PROCESS SYSTEMS OPPORTUNITIES
IN POWER GENERATION,
STORAGE AND DISTRIBUTION

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Reliability and Dispatch

Nuclear

Coal Fired

Gas Turbine

Transmission and Distribution

Demand
Impact of Renewable Sources

Nuclear  Coal Fired  Gas Turbine

Transmission and Distribution

Renewable

Demand

Power (MW)

Time (days)
Impact of Energy Storage

Nuclear  Coal Fired  Gas Turbine

Transmission and Distribution

Storage

Renewable

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Presentation Outline

- Nuclear
- Coal Fired
- Gas Turbine
- Transmission and Distribution
- Storage
- Renewable
- Demand
Exploration of a New World
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(Chmielewski)

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Control in Transmission and Distribution

- **Power Management Level**
  - Voltage Control
  - Frequency Control
  - Transmission Network

- **Energy Management Level**
  - Unit Commitments
  - Day-ahead and Hour-ahead
  - Optimal Power Flow

- **Expansion Planning Level**
  - Equipment Commissioning / De-commissioning
  - Maintenance Scheduling

- **Horizon**
  - Decades
  - Months-Years
  - Days-Hours
  - Minutes
  - Seconds
Control in Transmission and Distribution

Figure 19.1 The five levels of process control and optimization in manufacturing. Time scales are shown for each level.
Power Networks
Power Networks: 54 and 118 Bus Examples
Load Flow Analysis

Provides the underlying model for a transmission network
Load Flow Analysis
(current and voltage)

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:

\[
Y = \begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3 \\
Y_4 \\
Y_5
\end{bmatrix}
\]

Voltage-current relation:  \[ I = YE \]
Load Flow Analysis
(injected power)

Power injected at bus \( k \):

\[
\Rightarrow S_k = E_k I_k^*
\]

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

* is complex conjugate

Complex power at bus \( k \):

\[
S_k = P_k + jQ_k
\]

Voltage in phasor form:

\[
E_k = U_k e^{j\theta_k}
\]
Load Flow Analysis
(Degrees of Freedom)

Four variables at each bus $k$:

\[ P_k, Q_k, U_k \text{ and } \theta_k \]

Two equations at each bus $k$:

\[ P_k = \Re \{ E_k Y_k^* E^* \} \]
\[ Q_k = \Im \{ E_k Y_k^* E^* \} \]

If $N$ buses, then $4N$ variables and $2N$ equations.

$\Rightarrow 2N$ variables must be specified (generally 2 per bus)
Load Flow Analysis
(Bus Types)

Source Buses:
- Bus 1
  - \( P_1 \), \( Q_1 \), \( \theta_1 \), \( U_1 \)

Load Buses:
- Bus 5
  - \( P_5 \), \( Q_5 \), \( \theta_5 \), \( U_5 \)

Slack Bus:
- Bus 2
  - \( P_2 \), \( Q_2 \), \( \theta_2 \), \( U_2 \)

- Bus 3
  - \( P_3 \), \( Q_3 \), \( \theta_3 \), \( U_3 \)

Bus 4
  - \( P_4 \), \( Q_4 \), \( \theta_4 \), \( U_4 \)
Why Load Flow Analysis?

System operator must select generator states (mechanical power input and field coil voltages) 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: \( P_{km} \leq P_{km}^{\text{max}} \)

\[
P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m)
\]
Transmission Control Hierarchy

- Power Management Level
- Frequency Control
- Transmission Network

Horizon
Seconds
Frequency Control
Frequency Control

- **Servo-loop at each generator**
- **Control Variable:** System frequency
- **Manipulated Variable:** Mechanical power
- **Disturbance:** Load power
Transmission Control Hierarchy

- Power Management Level
  - Voltage Control
  - Frequency Control

Transmission Network

- Horizon
- Seconds
Voltage Control

Voltage Control-Loop?
Load Flow Analysis
(Voltage Magnitude and Reactive Power Flow)

Coupling between $Q_k$ and $U_k$:

$$Q_{km} = \frac{U_k^2 - U_k U_m}{X_{km}} \cos(\theta_k - \theta_m) \Rightarrow Q_{km} \propto (U_k - U_m)$$

Reactive power, $Q_k$, required for voltage, $U_k$, support
Power from a Generator
Power from a Generator

- Reactive Power into System
- Overexcitation (+MVAr)
- Rotor Winding Limited
- Normal Overexcited Operation
- Stator Winding Limited
- Underexcited Operation

- Reactive Power into Generator
- Steady State Liability Limit
- Underexcited (-MVAr)

$Q_k$ and $P_k$ represent the power components.
Transmission lines consume $Q_k$

So, it is good idea to produce $Q_k$ locally
(using capacitors and reactors)
Reactive Power Sources
Reactive Power from a Reactor

\[ Q_k \]

\[ P_k \]
Voltage Control

- Servo-loop at each reactive generator
- Control Variable: Voltage magnitude
- Manipulated Variable: Reactive power
- Disturbances: Reactive load and losses
Transmission Control Hierarchy

Power Management Level

Optimal Power Flow

Voltage Control

Frequency Control

Transmission Network

Minutes

Seconds

Horizon
Optimal Power Flow

• System wide perspective

• Sends dispatch commands to generators

• Uses explicit load flow calculations

• Optimizes with respect to
  - operating cost
  - transmission losses
  - active and reactive reserves
  - N-1 security
Generator Operating Costs

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

- $110/MWhr
- $65/MWhr

![Diagram showing power output vs. operating cost for Coal Plant and Gas Turbine.]
State Estimation for Optimal Power Flow

- Real-time measurements of network conditions
- Load Flow Model must be observed
- Sensor errors likely and sensor faults possible

Mathematically the same as Steady-State Nonlinear Data Reconciliation and Gross Error Detection used in the CPI
Transmission Control Hierarchy

Horizon
- Months-Years
- Days-Hours
- Minutes
- Seconds

Energy Management Level

Power Management Level

Maintenance Scheduling

Unit Commitments
- Day-ahead and Hour-ahead

Optimal Power Flow

Voltage Control

Frequency Control

Transmission Network
Unit Commitment Question

Gas Turbines

Coal Fired

Nuclear

Demand

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Gas Turbines

Coal Fired

Nuclear

Demand

Unit Commitment Question

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Unit Commitment Problem

Under Regulation (single operator)

• Similar to Optimal Power Flow

• Explicit Load Flow Analysis

• Larger horizon (day-ahead and hour-ahead)

• Optimizes with respect to
  - costs, losses, reserves, $N$-1 security (same as OPF)
  - Integer variables for unit start-up and shut-down
  - Slow start-up units (Nuclear and Coal) in day-ahead policy
  - Fast start-up units (Gas Turbines) in hour-ahead policy
Unit Commitment Problem

Under Deregulation (multiple operators)

- Auction based rather than centralized decisions
- Managed by an Independent System Operator (ISO)
- Many types of auction schemes
  1. Pay as bid (if accepted)
  2. Pay as highest accepted bid (if accepted)
- Many think option 2 gives policy similar to centralized optimization based policy
Transmission Control Hierarchy

Expansion Planning Level

Energy Management Level

Power Management Level

Equipment Commissioning / De-commissioning

Maintenance Scheduling

Unit Commitments Day-ahead and Hour-ahead

Optimal Power Flow

Voltage Control

Frequency Control

Transmission Network

Horizon
Decades
Months-Years
Days-Hours
Minutes
Seconds

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Load Flow Analysis
(Active Power Flow and Voltage Angle)

DC – Approximation:

\[ U_k \approx 1 \text{ p.u.} \quad Q_{km} \approx 0 \]

\[ P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m) \quad \Rightarrow \quad P_{km} \approx \frac{1}{X_{km}} (\theta_k - \theta_m) \]
PSE Opportunities

- Expansion Planning
- Maintenance Scheduling
- Unit Commitments
- Optimal Power Flow
- Voltage Control
- Frequency Control
- Transmission Network

Day-ahead and Hour-ahead Maintenance Scheduling

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PSE Opportunities

- Expansion Planning
- Maintenance Scheduling
- Unit Commitments
  - Day-ahead and Hour-ahead
- Optimal Power Flow
- Voltage Control
- Frequency Control
- Transmission Network

Similar to PI – MPC Relationship
PSE Opportunities

Similar to MINLP
Process Synthesis

Expansion Planning

Maintenance Scheduling

Unit Commitments
Day-ahead and Hour-ahead

Optimal Power Flow

Voltage Control

Frequency Control

Transmission Network
PSE Opportunities

Similar to Process Scheduling and Opportunities for Demand Response with Flexible Manufacturing
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