Controller Design for Dispatch of IGCC Power Plants

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Illinois Institute of Technology

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Outline

• Motivation and Objective

• Market Responsive Control (MRC)

• Equipment Design with Embedded MRC (MRC-EED)

• Case Study
Power System Reliability

Power Produced  Equals  Power Consumed
Overview of Smart Grid

Generators

Transmission

Consumer Demand

Generator Dispatch

Renewable with Storage

Smart Homes

Commercial Buildings

Smart Manufacturing
Power System Operation

Gas Turbine
Coal Fired
Nuclear
Grid
Demand
Merchant Producers

Electricity Spot Price

Gas Turbines and PC Boilers:
- Driven by Opportunity
- Attention to Market Prices
- Focused on Revenue
IGCC Role: Conventional Wisdom

- Gas Turbine
- Grid
- Coal Fired
- IGCC
- Nuclear
- Demand

Illinois Institute of Technology
Department of Chemical and Biological Engineering
IGCC Role: With Dispatchability

IGCC  Gas Turbine  Grid
Coal Fired  Nuclear  Demand

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Integrated Gasification Combined Cycle
IGCC Merchant Producers

Electricity Spot Price

IGCC Opportunity:
- Respond to Market Prices
- Increase Average Revenue
IGCC with Synthesis Gas Storage
IGCC with Compressed Air Storage
IGCC with Throughput Manipulation

Manipulation of Fuel Flow
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IGCC with Dispatch 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**
($M_A$)

**MAC**
ASU Main Air Compressor

**$V_{coal}$**

**$V_{s,A}$**

**$V_{ASU}$**

**$V_{H2}$**

**$V_{s,H2}$**

**$V_{G}$**

**$P_C$**

**$P_G$**

**$P_N$**

**$H_2$ Storage**
($M_{H2}$)
Dispatch Manipulations

Compressed Air Storage ($M_A$)

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(Includes ASU Distillation, Gasifier and Acid Gas Removal)

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$H_2$ Storage ($M_{H2}$)

$V_G$

$P_C$ $P_G$

$P_N$


\[
\frac{dM_A}{dt} = \frac{P_C}{\beta_1} - \beta_2 \nu_{H2}
\]

\[
\frac{dM_{H2}}{dt} = \nu_{H2} - \frac{P_G}{\beta_3}
\]

Compressed Air Storage \( (M_A) \)  

MAC  
ASU Main Air Compressor  

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

V_{\text{coal}}  

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

\( P_C \)  
\( P_G \)  
\( P_N \)  

\( \nu_{\text{coal}} \)  

\( \nu_{H2} \)  

\( \nu_{\text{ASU}} \)  

\( \nu_{C} \)  

\( V_{\text{G}} \)  

\( V_{H2} \)  

\( V_{\text{ASU}} \)  

\( V_{\text{s}, \text{ASU}} \)  

\( V_{\text{s}, \text{A}} \)  

\( \beta \)  

\( H_2 \) Storage \( (M_{H2}) \)
Constrained Process Model

\[ 0 \leq M_A \leq M_A^{\text{max}} \]
\[ 0 \leq M_{H2} \leq M_{H2}^{\text{max}} \]
\[ 0 \leq \nu_{H2} \leq \nu_{H2}^{\text{max}} \]
\[ 0 \leq P_C \leq P_C^{\text{max}} \]
\[ 0 \leq P_G \leq P_G^{\text{max}} \]

\[
\frac{dM_A}{dt} = \frac{P_C}{\beta_1} - \beta_2 \nu_{H2}
\]
\[
\frac{dM_{H2}}{dt} = \nu_{H2} - \frac{P_G}{\beta_3}
\]
Average Revenue

\[ \overline{R} = \lim_{T \to \infty} \left\{ \frac{1}{T} \int_{0}^{T} \left( C_e P_N - c_f \nu_{coal} \right) dt \right\} \]

\[ \nu_{coal} = \beta_4 \nu_{H2} \]
Economic MPC

Maximize Revenue over Horizon $T$

$$\overline{R} \approx \frac{1}{T} \int_{0}^{T} C_e P_N dt$$

- Braun, 1992
- Baumrucker and Biegler, 2010
- Lima et al., 2011
- Rawlings and Amrit, 2009
- Heidarinejad, et al., 2012
Market Responsive Control

$$\bar{R} = E[C_e P_N]$$
Market Responsive Control

\[
\bar{R} = E[C_e P_N]
\]

Enforce the condition:

\[
\tilde{P}_N = \alpha \tilde{C}_e
\]

where:

\[
\tilde{P}_N = P_N - \bar{P}_N
\]
\[
\tilde{C}_e = C_e - \bar{C}_e
\]
Market Responsive Control

\[
\overline{R} = E[C_e P_N]
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Enforce the condition:

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\]

where:

\[
\tilde{P}_N = P_N - \overline{P}_N
\]

\[
\tilde{C}_e = C_e - \overline{C}_e
\]

Then:

\[
\overline{R} = E[\tilde{C}_e \tilde{P}_N] + \overline{C}_e \overline{P}_N
\]

\[
= E[\alpha \tilde{C}_N^2] + \overline{C}_e \overline{P}_N
\]

\[
= \alpha \sum C_e + \overline{C}_e \overline{P}_N
\]
Electric Price Model

White Noise Input → Shaping Filter → Sequence with Electricity Price Characteristics
Electric Price Prediction

White Noise Input → Shaping Filter → Sequence with Electricity Price Characteristics

Measured Electricity Price → State Estimator and/or Predictor → Prediction of Electricity Price
Electric Price Model

\[ W \quad \text{White Noise Input} \quad \text{Shaping Filter} \quad \text{Sequence with Electricity Price Characteristics} \quad C_e \]

\[
\begin{align*}
\dot{f}_1 &= f_2 \\
\dot{f}_2 &= \omega_c^2 (\alpha w - f_3) - \omega_c^2 f_1 - 2 \chi \omega_c f_2 \\
\dot{f}_3 &= (\alpha w - f_3) / \tau_h \\
C_e &= f_1 / \alpha + \overline{C_e}
\end{align*}
\]
Electric Price Spectral Density

\[ W \rightarrow \text{Shaping Filter} \rightarrow \text{Sequence with Electricity Price Characteristics} \rightarrow C_e \]

The diagram illustrates the process of shaping white noise input into a sequence with electricity price characteristics. The spectral density is plotted against frequency, showing a peak at a certain frequency range.
Electricity Electric Price Realization

\[ W \quad \text{White Noise Input} \xrightarrow{\text{Shaping Filter}} \quad \text{Sequence with Electricity Price Characteristics} \quad \mathcal{C}_e \]

![Graph showing electricity price over time with white noise input processed through a shaping filter.](image)

- **Electricity Value ($/MW hr)**
- **Time (days)**

**Graph Details:**
- Time range: 100 to 109 days
- Electricity value range: 70 to 110 $/MW hr

**Legend:**
- \( W \): White Noise Input
- \( \mathcal{C}_e \): Sequence with Electricity Price Characteristics

**Notation:**
- \( \mathcal{C}_e \): Electricity Price Characteristics
Market Responsive Control

\[
\max \left\{ \alpha \sum_{Ce} + c_{H2} (\bar{v}_{H2} - v_{H2}^{\text{max}}) \right\}
\]

\[
s.t.
\frac{dM_A}{dt} = P_C / \beta_1 - \beta_2 v_{H2}^{\text{max}}
\]

\[
\frac{dM_{H2}}{dt} = v_{H2} - P_G / \beta_3
\]

\[
P_N = P_G - P_C
\]

\[
\dot{f}_1 = f_2
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\[
\dot{f}_2 = \omega_c^2 (\alpha w - f_3) - \omega_c^2 f_1 - 2 \chi \omega_c f_2
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\dot{f}_3 = (\alpha w - f_3) / \tau_h
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\[
C_e = f_1 / \alpha + \bar{C}_e
\]

\[
0 \leq M_A \leq M_A^{\text{max}}
\]

\[
0 \leq M_{H2} \leq M_{H2}^{\text{max}}
\]

\[
0 \leq v_{H2} \leq v_{H2}^{\text{max}}
\]

\[
0 \leq P_C \leq P_C^{\text{max}}
\]

\[
0 \leq P_G \leq P_G^{\text{max}}
\]
MRC Example

![Graphs showing time series data for Value ($/MW hr), Power (MW), and Mass (tonnes) over a period of 100 to 109 days.](image)

- **Value ($/MW hr)**
  - Instantaneous
  - Average
  - Maximum
  - $C_e$

- **Power (MW)**
  - $P_G$

- **Mass (tonnes)**
  - $M_{H2}$
MRC Example

![Graph showing revenue over time with dispatch and no dispatch markers.](image-url)
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Equipment Size Variables

\[
\max \left\{ PV_f (\alpha \Sigma_{Ce} + c_{H2}(\bar{v}_{H2} - v_{H2}^{\text{max}}) - c_A M_A^{\text{max}} - c_{H2} M_{H2}^{\text{max}} - c_A M_A^{\text{max}} - c_{H2} M_{H2}^{\text{max}}) \right\}
\]

s.t.

\[
\frac{dM_A}{dt} = P_C / \beta_1 - \beta_2 v_{H2}
\]

\[
\frac{dM_{H2}}{dt} = v_{H2} - P_G / \beta_3
\]

\[
P_N = P_G - P_C
\]

0 ≤ M_A ≤ M_A^{\text{max}}

0 ≤ M_{H2} ≤ M_{H2}^{\text{max}}

0 ≤ v_{H2} ≤ v_{H2}^{\text{max}}

0 ≤ P_C ≤ P_C^{\text{max}}

0 ≤ P_G ≤ P_G^{\text{max}}
Capital Costs of Equipment

\[
\max \left\{ PV_f \left( \alpha \sum_{Ce} + c_{H2} (\bar{v}_{H2} - v_{H2}^{\text{max}}) \right) \right. \\
\left. - c_A M_A^{\text{max}} - c_{H2} M_{H2}^{\text{max}} - c_A M_A^{\text{max}} - c_{H2} M_{H2}^{\text{max}} \right\}
\]

s.t. 

\[
\frac{dM_A}{dt} = P_C / \beta_1 - \beta_2 v_{H2}
\]

\[
\frac{dM_{H2}}{dt} = v_{H2} - P_G / \beta_3
\]

\[P_N = P_G - P_C\]

\[0 \leq M_A \leq M_A^{\text{max}}\]

\[0 \leq M_{H2} \leq M_{H2}^{\text{max}}\]

\[0 \leq v_{H2} \leq v_{H2}^{\text{max}}\]

\[0 \leq P_C \leq P_C^{\text{max}}\]

\[0 \leq P_G \leq P_G^{\text{max}}\]
Present Value Factor

\[
\begin{align*}
PV_f & = \max \left\{ \alpha \Sigma_{Ce} + c_{H_2} (\bar{\nu}_{H_2} - \nu_{H_2}^{\text{max}}) \right. \\
& \left. - c_A M_A^{\text{max}} - c_{H_2} M_{H_2}^{\text{max}} - c_A M_A^{\text{max}} - c_{H_2} M_{H_2}^{\text{max}} \right\}
\end{align*}
\]

s.t.

\[
\frac{dM_A}{dt} = \frac{P_C}{\beta_1} - \beta_2 \nu_{H_2}
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\[
\frac{dM_{H_2}}{dt} = \nu_{H_2} - \frac{P_G}{\beta_3}
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P_N = P_G - P_C
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0 \leq P_C \leq P_C^{\text{max}}
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Case Study Process Parameters

Adapted from NETL Baseline Report (Case 2)

- $P_N^{\text{nom}} = 544 \text{MW}$  \quad $P_G^{\text{nom}} = 611 \text{MW}$  \quad $P_C^{\text{nom}} = 67 \text{MW}$

- $\nu_{H2}^{\text{nom}} = \nu_G^{\text{nom}} = 90 \text{ tonne } H_2/\text{hr}$
  \quad $\nu_C^{\text{nom}} = \nu_{ASU}^{\text{nom}} = 790 \text{ tonne compressed air/\text{hr}}$
  \quad $\nu_{\text{coal}}^{\text{nom}} = 220 \text{ tonne coal/\text{hr}}$

- $\beta_1 = 0.085 \text{ MW hr /tonne air}$
  \quad $\beta_2 = 8.78 \text{ tonne air / tonne } H_2$
  \quad $\beta_3 = 6.79 \text{ MW hr /tonne } H_2$
  \quad $\beta_4 = 2.44 \text{ tonne coal /tonne } H_2$
Case Study Economic Parameters

Adapted from NETL Baseline Report (Case 2)
- $c_f = $33/tonne coal
- $c_G = 2.55 \times 10^5$/MW
  $c_C = 1.04 \times 10^6$/MW
- $c_A = $35.2/tonne compressed air
  $c_{H2} = $540/tonne $H_2$
- Interest Rate = 7%
  Project Horizon = 30yrs
  Average Price of Electricity = $90/MW hr
Case 1

Standard Deviation Electricity Price is $20/MWhr
$\Sigma_{Ce} = (\$20/MWhr)^2$

\[
M_{\text{max}A}^\star = 0.0 \text{ tonne air} \quad P_{\text{max}C}^\star = 67 \text{ MW}
\]
\[
M_{\text{max}H_2}^\star = 705 \text{ tonne } H_2 \quad P_{\text{max}G}^\star = 1222 \text{ MW}
\]
\[
V_{\text{H}_2}^\star = 90 \text{ tonne } H_2/\text{hr},
\]

Present value of $5.08 \times 10^8$ and
Revenue increase of 14.6%
Case 1: \( \Sigma C_e = (\$20/\text{MWhr})^2 \)
Case 1: $\Sigma_{Ce} = ($20/MW\text{hr})^2$
# Changes in Electric Price Variation

<table>
<thead>
<tr>
<th>$\Sigma_{Ce}$ ($/\text{MWhr})^2$</th>
<th>$\overline{V}_{H2}^*$ (tonne/hr)</th>
<th>$M_A^{\text{max}^*}$ (tonne)</th>
<th>$P_C^{\text{max}^*}$ (MW)</th>
<th>$M_{H2}^{\text{max}^*}$ (tonne)</th>
<th>$P_G^{\text{max}^*}$ (MW)</th>
<th>Present Value ($x10^6$)</th>
<th>Revenue Increase (%)</th>
</tr>
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<tr>
<td>$20^2$</td>
<td>90</td>
<td>0.0</td>
<td>67</td>
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<td>1222</td>
<td>508</td>
<td>14.6</td>
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<td>175</td>
<td>7.3</td>
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Case 5: $\Sigma_Ce = (\$45/\text{MWhr})^2$
Case 5: $\Sigma_{Ce} = ($45/MWhr$)^2$
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  Professor Javad Abbasian (ChBE, IIT)

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  Chemical & Biological Engineering Department, IIT
Conclusions

1. Three opportunities to make IGCC dispatchable investigated.
   - H$_2$ storage found to be most viable.
   - Gasifier throughput found to be non-viable.
   - Compressed air storage only viable under extreme price variability.

2. Analytic approach to EMPC developed.

3. Non-convex, but global solution methods available.