Tutorial Overview:

Modeling and Control of Power Transmission Networks

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Overview of Smart Grid

Conventional Generation

Renewable Generation

Transmission

Energy Storage

Consumer Demand

Smart Homes

Smart Buildings

Smart Manufacturing
Overview of Smart Grid

- Conventional Generation
- Renewable Generation
- Energy Storage
- Transmission
- Consumer Demand
- Smart Homes
- Smart Buildings
- Smart Manufacturing
Presentation Outline

- Load Flow Modeling
- Control System Hierarchy
  - Servo Level
  - Predictive Level
  - Planning Level
- De-regulation and Real-time Prices
Some Example Transmission Networks

15 – Bus Network

6 – Bus Network
Some Larger Examples

54 – Bus Network

118 – Bus Network
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

Voltage in phasor form:

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

Complex power at bus $k$:

\[
S_k = P_k + jQ_k
\]

Active Power: $P_k$

Reactive Power $Q_k$
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
P₁ Q₁ θ₁ U₁
Bus 4
P₄ Q₄ θ₄ U₄
Bus 5
P₅ Q₅ θ₅ U₅
Load Buses

Slack Bus
Bus 2
P₂ Q₂ θ₂ U₂
Bus 3
P₃ Q₃ θ₃, U₃
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:

\[
P_{km} \leq P_{km}^{\text{max}}
\]

\[
P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m)
\]
Presentation Outline

- Load Flow Modeling
- Control System Hierarchy
  - Servo Level
  - Predictive Level
  - Planning Level
- De-regulation and Real-time Prices
Control System Hierarchy for Chemical Processes

1. Measurement and actuation
   - (< 1 second)
   - Sensor and actuator validation, limit checking

2. Safety, environmental/equipment protection
   - (< 1 second)
   - Alarm management, emergency shutdown

3a. Regulatory control
   - (seconds-hours)
   - PID control, advanced control techniques, control loop performance monitoring

3b. Multivariable and constraint control
   - (minutes-hours)
   - Multivariable control, model predictive control

4. Real-Time optimization
   - (hours-days)
   - Plant-wide and individual unit real-time optimization, parameter estimation, supervisory control, data reconciliation

5. Planning and scheduling
   - (days-months)
   - Demand forecasting, supply chain management, raw materials and product planning/scheduling

Figure 19.1 The five levels of process control and optimization in manufacturing. Time scales are shown for each level.
Control System Hierarchy for Transmission Networks

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

- **Energy Management Level**
  - Maintenance Scheduling
  - Unit Commitments
    - Day-ahead and Hour-ahead

- **Power Management Level**
  - Optimal Power Flow
  - Voltage Control
  - Frequency Control

- **Transmission Network**

**Horizon**
- Decades
- Months-Years
- Days-Hours
- Minutes
- Seconds
Control System Hierarchy for Transmission Networks

- Power Management Level
- Frequency Control
- Transmission Network

Horizon: Seconds
Frequency Control

Bus 1

Bus 2

Bus 3

Bus 4

Bus 5

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

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

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

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

$P_5$, $Q_5$, $\theta_5$, $U_5$
Frequency Control

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

- **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 Reactive Power - $Q_k$
and Voltage Magnitude - $U_k$:

Reactive Power provides Voltage support

Transmission lines consume $Q_k$

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

Diagram showing a generator with labeled components and axes for $P_k$ and $Q_k$. The diagram illustrates various operational limits such as reactive power into system, overexcitation, rotor winding limited, stator winding limited, underexcitation limiter, and steady state liability limit.
Reactive Power Sources
Reactive Power from a Reactor

- Reactive Power into System
- Overexcited (+MVAr)
- Overexcitation Limiter
- Rotor Winding Limited
- Normal Overexcited Operation
- Underexcited (-MVAr)
- Underexcitation Limiter
- Stator Winding Limited
- Undervolted Operation
- Reactive Power into Generator
- Stator End Iron Limited
- Steady State Liability Limit
- Real Power into System

$Q_k$ and $P_k$
Voltage Control

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

- **Power Management Level**
  - Voltage Control
  - Frequency Control
  - Optimal Power Flow

- **Transmission Network**

- **Horizon**:
  - Minutes
  - Seconds
Optimal Power Flow

- System wide perspective
- Sends dispatch commands to generators
- Uses explicit load flow calculations
- Optimizes with respect to:
  - operating cost
  - transmission line losses
  - active and reactive reserves
  - $N$-1 security
Generator Operating Costs

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

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

- \$110/MWhr
- \$65/MWhr

Operating Cost ($1000/hr) vs. Power Output (MW)
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
Control System Hierarchy for Transmission Networks

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

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

Energy Management Level
Power Management Level
Unit Commitment Question

Gas Turbines

Coal Fired

Nuclear

Demand
Unit Commitment with Small Demand

Gas Turbines

Coal Fired

Nuclear

Demand
Unit Commitment with Large Demand

Gas Turbines
Coal Fired
Nuclear

Demand

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Unit Commitment Problem

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
Maintenance Scheduling

Gas Turbines

Coal Fired

Nuclear

Demand

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Control System Hierarchy for Transmission Networks

- **Transmission Network**
  - **Optimal Power Flow**
    - **Unit Commitments**
      - **Day-ahead and Hour-ahead**
    - **Maintenance Scheduling**
      - **Equipment Commissioning / De-commissioning**
  - **Voltage Control**
  - **Frequency Control**

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

**Expansion Planning Level**

**Energy Management Level**

**Power Management Level**
Expansion Planning

- Bus 1: $P_1 Q_1 \theta_1 U_1$
- Bus 2: $P_2 Q_2 \theta_2 U_2$
- Bus 3: $P_3 Q_3 \theta_3 U_3$
- Bus 4: $P_4 Q_4 \theta_4 U_4$
- Bus 5: $P_5 Q_5 \theta_5 U_5$
Load Flow Analysis
(Active Power Flow and Voltage Angle)

DC – Approximation:

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

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

• Load Flow Modeling

• Control System Hierarchy
  - Servo Level
  - Predictive Level
  - Planning Level

• De-regulation and Real-time Prices
Generators Owned by Merchant Producers

- Gas Turbines
- Coal Fired
- Nuclear

Demand
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
Role of the Load-Serving Entity

Gas Turbines

Coal Fired

Nuclear

ISO

LSE

LSE

LSE

Consumers

Consumers

Consumers
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