High Penetration Solar Forum

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Development and Analysis of a Progressively Smarter Distribution System

Scott Samuelsen and Allie Auld
Advanced Power and Energy Program—UC Irvine

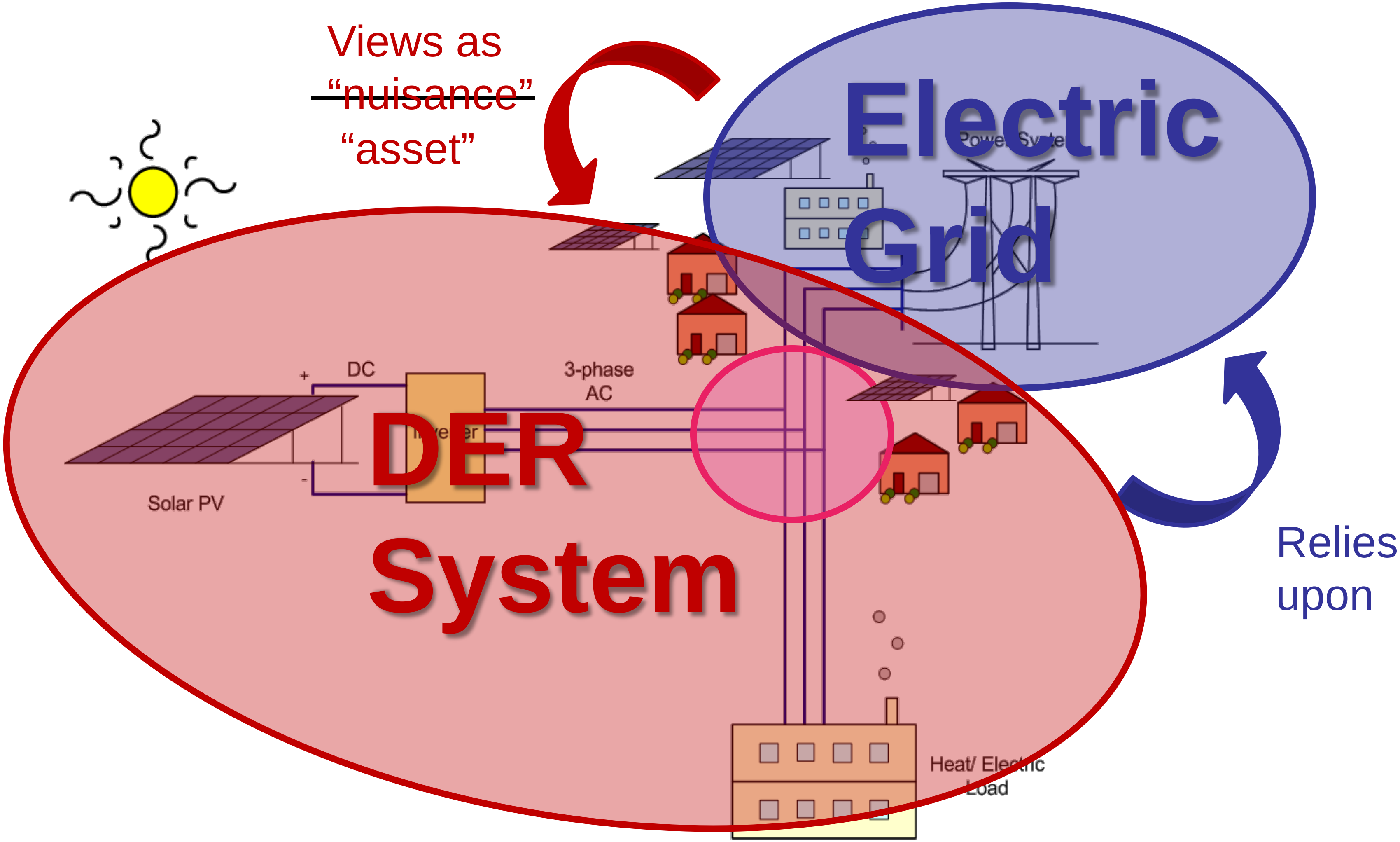
Matt Heling
Pacific Gas and Electric Company

Project Goals

Develop, evaluate, and utilize modeling and simulation to:

- Quantify PV integration limitations (e.g, voltage)
- Develop and evaluate progressively smarter distribution systems

Motivation



Views as
“nuisance”
“asset”
Electric
Grid
Power System
DC
3-phase
AC
Inverter
DER
System
Solar PV
Heat/ Electric
Load
Relies
upon

Focus Areas

Planning/Modeling for High Penetration PV

- Enhance T&D models
- Inform and evaluate with calm and stressed circuit performance data

Testing and Demonstration of Hardware/Software for High Penetration PV

- Monitoring and communications software and systems
- Controls systems and operations

Research Approach

Task 1: Project management

Task 2: Model development and evaluation

- Model scenarios and compare to grid monitored data

Task 3: Quantify PV integration limits

- Determine limits for PV penetration within existing circuit architectures and with existing technology

Task 4: Advanced inverter control

- Assess the risks and benefits of advanced inverter control

Task 5: Integrated distribution grid control

- Progressively introduce and assess smart integrated distribution system technologies/ controls to determine impacts on PV penetration

Task 6: Practical feasibility and outreach

- Determine market potential of technology and encourage adoption

Key Deliverables

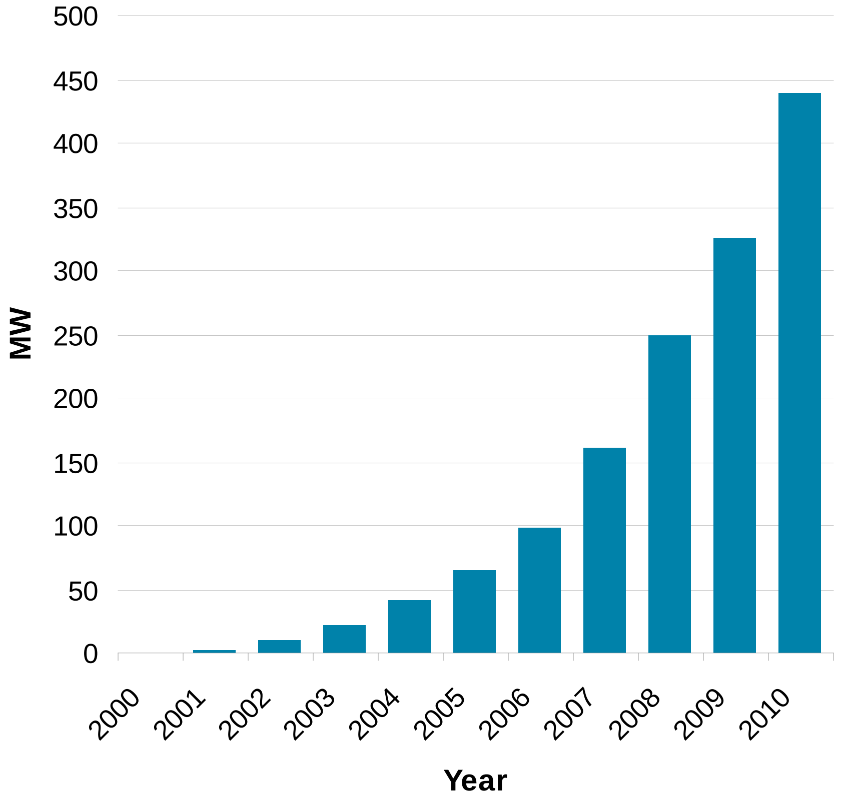
Tasks	Deliverables
2. Model development and evaluation	Model scenarios and comparisons to grid monitored data
3. Quantify PV integration limits	PV integration limits in typical distribution circuits
4. Advanced inverter control	Risks and benefits of advanced inverter control
5. Integrated distribution grid control	Progressively smarter integrated distribution system controls
6. Practical feasibility and outreach	Practical feasibility of the proposed controls and design

PG&E Perspective

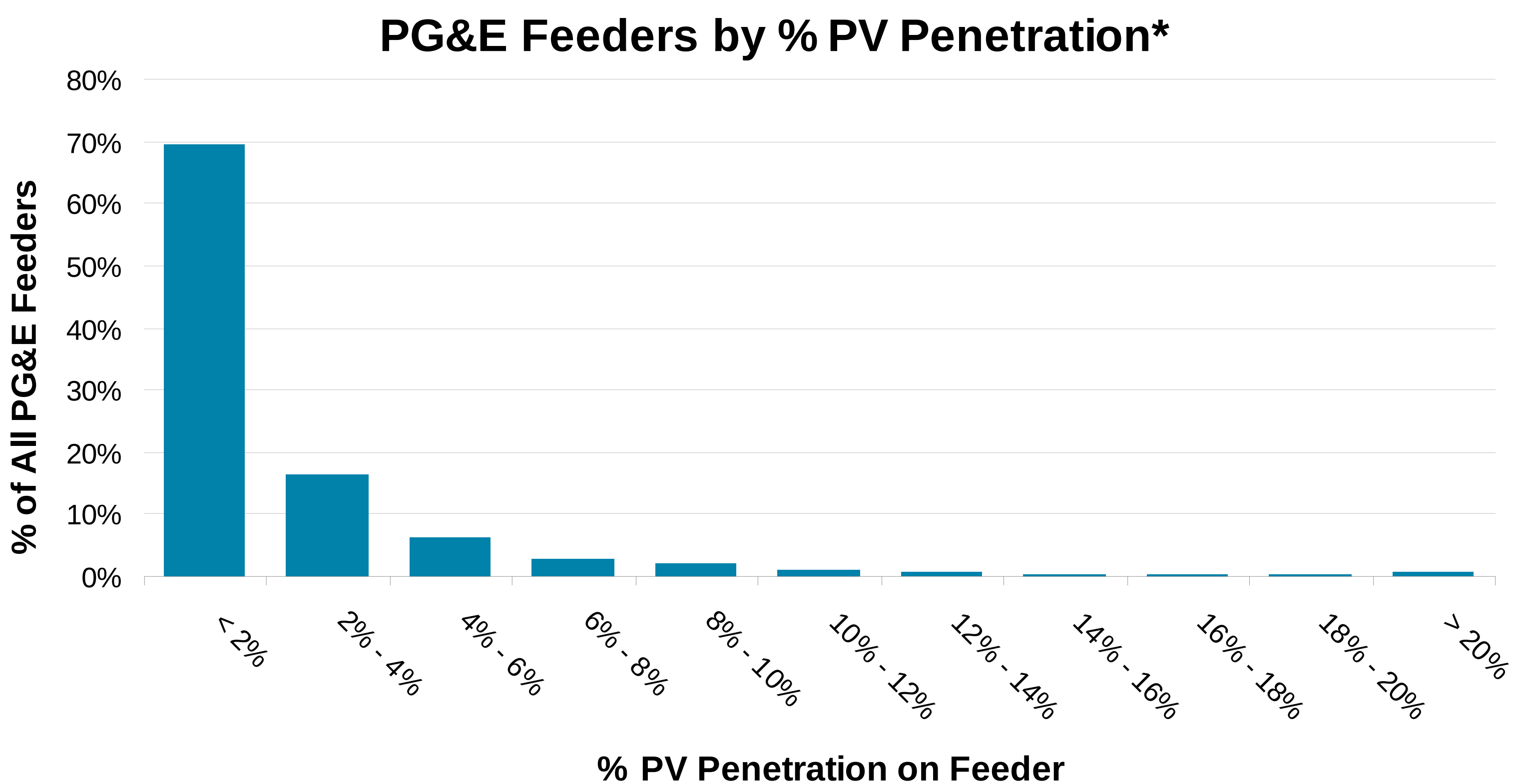
PG&E is a leader in distributed PV

- Over **45,000 installations**
- Over **400 MW** (CEC AC)
- Approx. **35% of US total**
- PG&E serves ~5% of US population

Distributed PV Installed in PG&E Territory by Year
(MW; CEC AC; Cumulative)



PG&E Perspective



While territory-wide penetration is significant, "high" concentrations exist on only a small number of feeders… at least, for now.

** % PV Penetration = PV MW (CEC AC) / 2009 Feeder Max Demand (MW)*

PG&E Perspective

- How are negative grid impacts of distributed PV addressed today?

Generally by **adjusting settings** on distribution system equipment, including:

Capacitor banks

Load tap changers

Voltage regulators

Bucking transformers*

** Typically for PV subdivisions*

PG&E Perspective

- Examples of grid problems caused by PV and mitigation strategies employed

Concern	Mitigation Strategy
A facility's 10-kW PV system (inverter) trips off-line when customer load is light due to high service voltage	Adjust voltage regulator settings
Generators at a facility downstream of a 1-MW PV system trip off-line due to high service voltage	Adjust capacitor bank settings

- Generally, few impacts today despite the relatively high number of PV systems
- However, requirements for mitigation may increase in future with increased penetration of PV in localized areas

PG&E Perspective

- In the future, the negative impacts of PV on the grid may be mitigated in a variety of ways

Reconductor lines

Distribution Management Systems (DMS) (e.g., Volt/Var Optimization (VVO)

Require curtailment of PV generation

Install new equipment (e.g., voltage regulators

"Smart" inverters

Approach

- Research approach
- Model development
- Feeder selection
- Operating criteria
- Fuel cell integration challenges (selected past results)
  - Solid oxide fuel cell and load integration
  - Generic distribution circuit models

Research Approach

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Research Approach

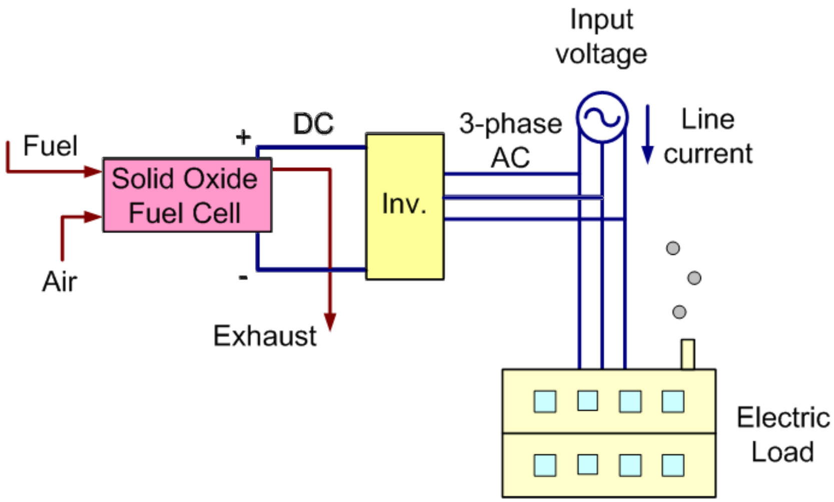
Task 2: Model development and evaluation

- Build distribution circuit models (primary) of three PG&E feeders
- Resolve a selected service transformer (secondary) from each feeder
- Simulate models (primary and secondary) with typical and extreme load conditions
- Compare simulation results to available PG&E circuit data

Task 3: Quantify PV integration limits

- Simulate increased PV installation on circuit parametrically
- Identify and quantify conditions of unacceptable circuit operation

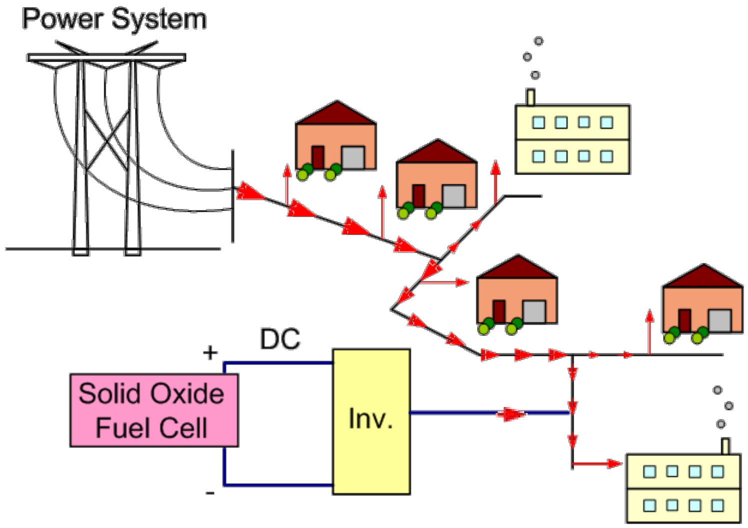
Modeling Approach



Single and two-bus models

- Advantages:
  - Resolves distribution transformer secondary
  - Measured load data
  - Detailed component models
- Disadvantages:
  - Isolated system
  - Case-by-case

Modeling Approach



Multi-bus radial feeder models

- Advantages:
  - Resolves distribution circuit primary
  - Includes many loads and distribution system equipment
- Disadvantages:
  - Assumes balanced and aggregated load
  - Neglects harmonics
  - Generalized DER models

Selection Criteria

- Available substation data
  - Real and reactive power flow
  - Voltage

  } Simulation inputs

- Solar PV installations
  - High penetration existing solar PV

  } Relevant locations

- Customer types:
  - Residential
  - Commercial

  } Span different feeder types

Selected distribution feeders

Commercial circuit

- Installed solar PV

Solar shade:	1,000 kW
Warehouse roof:	623 kW
Warehouse roof:	325 kW
Total:	1,858 kW

- Feeder characteristics:
  - Peak power in 2009: 13.8 MW (12:45 pm weekday)
  - Minimum base power in 2009: 2.8 MW (1:30 pm weekend)
  - Normal daily base power: 4 MW
  - Normal daily peak power: 7 MW

Selected distribution feeders

Residential circuit

- Installed solar PV

170 installations:	<50 kW
1 installation:	50 to 500 kW
Total:	1,105 kW

- Feeder characteristics:
  - Peak power in 2009: 8.7 MW (6:30 pm weekend)
  - Minimum base power in 2009: 0.5 MW (3:00 am holiday)
  - Normal daily base power: 3 MW
  - Normal daily peak power: 6 MW

Operating Criteria

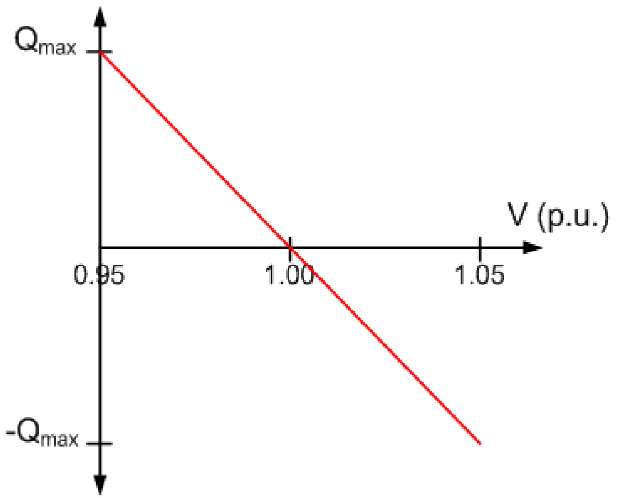
DG interconnection can be classified by three levels of citizenship:

	Model citizen	Good citizen	Poor citizen
Voltage maximum	$V_{max} < 1.05$	$V_{max} \leq 1.05$	$V_{max} > 1.05$
Voltage minimum	$V_{min} = 0.98$	$V_{min} \geq 0.98$	$V_{min} < 0.98$
Real power importation	Load leveling	$P_{dem} \leq P_{dem,max}$	$P_{dem} > P_{dem,max}$
Reactive power importation	Load leveling	$Q_{dem} \leq Q_{dem,max}$	$Q_{dem} > Q_{dem,max}$
Harmonic distortion	Lower	No change	Higher

Previously Investigated Control Strategies

Traditional inverter control strategies:

- Baseline control
  - DG provides rated capacity of real power
  - Recommended by IEEE-1547
- Power factor correction (PFC)
  - DG provides rated capacity of real power
  - Q output equal to local Q consumption
  - Allowed by IEEE-1547
- Local voltage regulation (LVR)
  - DG provides rated capacity of real power
  - Q output as function of local voltage
  - Forbidden by IEEE-1547



LVR: Q output as a function of voltage

Previously Investigated Control Strategies

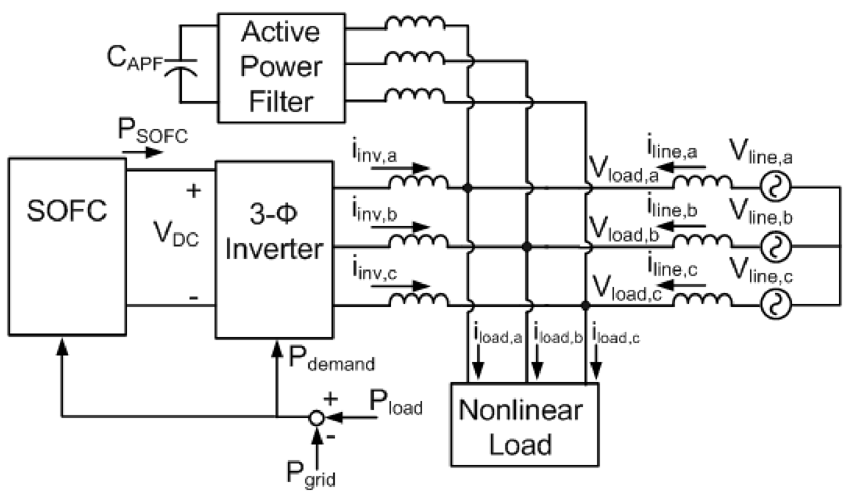
Traditional inverter control strategies:

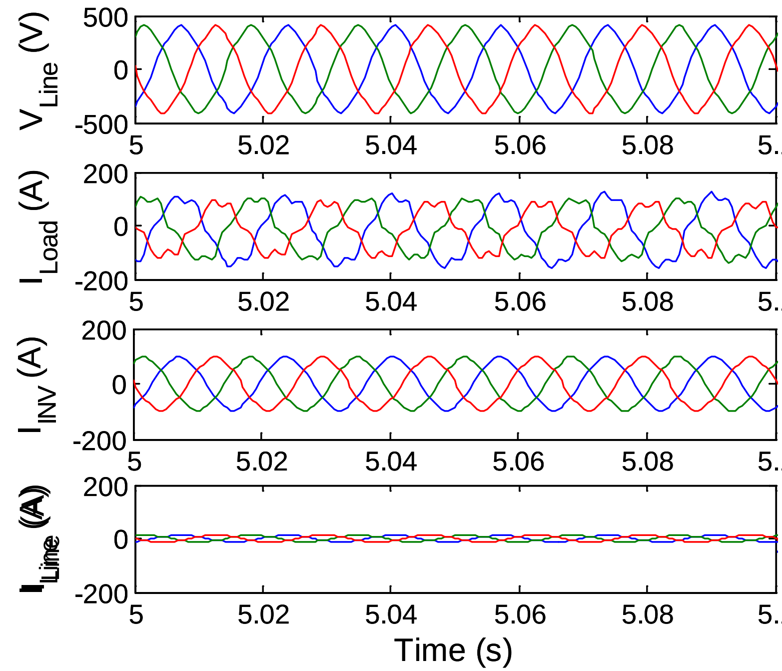
- Real power curtailment
  - Uses local voltage to determine real power
  - V > 1.05 p.u. : Reduces real power output
  - 1.05 > V > 1.04 p.u. : Maintain power output
  - V < 1.04 p.u. : Increase real power if below rated capacity

Single-Bus System

Baseline SOFC interconnection case:

- Assume desired P_{grid} = 10 kW
- Inverter uses voltage reference
- Addition of APF





APF compensates harmonics and improves the line current provided by the grid

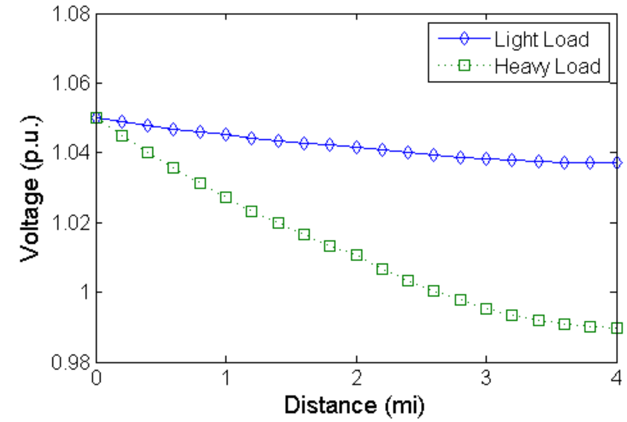
Inverter-only design is insufficient to improve the line harmonics

Auld, A.E., Mueller, F., Smedley, K.M., Samuelsen, S., and Brouwer, J., "Applications of one-cycle control to improve the interconnection of a solid oxide fuel cell and electric power system with a dynamic load," *Journal of Power Sources*, vol. 179, pp. 155-163, 2008.

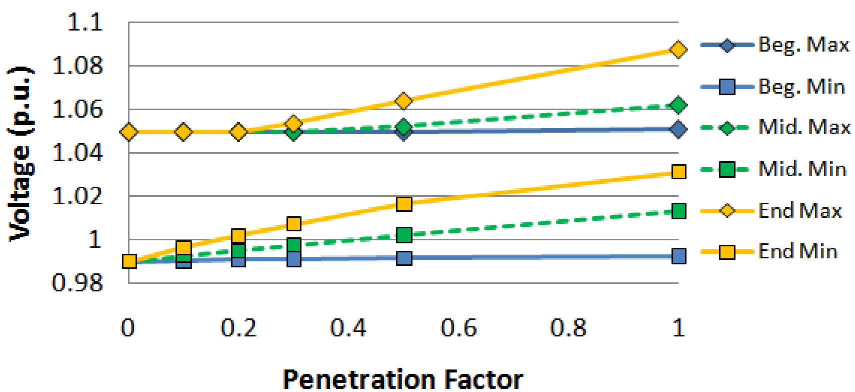
Circuit A

Generic sample circuit A:

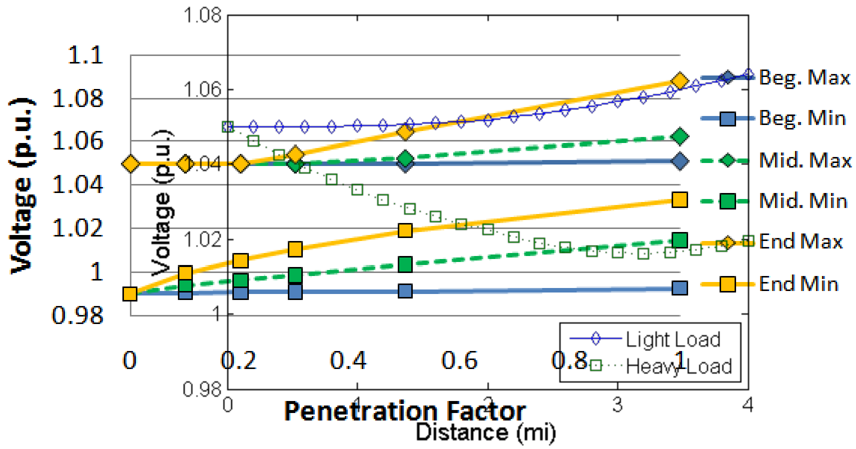
- Substation: Fixed 1.05 p.u.
- 4-mile long
- No capacitors
- Voltage limit: 0.98 - 1.05 p.u.
- Urban circuit



No DG

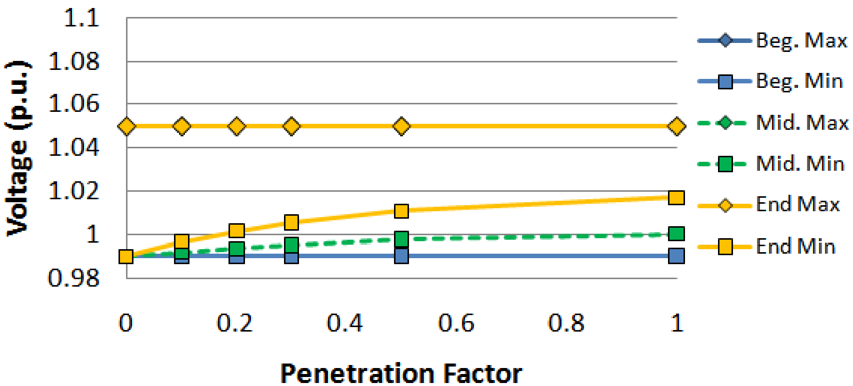


Baseline control

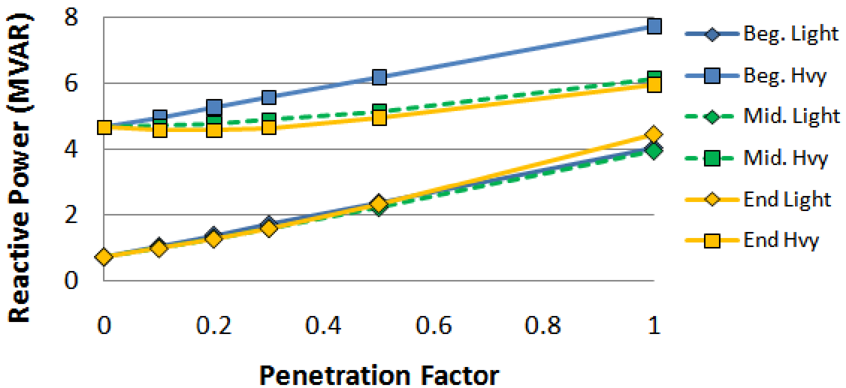


Power factor control
3.5 MW DG at end

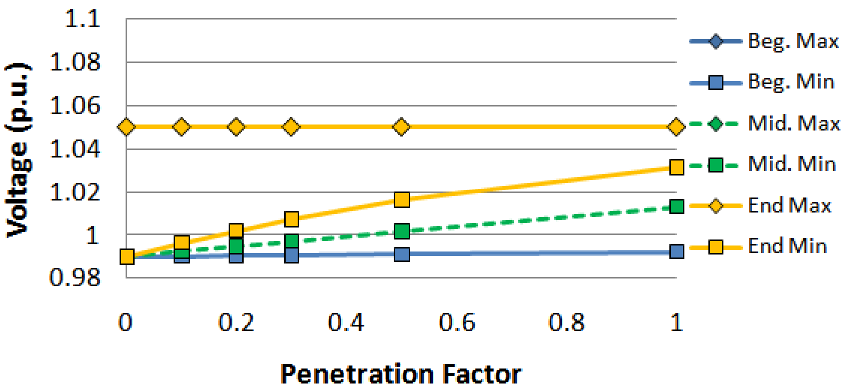
Circuit A



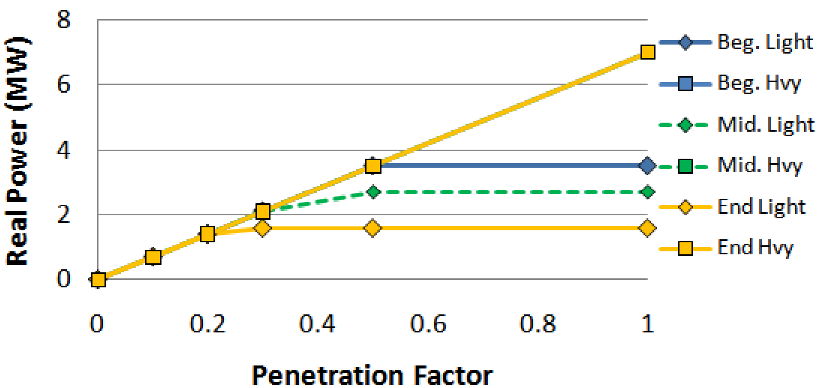
Local voltage regulation



Substation reactive power



Real power curtailment

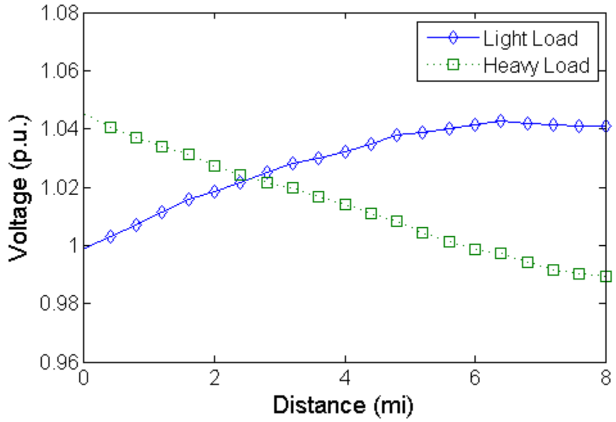


Generator real power

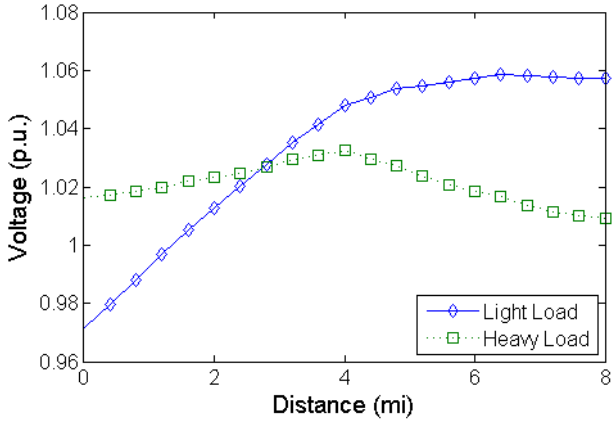
Circuit B

Generic sample circuit B:

- Substation: Regulated with LDC
- 8-mile long
- Four capacitor banks (1200 kVAR)
- Voltage limit: 0.98 - 1.05 p.u.
- Suburban/rural circuit



No DG



7 MW DG at middle

Circuit B

Generic sample circuit B:

	Baseline	LVR	RPC
Overvoltage	Middle (50%+)	Fixes	No Effect
	End (10%+)	Fixes	Fixes
Undervoltage	Beginning (30%+)	WORSE	No Effect
	Middle (50-100%)	Fixes	No Effect
	End (50-100%)	Fixes	Fixes

Auld, A.E., Smedley, K.M., Brouwer, J., and Samuelsen, G.S., "Effect of Distributed Generation on Voltage Levels in a Radial Distribution Network without Communication," *ASME Journal of Fuel Cell Science and Technology*, in print.

DG Citizenship

[illegible]	Location	Baseline	LVR	Curtailment
Circuit A	Beginning	Good	Poor (Q)	Good
	Middle	Good	Good	Model
	End	Model	Model	Model
Circuit B	Beginning	Good	Poor (Q)	Good
	Middle	Good	Good	Good
	End	Poor (V)	Good	Model
Circuit C	Beginning	Good	Good	Good
	Middle	Good	Good	Good
	End	Model	Good	Model
Circuit D	Beginning	Good	Model	Good
	Middle	Model	Model	Model
	End	Model	Model	Model

Need for further development and innovations

Summary

Tasks	Schedule
Task 1. Project management	May 15 and Nov 15 annually
Task 2. Model development and evaluation	December 2010 to July 2011
Task 3. Quantify PV integration limits	April 2011 to December 2011
Task 4. Advanced inverter control	July 2011 to January 2012
Task 5. Integrated distribution grid control	January 2011 to November 2012
Task 6. Practical feasibility and outreach	April 2011 to December 2012

Summary

Complementary research activities:

RESCO Pilot Project

- Funding agency:
  - California Energy Commission
- Renewable-Based Energy Secure Communities (RESCOs)
- Task 2: Distribution Grid Infrastructure
- Electric modeling and simulation of UC Irvine campus to understand:
  - Preferred RESCO substation and distribution circuit configurations
  - UCI substation and distribution circuit infrastructure
  - Cost and performance of infrastructure improvements

Summary

Complementary research activities:

California Solar Initiative RD&D Grant #2

- Partners:
  - Amonix (prime)
- Funding agency:
  - California Public Utilities Commission
- Installation, monitoring, and integration of nine Amonix 53-kW concentrated solar PV (CPV) systems
- Electric modeling and simulation of UCI campus to understand:
  - Detailed monitoring of CPV systems and the associated electric circuits
  - Preferred integration assessment of CPV with existing UCI campus including central plant
  - Coordination with RESCO and local utility Southern California Edison

Project team

- Project Investigator: Scott Samuelsen

- Technical Manager: Jack Brouwer
- Collaborator: Keyue Smedley
- PG&E Project Manager: Matt Heling

- UCI APEP Postdoctoral Researcher: Allie Auld
- UCI APEP Graduate Student Researchers
  - Josh Payne
  - Renee Cinar

Project Sponsors and Partners

CSI Solar RD&D Program
www.calsolarresearch.ca.gov

Itron CSI RD&D Program Manager

Scott Samuelsen
gss@apep.uci.edu

Jack Brouwer
jb@apep.uci.edu

Q &A