EAGERS

NREL kick-off meeting
9-14-16
How do generators and complementary systems integrate with a building and the grid?
Hierarchical MPC Overview

- Forecast (Load & prices)
- Economic Dispatch (15min)
- On-Line Optimization (<1min)
- Threshold
  - ON
  - OFF
- MPC (<1s)
  - LC 1
  - LC 2
  - LC 3

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Multiple Time-Scales

Forecast
- Temperature
- Loads
- Utilities
24 Hours

Dispatch
- Generators
- Heaters/Chillers
- Energy Storage
24 Hours

Threshold
- Time
- Demand
- SOC
15 min to 1 Hour

Control
- Re-optimize DER
- Adjust generator set-points
- Apply MPC
60 Seconds, 1 sec

Balance
- Distribute un-met load between grid and ES
<1 sec
Step 1: Forecast Temperature

- Average of yesterday’s temperature & historical profile for current season or month
- Avoid Discontinuity: blend current temperature to forecasted temperature over 8 hours
Step 2: forecast loads

- Use 2-D surface fits of historical data (electricity, heating, cooling)
- Use forecasted temperature and time of day to interpolate load
- Apply same technique to average yesterday's load & the historical load
- Use different 2-D surface for weekdays & weekend/holidays
Minimize the cost of generators + utility + storage while meeting the demands at each time step, subject to constraints...

Mathematically:

\[
\min C = \sum_{k=1}^{N} \left[ \sum_{h=1}^{m} F_{h,k} \left( P_{h,k} \right) + \sum_{f} F_{f,k} \left( P_{f,k} \right) \right] + \sum_{r=1}^{s} F_r \left( SOC_{r,N} \right) / \eta_d
\]

**Demand constraint:**

\[
\sum_{h=1}^{m} P_{h,k} + P_{\text{grid},k} + \sum_{r=1}^{s} \left( P_{r,k} - \phi_{r,k} \right) = P_{\text{load},k} - P_{\text{unctrl},k}
\]

**Range constraint:**

\[
P_{h,k}^{\text{min}} \leq P_{h,k} \leq P_{h,k}^{\text{max}}
\]

**Ramp constraint:**

\[
\left| P_{h,k} - P_{h,k-1} \right| \leq r_h^{\text{max}} \cdot \Delta t_k
\]

**Grid constraint:**

\[
P_{\text{grid},k}^{\text{min}} \leq P_{\text{grid},k} \leq P_{\text{grid},k}^{\text{max}}
\]
1) non-linear cost curve
2) Discontinuity: zero cost at zero power, finite cost at lower operating condition

≥ For any given demand you can solve the combinatorial problem and find the best configuration of generators to meet the demand
≥ $2^{m-1}$ combinations
Does it have a cost?

Do you need to solve the entire horizon simultaneously?

Now you have $2^{(m-1)*N}$ feasible combinations

What about charging/discharging inefficiencies?

Our approach:

Relate Power to SOC:

$P_{r,k} = (SOC_{r,k} - SOC_{r,k-1}) \cdot \eta_d / \Delta t_k$

Charging penalty:

$\phi_{r,k} \geq \left( SOC_{r,k-1} - SOC_{r,k} \right) / (\eta_c \cdot \Delta t_k) - P_{r,k}$

$\phi_{r,k} \geq 0$

Bounds:

$SOC_r^{\text{min}} \leq SOC_{r,k} \leq SOC_r^{\text{max}}$
» Piecewise quadratic curves

- Best possible while remaining convex

Fit A: has zero y-intercept

\[
F_{h,k}(P_{h,k}) = \left(a_{1,h}\beta_{h,k} + a_{2,h}\gamma_{h,k} + \frac{1}{2} \cdot a_{3,h}\gamma_{h,k}\right) \cdot \Delta t_k
\]

Fit B: has non-zero y-intercept

\[
F_{h,k}(P_{h,k}) = \left(b_{1,h}\beta_{h,k} + b_{2,h}\gamma_{h,k} + \frac{1}{2} \cdot b_{3,h}\gamma_{h,k} + b_{4,h}\right) \cdot \Delta t_k
\]

Storage end condition value

- Prevents completely depleting storage

\[
F_r(SOC_{r,N}) = c_{1,r} \cdot SOC_{r,N} + \frac{1}{2} c_{2,r} \cdot SOC_{r,N}^2
\]

\[
c_{1,r} = -1.05 \cdot \max \left( b_{2,h} + b_{3,h} \cdot (UB_h - I_h) \right)
\]

\[
c_{2,r} = \left(-c_{1,r} - 0.95 \cdot \min \left( b_{1,h} \right) \right) / (2 \cdot UB_h)
\]
Step 1) Solve the entire optimization with all constraints, except relax the lower boundary constraints (i.e. $P_{h,k}^{\text{min}}=0$ and $F_{h,k}(0)=0$) and use fit A. This creates Schedule 1.

Step 2) Add up the generation at each step (including what charges the storage) and solve the combinatorial problem to find the best generator combo at that moment. Use fit B and enforce the lower boundary constraints. Ramping constraints are not considered, since it is only solving 1 step at a time. This becomes Schedule 2.

Step 3) Apply a series of rules to Schedule 1 and Schedule 2 to determine when generators are on and off. Then solve the full optimization at all steps, with all constraints enforced. This results in Schedule 3, which is used for the next step.
# Standard Dynamic Economic Dispatch

## Complementary QP Approach

### Table 1: Generation and Storage Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (kW)</th>
<th>Lower Limit</th>
<th>Peak eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen1</td>
<td>100</td>
<td>25.0</td>
<td>39.3</td>
</tr>
<tr>
<td>Gen2</td>
<td>100</td>
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<tr>
<td>Gen3</td>
<td>80</td>
<td>25.0</td>
<td>33.0</td>
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<tr>
<td>Gen4</td>
<td>80</td>
<td>10.0</td>
<td>27.9</td>
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<tr>
<td>Gen5</td>
<td>40</td>
<td>10.0</td>
<td>30.5</td>
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</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (kW)</th>
<th>Lower Limit (kW)</th>
<th>Peak COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller1</td>
<td>200</td>
<td>100</td>
<td>6.3</td>
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<tr>
<td>Chiller2</td>
<td>120</td>
<td>60</td>
<td>5.6</td>
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<tr>
<td>Chiller3</td>
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<td>40</td>
<td>4.8</td>
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<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (kWh)</th>
<th>Peak Out (kW)</th>
<th>Eff (%)</th>
</tr>
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<tbody>
<tr>
<td>Battery</td>
<td>500</td>
<td>130</td>
<td>96</td>
</tr>
<tr>
<td>TES</td>
<td>4,000</td>
<td>800</td>
<td>99</td>
</tr>
</tbody>
</table>

### Figure 1: Generation Costs

- **Cost**: $332.33

### Figure 2: Generation Costs

- **Cost**: $298.4
Electric storage can keep generator #4 off

Cost: $293.32
Thermal storage can work like electric storage
» **List of attributes**
  > Utilizes quadratic rather than linear cost functions for each generator
  > Determines best use of energy storage by optimizing over time horizon
  > No arbitrary costs assigned to use of storage (no solution shaping)
  > Respects lower operating constraints of generators & start-up costs
  > Computation scales linearly with # of intervals ($t \cdot 2^n$ rather than $2^{n \cdot t}$)

» **Current Functionality**
  > Considers electricity+heat+cooling together
  > Incorporates charging/discharging inefficiencies
  > Incorporates self-discharging (losses) of energy storage
  > Variable time step horizon

» **Future functionality**
  > Ambient temperature dependence of generator limits/cost
  > Co-production of steam (for steam turbine) or hydrogen
  > Spinning reserve
  > Transmission constraints & line losses
Multiple Time-Scales

- **Forecast**
  - Temperature
  - Loads
  - Utilities
  - Duration: 24 Hours

- **Dispatch**
  - Generators
  - Heaters/Chillers
  - Energy Storage
  - Duration: 24 Hours

- **Threshold**
  - Time
  - Demand
  - SOC
  - Duration: 15 min to 1 Hour

- **Control**
  - Re-optimize DER
  - Adjust generator set-points
  - Apply MPC
  - Duration: 60 Seconds, 1 sec

- **Balance**
  - Distribute un-met load between grid and ES
  - Duration: <1 sec
Uncertainty & error in prediction

> Just because your prediction says you should turn a generator on (or off), does not mean you should

> Setting thresholds, upper and lower boundaries, and waiting for the load to pass this threshold before taking action is one way to adjust for errors in prediction

> Thresholds can also be set by time or by SOC for a storage system
Every ~60 sec: re-optimize generator output

- Horizon is the time interval of the dispatch (15 min)
- Boundaries for generators determined from dispatch
  + Ex) may need generator #1 to be ramping up continuously
- SOC of storage targets an end condition determined by dispatch (end of 1st dispatch interval)
  + penalties for over or under charging (larger penalty for under charging)
- Send targets to MPC controller

Every ~1sec: MPC controller sends updated set-point to generators
A. Grid Only
   > Purchase any additional power necessary to balance supply & demand
   > Excess power is dumped onto grid

B. Storage Only
   > Balance demand by charging/discharging storage

C. Grid & Storage
   > Dispatch determines a target amount of charging/discharging for current step
   > If charging:
   > If discharging:

<table>
<thead>
<tr>
<th>Over-production</th>
<th>Under-production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-production</td>
<td>Under-production</td>
</tr>
<tr>
<td>1) Reduce discharging</td>
<td>1) Reduce power sold to grid</td>
</tr>
<tr>
<td>2) Reduce grid purchases</td>
<td>2) Increase grid purchases</td>
</tr>
<tr>
<td>3) Sell power back to grid</td>
<td>3) Discharge more storage</td>
</tr>
</tbody>
</table>
Hierarchical MPC Overview

Forecast (Load & prices) → Economic Dispatch (15 min) → On-Line Optimization (<1 min) → MPC (<1 s) → LC 1, LC 2, LC 3

Threshold (ON → OFF)
### SIMO Response

Continuous-Time

\[ x' = Ax + Bu \]

\[
A = \begin{bmatrix} 235e^{-22} & -0.0013 \\
B = \begin{bmatrix} 0.002229 \\
C = [1000; 0] \\
D = [0; 0] \\
\end{bmatrix}
\]

Note: GRID-MEN

![Graph Plot](kW)

<table>
<thead>
<tr>
<th>Time</th>
<th>Electricity</th>
<th>Heat</th>
<th>Input</th>
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<tr>
<td>2</td>
<td>50</td>
<td>0</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<tr>
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<td>900</td>
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<td>130</td>
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</tbody>
</table>

Values represent normalized output 1 = 100%

- **Add Row**
- **Delete Row**
- **Revert**
- **Finished**

**Edit Startup**

**Edit Shutdown**
» Same idea for electric & gas utilities
» Also can create district heating/cooling utilities
Running a Test

Communicates with LabView

Uses user-supplied SS model to simulate generator response