

TSFS17 Elkraftsystem

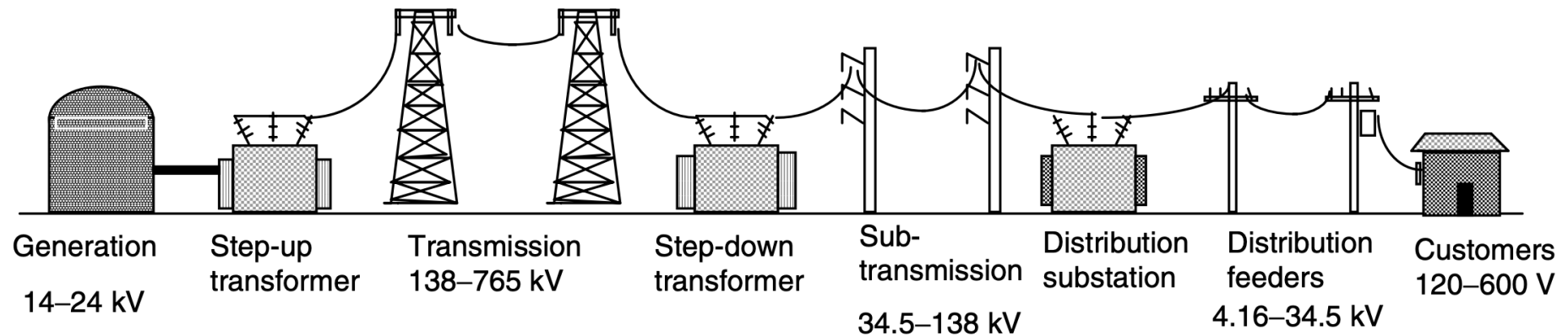
Fö 6 - Dynamik, Distribution.

Lars Eriksson, professor

ISY, Fordonssystem

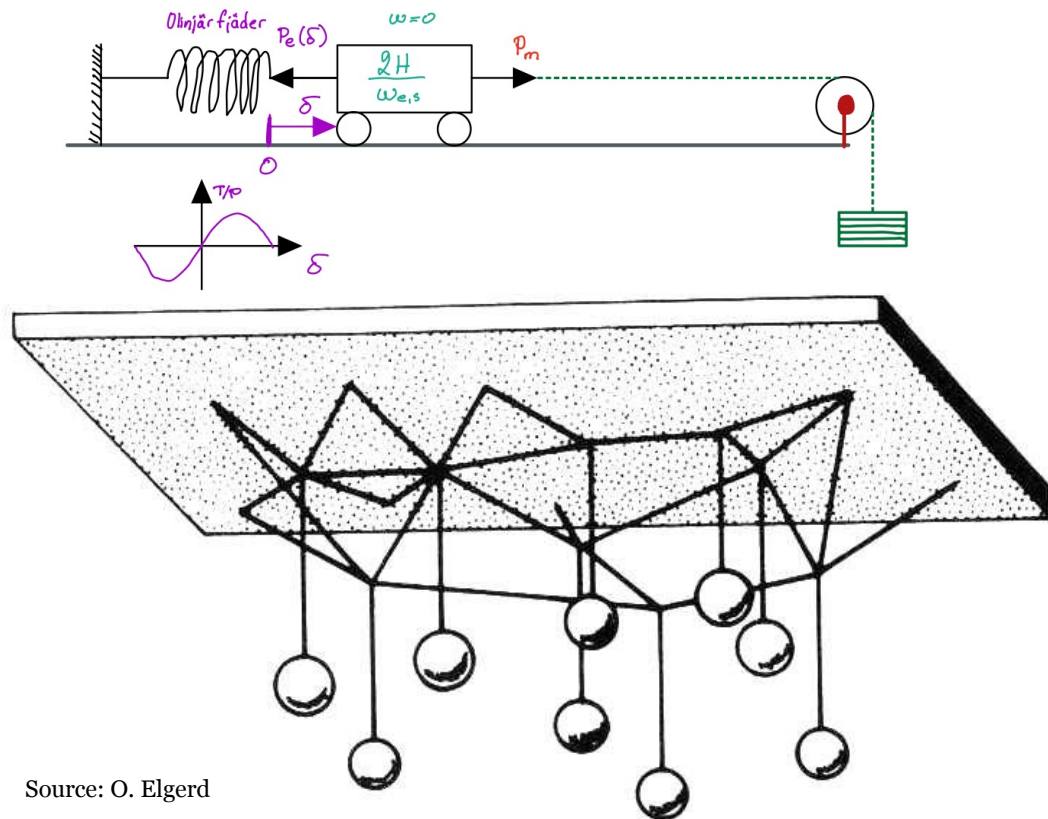
1. Introduktion och översikt

En-dimensionell bild av Elkraftsystemet

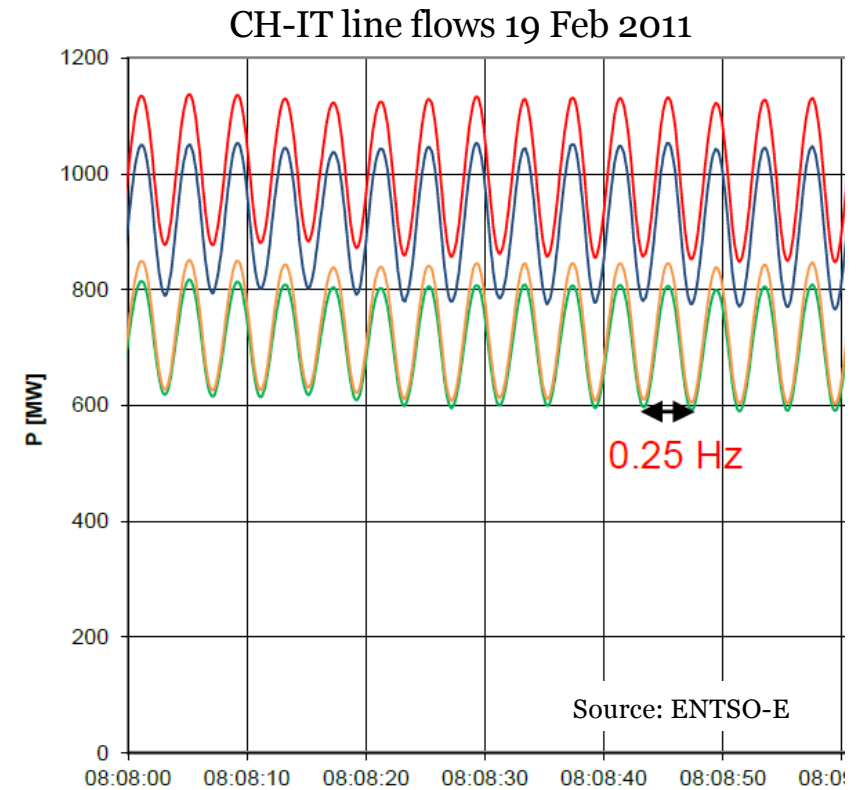


- Idag: Avslutning transmissionsnätets oscillationer, övergång till distributionsnätet.

Dynamik - Bild: fjäder och massa i rörelse



Source: O. Elgerd

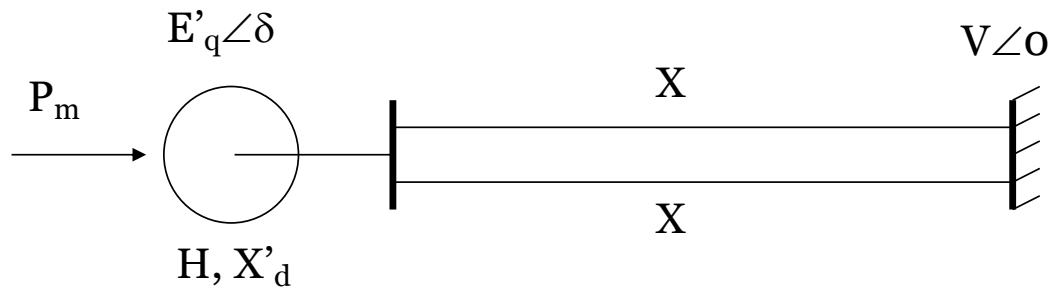


3. Maskinstabilitet igen

Repetition och dynamiska tillstånd och förlopp

Ensam maskin på oändlig buss

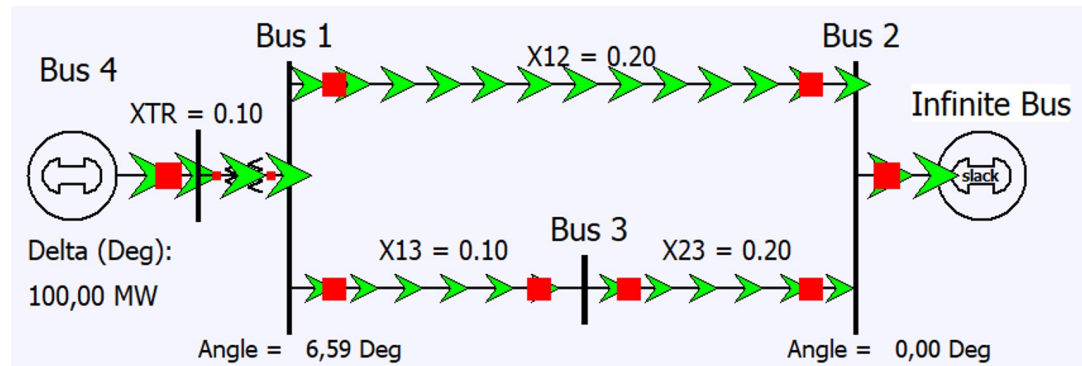
Representerar en generator kopplad till ett stort system



”Classical model”:

•Swing equation for dynamics

- Fixed E'_q behind X'_d (Thévenin!)
- Constant P_m
- No damping, no saliency



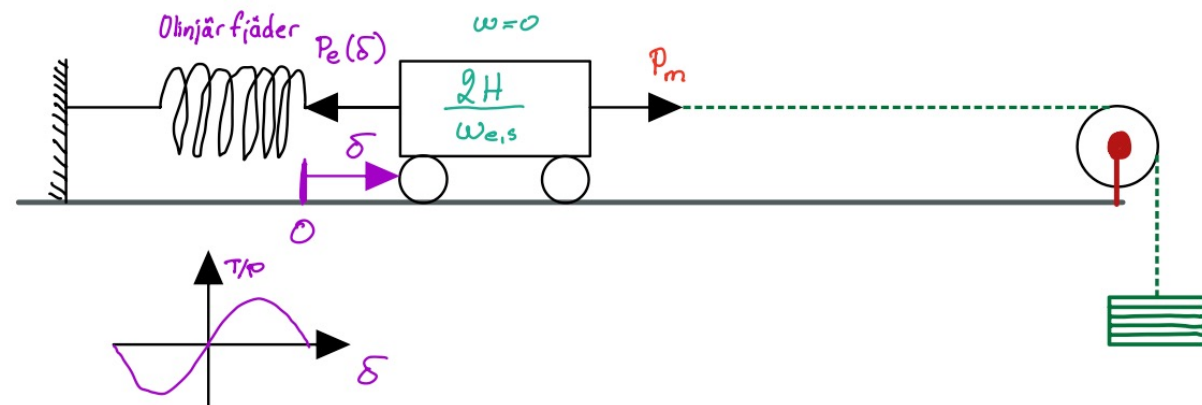
”Infinite bus” generator:

- Infinite H
- Fixed voltage $V \angle 0$
- Zero Thévenin impedance

Klassisk dynamisk generator modell

Synkrongenerator kopplad till oändling bus:

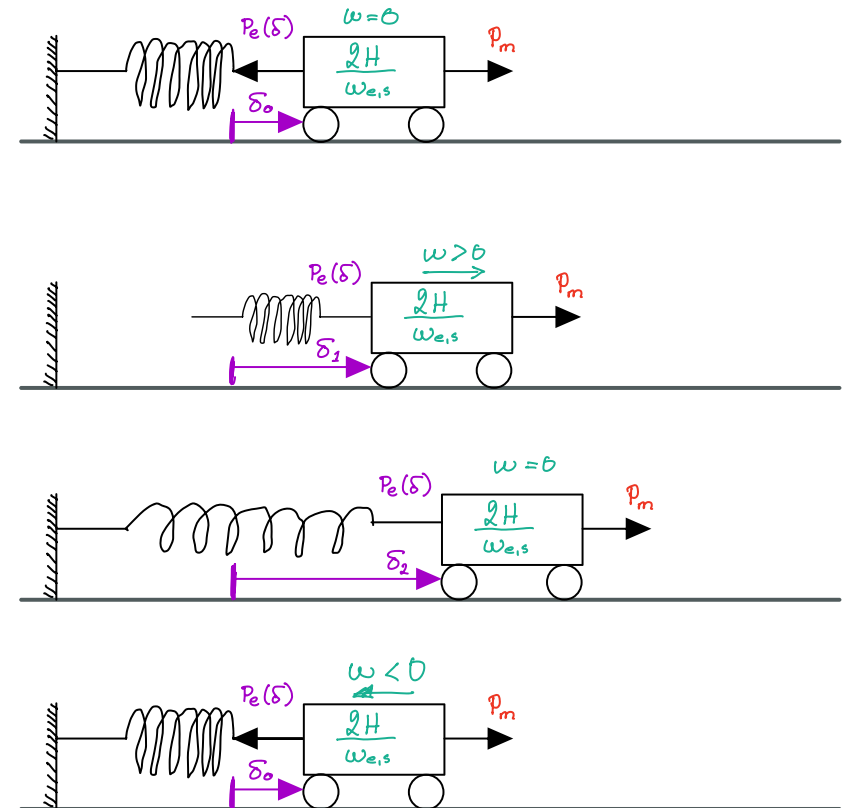
$$\begin{cases} \frac{2H}{\omega_{e,s}} \frac{d\omega_e}{dt} = P_m - P_e(\delta) \\ \frac{d\delta}{dt} = \omega_e - \omega_{e,s} \end{cases}$$



- δ i rad, ω_e i rad/s, $\omega_{e,s}$ typically 100π rad/s
- Andra ordningens dynamik med låg dämpning
- Elektro-mekanisk eller "swing" (gunga) dynamic

Andra ordningens dynamik och svar

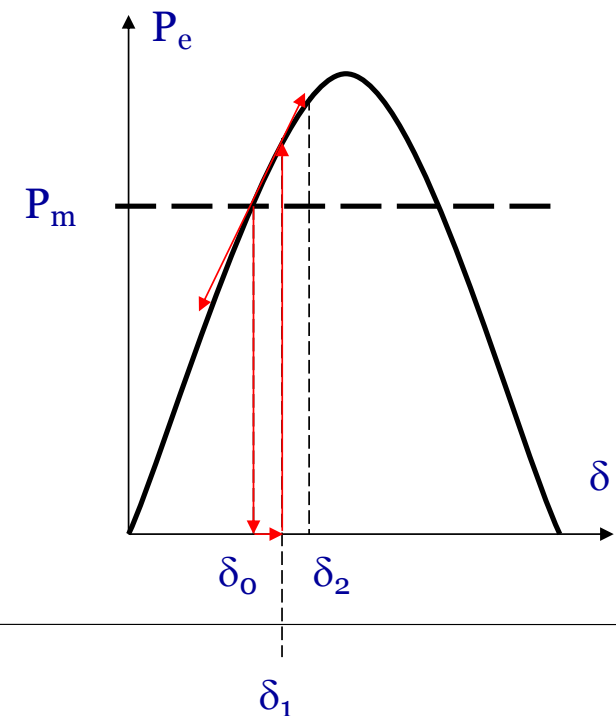
- $P_e=0$ vid kortslutning nära gen (Källan driver bara $X \rightarrow Q$)
- Steg i VL: $P_m - P_e$
- Mekaniska tillstånd långsamma
- Startar med δ_0 och $P_e(\delta_0)$
- Acceleration under felet.
- Felet rensas vid $\delta = \delta_1 = \text{clearing angle}$
- Översläng till δ_2 och $P_e(\delta_2)$
- Oscillerar runt jämviktspunkt δ_0 , $P_e(\delta_0) = P_m$



Andra ordningens dynamik och svar

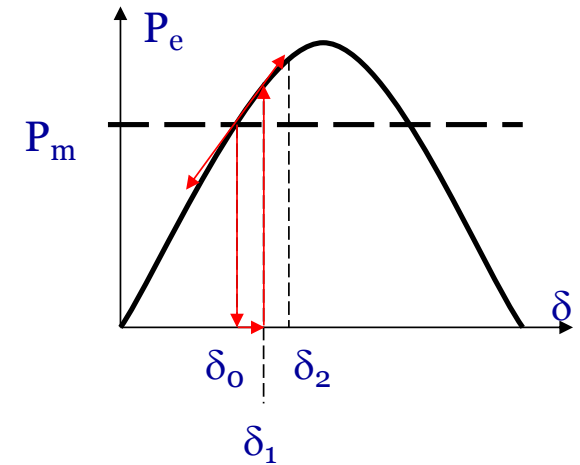
- $P_e=0$ vid kortslutning nära gen (Källan driver bara $X \rightarrow Q$)
- Steg i VL: $P_m - P_e$
- Mekaniska tillstånd långsamma
- Startar med δ_0 och $P_e(\delta_0)$
- Acceleration under felet
- Dubbelintegrering av konstant
- Felet rensas vid $\delta = \delta_1 = \text{clearing angle}$
- Översläng till δ_2 och $P_e(\delta_2)$
- Oscillerar runt jämviktspunkt δ_0 , $P_e(\delta_0) = P_m$

Skillnad på stationär gräns och dynamisk gräns
Över P_m acceleration



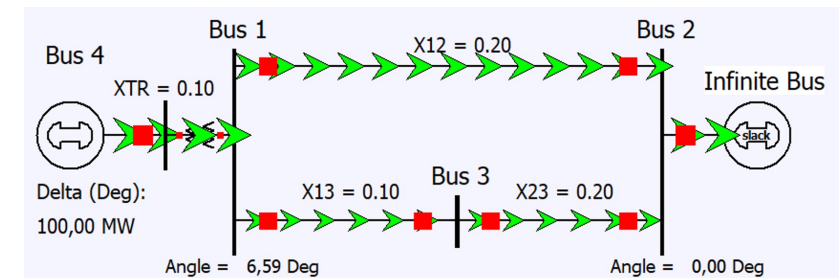
Transient, kopplat till gräns för störningar

- δ_0 måste vara mindre än stationära gränsen 90°
- δ_2 har också en gräns – transient angle stability limit



Frågor:

- Hur stor kan δ_2 var?
- Vad händer när den blir för stor?
- Vad är den största tillåtna störningen?
- Små avvikelser (nästan linjärt, ren sinus)
- Stora avvikelser (olinjäriteter syns, inte ren sinus)

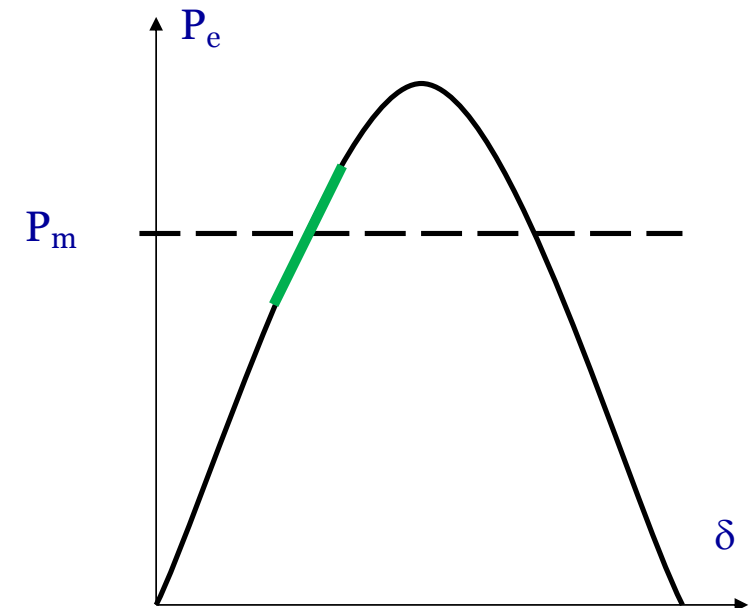


Live demonstration:

PW Exempel 12.5 7th ed
tcl=0.05-0.1895

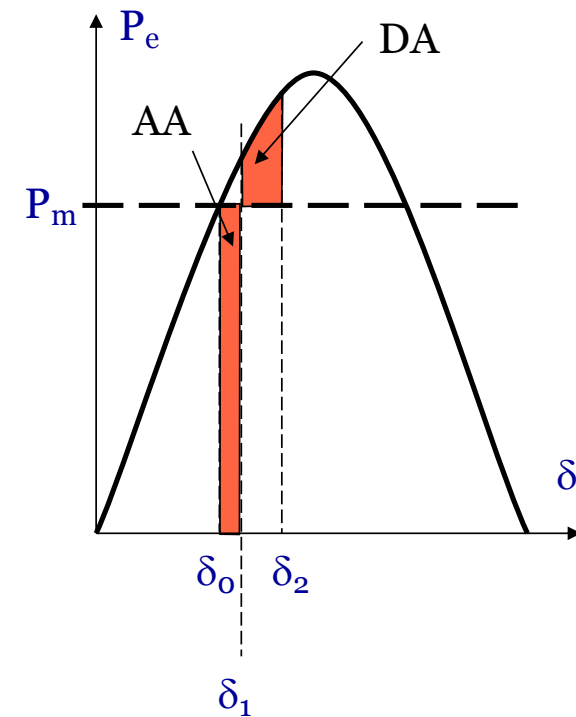
Bortom stabilitetsgränsen

- $d\omega/dt$ blir aldrig noll
- Rotorn accelererar ännu mer
- Maskinen “transiently unstable” = tappar synk
- Måste koppla ifrån och återstarta i synkroniserad mod igen



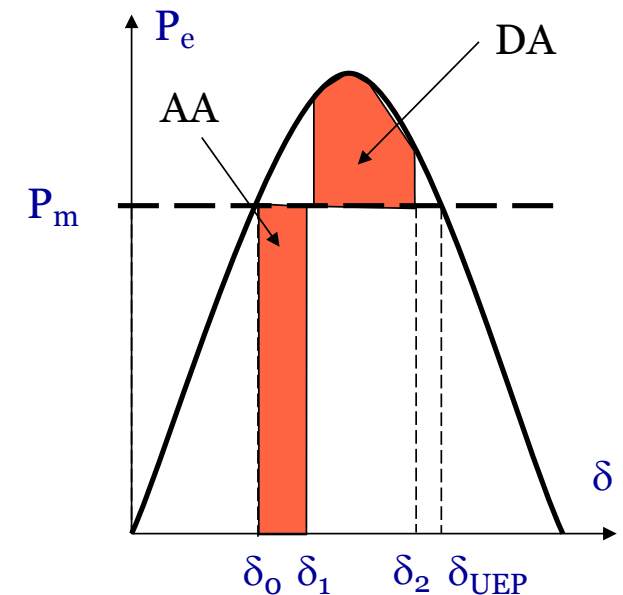
"The Equal Area Criterion"

- Short-circuit: $P_e = \text{zero}$
Mark areas between $P_e(\delta)$ and P_m
in interval δ_0 to δ_2
- Accelerating Area (AA): Below P_m
- Decelerating Area (DA): Above P_m
- For stable system **AA=DA**



Transient stability limit

- More severe disturbance:
 - Greater clearing angle δ_1 makes AA larger
 - Greater DA makes δ_2 larger
- Maximum AA and DA when $\delta_2 = \delta_{UEP} = 180^\circ - \delta_0$
 - Then δ_1 has its maximum value
 - $\delta_1 = \delta_{ccl}$ Critical clearing angle
- For larger δ_2 it is AA that grows...

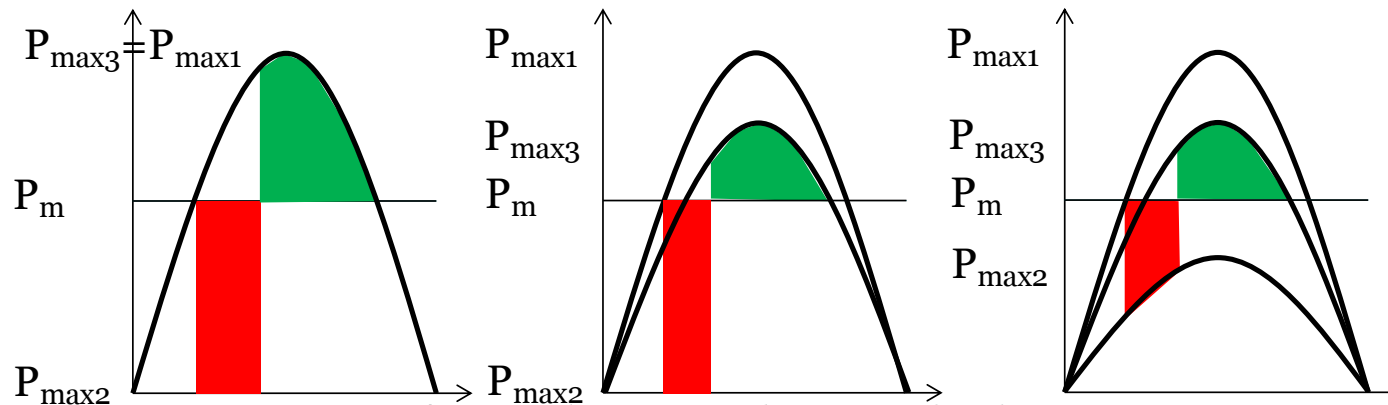


UEP=Unstable Equilibrium Point

Typical EAC scenarios

$P_{\max 1}$ pre-fault
 $P_{\max 2}$ during fault
 $P_{\max 3}$ post-fault

- Short-circuit at bus ($P_{\max 2} = 0$), self-extinguishes ($P_{\max 3} = P_{\max 1}$)
- Short-circuit on line near bus ($P_{\max 2} = 0$), line trip ($P_{\max 3} < P_{\max 1}$)
- Short-circuit on line ($P_{\max 2} > 0$), line trip ($P_{\max 3} < P_{\max 1}$)

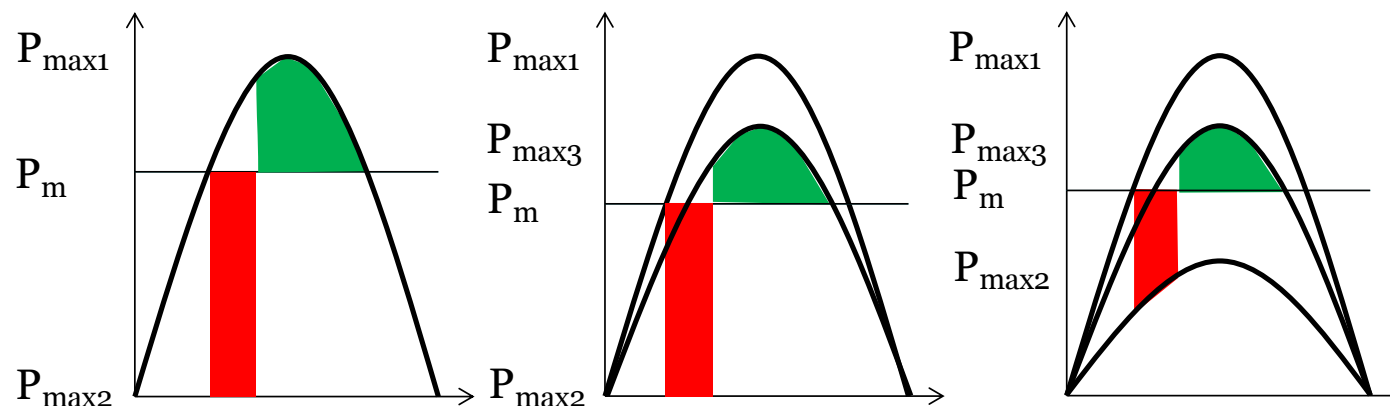


- Recipe: Determine P_{\max} for each stage, draw, calculate
- With fault on line (not at/near bus) – use Thévenin equivalent

Use of Equal Area Criterion

- Stability check for known disturbance
Use EAC for δ_2 and check $\delta_2 < \delta_{UEP}$
- Max disturbance from stability limit
Determine disturbance for $\delta_2 = \delta_{UEP}$
- The clearing angle corresponds to the fault clearing time where relay protection delay is central
- But EAC calculations do not include time
Time simulations! (textbook shows approximation)

Transfer capacity



a. $P_e=0$ at fault, no line lost

b. $P_e=0$ at fault, one line lost
Worse than a.

c. $P_e>0$ at fault, one line lost
Better than b.

- Total transferred MW on the lines = P_m
- High line transfer \Leftrightarrow efficient use of lines, network and system
- But higher P_m gives greater AA and smaller DA
- **Transient stability** thus **limits line transfer** just like voltage stability and the steady state limit (max angle separation 90°)

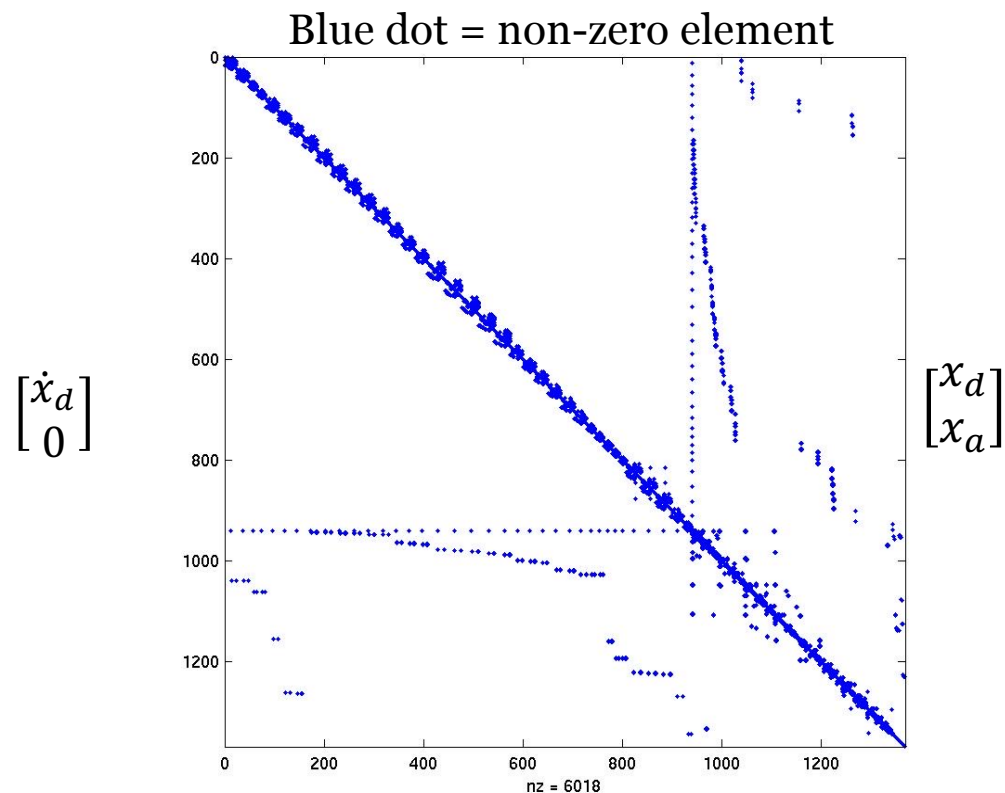
2. Stora System och Egen-moder

Snabb genomgång. – Huvudbudskap: det finns matematiska verktyg.

Numerical stability analysis

- Time simulation
- Computer application since the beginning of computers!
- Voltages and currents as phasors or waveforms
- Multi-machine model with Differential Algebraic Equations
 - Set of Differential equations for each generator
 - Power flow for Algebraic network equations
 - All equations are normally non-linear

DAE matrix for Icelandic system



- 37 generators
- ≈ 590 dynamic states x_d
- 202 network nodes
- ≈ 810 algebraic states x_a
- $x_d = A_{ode} x_d \dots A_{ode} \approx 590 \times 590$
- $= A_{dae} \dots A_{dae} \approx 1400 \times 1400$

Small-signal angle stability

- Also small disturbance angle stability \rightarrow linear model OK
- Linearize at steady state $(\delta_o, \omega_o, P_{mo})$
- State space: $dx_d/dt = A_{ode}x_d + Bu$
- Compute eigenvalues λ_i of A_{ode}
- Compute right and left eigenvectors Φ_i and Ψ_i of A_{ode}
- Applies also to multi-machine models
- Popular and powerful application of control theory

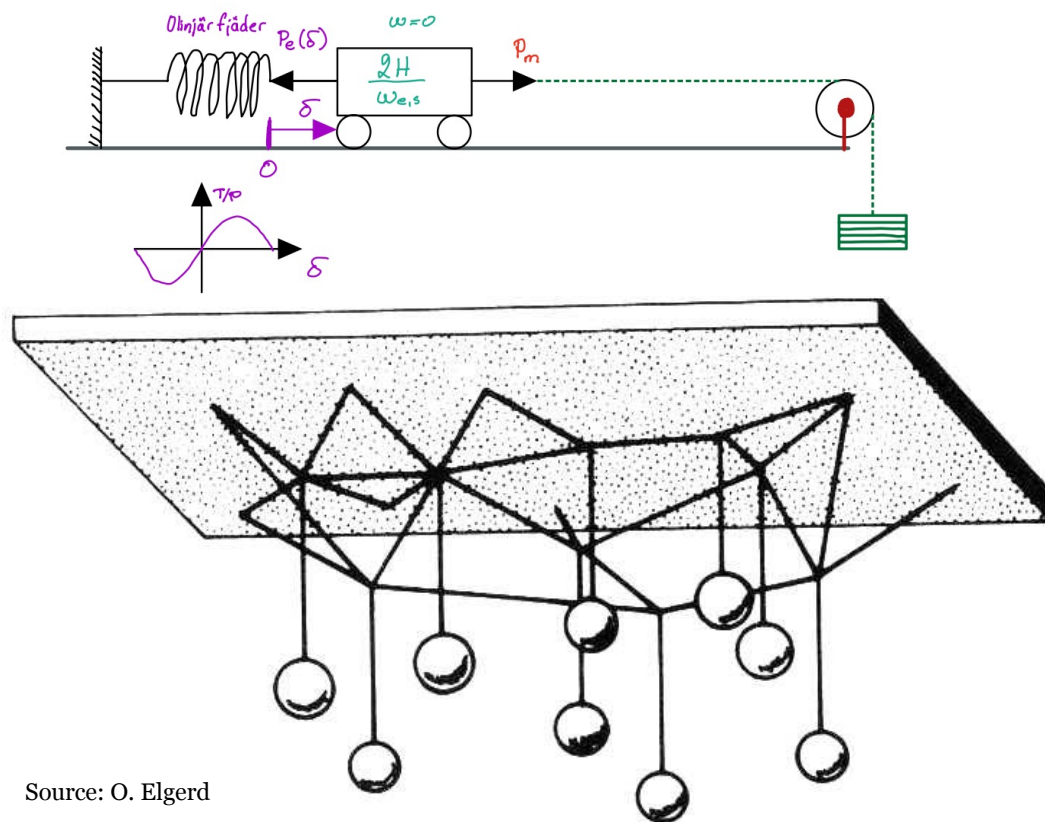
Eigenvalues and eigenvectors

- Message:
Mathematics relying on Linear algebra, important for analysis.
- Eigenvalue λ_i (stable if in Left Half Plane)
 $\text{Im}(\lambda_i)$ =resonance oscillation frequency (e.g. 0.35 Hz)
 $\text{Re}(\lambda_i)$ =resonance oscillation damping
 - ≤ 0 for all λ_i system is small-signal stable
 - > 0 for any λ_i system is small-signal unstable
- Right eigenvector Φ_i gives “mode shape”
Which generators participate in mode (resonance) i

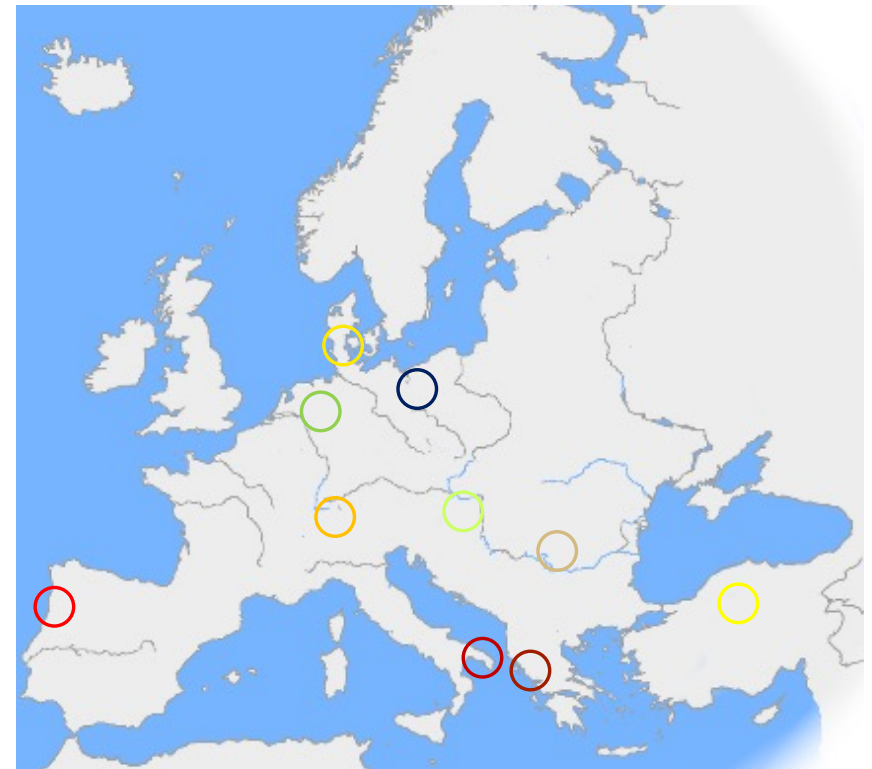
Small-signal damping

- Low $\gamma > 0$ for uncontrolled system
- Negative damping from controllers
 - Automatic Voltage Regulators
 - HVDC controllers
- Damping added by dedicated controls
 - Power System Stabilizers (PSS) on generator
 - Power Oscillation Damper (POD) on HVDC or FACTS
- FACTS=MW size power electronic devices

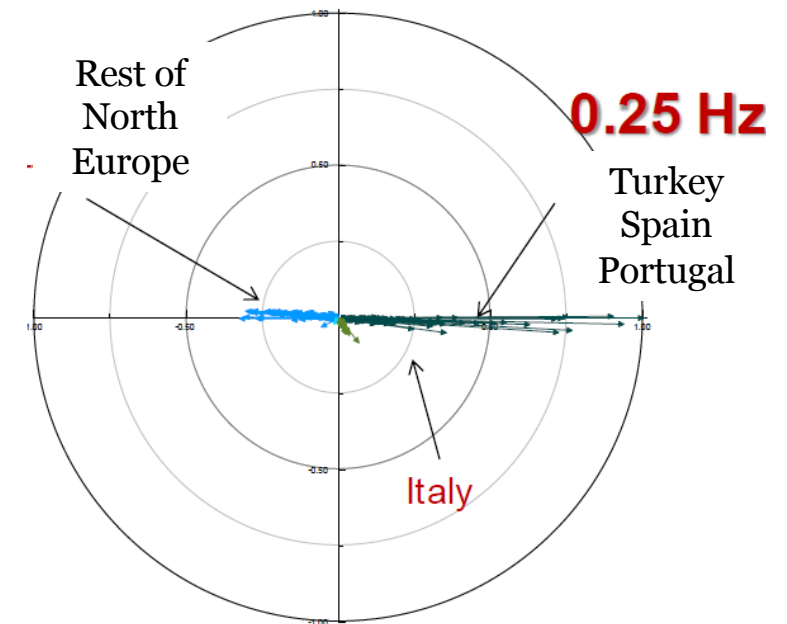
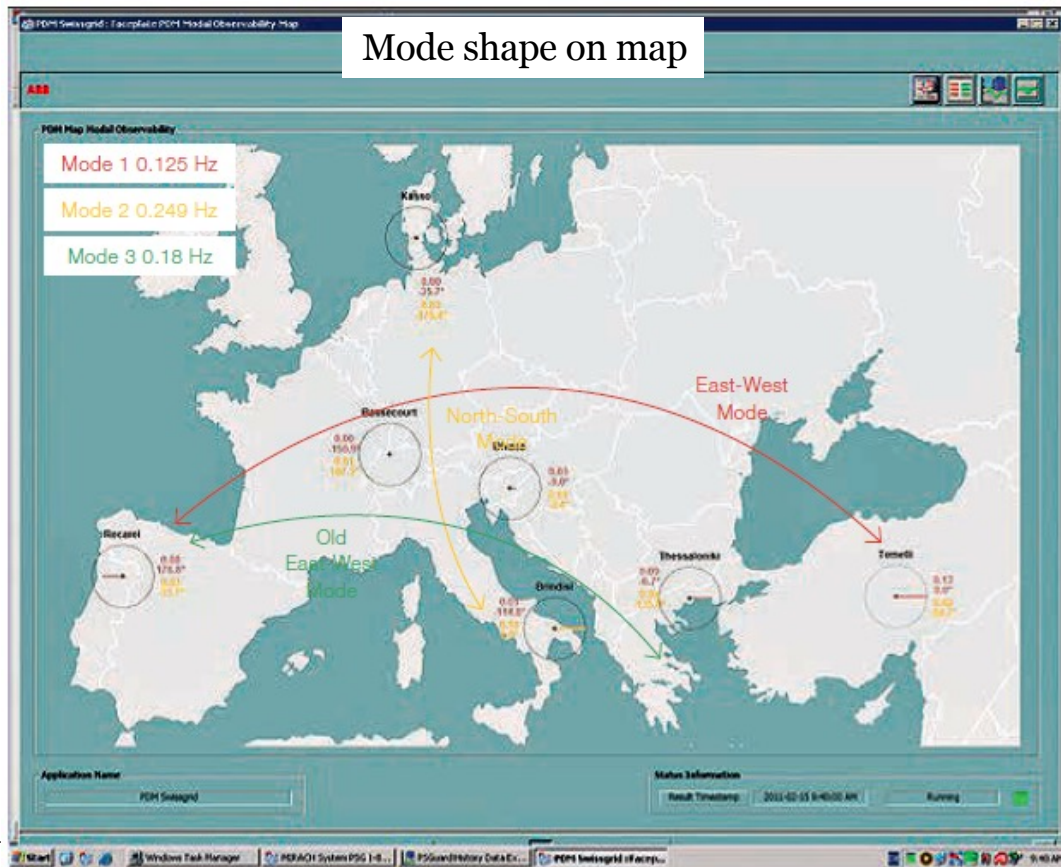
Dynamik - Mental bild: fjäder och massa i rörelse



Source: O. Elgerd

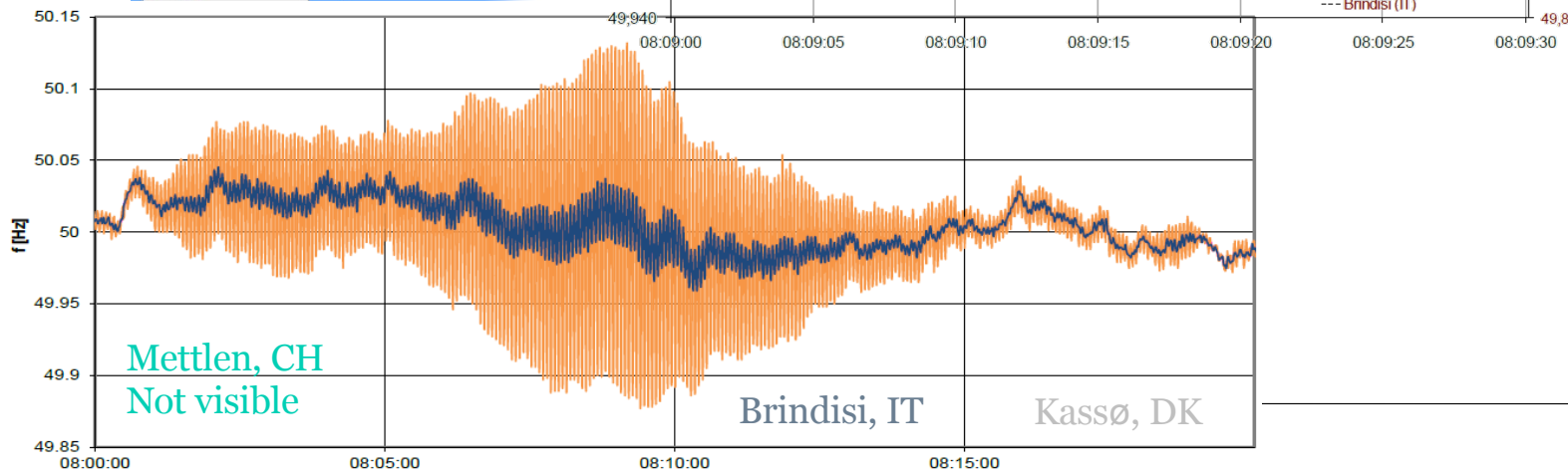
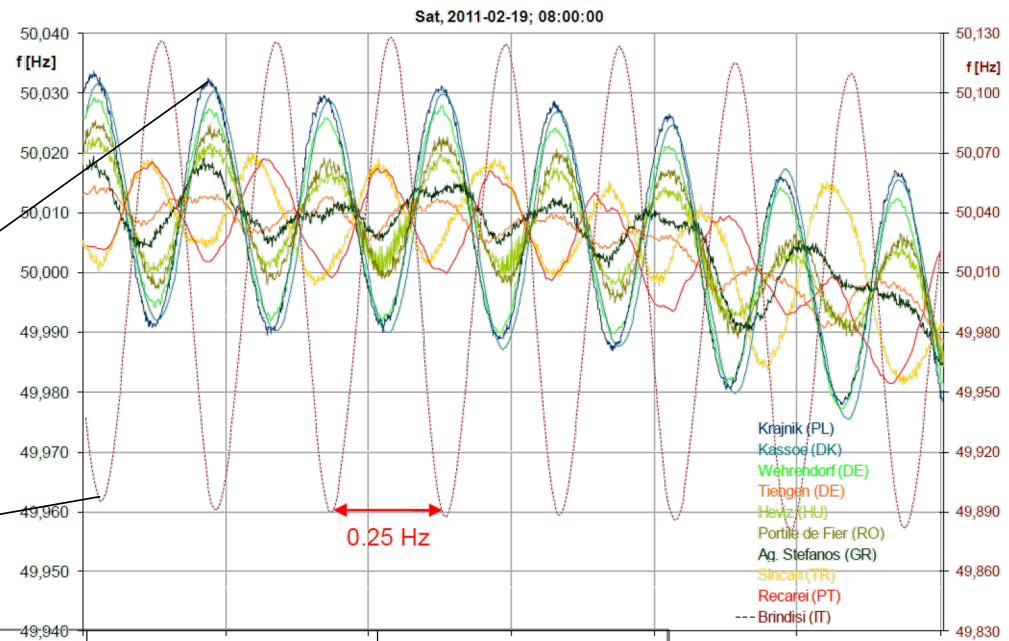
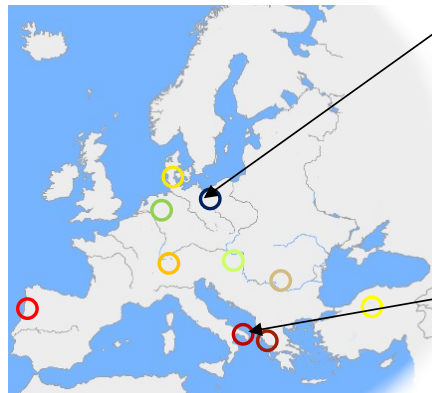


Oscillation event 19 February 2011

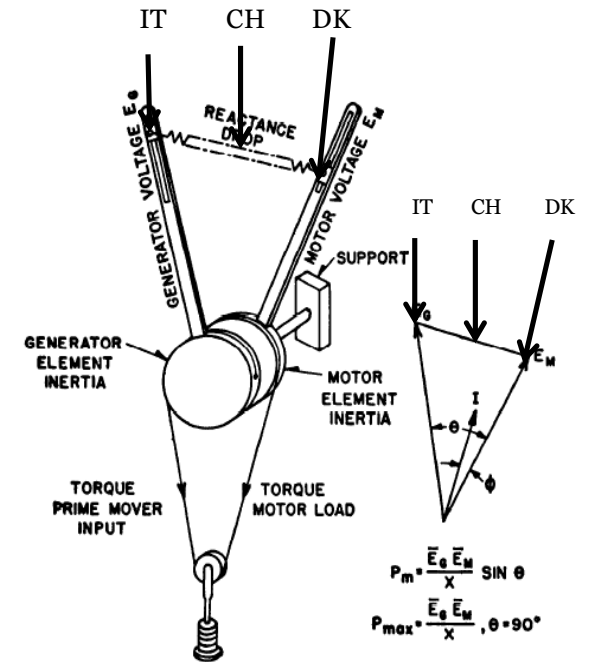
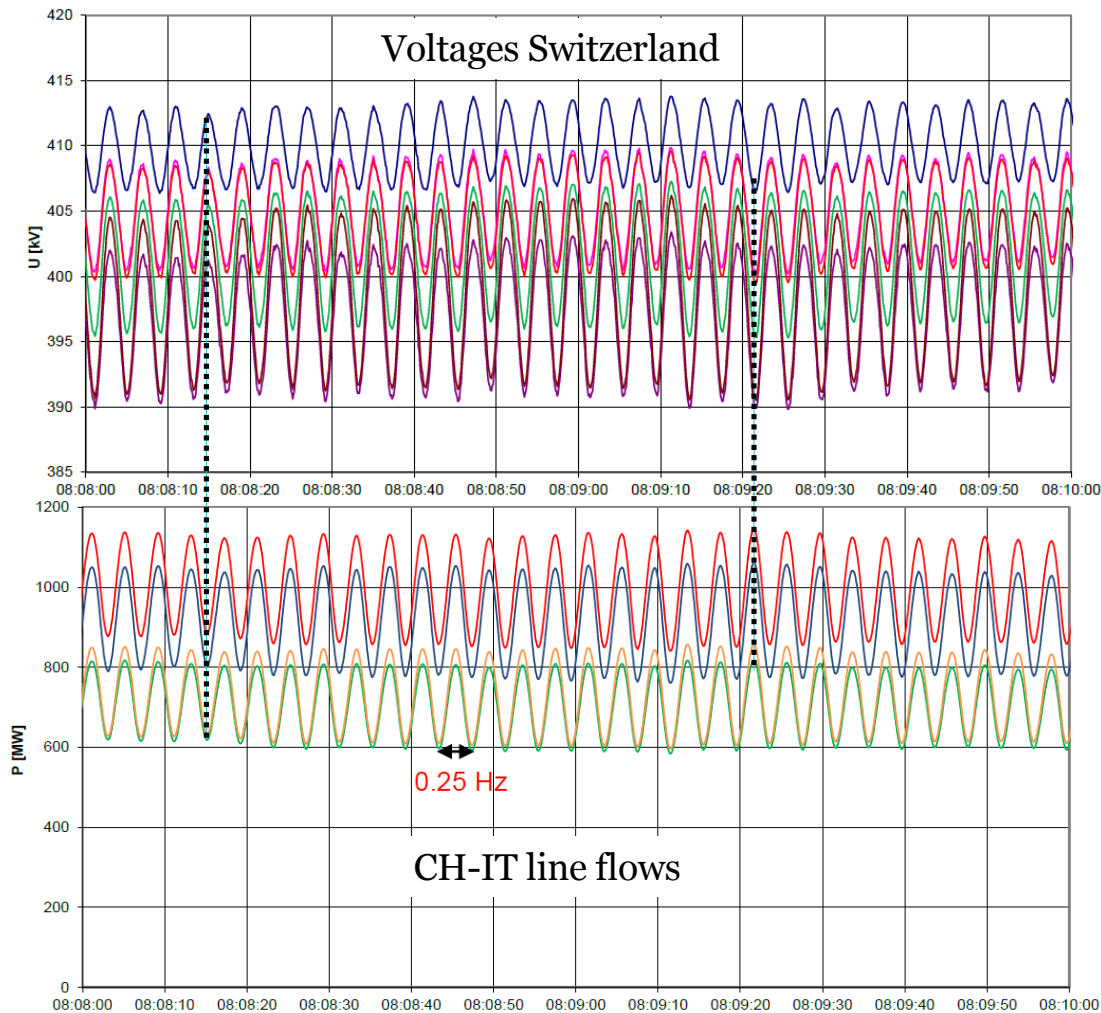


Right eigenvector from model
↔
Mode shape in complex plane

Oscillation event 19 February 2011



Oscillation event 19 February 2011



Mechanical analog confirms that voltage at midpoint is low when P and angle separation δ (here θ) is high

Slutsats från ENTSOE rapporten

ENTSOE - European Network of Transmission System Operators for Electricity

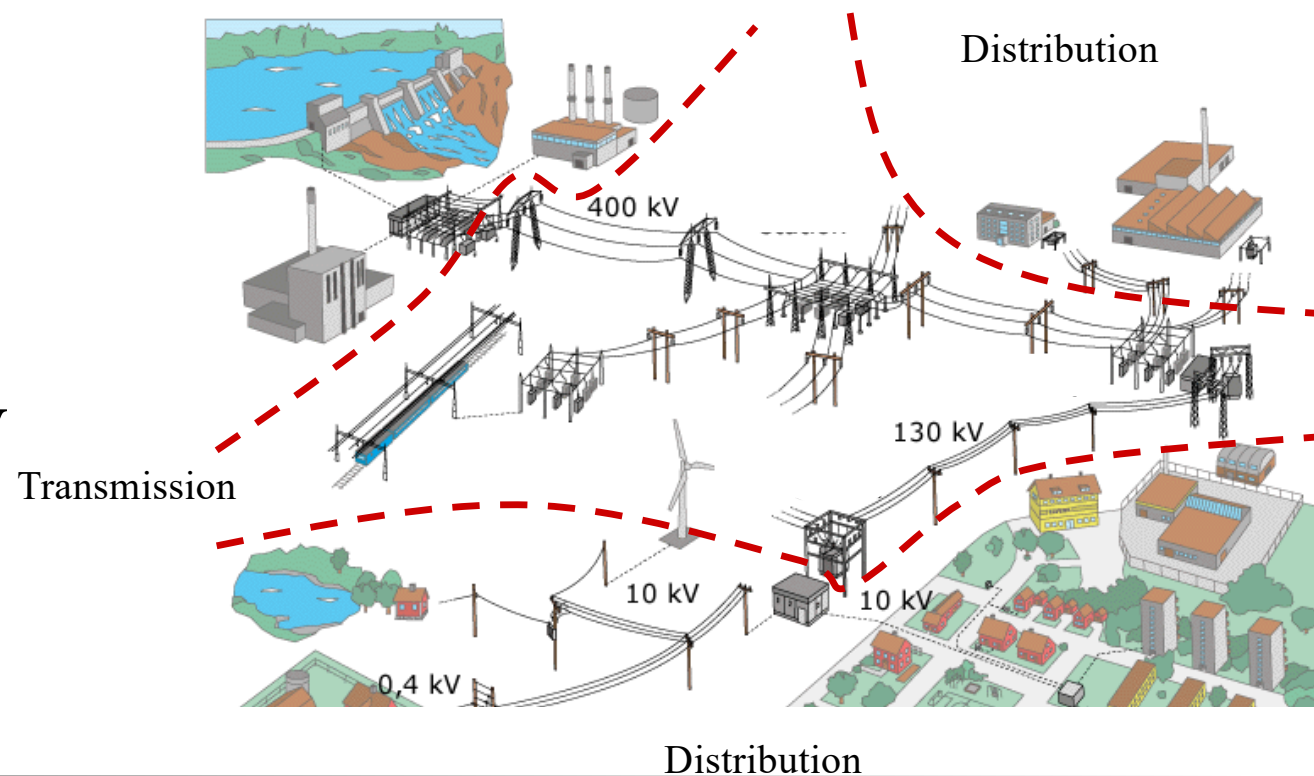
The oscillations of 19 and 24 February 2011 showed the following characteristics (results of Terna study under consideration of recordings)

- TURKEY HAS CHANGED MODES DISPLACEMENT;
- THERE IS A SUPERPOSITION OF 0.18 HZ (EAST-WEST MODE) AND 0.25 HZ (NORTH-SOUTH MODE) MODES;
- THE FREQUENCY AND THE DAMPING CONTINUOUSLY OSCILLATE BETWEEN LOW AND HIGH VALUES, DUE TO DIFFERENT COMPOSITION OF OSCILLATIONS;
- THE DISPERSED GENERATION (SUCH AS WIND AND PV) DON'T INFLUENCE NEGATIVELY BUT SUBTRACT "STABILIZED INERTIA" FROM CLASSICAL GROUPS EQUIPPED WITH PSS.

3. Distributionsnätet

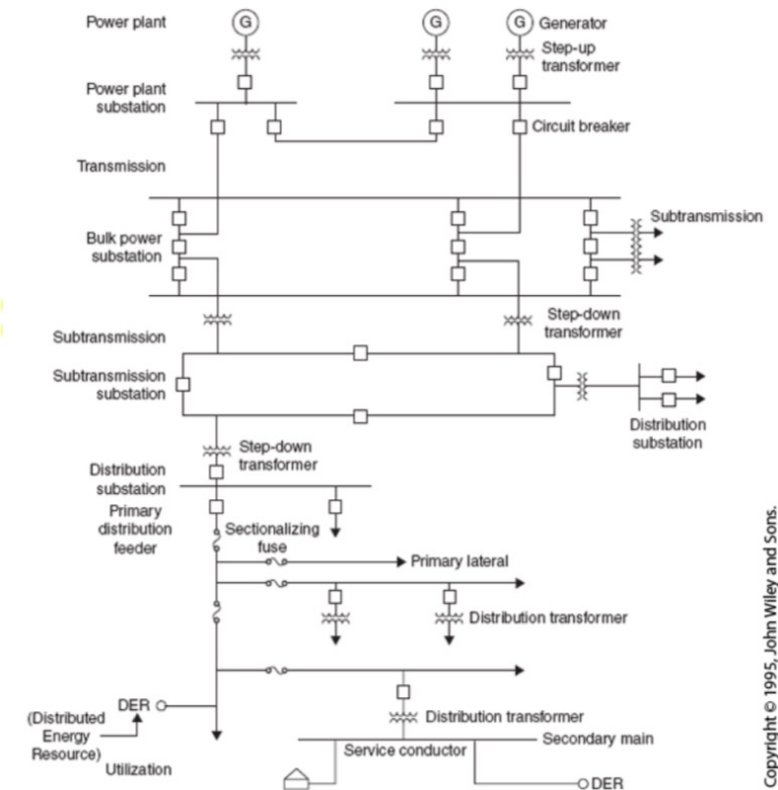
På väg ned till Distributionsnätet

- Transmissionsnätet:
400, 220 kV
- Subtransmissionsnätet:
130, 70 kV.
- Distributionsnätet:
40, 30, 20, 10, 6, 3, 0.4 kV



Från generator till kund

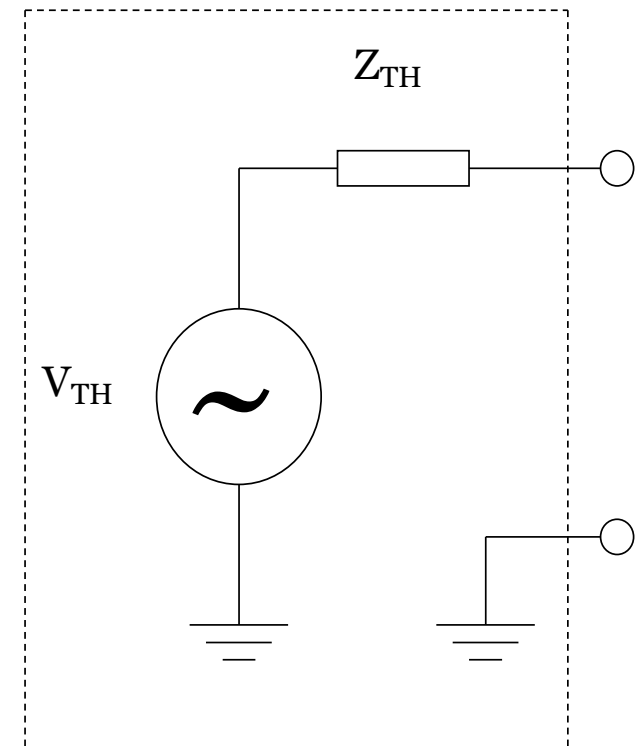
- Generator:
20 kV (balans isolation/volym)
- Transmissionsnätet:
400, 200 kV
- Subtransmissionsnätet:
130, 70 kV.
- Distributionsnätet:
40, 30, 20, 10, 6, 3, 0.4 kV



(Per fas) Thévenin ekvivalent

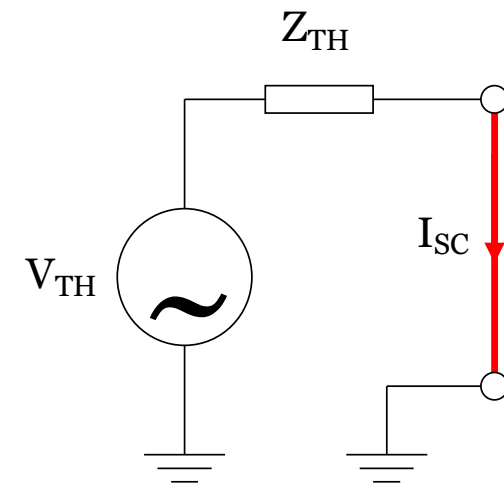
- Z_{TH} Representerar passivt nätverk
– Även hela elkraftsystemet
- V_{TH} obleastat nät (tomgångsspänning)
- Z_{TH} kortslutningsimpedans
 - Ekvivalent Z för nätverket
 - Det som kan mätas vid terminalen när alla spänningskällor V är kortslutna.

Perfekt komplexitet för handräkningar.



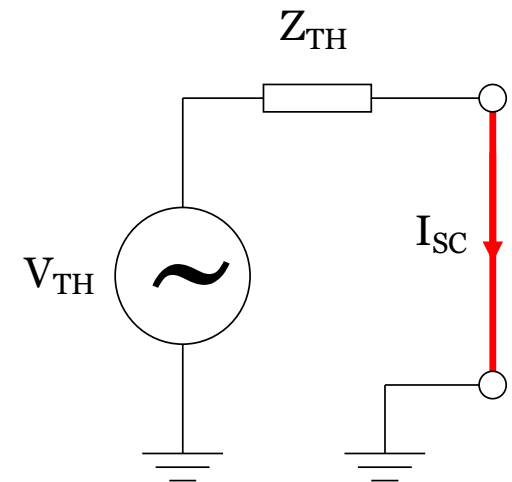
Z_{TH} bestämmer kortslutningsströmmen

- $Z=0$ inkopplad på terminalerna
- Kortslutningsströmmen
 - $I_{SC} = V_{TH} / (\sqrt{3}Z_{TH}) \approx 1 / (\sqrt{3}Z_{TH})$ p.u.
(V_{TH} line-line voltage)
 - Determines circuit breaker rating
(Sw märkström för effektbrytare)
- I_{SC} begränsas av Z_{TH}
 - In Z_{TH} $X \gg R$ for line, transf, synch gen
 - X limits current
 - If needed, extra X may be inserted
 - R gives losses and V_{drop} from active power



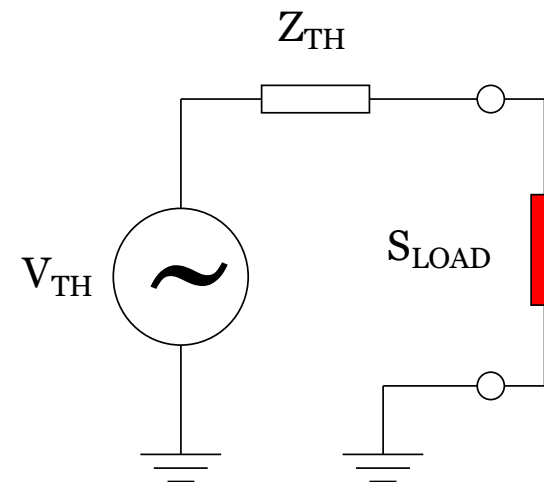
Z_{TH} ger kortslutningseffekt

- Short-circuit power in MVA (Sw kortslutningseffekt)
 - Also "short-circuit capacity"
 - Also "fault level"
- $S_{SC} = \sqrt{3} V_{TH} I_{SC}$ p.u.,
- Voltage before short-circuit times current during
- $S_{SC} = V_{TH}^2 / Z_{TH} \approx 1 / Z_{TH}$ p.u.
- S_{SC} not useful power

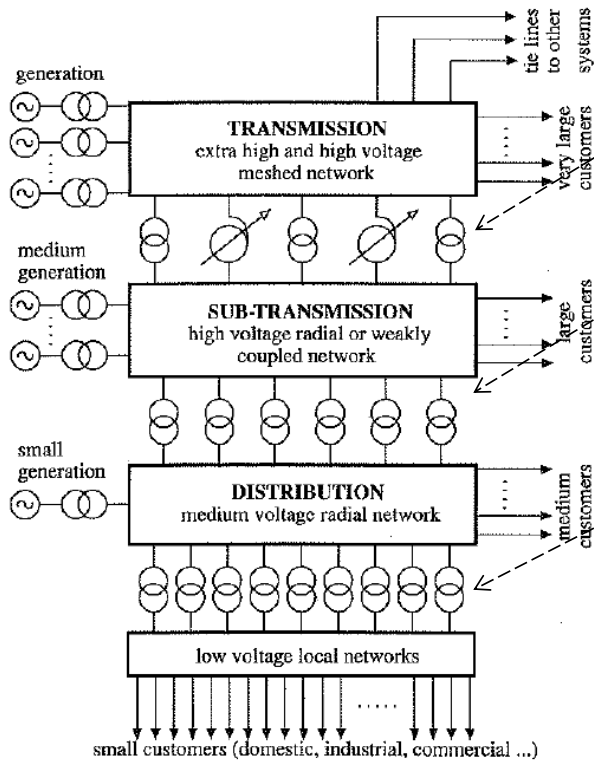


Z_{TH} bestämmer nätverkets styrka

- $Z_{LOAD} \gg Z_{TH} \Leftrightarrow S_{LOAD} \ll S_{SC}$
 - small voltage drop across Z_{TH}
 - load voltage insensitive of load
 - strong, urban load
- $Z_{LOAD} \text{ not } \gg Z_{TH} \Leftrightarrow S_{LOAD} \text{ not } \ll S_{SC}/2$
 - load voltage sensitive to load
 - weak, rural load
- $S_{LOAD} = S_{SC}/2$
 - Max S_{LOAD} @ impedance matching

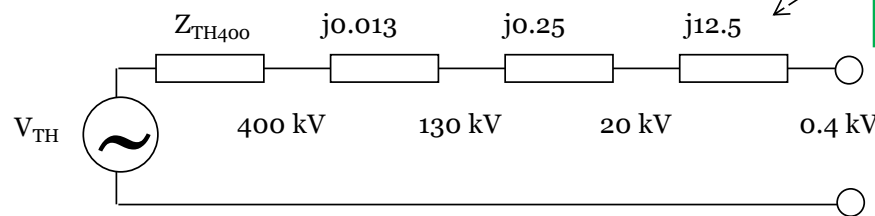


Exempel: Z_{TH} för olika spänningsnivåer



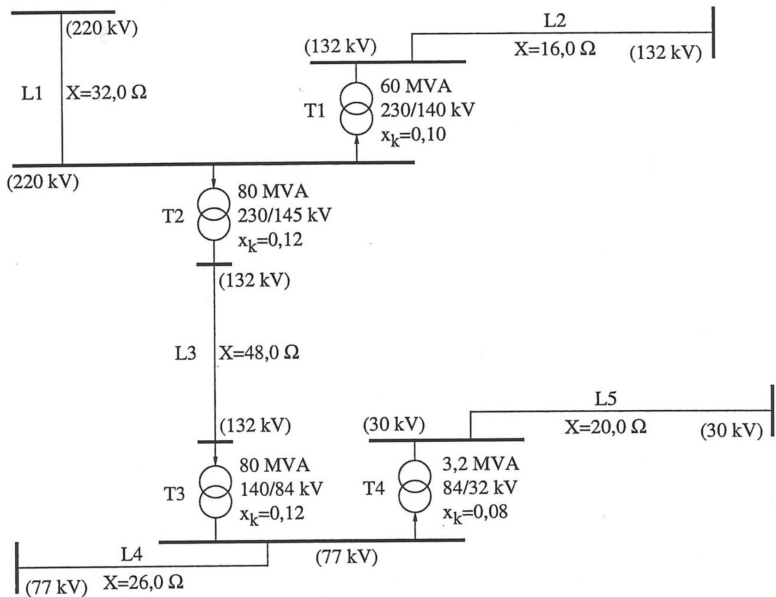
Alla transformatorer X på samma bas via multiplikation med $100 \text{ MVA}/S_{\text{base,old}}$

- 400/130 kV, $x=0.1 \text{ p.u. @ 750 MVA}$
 - **0.013 p.u. @ 100 MVA base**
- 130/20 kV, $x=0.1 \text{ p.u. @ 40 MVA}$
 - **0.25 p.u. @ 100 MVA base**
 - $18.75 \times 0.013 \text{ p.u.}$
- 20/0.4 kV, $x=0.1 \text{ p.u. @ 0.8 MVA}$
 - **12.5 p.u. @ 100 MVA base**
 - $50 \times 0.25 \text{ p.u. and } 937.5 \times 0.013 \text{ p.u.}$

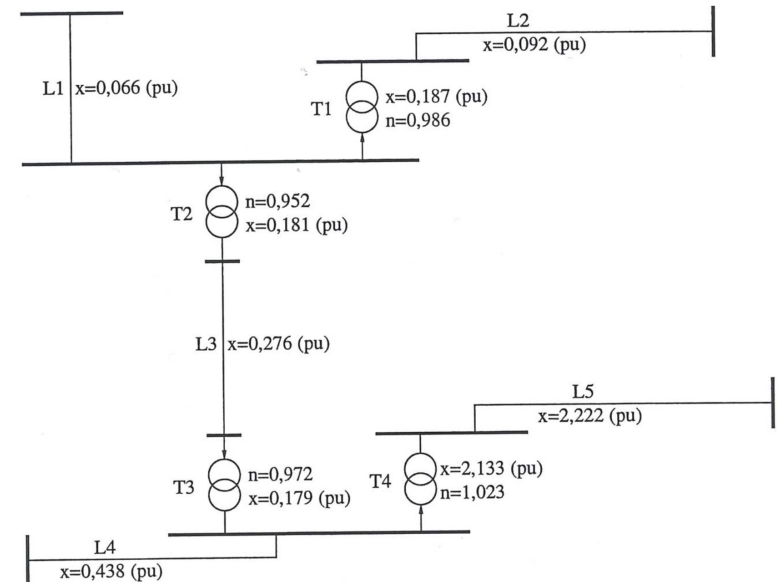


Take-away: Den sista transformatorn dominerar Z_{TH}

Nätverksmodell för system "nedströms"



->
Per enhet



Nätet grenar ut sig och slutar med många parallella ledare till små kunder.
Inte så konstigt att ledningen ut till varje kund har relativt sett hög impedans.

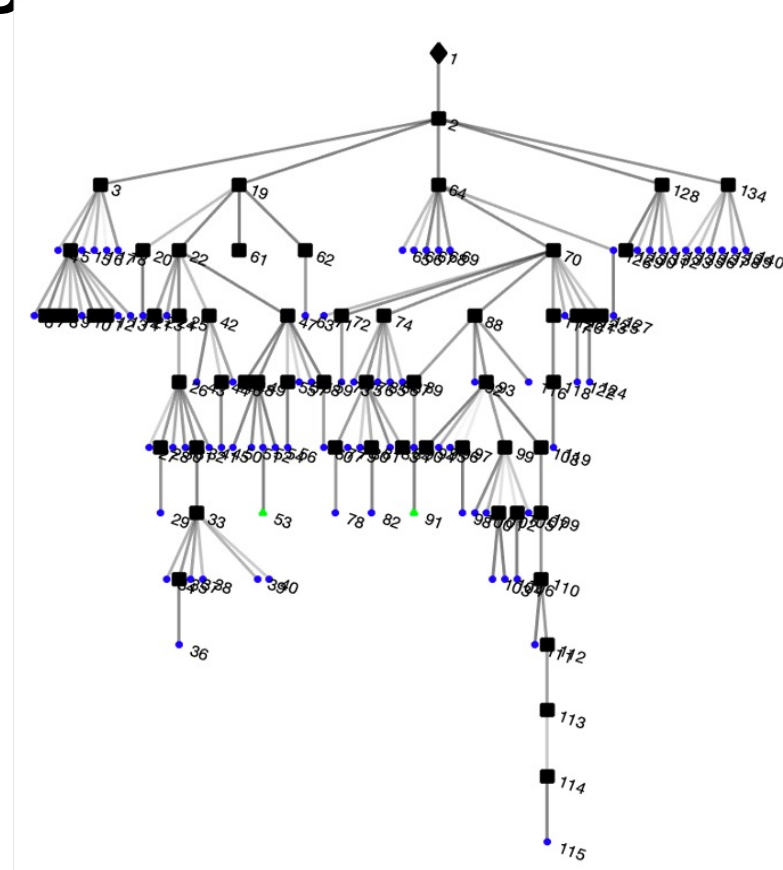
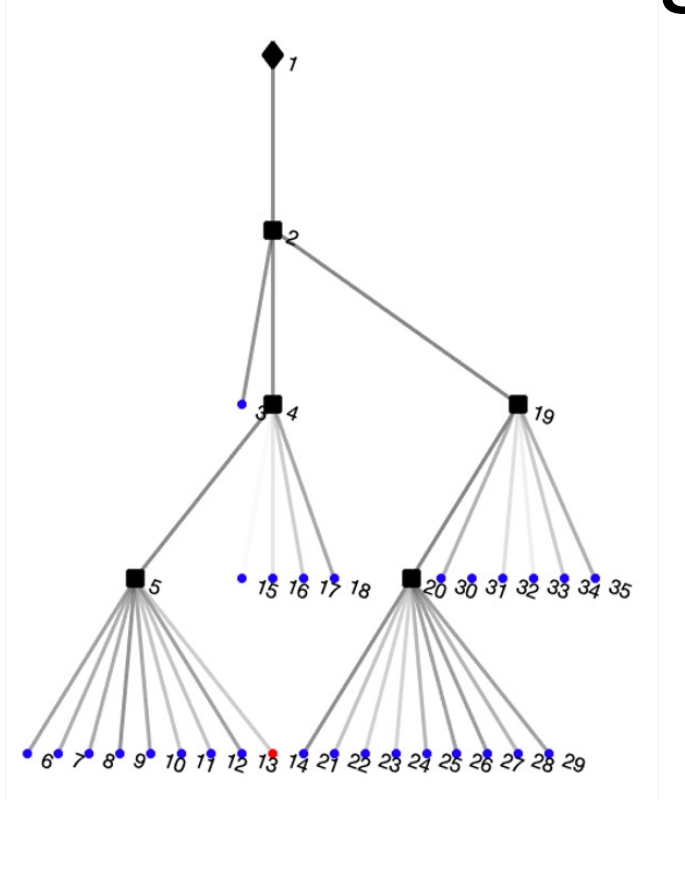
Olika lastmodeller i systemet

- Lasters spänningskänslighet $a = \left(\frac{\partial P}{\partial V}\right)$, $b = \left(\frac{\partial Q}{\partial V}\right)$, Power Factor (PF)
- Elektrisk uppvärmning, värme från resistans: PF=1, a=2, b=0.
- Glödtrådslampa, (incandescent lighting):
olinjär resistans. PF=1, a=1.5, b=0.
- Lysrör (fluorescent lighting): PF=0.9, a=1, b=1
- Motorlaster: PF=0.9-0.8, a=0.05-0.5, b=1-3
- Laster styrda av kraftelektronik: PF=1, a=0, b=0

Olika lastmodeller i systemet

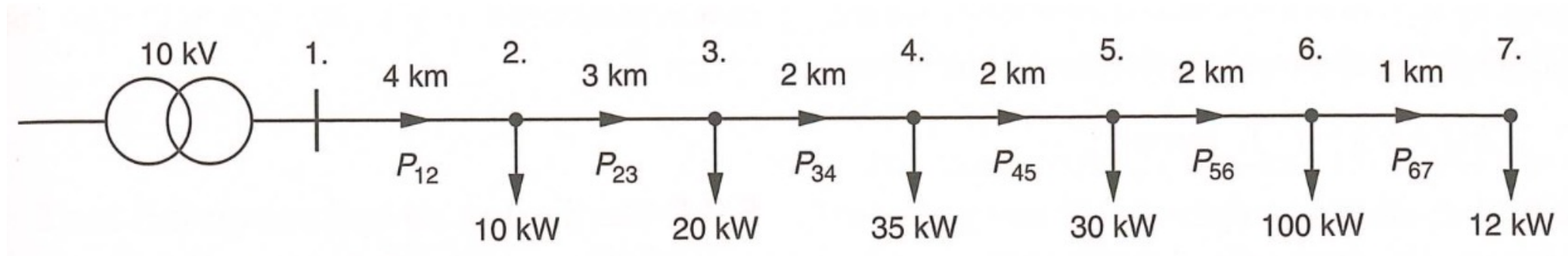
Type of Load	Power Factor	$a = \partial P / \partial V$	$b = \partial Q / \partial V$
Electric Heating	1.0	2.0	0
Incandescent Lighting	1.0	1.5	0
Fluorescent Lighting	0.9	1.0	1.0
Motor Loads	0.8–0.9	0.05–0.5	1.0–3.0
Modern Power Electronics–Based Loads	1.0	0	0

Exempel lådspänningsnät



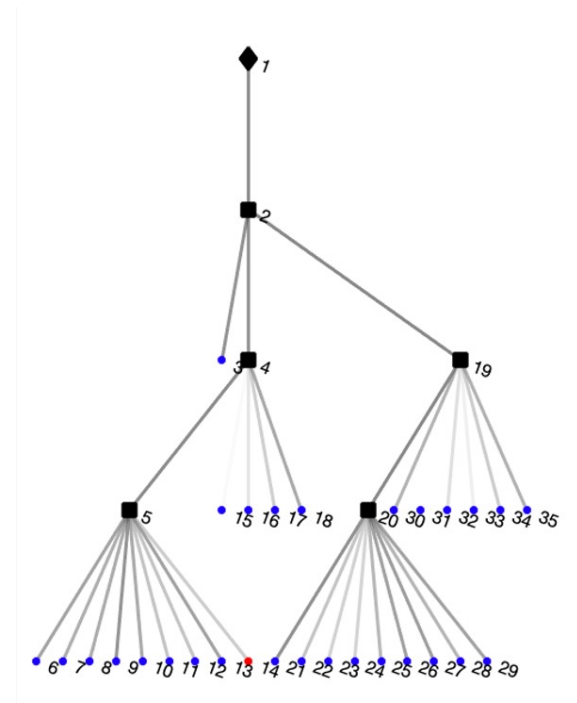
Resistiva förluster dominerar i "slutet"

- Beräkna spenningsfall längs kablarna som går ut till kund.



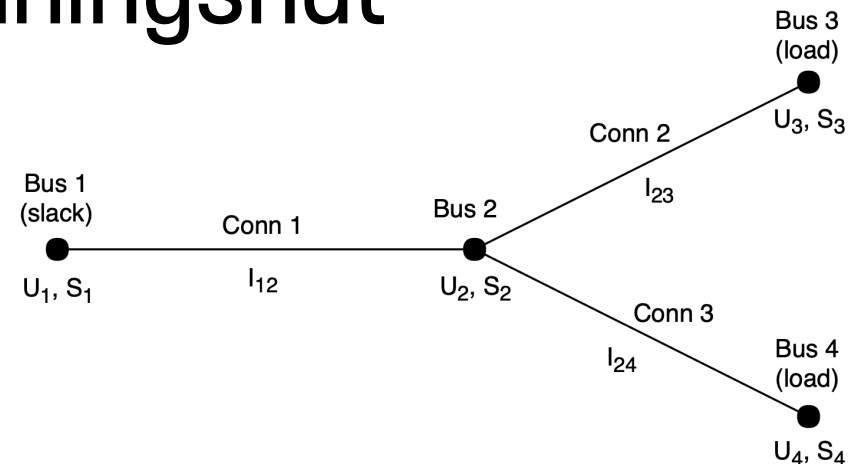
Busstyper lågspänningsnät

- Alla slutkonsumenter PQ-bussar
 - Kopplingspunkterna även modellerade som PQ bussar med nolleffekt.
- En slackbus (vid transformatorn)
- Ingen PV-buss
- Antal obekanta = $2 \cdot$ antalet PQ-bussar. I exemplet $2 \cdot (35-1) = 68$ stycken. 34 spänningsamplituder, och 34 spänningsriktningar.



Enkelt exempel - lågspänningsnät

- Alla kablar har impedansen $Z = 1 + j0.1$ och shuntkapacitanserna försummas.
- Spänningen $U_1 = 400 + j0$
- $S_3 = 3000 + j2250\text{VA}$ (induktiv last $\cos \varphi = 0.8$)
- $S_4 = 2000 - j1500\text{VA}$ (kapacitiv last $\cos \varphi = 0.8$)
- Beräkna effektuttaget i buss 1, samt spänningarna i noderna 2-4.



Problemet är implicit där strömmarnas storlek beror på spänningen, och spänningen beror på spänningsfall imledningar, som i sin tur beror på strömmen.

-Möjligt att räkna på för hand.

Beräkningar solceller och elbil

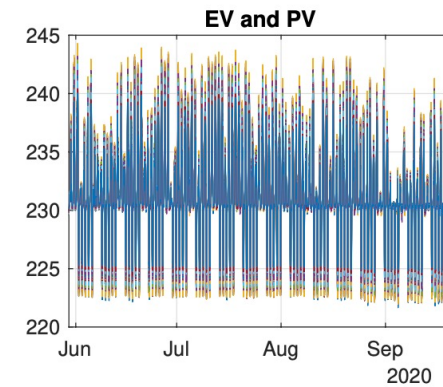
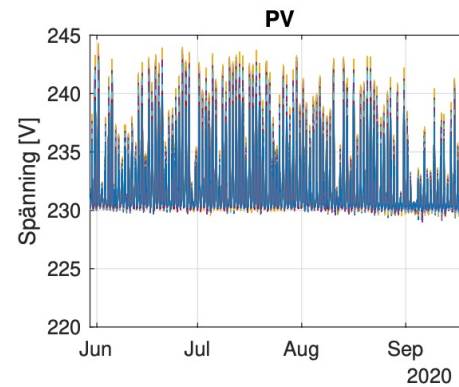
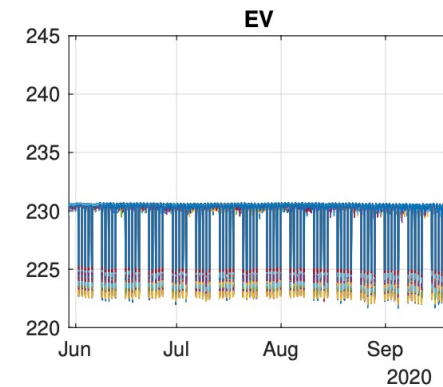
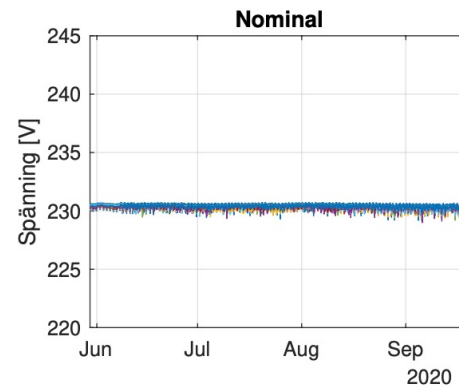
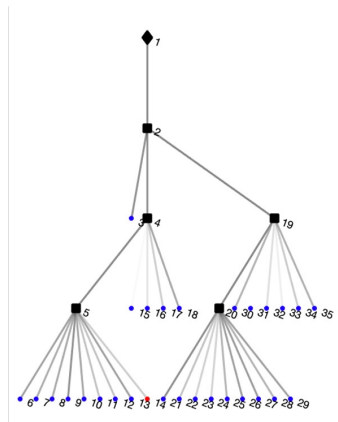
Solceller och elbilsladdning läggs till befintlig hushållskonsumtion.

Alla bilar laddas samtidigt.

$$P_{EV} = 5 \text{ kW}$$

$$P_{PV, \text{peak}} = 10 \text{ kW}$$

Schemaläggning



TSFS 17 Elkraftsystem

Föreläsning 6

<https://isy.gitlab-pages.liu.se/fs/courses/TSFS17/>

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