High Fidelity Solar Forecasting Demonstration for Grid Integration

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Project Sponsors and Partners

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Project Goals

• Reduce solar integration costs through more accurate solar forecasting
• Demonstrate distributed generation and system level solar forecasting
• Demonstrate forecast applications to net load forecasting and feeder control
Task Overview

• Task 2: Demonstrate forecast performance during meteorological conditions with greatest impact on SDG&E operations and recommend monitoring improvements
• Task 3: Day-Ahead Solar forecast models for marine layer clouds
• Task 4: Localized Solar Forecasting and Distribution Feeder Modeling
• Task 5: Forecast Integration with Utility Models for Resource Adequacy
Agenda Overview

• High PV penetration impacts on the distribution system
  – Five distribution feeders
  – Historical large ramp rates
  – Distribution system power flow simulations:
    • Sky imager solar resource assessment Questions
    • Distribution system simulation of PV impacts with highly resolved data
    • Sky imager forecasting and transformer tap operation control
      • Questions
  – Net load forecasting
• System-wide forecast demonstration
  – Optimizing ground monitoring networks
  – Day-ahead solar forecasting marine layer clouds
  – Questions
Distribution Feeder Properties

- Urban and rural feeders
- PV systems up to 2MW
- PV penetration = PV capacity / max load levels from 0% to 200% (simulated).
- Generated based on properties of existing systems

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Feeder length (km)</th>
<th># Loads</th>
<th>Total peak load (MW)</th>
<th># Capacitor banks</th>
<th># Transformers &amp; VRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>178</td>
<td>2246</td>
<td>11.1</td>
<td>2</td>
<td>7</td>
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<tr>
<td>B</td>
<td>40</td>
<td>3761</td>
<td>8.3</td>
<td>2</td>
<td>3</td>
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<tr>
<td>C</td>
<td>35</td>
<td>1466</td>
<td>4.8</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>52</td>
<td>471</td>
<td>3.7</td>
<td>1</td>
<td>1</td>
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<tr>
<td>E</td>
<td>116</td>
<td>1169</td>
<td>6.7</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

![Map Image]
Largest Aggregate PV Ramp Rates

5 Feeders, 1 Year, Satellite Solar Resource
Largest Aggregate Feeder PV Ramp Rates

Input:

- SolarAnywhere 30 min satellite solar resource data
- 2011 real PV fleets

Largest ramp at coastal feeder:

Number of ramps > 27% PTC capacity / hour:
Large Ramp Rates Conclusions

• Limited geographic diversity on distribution feeders for 30 min+ ramps
  – Large aggregate ramps
• Ramps driven by Feb – April storms and May - July morning marine layer
• Small difference across SDG&E territory
• Weather forecast models have limited skill in forecasting daily variability.
Distribution System High PV Penetration Modeling and Impact Mitigation Though Forecasting

5 Feeders, 3 Months, Sky Imager Solar Resource
Agenda Sky Imager Power Flow

- Sky imager resource assessment and forecasting on SDG&E feeders
- Distribution feeder modeling using sky imager solar resource maps
- Real-time control of transformer tap changes using solar forecasts
Solar resource assessment with sky imager

- In 'resource assessment' mode to generate input data for the PV impact research.
- 30 sec, 10m x 10m resolution.
- Basic steps [1, 2]:
  - Cloud detection
  - Cloud height determination
  - Cloud motion vectors
  - Projection on the ground for irradiance maps
  - Convert from irradiance to power


Sample of the forecasting process with sky imager
Sky imager resource assessment for DSS

- Novelty: High resolution and distributed generation profiles
- Location-specific solar irradiance for each PV system

Daily variability index comparison against ground measurement:
Corr coef = 0.90, MBE = 1.6, MAE = 2.0
Impacts of

- Spatiotemporal variabili
  smoothes the aggregate
  - No impact in clear condi
  overcast conditions.
Agenda Sky Imager Power Flow

- Sky imager resource assessment and forecasting on SDG&E feeders
- Questions?
- Distribution feeder modeling using sky imager solar resource maps
- Real-time control of transformer tap changes using solar forecasts
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• Line losses first decrease, then increase after 50% to 100% penetration

• ~1% smaller line losses for ‘multiple’ PV profiles
Voltage extremes comparison

• Feeder max voltage
  – Noon: If noon is clear or overcast, no change
  – Increase with PV penetration

• Feeder min voltage
  – Night: PV variability not a contributing factor
Tap Operations (TO)

- Daytime TO increase with PV penetration
  - Large range of TO from <<1 to 100s per day
- Same PV profile (single) overestimates TO
  - 8% for 25% pen to 46% overestimation for 200% penetration
  - 70% overestimation for feeders A, E
Agenda Sky Imager Power Flow

• Sky imager resource assessment and forecasting on SDG&E feeders
• Distribution feeder modeling using sky imager solar resource maps
• Simulated real-time control of transformer tap changes using solar forecasts
Potentially Unnecessary TO

- At 100% PV Penetration
  - 500 tap operations (TO) from 8 to 16 PST
  - 135 TO from 10 to 11 PST
- Normal #operation of OLTC: 20 TO/day [1]

Justification of TO Reduction

- High TO due to temporary variation of PV generation
- TO delay can cause TO to be out of phase with cloud cover
- Temporary voltage violations are acceptable at some levels (graph from ITIC-CBEMA)
Predictive TO Reduction

• At each time:
  – Simulate the feeder with forecasted PV outputs for the next 5 minutes
  – Observe the projected tap positions
  – Rule 1:
    • Observation: Tap reversal
    • Action: No tap operation
  – Rule 2:
    • Observation: Varying tap on one side
    • Action: Minimize TO
  – Go to next time step

• Forecast update frequency: 30 sec
Example TO Reduction

- **#TO on Jan 19, 10:00am - 12:30pm**
  - No control: 135 TO
  - Actual forecast: 17 TO
  - Perfect Forecast: 2 TO
TO Reduction Statistics

- Perfect forecast scenario
  - Average 55% reduction
  - Maximum 79%
  - Similar results for actual forecast

- TO Reduction vs. initial #TO
  - Xfm3: Higher TO, higher reduction
  - Xfm7: Low TO, zero reduction
Impacts on Voltage Quality

- Max Max voltage exceeds the limits because:
  - Exceedance in base case
  - TO reduction
- Voltages typically similar as w/o TO control, but a few large excursions
Conclusions – High Pen Impacts

- Geographic diversity acts to smooth PV power output profiles across a distribution feeder
  - Sky images provide realistic high resolution spatio-temporal irradiance
- Reduction in voltage variability, line losses (albeit small), tap operations
  - Max and min voltage not significantly affected
  - Reduction primarily in partly cloudy conditions
- Tap operations are overestimated by up to 70% at 200% penetration
  - Depends on feeder and penetration level
- Predictive Tap Operation Reduction Using Sky Imager data
  - Algorithm robust against real forecast error
  - TO are reduced by another 56%
  - Rare adverse effect on voltage quality, but still concerning
- Irradiance fields freely available to other researchers
Summary

• Ramp rate analysis sets bounds and allows creating scenarios for what voltage regulation is needed with high PV penetration.
  – Smart inverter penetration
  – Other voltage regulation equipment
• More accurate solar integration studies
  – Facilitate better decision on capital investment in mitigation measures
• Reduction in tap changes reduces O&M costs related to solar variability
• Questions?
Distribution System Substation Net Load Forecasting

5 Feeders, 1.25 Years, Machine Learning Techniques
Operational Substation Net Load forecasts

• Goal: Real-time operational load forecast for Fast Demand Response Event

• Data: 3/1/2012 – 6/30/2013

Datasets

Load data set: 15-min resolution load time-series from five SDG&E feeders with different levels of solar penetration

Solar power data: Estimated solar-power using Solar Anywhere data with 30-min time resolution

<table>
<thead>
<tr>
<th>SDGE feeder name</th>
<th>Solar penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A*</td>
<td>24%</td>
</tr>
<tr>
<td>B*</td>
<td>13%</td>
</tr>
<tr>
<td>C*</td>
<td>9.3%</td>
</tr>
<tr>
<td>D*</td>
<td>5.8%</td>
</tr>
<tr>
<td>E*</td>
<td>2.4%</td>
</tr>
</tbody>
</table>
Feeder net load time-series

- Evening peak (residential)
- Daytime impact of solar PV
Net Load Forecast Methodology

- **Forecast model setup**
  - Training set: Load data for 2011
  - Validation set: Load data for 2012

- **Forecast horizon**
  - 15 min
  - 30 min
  - 1 h

- **Forecast model parameters**
  - Model set-up: Time-series style
  - Input: Lagged values of past load data
  - Kernel: Radial basis function
  - Cost function
Forecast Error versus Forecast Horizon

- Load forecast error increases with increasing forecast-horizon
- C load unpredictable due to sudden increase in load demand

<table>
<thead>
<tr>
<th>Feeder - Solar Penetration [%]</th>
<th>MAPE at 30 min</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - 23.8%</td>
<td>5.43</td>
<td>0.96</td>
</tr>
<tr>
<td>B - 13.3%</td>
<td>3.06</td>
<td>0.97</td>
</tr>
<tr>
<td>C - 9.2%</td>
<td>4.52</td>
<td>0.92</td>
</tr>
<tr>
<td>D - 5.8%</td>
<td>2.10</td>
<td>0.98</td>
</tr>
<tr>
<td>E - 2.4%</td>
<td>3.16</td>
<td>0.99</td>
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</tbody>
</table>
Impact of solar penetration on 30 min ahead load forecast at A*

- Absolute error increases for cloudy days especially during solar production time
- Since solar power data is at 30 min. resolution, further analysis is all based on 30-min ahead forecast
With low solar penetration, error is independent of solar variability whereas as solar penetration increases, the load forecast error increases and it is a linear function of solar variability.
Net Load Forecast Summary

• Under high PV penetration, solar penetration and solar variability drives the forecast error.
• Exogenous inputs like weather and solar forecast may further enhance forecast accuracy.
• Forecast models are ready to be implemented in real-time.
• Net load forecasts improve switching operations, power flow estimates, and outage management.
System-wide Solar Resource Monitoring and Forecasting
Observation Targeting

• SDG&E has 100+ weather stations and 60+ are equipped with a pyranometer
• Identify locations that would benefit from greater station coverage for
  – Modeling real-time PV generation
  – Forecasting PV generation
• Methodology applicable anywhere
Observation Targeting

- Identified most critical locations for SDG&E pyranometers

- Solar variability climate zones
Results – Observation Targeting

• 8 coherent regions capture the daily variability over the SDG&E territory.
  – Optimal location for the placement of ground based sensors

• Utilities and system operators can tailor ground measurements to forecasting activities.

• Smarter investments in expensive monitoring infrastructure
Task 3
Marine Layer Forecasting
Summer 2013 Trial

SRAF Laboratory
Solar Resource Assessment and Forecasting
Forecast Trial

Irradiance forecasts created across San Diego County

a) UCSD High-Resolution Model
   - 2.5 km
   - Cloud Assimilation
   - Physics parameterizations optimized for Marine Layer forecasting

b) Operational NWS Models at lower Resolution
   - North American Model + Global Forecast System

![Map of San Diego County showing irradiance forecasts with various models and units of GHI (W m⁻²)].

![Graph showing GHI (W m⁻²) over time from 7/01/2013 5:00 to 4:00 PDT with models GFS, NAM, WRF1, WRF2, WRF3, and PWS1].
Forecast Results – Binary
Aug 8-25, 2013

- NOAA models never cloudy
  - NWS post-processing helps
- UCSD, persistence best
- Skill score for all 8 stations:

**Hit Score:**
0.5 (Cloudy hit [%] + Clear hit [%])
Overall Forecast MAE – Raw Models

- NOAA / NWS models far worse than persistence
- But: persistence unable to capture changing conditions

MAE [W m⁻²]
Ensemble System and Post-Processing

- Performance of raw NWP forecasts not satisfactory
- Ensemble forecast system based on WRF
- Taylor Expanded Solar Analog Forecasting postprocessor

<table>
<thead>
<tr>
<th>Ensemble Name</th>
<th>Cumulus</th>
<th>Radiation</th>
<th>Microphysics</th>
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</thead>
<tbody>
<tr>
<td>Cumulus1</td>
<td>Kain-Fritsch (1)</td>
<td>Dudhia (1) / RRTM (1)</td>
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<tr>
<td>Microphysics8</td>
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<td>Thompson (8) (8)</td>
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<td>CLDDA</td>
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<tr>
<td>CLDDA&amp; Cumulus 3</td>
<td>Grell-Freitas (GF) (3)</td>
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</table>
Postprocessed Ensemble Forecast System Results

- Best ensemble improves 20% to 40% over persistence
Ensemble Forecast System Results

- Difference by NWP
  - Small at coastal
  - Large at inland sites
Key Deliverables

• Available at calsolarresearch.org
• Optimal weather station locations
• Day-ahead marine layer forecast models and reports on validation
• Reports on distribution feeder modeling
• Report on net load forecasting
Overall Summary / Outcomes

• Hours-ahead and day-ahead solar forecast now implemented at SDG&E
• Improved accuracy of distribution system modeling and forecasting tools
• Facilitates solar power integration through
  – Better foresight for power system operation
  – Better understanding of distribution system O&M costs and mitigation options
  – Smarter investment in monitoring infrastructure