Smart Grid Coordination in the Process Industry

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Presentation Outline

- What is the smart grid? (intuitive answer)
- What is the smart grid? (decomposed answer)
- Operation of smart grid coordinated processes
- Design of smart grid coordinated processes
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What is the Smart Grid?

Wikipedia:
A smart grid is an electrical grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.

ABB Website:
A smart grid is an evolved grid system that manages electricity demand in a sustainable, reliable and economic manner, built on advanced infrastructure and tuned to facilitate the integration of all involved.
What is the Smart Grid?

(CEP, Aug 2014)
What’s wrong with the Dumb Grid?

A balance between power generation and power consumption must be maintained at all times.
What’s wrong with the Dumb Grid?

Gas Turbines
Coal Fired
Nuclear

If demand is low then few generators needed

Consumers

Consumer Demand

If demand is low then few generators needed.
What’s wrong with the Dumb Grid?

If demand is high then many generators needed

Gas Turbines

Coal Fired

Nuclear

Consumers

Consumer Demand

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What’s wrong with the Dumb Grid?

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

Consumers

Consumer Demand
The Dispatch Problem

- Gas Turbines
- Coal Fired
- Nuclear
- Renewable Sources

If demand is low and renewable high then some generators may need to be off-line.

Consumers

Renewable Sources

Consumer Demand

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The Dispatch Problem

If demand is high and renewable low then there may not be enough generators.

Gas Turbines, Coal Fired, Nuclear, Renewable Sources, Consumers, Consumer Demand
Some Solutions to the Dispatch Problem

- Gas Turbines
- Coal Fired
- Nuclear
- Renewable Sources
- The Smart Grid
- Massive Energy Storage
- Consumer Flexibility
- Consumers
What is the Smart Grid?

(CEP, Aug 2014)
Centralized Power Systems

Gas Turbines

Coal Fired

Nuclear

Renewable

Electric Utility

Consumers

Consumers

Consumers

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Deregulated Power Systems

- Gas Turbines
- Coal Fired
- Nuclear
- Renewable

Independent System Operator

Consumers

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If demand is 600 MW then, electricity price is $18/MW-hr.
If demand is 1200MW then, electricity price is $33/MW-hr
Real-time Pricing for Electricity

Texas Hub: July 2012
Load-Serving Entity

Gas Turbines
Coal Fired
Nuclear
Renewables

ISO

LSE
LSE
LSE

Consumers
Consumers
Consumers

Electricity price to consumers is the annual average
Presentation Outline

- What is the smart grid? (intuitive answer)
- What is the smart grid? (decomposed answer)
- Operation of smart grid coordinated processes
- Design of smart grid coordinated processes
Time-Scale Decomposition

**Operational Time-Scale**

- Hours
  - Real-time Optimization
- Minutes
  - Multivariate Constrained Control
- Seconds
  - Regulatory (PID) Control
  - Chemical Plant
  - Safety Systems and Emergency Shutdown
The Transmission Network

**Generation**
Electricity is generated at various kinds of power plants by utilities and independent power producers.

**Transmission**
Electric transmission is the vital link between power production and power usage. Transmission lines carry electricity at high voltages over long distances from power plants to communities.

**DISTRIBUTION**
Electricity from transmission lines is reduced to lower voltages at substations, and distribution companies then bring the power to your home and workplace.
Some Transmission Network Examples

6 – Bus Network

118 – Bus Network
Power System Model - Load Flow Analysis

Voltage at each bus:

\[ E = [E_1 \ E_2 \ E_3 \ E_4 \ E_5]^T \]

Current injected at each bus:

\[ I = [I_1 \ I_2 \ I_3 \ I_4 \ I_5]^T \]

Admittance Matrix gives voltage-current relation:

\[ I = YE \]
Load Flow Analysis – Power Calculations

Power injected at bus $k$:

\[ S_k = E_k Y_k^* E^* \]

* is complex conjugate

\[ S_k = P_k + jQ_k \]

Voltage in phasor form:

\[ E_k = U_k e^{j\theta_k} \]

- $P_k$ - Active Power
- $Q_k$ - Reactive Power
- $U_k$ - Voltage Magnitude
- $\theta_k$ - Voltage Angle
Load Flow Analysis (bus types)

Source Buses

Bus 1

$P_1$ $Q_1$ $\theta_1$ $U_1$

Bus 4

$P_4$ $Q_4$ $\theta_4$ $U_4$

Bus 5

$P_5$ $Q_5$ $\theta_5$ $U_5$

Load Buses

Bus 3

$P_3$ $Q_3$ $\theta_3$, $U_3$

Bus 2

$P_2$ $Q_2$ $\theta_2$ $U_2$

Slack Bus

Bus 1

$P_1$ $Q_1$ $\theta_1$ $U_1$
Time-Scale Decomposition

- Unit Commitments
- Optimal Power Flow
- Frequency Control
- Electric Power Network
  - Security Constraints and Contingency Response

Operational Time-Scale
- Hours
- Minutes
- Seconds

- Real-time Optimization
  - Multivariate Constrained Control
  - Regulatory (PID) Control
  - Chemical Plant
    - Safety Systems and Emergency Shutdown
Frequency Control
Frequency Control

Servo-loop at each generator

- **Control Variable:** System frequency
- **Manipulated Variable:** Active power
- **Disturbance:** Load power
Time-Scale Decomposition

**Operational Time-Scale**

- Unit Commitments
  - Optimal Power Flow
    - Frequency Control
      - Electric Power Network
        - Security Constraints and Contingency Response
  
- Real-time Optimization
  - Multivariate Constrained Control
    - Regulatory (PID) Control
      - Chemical Plant
        - Safety Systems and Emergency Shutdown
Optimal Power Flow?

System operator selects generator states such that

- all load demands are met: $P_k$ and $Q_k$ at loads fixed

- all buses satisfy voltage constraints: $0.9 \leq U_k \leq 1.1$ p.u.

- all transmission lines are below limits: $P_{km} \leq P_{km}^{\text{max}}$

$$P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m)$$

Optimizes with respect to

- operating cost
- transmission line losses
- active and reactive reserves
Time-Scale Decomposition

- **Unit Commitments**
  - **Optimal Power Flow**
  - **Frequency Control**
  - **Electric Power Network**
  - **Security Constraints and Contingency Response**

**Operational Time-Scale**
- Hours
- Minutes
- Seconds

- **Real-time Optimization**
  - **Multivariate Constrained Control**
  - **Regulatory (PID) Control**
  - **Chemical Plant**
  - **Safety Systems and Emergency Shutdown**

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Unit Commitment Problem

Similar to Optimal Power Flow

• Explicit load flow analysis

• Optimizes with respect to
  - Costs, losses, reserves (same as OPF)
  - Integer variables for unit start-up and shut-down

• Larger horizon (day-ahead and hour-ahead)
Time-Scale Decomposition

Operational Time-Scale

- Unit Commitments (Hours)
- Optimal Power Flow (Minutes)
- Frequency Control (Seconds)
- Electric Power Network
  - Security Constraints and Contingency Response

Real-time Optimization

- Multivariate Constrained Control (Seconds)
- Regulatory (PID) Control
- Chemical Plant (Seconds)
  - Safety Systems and Emergency Shutdown
What if a generator trips off-line?

A balance between power generation and power consumption must be maintained at all times.
Spinning Reserves and N-1 Security

The diagram illustrates the relationship between reactive and real power with notation $Q_k$ and $P_k$. The diagram highlights various system limits and operations, including:

- Reactive Power into System
- Overexcited (+MVAR)
- Rotor Winding Limited
- Normal Overspeeded Operation
- Stator Winding Limited
- Undirected Operation
- Underexcited (-MVAR)
- Reactive Power into Generator
- Stator End Iron Limited
- Steady State Liability Limit
The Not So Dumb Grid!

Centralized Operation

- Unit Commitment Problem (UCP)
- Optimal Power Flow (OPF)
- Frequency Control
- Emergency Planning (N-1 Security)
Centralized Operation

Gas Turbines
Coal Fired
Nuclear
Renewable

Electric Utility

Consumers
Consumers
Consumers
Decentralized Operation

Gas Turbines

Coal Fired

Nuclear

Renewables

ISO

LSE

LSE

LSE

Consumers

Consumers

Consumers
Deregulated Operation

Centralized Operation
- Unit Commitment Problem (UCP)
- Optimal Power Flow (OPF)
- Frequency Control
- Emergency Planning (N-1 Security)

Deregulated Operation
- Day-Ahead Market
- Real-Time Market
- Regulation Market
- Frequency Control
- Emergency Capacity Market
Consumer Participation

**Centralized Operation**
- Unit Commitment Problem (UCP)
- Optimal Power Flow (OPF)
- Frequency Control
- Emergency Planning (N-1 Security)

**Deregulated Operation**
- Day-Ahead Market
- Real-Time Market
- Regulation Market
- Frequency Control
- Emergency Capacity Market

**Demand Response Opportunities**
- Economic Response
- Regulation Response
- Contingency Response
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Alcoa and Aluminum Smelting

- 40% of cost to produce aluminum is electricity
- Production is proportional to power input
Evolution of Alcoa Demand Response

Base Load Consumption

- Smelting provides steady 24/7 grid load
- Limited collaboration with energy system
Hot Oil Utility Plant

*Hot Utility Oil (to the process)*

*Fuel*

*Furnace*

*Cold Utility Oil (from the process)*
Utility Plant with Electric Power Option

- Hot Utility Oil (to the process)
- Fuel
- Furnace
- Cold Utility Oil (from the process)
- Electric Power (from the grid)
- Electric Heater
Energy Costs in 2005

Energy Costs 2005

- Electricity
- Natural Gas

Day of the Year

Energy Cost ($/MWhr)
Energy Costs – 2008 and 2012

Energy Costs 2008

Energy Costs 2012

Electricity
Natural Gas
Operating Profiles in 2005
Comparison of 2008 and 2012

![Comparison of Energy Rate and Cost](image)

- **Energy Rate (MW)** or Cost ($/MWhr)
- **Day of the Year**

**Graph Details:**
- **Electricity Price** (2008 and 2012)
- **Fuel Price** (2008 and 2012)
- **Electric Power** (2008 and 2012)
- **Fuel Usage** (2008 and 2012)
## Annual Operating Costs (in millions)

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2008</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$37.4</td>
<td>$32.9</td>
<td>$18.8</td>
</tr>
<tr>
<td>With Electric Heater</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Savings</td>
<td></td>
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Utility Plant with Electric Power Option

- **Hot Utility Oil**
  - (to the process)

- **Cold Utility Oil**
  - (from the process)

- **Electric Power**
  - (from the grid)

**Furnace**

**Electric Heater**

**Fuel**
Electric Heaters

http://www.armstrong-chemtec.com
Cost of Electric Heaters

- Cost of 5MW electric heater is $1.1 million
- Installed cost of 5MW heater is $3.3 million

- If economy-of-scale is linear, then
  - 35MW installed is $23.1 million
- If economy-of-scale is 0.6 rule, then
  - 35MW installed is $10.6 million
## Payback Period

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2008</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Savings from electric heater</strong></td>
<td>$3.7</td>
<td>$2.6</td>
<td>$0.5</td>
</tr>
<tr>
<td><strong>Heater Cost (Linear EOS)</strong></td>
<td>$23.1</td>
<td>$23.1</td>
<td>$23.1</td>
</tr>
<tr>
<td><strong>Payback (years)</strong></td>
<td>6.2</td>
<td>8.8</td>
<td>46</td>
</tr>
</tbody>
</table>
Utility Plant with Thermal Energy Storage

- Hot Utility Oil (to the process)
- Cold Utility Oil (from the process)
- Electric Power (from the grid)
- Fuel
- Furnace
- Heat Exchanger
- Electric Heater
- Molten Salt Energy Storage
Integrated Gasification Combined Cycle
Simplified view of IGCC

\[
\min_{P_G(t)} \left\{ \sum_{t=0}^{N-1} C_e(t) P_G(t) \right\}
\]

- **Gasification Block** (Includes ASU Distillation, Gasifier and Acid Gas Removal)
  - \(\nu_{\text{coal}}\)
  - \(\nu_{\text{ASU}}\)
  - \(\nu_{H2}\)

- **Power Block** (Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)
  - \(P_C\)
  - \(P_N\)
  - \(P_G\)

**MAC**
ASU Main Air Compressor

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Economic MPC operation

Value of Electricity ($/MW)

Power Generated (MW)

H₂ in Storage (tonnes)

Time (days)
Dispatch Requires Equipment Upgrade

**Gasification Block**
(Includes ASU Distillation, Gasifier and Acid Gas Removal)

**Power Block**
(Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)

Net Present Value analysis is required
Smart Grid Equipment Design Problem

Design problem is a Stochastic Program

\[
\min \left\{ PV_f \cdot OpCost + CapCost \right\}
\]

\[
OpCost \approx \min_{0 \leq OpVar_k \leq EqipSize} \left\{ \frac{1}{N} \sum_{k=1}^{N} InstOpCost(OpVar_k) \right\}
\]

If no energy storage, then two-stage problem
If energy storage is allow, then a multistage problem
A Solution Method

Capital Cost =

\[ c_0 \delta + c_1 \left( \frac{M_{\text{max}}}{H_2} \right)^{0.6} \]

where

\[ \delta \in \{0, 1\} \]

**NPV(Equip Size)**

is non-convex

---

Search over NPV

\[
\min \{ \text{Capital Cost} + \text{Operating Costs} \}
\]

Monte Carlo Simulation using EMPC

---

Average Operating Cost

Equipment Size

---

Capital Cost =

\[ c_0 \delta + c_1 \left( \frac{M_{\text{max}}}{H_2} \right)^{0.6} \]

where

\[ \delta \in \{0, 1\} \]
NPV has Local Optima

![Graph showing NPV has Local Optima with Equipment Variables on the x-axis and Neg Net Present Value on the y-axis. The graph has a curve with local minima.]
Approximate NPV for Global Search

Neg Net Present Value vs Equipment Variables
Starting Point for Gradient Search

Neg Net Present Value vs. Equipment Variables
Novel Two-Step Solution Procedure

Global Search over approximate NPV

Economic Linear Optimal Control (ELOC) as surrogate policy
ELOC Simulation

Value of Electricity ($/MW)

0 1 2 3 4 5 6 7 8 9 10
-2000
0
2000
4000
Time (days)

EMPC ELOC

Power Generated (MW)

0 1 2 3 4 5 6 7 8 9 10
-2000
0
2000
4000
Time (days)

EMPC ELOC

H₂ in Storage (tonnes)

0 1 2 3 4 5 6 7 8 9 10
-1000
0
1000
2000
Time (days)

EMPC ELOC
ELOC Based Design (Global Solution)

\[
\min \left\{ \begin{array}{c}
g_{op.cost}(\bar{q}) + g_{cap.cost}(q_{\min},q_{\max}) \\
\end{array} \right\}
\]

\[\begin{align*}
\bar{s}, \bar{m}, \bar{q}, & \quad \sigma_z, \Sigma_z, X, Y, \\
q_{\max}, q_{\min} &
\end{align*}\]

s.t. \[\bar{s} = A\bar{s} + B\bar{m} + G\bar{p} \quad \bar{q} = D_x\bar{s} + D_u\bar{m}\]

\[\sigma_z \leq q_{\max} - \bar{q} \quad \sigma_z \leq \bar{q} - q_{\min}\]

\[\sqrt{\text{diag}(\Sigma_z)} \leq \sigma_z\]

\[
\begin{bmatrix}
\Sigma_z & (D_x X + D_u Y) \\
(D_x X + D_u Y)^T & X
\end{bmatrix} > 0
\]

\[
\begin{bmatrix}
X - G \Sigma_w G^T & (AX + BY) \\
(AX + BY)^T & X
\end{bmatrix} > 0
\]

Generalized Benders Decomposition

Master Problem (BARON)

Primal Problem (SDP solver)
Example of ELOC Based Design

Gasification Block
(Includes ASU Distillation, Gasifier and Acid Gas Removal)

H₂ Storage
(Mₜₒ₀₂)

Power Block
(Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)

Capital Cost = \( c_0^{H_2} \delta_{H_2} + c_1^{H_2} \left( M_{H_2}^{\text{max}} \right)^{0.6} + c_0^G \delta_G + c_1^G \left( P_G^{\text{new}} \right)^{0.6} \)

where \( \delta_{H_2} \in \{0, 1\} \) \( 0 \leq M_{H_2}^{\text{max}} \leq \delta_{H_2} \overline{M}_{H_2}^{\text{max}} \)

and \( \delta_G \in \{0, 1\} \) \( 0 \leq P_G^{\text{max}} \leq \delta_G \overline{P}_G^{\text{max}} \)
Discontinuous Non-convex Capital Costs

![Graph showing capital costs vs. hydrogen storage unit size](image1)

![Graph showing capital costs vs. new power block size](image2)
Grid Search and Two-Step Search

Monte Carlo Simulation using EMPC

Equipment Size

Average Operating Cost

Negative NPV

Generated Power (MW)

H₂ in Storage (tonnes)

0 500 1000 1500 2000

0

200

400

600

800

1000

1200

1400

1600

1800

2000
EMPC with Different Equipment Sizes

Value of Electricity ($/MW)

Time (days)

Power Generated (MW)

ELOC Search  Gradient Search

H₂ in Storage (tonnes)

Time (days)
Global Solution?

Negative NPV

-100 0 100 200 300 400 500
H₂ in Storage (tonnes)

0 500 1000 1500 2000
Generated Power (MW)

NNPV ($ \times 10^6$)
Global Solution?

\[ \Sigma C_e = 20^2 \, \$ / \text{MWh} \]
Change in Electricity Price Variance?

Negative NPV

\[ \sum_{C_e} = 15^2 \$ / \text{MWh} \]
Other Smart Grid Opportunities

Gasification Block
(Includes ASU Distillation, Gasifier and Acid Gas Removal)

Power Block
(Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)

Compressed Air Storage

Air Compressor

CO₂ Storage

CO₂ Compressor

MeOH Plant

H₂ Storage

Coal

H₂

CO₂

L MeOH Plant

Gasification Block
(Includes ASU Distillation, Gasifier and Acid Gas Removal)

Power Block
(Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)
Conclusions

- Control of a power network is similar to that of a chemical plant.
- Market layer gives opportunities for chemical plants to lower operating costs / generate new revenue streams.
- Smart grid coordinated operation likely to require new or expanded equipment.
- Novel design strategy for smart grid coordinated systems has been proposed.
Other Smart Grid Opportunities

Gasification Block
(Includes ASU Distillation, Gasifier and Acid Gas Removal)

- \( v_{\text{coal}} \)
- \( v_{\text{ASU}} \)
- \( v_{\text{H}_2} \)
- \( v_{\text{CO}_2} \)

- \( v_{s, A} \)
- \( v_{s, C} \)
- \( v_{s, H_2} \)

- \( v_{G} \)
- \( v_{L} \)

Power Block
(Includes Expansion Turbine, Combustion Turbine, HRSG, and Steam Turbine)

- \( P_G \)
- \( P_{AC} \)
- \( P_{CC} \)
- \( P_N \)

MeOH Plant

\( H_2 \) Storage

CO\(_2\) Storage

Air Compressor

Compressed Air Storage

\( P_{\text{PGAC}} \)

\( P_{\text{PN}} \)
Other Smart Grid Opportunities
District Cooling System
District Cooling System
District Cooling System with Storage