Increased Stability of a Power Grid by Energy Storage of Cryogenic Carbon Capture

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Stability of Power Grid

Power Supply Curve
NREC Region, 2010

Low Utilization = High Cost / MWh

Deloitte Center for Energy Solutions, 2011
New regulations for CO$_2$ emission from power plants:

- EPA’s regulation for existing power plants (2015)
  - 30% reduction in CO$_2$ from 2005 levels by 2030
- EPA’s regulation for new power plants (2015)
  - 1100 lbs/MWh CO$_2$ for gas-fired power plants
  - 1400 lbs/MWh CO$_2$ for coal-fired power plants
Solutions to Increase Stability

- Advanced Metering Infrastructure
- Demand Response
- Distribution Automation
- Renewable Resource Forecasting
- Distributed Storage (Electric Vehicles with V2G capability and batteries)
- Microgrids (distributed generation)
- Bulk energy storage (Pumped stored hydropower, compressed air energy storage, thermal storage)
Benefits of Energy Storage

- Grid frequency and voltage regulation (grid stabilization and power quality control)
- Shaving of load peaks
- Smoothing of renewable power variability (ramp rate control)
- Energy arbitrage
- Backup power
Cryogenic Carbon Capture (CCC)

Advantages of the CCC Process

- Lower energy consumption
- Scalable energy storage
- Rapid-load-change capability
- Flexible operation
- Energy recovery

Jensen, PhD Dissertation, Brigham Young University, 2015
Hybrid System of Power Generation and CCC

- Two refrigeration cycles
- Overproduction and storage of LNG during low electricity demand
- Using stored LNG during peak hours
- More power available by ramping down the refrigeration compressor load
- Power production in a gas turbine during peak demand
Improved Profitability through Integration

- Dynamic integration of CCC with power generation units
- Assumed 90% CO$_2$ capture rate
- Meet residential and CCC electricity demands
- Maximize operational profit of the hybrid system
- Minimize cycling of the coal power plant
Optimization Approach

- Objective function: $\ell_1$-norm
  
  $\min_{x,y_m,u} \Phi = w_{hi}^T e_{hi} + w_{ho}^T e_{lo} + y_m^T c_y + u^T c_u + \Delta u^T c_{\Delta u}$

- Dead-band for the controlled variable
- Prioritize multi-objective functions
- Orthogonal collocation on finite elements for DAE to NLP conversion
- Active Set or Interior Point Solvers
  - APOPT or IPOPT
- APMonitor Modeling Language

Subject to:

- $0 = f(\dot{x}, x, u, d)$
- $0 = g(y_x, x, u, d)$
- $a \geq h(x, u, d) \geq b$
- $\tau_c \frac{\delta y_{t,hi}}{\delta t} + y_{t,hi} = sp_{hi}$
- $\tau_c \frac{\delta y_{t,lo}}{\delta t} + y_{t,lo} = sp_{lo}$
- $e_{hi} \geq (y_m - y_{t,hi})$
- $e_{lo} \geq (y_{t,lo} - y_m)$
Power Production vs. Electricity Demand

Baseline Boiler

- Meet the total electricity demand
- Refrigerant storage used in gas turbine
- 100% utilization of the wind power

Load-following Boiler
Impact of Energy Storage on Baseline Case

With Energy Storage & Combined Cycle Power Production

Without Energy Storage & Simple Cycle Power Production
Comparison of Power Production

Grounded Power = Total Power – Total Demand

With Energy Storage & Combined Cycle Power Production

Without Energy Storage & Simple Cycle Power Production
Profitability

- $13.6k/hr average profit
- $58k/hr average hourly revenue
- Recovery of most of the CCC constructional expenses by taking advantage of the arbitrage of energy
Cycling Cost

- Increased thermal, pressure, and mechanical related stress and fatigue

- Cycling scenarios: Cold start, Hot start, Warm start, and Load-following
Cycling Cost (Continued)

- **Rainflow cycle counting algorithm**

<table>
<thead>
<tr>
<th></th>
<th>With Wind</th>
<th>Without Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load-following</td>
<td>Baseline Boiler</td>
</tr>
<tr>
<td></td>
<td>boiler</td>
<td>Boiler</td>
</tr>
<tr>
<td># cycles in Boiler</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>(cost)</td>
<td>($88200)</td>
<td>($4410)</td>
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<tr>
<td># cycles in gas turbine</td>
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<td>21</td>
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<tr>
<td>(cost)</td>
<td>($10880)</td>
<td>($13440)</td>
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<tr>
<td>Total cycling costs</td>
<td>$99080</td>
<td>$17850</td>
</tr>
</tbody>
</table>

- **Key Result:** **80-85% reduction in cycling damage with energy storage**
Conclusion

- CCC process removes 99% of CO$_2$ with lowest cost per kg CO$_2$
- Large-scale energy storage improves renewable adoption
- CCC + energy storage reduces cycling costs by 80-85%
- Reduction in the need to spinning reserves
- Power grid stability
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