Optimization-based Management of Energy Systems

Authors: Yiqing Lin, Stella M Oggianu, Suman Dwari, Luis Arnedo

Presented by: Stella Maris Oggianu, PhD
May 11, 2010

for
ENVIRONMENT, ENERGY SECURITY & SUSTAINABILITY SYMPOSIUM & EXHIBITIONE2S2

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Why Distributed Power Systems / Energy Microgrids?

Security of supply, reduced energy, and minimized environmental impact

Security of energy supply
- **Vulnerable loads** served under all operating conditions.
- ‘Customizable’ **power quality and reliability**
- **Seamless transition** between islanding and off-grid operation

Reduced energy costs and environmental impact
- Improved power systems architectures
  - **Waste heat utilization**
    - 85-90% fuel utilization vs. 40-50% for central power
  - **Renewable sources with energy storage**
  - **Maximize ROI**
- Integrated demand/supply management:
  - **Reduced energy consumption/cost,**
  - **Peak shaving**
- **Decrease in T&D losses and required infrastructure**

- **Energy microgrids are distributed power systems with the capability to work seamless in islanding and grid-connected modes.**
- **They include thermal and electrical systems**
Energy Microgrids and Energy Management System (EMS)

Value and benefits

Objective

- To evaluate the benefits of microgrid and optimization-based supervisory system
- To understand the impact of equipment down-time and the value of perfect weather/loads information

Challenges

- Uncertainty in data and forecasts
- Results depend on microgrid architecture, weather and prices

Test cases architectures

- Determined by minimizing initial cost with renewable usage constraints

<table>
<thead>
<tr>
<th></th>
<th>NC</th>
<th>CO</th>
<th>OK</th>
<th>NY</th>
<th>TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Yes, unlimited</td>
<td>Yes, unlimited</td>
<td>Yes, unlimited</td>
<td>Yes, unlimited</td>
<td>Yes, unlimited</td>
</tr>
<tr>
<td>Solar PV (KW)</td>
<td>35 MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20 MW</td>
</tr>
<tr>
<td>Wind turbines (kW)</td>
<td>65 MW</td>
<td>70 MW</td>
<td>65 MW</td>
<td>55 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td>CHP (microturbines+absChiller)</td>
<td>5 MW microturbines</td>
<td>17.5 MW microturbines</td>
<td>35 MW microturbines</td>
<td>27.5 MW microturbines</td>
<td>12.5 MW microturbines</td>
</tr>
<tr>
<td>Diesel generators</td>
<td>4 MW</td>
<td>2 MW</td>
<td>8 MW</td>
<td>12 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td>Batteries, LiI (kWh capacity)</td>
<td>1 MWh</td>
<td>1 MWh</td>
<td>1 MWh</td>
<td>1 MWh</td>
<td>1 MWh</td>
</tr>
</tbody>
</table>
Energy Microgrids and Energy Management System (EMS)

*Value and benefits:* Optimization-based EMS could provide 5-20% cost savings compared to rule-based approaches

**Key Results**
- Feasible microgrids architectures are able to provide 50-60% annual operating cost reduction
- Optimization-based supervisory microgrid control provides an average annual 5-20% cost reduction compared with simple rule-based control strategy

### Annual Operating Cost Comparison

**Operating Cost by Category (Site: NC)**

### Annual Cost Savings of Microgrid

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NC</th>
<th>CO</th>
<th>OK</th>
<th>NY</th>
<th>TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2 (Grid &amp; Renewable)</td>
<td>17%</td>
<td>13%</td>
<td>19%</td>
<td>16%</td>
<td>21%</td>
</tr>
<tr>
<td>Scenario 3 (Grid &amp; Microgrid, Rule-based)</td>
<td>41%</td>
<td>49%</td>
<td>58%</td>
<td>51%</td>
<td>54%</td>
</tr>
<tr>
<td>Scenario 4 (Grid &amp; Microgrid, Optimization-based)</td>
<td>60%</td>
<td>56%</td>
<td>64%</td>
<td>61%</td>
<td>61%</td>
</tr>
</tbody>
</table>

### CO₂ Reduction

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NC</th>
<th>CO</th>
<th>OK</th>
<th>NY</th>
<th>TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 4 (Grid &amp; Microgrid, Optimization-based)</td>
<td>33%</td>
<td>35%</td>
<td>36%</td>
<td>35%</td>
<td>36%</td>
</tr>
</tbody>
</table>
Energy Management System for Energy Systems

Overview

- Energy Management System (EMS) performs effective coordination and dispatching of distributed energy resources
  - Functionally similar to economic dispatch & unit commitment in power systems
  - Selects combination of sources and storage to meet demand
  - Considers constraints on availability of supply and operational limitations
  - Interfaces with customers and utilities

- Conventional dispatching systems are optimization-based and use steady-state models

- Renewable intermittency and memory associated with storage require planning and forecasting

- Systematic decision-making with uncertainties in demand and availability of renewable resources
EMS performs effective *coordination* and *dispatching* of distributed energy resources

- Renewable intermittency and memory associated with storage → planning & forecasting
- Combines elements of forecasting, model prediction, and state estimation
- Repeated solution of finite-horizon stochastic programming problems

\[
\begin{align*}
\text{min } & \sum_{j=1}^{N} \Phi(C(j), x(j), u(j)) \\
\text{s.t. } & x(i) = f(x(i-1), u(i-1), L(i-1)) \\
& g(x(i), u(i')) \geq 0 \\
& x(0) = x_0
\end{align*}
\]
Energy Management System Framework

Real-time Model Predictive Methodology

Repeated decision-making over finite horizons
Operational decisions have to be made in the face of renewable resources and load forecast uncertainty.

We explored different methods to determine set-points for optimal operation:

- **Method 1. Perfect information**: Use perfect/exact forecast
- **Method 2. Expected-value solution**: Use the average of different forecasted scenarios
- **Method 3. Stochastic solution**: Factors uncertainties for decision-making using a stochastic programming formulation. It assumes that:
  - It is impossible to find a solution that is ideal under all circumstances
  - Decisions are balanced, or hedged against the various scenarios
- Grid-connected system
- Realistic cost data; objective to minimize monthly operating cost
- Load forecast is exact (can be easily relaxed)
- 24 hr horizon with 15 minute time-step
Energy Management Framework: *Dealing with Uncertainties*

*Test Cases used to exploit Methods of Dealing with Uncertainties*

Solar Radiation Forecast:
- Three cases (and predictive mean) considered
- Error in solar radiation forecast translates to error in PV power

Loads Forecast
- Two cases to capture effect of sizing and component interaction
  - Load 1: Load comparable to onsite generation capability
    - Stronger interaction between microgrid components
    - “Good” sizing of micro-grid towards grid independence
  - Load 2: Load larger than onsite generation
    - Weak interaction between microgrid components
    - Grid dependence
### Energy Microgrid Framework Test Cases: Results

**Exploring Methods of Dealing with Uncertainties**

- Maximum cost of perfect information = Expected value of perfect information
- Average cost difference between Method 3 and Method 1

#### Load 1 (Loads comparable with onsite power generation capacity)

<table>
<thead>
<tr>
<th></th>
<th>Method 1 Perfect Information</th>
<th>Method 2 Use Predictive mean</th>
<th>% Deviation Method 1 &amp; Method 2</th>
<th>Method 3 Stochastic Programming</th>
<th>% Deviation Method 1 &amp; Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$6,404</td>
<td>$6,534</td>
<td>2.0</td>
<td>$6,694</td>
<td>4.5</td>
</tr>
<tr>
<td>Case 2</td>
<td>$8,331</td>
<td>$9,246</td>
<td>11.0</td>
<td>$8,344</td>
<td>0.2</td>
</tr>
<tr>
<td>Case 3</td>
<td>$7,429</td>
<td>$7,908</td>
<td>6.4</td>
<td>$7,560</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Avg: 6.46%

#### Load 2 (Loads larger with onsite power generation capacity)

<table>
<thead>
<tr>
<th></th>
<th>Method 1 Perfect Information</th>
<th>Method 2 Use Predictive mean</th>
<th>% Deviation Method 1 &amp; Method 2</th>
<th>Method 3 Stochastic Programming</th>
<th>% Deviation Method 1 &amp; Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$14,020</td>
<td>$14,152</td>
<td>0.9</td>
<td>$14,157</td>
<td>1.0</td>
</tr>
<tr>
<td>Case 2</td>
<td>$17,996</td>
<td>$18,121</td>
<td>0.7</td>
<td>$18,082</td>
<td>0.5</td>
</tr>
<tr>
<td>Case 3</td>
<td>$16,161</td>
<td>$16,683</td>
<td>3.2</td>
<td>$16,489</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Avg: 1.6%
Energy Management Framework: Conclusions

Future Work and Implementation

Conclusions:
- Stochastic programming helps with decision making under uncertainty
- Stochastic programming tools can drastically reduce the value of perfect information
- Sizing, architecture and magnitude of loads dictate the required accuracy of forecasts

Future work:
- Include equipment reliability in the models / problem formulation
- Extension to include thermal power
- Extension to include load management (combined supply / demand)

The Energy Management Framework introduced in this presentation will be implemented in two energy microgrids demonstrations being prepared for DoD-ESTCP and DoE funded programs.