Virginia Tech: Jason Lai, Jason Dominic, Bin Gu, Nathan Kees, Ben York, Wensong Yu

Electric Power Research Institute: Jeff Smith, Tom Key, Chris Trueblood

Baylor University: Mack Grady

Jason Lai, James S. Tucker Professor
Virginia Tech

Jeff Smith, Senior Manager
EPRI

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

Measured Voltage as Function of PV Output

Increasing PV Output (kW) →

1.07
1.06
1.05
1.04
1.03
1.02
1.01

---

Measured Overvoltage Due to PV

Increasing PV Output (kW) →

1.08
1.07
1.06
1.05
1.04
1.03
1.02

---

PV Site - 2.06 ckt mi from TV

1Ph Line

TV Substation

1 mi

3Ph Lines

Feeder A

Feeder B

PV Site - 4 miles from Sub

Capacitor Bank

Regulator

Substation
Measurement Data
Solar Monitoring

- DPV Pole-Mount Panels
- Metered Large-Scale PV
Time Series Response with Existing PV

Normalized Power Production

Distance from Substation

Net Feeder Demand (kW)

Cumulative Tap Operations

Total Power Production (MW)

Cumulative Cap Operations

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Hosting Capacity Comparison
Quick Look at Overvoltage Impacts

Feeder B

Minimum Hosting Capacity
Maximum Hosting Capacity

5000 cases shown
Each point = highest primary voltage

ANSI voltage limit

Increasing penetration (kW)

Maximum Feeder Voltages (pu)

Increasing penetration (kW)

No observable violations regardless of size/location
Possible violations based upon size/location
Observable violations occur regardless of size/location
## Hosting Capacity Comparison

<table>
<thead>
<tr>
<th>Feeder Characteristics</th>
<th>Feeder A</th>
<th>Feeder B</th>
</tr>
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<td>12.47</td>
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<td>Peak Load</td>
<td>5 MW</td>
<td>6 MW</td>
</tr>
<tr>
<td>Minimum Load</td>
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<td>0.7 MW</td>
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<td>Min Daytime Load</td>
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</tr>
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<td>Existing PV (MW)</td>
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</tr>
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<td>Total Circuit Miles</td>
<td>28</td>
<td>58</td>
</tr>
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### Minimum Hosting Capacity (kW)

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<td></td>
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<tr>
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<td>&gt;3500</td>
<td>420</td>
</tr>
<tr>
<td>Regulator Deviation</td>
<td>&gt;3500</td>
<td>250</td>
</tr>
<tr>
<td>Protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Fault Contribution</td>
<td>&gt;3500</td>
<td>1685</td>
</tr>
<tr>
<td>Sympathetic Tripping</td>
<td>1478</td>
<td>1426</td>
</tr>
<tr>
<td>Reduction of Reach</td>
<td>&gt;3500</td>
<td>1489</td>
</tr>
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<td>Fuse Saving</td>
<td>1771</td>
<td>1426</td>
</tr>
<tr>
<td>Anti-Islanding – Breaker</td>
<td>400</td>
<td>390</td>
</tr>
</tbody>
</table>

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

### Without Volt/var Control

**Primary Voltage Deviation**
- 1st violation: 938
- 50% scenarios with violation: 1323
- All scenarios with violation: 1673

**Primary Over Voltage**
- 1st violation: 540
- 50% scenarios with violation: 871
- All scenarios with violation: 1173

### Volt/var Control

**Primary Voltage Deviation**
- 1st violation: >2500
- 50% scenarios with violation: >2500
- All scenarios with violation: >2500

**Primary Over Voltage**
- 1st violation: 880
- 50% scenarios with violation: 1464
- All scenarios with violation: 2418

160% increase in hosting capacity
60% increase in hosting capacity
Maximum Voltages, Minimum load

Without Volt/var Control

Volt/var Control w/ deadband

2500 cases shown
Each point = highest primary voltage

ANSI voltage limit

Increasing penetration (kW)

Maximum Feeder Voltage (pu)

Volt/var Control w/o deadband

Maximum Voltages, Minimum load
### Improvement in Hosting Capacity

#### Offpeak Load

<table>
<thead>
<tr>
<th>Voltage Deviation</th>
<th>PV Hosting Capacity (kW)</th>
<th>Hosting Capacity increase with volt/var (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Volt/var</td>
<td>4pt volt/var</td>
</tr>
<tr>
<td>Primary</td>
<td>1132 kW</td>
<td>inf</td>
</tr>
<tr>
<td>Regulator</td>
<td>397</td>
<td>Inf</td>
</tr>
<tr>
<td>Secondary</td>
<td>2275</td>
<td>inf</td>
</tr>
<tr>
<td>Primary</td>
<td>421</td>
<td>689</td>
</tr>
<tr>
<td>Secondary</td>
<td>229</td>
<td>1409</td>
</tr>
</tbody>
</table>

#### Peak Load

<table>
<thead>
<tr>
<th>Voltage Deviation</th>
<th>PV Hosting Capacity (kW)</th>
<th>Hosting Capacity increase with volt/var (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Volt/var</td>
<td>4pt volt/var</td>
</tr>
<tr>
<td>Primary</td>
<td>970 kW</td>
<td>105 %</td>
</tr>
<tr>
<td>Regulator</td>
<td>288</td>
<td>21</td>
</tr>
<tr>
<td>Secondary</td>
<td>1795</td>
<td>Inf</td>
</tr>
<tr>
<td>Primary</td>
<td>540</td>
<td>95</td>
</tr>
<tr>
<td>Secondary</td>
<td>877</td>
<td>283</td>
</tr>
</tbody>
</table>
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

![Graph showing AC Power kW over time with significant ramping events highlighted.](image-url)}
Hardware-in-the-Loop (HIL) Simulation for a Grid-Connected Inverter

Diagram showing the components of a grid-connected inverter including:
- PV Stack
- DC-AC Inverter
- Relay
- Grid

The diagram includes blocks for:
- MPPT
- PWM
- A/D & low-pass filters
- Gating signals
- Current controller
- Look-up table
- Phase lock loop (PLL)
- Calculate $i_{ref}$

Symbols used in the diagram include:
- $P_{ref}$
- $Q_{ref}$
- $i_{ref}$
- $i_{ac}$
- $v_{ac}$
- $v_{g}$
- $v_{sense}$
- $i_{sense}$
- $L_{i}$
- $L_{g}$
- $L_{s}$
- $C_{f}$
- $G_{i}(s)$
- $P_{PV}$
- $V_{PV}$
- $I_{PV}$

The diagram illustrates the flow of energy from the PV stack through the inverter to the grid, including MPPT, PWM, and A/D & low-pass filters.
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.

![Diagram](image)

**Graph:**
- Grid Voltage ($v_g$) vs Equivalent PV Penetration Level
  - PF = 1.0
  - PF = 0.8 lagging

**Table:**

<table>
<thead>
<tr>
<th>Equivalent PV Penetration Level (%)</th>
<th>Grid Voltage ($v_g$) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.96</td>
</tr>
<tr>
<td>20%</td>
<td>0.97</td>
</tr>
<tr>
<td>40%</td>
<td>0.98</td>
</tr>
<tr>
<td>60%</td>
<td>0.99</td>
</tr>
<tr>
<td>80%</td>
<td>1.00</td>
</tr>
<tr>
<td>100%</td>
<td>1.01</td>
</tr>
<tr>
<td>120%</td>
<td>1.02</td>
</tr>
<tr>
<td>140%</td>
<td>1.03</td>
</tr>
<tr>
<td>160%</td>
<td>1.04</td>
</tr>
</tbody>
</table>
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.
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

<table>
<thead>
<tr>
<th>Voltage range (%)</th>
<th>Disconnection Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE 1547</td>
</tr>
<tr>
<td>$V &lt; 50$</td>
<td>0.16</td>
</tr>
<tr>
<td>$50 \leq V &lt; 88$</td>
<td>2.00</td>
</tr>
<tr>
<td>$110 &lt; V &lt; 120$</td>
<td>1.00</td>
</tr>
<tr>
<td>$V \geq 120$</td>
<td>0.16</td>
</tr>
</tbody>
</table>

#### Abnormal frequency test results

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Disconnection Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE 1547</td>
</tr>
<tr>
<td>$f &gt; 60.5$</td>
<td>0.16</td>
</tr>
<tr>
<td>$f &lt; 59.3$</td>
<td>0.16</td>
</tr>
</tbody>
</table>
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

- 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

PV voltage $V_{PV}$, DC bus voltage $V_{dc}$, Grid, MPPT Control, PWM, DC-DC Converter, DC-AC Inverter, PLL, i_ac, V_PV*, G_v1(s), G_v2(s), G_i1(s), G_i2(s), H(s).
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
Jason Lai: laijs@vt.edu 540.231.4741
Jason Dominic: jcd2362@vt.edu 540.808.0217
Bin Gu: gubin@vt.edu 540.808.0217
Nathan Kees: nkees@vt.edu 540.808.0217
Ben York: benyork@vt.edu 540.808.0217
Wensong Yu: wensong@vt.edu 540.808.0217
Jeff Smith: jsmith@epri.com 865.218.8069
Tom Key: tkey@epri.com 865.218.8082
Chris Trueblood: ctrueblood@epri.com 865.218.8118
Mack Grady: mack_grady@baylor.edu 254.710.3307

Q &A AND DISCUSSION
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 $V \cdot s$ 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%).

![Graph comparing current waveform for VT and Enphase microinverters]

- **VT microinverter**
  - Output current
  - Transition between CCM and DCM

- **Enphase microinverter**
  - Output current

![Graph showing THD percentage against percent load for VT and Enphase]

- VT THD:
  - Continuous operation: THD <2.5%
  - Percent load: 20 to 100

- Enphase THD:
  - Modulates between CCM and DCM, resulting in THD >3%.
Design of Hardware-in-the-loop Simulation

Target Hardware System Circuit Model (in PSIM)

- **PV Panels**
- **Inverter**
- **Feeder circuit network**
  - Generator
  - Distribution line
  - Load

---

- **Voltage and Current Feedback**
- **DSP Controller**
  - A-to-D
  - Var and frequency control
  - Pulse width modulation

---

- **Gating signals**
- **Monitoring results**
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

### Hosting Capacity Comparison Table

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<td>Existing PV (MW)</td>
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<td>Total Circuit Miles</td>
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#### Minimum Hosting Capacity (kW)

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<th>Voltage</th>
<th>Primary Overvoltage</th>
<th>Regulator Deviation</th>
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<td></td>
<td>&gt;3500</td>
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<tr>
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<tr>
<td></td>
<td>777</td>
</tr>
<tr>
<td></td>
<td>390</td>
</tr>
</tbody>
</table>

- Customer-based PV results shown
- 70% of Peak Load
- 4% of Peak Load
Leveraging Work Throughout Industry

From Research to Application

Development of Solar PV System Modeling
DOE Hi-Pen Phase I

Hi-res PV Monitoring and Hosting Capacity Analysis of 2 feeders
DOE Hi-Pen Phase II

Hosting Capacity results with smart inverters, PV data resource DB
DOE Hi-Pen Phase III

Development of “Hosting Capacity” Method
Hi-Pen Analysis of large set of feeders
EPRI DPV Feeder Analysis Project

Development of smart inverter functions in OpenDSS
EPRI member-funded project

Development of Alternate Screening Methods
CPUC/DOE/EPRI Funded Project
Categories for Daily Variability Conditions
Sandia’s variability index (VI) and clearness index (CI) to classify days

- **High Penetration**: VI > 10
- **Moderate**: 5 ≤ VI < 10
- **Mild**: 2 ≤ VI < 5
- **Overcast**: VI < 2, CI ≤ 0.5
- **Clear**: VI < 2, CI ≥ 0.5

**Clear Sky POA Irradiance**
**Measured POA Irradiance**
# Daily Variability Conditions by Season

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

<table>
<thead>
<tr>
<th>Season</th>
<th>High</th>
<th>Moderate</th>
<th>Mild</th>
<th>Clear</th>
<th>Overcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Jan-Mar)</td>
<td>11%</td>
<td>35%</td>
<td>29%</td>
<td>14%</td>
<td>11%</td>
</tr>
<tr>
<td>(Apr-Jun)</td>
<td>20%</td>
<td>46%</td>
<td>17%</td>
<td>13%</td>
<td>9%</td>
</tr>
<tr>
<td>(Jul-Sep)</td>
<td>28%</td>
<td>28%</td>
<td>31%</td>
<td>9%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Relative Number of Days

- High
- Moderate
- Mild
- Clear
- Overcast

Emoji: ☀ = 4%
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
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 $P_{\text{max}}$ for the given time of day and panel orientation.
- When inside a 50-second diameter, or $A$, use $P_{\text{max}}/3$.
- When inside a 5-second circular transition ring, or $C - A$, the power is assumed to be linearly varied between $P_{\text{max}}$ and $P_{\text{max}}/3$. 

$5$ to $7$ meters per second