Lecture 3
Intelligent Energy Systems:
Control and Monitoring Basics

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Traditional Grid

• Worlds Largest Machine!
  – 3300 utilities
  – 15,000 generators, 14,000 TX substations
  – 211,000 mi of HV lines (>230kV)

• A variety of interacting control systems
Smart Energy Grid

Intelligent Energy Network

Source IPS

Load IPS

Intelligent Power Switch

Energy subnet

Conventional Electric Grid

Conventional Internet

Generation

Transmission

Distribution

Load

Smart Energy System
Intelligent Energy Applications

Computer

Tablet

Smartphone

Communications

Energy Application

Presentation Layer

Application Logic
(Intelligent Functions)

Database
Control Function

• Control function in a systems perspective
Analysis of Control Function

- Control analysis perspective
- Goal: verification of control logic
  - Simulation of the closed-loop behavior
  - Theoretical analysis
Key Control Methods

- Control Methods
  - Design patterns
  - Analysis templates
- P (proportional) control
- I (integral) control
- Switching control
- Optimization
- Cascaded control design
Generation Frequency Control

- Example

  control command
  
  Controller
  
  sensor measurements
  
  Turbine /Generator
  
  disturbance
  
  Load
Generation Frequency Control

- Simplified classic grid frequency control model
  - Dynamics and Control of Electric Power Systems, G. Andersson, ETH Zurich, 2010
    http://www.eeh.ee.ethz.ch/en/eeh/education/courses/viewcourse/227-0528-00l.html

Swing equation: \[ I \omega \Delta \dot{\omega} = \Delta P_m - \Delta P_e \]

\[ \dot{x} = u + d \]

\[ \Delta \dot{\omega} = \dot{x} \]

\[ \frac{\Delta P_m}{I \omega} = u \]

\[ -\frac{\Delta P_e}{I \omega} = d \]
P-control

- P (proportional) feedback control
  \[ u = -k_P x \]

- Closed-loop dynamics
  \[ \dot{x} = -k_P x + d \]

- Steady state error
  \[ x_s = \frac{d_s}{k_P} \]

frequency droop
AGC Control Example

- AGC = Automated Generation Control
- AGC frequency control

Diagram:
- Generation command
- Frequency measurement
- Disturbance
- Load

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AGC Frequency Control

• Frequency control model
  \[ x = g \cdot u + c \cdot l, \]
  – \( x \) is frequency error
  – \( c_l \) is frequency droop for load \( l \)
  – \( u \) is the generation command

• Control logic
  \[ \dot{u} = -k_I x \]
  – I (integral) feedback control

• This is simplified analysis
P and I control

• P control of an integrator

\[ u = -k_p x \]
\[ \dot{x} = bu + d \]

\[ \quad \]

• I control of a gain system. The same feedback loop

\[ \dot{u} = -k_1 x \]
\[ x = g \cdot u + c \cdot l, \]
Cascade (Nested) Loops

- Inner loop has faster time scale than outer loop
- In the outer loop time scale, consider the inner loop as a gain system that follows its setpoint input

Diagram:
- Outer loop setpoint (command)
- Inner loop setpoint
- Outer Loop Control
- Inner Loop Control
- Plant
- Output
Switching (On-Off) Control

- State machine model
  - Hides the continuous-time dynamics
  - Continuous-time conditions for switching
- Simulation analysis
  - Stateflow by Mathworks

\[ x = 70 \]

setpoint

\[ x = 69 \]

\[ x = 71 \]

\[ x = 72 \]

passive cooling

furnace heating

cooling heating setpoint
Optimization-based Control

- Is used in many energy applications, e.g., EMS
- Typically, LP or QP problem is solved
  - Embedded logic: at each step get new data and compute new solution

![Diagram of optimization-based control system]

- Measured Data → Optimization Problem Formulation → Embedded Optimizer Solver → Control Variables
- Sensors → Plant → Actuators
Cascade (Hierarchical) Control

• Hierarchical decomposition
  – Cascade loop design
  – Time scale separation
Hierarchical Control Examples

• Frequency control
  – I (AGC) → P (Generator)
• ADR – Automated Demand Response
  – Optimization → Switching
• Energy flow control in EMS
  – Optimization → PI
• Building control:
  – PI → Switching
  – Optimization
Power Generation Time Scales

- Power generation and distribution
- Energy supply side

Power Supply Scheduling

Tie Line Power and Frequency Control

Turbine Control

Voltage Control

Protection

1/10 1 10 100 1000  Time (s)

http://www.eeh.ee.ethz.ch/en/eeh/education/courses/viewcourse/227-0528-00l.html
Power Demand Time Scales

• Power consumption
  – DR, Homes, Buildings, Plants

• Demand side

- Demand Response
  - Home Thermostat
  - Building HVAC
  - Enterprise Demand Scheduling
Research Topics: Control

• Potential topics for the term paper.
  • Distribution system control and optimization
    – Voltage and frequency stability
    – Distributed control for Distributed Generation
    – Distribution Management System: energy optimization, DR
Monitoring & Decision Support

- Open-loop functions
  - Data presentation to a user
Monitoring Goals

• Situational awareness
  – Anomaly detection
  – State estimation

• Health management
  – Fault isolation
  – Condition based maintenances
Condition Based Maintenance

- CBM+ Initiative

65-80% of the Life-Cycle Cost

Operations & Support

Pre-Systems Acquisition

Systems Acquisition

Systems Sustainment

RDT&E Funds

Procurement Funds

Operations & Maintenance Funds
SPC: Shewhart Control Chart

- W. Shewhart, Bell Labs, 1924
- Statistical Process Control (SPC)
- UCL = mean + 3·σ
- LCL = mean - 3·σ
Multivariable SPC

- Two correlated univariate processes \( y_1(t) \) and \( y_2(t) \)
  \[
  \text{cov}(y_1, y_2) = Q, \quad Q^{-1} = LL^T
  \]
- Uncorrelated linear combinations
  \[
  z(t) = L \cdot [y(t) - \mu] \quad \mu = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}
  \]
  \[
  |z|^2 = (y - \mu)^T Q^{-1} (y - \mu) \sim \chi^2_2
  \]
- Declare fault (anomaly) if
  \[
  (y - \mu)^T Q^{-1} (y - \mu) > c^2
  \]
Multivariate SPC - Hotelling's $T^2$

- Empirical parameter estimates

$$\hat{\mu} = \frac{1}{n} \sum_{t=1}^{n} y(t) \approx E(X)$$

$$\hat{Q} = \frac{1}{n} \sum_{t=1}^{n} (y(t) - \mu)(y^T(t) - \mu^T) \approx \text{cov}(y - \mu)$$

- Hotelling's $T^2$ statistics is

$$T^2 = (y(t) - \mu)^T \hat{Q}^{-1} (y(t) - \mu)$$

- $T^2$ can be trended as a univariate SPC variable
Advanced Monitoring Methods

• Estimation is dual to control
  – SPC is a counterpart of switching control
• Predictive estimation – forecasting, prognostics
  – Feedback update of estimates (P feedback → EWMA)
• Cascaded design
  – Hierarchy of monitoring loops at different time scales
• Optimization-based methods
  – Optimal estimation
Research Topics: Monitoring

- Potential topics for the term paper.
- Asset monitoring
  - Transformers
- Electric power circuit state monitoring
  - Using phasor measurements
  - Next chart
Electric Power Circuit Monitoring

\[ 0 = Ax + Bf + w \]
\[ y = Cx + Df + v \]

Optimization Problem

Electric Power System

Measurements:
- Currents
- Voltages
- Breakers, relays

State estimate
- Fault isolation

ACC, 2009

Intelligent Energy Systems
End of Lecture 3