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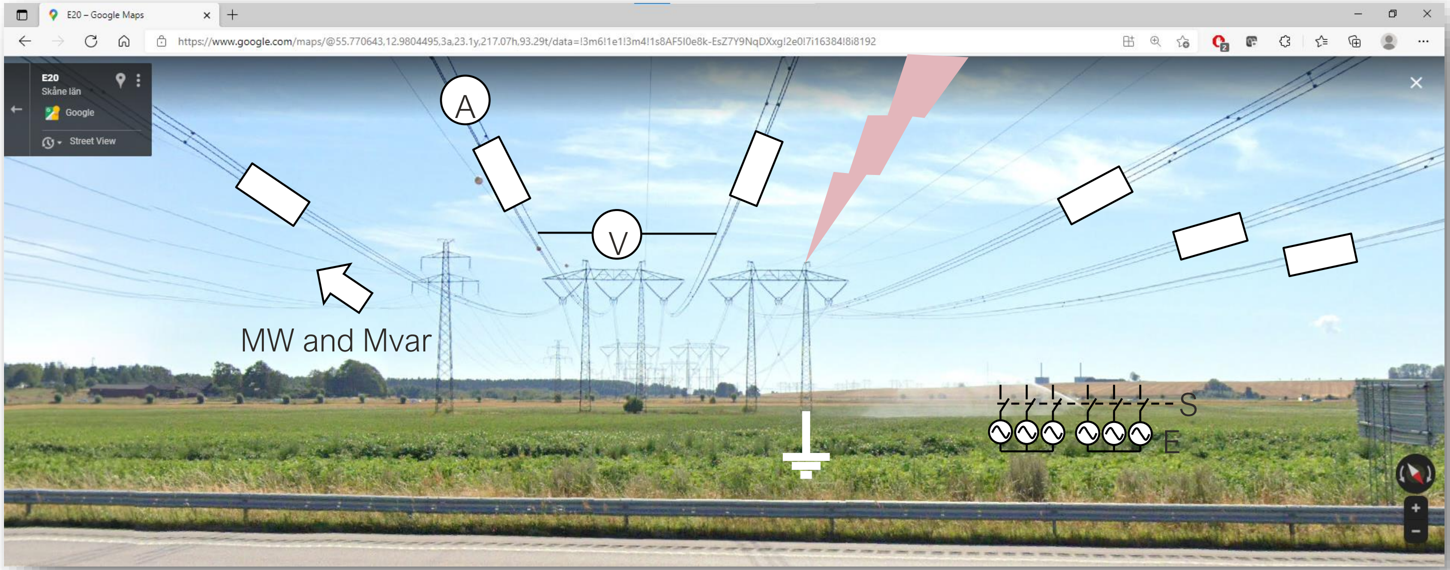
FACULTY OF ENGINEERING



Physical modelling – AC Power systems

OLOF SAMUELSSON, INDUSTRIAL ELECTRICAL ENGINEERING AND AUTOMATION

Outline

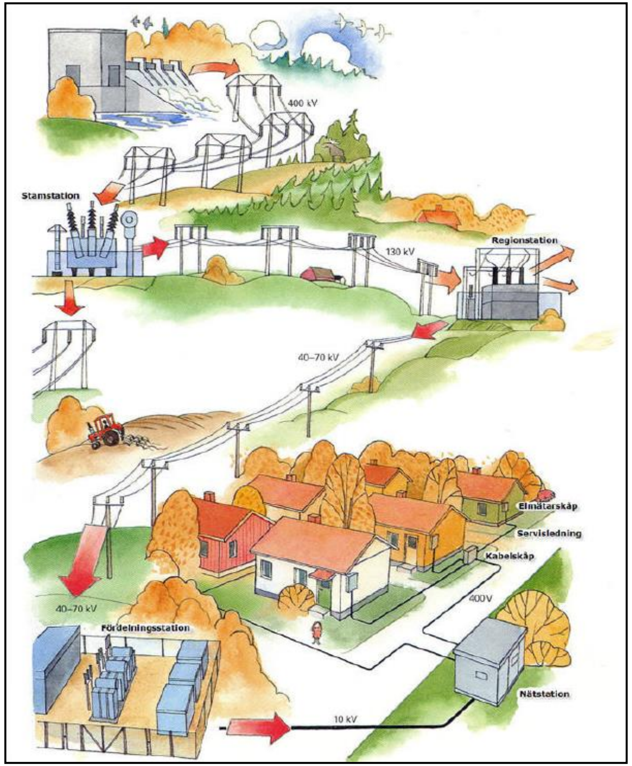
- The electric power system
- Electromagnetic transients
- Phasor model at steady state – power flow
- Electro-mechanical and mechanical oscillations
- Dynamic phasor simulation
- Linearized DAE and ODE
- Modal analysis
- Case study: Iceland

The Nordic synchronous area

- Three main parts of a power system
  - Electricity **consumption** – demand
  - Electricity **generation** – power plants
  - Electricity **network** or grid

- Nordic area is one dynamic system
  - National borders just organizational boundaries
  - HVDC links permit trading but block most dynamics
  - Western Denmark in Continental Europe area

Voltage levels

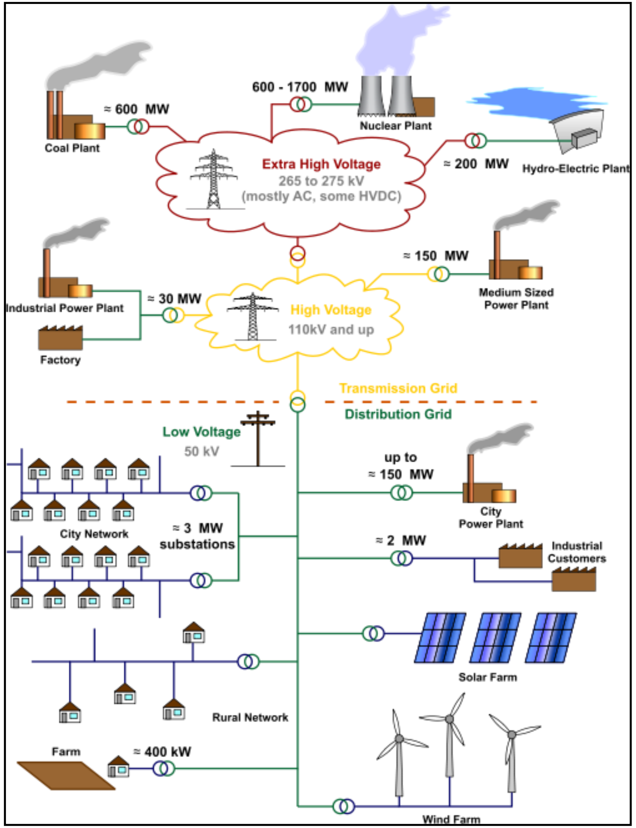


- Transmission 420 kV and 230 kV
- **TSO** Svenska Kraftnät
- Meshed structure

- Subtransmission 145 kV
- **DSO** Vattenfall, E.ON, Ellevio + few
- Meshed structure

- MV distribution 10-70 kV
- **DNO** Göteborg Energi, Kraftringen, DSOs + hundreds
- Radial structure

- LV distribution 0.4 kV
- See MV distribution
- Radial structure



Inputs – What drives the system?

- Power flow variations
  - Consumer demand determines consumption
  - Electricity market determines production
  - Weather determines variable production
- Disturbances
  - Weather
  - Equipment failure
  - Human error

Operation

- Goals

1. Clear faults fast (safety) and selectively
2. Voltage should be less than 10 % from nominal value
3. Frequency should be less than 0.1 Hz from nominal 50 Hz
   – Schedule generation to balance consumption
   – Frequency control manages deviations in power balance

- Challenges
  – Many owners
  – Large distance
  – Many components
  – Many time scales
  – Limited observability
  – Limited controllability

Power system automation by time scale

- Protection (50 ms – 3 s)
  - For each component: Detect abnormal situation and isolate fault
- Frequency control (s)
  - Turbine control
- Stability controls (1 Hz)
  - Power oscillation damping
- Voltage control (s-min)
  - Transformers, generators, capacitors

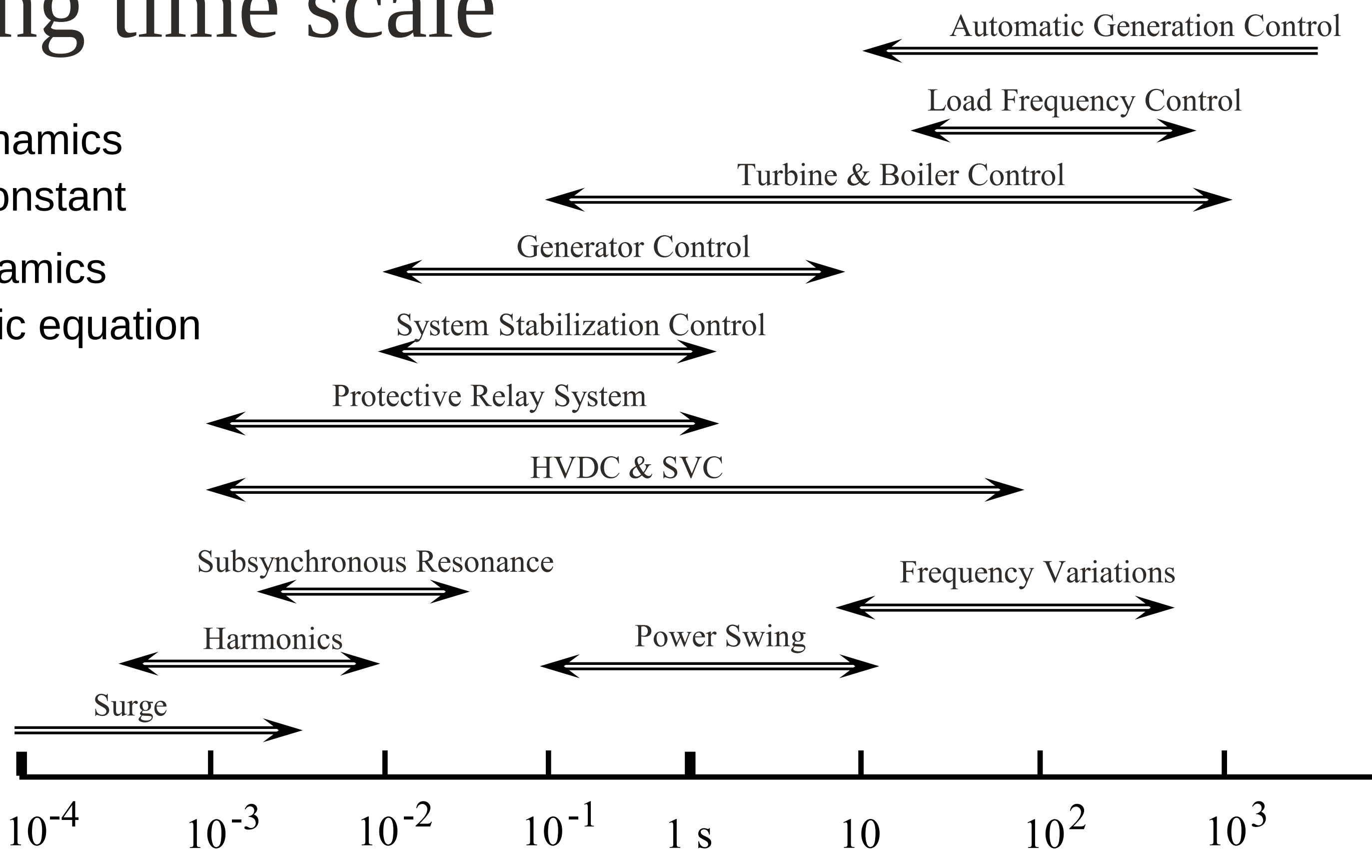
- Control room: Mainly monitoring + dispatch of repair crew

Modelling challenges

- Model scope
  - Different models for different purposes
  - Models are geographically limited – extent and resolution
  - Models are temporally limited
- Keeping model valid
  - Svenska Kraftnät manages transmission+subtransmission model
  - Each DNO manages MV+LV distribution model (asset database, GIS)
  - Control room software manages network topology (breaker status)
  - Least square fitting of actual operating point to data + measurements

Selecting time scale

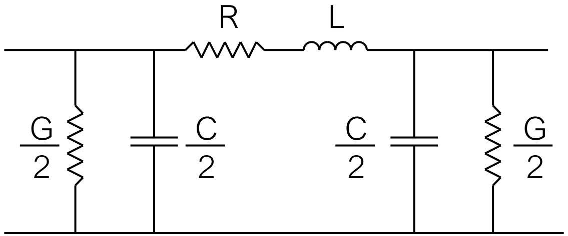
- Too slow dynamics
  - Make constant
- Too fast dynamics
  - Algebraic equation



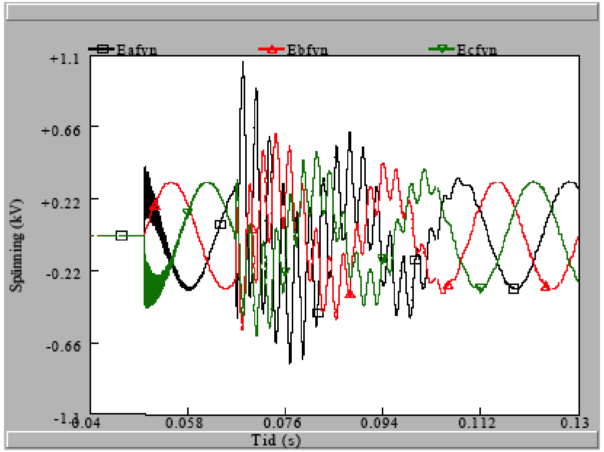
Power line physics

- Magnetic field from current in conductors
  - Series inductance L in H/km
- Ohmic losses from current in conductors
  - Series resistance R in Ω/km
- Electrostatic field between different potentials
  - Shunt capacitance C in F/km
- Ohmic losses from discharges to air
  - Shunt conductance G in Ω^{-1}/km

π-model of one phase



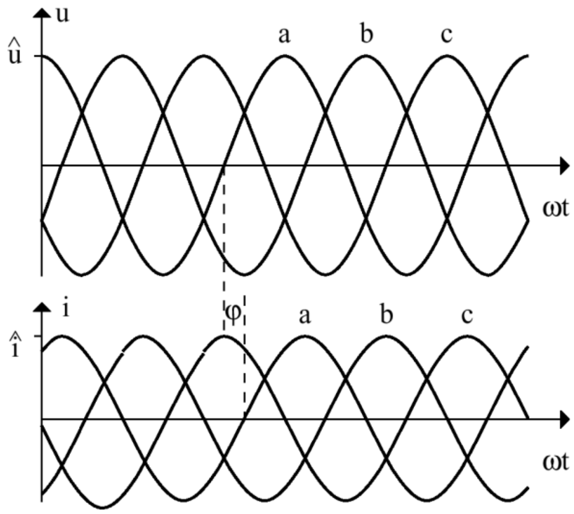
Electromagnetic transients (EMT)

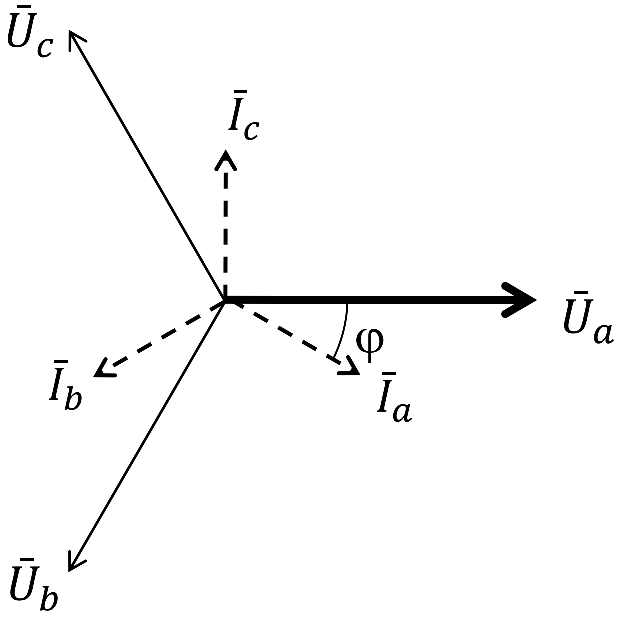


- Relevant waveform resolution: ns to μs
- Purpose: Matching with high voltage lab measurements
- Modelling
  - Explicit waveforms represent voltages and currents
  - Three-phase line π-model has nine dynamic states
- Simulation software
  - EMTP, PSCAD/EMTDC, RSCAD/EMTDC
  - Everything modelled as RLC-circuits with sources
  - Typically fixed time step ns to μs

Complex phasors

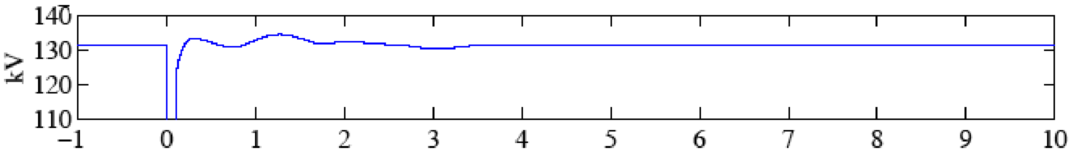
- During a cycle, an AC quantity can be represented by a complex number
- In power engineering, absolute value of phasor is rms value
- Frequency is implicit; typically nominal





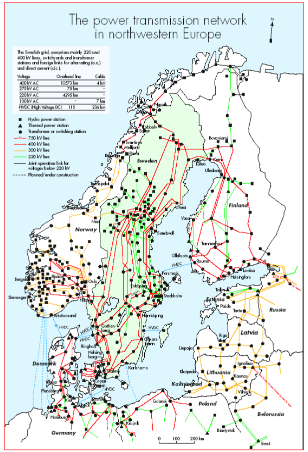
Dynamic phasor simulation

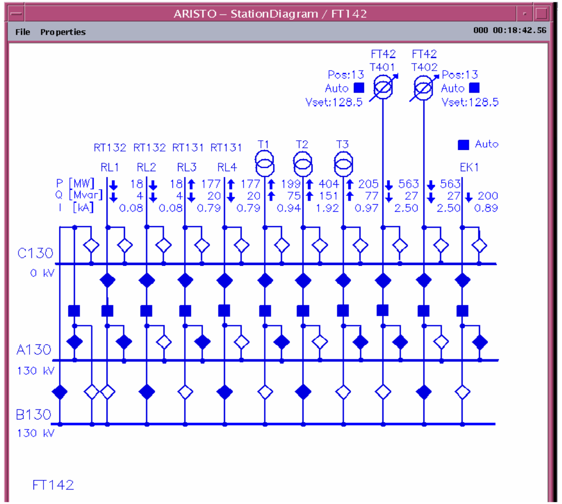
- Relevant waveform resolution: few cycles and up
- Purpose: Analyse behaviour of entire system
- Modelling
  - Complex phasors represent voltages and currents
  - Three-phase line π-model has no dynamic states
- Simulation software
  - PSS/E, PowerFactory, EUROSTAG, ARISTO
  - Network modelled as complex impedances, dynamics in generators
  - Typically variable time step ms and up



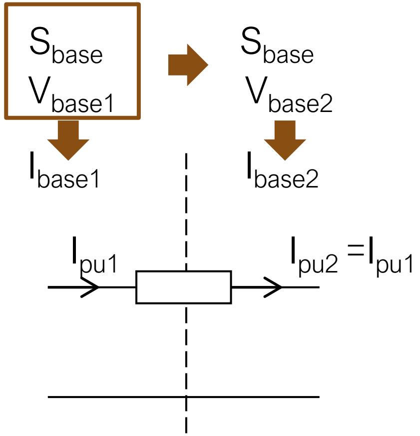
ARISTO real-time simulator

- By Svenska Kraftnät/ABB
  - For operator training
  - EMS can use SCADA or ARISTO as data source
- Circuit breaker-based model
  - Connecting/sectionalizing bus bars changes topology
- Full Nordic model
  - 29 000 switches
  - 1500 generators
  - 3000 loads
  - 3200 switchyards →





Normalization eliminates transformers

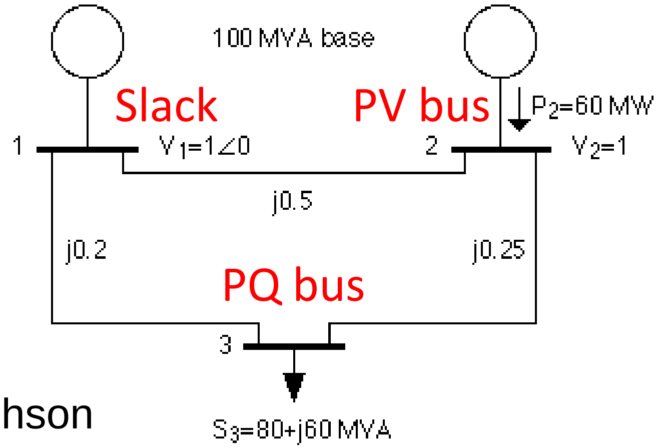


- At each voltage level an admittance matrix captures all lines
- An admittance matrix capturing several voltage levels very complicated

- Working with normalized – “per unit” quantities
  - Normalizing to common MVA base eliminates transformers
  - Normalizing to MVA base of each component → parameters similar
- Normalized quantities is numerically advantageous
  - Power systems analysis key application of early computer analysis

Steady state power flow

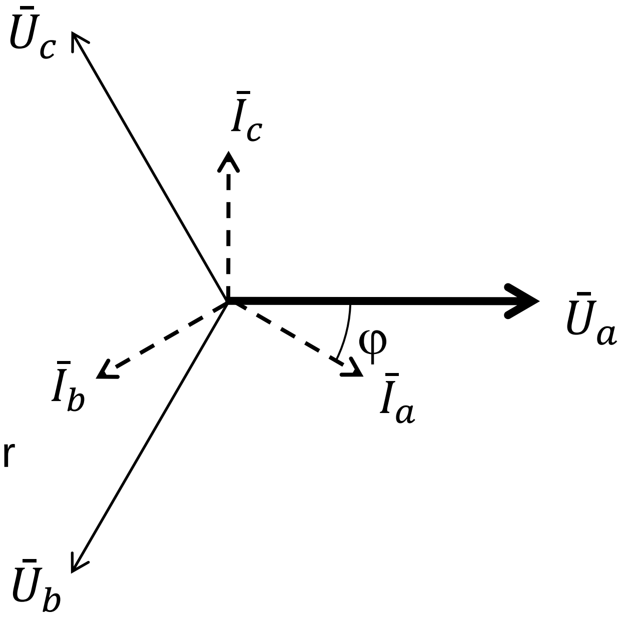
- Find V and θ and based on that flows and losses
- Example:
- Unknowns: $x=[\theta_2\ \theta_3\ V_3]^T$
- y=f(x):
  $f(x)=[P_2(x)\ P_3(x)\ Q_3(x)]^T$,
  $P_k(x)$ is P from bus k to rest of network
  $y=[60\ -80\ -60]^T$
- Solve numerically often with Newton-Raphson
- Jacobian inherits structure of admittance matrix
- Power flow calculations basis for power system planning



$$J=\frac{\partial f_i}{\partial x_j}=\begin{bmatrix}\frac{\partial P_2}{\partial \theta_2} & \frac{\partial P_2}{\partial \theta_3} & \frac{\partial P_2}{\partial V_3}\\ \frac{\partial P_3}{\partial \theta_2} & \frac{\partial P_3}{\partial \theta_3} & \frac{\partial P_3}{\partial V_3}\\ \frac{\partial Q_3}{\partial \theta_2} & \frac{\partial Q_3}{\partial \theta_3} & \frac{\partial Q_3}{\partial V_3}\end{bmatrix}$$

Symmetry

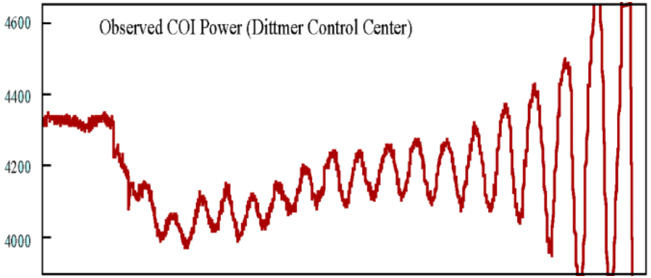
- Symmetry = All phase quantities have same magnitude and ±120° phase separation
  - Enough to compute one phase
  - Other phases only differ by phase angle
  - Three-phase power = 3 x single phase power



- Most faults are unsymmetric
  - Tree leaning on one phase conductor
  - Lightning strike
  - Object falling on two phase conductors etc.
- Unsymmetry is managed by change of coordinates using “sequence components”

Electro-mechanical oscillations

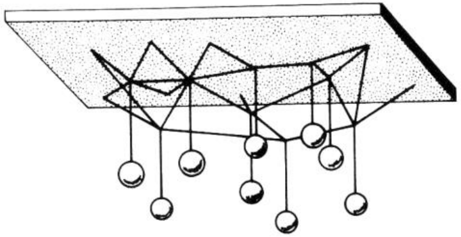
- Generator speeds
  - All tend towards 50 Hz, oscillation around 50 Hz (Americas 60 Hz)
  - Kinetic energy $(J\omega^2)/2$ varies, power oscillates
- Resonance!
  - 1-3 Hz single generator, <1 Hz generator groups

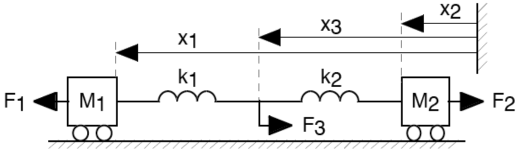


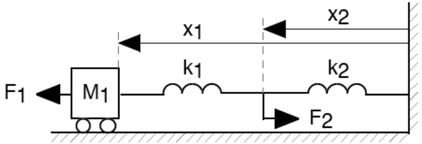
0-90 s
ca 0.25 Hz

MW flow California-Oregon, 10 August 1996
just before blackout of 7.5 million people

Mechanical oscillations







- General system
  - Many resonances (modes)
  - Complex mode shapes
- Two-mass system
  - M1 vs M2 = swing mode
  - M1 with M2 = rigid body
  - Frequency dynamics
- Single-mass system
  - Only swing mode

Dynamic phasor model

- Complex variables represented as $[Re(\cdot) \quad Im(\cdot)]^T$ or $[Abs(\cdot) \quad Arg(\cdot)]^T$
- Network equations with bus admittance matrix: $I = Y_{bus}V$
- Nonlinear differential-algebraic equations for component i:

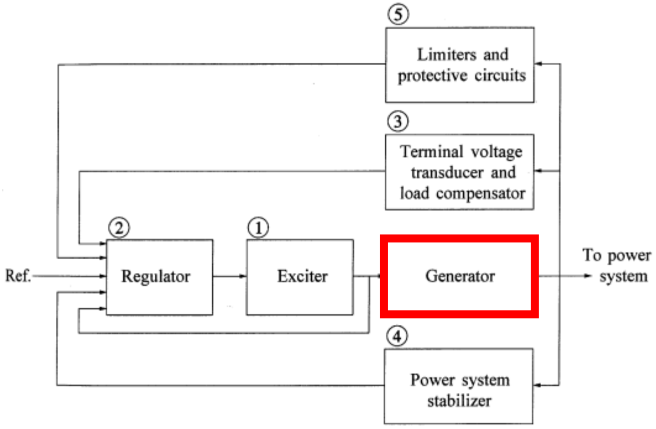
$$\begin{cases} \dot{x}_{d,i} = f_i\,(x_{d,i}, x_{a,i}, u_i) \\ 0 = g_i\,(x_{d,i}, x_{a,i}, u_i) \\ y_i = h_i\,(x_{d,i}, x_{a,i}, u_i) \end{cases}$$

, d=dynamic, a=algebraic, u=inputs, y=outputs

- Build system:

$$\begin{cases} \dot{x}_d = f\,(x_d, x_a, u) \\ 0 = g\,(x_d, x_a, u) \\ y = h\,(x_d, x_a, u) \end{cases} \text{ where } x_d = \begin{bmatrix} x_{d,1} \\ \vdots \\ x_{d,k} \end{bmatrix}, x_a = \begin{bmatrix} x_{a,1} \\ \vdots \\ x_{a,k} \\ y \\ V \end{bmatrix}, u = \begin{bmatrix} u_1 \\ \vdots \\ u_k \end{bmatrix}, y = \begin{bmatrix} y_1 \\ \vdots \\ y_k \end{bmatrix}$$

Synchronous generator



From EUROSTAG reference manual

$$-r\frac{\omega_o r_f}{M_{dv}}E_{fd} + \frac{\omega_o r_f}{DET}\left[\frac{L''_{MD} l_D^2}{DET} - (l_D + mrc)\right]\lambda_f + \frac{\omega_o r_f}{DET}\left[mrc + \frac{L''_{MD} l_D l_f}{DET}\right]\lambda_D + \frac{\omega_o r_f}{DET} l_D L''_{MD} i_d - \frac{d\lambda_f}{dt} = 0 \quad \text{(8-a)}$$

$$\frac{\omega_o r_D}{DET}\left[mrc + \frac{L''_{MD} l_f l_D}{DET}\right]\lambda_f + \frac{\omega_o r_D}{DET}\left[l_f^2 \frac{L''_{MD}}{DET} - (l_f + mrc)\right]\lambda_D + \frac{\omega_o r_D}{DET} l_f L''_{MD} i_d - \frac{d\lambda_D}{dt} = 0 \quad \text{(8-b)}$$

$$\frac{\omega_o r_{Q1}}{l_{Q1}}\left(\frac{L'_{MQ}}{l_{Q1}} - 1\right)\lambda_{Q1} + \frac{\omega_o r_{Q1}}{l_{Q1}}\frac{L'_{MQ}}{l_{Q2}}\lambda_{Q2} + \frac{\omega_o r_{Q1}}{l_{Q1}} L'_{MQ} i_q - \frac{d\lambda_{Q1}}{dt} = 0 \quad \text{(8-c)}$$

$$\frac{\omega_o r_{Q2}}{l_{Q2}}\left(\frac{L'_{MQ}}{l_{Q2}} - 1\right)\lambda_{Q2} + \frac{\omega_o r_{Q2}}{l_{Q2}}\frac{L'_{MQ}}{l_{Q1}}\lambda_{Q1} + \frac{\omega_o r_{Q2}}{l_{Q2}} L'_{MQ} i_q - \frac{d\lambda_{Q2}}{dt} = 0 \quad \text{(8-d)}$$

$$-\omega(l_q + X_T)i_q - \omega\left(\frac{L'_{MQ}}{l_{Q1}}\lambda_{Q1} + \frac{L'_{MQ}}{l_{Q2}}\lambda_{Q2} + L'_{MQ} i_q\right) + (r + R_T)i_d + \sin\theta.U_R - \cos\theta.U_i = 0 \quad \text{(8-e)}$$

$$\omega(l_d + X_T)i_d + \omega\left(\frac{L''_{MD}}{DET} l_D \lambda_f + \frac{L''_{MD}}{DET} l_f \lambda_D + L''_{MD} i_d\right) + (r + R_T)i_q + \cos\theta.U_R + \sin\theta.U_i = 0 \quad \text{(8-f)}$$

in which : $DET = l_f l_D + mrc\,(l_f + l_D)$

$$\frac{1}{L''_{MD}} = \frac{1}{M_d} + \frac{l_f}{DET} + \frac{l_D}{DET}$$

$$\frac{1}{L'_{MQ}} = \frac{1}{M_q} + \frac{1}{l_{Q1}} + \frac{1}{l_{Q2}}$$

$$\frac{P_N}{SNREF}Cm + D(\omega_{ref} - \omega) + \frac{L''_{MD}}{DET} l_D i_q \lambda_f + \frac{L''_{MD}}{DET} l_f i_q \lambda_D - \frac{L'_{MQ}}{l_{Q1}} i_d \lambda_{Q1} - \frac{L'_{MQ}}{l_{Q2}} i_d \lambda_{Q2} + (L''_{MD} - l'_{MQ}) i_d i_q - 2H\frac{d\omega}{dt} = 0 \quad [13]$$

$$-\omega_0\omega_{ref} + \omega_0\omega - \frac{d\theta}{dt} = 0 \quad [14]$$

6th order model

3rd order model

$$-r\frac{\omega_o r_f}{M_{dv}}E_{fd} + \frac{\omega_o r_f}{lf}\left(L'_{MD} i_d + \left(\frac{L'_{MD}}{l_f} - 1\right)\lambda_f\right) - \frac{d\lambda_f}{dt} = 0 \quad \text{(8-a')}$$

$$-\omega(l_q + X_T)i_q - \omega M_q i_q + (r + R_T)i_d + \sin\theta.U_R - \cos\theta.U_i = 0 \quad \text{(8-e')}$$

$$\omega(l_d + X_T)i_d + \omega L'_{MD}\left(i_d + \frac{\lambda_f}{l_f}\right) + (r + R_T)i_q + \cos\theta.U_R + \sin\theta.U_i = 0 \quad \text{(8-f')}$$

in which $\frac{1}{L'_{MD}} = \frac{1}{M_d} + \frac{1}{l_f}$

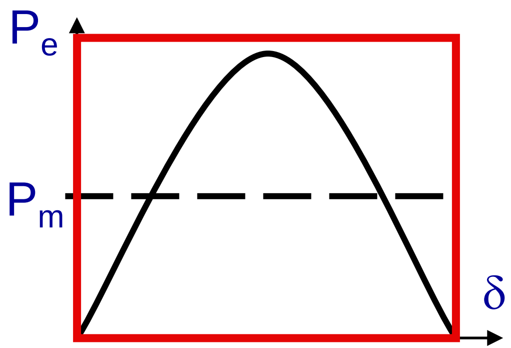
$$\frac{P_N}{SNREF}Cm + D(\omega_{ref} - \omega) + \frac{1}{l_f} i_q \lambda_f + (L'_{MD} - M_q) i_d i_q - 2H\frac{d\omega}{dt} = 0 \quad [13']$$

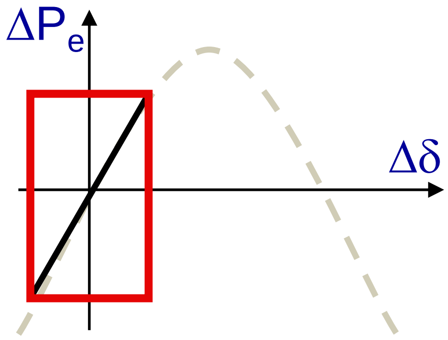
$$-\omega_0\omega_{ref} + \omega_0\omega - \frac{d\theta}{dt} = 0 \quad [14]$$

Analysis methods

- Non-linear **time simulations**
  - Anything can be simulated
  - Operating point must be selected
  - Disturbance must be selected – only excites <u>some</u> dynamics
- **Modal analysis** of linearized model
  - Steady state operating point must be selected
  - Only valid near linearization point
  - Reveals <u>all</u> dynamics
- Best to **combine**!

Linearization simplifies





- Size of disturbance

  Nonlinear model for large changes $P_e = K_1 \cdot \sin\delta$

  Linearized model for small changes $\Delta P_e = K_2 \cdot \Delta\delta$

- How small is small?

  ”Small” is when linear model is valid ☺

Linearized DAE

- Linearize around operating point

$$\Delta x_d = x_d - x_d^0$$
$$\Delta x_a = x_a - x_a^0$$
$$\Delta u = u - u^0$$
$$\Delta y = y - y^0$$

- Then

$$E_{dae}\frac{d}{dt}\begin{bmatrix}\Delta x_d \\ \Delta x_a\end{bmatrix} = A_{dae}\begin{bmatrix}\Delta x_d \\ \Delta x_a\end{bmatrix} + B_{dae}\Delta u$$

$$\Delta y = C_{dae}\begin{bmatrix}\Delta x_d \\ \Delta x_a\end{bmatrix} + D_{dae}\Delta u$$

where $E_{dae} = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$ $\quad A_{dae} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial x_d} & \frac{\partial f}{\partial x_a} \\ \frac{\partial g}{\partial x_d} & \frac{\partial g}{\partial x_a} \end{bmatrix}$ $\quad B_{dae} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial u} \\ \frac{\partial g}{\partial u} \end{bmatrix}$

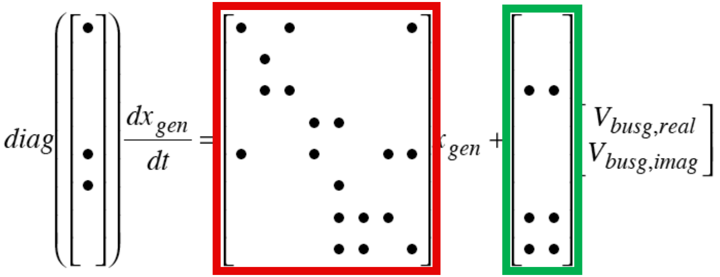
$$C_{dae} = \begin{bmatrix} C_1 & C_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial h}{\partial x_d} & \frac{\partial h}{\partial x_a} \end{bmatrix} \qquad D_{dae} = D_1 = \frac{\partial h}{\partial u}$$

- Collect all vectors in one: $\Delta x = \begin{bmatrix}\Delta x_d \\ \Delta \tilde{x}_a\end{bmatrix} = \begin{bmatrix}\Delta x_d \\ \Delta x_a \\ \Delta u \\ \Delta y\end{bmatrix}$ then $E\Delta\dot{x} = A\Delta x$

Example: IEEE 9-bus

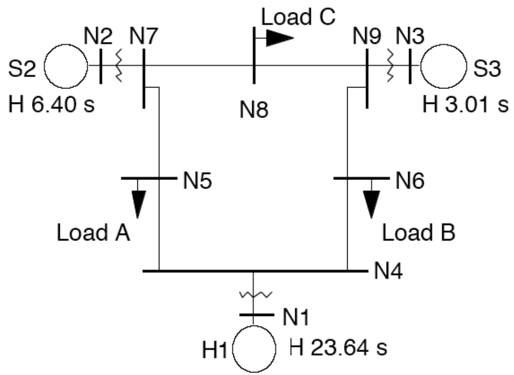
- One generator: $x_{gen} = \left[\lambda_f \; V_{ref} \; E_{FD} \; T_m \; \omega \; \delta \; I_q \; I_d \right]^T$

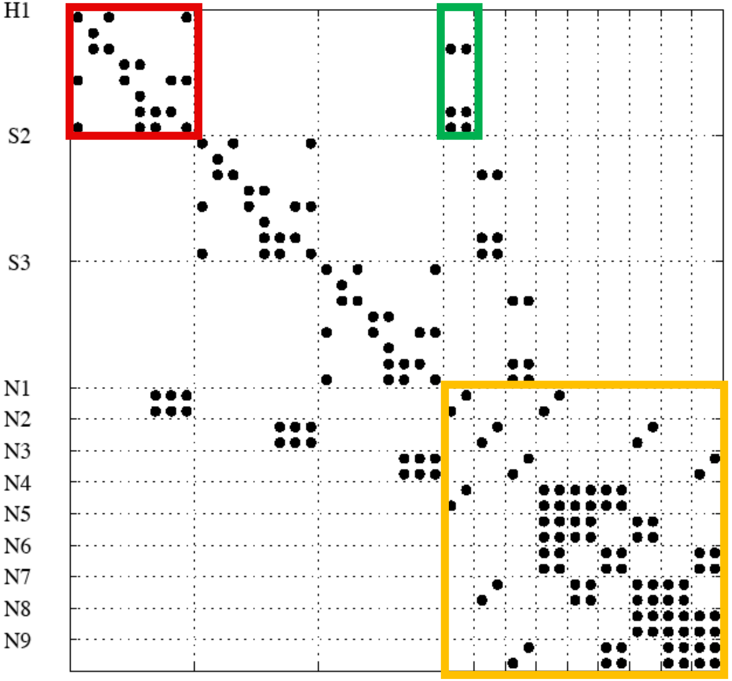
$$E_{gen} \frac{dx_{gen}}{dt} = A_{gen} x_{gen} + B_{gen} V_{busg}$$



- Full system: $x^T = \left[x_{gen1}^T \; x_{gen2}^T \; x_{gen3}^T \; V_{bus1}^T \; \cdots \; V_{bus9}^T \right]$

$$diag\left(\begin{bmatrix} E_{gen1} \\ E_{gen2} \\ E_{gen3} \\ 0 \end{bmatrix} \right) \frac{dx}{dt} = \begin{bmatrix} A_{gen1} & & & B_{gen1} \\ & A_{gen2} & & B_{gen2} \\ & & A_{gen3} & B_{gen3} \\ C_{gen1} & C_{gen2} & C_{gen3} & Y_{bus} \end{bmatrix} x$$





Eliminate algebraic variables

- Inserting $x_a = -A_{22}^{-1}(A_{21}x_d + B_2 u)$
- gives the ODE
$$\dot{x}_d = A_{ode}x_d + B_{ode}u$$
$$y = C_{ode}x_d + D_{ode}u$$
- where
$$A_{ode} = A_{11} - A_{12}A_{22}^{-1}A_{21}$$
$$B_{ode} = B_1 - A_{12}A_{22}^{-1}B_2$$
$$C_{ode} = C_1 - C_2A_{22}^{-1}A_{21}$$
$$D_{ode} = D_1 - C_2A_{22}^{-1}B_2$$
- Note: D_{ode} generally not zero

Modal analysis ODE

- Right modal matrix holds the right eigenvectors with **mode observability** information of the dynamic states:

$$\Phi^{-1} A_{ode} \Phi = \Lambda$$

$$A_{ode} \Phi = \Phi \Lambda$$

- Left modal matrix holds the left eigenvectors with **mode controllability** information of the dynamic states:

$$\Psi A_{ode} \Psi^{-1} = \Lambda$$

$$\Psi A_{ode} = \Lambda \Psi$$

Modal analysis DAE

- Right eigenvectors

$$A\Phi_{dae} = E\Phi_{dae}\Lambda$$

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Phi_{dae,d} \\ \Phi_{dae,a} \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Phi_{dae,d} \\ \Phi_{dae,a} \end{bmatrix} \Lambda$$

- **Mode observability** in **algebraic** variables:

$$\Phi_{dae,a} = -A_{22}^{-1} A_{21} \Phi_{dae,d}$$

- Left eigenvectors

$$\Psi_{dae} A = \Lambda \Psi_{dae} E$$

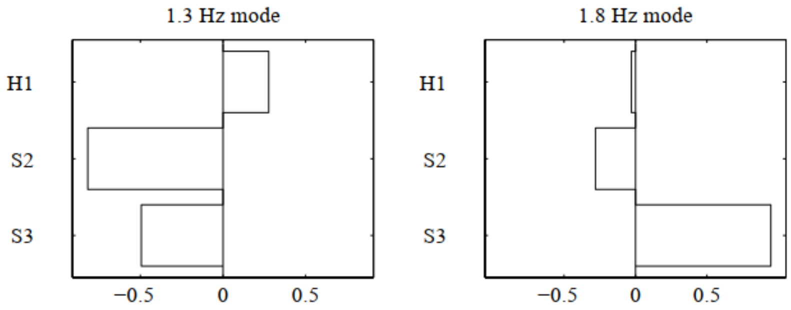
$$\begin{bmatrix} \Psi_{dae,d} & \Psi_{dae,a} \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \Lambda \begin{bmatrix} \Psi_{dae,d} & \Psi_{dae,a} \end{bmatrix} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$$

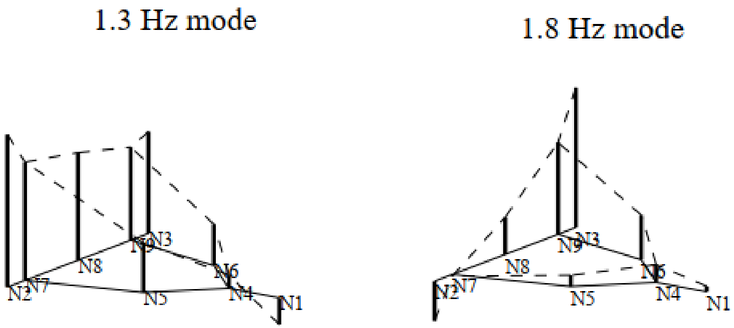
- **Mode controllability** in **algebraic** variables:

$$\Psi_{dae,a} = -\Psi_{dae,d} A_{12} A_{22}^{-1}$$

Example: IEEE 9-bus

- ODE mode shapes
  = generator speed elements in right eigenvectors
- DAE mode shapes
  = phase angle information from algebraic parts of right eigenvectors





Time-scale decomposition

- RL-circuit example: $L\frac{di}{dt} + Ri = u \Leftrightarrow L\frac{di}{dt} = -Ri + u \;\Leftrightarrow \frac{L}{R}\frac{di}{dt} = -i + \frac{u}{L}$

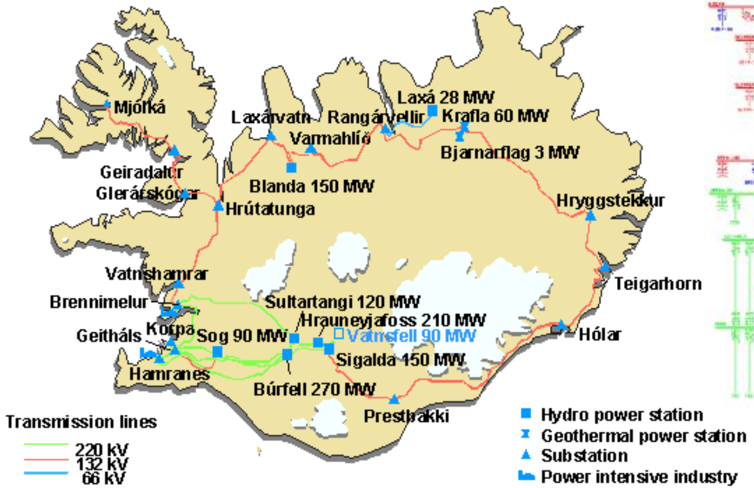
Time constant!

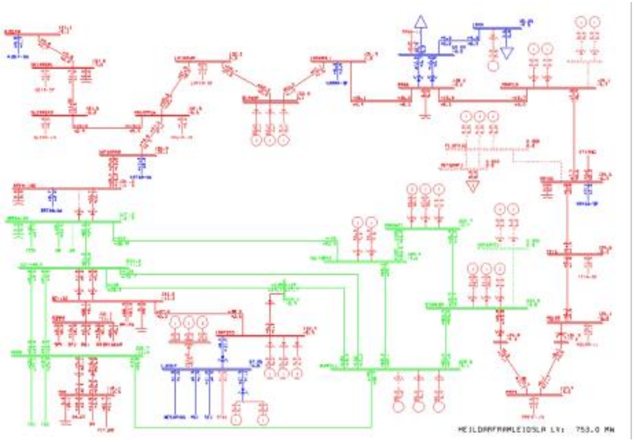
- Scale row i of A and B matrices so that A(i,i)=-1
- Then the factor in front of $\dot{x}_{d,i}$ can be interpreted as a time constant
- If some time constants are small enough

$$\begin{bmatrix} I & 0 \\ 0 & \varepsilon \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \Delta x_{slow} \\ \Delta x_{fast} \end{bmatrix} = A \begin{bmatrix} \Delta x_{slow} \\ \Delta x_{fast} \end{bmatrix}$$

- setting them to zero yields algebraic equations, like for the network equations in a phasor model

The Icelandic power system 2002





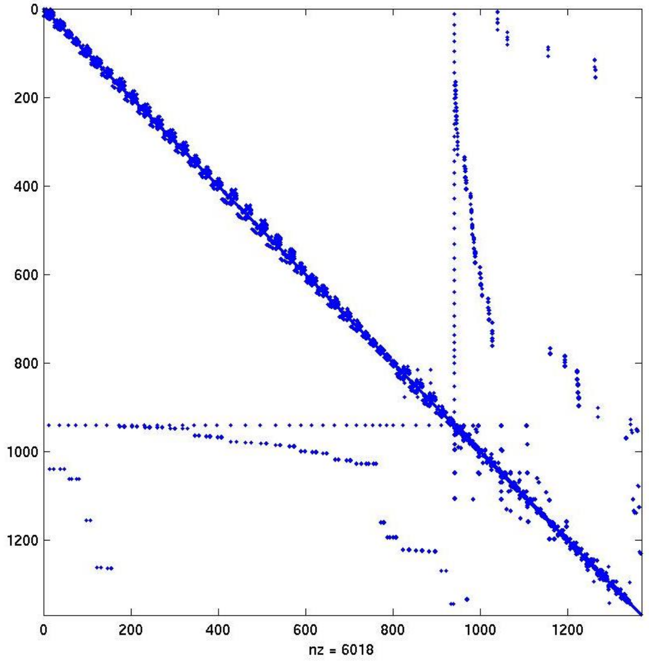
- Peak load 2002 1000 MW (Sweden 28 000 MW)
- New plant of 690 MW (!) on-line 2007

Case study and solution structure

- Scope
  - Icelandic national power system with electro-mechanical oscillations
  - Find the difficult situations challenging stability
  - Suggest damping controller!

- Multi-dimensional problem
  - Many fault locations → many linearized models
  - Many possible control signals
  - Many possible measurement signals
  - Before, combine all with all, after

Model of Icelandic power system



- 37 generators
- ≈590 dynamic states
- 202 network nodes
- ≈810 algebraic states
- Adae ≈1400x1400
- Aode ≈590x590

Control design: Measurement signal

- What quantity is best to measure?
  - Generator speed or power
  - Voltage magnitude
  - Voltage phase angle by GPS-based PMU:s
- Where to measure?
  - Location of generator or network node
- If choice not optimum
  - Oscillation not visible
  - Oscillation less visible - need more gain

Control design: Control signal

- What to control?
  - Generator voltage (for free)
  - Real power (requires new actuator)
- Where to control?
  - Location of generator or network node
- If choice not optimum
  - Less impact on oscillation
  - Actuator must be larger (expensive!)

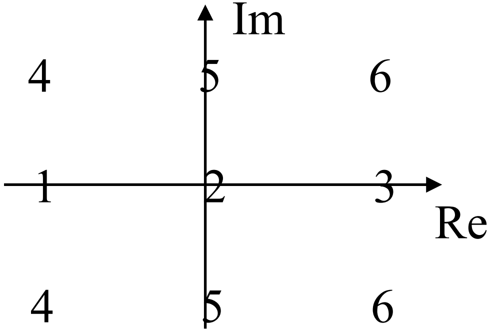
Control design: Closing the loop

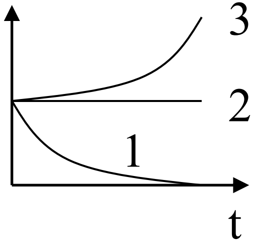
- Control signal selected
- Measurement signal selected
- Local control or communication need
- Design controller
  - Phase characteristic
  - Gain
  - Root locus plot for both

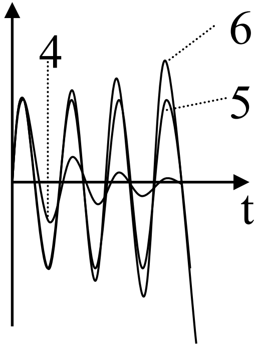
Eigenvalues $A\varphi = \varphi\lambda \quad |\lambda I - A| = 0 \quad \lambda = \sigma \pm j\omega$

- Response of one mode ~ $|\varphi_i| e^{\lambda t - \arg \varphi_i} = |\varphi_i| e^{\sigma t} \cos(\omega t - \arg \varphi_i)$

- σ is damping and ω is frequency



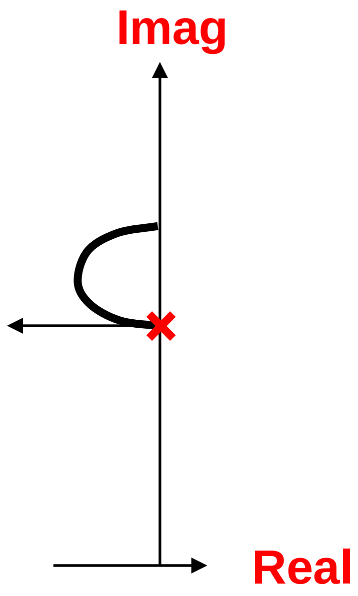




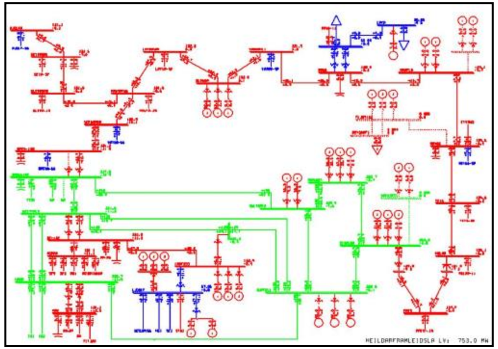
- Complex pair = resonance = *mode*

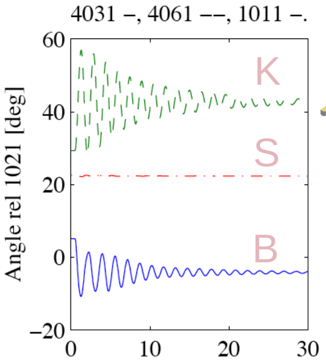
Controller

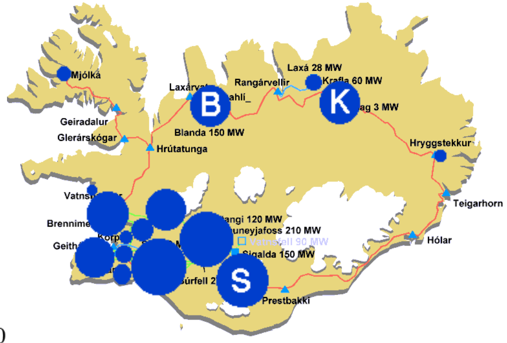
- Increase gain from zero
- Plot eigenvalues
  - Root locus plot
- If direction is α degrees wrong
  - Phase compensation of α degrees at mode frequency



Spring-mass model



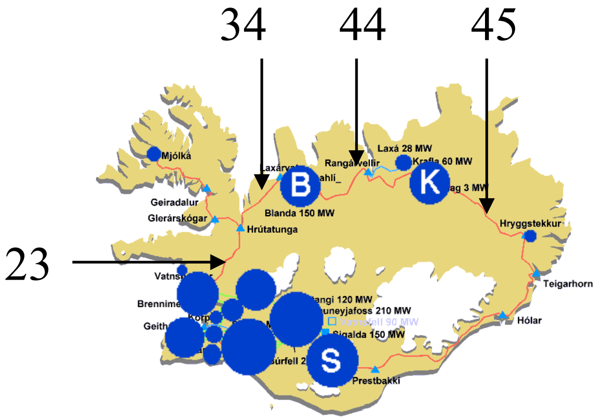




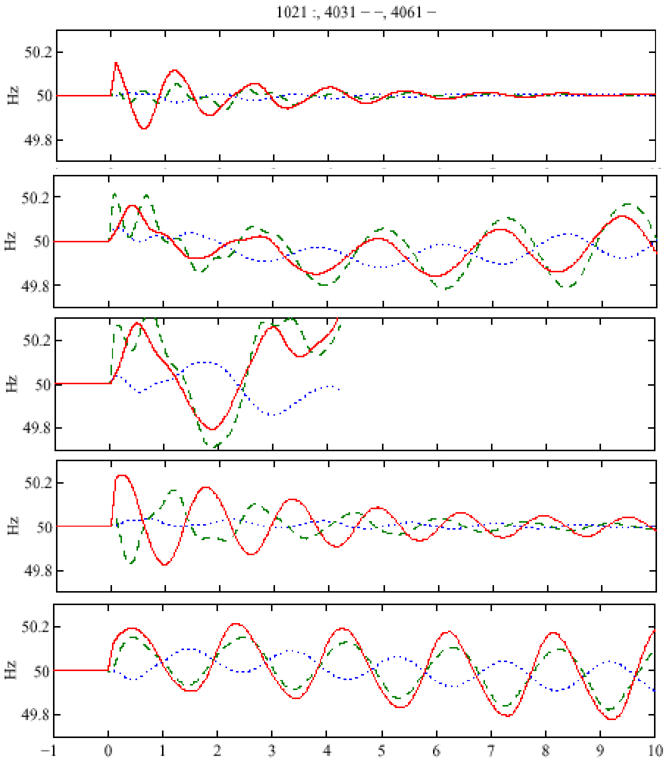
- Circle area ~ kinetic energy in power plant
- Distance ~ impedance ~ spring length
- Think
  - One large mass and two small
  - Long springs

Critical faults

- Scenarios
  - Intact system
  - Fault at 23
  - Fault at 34
  - Fault at 44
  - Fault at 45

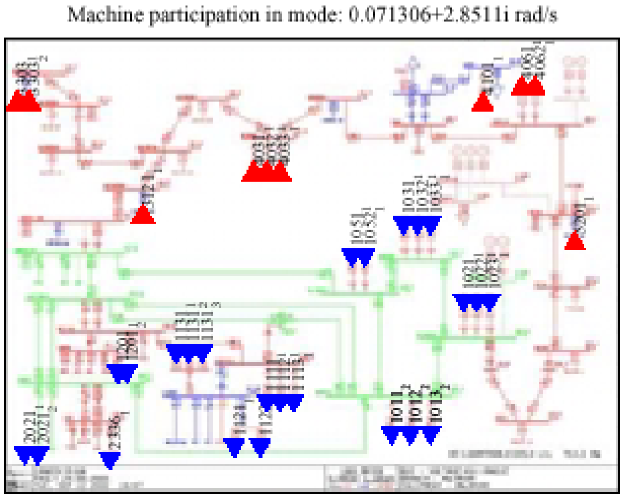


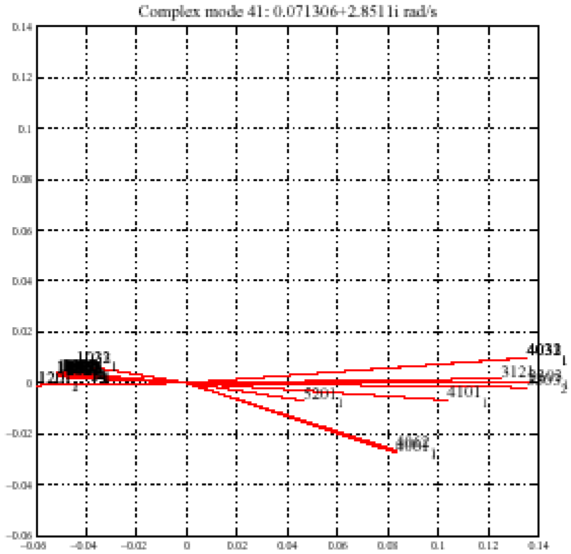
Time simulations Modes



Case	Eigenvalue	Rel. damping
0	-0.39±j4.4	+0.089
23	+0.07±j2.9	-0.025
34	+0.17±j2.5	-0.066
44	-0.12±j4.1	+0.030
45	+0.04±j3.3	-0.012

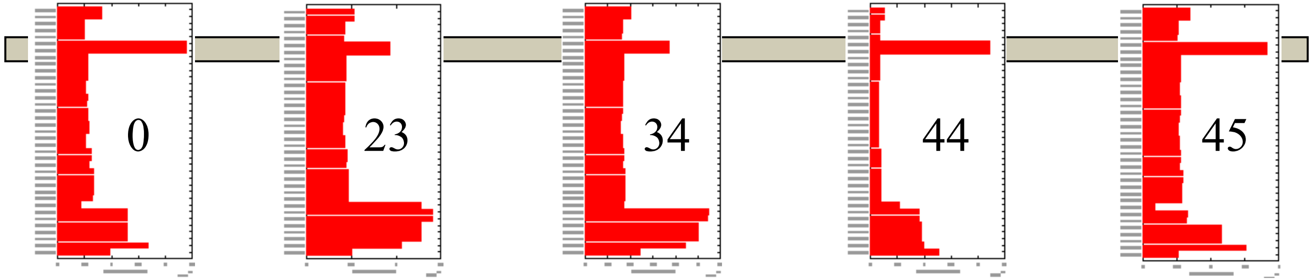
Mode shape case 23

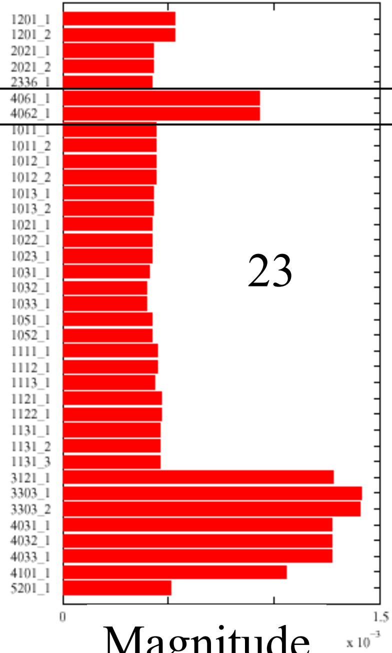




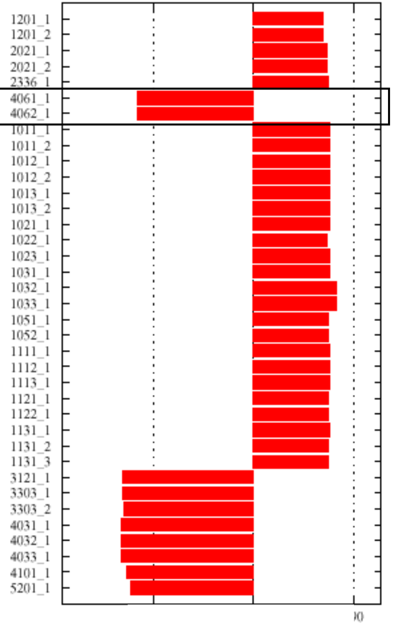
- Interarea mode involves all generators

Right eigenvector → Mode observability – speed





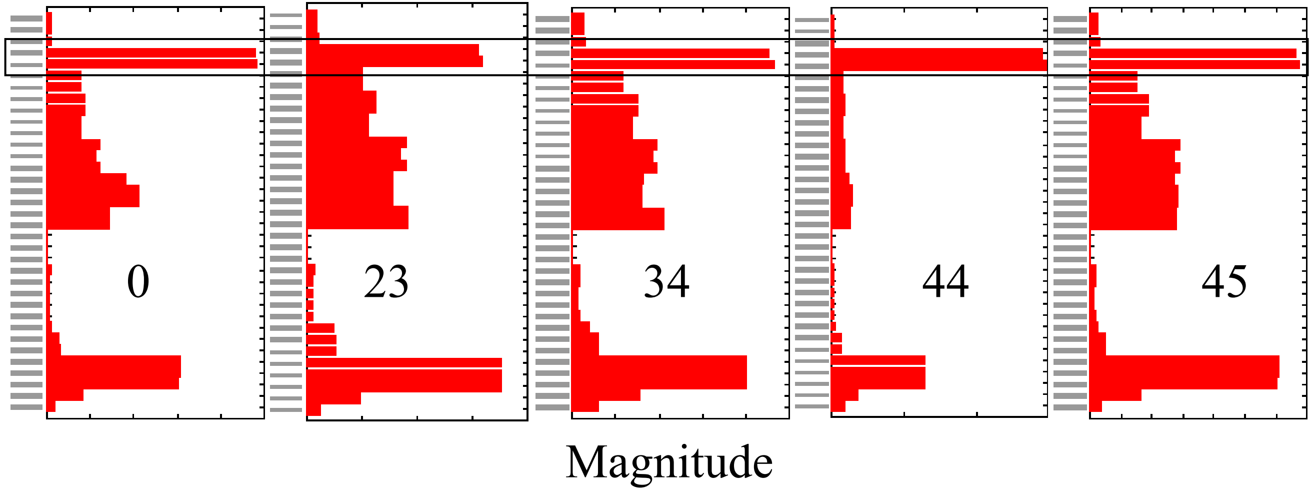
Magnitude



Argument

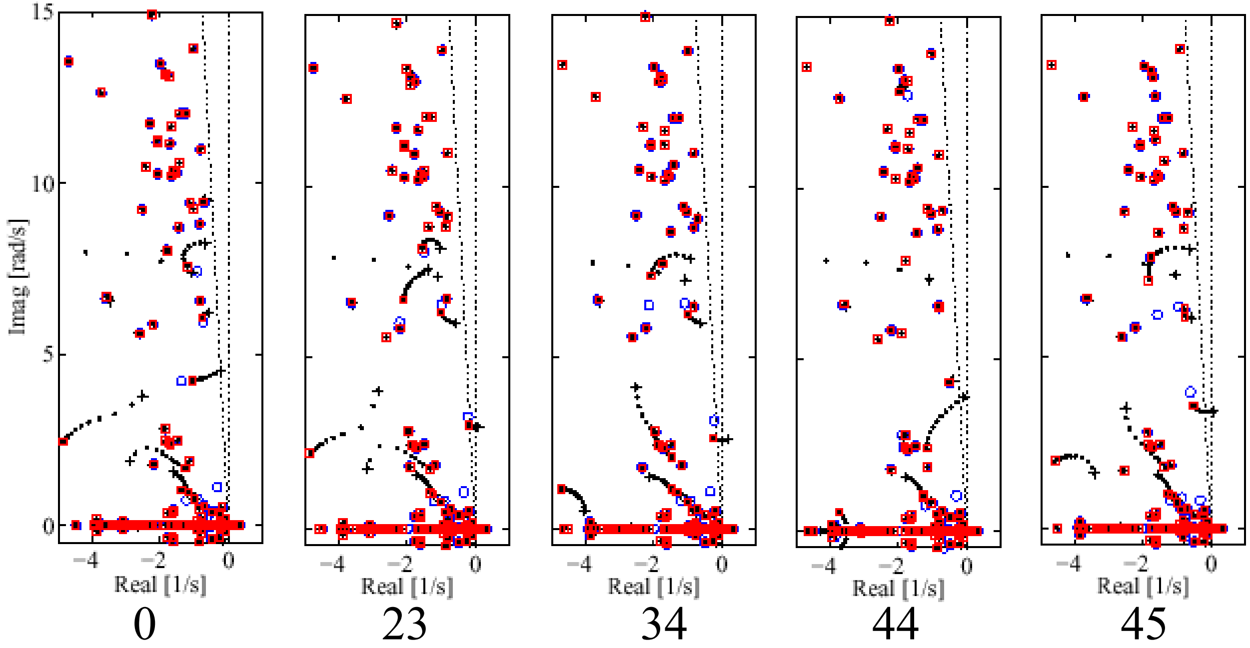
Interarea mode observable at 4061/2

Left eigenvector → Mode controllability – Voltage controller setpoint



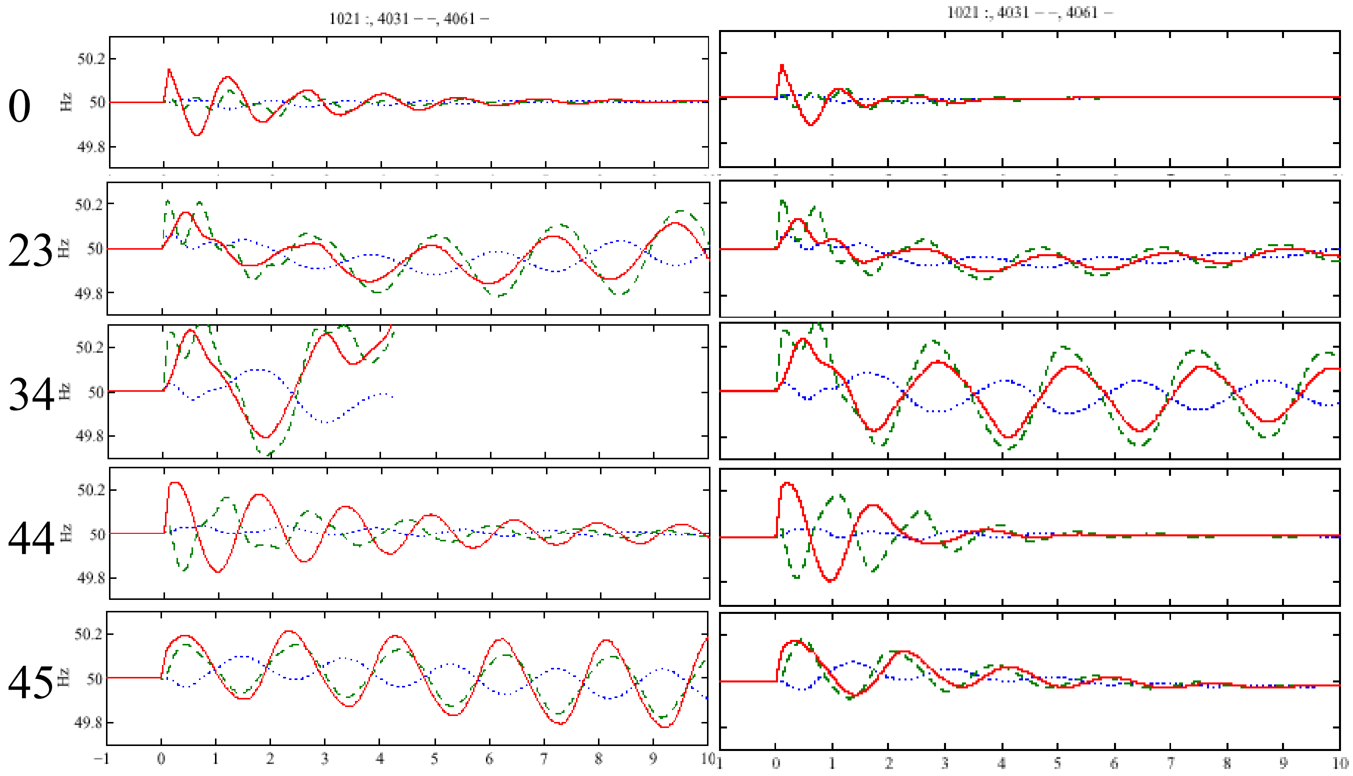
- Interarea mode controllable at 4061/2

Root locus plots



- Interarea mode damped in all cases
- Gain selected

Time simulations



Before

After

Power system modelling – summary

- Dynamics in time scales from μs to decades
- Active and reactive power as important as voltage and current
- Waveforms, one or three complex phasors represent three-phase AC quantity
- (Steady state) Operating point important – in practice one every hour
  - Time simulations – valid for one disturbance at one operating point
  - Modal analysis – valid for any disturbance at one operating point
- In modal analysis: Use information in algebraic variables of DAE
- Physical understanding necessary to debug and interpret simulations
- Great effort to keep large models up to date

“The purpose of computing is insight, not numbers”

Richard Hamming, Numerical Methods for Scientists and Engineers (1962)

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