Basics of Power System Studies

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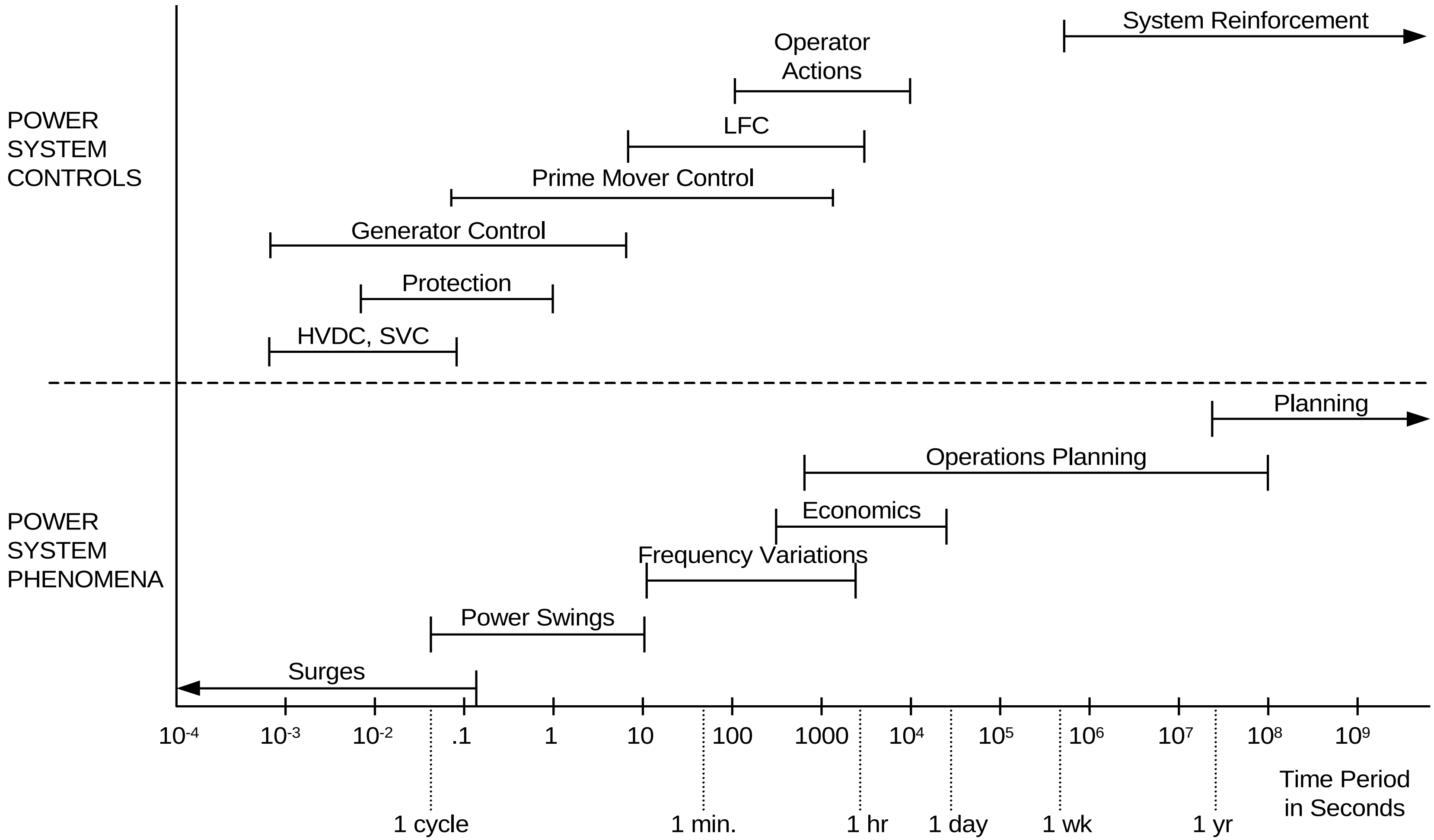
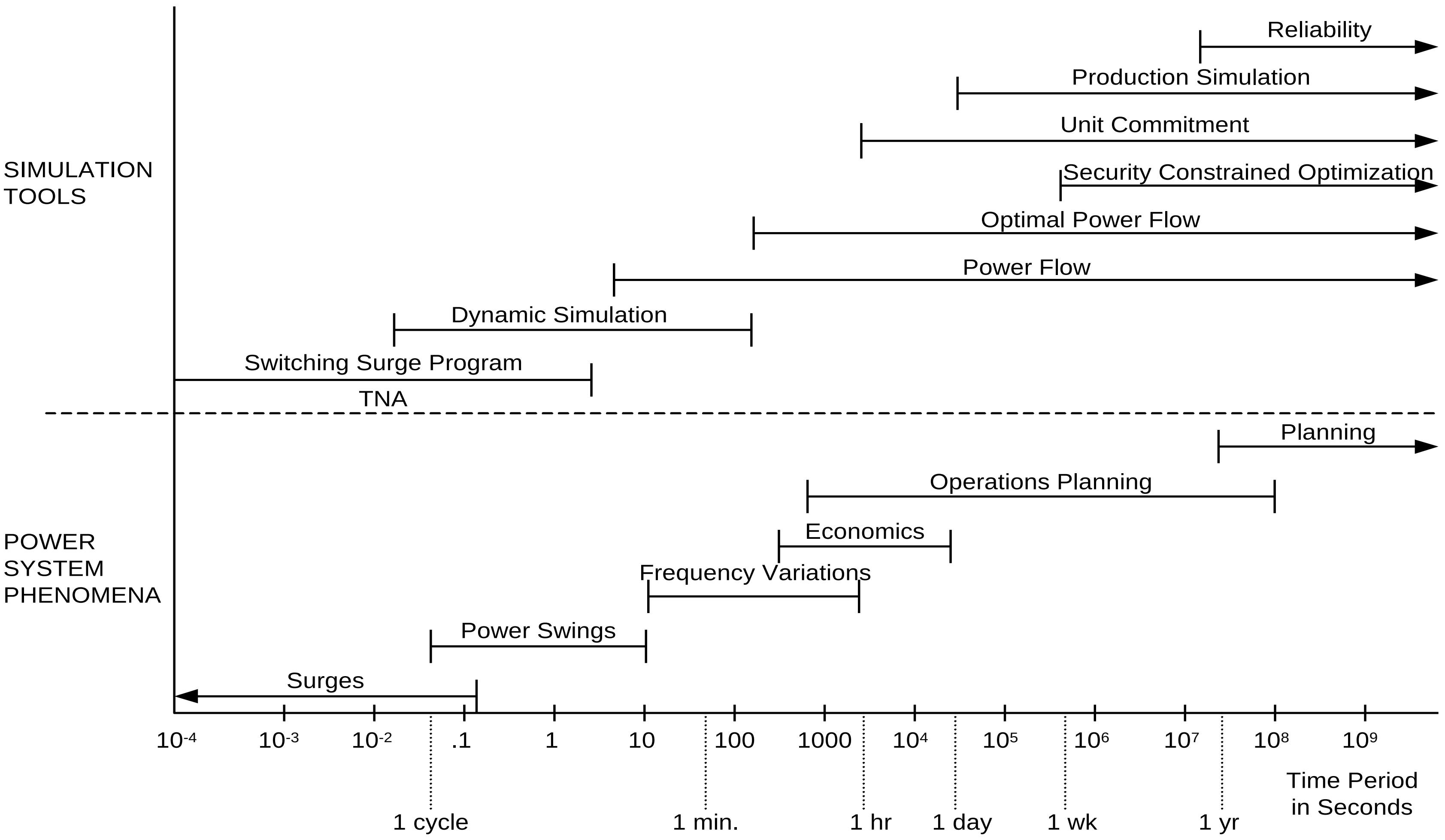
Power System Time Continuum



Simulation Tool Continuum



Power System Time Scales and Transient Stability

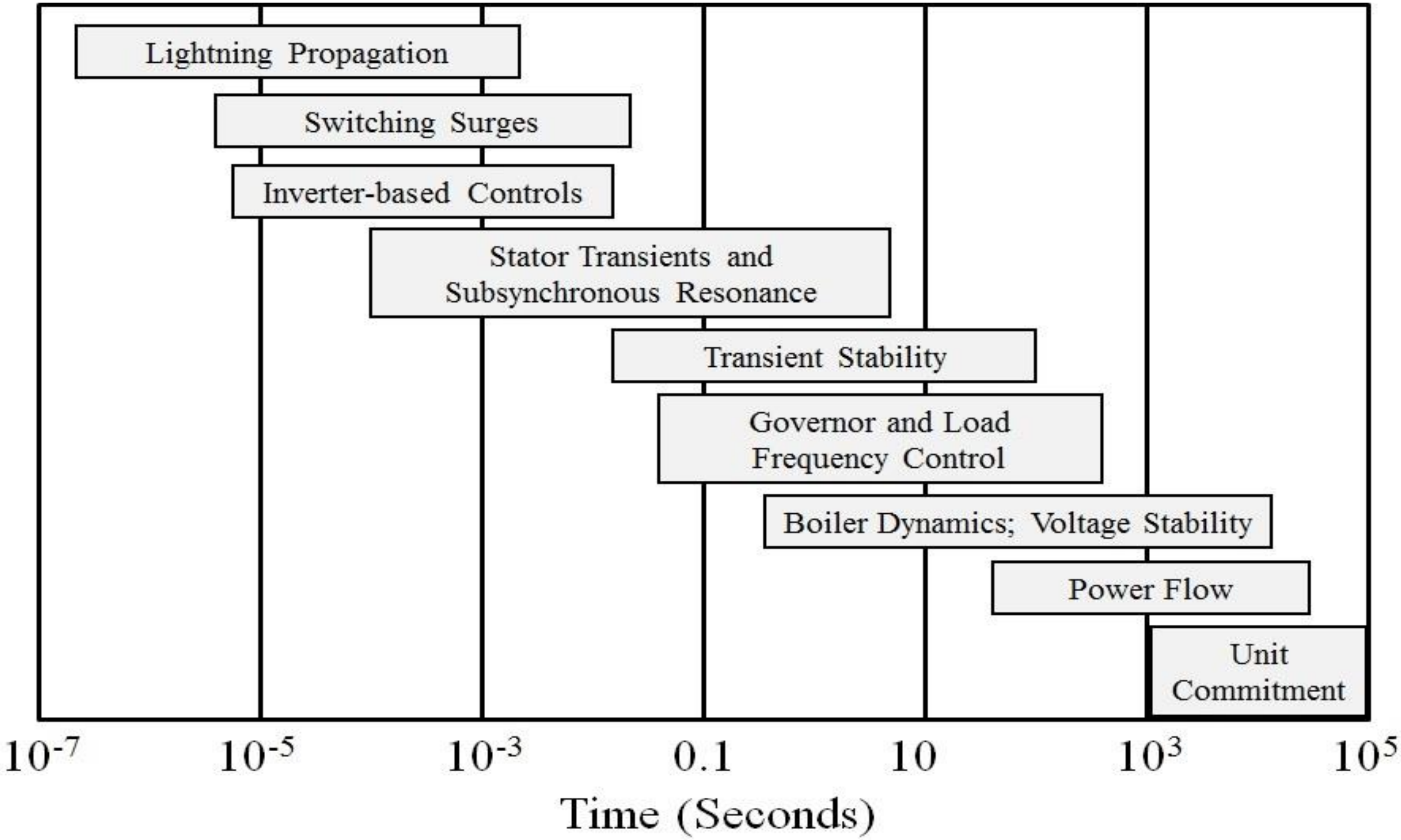
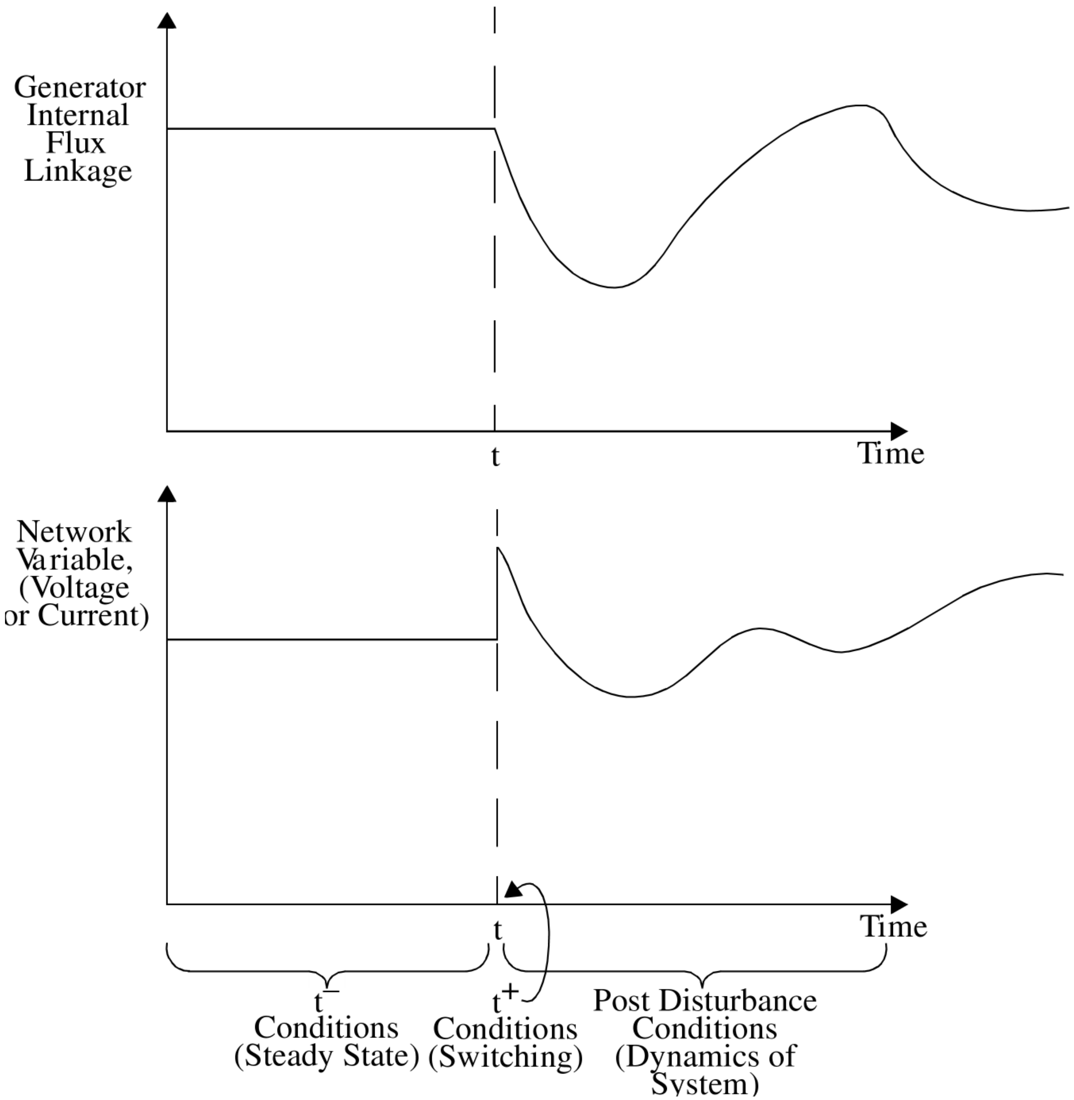


Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 1997.

Time Regimes Considered in Power System Simulations



Per Unit Calculations

- A key problem in analyzing power systems is the large number of transformers.
  - It would be very difficult to continually have to refer impedances to the different sides of the transformers
- This problem is avoided by a normalization of all variables.
- This normalization is known as per unit analysis.

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

Note, per unit conversion affects magnitudes, not the angles. Also, per unit quantities no longer have units (i.e., a voltage is 1.0 p.u., not 1 p.u. volts)

Three Phase Per Unit

1. Pick a 3ϕ VA base for the entire system, $S_B^{3\phi}$
2. Pick a voltage base for each different voltage level, V_B. Voltages are line to line.
3. Calculate the impedance base

$$Z_B = \frac{V_{B,LL}^2}{S_B^{3\phi}} = \frac{(\sqrt{3}\,V_{B,LN})^2}{3S_B^{1\phi}} = \frac{V_{B,LN}^2}{S_B^{1\phi}}$$

Exactly the same impedance bases as with single phase!

Three Phase Per Unit, cont'd

4. Calculate the current base, I_B

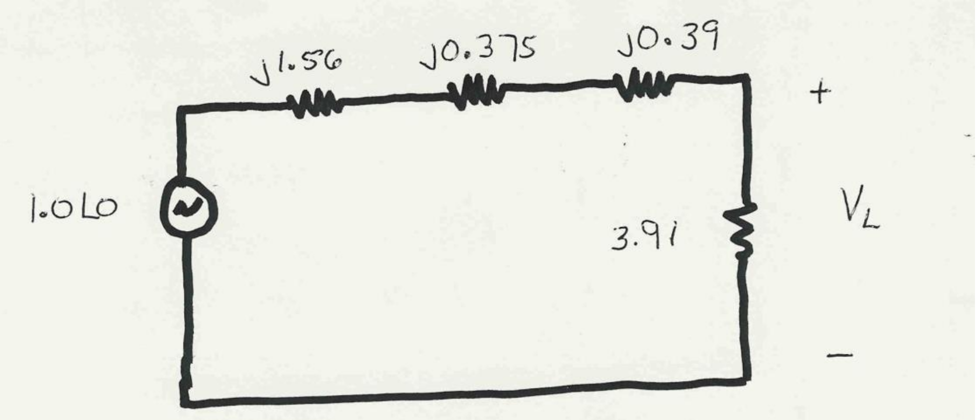
$$\mathrm{I}_{\mathrm{B}}^{3\phi} = \frac{S_B^{3\phi}}{\sqrt{3}\,V_{B,LL}} = \frac{3\,S_B^{1\phi}}{\sqrt{3}\,\sqrt{3}\,V_{B,LN}} = \frac{S_B^{1\phi}}{V_{B,LN}} = \mathrm{I}_{\mathrm{B}}^{1\phi}$$

Exactly the same current bases as with single phase!

5. Convert actual values to per unit

Three Phase Per Unit Example

Solve for the current, load voltage and load power in the previous circuit, assuming a 3ϕ power base of 300 MVA, and line to line voltage bases of 13.8 kV, 138 kV and 27.6 kV. Also assume the generator is Y-connected so its line to line voltage is 13.8 kV.



3ϕ Per Unit Example, cont'd

$$I = \frac{1.0\angle 0^\circ}{3.91 + j2.327} = 0.22\angle -30.8^\circ \text{ p.u. (not amps)}$$

$$\begin{aligned} \mathrm{V_L} &= 1.0\angle 0^\circ - 0.22\angle -30.8^\circ \times 2.327\angle 90^\circ \\ &= 0.859\angle -30.8^\circ \text{ p.u.} \end{aligned}$$

$$S_L = V_L I_L^* = \frac{|V_L|^2}{Z} = 0.189 \text{ p.u.}$$

$$S_G = 1.0\angle 0^\circ \times 0.22\angle 30.8^\circ = 0.22\angle 30.8^\circ \text{ p.u.}$$

3ϕ Per Unit Example, cont'd

Differences appear when we convert back to actual values

$$V_L^{Actual} = 0.859\angle -30.8° \times 27.6 \text{ kV} = 23.8\angle -30.8° \text{ kV}$$

$$S_L^{Actual} = 0.189\angle 0° \times 300 \text{ MVA} = 56.7\angle 0° \text{ MVA}$$

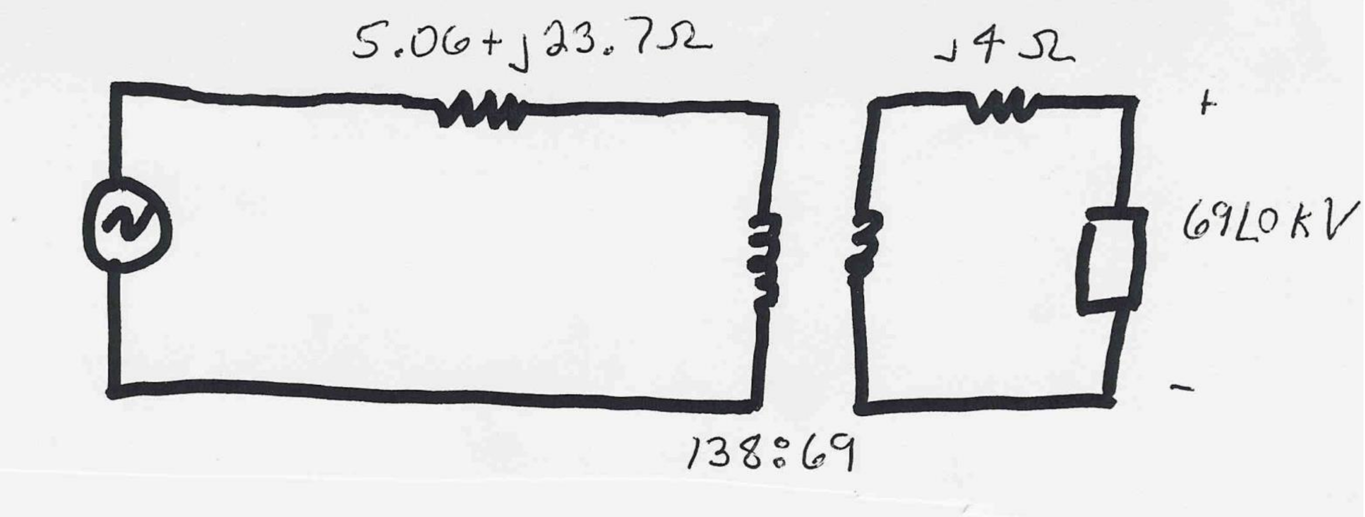
$$S_G^{Actual} = 0.22\angle 30.8° \times 300 \text{ MVA} = 66.0\angle 30.8° \text{ MVA}$$

$$I_B^{Middle} = \frac{300 \text{ MVA}}{\sqrt{3}\, 138 \text{ kV}} = 1250 \text{ Amps}$$

$$I_{Middle}^{Actual} = 0.22\angle -30.8° \times 1250 \text{ Amps} = 275\angle -30.8° \text{ A}$$

3ϕ Per Unit Example 2

- Assume a 3ϕ load of 100+j50 MVA with V_{LL} of 69 kV is connected to a source through the below network:



What is the supply current and complex power?

Answer: I=467 amps, S = 103.3 + j76.0 MVA

Per Unit Change of MVA Base

- Parameters for equipment are often given using power rating of equipment as the MVA base
- To analyze a system all per unit data must be on a common power base

$$Z_{pu}^{OriginalBase} \rightarrow Z_{actual} \rightarrow Z_{pu}^{NewBase}$$

$$\text{Hence} \quad Z_{pu}^{OriginalBase} \times \frac{V_{base}^2}{S_{Base}^{OriginalBase}} / \frac{V_{base}^2}{S_{Base}^{NewBase}} = Z_{pu}^{NewBase}$$

$$Z_{pu}^{OriginalBase} \times \frac{S_{Base}^{NewBase}}{S_{Base}^{OriginalBase}} = Z_{pu}^{NewBase}$$

Per Unit Change of Base Example

- A 54 MVA transformer has a leakage reactance of 3.69%. What is the reactance on a 100 MVA base?

$$X_e = 0.0369 \times \frac{100}{54} = 0.0683 \ \text{p.u.}$$

Transformer Reactance

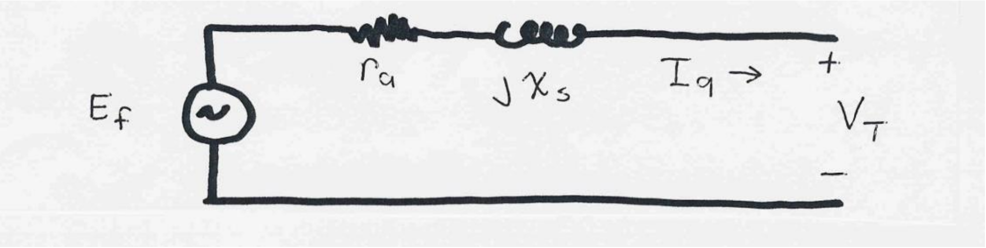
- Transformer reactance is often specified as a percentage, say 10%.
- This is a per unit value (divide by 100) on the power base of the transformer.
- Example: A 350 MVA, 230/20 kV transformer has leakage reactance of 10%. What is p.u. value on 100 MVA base? What is value in ohms (230 kV)?

$$X_e = 0.10 \times \frac{100}{350} = 0.0286 \ \ \text{p.u.}$$

$$0.0286 \times \frac{230^2}{100} = 15.1\,\Omega$$

Generator Models

- Engineering models depend upon application
- Generators are usually synchronous machines
- For generators we will use two different models:
  - a steady-state model, treating the generator as a constant power source operating at a fixed voltage; this model will be used for power flow and economic analysis
  - a time domain model treating the generator as a constant voltage source behind a time-varying reactance



Load Models

- Ultimate goal is to supply loads with electricity at constant frequency and voltage
- Electrical characteristics of individual loads matter, but usually they can only be estimated
  - actual loads are constantly changing, consisting of a large number of individual devices
  - only limited network observability of load characteristics
- Aggregate models are typically used for analysis
- Two common models
  - constant power: $S_i = P_i + jQ_i$
  - constant impedance: $S_i = |V|^2 / Z_i$

Power Flow Analysis

- The most common power system analysis tool is the power flow (also known sometimes as the load flow)
  - power flow determines how the power flows in a network
  - also used to determine all bus voltages and all currents
  - because of constant power models, power flow is a nonlinear analysis technique
  - power flow is a steady-state analysis tool

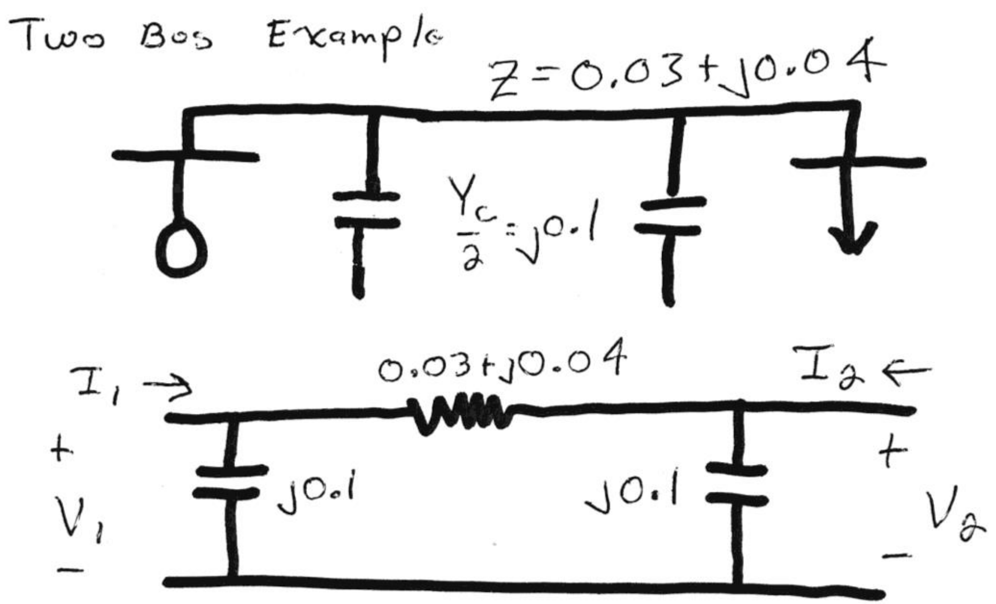
Bus Admittance Matrix or Y_{bus}

- First step in solving the power flow is to create what is known as the bus admittance matrix, often call the $\mathbf{Y}_{bus}$.
- The $\mathbf{Y}_{bus}$ gives the relationships between all the bus current injections, **I**, and all the bus voltages, **V**,

$$\mathbf{I} = \mathbf{Y}_{bus}\,\mathbf{V}$$

- The $\mathbf{Y}_{bus}$ is developed by applying KCL at each bus in the system to relate the bus current injections, the bus voltages, and the branch impedances and admittances

Two Bus System Example



$$I_1 = \frac{(V_1 - V_2)}{Z} + V_1 \frac{Y_c}{2} \qquad \frac{1}{0.03 + j0.04} = 12 - j16$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 12 - j15.9 & -12 + j16 \\ -12 + j16 & 12 - j15.9 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

Using the Y_{bus}

If the voltages are known then we can solve for the current injections:

$$\mathbf{Y}_{bus}\mathbf{V} = \mathbf{I}$$

If the current injections are known then we can solve for the voltages:

$$\mathbf{Y}_{bus}^{-1}\mathbf{I} = \mathbf{V} = \mathbf{Z}_{bus}\mathbf{I}$$

where $\mathbf{Z}_{\text{bus}}$ is the bus impedance matrix

Power Flow Requires Iterative Solution

In the power flow we assume we know S_i and the $\mathbf{Y}_{bus}$. We would like to solve for the V's. The problem is the below equation has no closed form solution:

$$S_i = V_i I_i^* = V_i \left(\sum_{k=1}^{n} Y_{ik} V_k \right)^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^*$$

Rather, we must pursue an iterative approach.

Three Types of Power Flow Buses

- There are three main types of power flow buses
  - Load (PQ) at which P/Q are fixed; iteration solves for voltage magnitude and angle.
  - Slack at which the voltage magnitude and angle are fixed; iteration solves for P/Q injections
  - Generator (PV) at which P and |V| are fixed; iteration solves for voltage angle and Q injection

Slack Bus

- Angle reference bus.
- We can not arbitrarily specify S at all buses because total generation must equal total load + total losses
- To solve these problems we define one bus as the "slack" bus.
- This bus has a fixed voltage magnitude and angle, and a varying real/reactive power injection.

Generation Changes and The Slack Bus

- The power flow is a steady-state analysis tool, so the assumption is total load plus losses is always equal to total generation
  - Generation mismatch is made up at the slack bus
- When doing generation change power flow studies one always needs to be cognizant of where the generation is being made up
  - Common options include system slack, distributed across multiple generators by participation factors or by economics

Newton-Raphson Power Flow

- Advantages
  - fast convergence as long as initial guess is close to solution
  - large region of convergence
- Disadvantages
  - each iteration takes much longer than a Gauss-Seidel iteration
  - more complicated to code
- Newton-Raphson algorithm is very common in power flow analysis

Fast Decoupled Power Flow

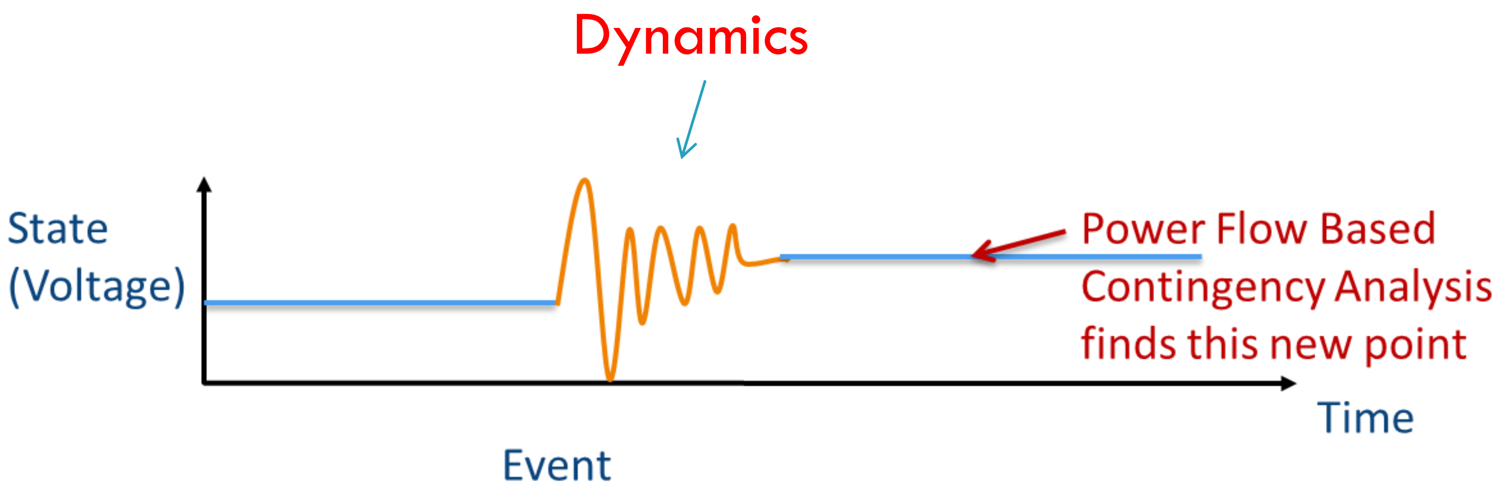
- By continuing with our Jacobian approximations we can actually obtain a reasonable approximation that is independent of the voltage magnitudes/angles.
- This means the Jacobian need only be built/inverted once.
- This approach is known as the fast decoupled power flow (FDPF)
- FDPF uses the same mismatch equations as standard power flow so it should have same solution
- The FDPF is widely used, particularly when we only need an approximate solution

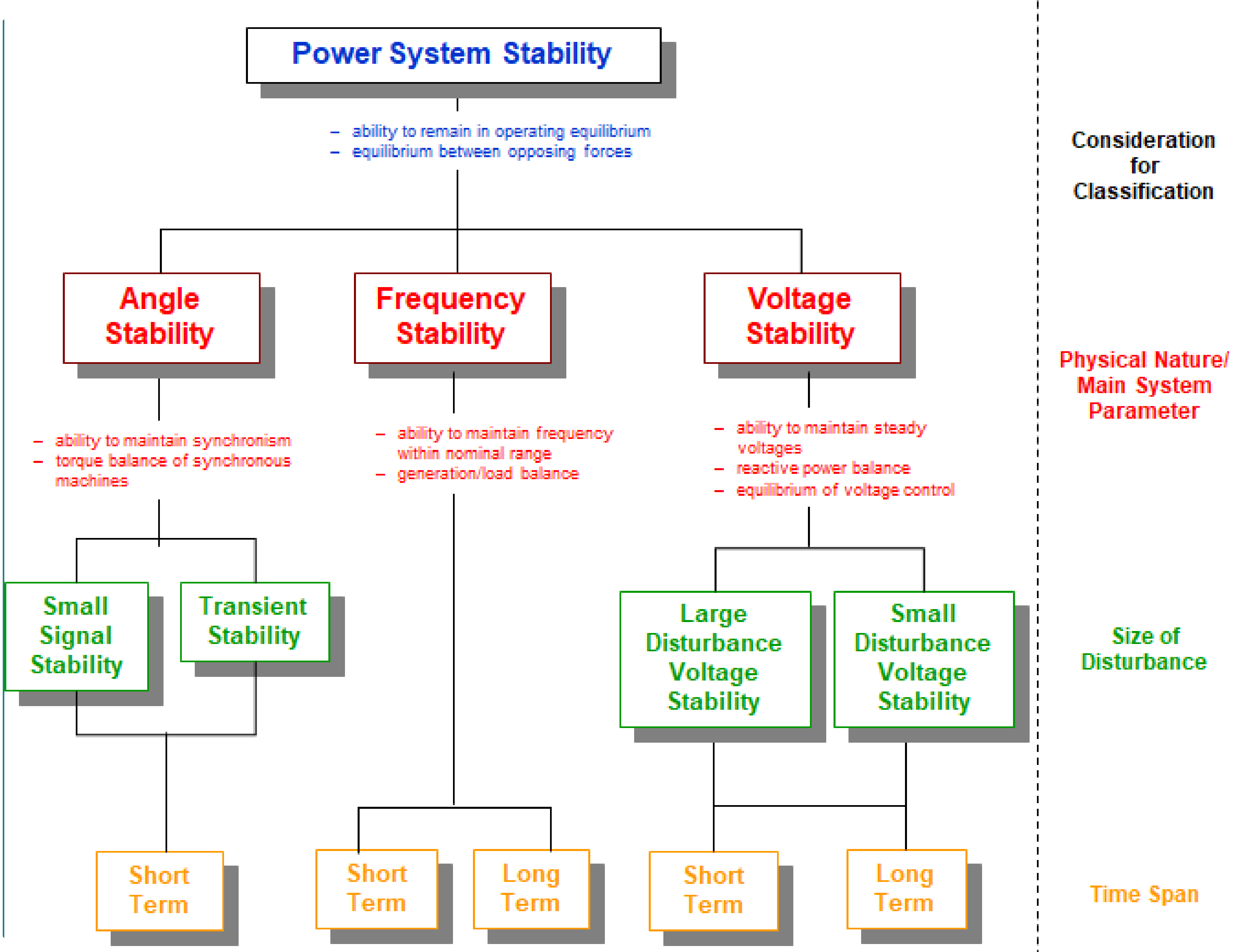
Fault Analysis

- Fault currents cause equipment damage due to both thermal and mechanical processes
- Goal of fault analysis is to determine the magnitudes of the currents present during the fault
  - need to determine the maximum current to insure devices can survive the fault
  - need to determine the maximum current the circuit breakers (CBs) need to interrupt to correctly size the CBs
- Time domain simulation ?

Power Flow vs Dynamics

- The power flow is used to determine a quasi steady-state operating condition for a power system
- Dynamics simulations is used to determine whether following a contingency the power system returns to a steady-state operating point




Power System Stability
– ability to remain in operating equilibrium
– equilibrium between opposing forces
Angle Stability
Frequency Stability
Voltage Stability
– ability to maintain synchronism
– torque balance of synchronous machines
– ability to maintain frequency within nominal range
– generation/load balance
– ability to maintain steady voltages
– reactive power balance
– equilibrium of voltage control
Small Signal Stability
Transient Stability
Large Disturbance Voltage Stability
Small Disturbance Voltage Stability
Short Term
Short Term
Long Term
Short Term
Long Term
Consideration for Classification
Physical Nature/ Main System Parameter
Size of Disturbance
Time Span

Thank You !!