Analysis of High-Penetration Levels of PV into the Distribution Grid in California

Barry Mather Ph.D.
National Renewable Energy Laboratory
Golden, CO
Project Sponsors and Team Members

Sponsors:

1. U.S. Department of Energy
   - Energy Efficiency & Renewable Energy

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

3. Itron
   - CSI RD&D
   - Program Manager

Team Members:
Project Background

• SCE will install 500MW of distributed solar over the next 5 years
  – 250MW – SCE owned
  – 250MW – IPP
  – Most expected to be commercial rooftops (1-3MW)
Project Focus Areas

- Distribution system modeling and simulation for high-penetration PV scenarios
- Identifying the effects of high-penetration PV and developing methods to mitigate these effects
- Advanced inverter functionality development and testing
- High-penetration PV demonstration
Project Activities Overview

• Distribution system assessment
  – Measure the effects of high-penetration PV

• Modeling and simulation
  – Understand and predict the effects of high-penetration PV

• Laboratory Testing
  – Test advanced functionality inverters

• Field Testing
  – Deploy advanced functionality inverters

• Results publication and information dissemination
  – Ultimately: High-penetration PV integration best practices handbook
Major Project Deliverables

• Initial Project Assessment Report (Year 1)
• Report on distribution system simulation and analysis
• Report on field validation – existing hardware and integration
• Report on field validation – new operations and hardware
• Distribution best practices handbook for high-penetration PV
SCE Service Territory

• Serves a population of about 14 million people in a 50,000-square-mile service area within central, coastal and Southern California
• 5 million electric meters
• 5,000 MW of generating capacity from interests in nuclear, hydroelectric, and fossil-fueled power plants
• Award-winning energy efficiency & DR customer programs
• Industry leader in renewable energy, electric transportation, Smart Grid and smart metering
Porterville, CA Study Feeder

- 12.47 kV feeder, 47.2 miles
- Feeder capacity: 8.3 MVA
- PV AC rating: 5 MW
- PV capacity penetration: 60%
- Voltage regulation via switched capacitor banks
Chino, CA Study Feeder

- 12.47 kV feeder, 12.4 miles
- Feeder capacity: 11.9 MVA
- PV AC rating: 750 kW, 3 MW total in queue
- PV capacity penetration: 6%, 25% with 3 MW build out
- Voltage regulation via switched capacitor banks: 7.2 MVAr
Fontana, CA Study Feeder

- 12.47 kV feeder, 7.8 miles
- Feeder loading capacity: 11.9 MVA
- PV AC rating: 2 MW, 5.5 MW total in queue
- PV capacity penetration: 17%, 46% with 5.5 MW build out
- Voltage regulation via switched capacitor banks: 4.8 MVAr
Fontana, CA Study Feeder

- 12.47 kV feeder, 7.8 miles
- Feeder loading capacity: 11.9 MVA
- PV AC rating: 2 MW, 5.5 MW total in queue
- PV capacity penetration: 17%, 46% with 5.5 MW build out
- Voltage regulation via switched capacitor banks: 4.8 MVAr
Hi-Pen PV Impacts on Feeder

- Voltage fluctuations beyond the permissible range
- Reverse power flow:
  - Exceeding thermal rating of feeder equipment
  - Change in settings of automatic voltage regulation devices due to shift in load center
- Feeder re-configuration
- Reduced sensitivity to faults
- Capacitor bank switching

![Graph showing PCC Voltage and Cap bank switching over time](image)
Hi-Pen PV Integration Study Example

Study Initiation

PV System Modeling and Simulation:
Define Expected PV Operation

Distribution System Modeling and Analysis:
Determine System Impacts

Distribution System Data Acquisition:
Model Verification

Mitigation of Hi-Pen PV Impacts:
Advanced Inverter Functionality

Study Completion
SolarAnywhere

NOAA GOES satellite images

Clear sky radiation
Haze (turbidity)
Clouds

NOAA METAR and National Forecast Database

Reflectivity (albedo)

Wind
Temperature
Creating PV Simulation File

PV system attributes

Hourly PV Simulation Model

Historical irradiance and temperature data (10 years)

Statistical Calculations

Distribution Circuit Analysis
PV Model Data Resolution

Low resolution:
10 km x 10 km
1 hour

High resolution:
1 km x 1 km
½ hour
PV Model Output

- **PV_System_1**
  - CustomerID
  - Maximum Power in kW (matrix of 12 months x 24 hours)
  - Average Power in kW (matrix of 12 months x 24 hours)
  - Standard Deviation in kW (matrix of 12 months x 24 hours)
- **PV_System_2**
  - CustomerID
  - Maximum Power in kW (matrix of 12 months x 24 hours)
  - Average Power in kW (matrix of 12 months x 24 hours)
  - Standard Deviation in kW (matrix of 12 months x 24 hours)
- **PV_System_3**
  - Etc...
Hi-Pen PV Integration Study Example

Study Initiation

PV System Modeling and Simulation: Define Expected PV Operation

Distribution System Modeling and Analysis: Determine System Impacts

Distribution System Data Acquisition: Model Verification

Mitigation of Hi-Pen PV Impacts: Advanced Inverter Functionality

Study Completion
DEW Solar Measurement Data Input

- Solar measurements inputs can be PVwatts/IMBY and Clean Power Research PV Model Datasets
- The interval is shown per hour for 8760 time points but maybe modified for more granular data
DEW Modeling & Analysis Capability

– **Power Flow** - Solves large scale problems from transmission level voltages down to secondary service points, including heavily meshed secondary systems.

– **Network Fault** - Calculates fault currents for radial and looped systems; and quantify the impacts on breaker duty, momentary interrupting capability, and protection/coordination.

– **Protection Coordination** – Locates protection and coordination concerns.

– **Power Quality** – Capable of addressing harmonic impacts, flicker, outages, momentary faults, and sag/swell concerns.

– **Feeder Performance** – The analysis addresses time varying load, such as all 8760 annual hourly load points. The efficiency is examined and quantified across the entire load spectrum.

– and more...
DEW Graphical Results Display – e.g. Daily Load Curves
DEW Geo-referenced Display– Colored Circuit Voltage

Blue > 118 volts
Green < 118 volts
Red < 114 volts
DEW Variable Range Display – Negative Flow
DEW Google Earth Interface

DEW Geo-referenced View

Google Earth Overlay
Circuit Load Type and Density

Brown is Residential
Green is Commercial
Red is Industrial

Height is proportional to annual kWhr consumption
Hi-Pen PV Integration Study Example

Study Initiation

PV System Modeling and Simulation: Define Expected PV Operation

Distribution System Modeling and Analysis: Determine System Impacts

Distribution System Data Acquisition: Model Verification

Mitigation of Hi-Pen PV Impacts: Advanced Inverter Functionality

Study Completion
Feeder Data Acquisition

Available SCADA points
Planned additional measurement points

March 1-2, 2011
DOE/CPUC High Penetration Solar Forum
Hi-Pen PV Integration Study Example

Study Initiation

PV System Modeling and Simulation: Define Expected PV Operation

Distribution System Modeling and Analysis: Determine System Impacts

Distribution System Data Acquisition: Model Verification

Mitigation of Hi-Pen PV Impacts: Advanced Inverter Functionality

Study Completion
SCE Fontana, CA 2 MW Rooftop Plant
Fontana, CA 4 x 500 kW Inverters

- 12.47 kV feeder from 66 kV Substation – mostly commercial loads
- Fontana 2 MW rooftop PV – Installed 2008 - Electrically close to Substation
- Three automatically switched capacitor banks
- 5.5 MW planned additional PV generation by mid-project
Fontana Inverter Upgrade Plan (Preliminary)

- Inverters will be upgraded to provide additional “Grid Smart” control capability
  - Real power curtailment
  - Two modes of reactive power control
    - Power Factor Control
    - Independent Reactive Power Control

- Site Controller will be installed to manage aggregate real and reactive power output
  - Communicates with all inverters using Modbus over RS-485 serial link
  - Sets real power curtailment level for all inverters
  - Sets reactive power control mode and reactive power commands for all inverters
  - Receives high-bandwidth site-level voltage and current signals from measurement PTs and CTs at the point of interconnection with utility feeder
  - Performs closed-loop control algorithms for different types of voltage regulation and real power ramping
  - Provides communication link to SCADA RTU if needed for remote control from utility control center
Advanced Inverter Capability

• Fontana Site is electrically close to substation
  • Several automatically-switched devices are presently regulating Fontana feeder voltage
  • Project objective
    • Demonstrate alternative methods for deploying reactive power output from the inverters, using the site controller to execute site-level control algorithms
      • Continuous automatic local voltage control (autonomous)
      • Aggregate reactive power vs. voltage schedule (spillover voltage control)
      • Aggregate output power factor vs. real power output schedule (load-dependent power factor)
    • Observe effect on the behavior of existing line regulators and switched capacitors
      • Note and correct any undesirable interactions
    • Observe effect on reactive power flow at substation
    • Observe voltage profile over entire feeder

• Fontana inverters can supply a large part of the reactive power for the feeder but the range of voltage regulation will be limited
  • Inverter apparent power output is limited by kVA rating
  • Availability of reactive power will depend on the prevailing real power curtailment setting
  • Real power curtailment is set automatically when operating under power factor control
  • For independent reactive control, the site controller continually (at regular intervals) resets the real power curtailment level slightly above prevailing real power output
  • The effect on voltage at the point of interconnection is expected to be small
    • Maximum 2 MVAR will give approximately +/- 1% voltage regulation (assuming 10 MVA substation transformer with X = 5%). Typical 400 kVAR would give +/- 0.2% regulation.
Near-term Next Steps

• Model study feeders and identify the major impacts of high-penetration PV
• Install additional data acquisition equipment and begin data collection period
• Develop and test PV inverters with advanced functionality to mitigate high-penetration PV impacts
Q &A

Please Contact:
Barry Mather
Distributed Energy Systems Integration Group
National Renewable Energy Laboratory
Barry.Mather@nrel.gov
(303)-275-4378

Team Member Websites:
www.nrel.gov
www.sce.com
www.cleanpower.com
www.satcon.com
www.quanta-technology.com
www.edd-us.com