Integration of Photovoltaics into Building Energy Usage through Advanced Control of Rooftop Units

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Introduction

- Solar power is governed by uncontrollable circumstances in the weather and may cause issues on the power system.
- Integrating a PV forecast with load control solutions can mitigate some of these challenges by absorbing variations in solar power into the load profile.
Facilities

- PV analysis performed at DECC (Distributed Energy Communications and Control Laboratory)
- Two PV arrays each rated at 6.5kW.
- DECC also has HVAC systems, energy storage (lithium ion batteries), and micro-grid control research.
Overview of forecasting procedure
Estimating Solar Irradiance

- Forecasted cloud cover images extracted from website.
- Cloud cover model is provided hourly for 48 hours ahead.
- Color code represents a percentage of cloud cover.
- Color of pixels over a region provides % cloud cover.

Oak Ridge, TN
Linking Cloud Cover & Solar Irradiance

- We use a neural network to transform forecasted cloud cover to solar irradiance.

- Training data:
  - Solar irradiance measurements,
  - solar angle,
  - forecasted cloud cover

- Weather data polled from weather underground.
Results of Training

- Percent cloud cover captured from images.
- Resulting solar irradiance estimates based on cloud cover.

Bad forecasted cloud cover will lead to errors in solar irradiance estimates.
PV Model

\[ I = I_{pv} - I_o \left[ e^{\left(\frac{(V+R_sI)}{V_t a}\right)} - 1 \right] - \frac{(V + R_sI)}{R_p} \]

\[ V_t = N_s kT/q \]

\[ I_{pv} = (I_{pvn} + K_I (T - T_n)) \frac{G}{G_n} \]

\[ I_o = \frac{I_{scn} + K_I (T - T_n)}{e^{\left(\frac{(V_{ocn}+K_V(T-T_n))}{V_t a}\right)} - 1} \]
Thermal model considers the area, depth, and other characteristics of the PV, to capture thermal changes due to convection, long and short wave radiation.

\[ C_{module} = \sum_{m} A_d m p_m C_m \]

\[ C_{module} \frac{dT}{dt} = q_{lw} + q_{sw} + q_{conv} - P_{out} \]

Validation: Measured ambient temperature and solar irradiance are inserted to the model. Module temperature is calculated and compared to measured results.
Validation of Thermal Model
Using the PV Model

- The resistance values $R_p$ and $R_s$ are calculated through an iterative process.
- Electrical schematic represents the physical system inserted into power systems toolbox in Mathworks Matlab program.
- Loading voltage is ramped from 0 to $V_{oc}$.
- Independent current source is driven by solar irradiance and temperature and loading.
- Full curves of P versus V and I versus V are created.
Calculation of PV Curves

- Fit model to 280W Hanwha Solar PV modules
- Curves validated against manufacturer specifications.
Validation of Model

- Inverter connected to PV panel governs actual power output.
- In many cases, small residential and commercial systems are set to maximum power point tracking (MPPT).
- These systems will adjust the output voltage on the DC link of the inverter to maximize output of PV panel.
- Validation: Input of temperature and solar irradiance measured, inserted into model and compared to output power measured at inverter.
Validation results

![Graph showing power (W) over time (Hrs) with Modeled PV Power and Measured PV Power lines.](image-url)
Testing forecast accuracy

- PV output is estimated hourly and interpolated.
- Actual measured PV power is measured is 5 minute. Rapid cloud changes are not captured.
- Future revisions will focus on faster forecasting with cloud pattern recognition from camera images and imaging processing.
Forecasting results
Anticipated use in MPC

- From previous work (see Paper 3494: “An inexpensive retrofit technology for reducing peak power demand in small and medium commercial buildings”), reduce peak demand by running \( N < M \) HVAC units in a building with \( M \) units.

- Which units selected to minimize out of band temperature:
  \[
  T^* = \sum_k \max \{ T_k' - (T_{ref,k} + \Delta T_{c,k}), 0 \} + \max \{ (T_{ref,k} - \Delta T_{h,k}) - T_k', 0 \}
  \]

- Use PV forecast to maximize use of PV power:
  \[
  P^* = \max \{ PN - P_{solar}, 0 \}
  \]

- New optimization function a weighted sum:
  \[
  w_1 T^* + w_2 P^*
  \]
Simulation with ideal forecasts

Simulated a building based on the one described in prior paper for a typical summer data in Knoxville, Tennessee.

Used weights
\[ w_1, w_2 = 1 - w_1 \]

PV forecast reduces energy consumption with a modest reduction in the ability to regulate temperature.

<table>
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<th>( w_1 )</th>
<th>Mean ( P^* ) (kW)</th>
<th>Mean ( T^* ) (deg. C)</th>
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</table>
Conclusion

- Energy use by HVAC units can be modestly reduced by integrating future availability of locally generated solar power into the scheduling of HVAC operation
- Have demonstrated a method for forecasting the availability of PV power
- Ongoing work to determine how accurate a forecast is required to achieve real energy savings