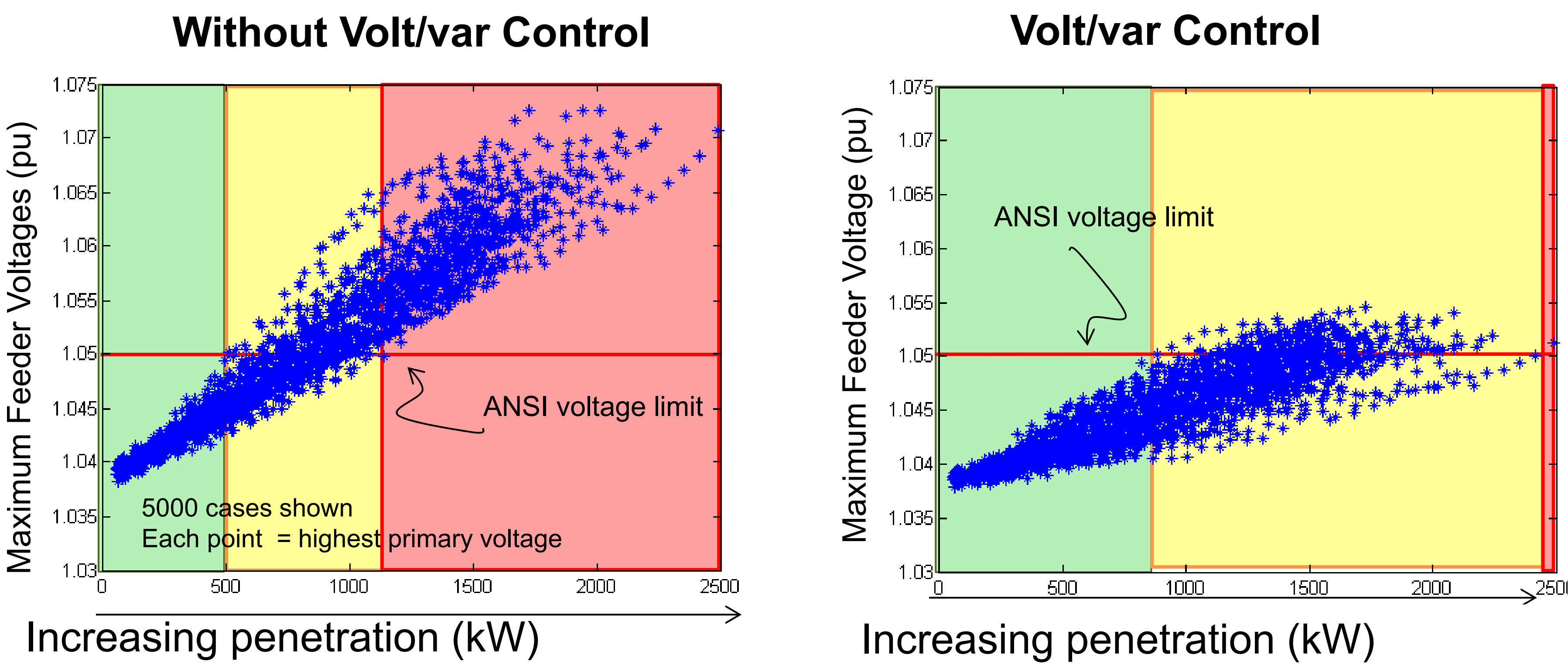
Dynamic Var Control**



*Currently in OpenDSS
**available in OpenDSS Q1 2013

Increasing Hosting Capacity with Smart Inverters

Sample Results from Feeder with Limited Hosting Capacity



		PV Hosting Capacity (kW)	
		Without Volt/var	With Volt/var
Primary Voltage Deviation	1st violation	938	>2500
	50% scenarios with violation	1323	>2500
	All scenarios with violation	1673	>2500
Primary Over Voltage	1st violation	540	880
	50% scenarios with violation	871	1464
	All scenarios with violation	1173	2418

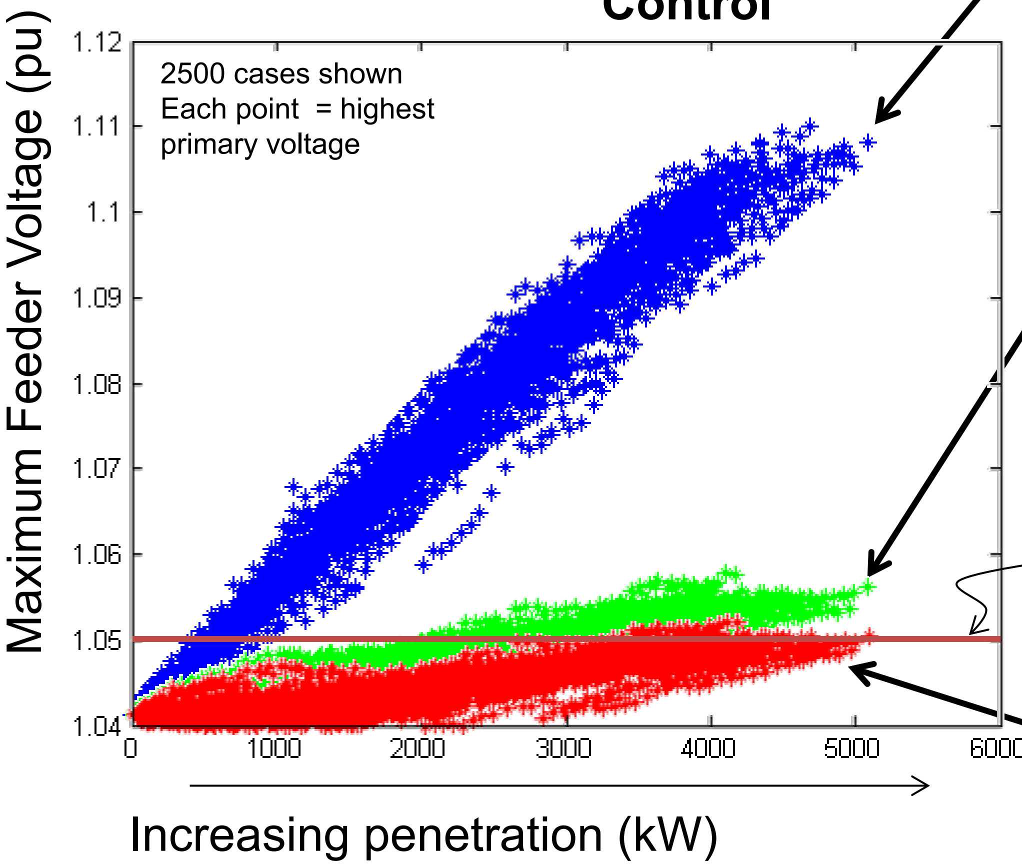
160% increase in hosting capacity

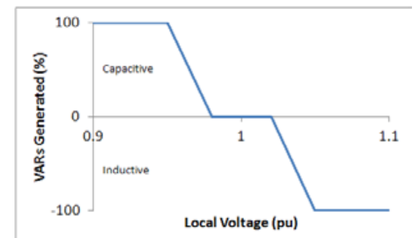
60% increase in hosting capacity

Maximum Voltages, Minimum load

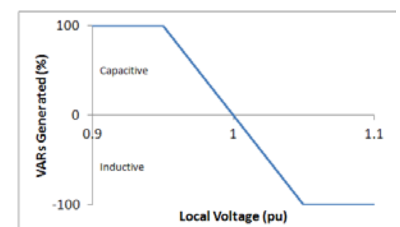
Without Volt/var Control

Volt/var Control w/ deadband





ANSI voltage limit



Volt/var Control w/o deadband

Improvement in Hosting Capacity

Offpeak Load

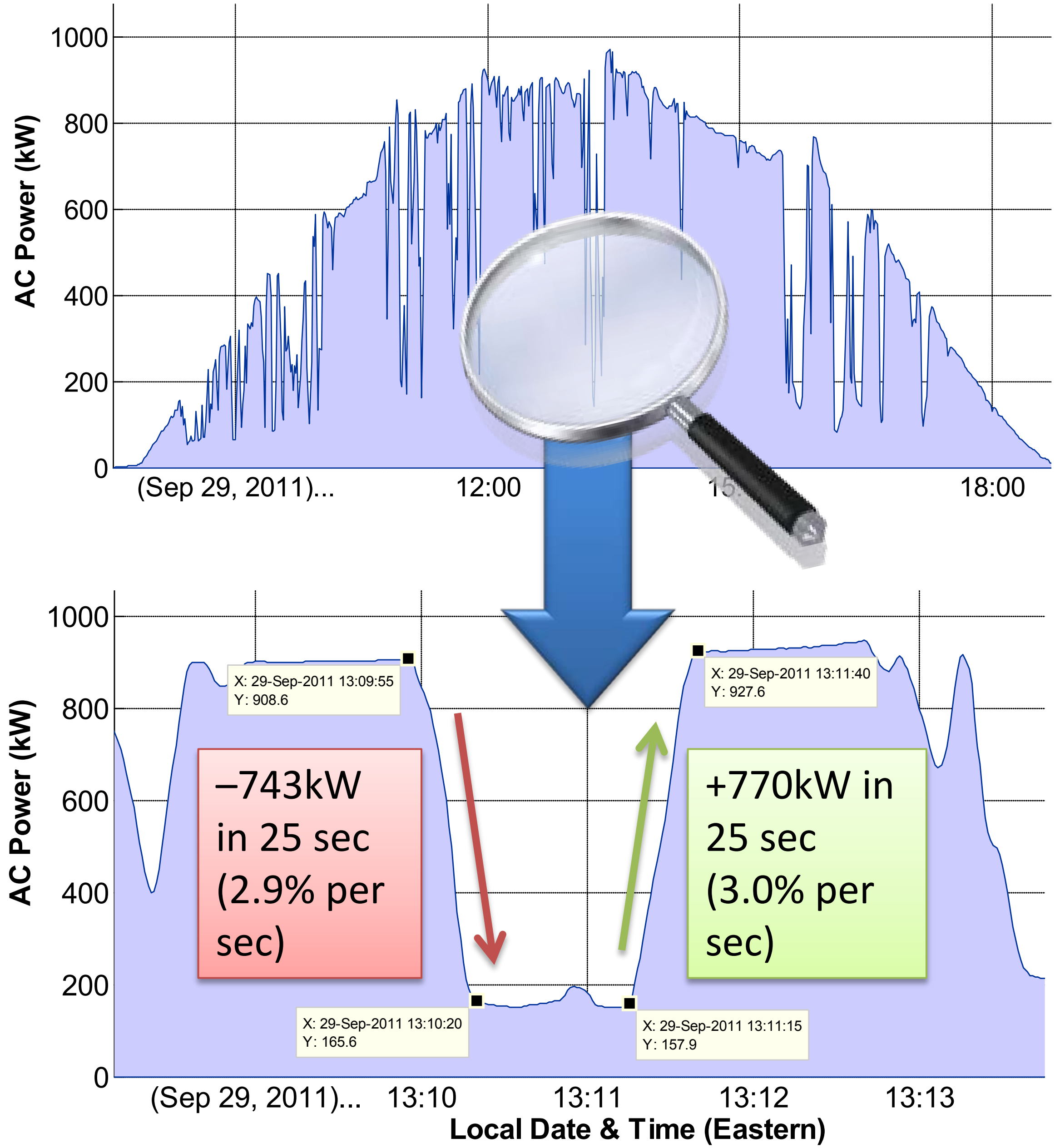
		PV Hosting Capacity (kW)	Hosting Capacity increase with volt/var (%)	
		Without Volt/var	4pt volt/var	6pt volt/var
Voltage Deviation	**Primary**	1132 kW	inf	inf
	Regulator	397	Inf	507 %
	Secondary	2275	inf	inf
Over Voltage	**Primary**	421	689	395
	Secondary	229	1409	832

Peak Load

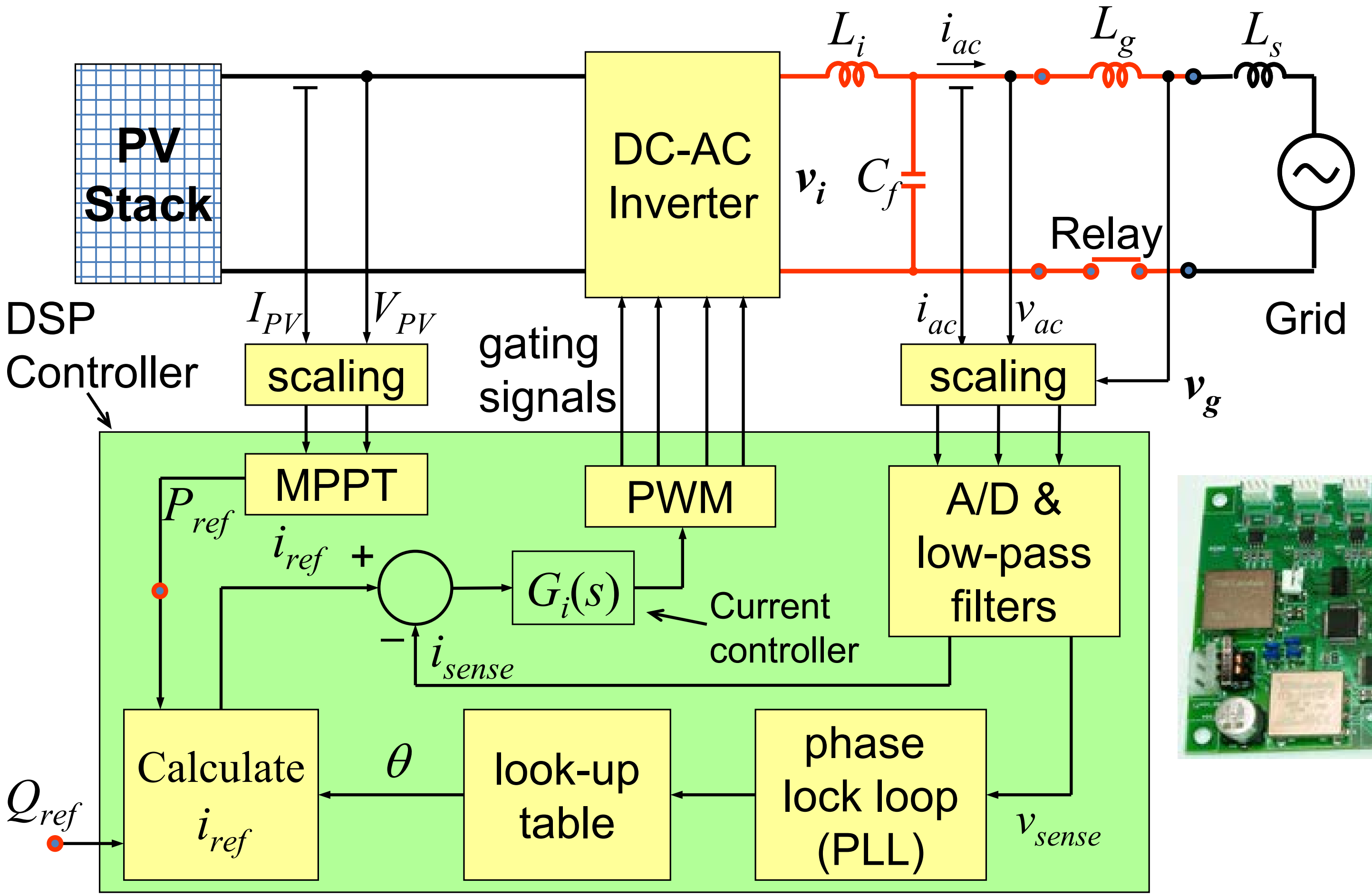
		PV Hosting Capacity (kW)	Hosting Capacity increase with volt/var (%)	
		Without Volt/var	4pt volt/var	6pt volt/var
Voltage Deviation	**Primary**	970 kW	105 %	17 %
	Regulator	288	21	0
	Secondary	1795	inf	109
Over Voltage	**Primary**	540	95	24
	Secondary	877	283	87

Ramp Rate Analysis

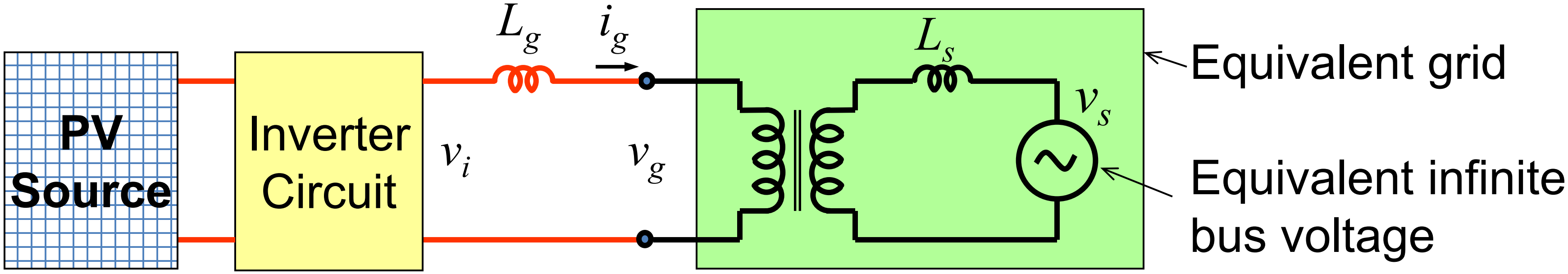
- **Benefit**
  - > How often and when significant ramping events occur
- **Time intervals**
  - > 10 seconds
  - > 1 & 10 minutes
  - > 1 hour
- **Scope**
  - > Single site: PV plant or representative single module
  - > Aggregated single modules

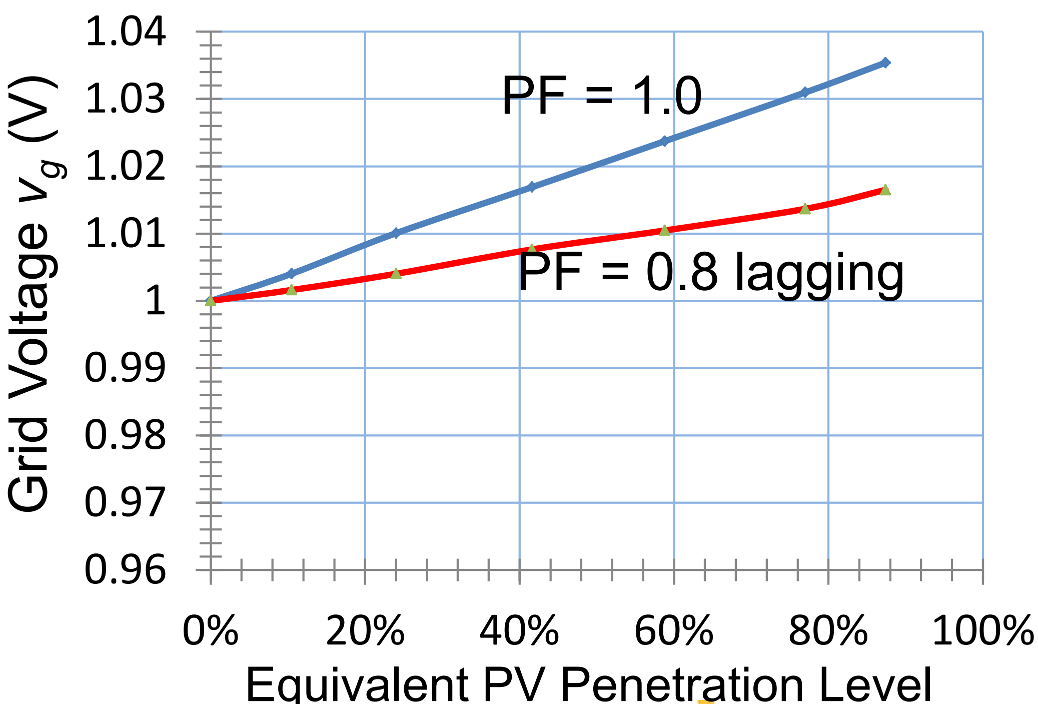


Hardware-in-the-Loop (HIL) Simulation for a Grid-Connected Inverter



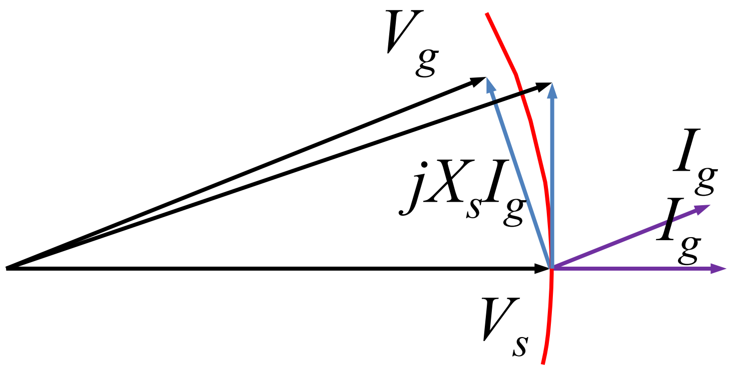
Experimental Voltage Level with Voltage-VAR Control Using a Scaled System

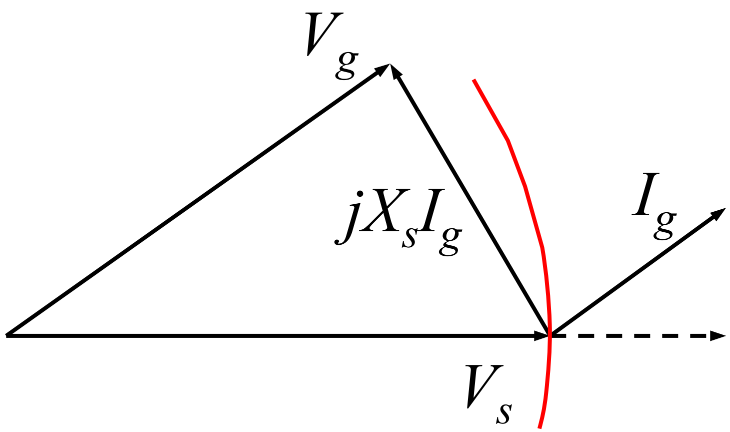


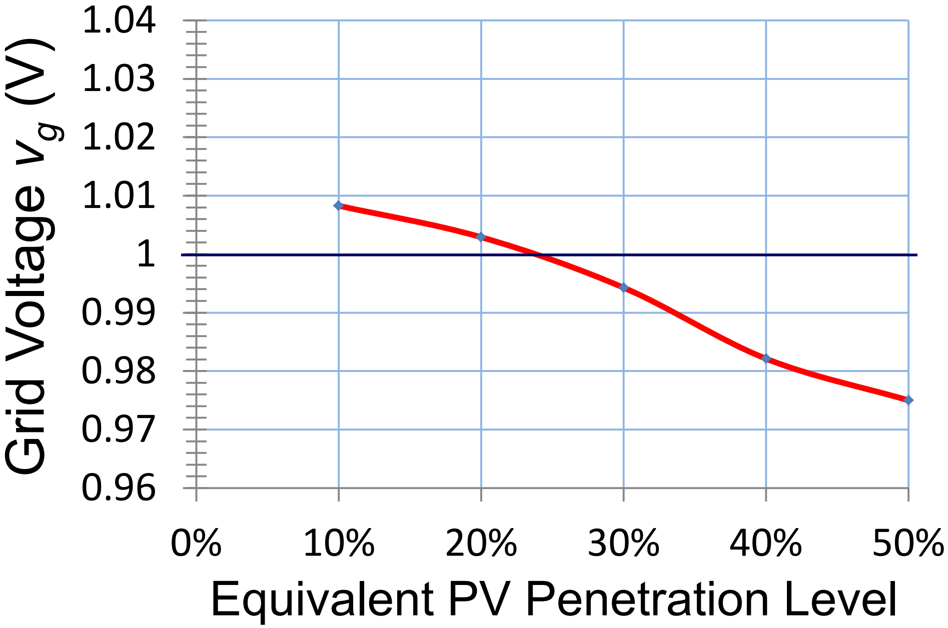


- **By making transformer power level equal to PV or inverter power level, the real power sent to grid represents PV penetration level**
- **Grid voltage increases as penetration level increases**
- **Unity power factor condition drives the grid voltage higher than that under lagging power factor condition**

Volt-Watt Control under Pure-Inductive Source Impedance Condition

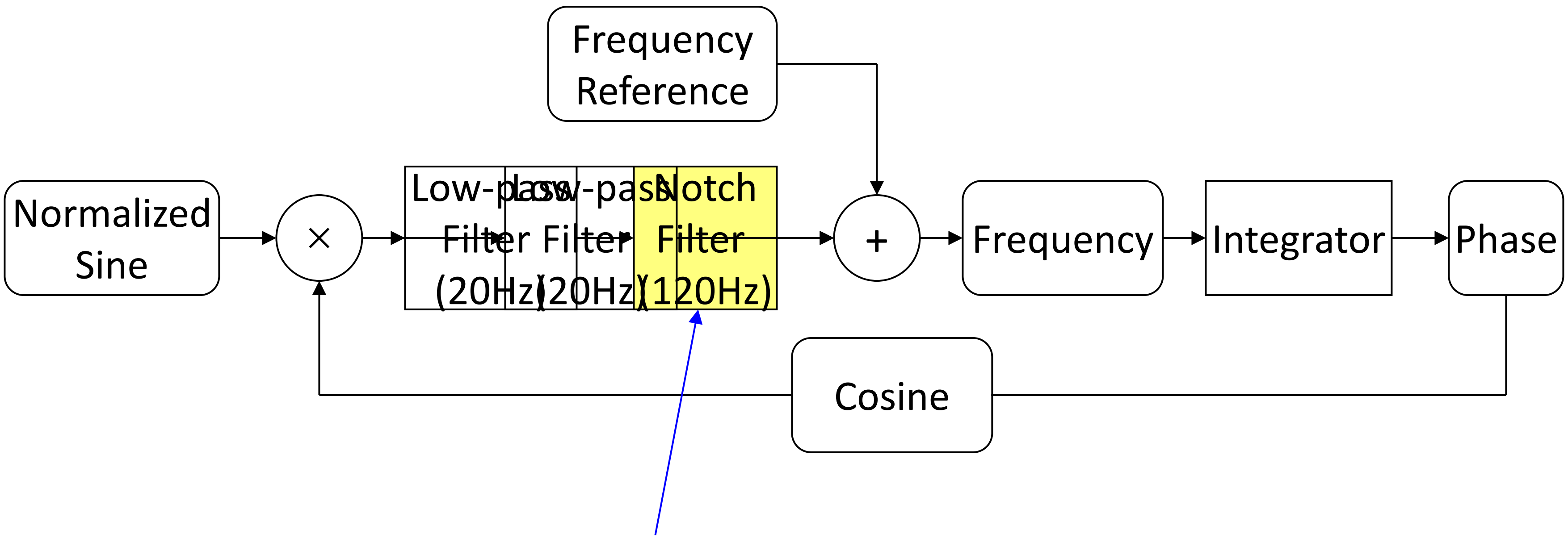






- HIL simulation reveals that due to the nature of a phase-locked loop, there is no guarantee that volt-watt will increase the grid voltage

Standards Compliance Design – A New PLL Algorithm for Abnormal Frequency Detection



A new phase-locked-loop (PLL) algorithm is proposed to add a notch filter to eliminate 120-Hz ripple for precise frequency detection

Summary IEEE 1547 Compliance Test with VT-FEEC Inverter

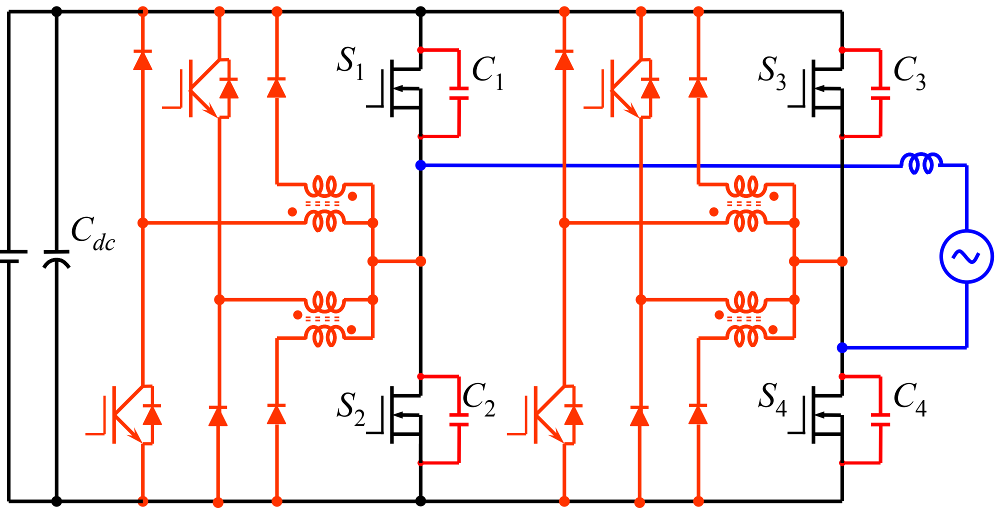
- Abnormal voltage test results

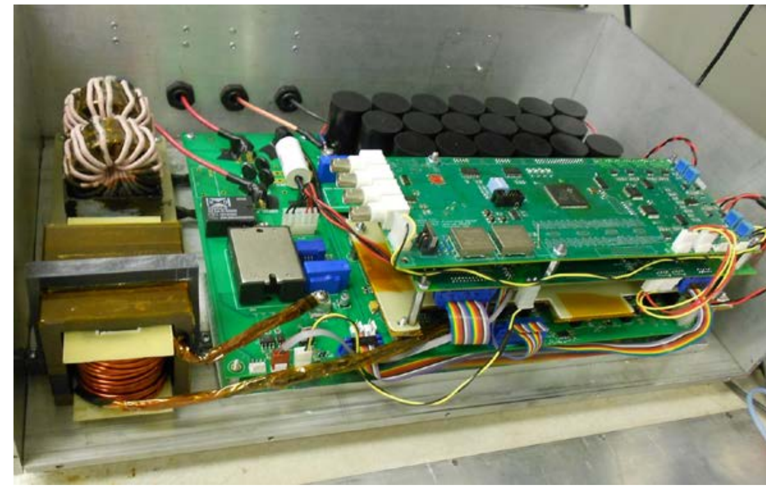
Voltage range (%)	Disconnection Time (s)	
	IEEE 1547	FEEC Inverter Test Result
V < 50	0.16	0.08
50 ≤ V < 88	2.00	1.60
110 < V < 120	1.00	0.64
V ≥ 120	0.16	0.11

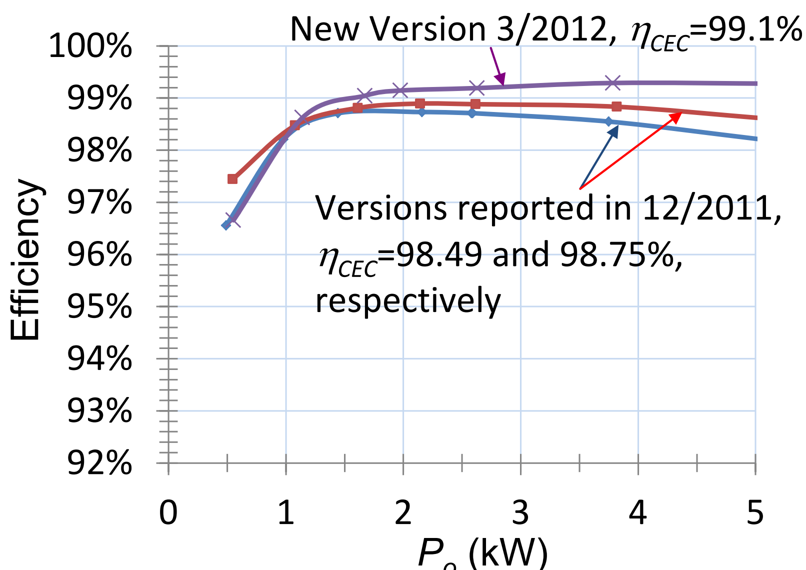
- Abnormal frequency test results

Frequency range (Hz)	Disconnection Time (s)	
	IEEE 1547	FEEC Inverter Test Result
$f > 60.5$ $f < 59.3$	0.16	0.084

High-Efficiency Soft-Switching Inverter





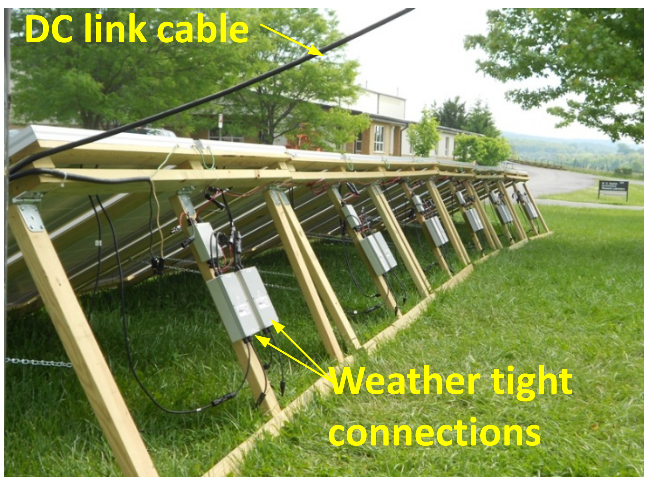


- VT soft-switching inverter achieved CEC efficiency >99%
- With natural convection, hot spot temperature was found at 51.9° after 1-hour operation ➔ no cooling fan is needed
- Output current THD < 2% under full-load condition

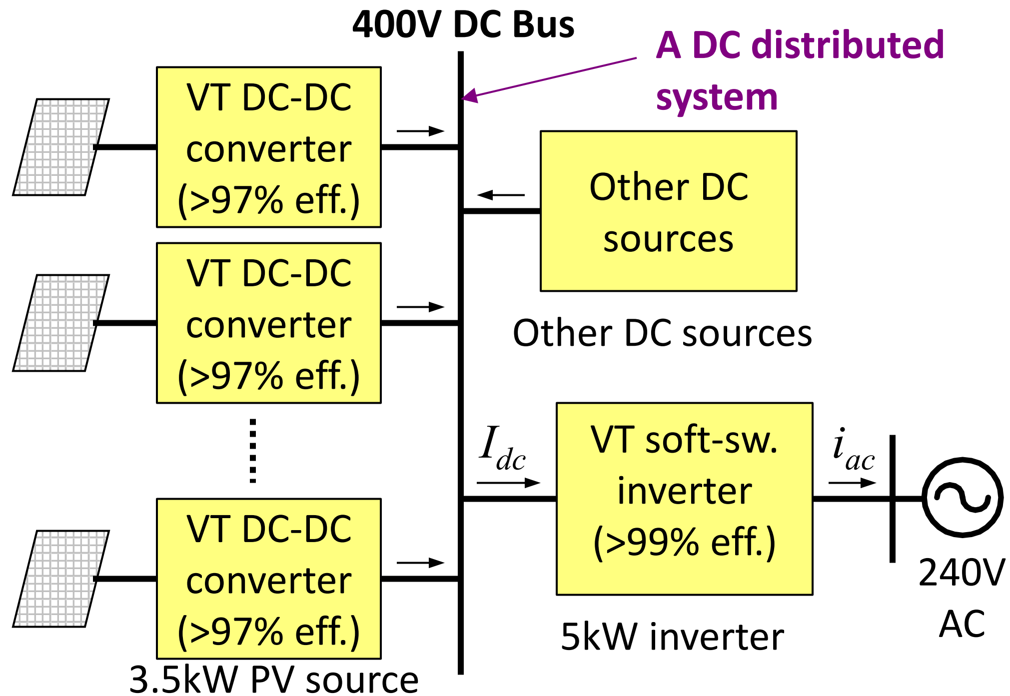
DC Distributed System Configuration

14×250W PV Panels, 3.5kW Total Installation

Front view of PV panels

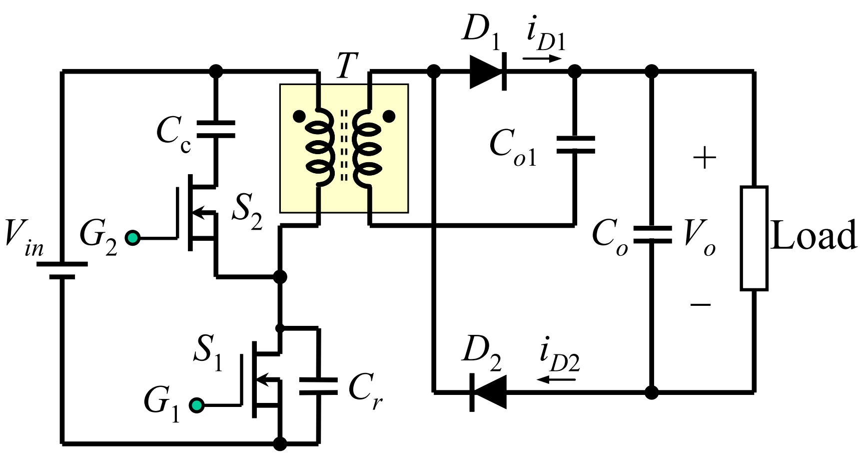


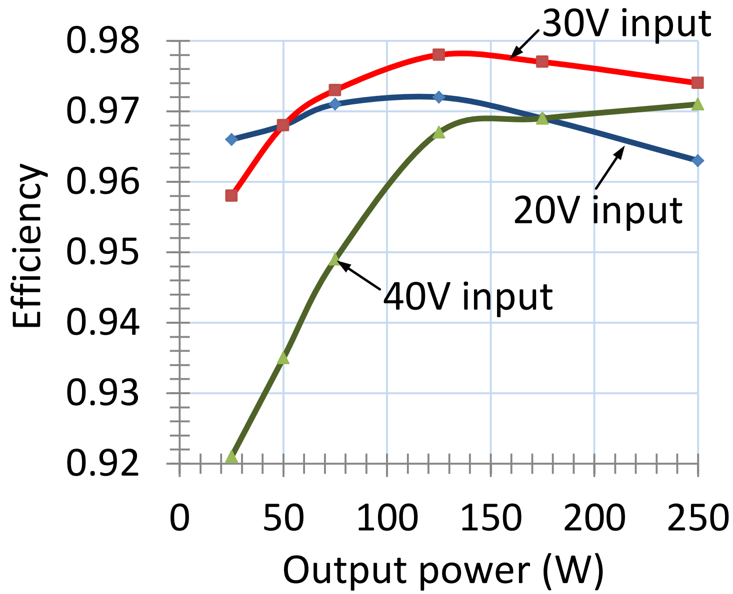
Back view of PV panels

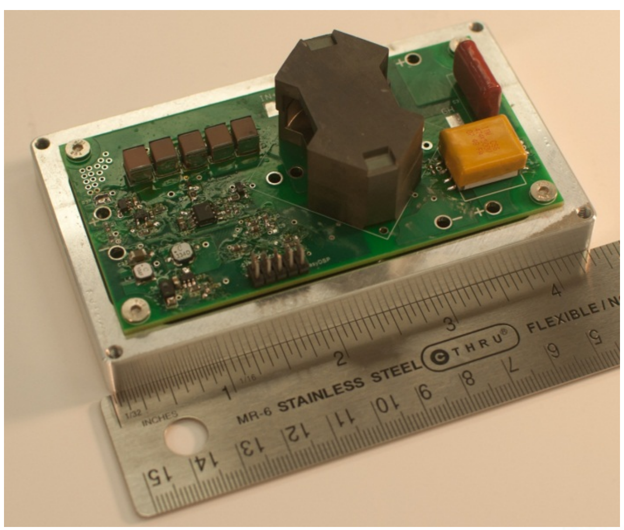


- **Paralleled power optimizers for individual panels**
- **High overall system efficiency (>96%) with VT micro-converter and soft-switching inverter**
- **DC micro-grid architecture with isolation and protection at local PV panels**
- **Potentially low cost with more integration**

A Soft-Switched Micro-converter Features Low Cost and High Efficiency

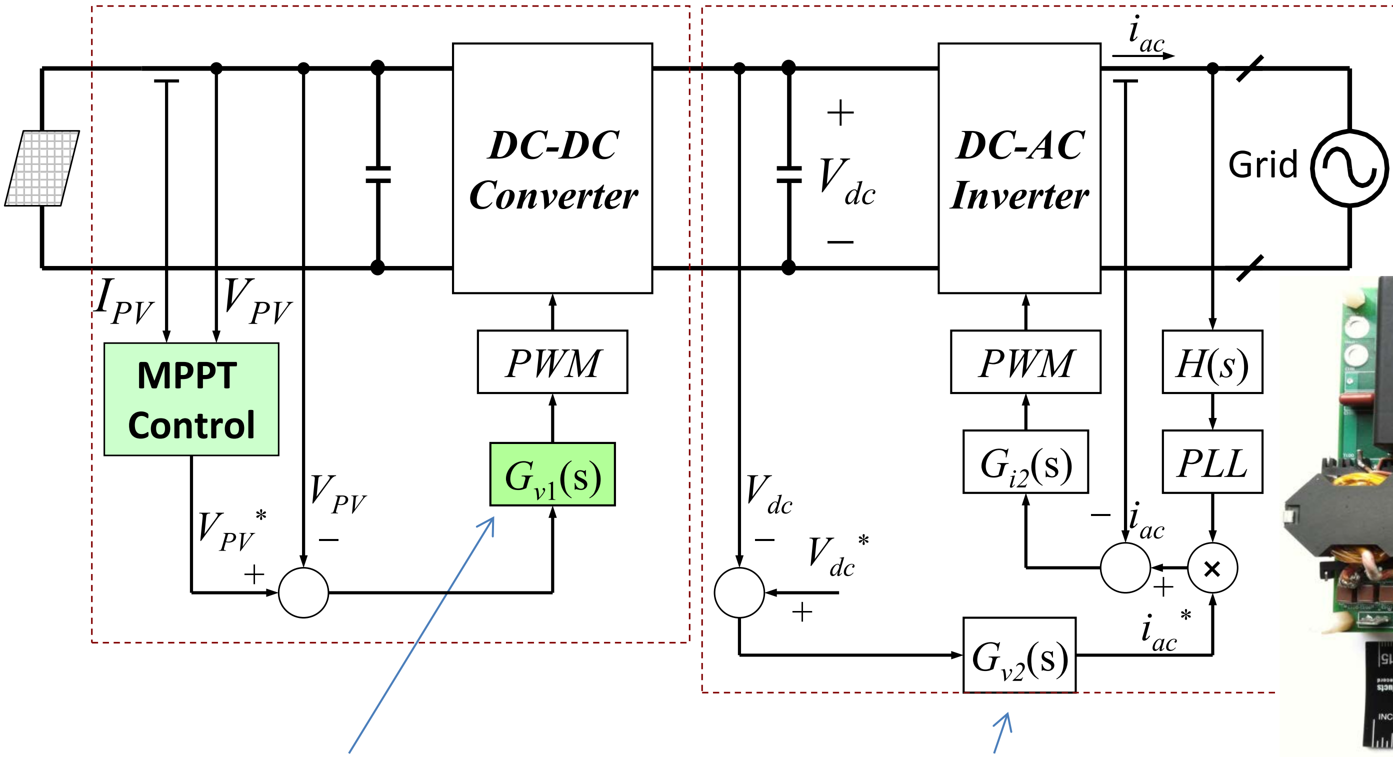






- **Low component counts ➔ low cost**
- **Soft switching ➔ high efficiency**
- **Galvanic isolation ➔ improved safety and protection**
- **No aluminum electrolytic capacitors**

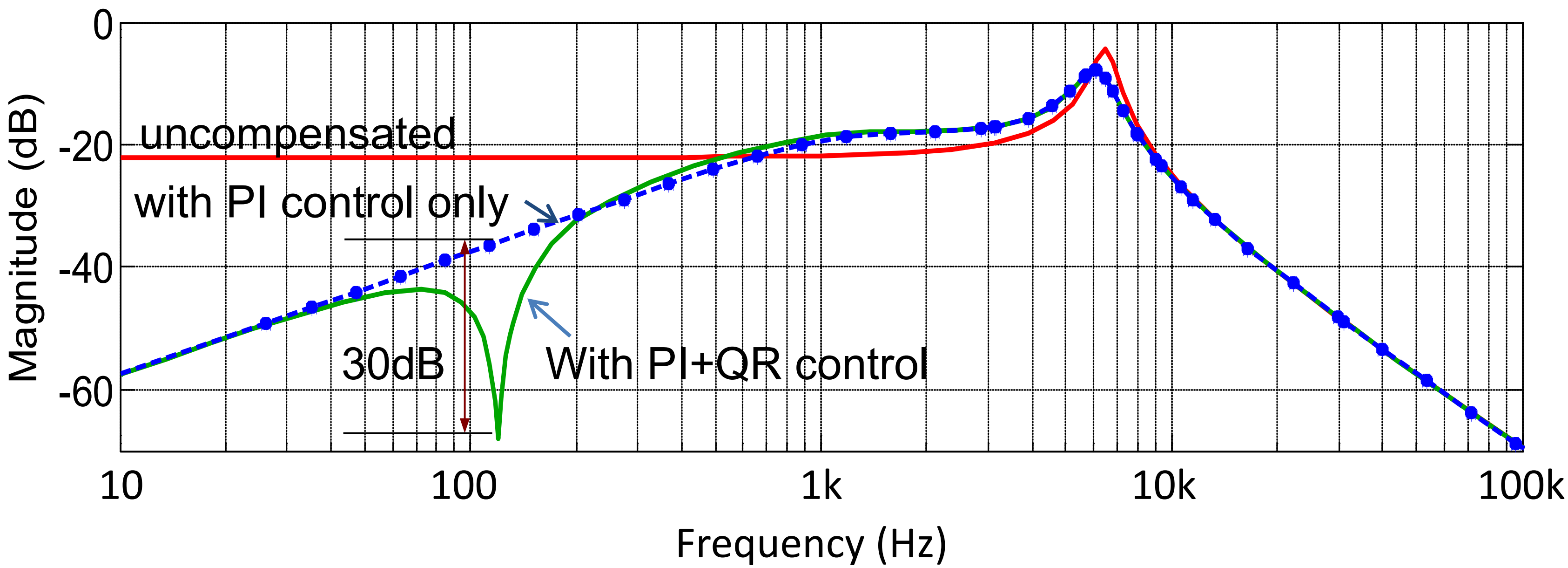
Eliminate Electrolytic Capacitors Using Advanced Control for PV-Inverters



PV voltage loop controller design with double line frequency rejection

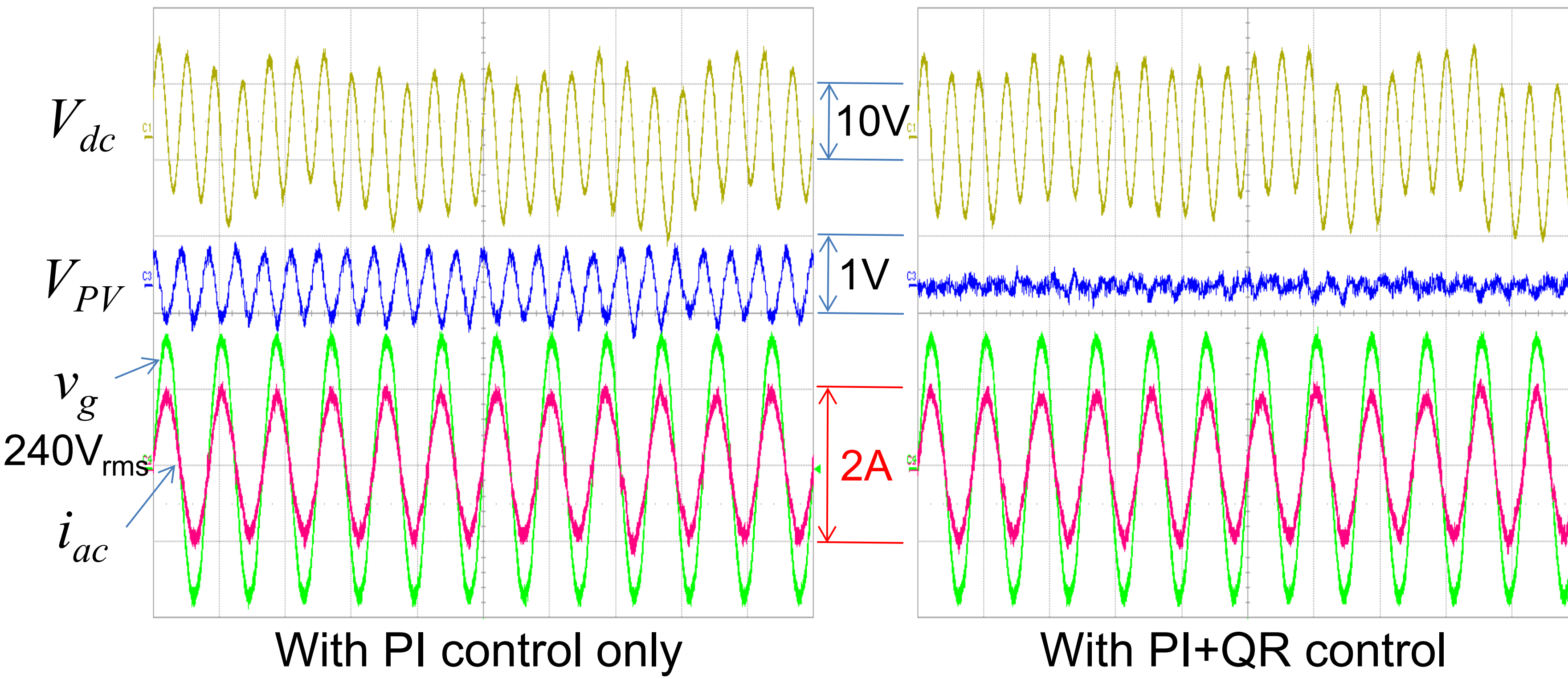
DC bus voltage loop controller design with double line frequency filter to avoid grid current distortion

Frequency Response Plot Showing Double-line Frequency Content Attenuation



- Using conventional proportional-integral (PI) controller for DC-DC converter, the double line frequency ripple is reduced by 16 dB (6.3X reduction)
- Using a novel PI plus quasi-resonant (QR) controller for the DC-DC converter stage, the double line frequency ripple is reduced by 46 dB (200X reduction)

Experimental Results Showing PV Voltage Ripple Elimination Using PI+QR Control



PV voltage ripple is significantly reduced with PI+QR control for the DC-DC converter ➔ Way to eliminate electrolytic capacitor without any added penalty

Summary

Modeling and Simulation

- Website hosting measurement data and feeder models
- Statistical analysis of PV variability at distribution level
- Study of hosting capacity boundary limits
- Evaluation of smart inverters that increase hosting capacity

Power Electronics

- Development of low-cost high-efficiency power electronics:
  - Micro-converter,
  - Micro-inverter,
  - String inverter
- Development of HIL simulation/hardware
- Novel abnormal voltage/ frequency detection

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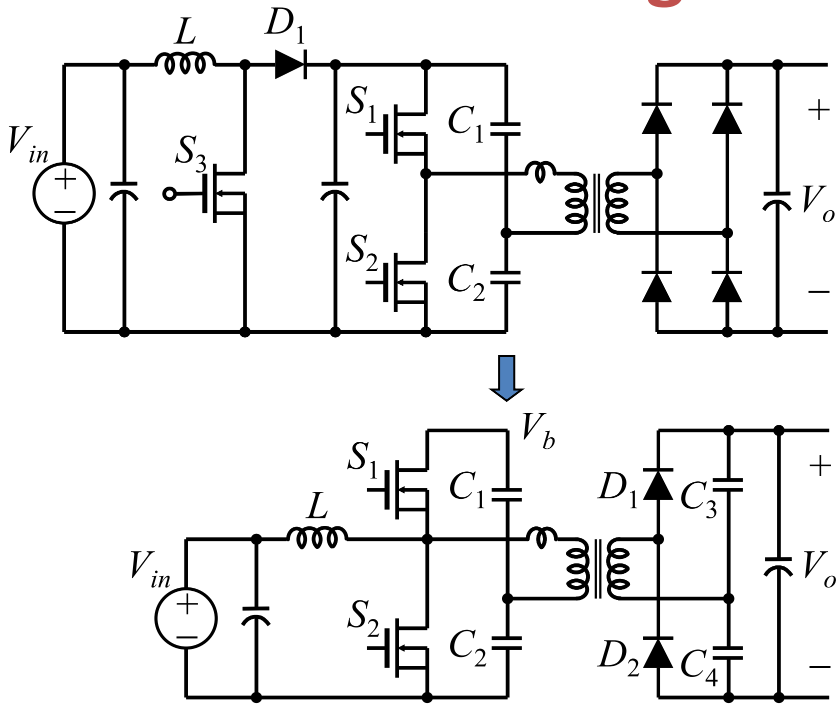
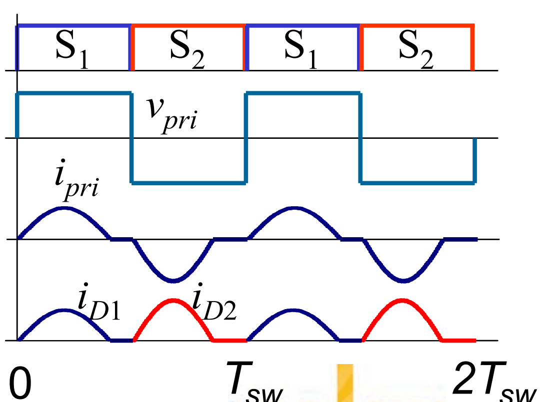
Q &A AND DISCUSSION

BACKUP SLIDES

An Integrated-Boost Resonant Converter for Isolated DC-DC Stage



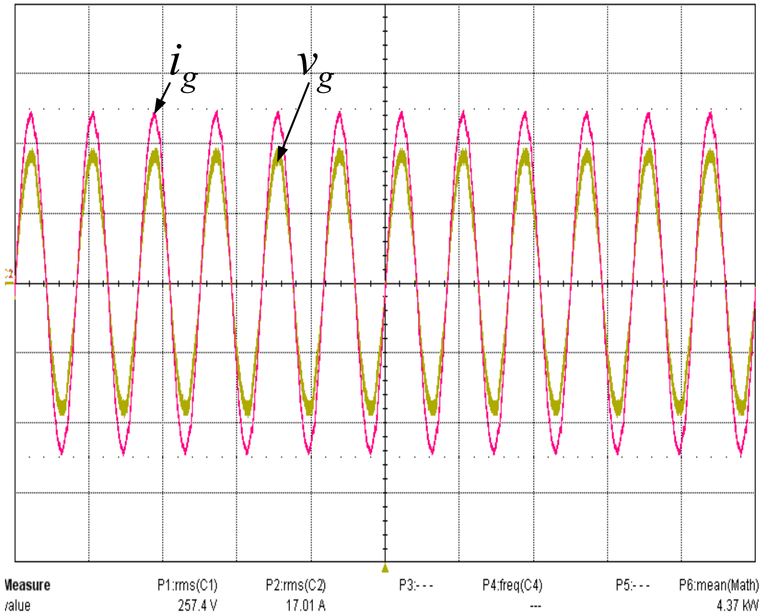


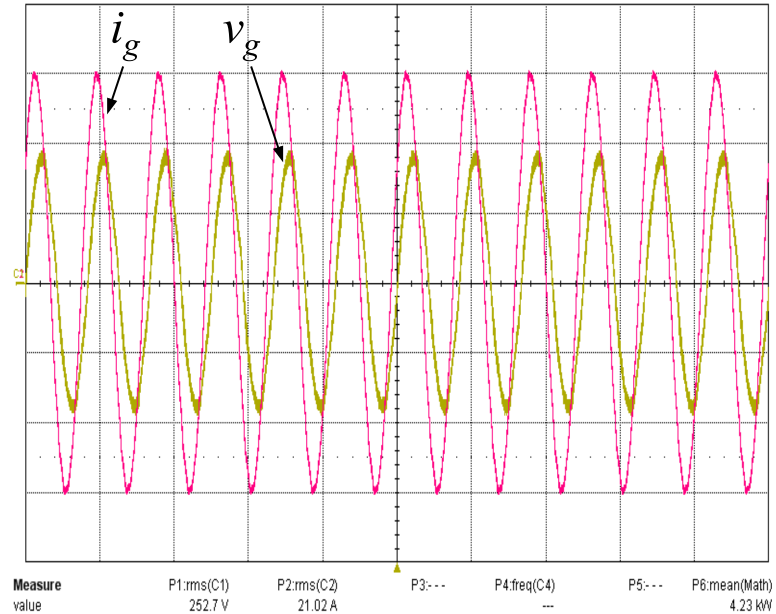
- Integrate a boost converter and a resonant half-bridge converter to reduce parts count
- The PWM duty cycle of S_2 controls the "boost voltage"

$$V_b = V_{in}/(1 - D)$$

- S_2 carries boost and resonant current and operates under hard switching
- S_1 operating under ZVS
- D_1, D_2 operating under ZVZCS
- Simple control
  - –Traditional duty-cycle modulation
  - –Constant voltage gain over load
- Guaranteed transformer V·s balanced

Experimental Waveforms with Voltage-VAR Control Using a Scaled System





CASE A: Inverter sends real power to the grid

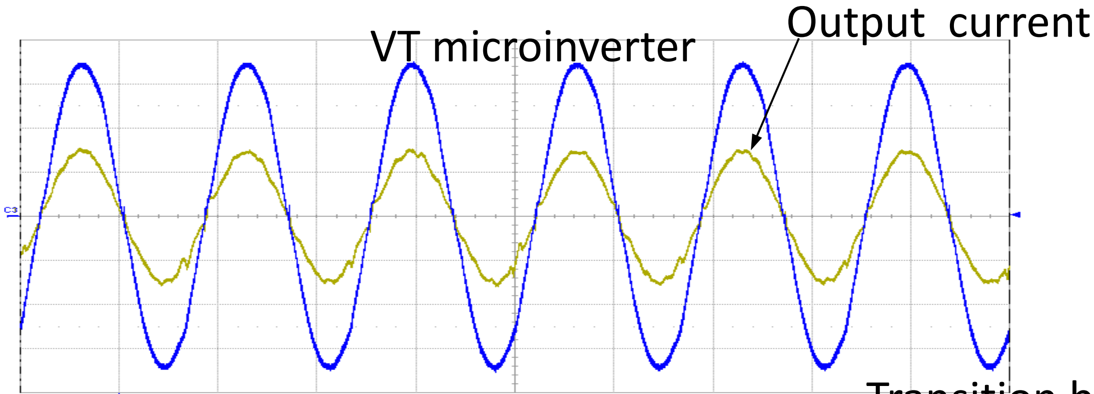
- Power factor = 1.0
- Equivalent PV penetration level: 88%
- Equivalent inverter KVA level: 0.88 pu
- Grid voltage increases by 3.5%

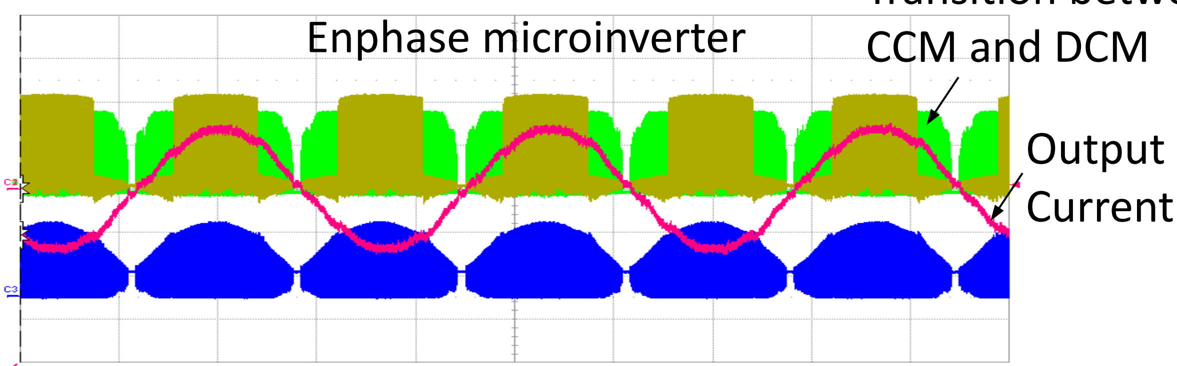
CASE B: Inverter sends real and reactive power to the grid

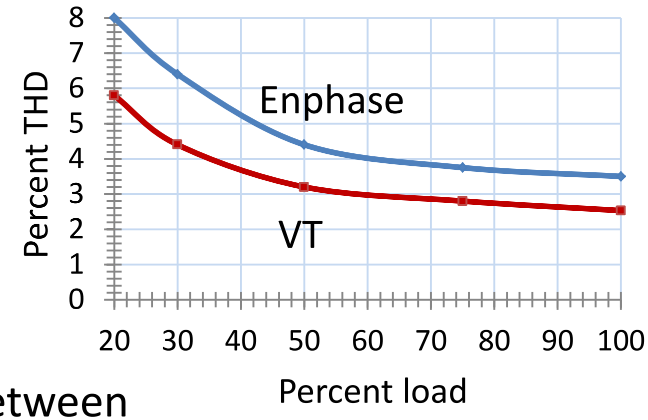
- Power factor = 0.8 lagging
- Equivalent PV penetration level: 85%
- Equivalent inverter KVA level: 1.06 pu
- Grid voltage increases by 1.7%

Current Waveform Comparison between VT and Enphase Microinverters

- With continuous operation, VT microinverter current THD is <2.5% under full-load condition
- Enphase modulates between continuous and discontinuous current modes (CCM and DCM), resulting poorer THD (>3%).

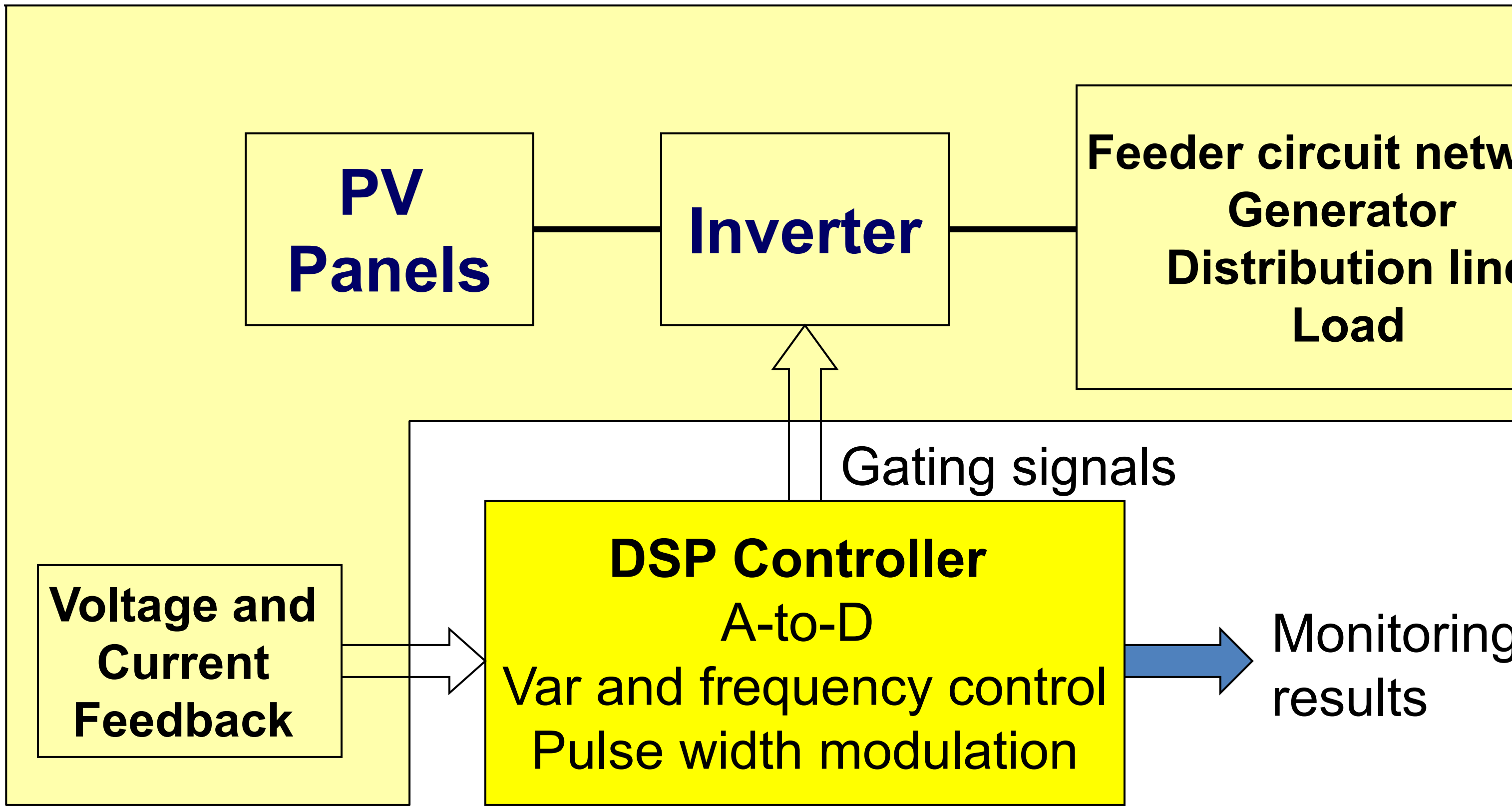




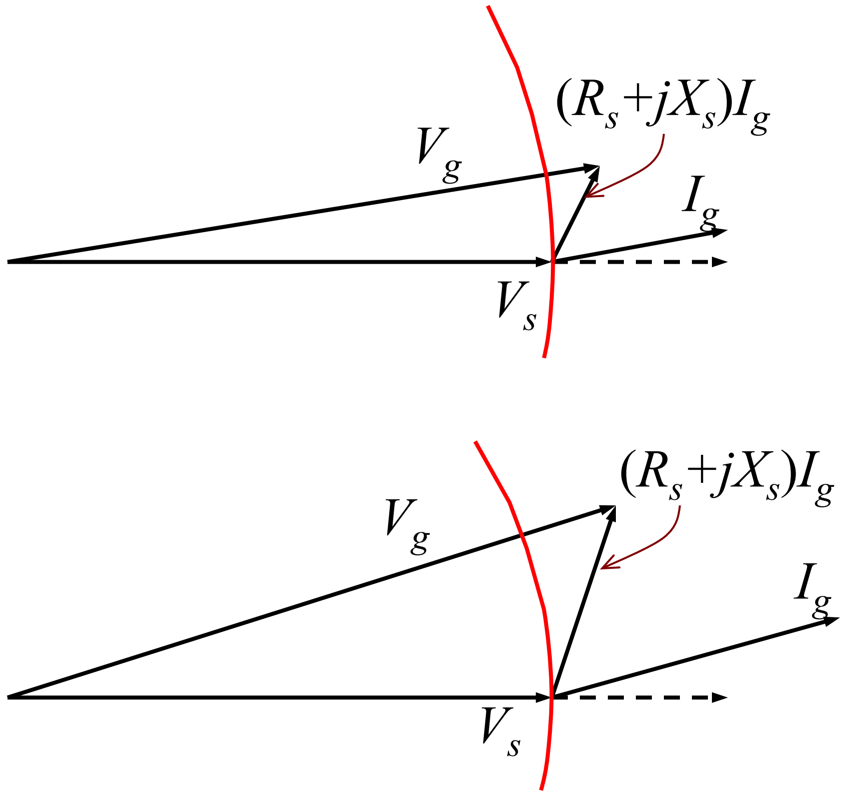


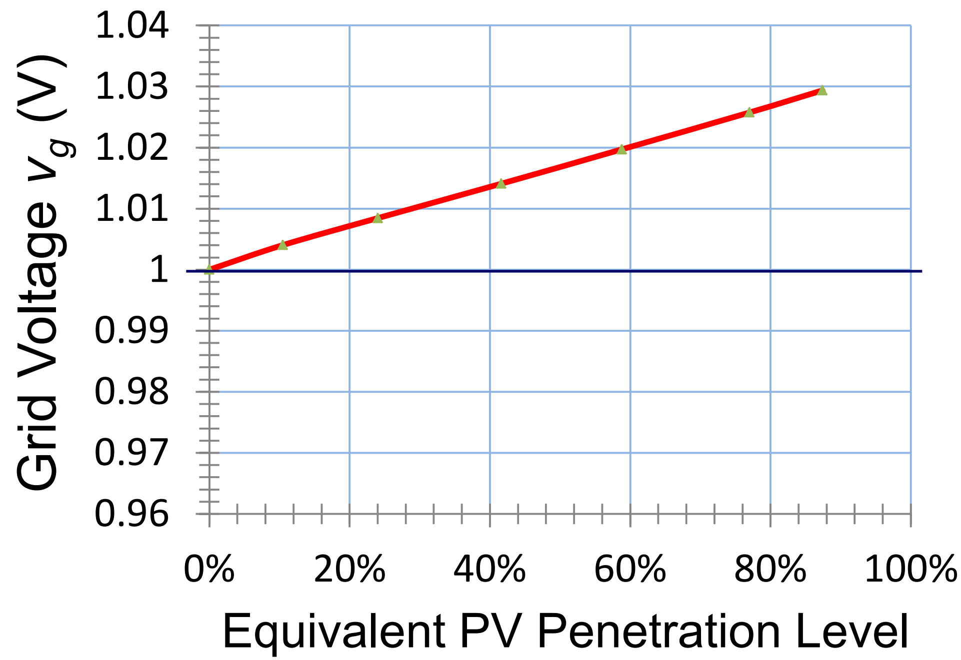
Design of Hardware-in-the-loop Simulation

Target Hardware System Circuit Model (in PSIM)



Grid Voltage Control under Resistive-Inductive Source Impedance Condition





With resistive-inductive source impedance condition, the grid voltage V_g, is generally driven higher under higher penetration PV levels.

Hosting Capacity Comparison

- Each feeder has **similar** characteristics that are **typically** used to classify feeders (load level and voltage class)
- Two significantly different PV penetration levels can be accommodated before violating voltage criteria

Feeder Comparison			
		Feeder A	Feeder B
Feeder Characteristics	Voltage (kV)	13.2	12.47
	Peak Load	5 MW	6 MW
	Minimum Load	0.8 MW	0.7 MW
	Min Daytime Load	1.1 MW	0.7 MW
	Existing PV (MW)	1.0	1.7
	Total Circuit Miles	28	58
Minimum Hosting Capacity (kW)			
Voltage	Primary Overvoltage	>3500	420
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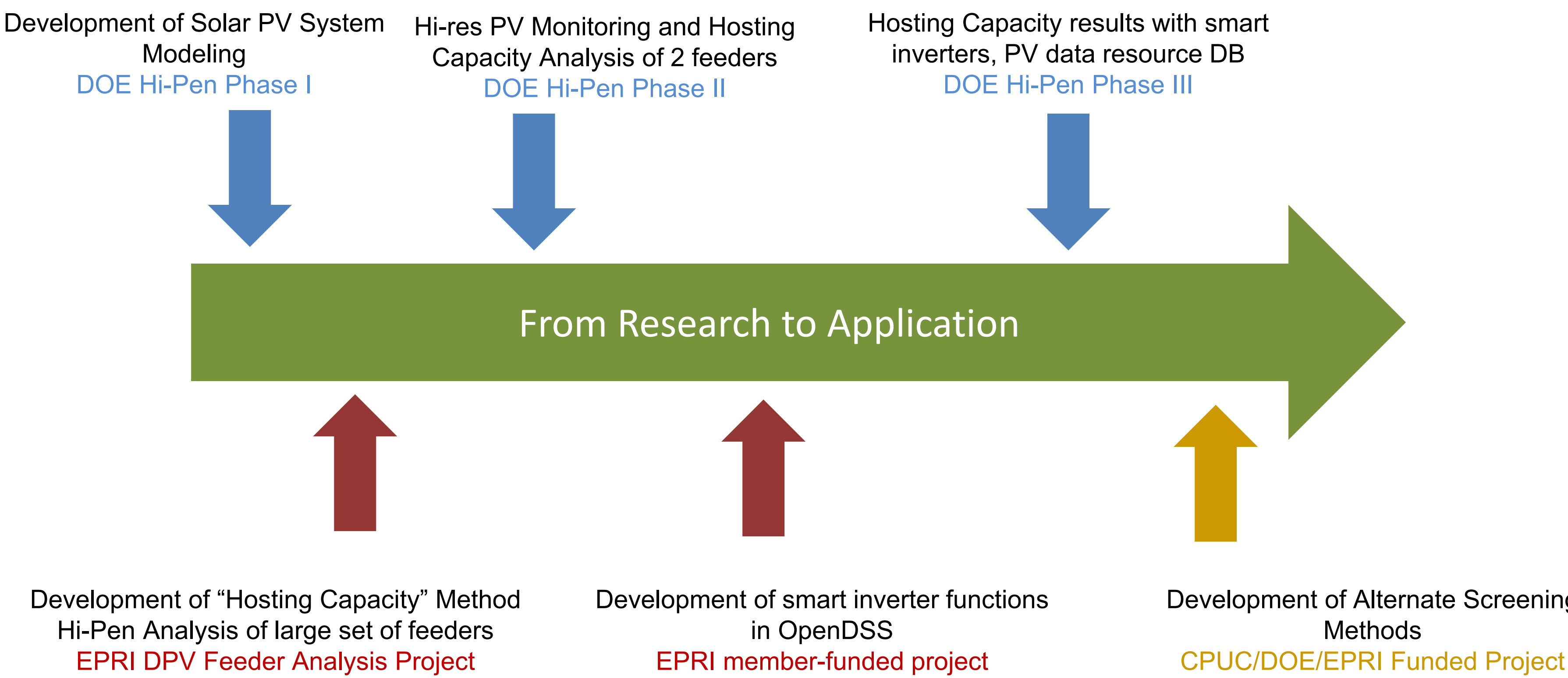
	Fuse Saving	1771	1426
	Anti-Islanding – Breaker	777	390

Customer-based PV results shown

70% of Peak Load

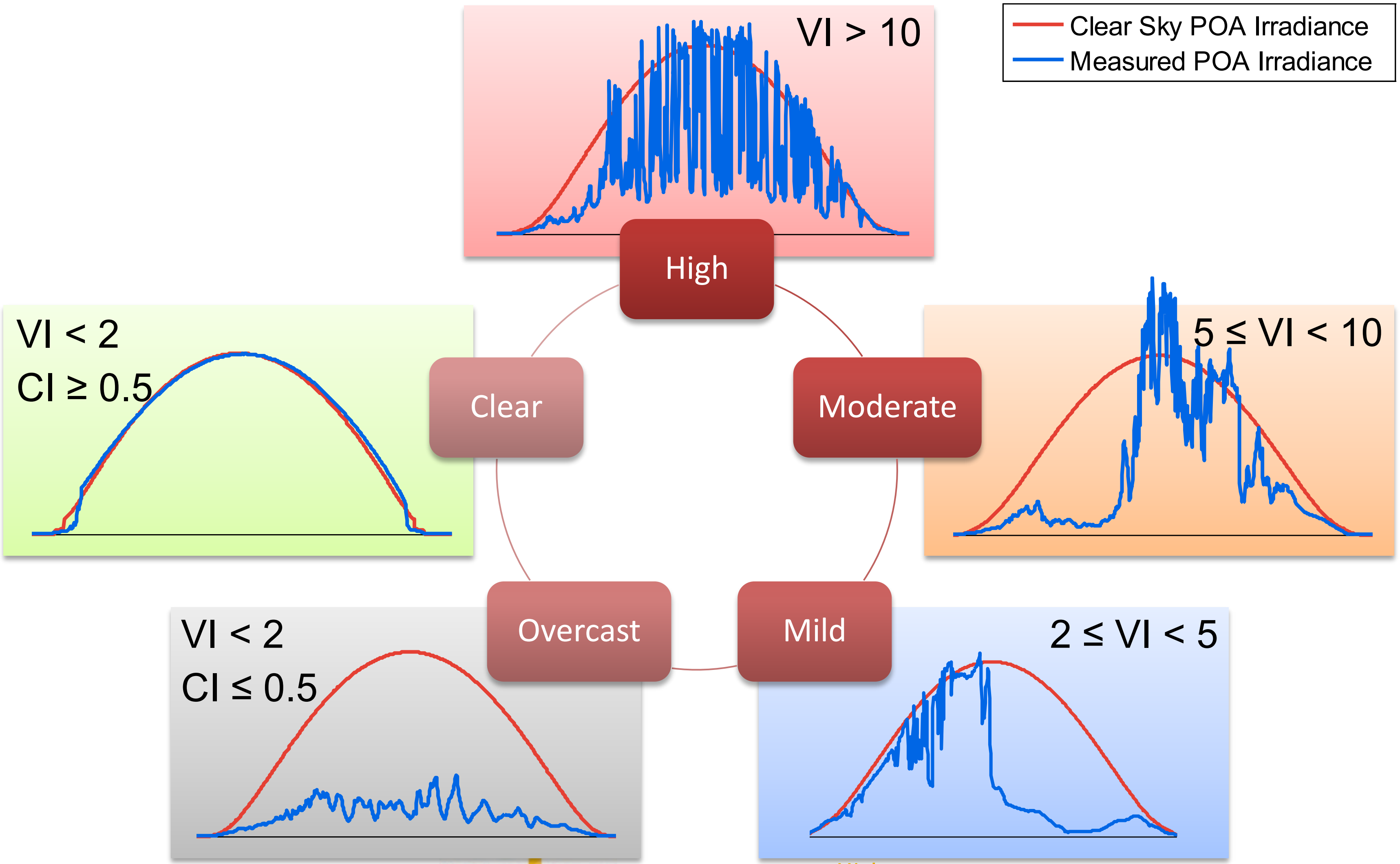
4% of Peak Load

Leveraging Work Throughout Industry



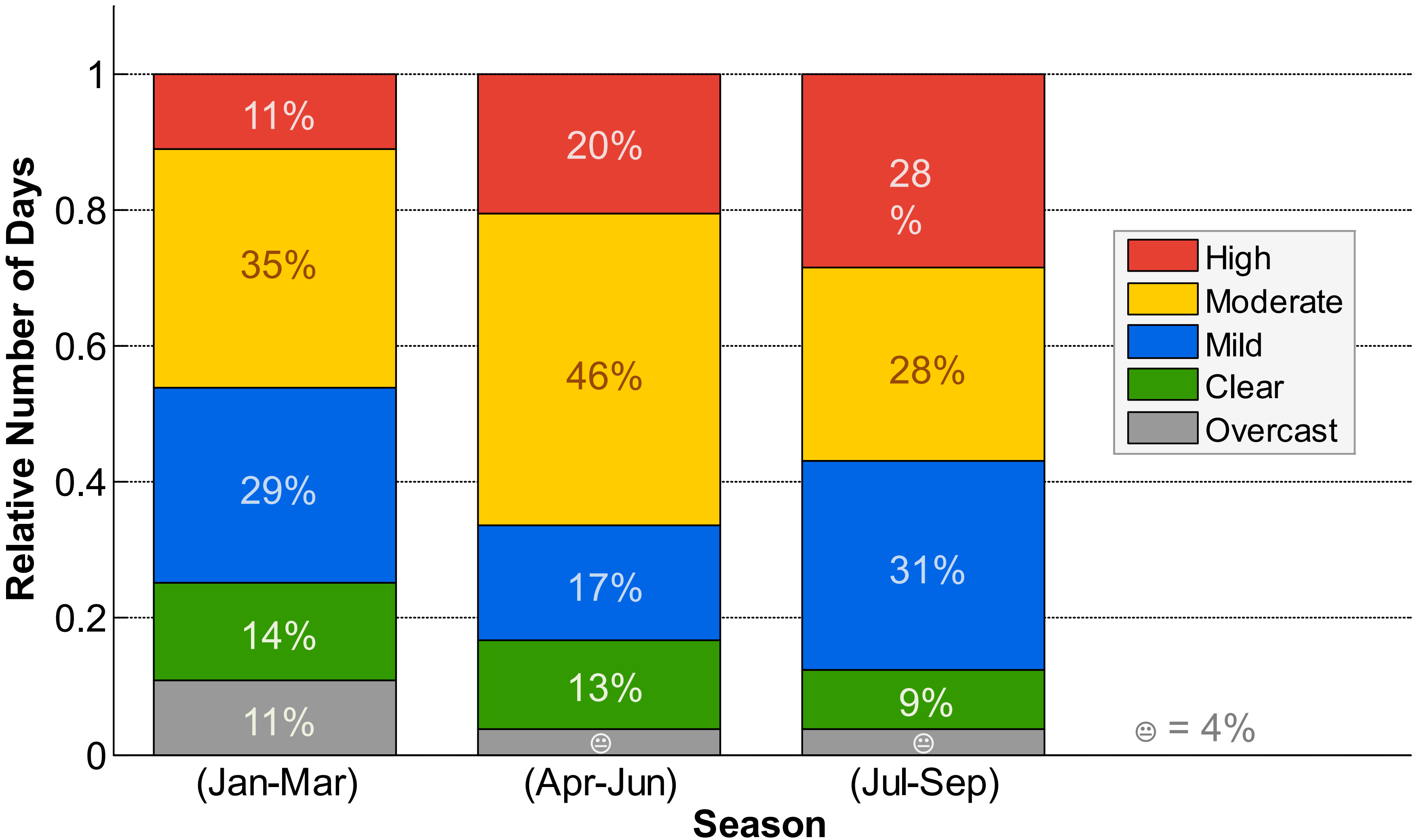
Categories for Daily Variability Conditions

Sandia's variability index (VI) and clearness index (CI) to classify days

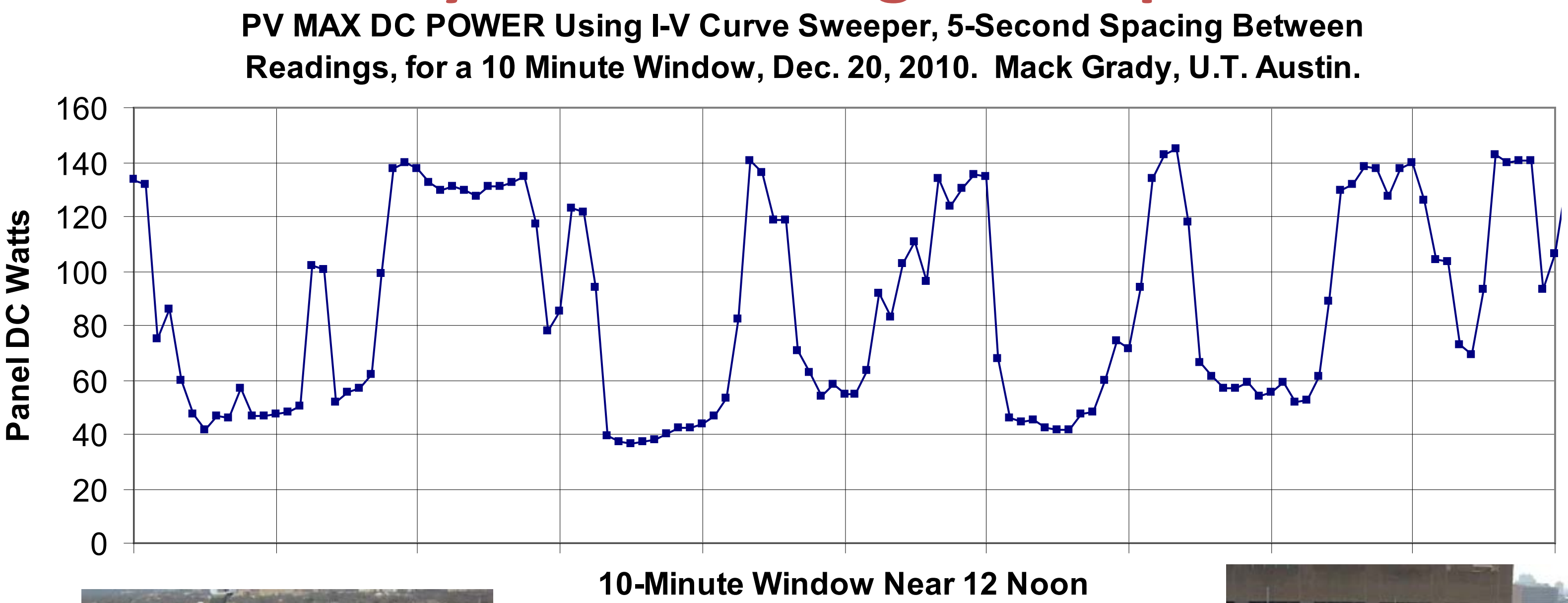


Daily Variability Conditions by Season

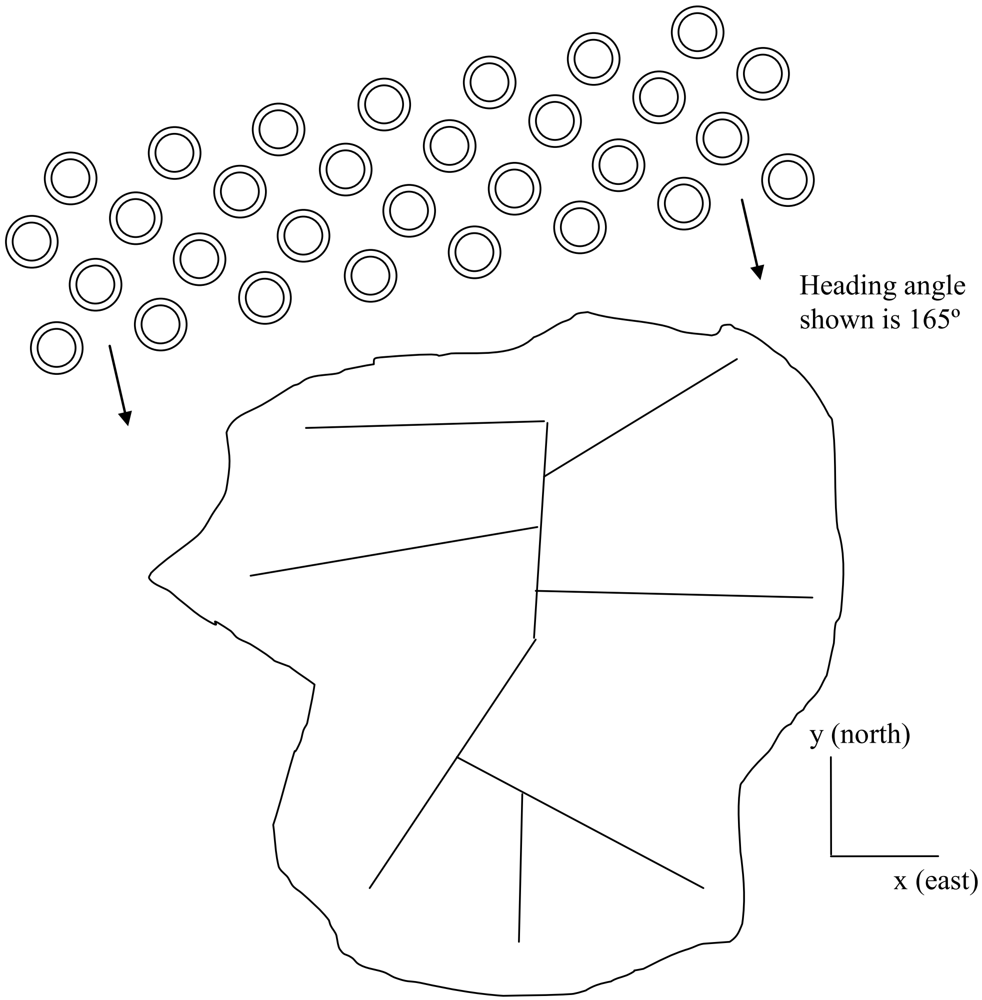
At 1MW plant on feeder A, measured with plane-of-array pyranometer



Predicting Cloud Movement Impact on Power Distribution Systems Having Widespread PV



Example Cloud Movement over a Substation with a Total Load about 20 to 40 MW



One substation transformer feeding approximately four distribution feeders and several hundred individual load busses with about 20 – 40 MW total load

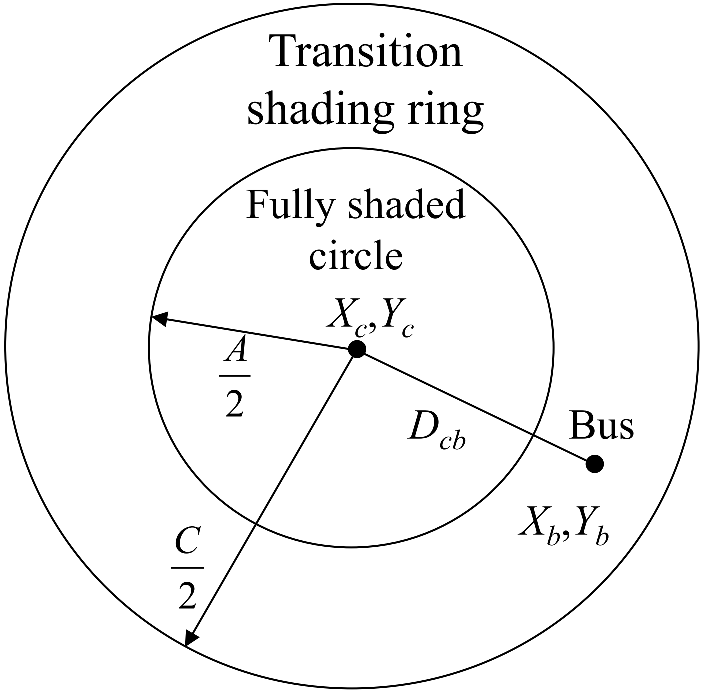
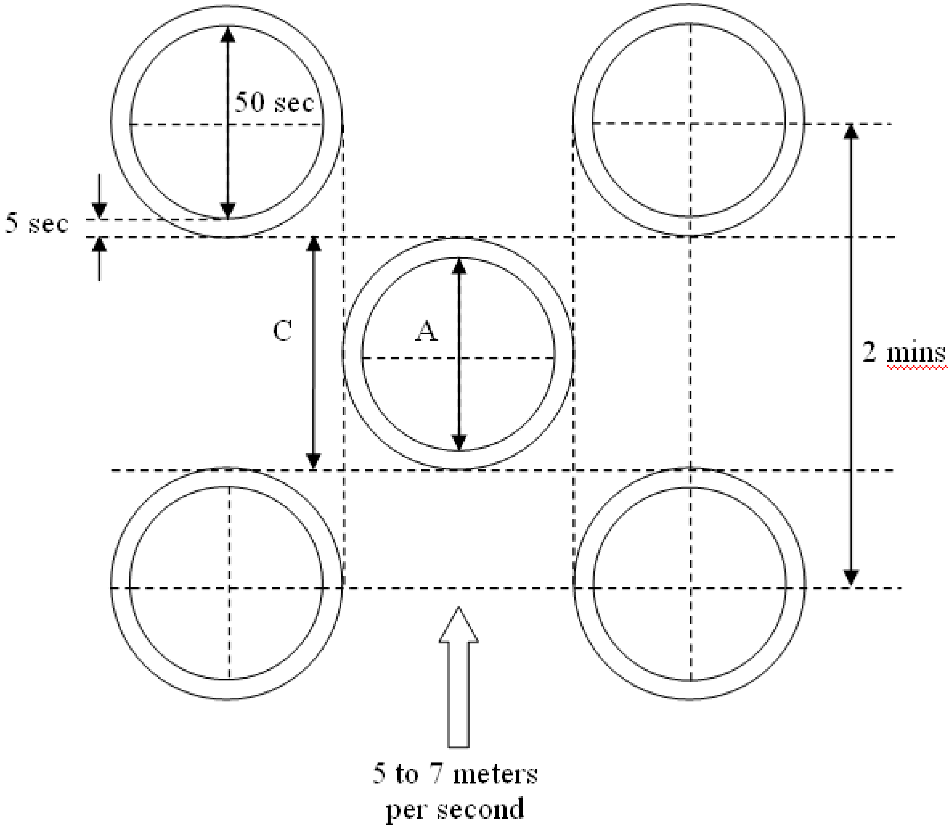


Illustration of calculation within the transition shading ring

Cloud Movement Model



For cloud shadow speed = 5 m/s, A = 250 meters, C = 300 meters
For cloud shadow speed = 7 m/s, A = 350 meters, C = 420 meters

- When there is no shadow, use panel clear sky P_{max} for the given time of day and panel orientation.
- When inside a 50-second diameter, or A, use $P_{max}/3$.
- When inside a 5-second circular transition ring, or $C - A$, the power is assumed to be linearly varied between P_{max} and $P_{max}/3$