ROYAL INSTITUTE OF TECHNOLOGY

Lecture 15
Power System Control Centers and EMS application

Davood Babazadeh

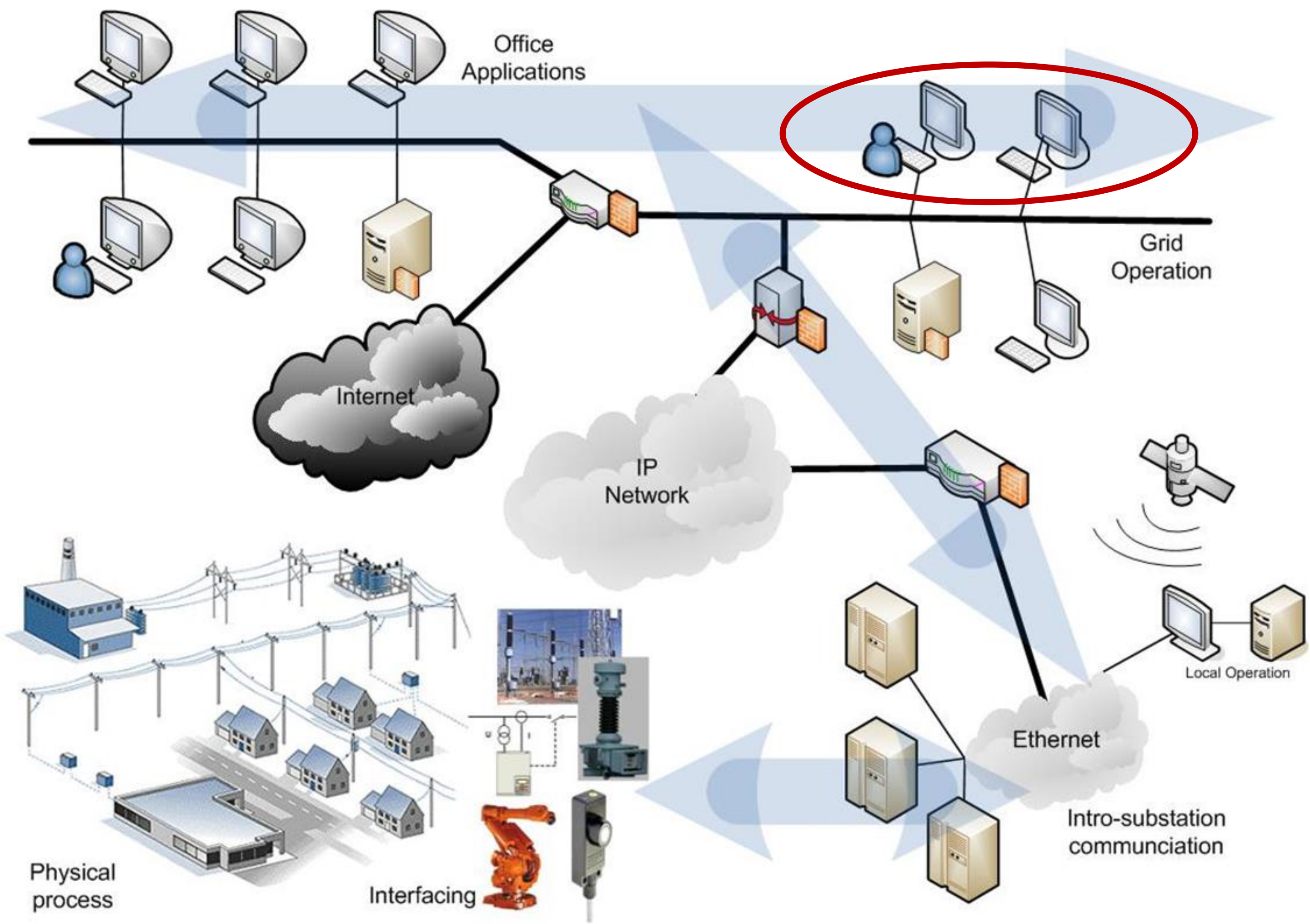
2015-12-01

ROYAL INSTITUTE OF TECHNOLOGY

Outline

- Control Centers
  - Grid Operation Princinples
  - Energy Management System (EMS)
- State estimation
  - What & Why
  - Weighted Leaset Square (WLS) algorithms
- Operational challenges
  - Guest lecture by Magnus from SvK)

Course road map

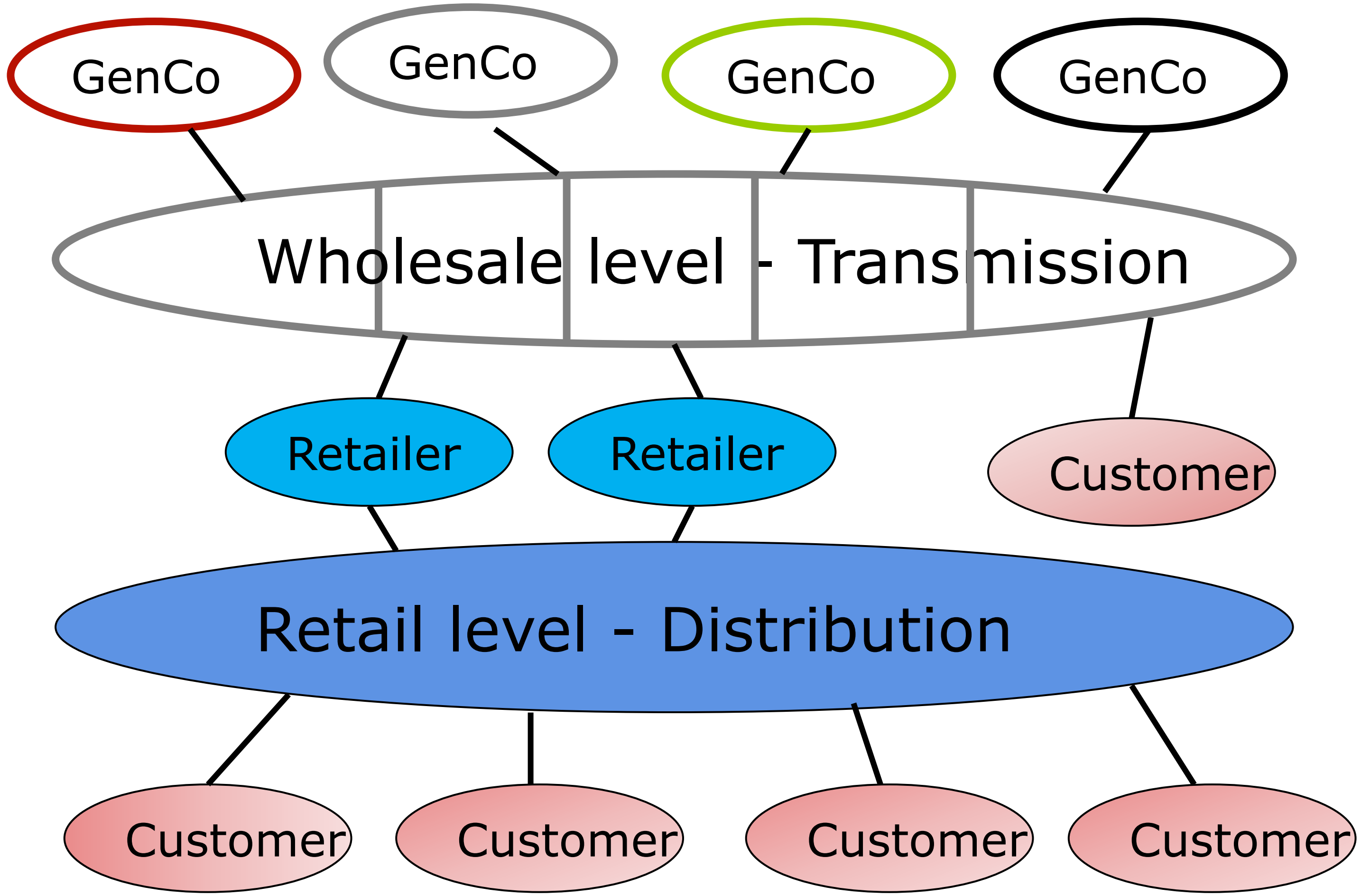


Power systems

- Transmission: backbone of the power systems and its main purpose is to transport energy in large volumes over large distance, from production to consumption center. With a purpose to minimize the resistive losses, the systems are operated at a high voltage levels, 100-400kV in EU.

- Distribution: deliver electrical energy to the end consumer. The network topology can be meshed but it is also possible to be operated as radial systems. Distribution grid employs all voltage levels between 100kV and 0.22kV.

De-regulated Power Industry



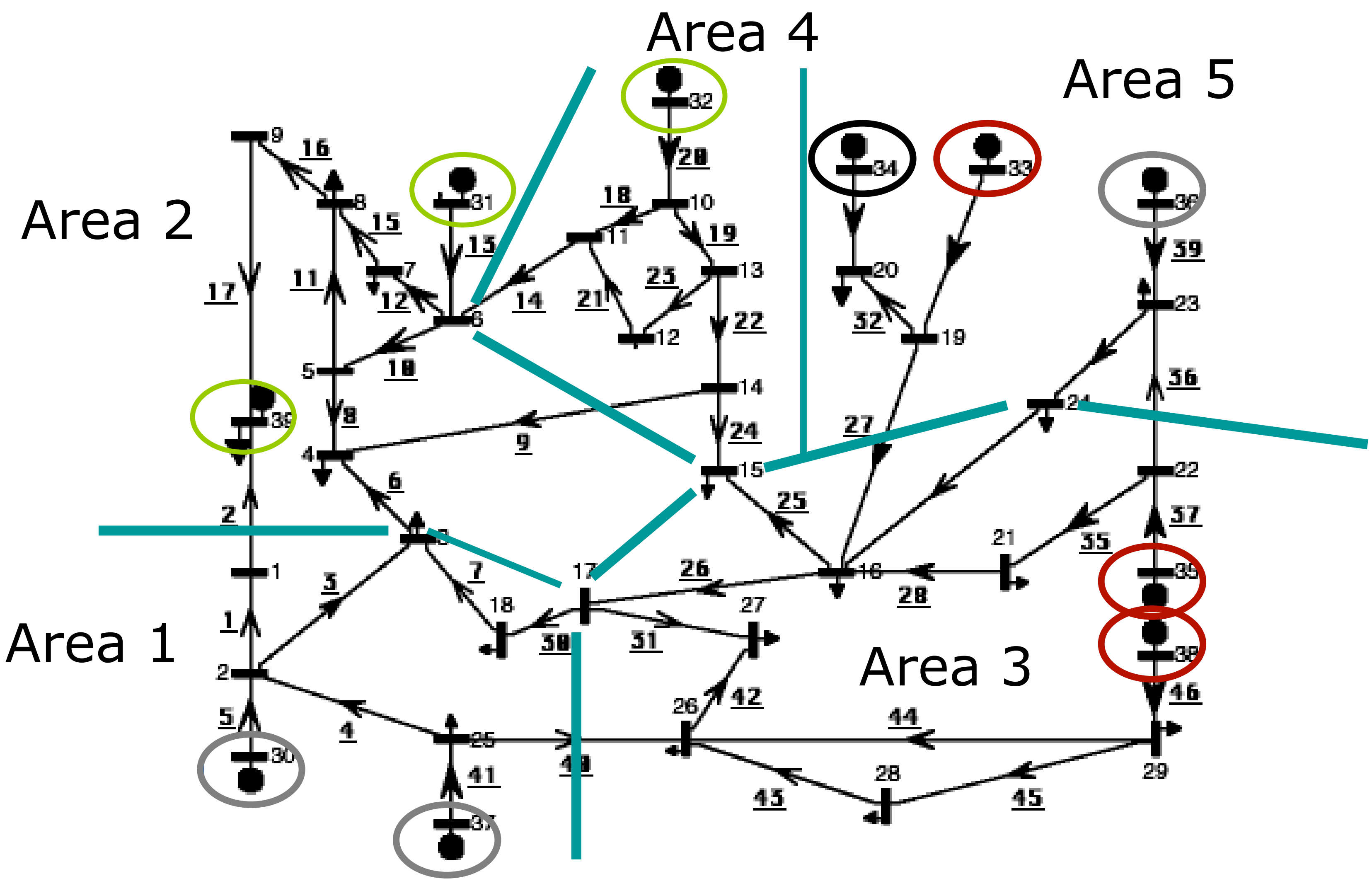
ROYAL INSTITUTE OF TECHNOLOGY

Consequences of De-regulation

- Unbundling of delivery and re-selling of electricity.
  - Freedom of choice of electric retailer
  - Separation of utilities into separate legal entities

- Increased awareness of the utilities operation among regulators, industry and consumers leading to focus on cost

De-regulated power industry



ROYAL INSTITUTE OF TECHNOLOGY

Transmission Grid Management

Operational criteria

- Safety
- Reliability
- Low environmental impact
- Cost efficiency

Grid owner role examples

- In the **United States**, a system of regional transmission organizations is being implemented to help coordinate the activities of individual transmission system operators within larger regional markets. Independent System Operators (ISO) have responsibility for system security and are involved in market operation.

- In the **Nordic region**, system operation is undertaken by Transmission System Owners (TSO) in each country with coordination achieved through cooperative agreements that address operational standards and emergency procedures. The Nordic TSOs are involved in electricity market operation

- In the **United Kingdom**, system operation is undertaken by a single independent transmission owner, and market operation is independent of the transmission owner.

Operation principles

- Operational principles are the rules that guide the decision making that is necessary for secure operation of the power system during real-time control

- Examples
  - Reliability criteria
  - Ancillary services
  - Transmission capacity

ROYAL INSTITUTE OF TECHNOLOGY

Reliability criteria: N-1 criterion

- The N-1 criterion states that the system shall withstand the loss of one single important component (transformer, generator or line) and remain stable. Each power system component loss is referred as one **contingency**.

- Within a certain time after a N-1 fault, the system shall be brought back to a state where it can withstand another N-1 fault.

- On different markets, this is enforced differently.

ROYAL INSTITUTE OF TECHNOLOGY

Reliability criteria cont’d

- The operational procedures of a TSO describes the consequences of the N-1 criteria to the specific network, and possible solutions.

- TSO can also specify certain faults, or situations in which N-2 is a necessary criterion.

Ancillary services

- Ancillary services are supply of active and reactive power that is not intended for consumers, but for system stability and safety.

- These include:
  - Losses in the transmission network
  - Reactive power compensation
  - Active power reserves
  - Load-shedding schedules.

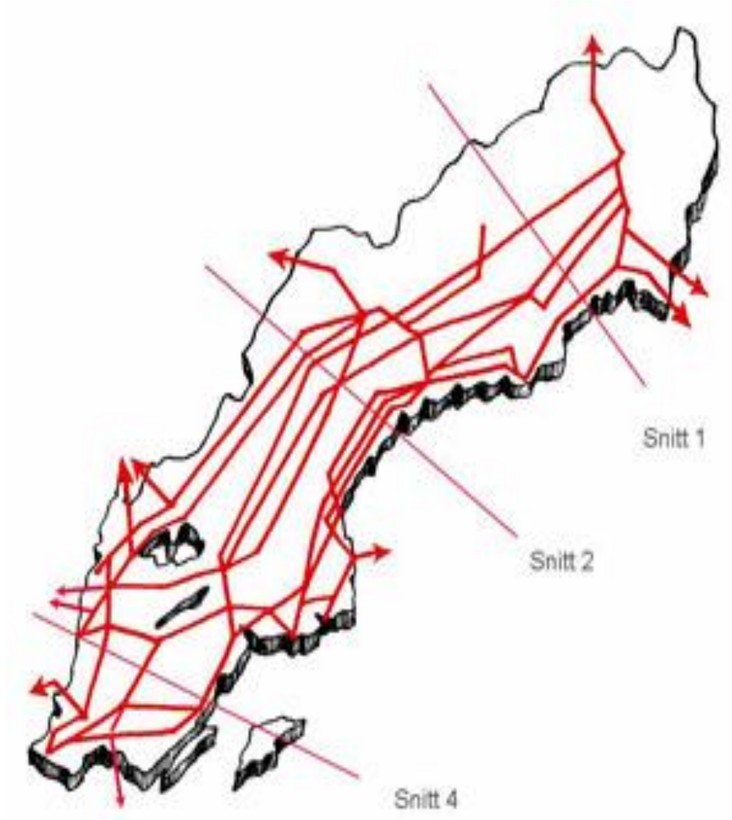
ROYAL INSTITUTE OF TECHNOLOGY

Ancillary services - pricing

- In a de-regulated market the TSO has no direct control of the ancillary services.
- This requires the TSO to:
  - Procure generation to compensate for losses
  - Procure power reserves
  - Secure load-shedding commitment
- All based on market prices and contracts.

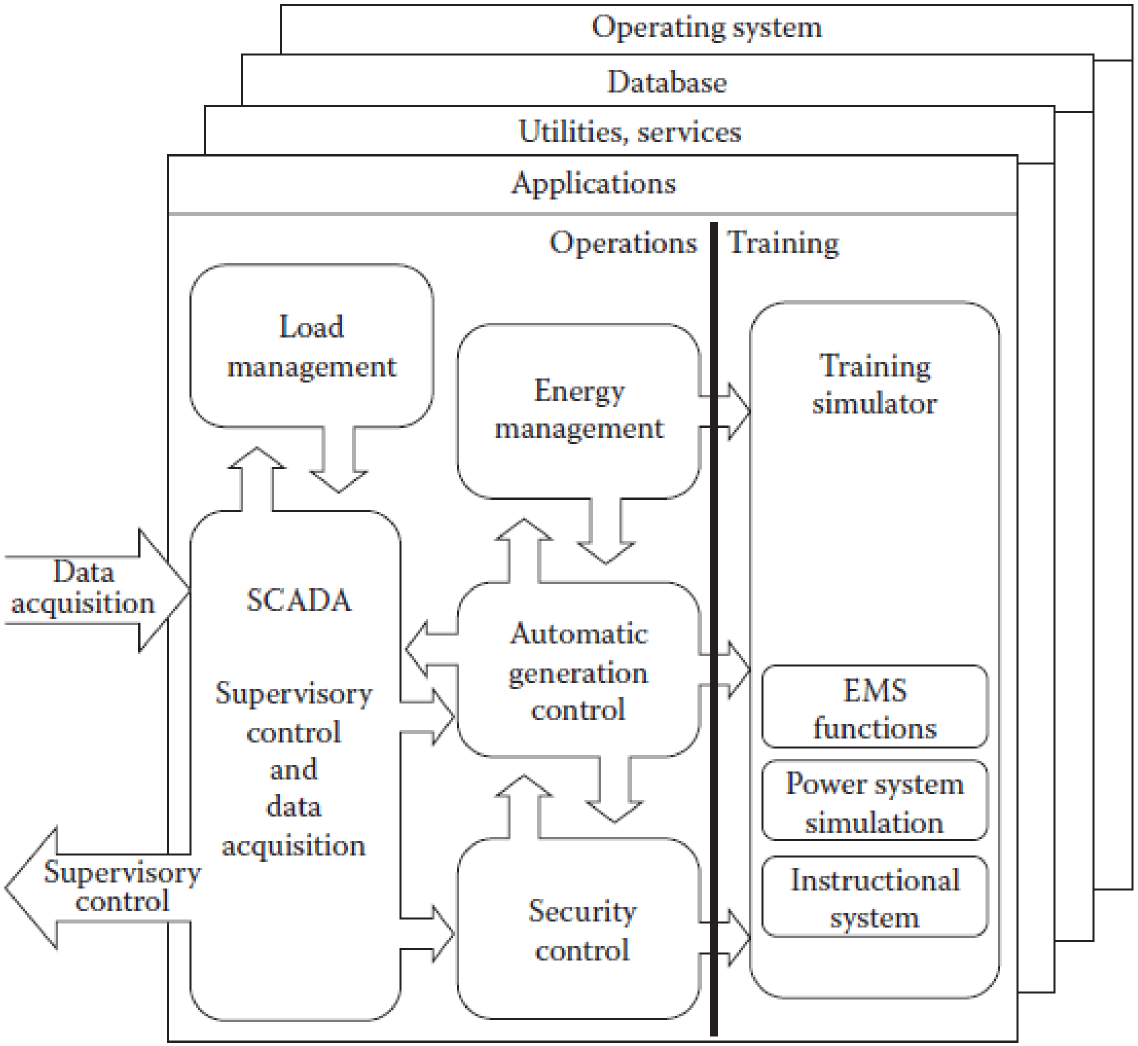
Transmission capacity

- Transmission capacity constraints need to be determined and monitored
- Rules for deviations from principles need to be set and enforced
- During real-time operation, the TSO may perform counter-trading to limit transmission



- How to manage all?

SCADA / EMS (Energy Management System)



ROYAL INSTITUTE OF TECHNOLOGY

EMS
Power System Operation Objectives

Security
- Enforce operational constraints
- Avoid disturbances
- Fast detection

Reliability
- Continuity of supply
- Minimize power outages
- Rapid restoration

Quality
- Power Quality: Voltage + Frequency
- Customer service

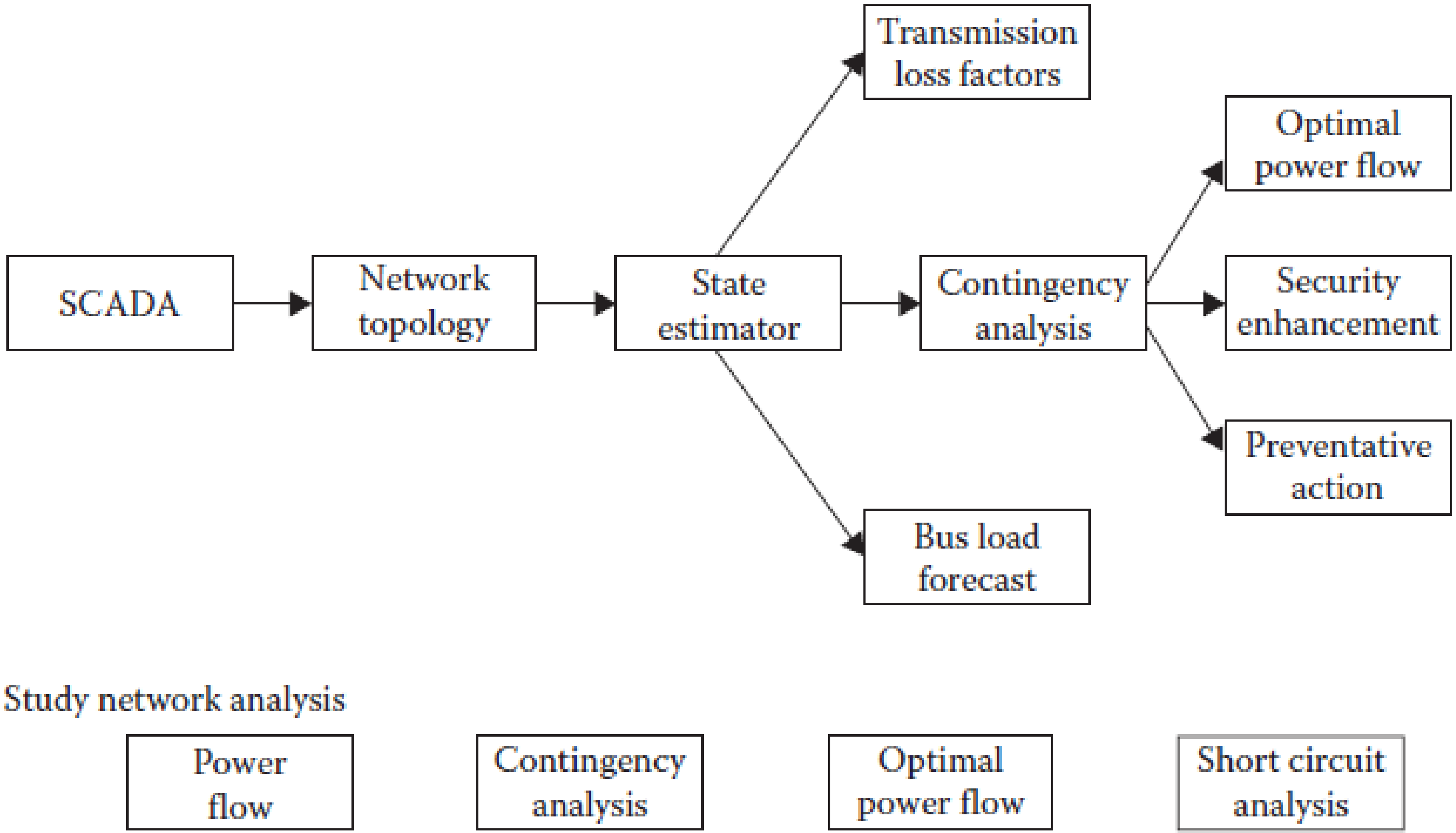
Economy
- Optimal Generation Planning
- Optimal Generation Dispatch and Control
- Energy Trading
- Transmission loss minimization
- Operate transmission network closer to the limits
- Facilities maintenance
- Deferred investments

Ref: Ventyx

Energy Management System (EMS)

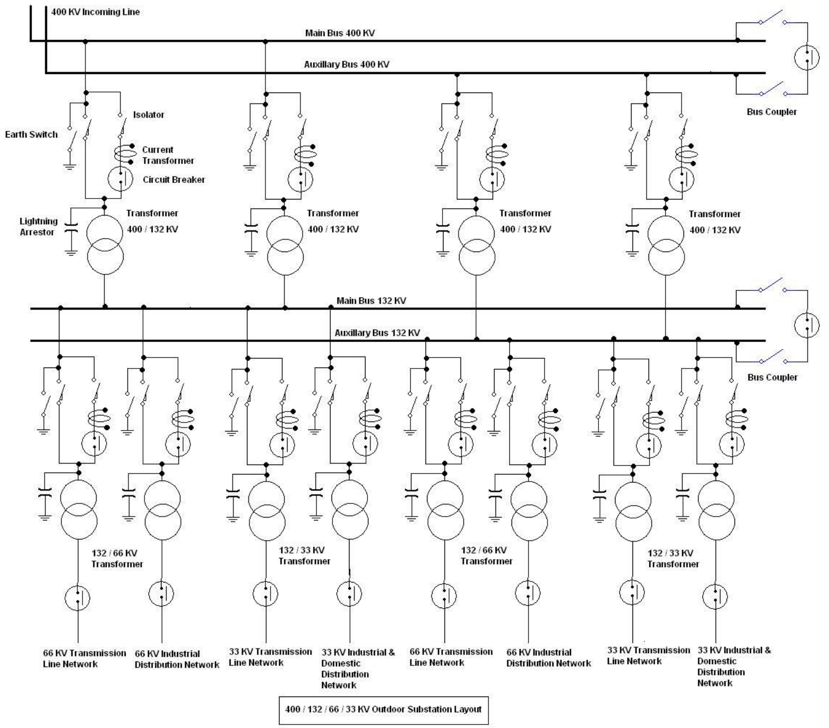
- Network topology
- Optimal power flow
  - Power system basic course
- Contingency analysis
  - Similar concept as power flow
- Short circuit analysis
- State estimation

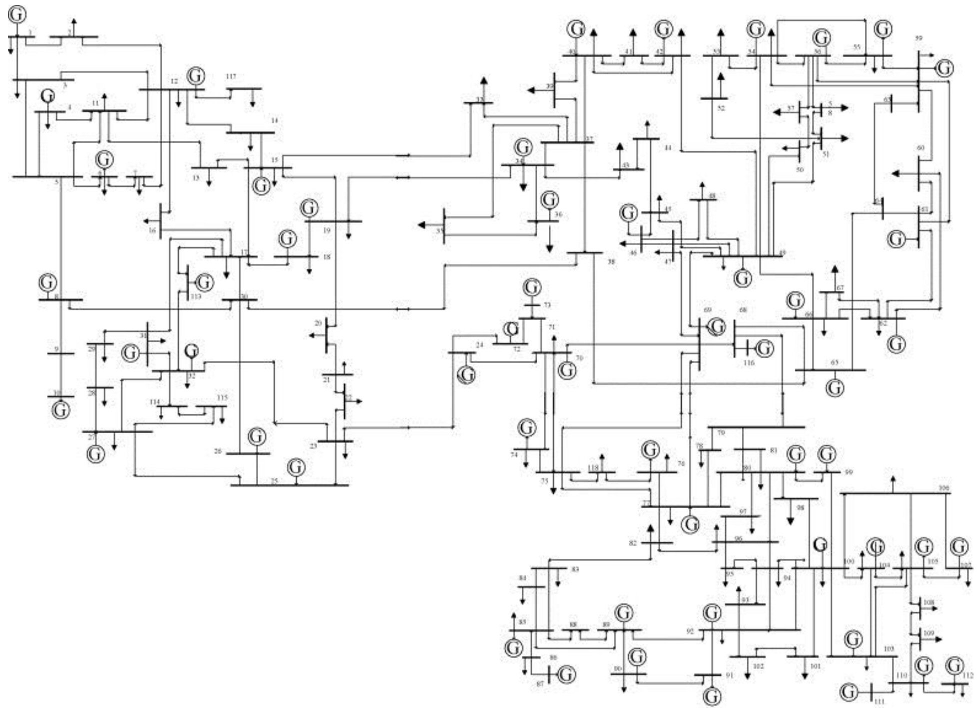
Real time network analysis



ROYAL INSTITUTE OF TECHNOLOGY

Power system models





Bus breaker model

Bus branch model

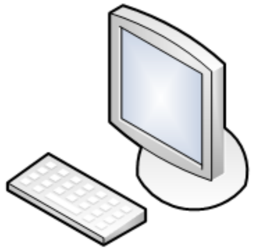
Contingency analysis

- A contingency is the loss or failure of a small part of the power system (e.g. a transmission line), or the loss/failure of individual equipment such as a generator or transformer. This is also called an unplanned "outage".

- Contingency Analysis (CA) is a "what if" scenario simulation that evaluates, provides and prioritizes the impacts on an electric power system when problems occur.

Contigency Analysis

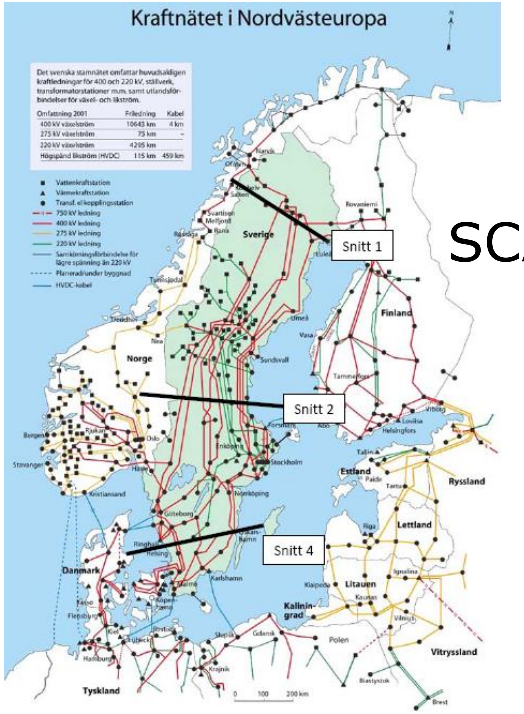
State Estimator



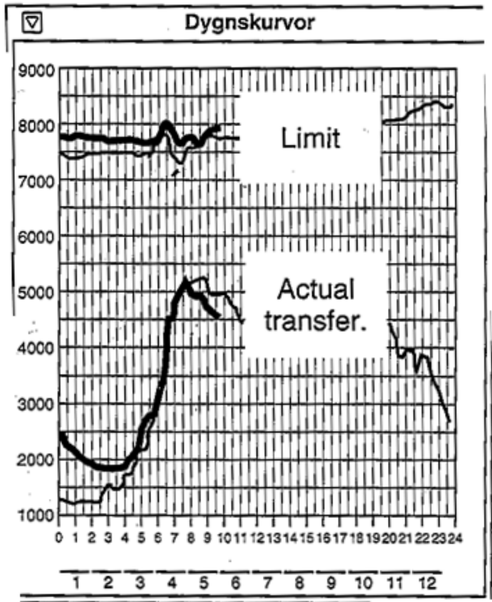
Planning Data Base

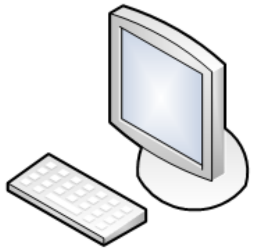
Estimates

SCADA Raw Data



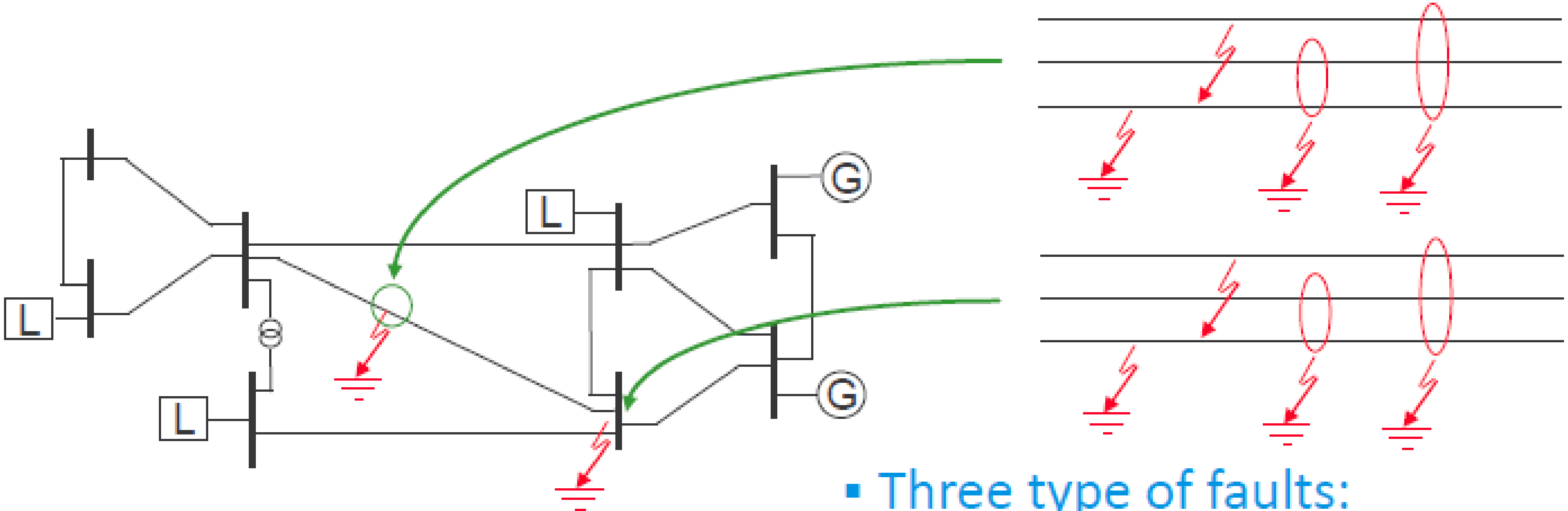
Courtesy of SvK





Contingency List

Short Circuit Analysis (SCA)

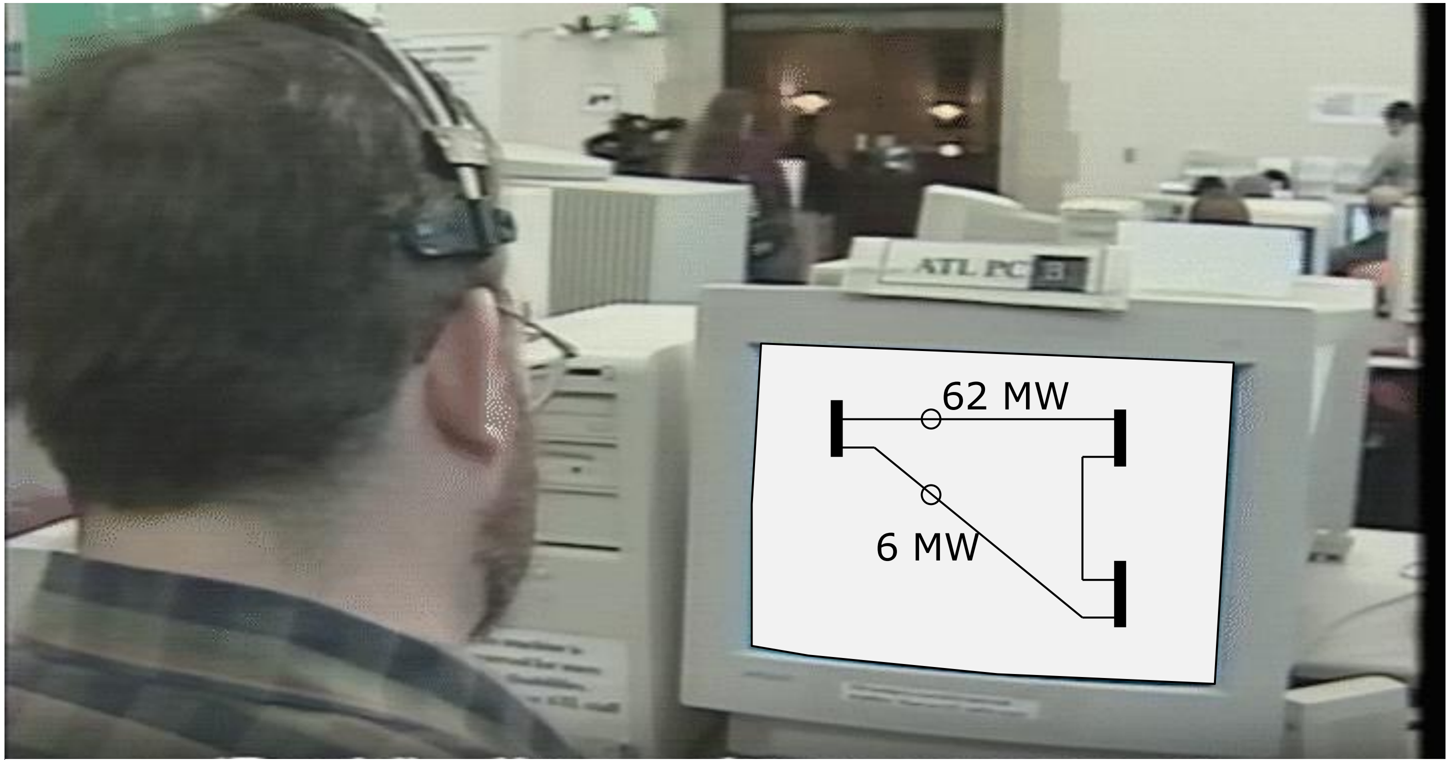


- Three type of faults:
  - Standard faults - bus faults
  - Intermediate faults - along lines
  - Phase-open faults
- Balanced and unbalanced faults:
  - Single-phase to ground
  - Double-phase to ground
  - Phase-to-phase
  - Three-phase faults
- Simulation of topology changes
- Breaker limit check
- Bus short-circuit violations and voltages on one-line diagrams
- Sub-transient currents

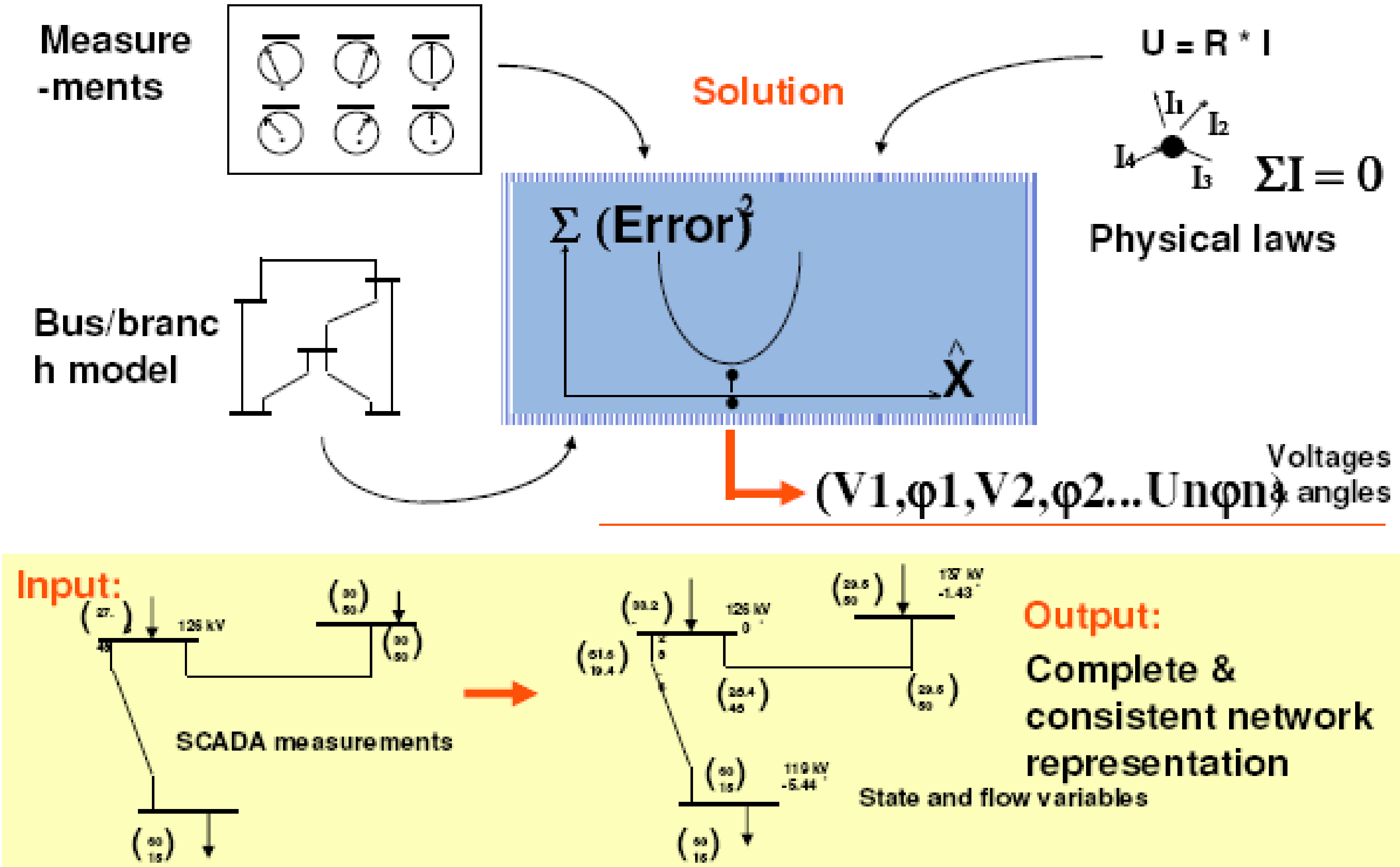
ROYAL INSTITUTE
OF TECHNOLOGY

Power System State Estimation Theory

How could the operator know the system?



The truth is out here!



Power system states: x

- The power system states are those parameters that can be used to determine all other parameters of the power system

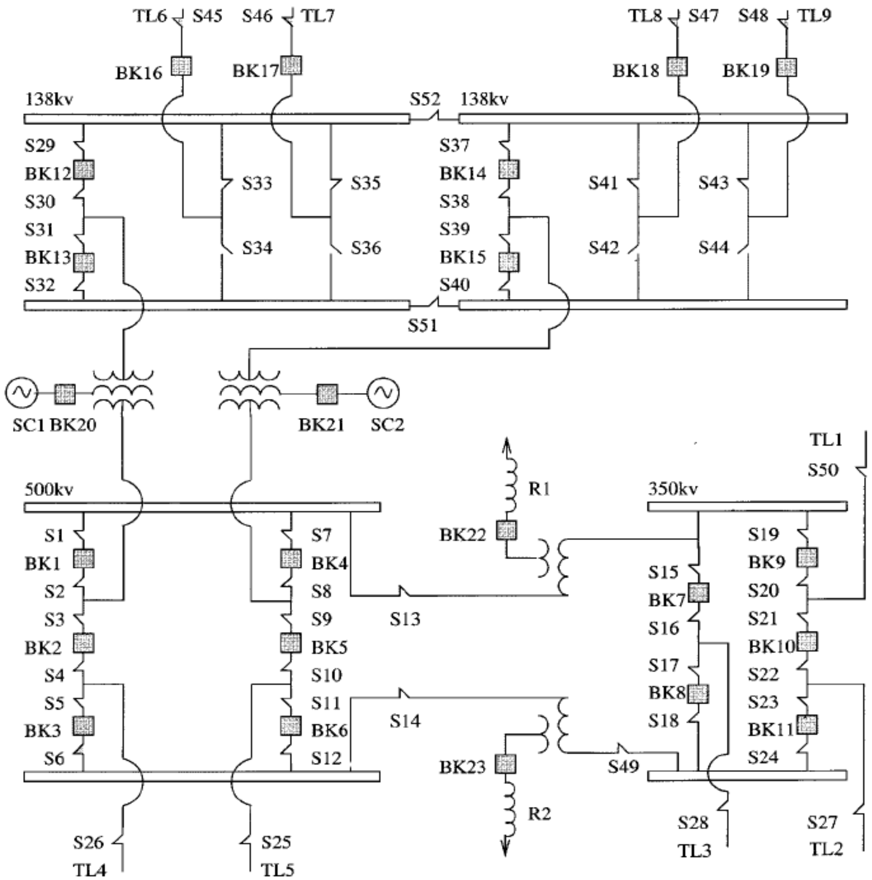
- Node voltage phasor
  - Voltage magnitude V_k
  - Phase angle Θ_k
- Transformer turn ratios
  - Turn ratio magnitude t_{kn}
  - Phase shift angle φ_{kn}
- Complex power flow
  - Active power flow P_{kn}, Pn_k
  - Reactive power flow Q_{kn}, Qn_k

ROYAL INSTITUTE OF TECHNOLOGY

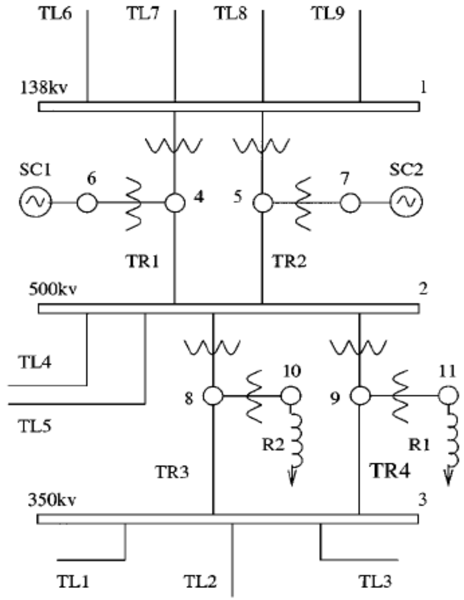
Analog measurements

- Voltage magnitude
- Current flow magnitude & injection
- Active & reactive power
  - Branches & groups of branches
  - Injection at buses
  - In switches
  - In zero impedance branches
  - In branches of unknown impedance
- Transformers
  - Magnitude of turns ratio
  - Phase shift angle of transformer
- Synchronized phasors from Phasor Measurement Unit

Network topology processing



Bus breaker model



Bus branch model

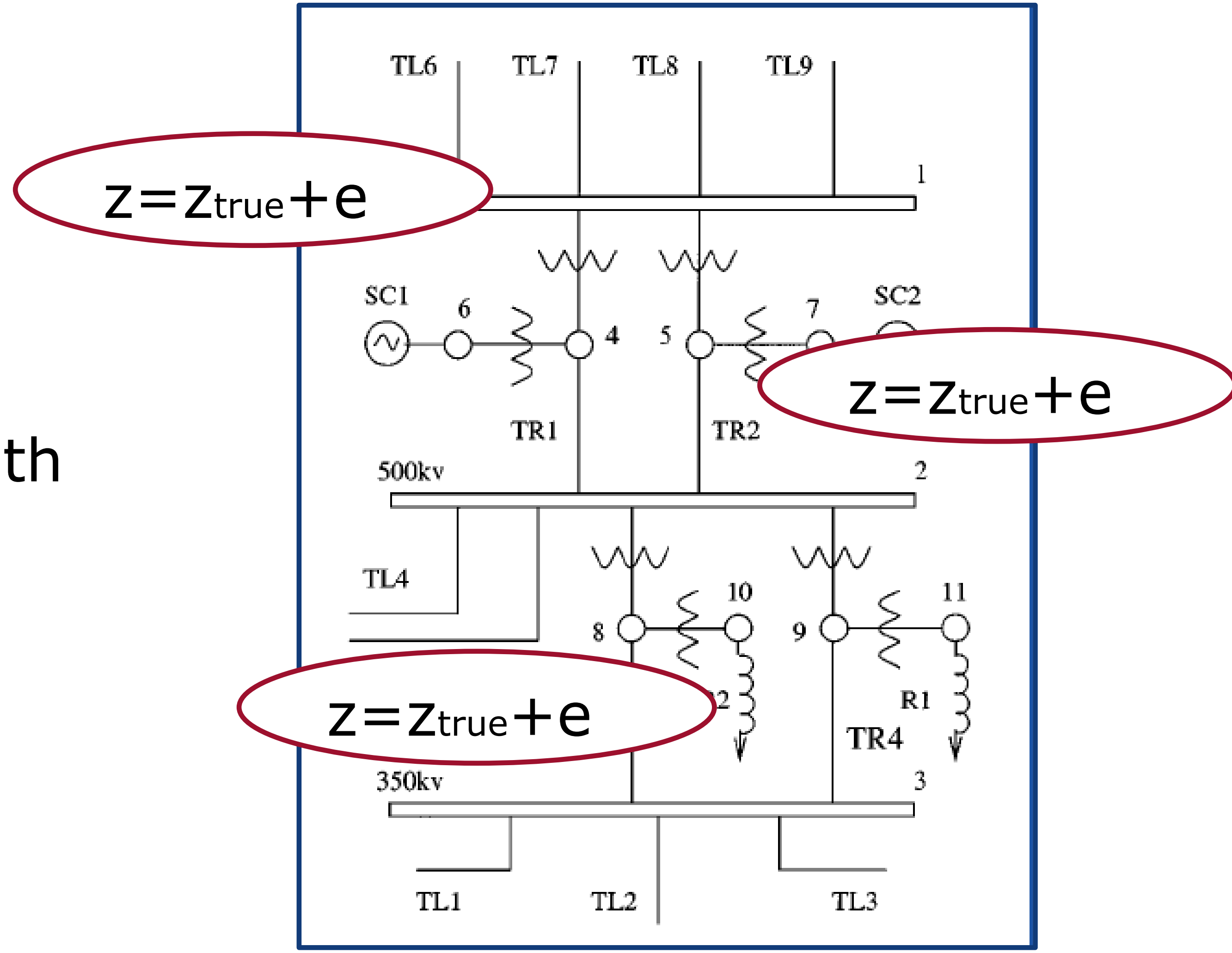
Power system measurements: z

z_{true}: power system truth

$z_{true}=h(x)$

e: measurement error

$e=e_{systematic}+e_{random}$



Measurement model

- How to determine the states (x) given a set of measurements (z)?

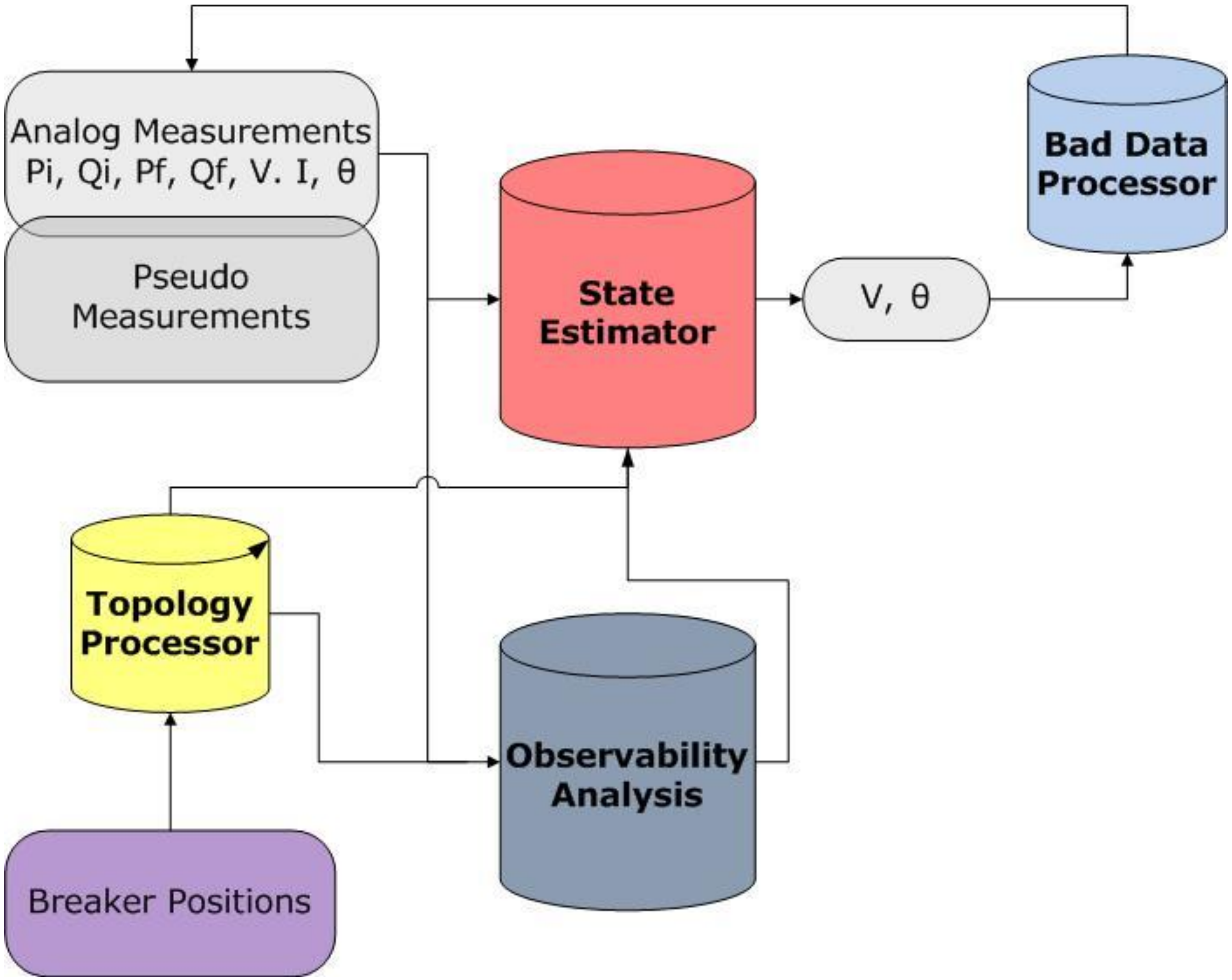
$$z_j = h_j(\boldsymbol{x}) + e_j$$

known *unknown* *unknown*

where

- x is the true state vector $[V_1, V_2, \ldots V_k, \Theta_1, \Theta_2, \ldots \Theta_k]$
- z_j is the jth measurement
- h_j relates the jth measurement to states
- e_j is the measurement error

State estimation process



Why do we need state estimation?

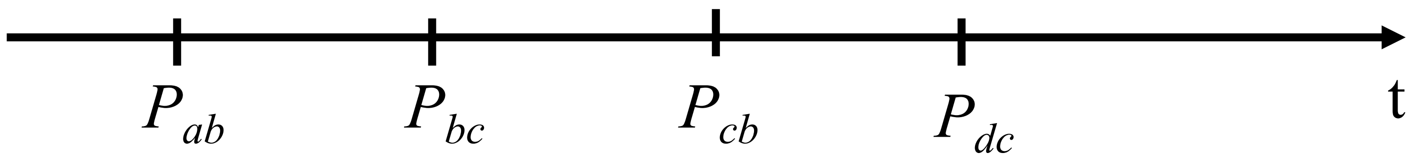
Measurements correctness

- Imperfections in
  - Current & Voltage transformer
  - Transducers
    - A/D conversions
    - Tuning
  - RTU/IED Data storage
  - Rounding in calculations
  - Communication links

- Result in uncertainties in the measurements

Measurement timeliness

- Due to imperfections in SCADA system the measurements will be collected at different points in time, time skew.



- If several measurements are missing how long to wait for them?
- Fortunately, not a problem during quasi-steady state.
- State estimation is used for off-line applications

ROYAL INSTITUTE OF TECHNOLOGY

How can the states be estimated?

ROYAL INSTITUTE OF TECHNOLOGY

Approaches

- Minimum variance method
  - Minimize the sum of the squares of the weighted deviations of the state calculated based on measurements from the true state
- Maximum likelihood method
  - Maximizing the probability that the estimate equals to the true state vector ***x***
- Weighted least square method (WLS)
  - Minimize the sum of the weighted squares of the estimated measurements from the true state

$$J(x) = \sum_{i=1}^{m} \frac{(z_i - h_i(x))^2}{R_{ii}}$$

Least square (Wiki)

- "Least squares" means that the overall solution minimizes the sum of the squares of the errors made in the results of every single equation.
- The method of **least squares** is a standard approach to the approximate solution of over determined system, i.e., sets of equations in which there are more equations than unknowns.
- The most important application is in data fitting.
- Carl Friedrich Gauss is credited with developing the fundamentals of the basis for least-squares analysis in **1795**.

WLS state estimation

- **Fred Schweppe** introduced state estimation to power systems in **1968**.
- He defined the state estimator as “a data processing algorithm for converting redundant meter readings and other available information into an estimate of the state of an electric power system”.
- Today, state estimation is an essential part in almost every energy management system throughout the world.

Felix F. Wu, “Power system state estimation: a survey”, International Journal of Electrical Power & Energy Systems, Volume 12, Issue 2, April 1990, Pages 8

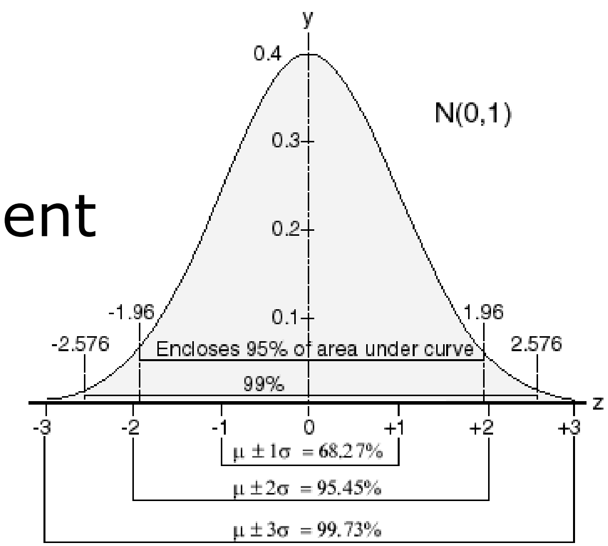
WLS state estimation model

$$z_j = h_j(\boldsymbol{x}) + e_j$$

known *unknown* *unknown*

Error characteristics

- The errors in the measurements is the sum of several stochastic variables
  - CT/VT, Transducer, RTU, Communication…
- The errors is assumed as a Gaussian Distribution with known deviations
  - Expected value $E[e_j] = 0$
  - Known deviation σ_j
- The errors are also assumed to be independent
  - $E[e_i e_j] = 0$



WLS objective function

$$J(x) = \sum_{i=1}^{m} \frac{(z_i - h(x))^2}{\sigma_i^2} = [z - h(x)]^T R^{-1} [z - h(x)]$$

where

i=1,2,…m

$$R = diag\{s_1^2, s_2^2, s_3^2, \ldots s_m^2\} = Cov(e) = E[e \times e^T]$$

Solution to above is iterative using newton methods

Newton iteration

- At the minimum, the first-order optimality conditions will have to be satisfied

$$g(x) = \frac{\partial J(x)}{\partial x} = H^T(x) R^{-1} [z - h(x)] = 0$$

$H^T(x) = [\frac{\partial h(x)}{\partial x}]$ is the measurement Jacobian matrix

Newton iteration cont'd

- Expanding the *g(x)* into its Taylor series around state vector x^k

$$g(x) = g(x^k) + G(x^k)(x - x^k) + ... = 0$$

where

$$G(x^k) = \frac{\partial g(x^k)}{\partial x} = H^T(x^k)R^{-1}H(x^k)$$

Newton iteration cont’d

- Neglecting the higher order terms leads to an iterative solutions scheme know as the Gauss-Newton method as :

$$x^{k+1} = x^k - [G(x^k)]^{-1} \cdot g(x^k)$$

k	is the iteration index,
x^k	is the solution vector at iteration k

ROYAL INSTITUTE OF TECHNOLOGY

Newton iteration IV

- Convergence

$$\max(\left|\Delta x^k\right|) \leq \xi$$

- If not, update

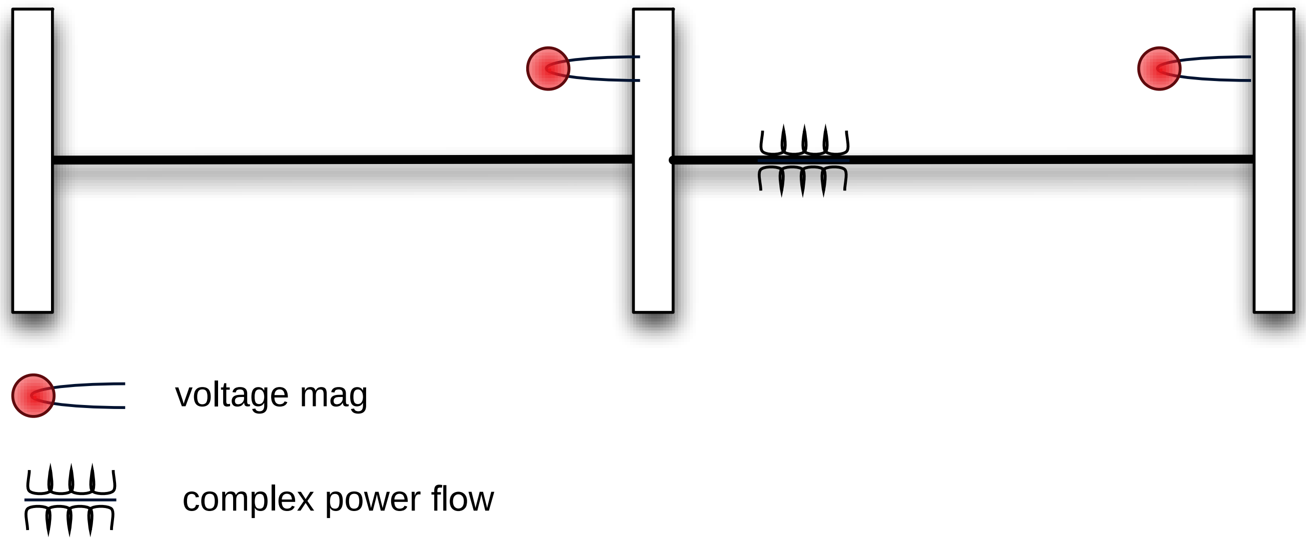
$$x^{k+1} = x^k + \Delta x^k$$

$$k = k + 1$$

Go back to the previous step

ROYAL INSTITUTE OF TECHNOLOGY

Why the measurements are weighted?



$$P_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

$$Q_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

ROYAL INSTITUTE OF TECHNOLOGY

Weight

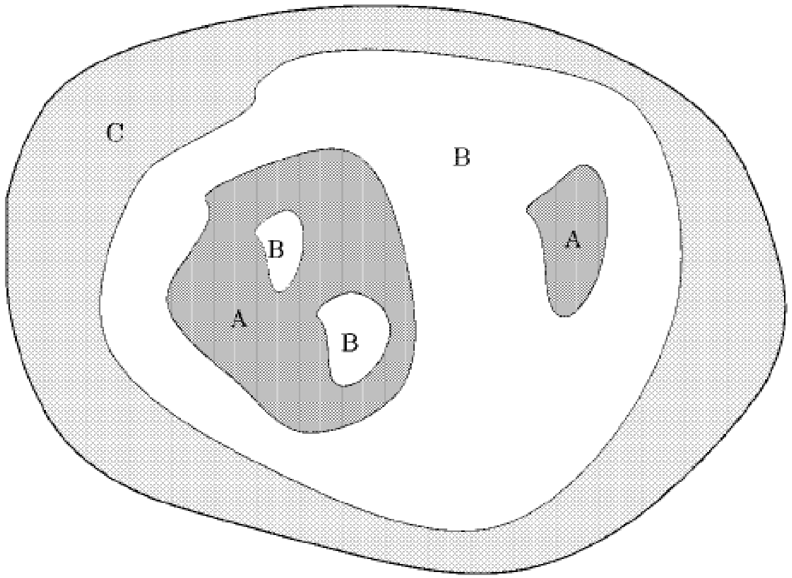
- Weight is introduced to emphasize the trusted measurement while de-emphasize the less trusted ones.

- WLS

$$W_i = \frac{1}{\sigma_i^2}$$

Observability

- Based on system topology and location of measurements parts of the power system may be unobservable.
- Unobservable parts of the system can be made observable via data exchange (CIM), pseudo measurements, etc…



A Observable part of the system of interest
B Unobservable part of the system of interest
C Rest of the interconnected system

ROYAL INSTITUTE OF TECHNOLOGY

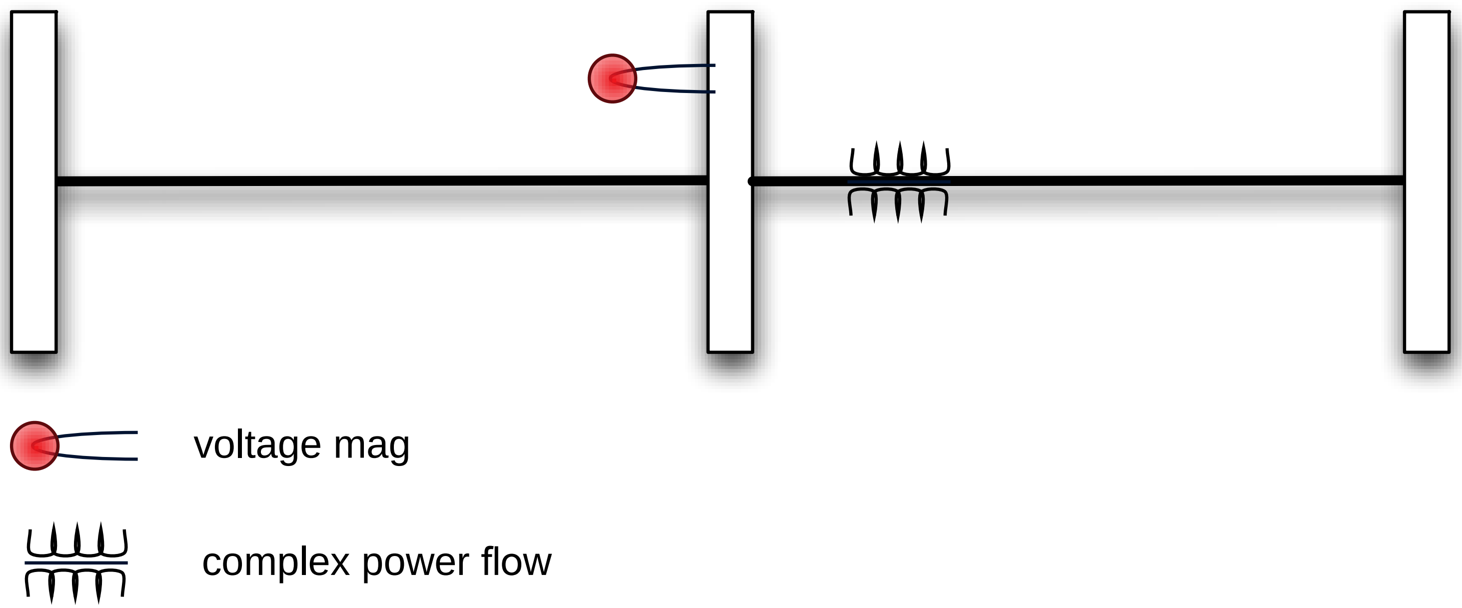
Network Observability

- Observability analysis can be done by direct evaluation of the rank of G, or by topological analysis of the measured network.

- A critical measurement is the one whose elimination decreases the rank of G and result in unobservable system

$$G(x^k) = \frac{\partial g(x^k)}{\partial x} = H^T(x^k)R^{-1}H(x^k)$$

Observability example



$$P_{ij} = f(v_i, v_j, q_i, q_j)$$

$$Q_{ij} = f(v_i, v_j, q_i, q_j)$$

Observability criterion

Necessary but not sufficient condition

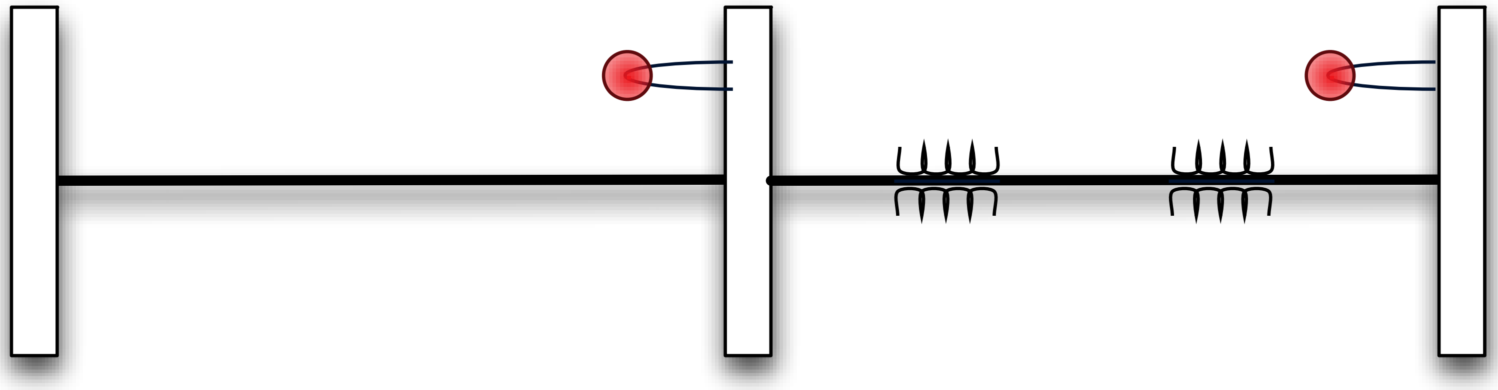
$$m \geq n$$

m: Number of measurements

n: Number of states

Is the system's observability guranteed in this case?

Observability example II



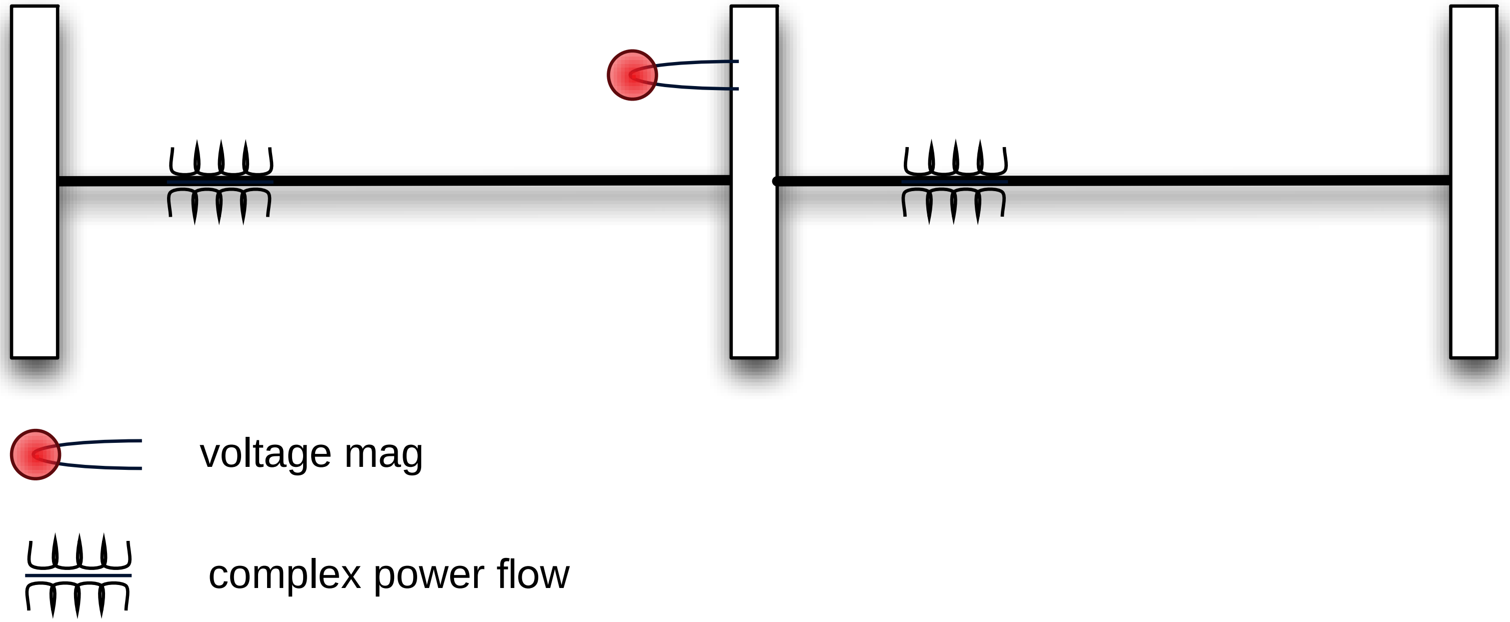
voltage mag

complex power flow

$$P_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

$$Q_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

n of *m* measurements has to be independent



$$P_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

$$Q_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

Summary of assumptions

- Quasi-steady system
  - No large variations of states over time
  - State estimator will be suspended when large disturbance happens.
- Errors in measurements are
  - Gaussian in nature with known deviation
  - Independent
- Strong assumption
  - Power system topology model is correct

ROYAL INSTITUTE OF TECHNOLOGY

Refinements

- Refinements of method for State Estimation has been the objective of much research.
- Reduce the numerical calculation complexity in order to speed up the execution.

  - 3000 bus node in 1-2 seconds
- Improve estimation robustness

  - less affected by erroneous input

Bad Data Detection

Data quality

- Analog measurement error
- Parameter error
- Topological error
  - Discrete measurement error
  - Model error

Bad Data Detection (Analog)

- Putting the measurements up to a set of logical test (Kirchhoff's laws) before they are input into the State Estimator
- Calculating $J(x)$ and comparing with a pre-determined limit. If the value exceeds the limit, we can assume there is “something” wrong in the measurements (Chi-square)

Bad Data Detection (Analog)

- Once the system state has been identified, i.e. we have an estimate of x
- We can use the estimate to calculate

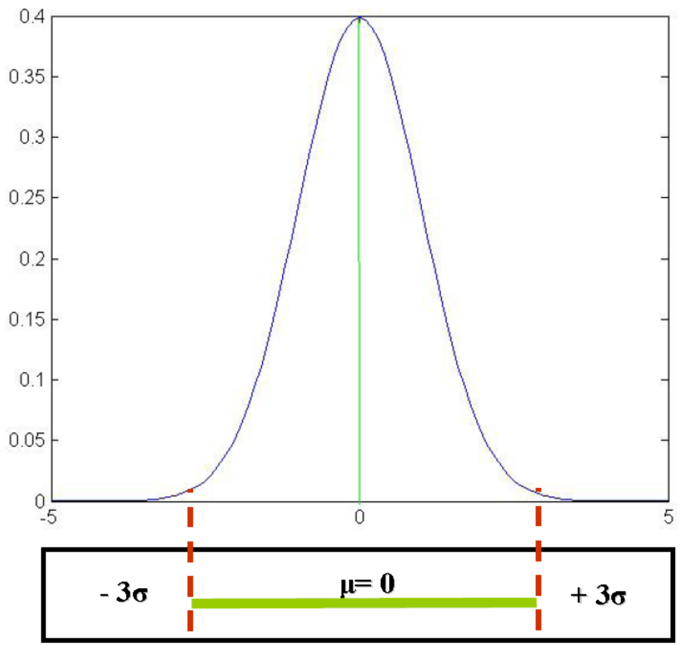
$$r_i = z_i - h_i(\hat{x})$$

- If there is any residual in this calculation that “stands-out” this is an indication that particular measurement is incorrect

Largest normalized residual

$$r_i^N = \frac{z_i - h(\hat{x})}{\sigma_i}$$

- The normalized residual follows the standard normal distribution



$N(0,\sigma^2)$

$\mu \pm \sigma$ (68.26%)

$\mu \pm 3\sigma$ (99.74%)

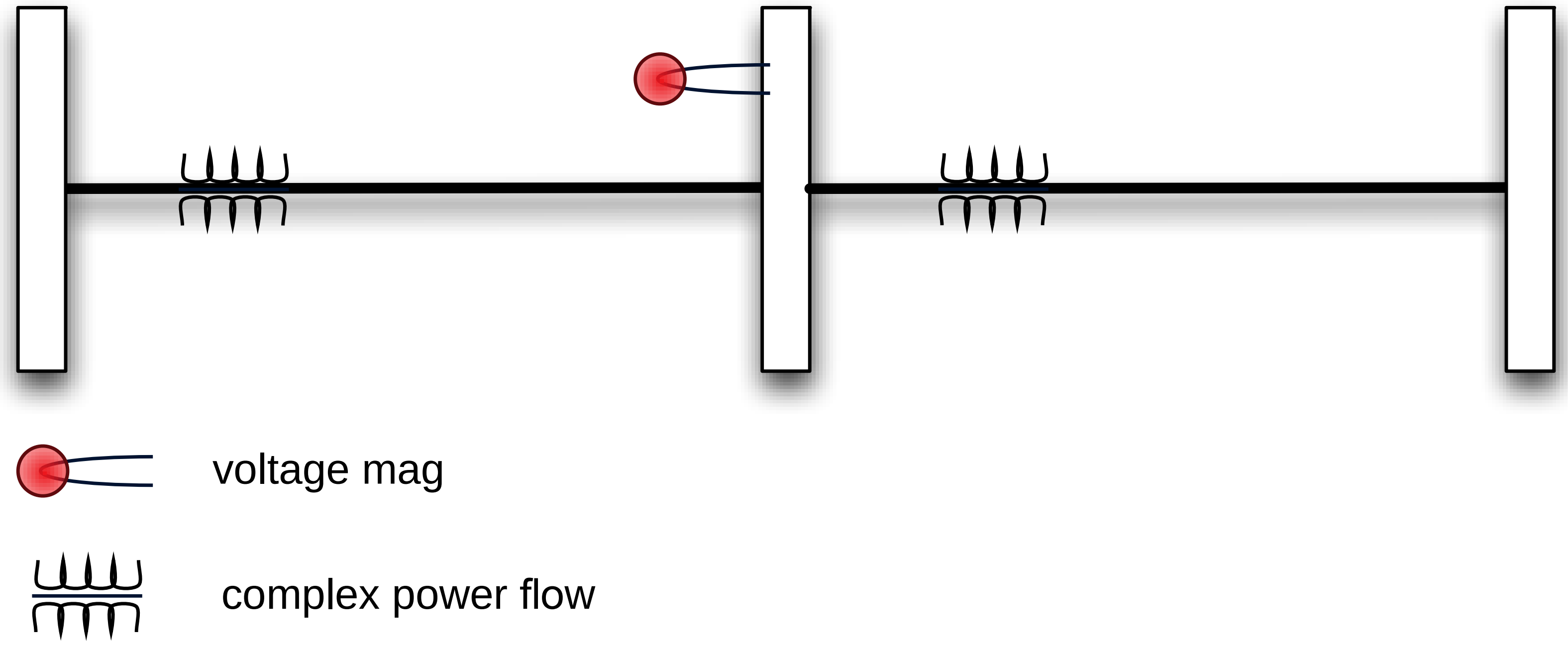
Limitations

- The critical measurements have zero residuals, hereby they can not be detected

$$\hat{z}_i = H_i (H^T H) H^T R^{-1} z = Kz$$
$$r = z - \hat{z} = (1 - K) z = Sz$$

$$S = \begin{bmatrix} t & t & t & t & t \\ 0 & 0 & 0 & 0 & 0 \\ . & . & . & 0 & . \\ . & t & . & . & . \\ 0 & 0 & 0 & 0 & t \end{bmatrix}$$

Critical measurement example



$$P_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

$$Q_{ij} = f(v_i, v_j, \theta_i, \theta_j)$$

Parameter and structural processing

$$z_i = h_i(x) + e_i \Rightarrow z_i = f_i(p) + e_i$$

- Similar theory can be applied

State estimation functions

1. Bad data processing and elimination given redundant measurements

2. Topology processing:

   create bus/branch model (similar to Y matrix)

3. Observebility analysis:

   all the states in the observable islands have unique solutions

4. Parameter and structural processing

Exercise session (Dec 10th, 15:00-17:00)

- State estimation exercises
  - Download tool (Power Education Toolbox) from course website
- Assignment Matlab code walk-through
  - Download matlab code from Course website
- Location (L52)