Control of Electric Power Transmission Networks with Massive Energy Storage using Economic MPC

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Outline

• Introduction to Utility Scale Power Systems

• Traditional Unit Commitment Policy
  - Without and With Wind Generation

• Unit Commitment with Energy Storage
  - Economic Model Predictive Control
  - Without and With Wind Generation
Overview of the Smart Grid

Dispatchable Generation

Renewable Generation

Energy Storage

Transmission

Consumer Demand

Smart Homes

Smart Buildings

Smart Manufacturing

Overview of the Smart Grid

Dispatchable Generation

Renewable Generation

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Consumer Demand

Smart Homes

Smart Buildings

Smart Manufacturing
Literature Review


5 Bus Example
Consumer Demand

Bus 1

Bus 2

Bus 4

Bus 5

Bus 3

$P_{G1}$

$P_{G2}$

$P_{14}$

$P_{45}$

$P_{45}$

$P_{L4}$

$P_{L5}$

$P_{L3}$
Time Varying Consumer Demand

Bus 1

Bus 2

Bus 4

Bus 5

Bus 3

\( P_{G1} \)

\( P_{G2} \)

\( P_{14} \)

\( P_{45} \)

\( P_{L4} \)

\( P_{L5} \)

\( P_{35} \)

\( P_{L3} \)

Bus 1 Load (MW)

Bus 2 Load (MW)

Bus 3 Load (MW)

Bus 4 Load (MW)

Bus 5 Load (MW)
Power Sources

Coal Plant

Gas Turbine

Bus 1

Bus 2

Bus 4

Bus 5

Bus 3

P_{G1}

P_{G2}

P_{14}

P_{45}

P_{L4}

P_{L5}

P_{L3}

P_{23}

P_{35}
Power Source Dispatch

\[ 0 \leq P_{G1} \leq P_{G1}^{\max} \]
\[ P_{G1}^{\max} = 500MW \]

Coal Plant

\[ 0 \leq P_{G2} \leq P_{G2}^{\max} \]
\[ P_{G2}^{\max} = 300MW \]

Gas Turbine

Bus 1

\[ P_{G1} \]

Bus 2

\[ P_{G2} \]

Bus 3

\[ P_{L3} \]

Bus 4

\[ P_{L4} \]

Bus 5

\[ P_{L5} \]
Operating Cost of Power Sources

\[ c_{Gi} = c_{0i} + c_{1i} P_{Gi} + c_{2i} (P_{Gi})^2 \]
Operating Cost of Power Sources

\[ c_{Gi} = c_{0i} + c_{1i}P_{Gi} + c_{2i}(P_{Gi})^2 \]

\( \$110/\text{MWhr} \)

\( \$65/\text{MWhr} \)
Transmission Lines

Bus 1

Bus 2

Bus 3

Bus 4

Bus 5

$P_{G1}$

$P_{G2}$

$P_{14}$

$P_{45}$

$P_{L4}$

$P_{L5}$

$P_{L3}$

$P_{23}$

$P_{35}$
Transmission Line Limits

\[ -500 \text{MW} \leq P_{14} \leq 500 \text{MW} \]
\[ -300 \text{MW} \leq P_{45} \leq 300 \text{MW} \]
\[ -400 \text{MW} \leq P_{23} \leq 400 \text{MW} \]
\[ -200 \text{MW} \leq P_{35} \leq 200 \text{MW} \]
Alternating Current (AC) Transmission Lines

Bus 1

\[ P_{G1}, Q_{G1}, \theta_{G1}, U_{G1} \]

Bus 2

\[ P_{G2}, Q_{G2}, \theta_{G2}, U_{G2} \]

Bus 4

\[ P_{L4}, Q_{L4}, \theta_{L4}, U_{L4} \]

Bus 5

\[ P_{L5}, Q_{L5}, \theta_{L5}, U_{L5} \]

Bus 3

\[ P_{L3}, Q_{L3}, \theta_{L3}, U_{L3} \]
Power Flow in AC Transmission Lines

\[ P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m) \]
\[ Q_{km} = \frac{U_k^2 - U_k U_m}{X_{km}} \cos(\theta_k - \theta_m) \]
DC-Approximation of AC Transmission Lines

\[
U_k \approx 1 \text{ p.u.} \quad \sin(\theta_k - \theta_m) \approx \theta_k - \theta_m \\
Q_{km} \approx 0 \quad \cos(\theta_k - \theta_m) \approx 0
\]
Power Flow in DC-Approximated Lines

\[ P_{14} = \frac{(\theta_1 - \theta_4)}{X_{14}} \]
\[ P_{45} = \frac{(\theta_4 - \theta_5)}{X_{45}} \]
\[ P_{23} = \frac{(\theta_2 - \theta_3)}{X_{23}} \]
\[ P_{35} = \frac{(\theta_3 - \theta_5)}{X_{35}} \]
Outline

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  - Without and With Wind Generation
Power System Model

Power Balance

0 = \( P_{G1} - P_{14} \)
0 = \( P_{G2} - P_{23} \)
0 = \( -P_{L3} + P_{23} - P_{35} \)
0 = \( -P_{L4} + P_{14} - P_{45} \)
0 = \( -P_{L5} + P_{34} + P_{45} \)
Power System Model

Power Balance

\[0 = P_{G1} - P_{14}\]
\[0 = P_{G2} - P_{23}\]
\[0 = -P_{L3} + P_{23} - P_{35}\]
\[0 = -P_{L4} + P_{14} - P_{45}\]
\[0 = -P_{L5} + P_{34} + P_{45}\]

Line Power Flows

\[P_{14} = (\theta_1 - \theta_4) / X_{14}\]
\[P_{23} = (\theta_2 - \theta_3) / X_{23}\]
\[P_{35} = (\theta_3 - \theta_5) / X_{35}\]
\[P_{45} = (\theta_4 - \theta_5) / X_{45}\]
**Power System Model**

**Power Balance**

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]
\[ 0 = -P_{L4} + P_{14} - P_{45} \]
\[ 0 = -P_{L5} + P_{34} + P_{45} \]

**Line Power Flows**

\[ P_{14} = (\theta_1 - \theta_4) / X_{14} \]
\[ P_{23} = (\theta_2 - \theta_3) / X_{23} \]
\[ P_{35} = (\theta_3 - \theta_5) / X_{35} \]
\[ P_{45} = (\theta_4 - \theta_5) / X_{45} \]

**Operating Limits**

\[-500MW \leq P_{14} \leq 500MW\]
\[-400MW \leq P_{23} \leq 400MW\]
\[-200MW \leq P_{35} \leq 200MW\]
\[-300MW \leq P_{45} \leq 300MW\]
\[0MW \leq P_{G1} \leq 500MW\]
\[0MW \leq P_{G2} \leq 300MW\]
Power System Model

**Power Balance**

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]
\[ 0 = -P_{L4} + P_{14} - P_{45} \]
\[ 0 = -P_{L5} + P_{34} + P_{45} \]

**Operating Limits**

\[-500MW \leq P_{14} \leq 500MW\]
\[-400MW \leq P_{23} \leq 400MW\]
\[-200MW \leq P_{35} \leq 200MW\]
\[-300MW \leq P_{45} \leq 300MW\]
\[0MW \leq P_{G1} \leq 500MW\]
\[0MW \leq P_{G2} \leq 300MW\]

**Line Power Flows**

\[ P_{14} = (\theta_1 - \theta_4) / X_{14} \]
\[ P_{23} = (\theta_2 - \theta_3) / X_{23} \]
\[ P_{35} = (\theta_3 - \theta_5) / X_{35} \]
\[ P_{45} = (\theta_4 - \theta_5) / X_{45} \]

**Operating Costs**

\[ c_{G1} = c_{01} + c_{11}P_{G1} + c_{21}(P_{G1})^2 \]
\[ c_{G2} = c_{02} + c_{12}P_{G2} + c_{22}(P_{G2})^2 \]
Classic Unit Commitment Policy

**Power Balance**

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]
\[ 0 = -P_{L4} + P_{14} - P_{45} \]
\[ 0 = -P_{L5} + P_{34} + P_{45} \]

**Line Power Flows**

\[ P_{14} = (\theta_1 - \theta_4) / X_{14} \]
\[ P_{23} = (\theta_2 - \theta_3) / X_{23} \]
\[ P_{35} = (\theta_3 - \theta_5) / X_{35} \]
\[ P_{45} = (\theta_4 - \theta_5) / X_{45} \]

**Operating Limits**

\[ -500 MW \leq P_{14} \leq 500 MW \]
\[ -400 MW \leq P_{23} \leq 400 MW \]
\[ -200 MW \leq P_{35} \leq 200 MW \]
\[ -300 MW \leq P_{45} \leq 300 MW \]
\[ 0 MW \leq P_{G1} \leq 500 MW \]
\[ 0 MW \leq P_{G2} \leq 300 MW \]

**Operating Costs**

\[ c_{G1} = c_{01} + c_{11} P_{G1} + c_{21} (P_{G1})^2 \]
\[ c_{G2} = c_{02} + c_{12} P_{G2} + c_{22} (P_{G2})^2 \]

**Optimal Operating Policy**

\[ \min \{ c_{G1} + c_{G2} \} \]

where \( P_{L3}, P_{L4}, P_{L5} \) are "known"
Unit Commitment Policy: 5 Bus Example
Unit Commitment Policy: 5 Bus Example
Unit Commitment Policy: Phase Plane Perspective

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

$P_{14}$ v. $P_{23}$

$P_{45}$ v. $P_{35}$
5 Bus Example with Wind Generation

Coal Plant

Bus 1

PG1

P14

PL4

Bus 4

PG2

P23

PL3

Bus 5

PL5

Bus 3

Wind Farm

Gas Turbine
Unit Commitment Policy with Wind Generation

**Power Balance**

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]
\[ 0 = -P_{L4} + P_{14} - P_{45} + P_W \]
\[ 0 = -P_{L5} + P_{34} + P_{45} \]

**Operating Limits**

\[-500 MW \leq P_{14} \leq 500 MW \]
\[-400 MW \leq P_{23} \leq 400 MW \]
\[-200 MW \leq P_{35} \leq 200 MW \]
\[-300 MW \leq P_{45} \leq 300 MW \]
\[0 MW \leq P_{G1} \leq 500 MW \]
\[0 MW \leq P_{G2} \leq 300 MW \]

**Line Power Flows**

\[ P_{14} = (\theta_1 - \theta_4) / X_{14} \]
\[ P_{23} = (\theta_2 - \theta_3) / X_{23} \]
\[ P_{35} = (\theta_3 - \theta_5) / X_{35} \]
\[ P_{45} = (\theta_4 - \theta_5) / X_{45} \]

**Operating Costs**

\[ c_{G1} = c_{01} + c_{11} P_{G1} + c_{21} (P_{G1})^2 \]
\[ c_{G2} = c_{02} + c_{12} P_{G2} + c_{22} (P_{G2})^2 \]

**Optimal Operating Policy**

\[ \min \{ c_{G1} + c_{G2} \} \]

where \( P_{L3}, P_{L4}, P_{L5}, P_W \) are "known"
5 Bus Example with Wind Generation
Unit Commitment Policy: with Wind Generation

- Bus 3 Load (MW)
- Bus 4 Load (MW)
- Bus 5 Load (MW)
- Wind Power (MW)

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

Transmitted Power at $P_{45}$ v. $P_{35}$

$P_{14}$ v. $P_{23}$
Unit Commitment Policy:
Without and With Wind

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)
Transmitted Power at $P_{23}$ and $P_{35}$ (MW)

$P_{45}$ v. $P_{35}$
$P_{14}$ v. $P_{23}$
Baseline Economics

The average cost of operation (taken over a 300 day simulation) is:

- $33,230/hr for the no wind case
- $18,965/hr for the wind case (wind power is assumed to be free)
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  - Without and With Wind Generation
5 Bus Example with Energy Storage

Coal Plant

Gas Turbine

Energy Storage
Network Model w/o Energy Storage

Power Balance

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]
\[ 0 = -P_{L4} + P_{14} - P_{45} \]
\[ 0 = -P_{L5} + P_{34} + P_{45} \]

Operating Limits

\(-500\, MW \leq P_{14} \leq 500\, MW\)
\(-400\, MW \leq P_{23} \leq 400\, MW\)
\(-200\, MW \leq P_{35} \leq 200\, MW\)
\(-300\, MW \leq P_{45} \leq 300\, MW\)
\(0\, MW \leq P_{G1} \leq 500\, MW\)
\(0\, MW \leq P_{G2} \leq 300\, MW\)
Network Model with Energy Storage

**Power Balance**

\[ 0 = P_{G1} - P_{14} \]
\[ 0 = P_{G2} - P_{23} \]
\[ 0 = -P_{L3} + P_{23} - P_{35} \]

\[ 0 = -P_{L5} + P_{34} + P_{45} \]

**Energy Balance**

\[ \dot{E}_4 = P_{S4} \]
\[ P_{S4} = -P_{L4} + P_{14} - P_{45} \]

**Operating Limits**

\[-500 \text{MW} \leq P_{14} \leq 500 \text{MW} \]
\[-400 \text{MW} \leq P_{23} \leq 400 \text{MW} \]
\[-200 \text{MW} \leq P_{35} \leq 200 \text{MW} \]
\[-300 \text{MW} \leq P_{45} \leq 300 \text{MW} \]
\[0 \text{MW} \leq P_{G1} \leq 500 \text{MW} \]
\[0 \text{MW} \leq P_{G2} \leq 300 \text{MW} \]

**Operating Limits**

\[0 \leq E_4 \leq E_4^{\text{max}} \]
\[P_{S4}^{\text{min}} \leq P_{S4} \leq P_{S4}^{\text{max}} \]
Network Model with Energy Storage

**Power Balance**

\[
0 = P_{G1} - P_{14} \\
0 = P_{G2} - P_{23} \\
0 = -P_{L3} + P_{23} - P_{35} \\
0 = -P_{L5} + P_{34} + P_{45}
\]

**Operating Limits**

\[-500MW \leq P_{14} \leq 500MW\]  
\[-400MW \leq P_{23} \leq 400MW\]  
\[-200MW \leq P_{35} \leq 200MW\]  
\[-300MW \leq P_{45} \leq 300MW\]  
\[0MW \leq P_{G1} \leq 500MW\]  
\[0MW \leq P_{G2} \leq 300MW\]

**Energy Balance**

\[
\dot{E}_4 = P_{S4} \\
P_{S4} = -P_{L4} + P_{14} - P_{45}
\]

**Operating Limits**

\[0 \leq E_4 \leq 3000MW \text{ hr}\]  
\[-\infty \leq P_{S4} \leq \infty\]
Unit Commitment Policy with Energy Storage

Economic Model Predictive Control

$$\min_{P_i(\tau), \theta_i(\tau)} \left\{ \int_t^{t+T} [c_{G1}(\tau) + c_{G2}(\tau)] d\tau \right\}$$

$$c_{G1}(\tau) = c_{01} + c_{11}P_{G1}(\tau) + c_{21}(P_{G1}(\tau))^2$$

$$c_{G2}(\tau) = c_{02} + c_{12}P_{G2}(\tau) + c_{22}(P_{G2}(\tau))^2$$

$$\vdots$$
Economic Model Predictive Control with 6 hour horizon

\[
\min_{P_i(\tau), \theta_i(\tau)} \left\{ \int_{t}^{t+T} \left[ c_{G1}(\tau) + c_{G2}(\tau) \right] d\tau \right\}
\]

\[0 \leq E_4 \leq 3000 MW hr\]
Economic Model Predictive Control with 6 and 24 hour horizon

Energy in Storage (MW hr) vs. time (days)

- 6 hour horizon
- 24 hour horizon

$0 \leq E_4 \leq 3000 MW hr$
Economic Model Predictive Control with 24 hour horizon

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

Transmitted Power at $P_{23}$ and $P_{35}$ (MW)

$P_{14}$ v. $P_{23}$

$P_{45}$ v. $P_{35}$

$P_{G1}, q_{G1}$

$Bus 1$

$P_{G2}, q_{G2}$

$Bus 2$

$P_{L3}, \theta_{L3}$

$Bus 4$

$P_{L5}, \theta_{L5}$

$Bus 5$

$P_{L3}, \theta_{L3}$

$Bus 3$
Phase Plane Plots with storage and without

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

$P_{14}$ v. $P_{23}$

$P_{45}$ v. $P_{35}$

Transmitted Power at $P_{23}$ and $P_{35}$ (MW)

$P_{45}$ v. $P_{35}$

$P_{14}$ v. $P_{23}$

Bus 1
$P_{G1}$, $\theta_{G1}$

Bus 2
$P_{G2}$, $\theta_{G2}$

Bus 3
$P_{L3}$, $\theta_{L3}$

Bus 4
$P_{L4}$, $\theta_{L4}$

Bus 5
$P_{L5}$, $\theta_{L5}$

Bus 6
$P_{L6}$, $\theta_{L6}$
Economics with No Wind Generation

The average cost of operation (taken over a 300 day simulation) is:

- $33,230/hr for the no storage case
- $32,604/hr for the storage case
- A reduction of 1.9%
5 Bus Example with Wind Generation and Energy Storage

Coal Plant

Gas Turbine

Wind Farm

Energy Storage
Economic Model Predictive Control with 24 hour horizon

\[ 0 \leq E_4 \leq 3000 \text{MW hr} \]
Economic Model Predictive Control with 24 and 72 hour horizon

\[ 0 \leq E_4 \leq 3000 MW \text{ hr} \]
Economic Model Predictive Control with 72 hour horizon

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

Transmitted Power at $P_{23}$ and $P_{35}$ (MW)

$P_{45}$ v. $P_{35}$

$P_{14}$ v. $P_{23}$

Bus 1

$P_{14}$

Bus 2

$P_{45}$

Bus 3

$P_{35}$

Bus 4

$P_{L4}$, $\theta_{L4}$

Bus 5

$P_{L5}$, $\theta_{L5}$

Bus 1

$P_{G1}$, $\theta_{G1}$

Bus 2

$P_{G2}$, $\theta_{G2}$
Phase Plane Plots with storage and without

Transmitted Power at $P_{14}$ and $P_{45}$ (MW)

Transmitted Power at $P_{23}$ and $P_{35}$ (MW)

$P_{45}$ v. $P_{35}$

$P_{14}$ v. $P_{23}$
Economics with Wind Generation

The average cost of operation (taken over a 300 day simulation) is:

- $18,965/hr for the no storage case
- $12,126/hr for the storage case
- A reduction of 36%
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AIChE Workshop on Smart Grid for the Chemical Process Industry
September 25-27, 2013 - Chicago

Will explore the opportunities and challenges associated with demand response in the chemical process industry.

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https://www.aiche.org/conferences/workshop-on-smart-grid-chemical-process-industry/2013
AIChE Workshop on Smart Grid for the Chemical Process Industry
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Confirmed Speakers

- Large Industrials and Demand Response in the United States
  David Heitzer, EDF Energy Services

- Economic Dispatch of a Combined Heat and Power Plant
  Jong S. Kim and Thomas F. Edgar, University of Texas at Austin

- Flexible and Efficient Operation for Power Generation and Process Industry – A GE Perspective
  Aditya Kumar, GE Global Research

- A Distributed Control Framework for Smart Grid Development
  Jinfeng Liu, University of Alberta and Panagiotis D. Christofides, University of California, Los Angeles

- Supply Driven-Operation of Processes
  Alexander Mitsos, Ganzhou Wang and Wolfgang Marquardt, RWTH Aachen University; Amin Ghobeity and Chris Williams, Massachusetts Institute of Technology

- Use of Low Cost Electrical Power in Petrochemical Process Units
  Dennis O’Brien, Jacobs Consultancy and Donald J. Chmielewski, Illinois Institute of Technology

- Active participation of Industry in the Smart Grid
  Ernst Scholtz, Xiaoming Feng, and Iiro Harjunkoski, ABB Corporate Research

- Assessing the Benefits of Stochastic Market Clearing
  Victor M. Zavala, Argonne National Laboratory

- Multiscale Optimization for Demand Side Management of Industrial Power-intensive Processes
  Qi Zhang Ignacio Grossmann, Carnegie Mellon University
Conclusions

• Renewable sources increase variability at generators
• Storage reduces variability at generators
• Value of storage postulated as generator cost reductions due to lower variability
• For the given example
  - $0.2/hr per MW hr for no wind case
  - $2.3/hr per MW hr for wind case