Lecture 3
Intelligent Energy Systems: Control and Monitoring Basics

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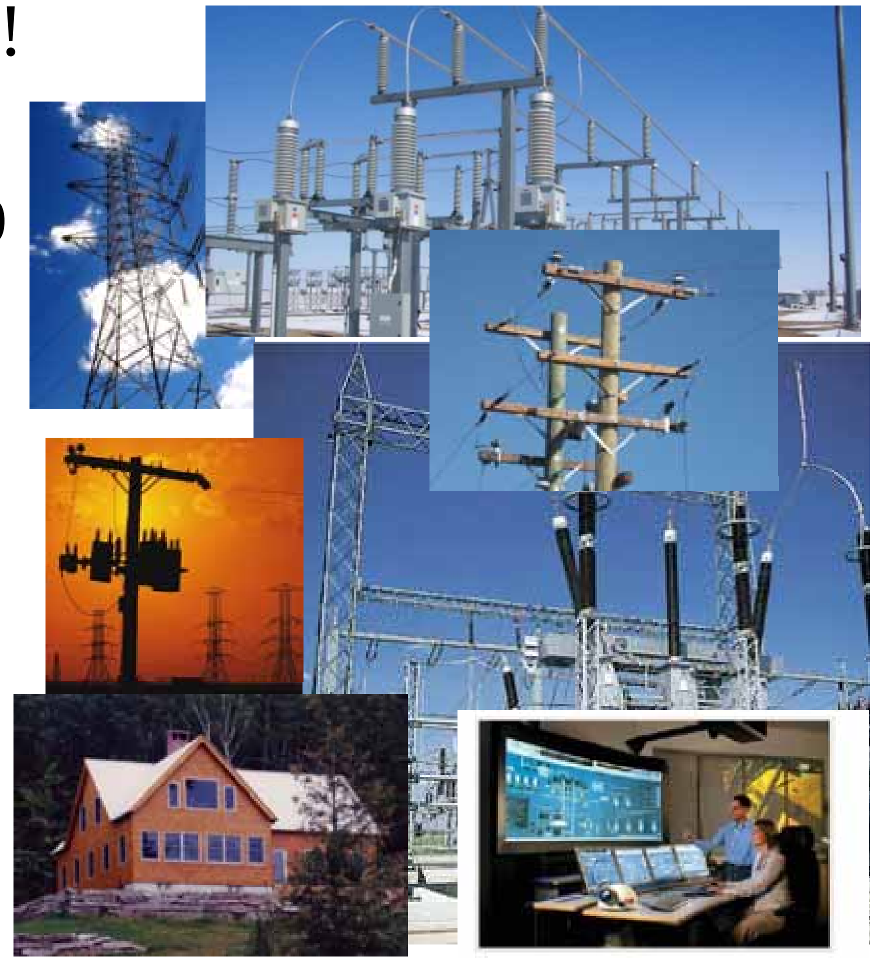
Traditional Grid

- 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



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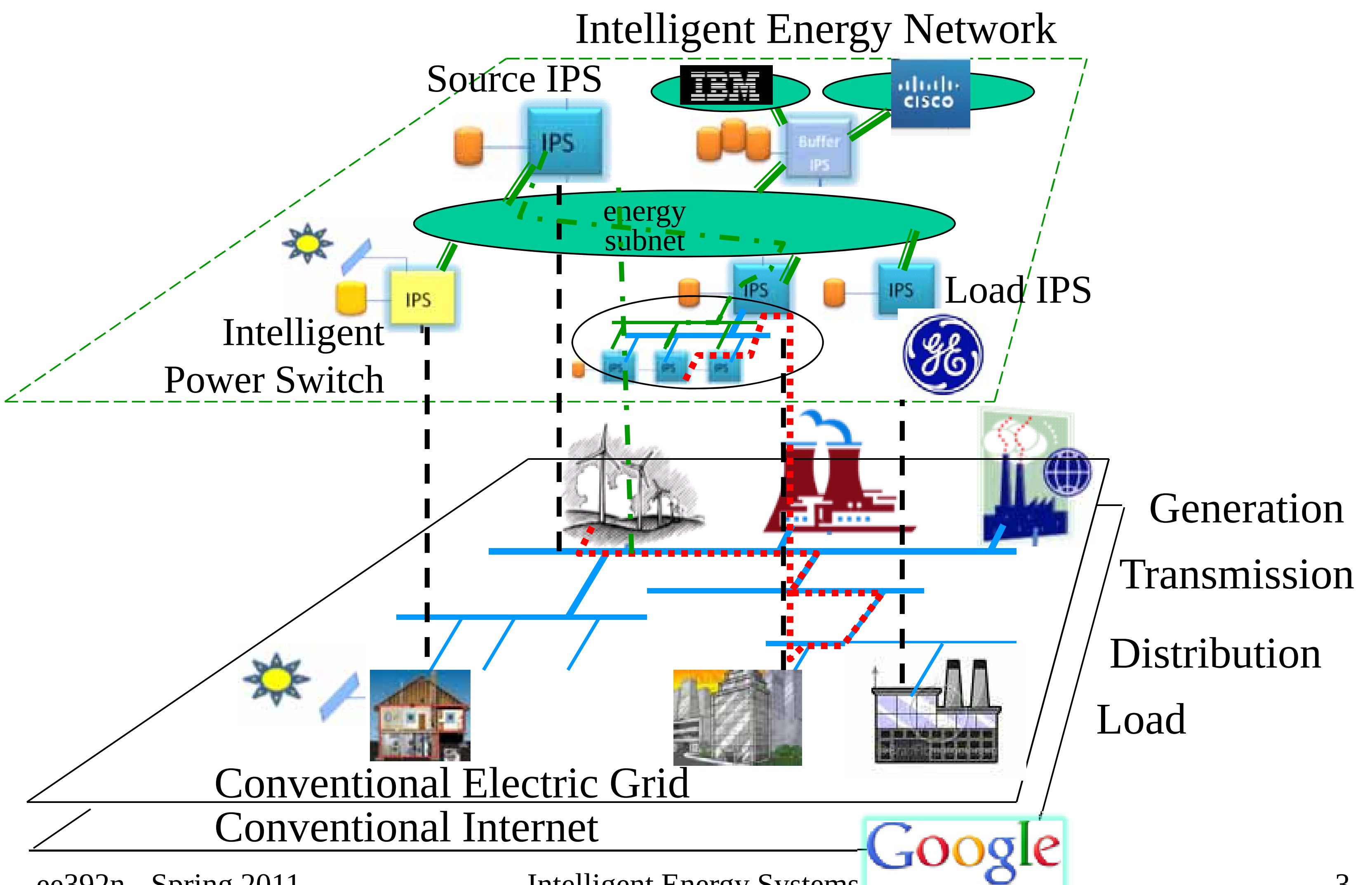
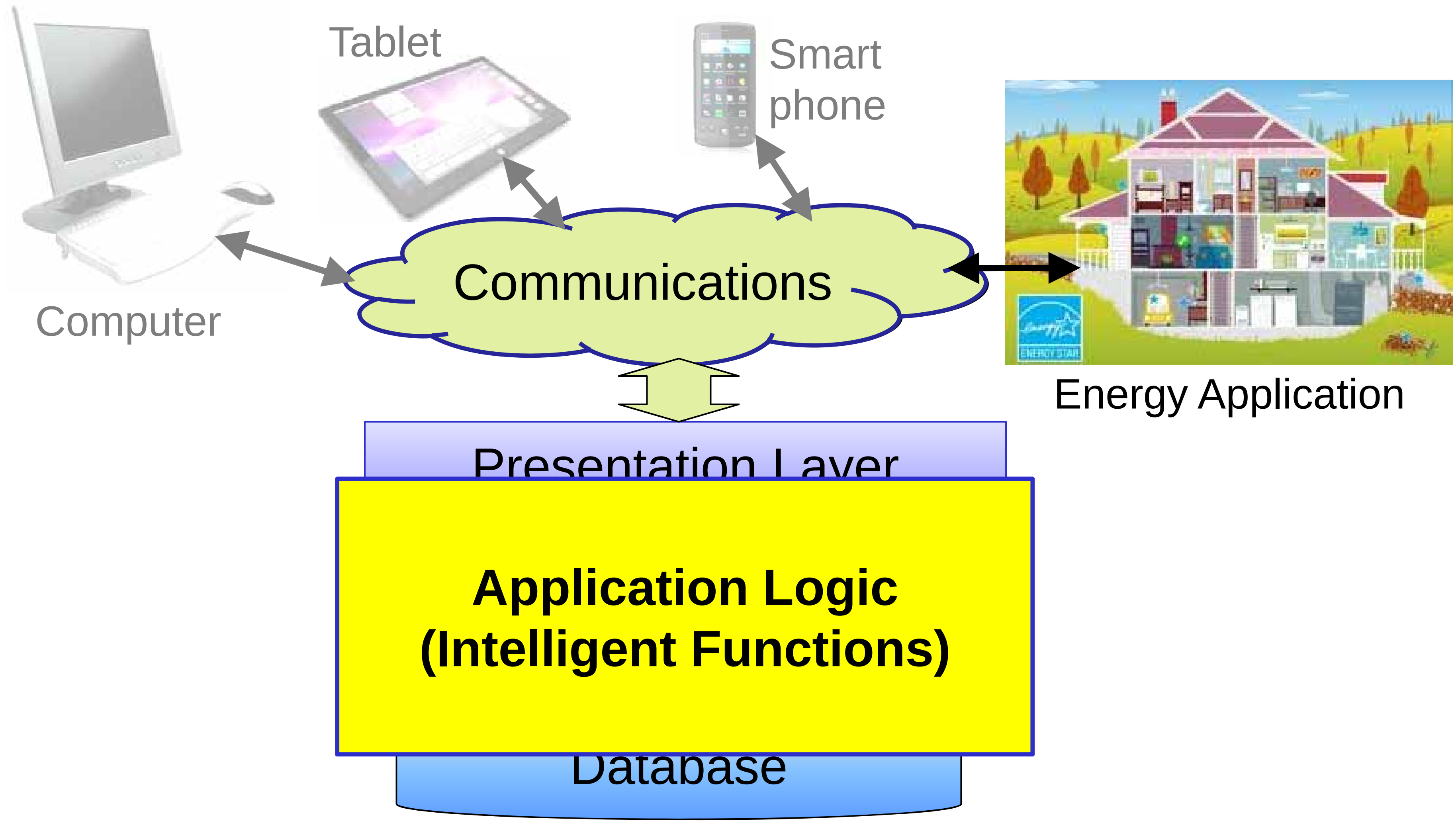
Smart Energy Grid

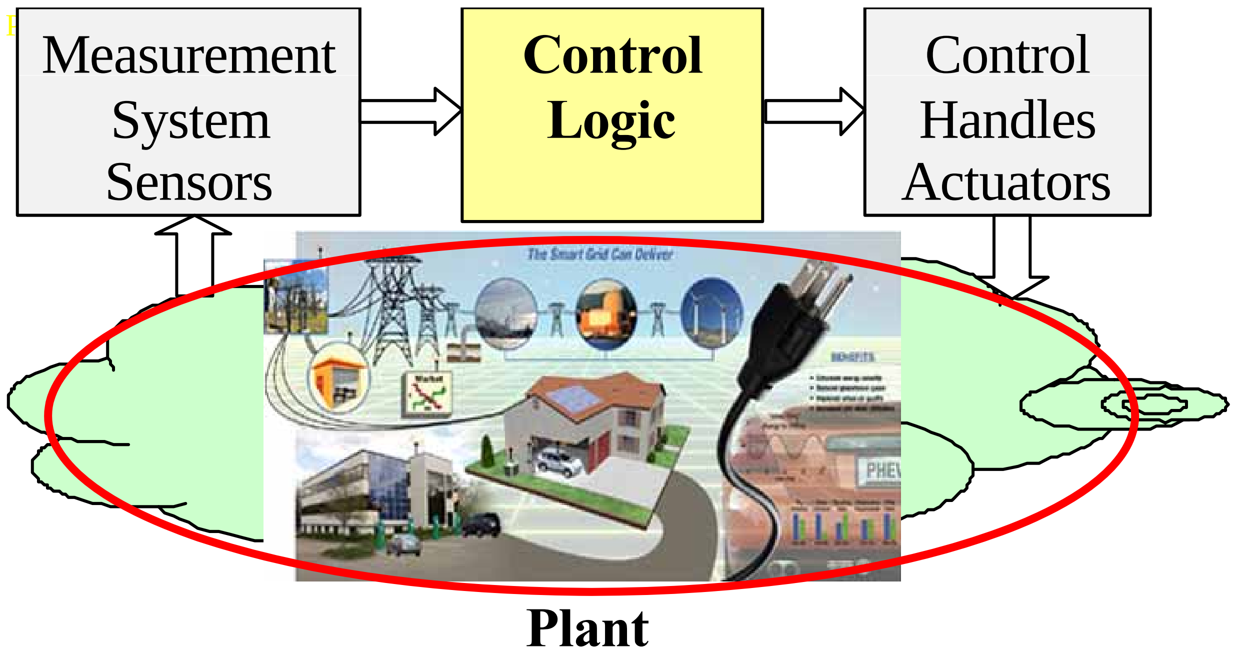


Intelligent Energy Applications



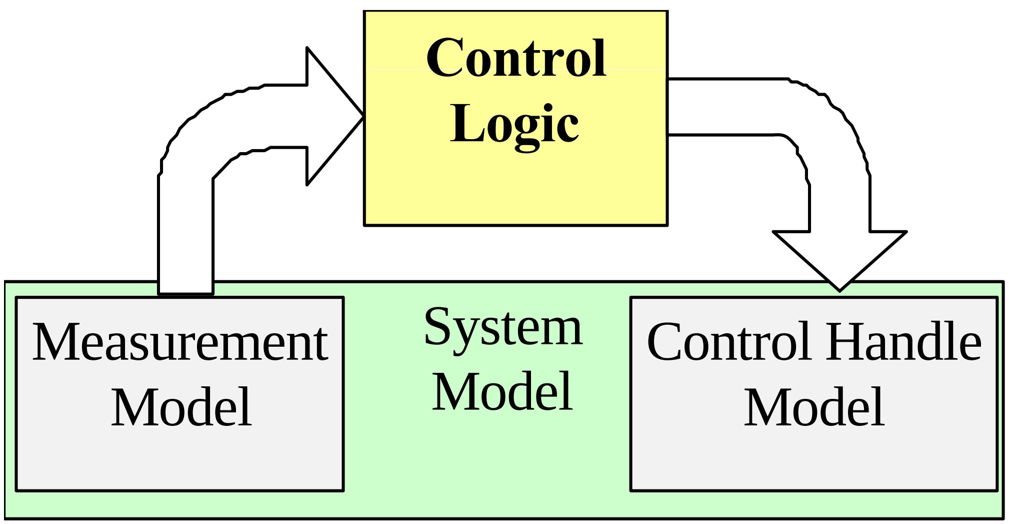
Control Function

- 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

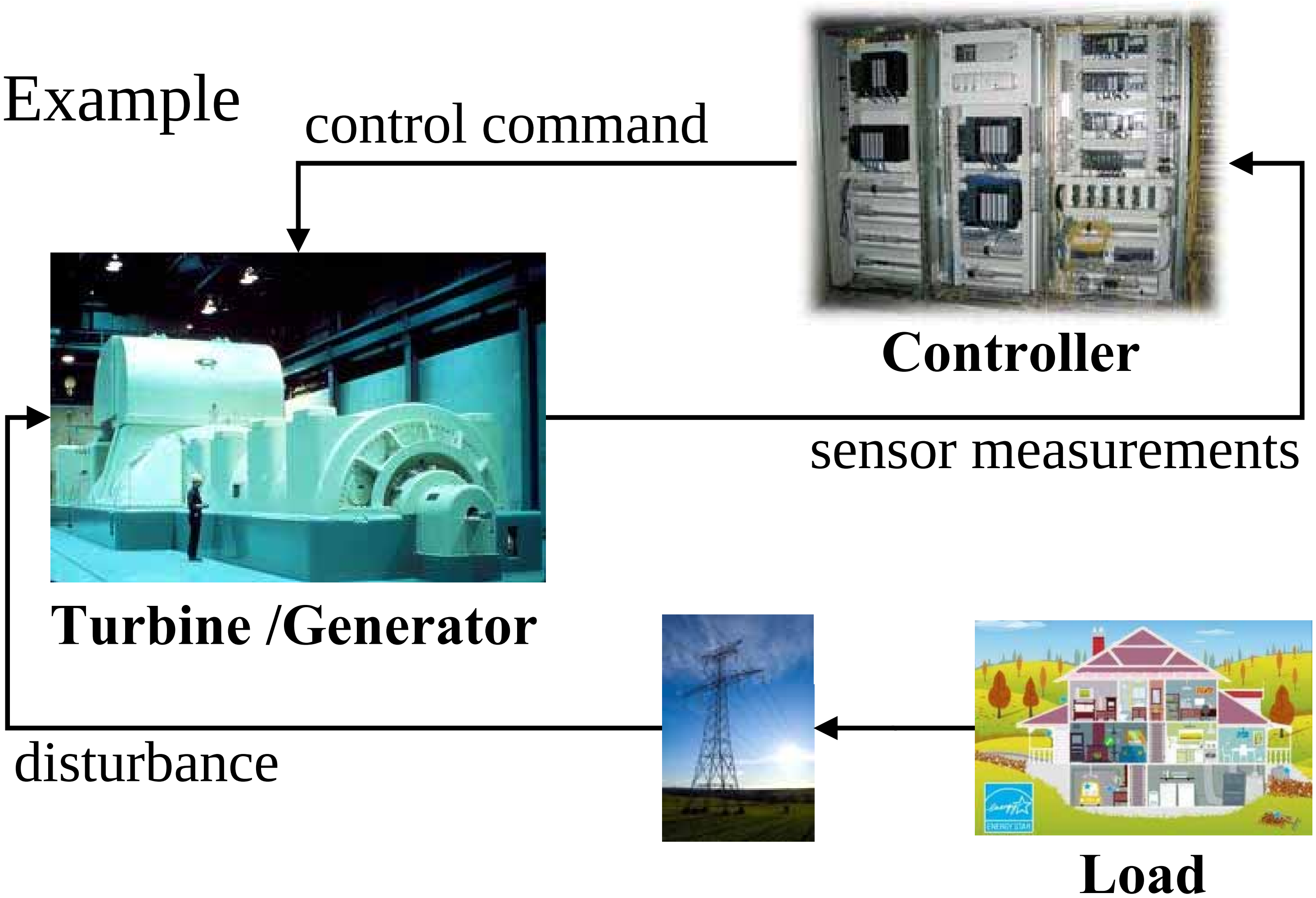


Key Control Methods

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

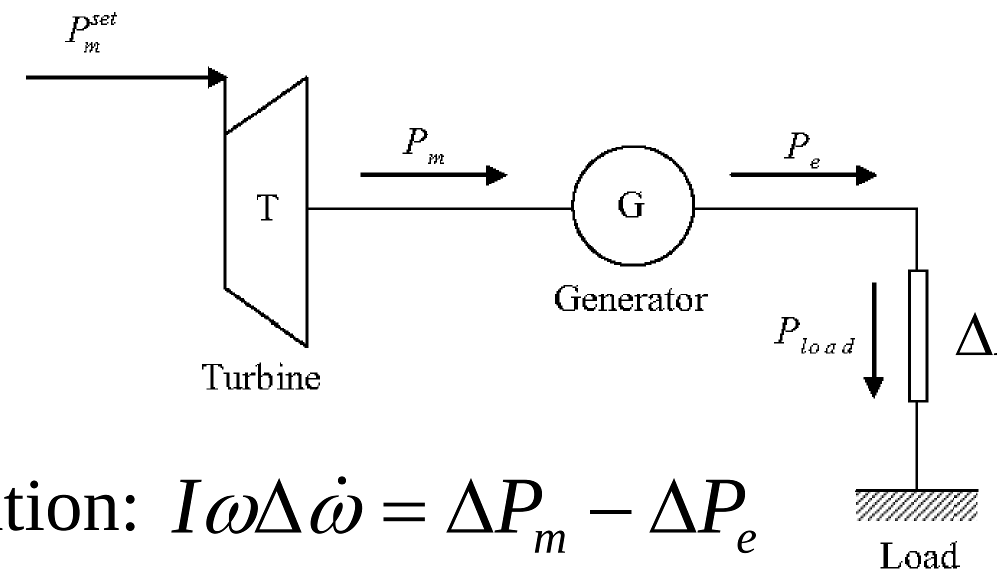
Generation Frequency Control

- Example



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



$$\Delta P_e = \Delta P_{load}$$

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

$$\dot{x} = u + d$$

$$\Delta\dot{\omega} = \dot{x}$$

$$\Delta P_m / I\omega = u$$

$$-\Delta P_e / I\omega = d$$

P-control

- P (proportional) feedback control

$$u = -k_P x$$

$$\dot{x} = u + d$$

- Closed –loop dynamics

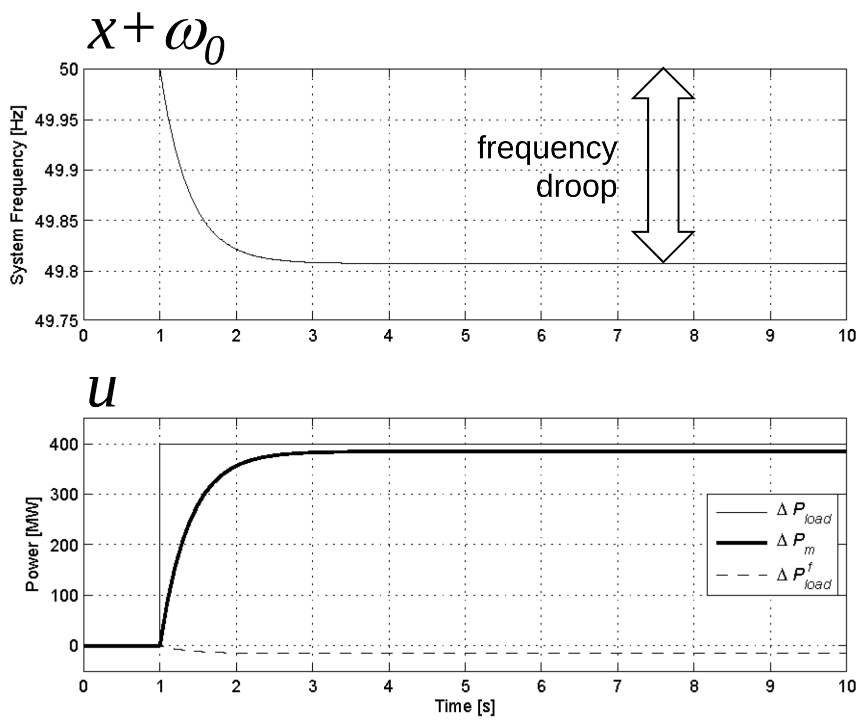
$$\dot{x} = -k_p x + d$$

$$x = x_0 e^{-k_p t} + \frac{1}{k_p} d(1 - e^{-k_p t})$$

- Steady state error

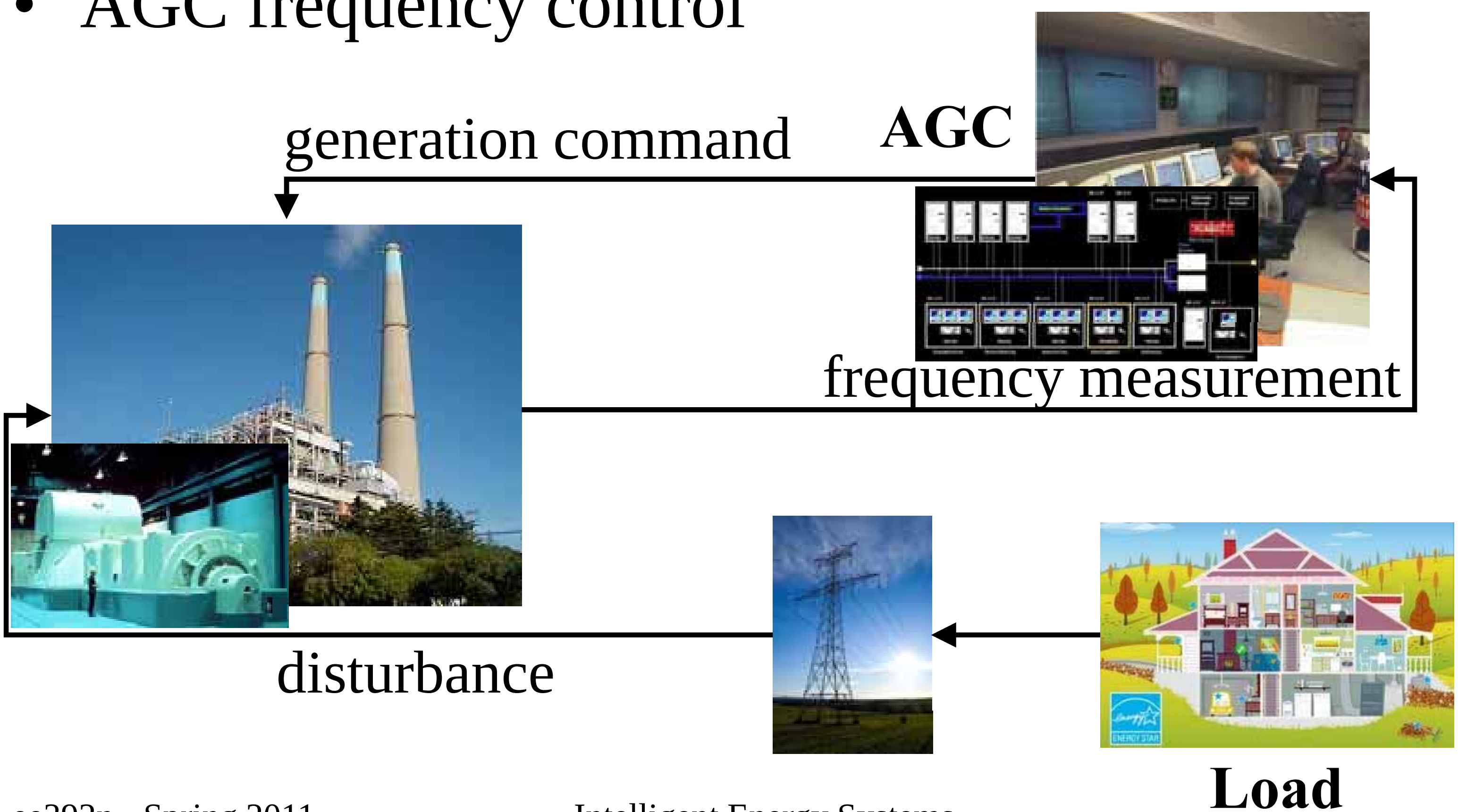
$$x_s = d_s / k_p$$

frequency droop



AGC Control Example

- AGC = Automated Generation Control
- AGC frequency control



AGC Frequency Control

- Frequency control model

  $$x = g \cdot u + c \cdot l,$$

  – x is frequency error

  – cl is frequency droop for load l

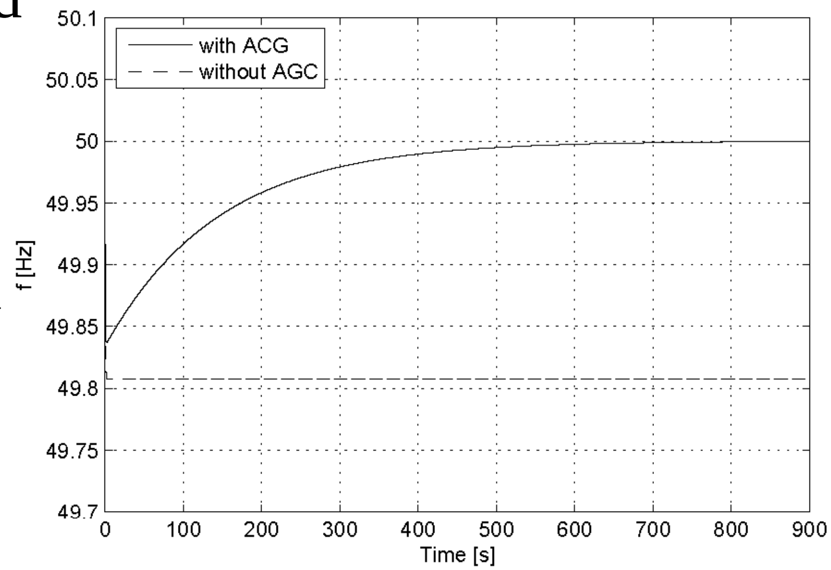
  – u is the generation command

- Control logic

  $$\dot{u} = -k_I x$$

  – I (integral) feedback control

- This is simplified analysis

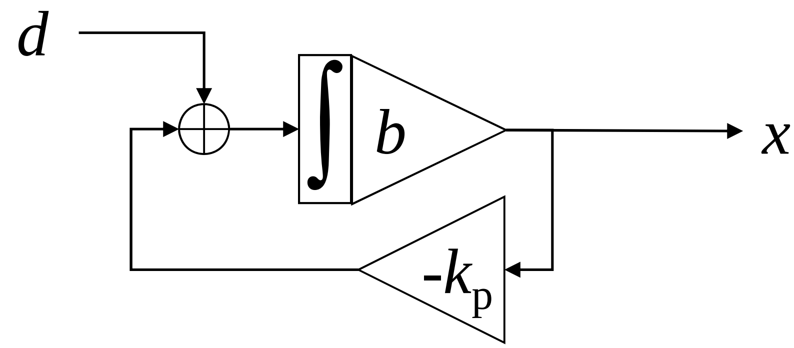


P and I control

- P control of an integrator

$$u = -k_P x$$

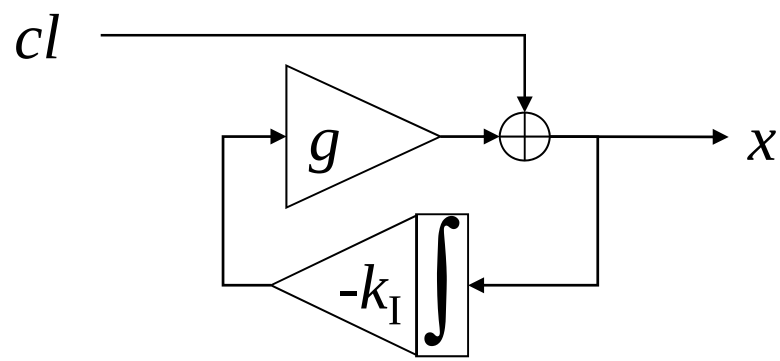
$$\dot{x} = bu + d$$



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

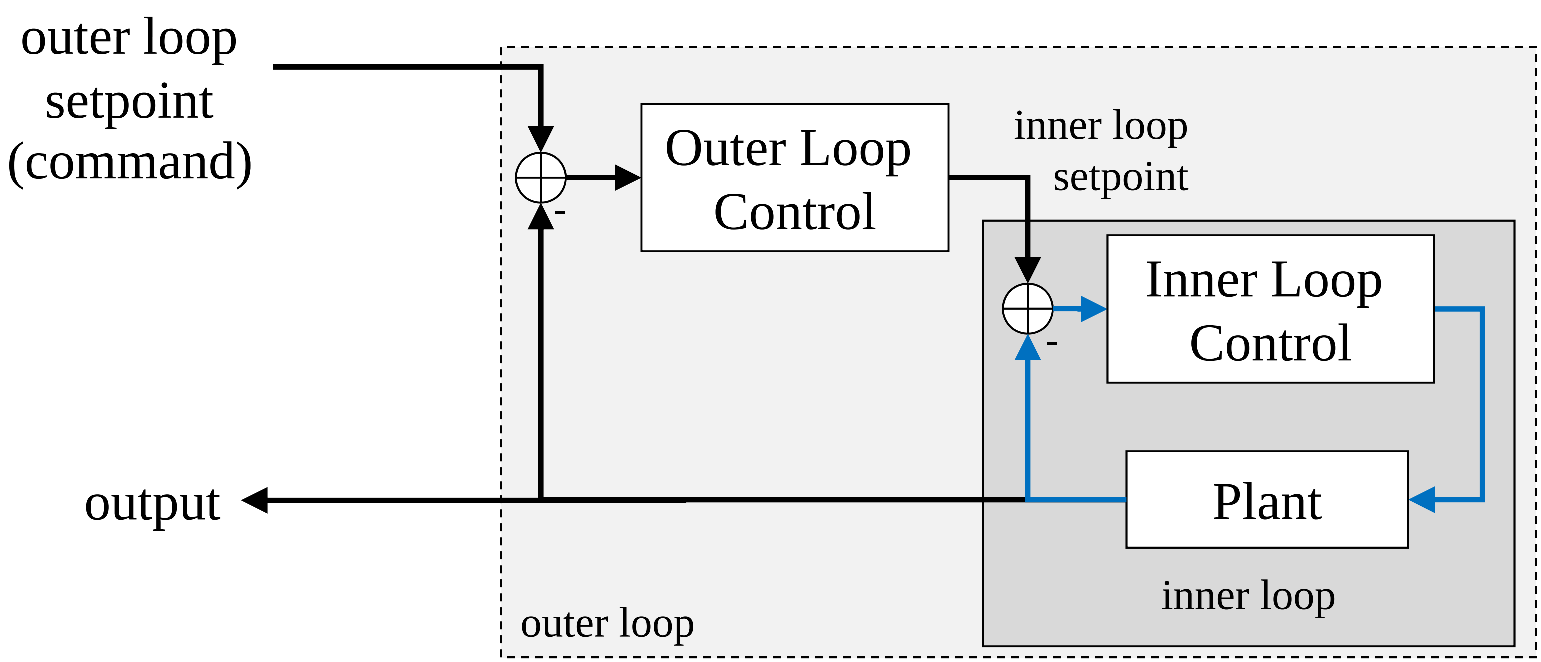
$$\dot{u} = -k_I x$$

$$x = g \cdot u + c \cdot l,$$



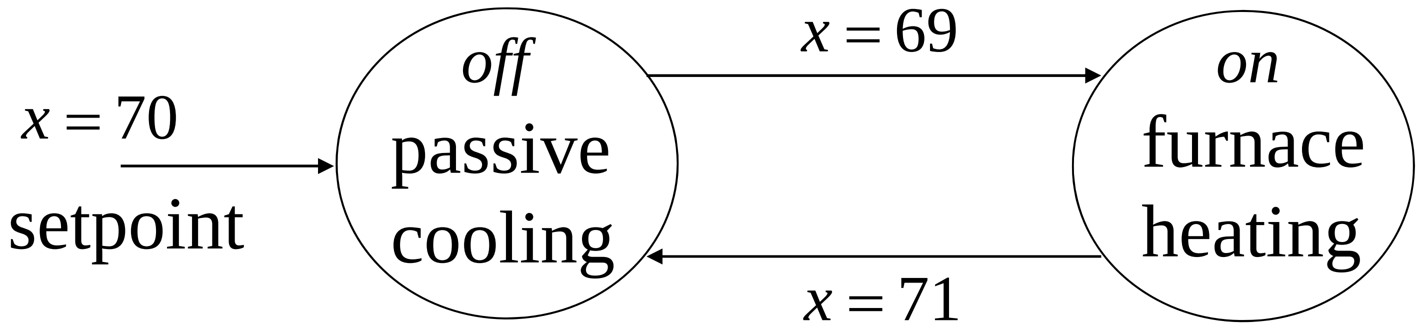
Cascade (Nested) Loops

- 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



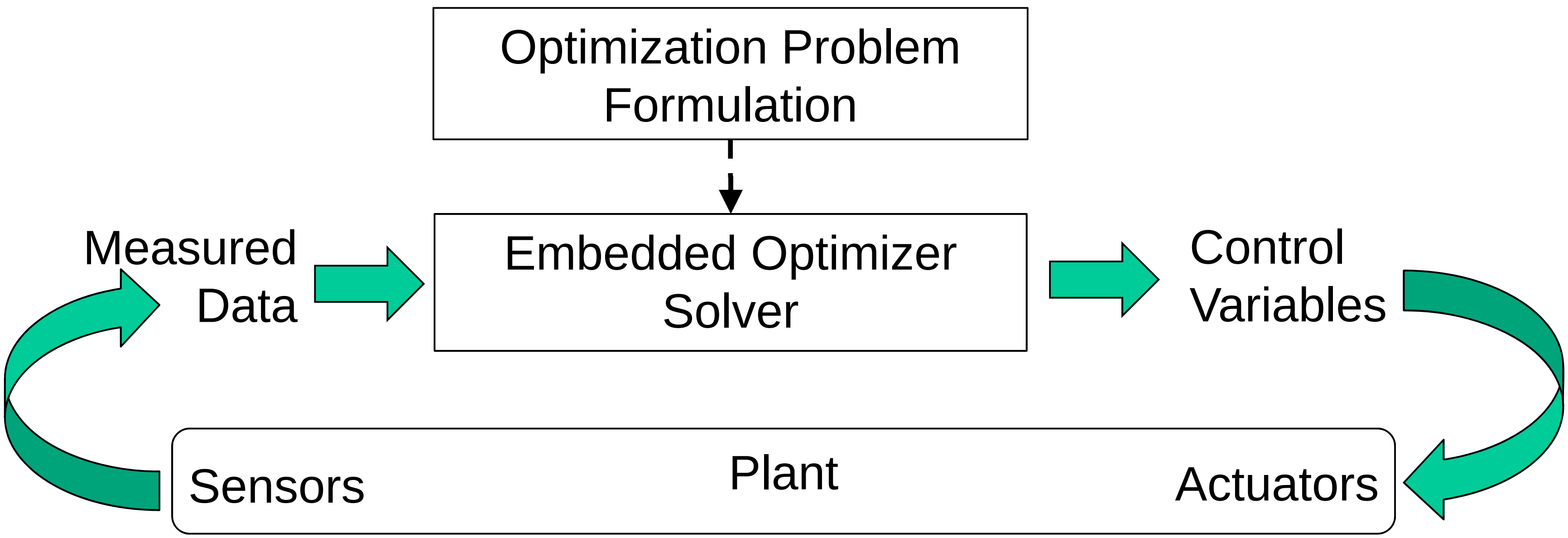
Switching (On-Off) Control

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



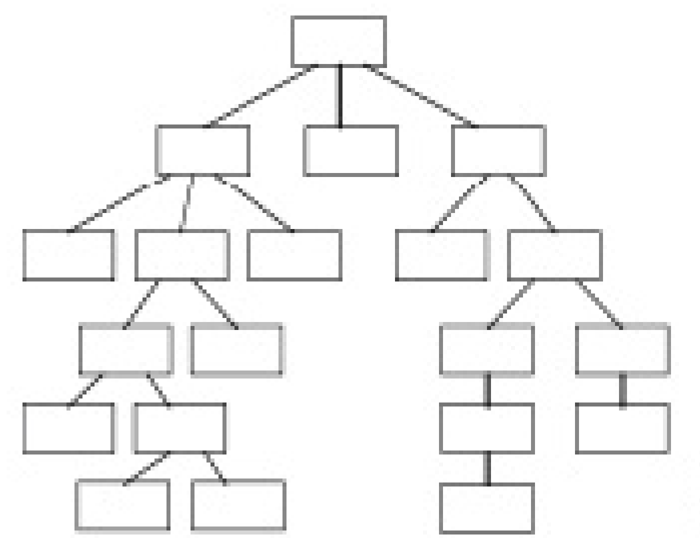
Optimization-based Control

- 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



Cascade (Hierarchical) Control

- Hierarchical decomposition
  - Cascade loop design
  - Time scale separation

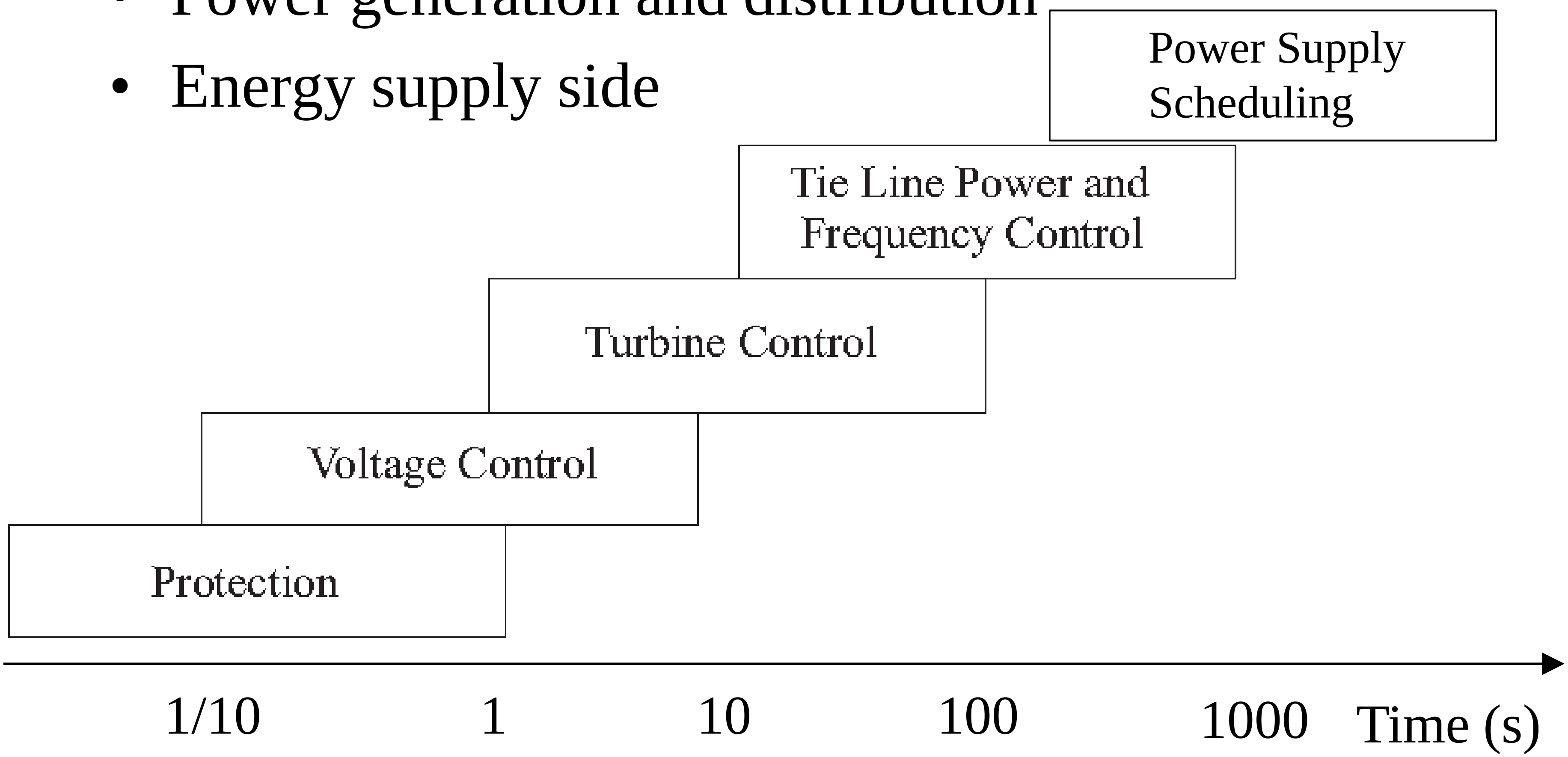


Hierarchical Control Examples

- 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

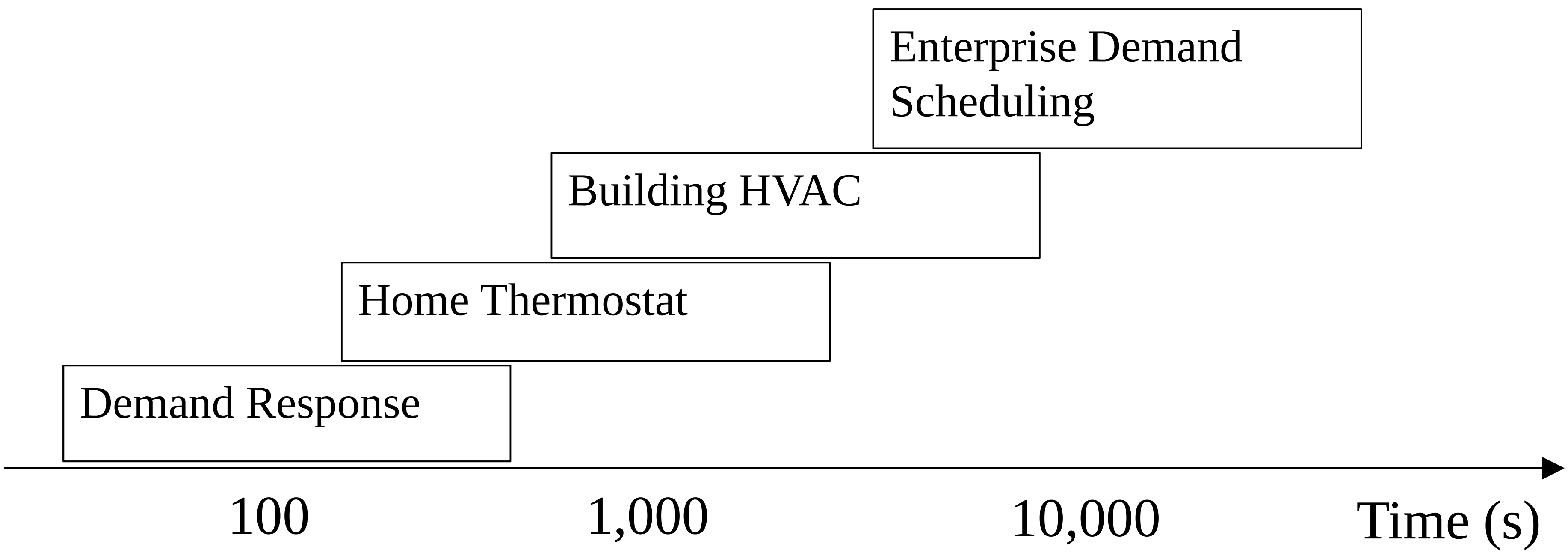
- Power generation and distribution
- Energy supply side



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

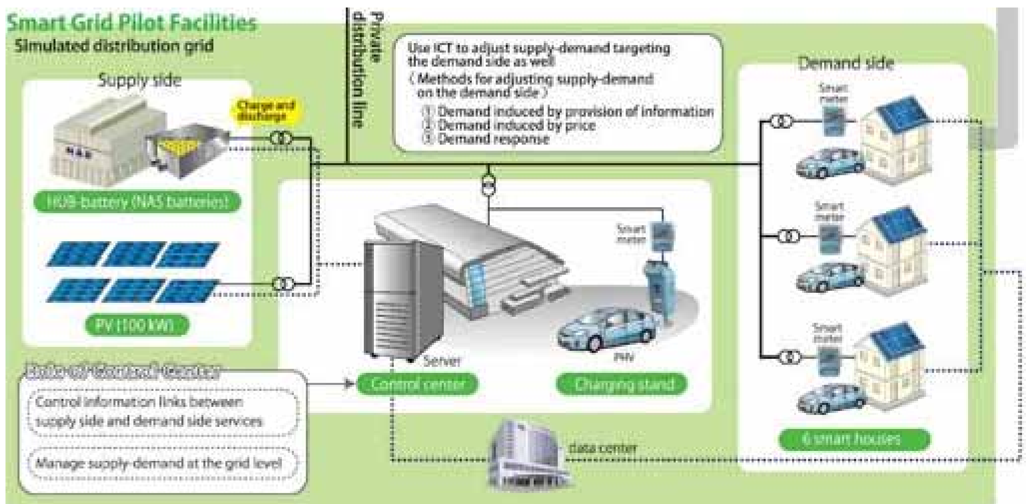
Power Demand Time Scales

- Power consumption
  - DR, Homes, Buildings, Plants
- Demand side



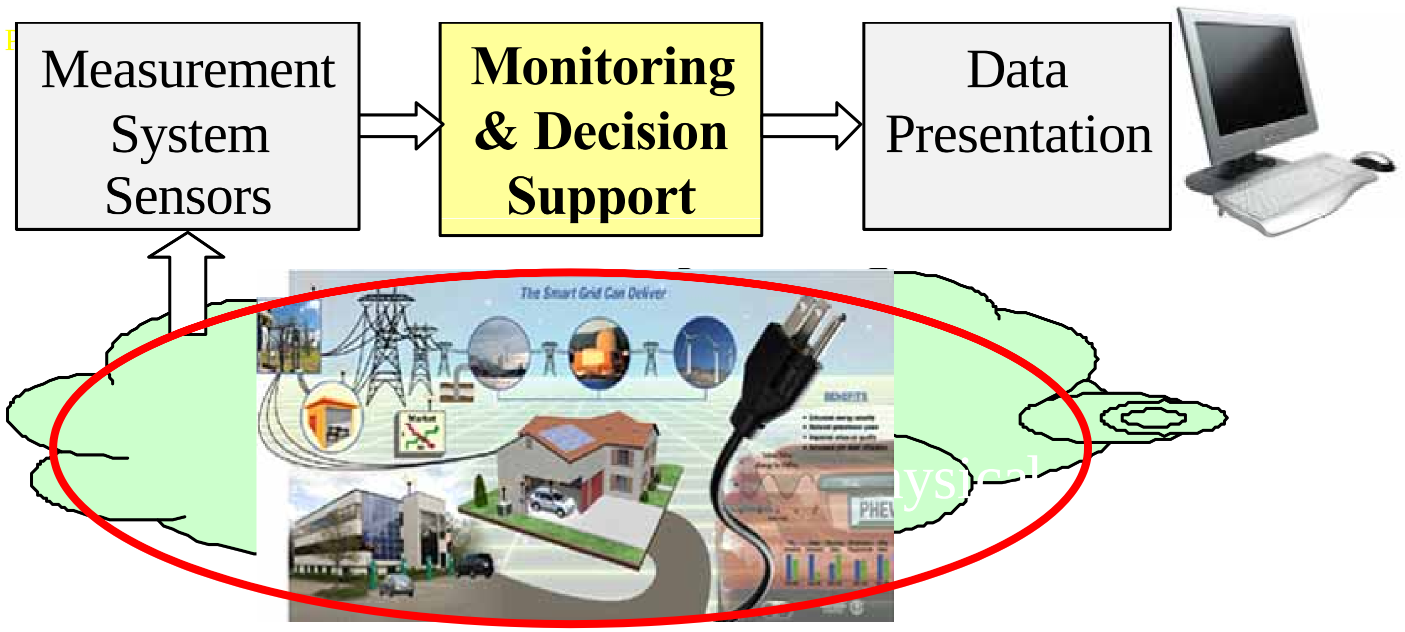
Research Topics: Control

- 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

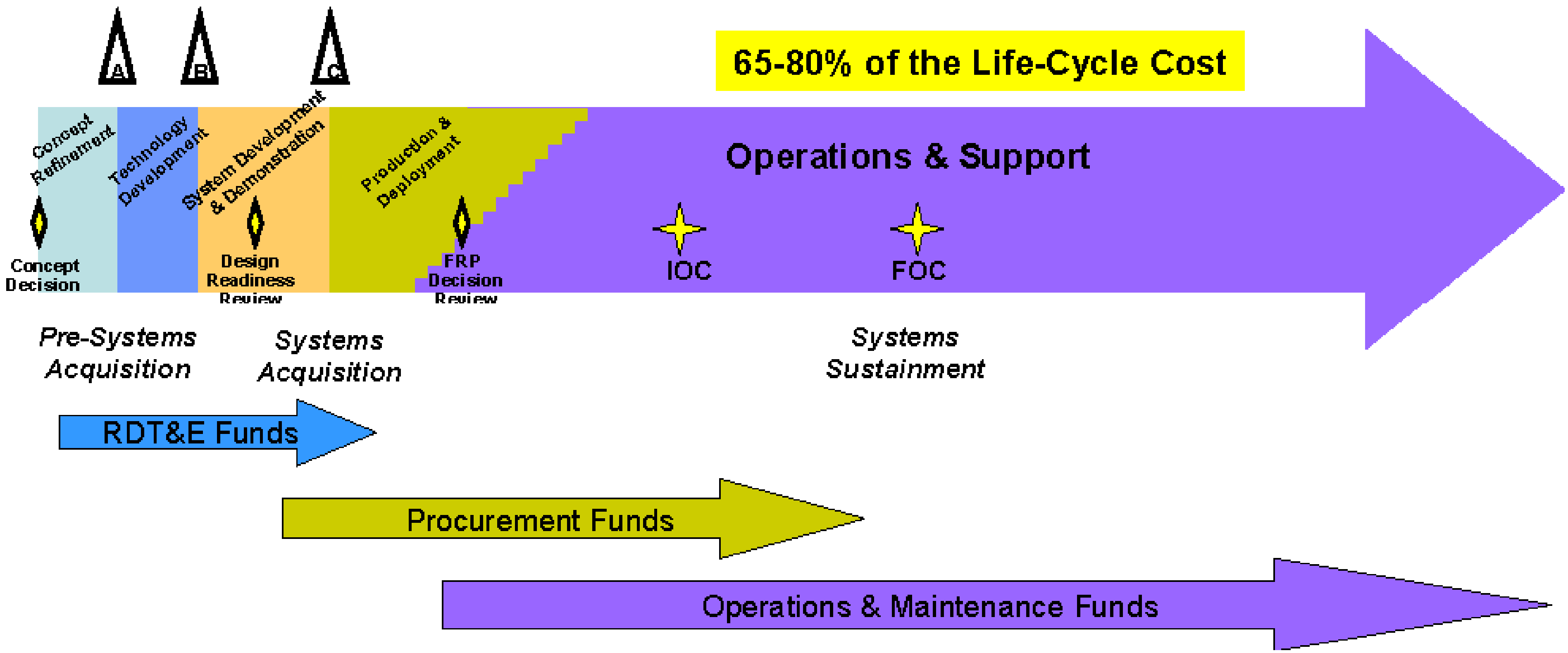


Monitoring Goals

- Situational awareness
  - Anomaly detection
  - State estimation
- Health management
  - Fault isolation
  - Condition based maintenances

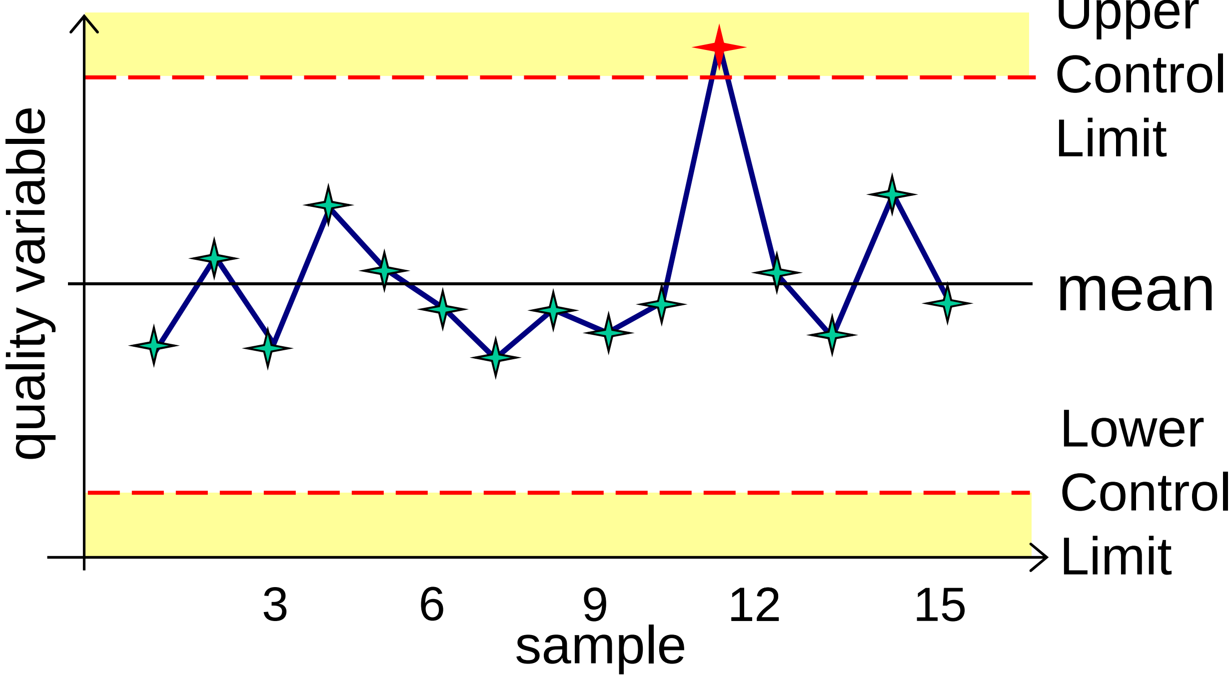
Condition Based Maintenance

- CBM+ Initiative



SPC: Shewhart Control Chart

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



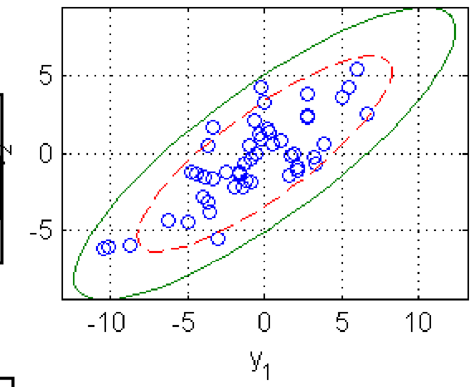
Walter Shewhart
(1891-1967)

Multivariable SPC

- Two correlated univariate processe $y_1(t)$ and $y_2(t)$

  $\mathrm{cov}(y_1,y_2) = Q, \quad Q^{-1} = L^{\mathrm{T}}L$

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$



- Uncorrelated linear combinations

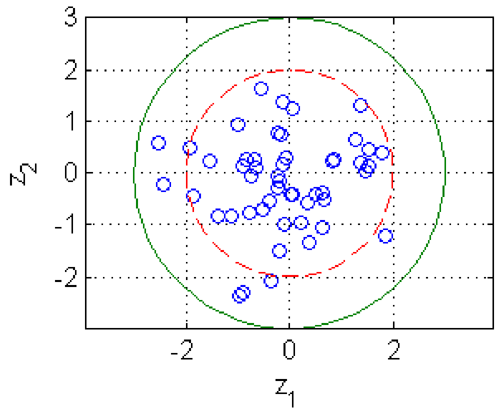
  $z(t) = L\cdot[y(t)-\mu]$

$$\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}$$

$$\|z\|^2 = (y-\mu)^T Q^{-1}(y-\mu) \sim \chi_2^2$$

- Declare fault (anomaly) if

$$(y-\mu)^T Q^{-1}(y-\mu) > c^2$$

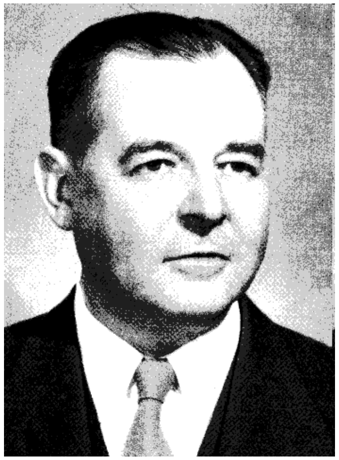


Multivariate SPC - Hotelling's T^2

- Empirical parameter estimates

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

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



Harold Hotelling
(1895-1973)

- 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

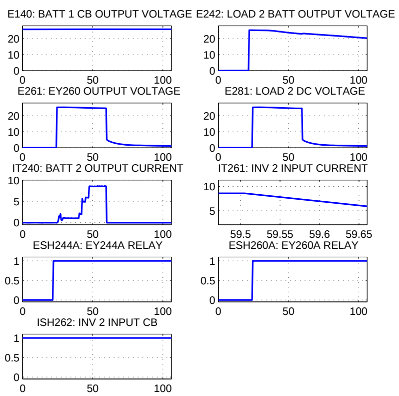
- Potential topics for the term paper.
- Asset monitoring
  - Transformers
- Electric power circuit state monitoring
  - Using phasor measurements
  - Next chart

Electric Power Circuit Monitoring

$$0 = Ax + Bf + w$$
$$y = Cx + Df + v$$

model

Optimization Problem

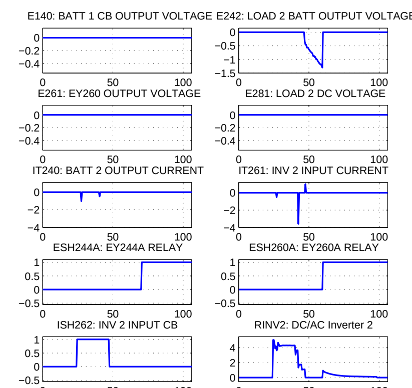


Measurements:

- Currents
- Voltages
- Breakers, relays

State estimate

- Fault isolation



ACC, 2009

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