

Transient Stability Analysis with PowerWorld Simulator



T1: Transient Stability Overview, Models and Relationships



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PowerWorld and Transient Stability



- PowerWorld has been working on transient stability since 2006, with a very simple implementation appearing in Version 12.5 (Glover/Sarma/Overbye book release).
- Some reasons for adding transient stability to PowerWorld
 - Growing need to perform transient stability/short-term voltage stability studies
 - There is a natural fit with PowerWorld – we have good expertise in power system information management and visualization and transient stability creates lots of data
 - Fills out PowerWorld's product line

Models and Model Relationships



- Overview of power system modeling in general
 - Time Scales
- Overview of the different model types supported by Simulator
 - Generator Models
 - Relationships between the different types of generator models
 - Wind Generator Models
 - Relationships for them
 - Also some discussion of Load Models

Analysis Time Scales

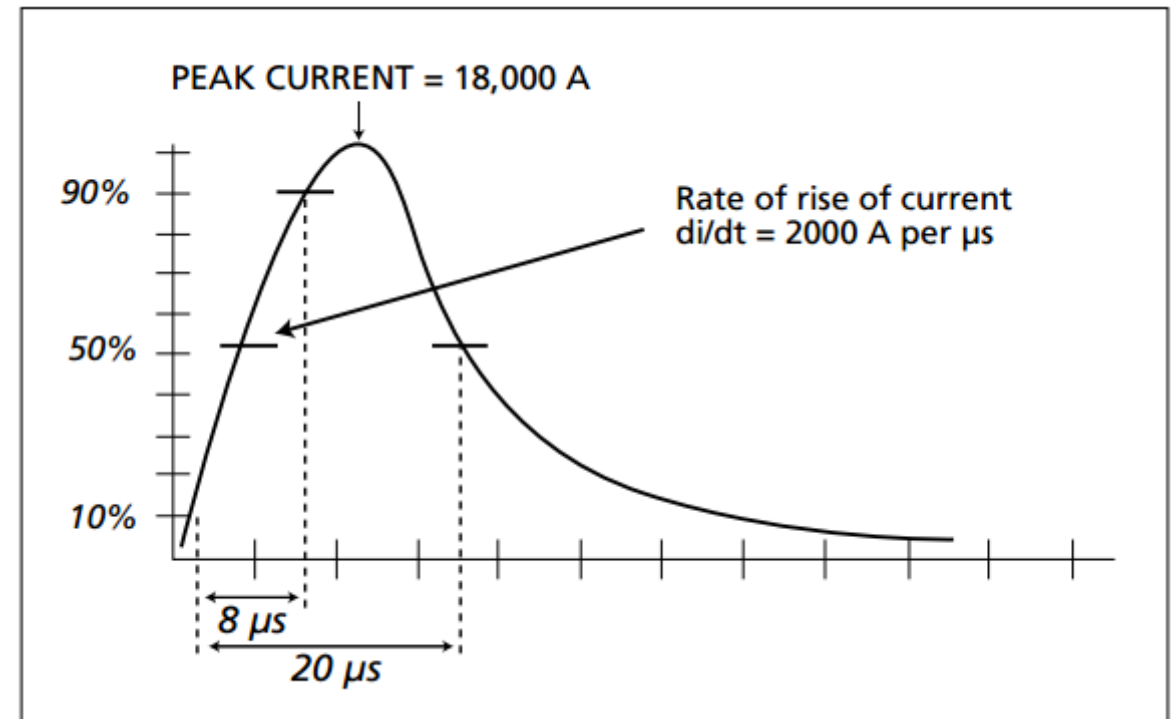


- Questions an engineer asks
 - What happens when lightning strikes a transmission line?
 - What happens during black start as you switch in transmission lines that are completely de-energized?
 - How long does it take to change the MW output of a very large coal plant?
 - What happens when a 2,400 MW of generation trips off-line unexpected?
 - What happens when you switch on a light?
- To answer these questions require completely different tools depending on the time scale

Ultra-Fast Transients



- Lightning current pulse (IEEE 8/20 Model)
 - Surge is over in 40 microseconds!
 - Frequencies would be in the 10s of kilohertz



Switching Surges



- Closing in a Transmission Line that's presently de-energized
 - 300 km line $\rightarrow$ $\frac{1}{4}$ wavelength standing wave will be
 - Wavelength * Frequency = Speed
 - Speed of Light $\sim 3E8$ m/s
 - Wavelength = $300E3 * 4$ m
 - Frequency = $3E8 / (300E3 * 4) = 250$ Hz
 - Thus frequency can be in the 100s of Hz for sure
 - Requires modeling the reflections of a standing wave on a transmission line
 - You can get a doubling of voltage at the far end during the initial transient

Stator Current Transients



- Fast Current Transients (100 – 200 Hz)

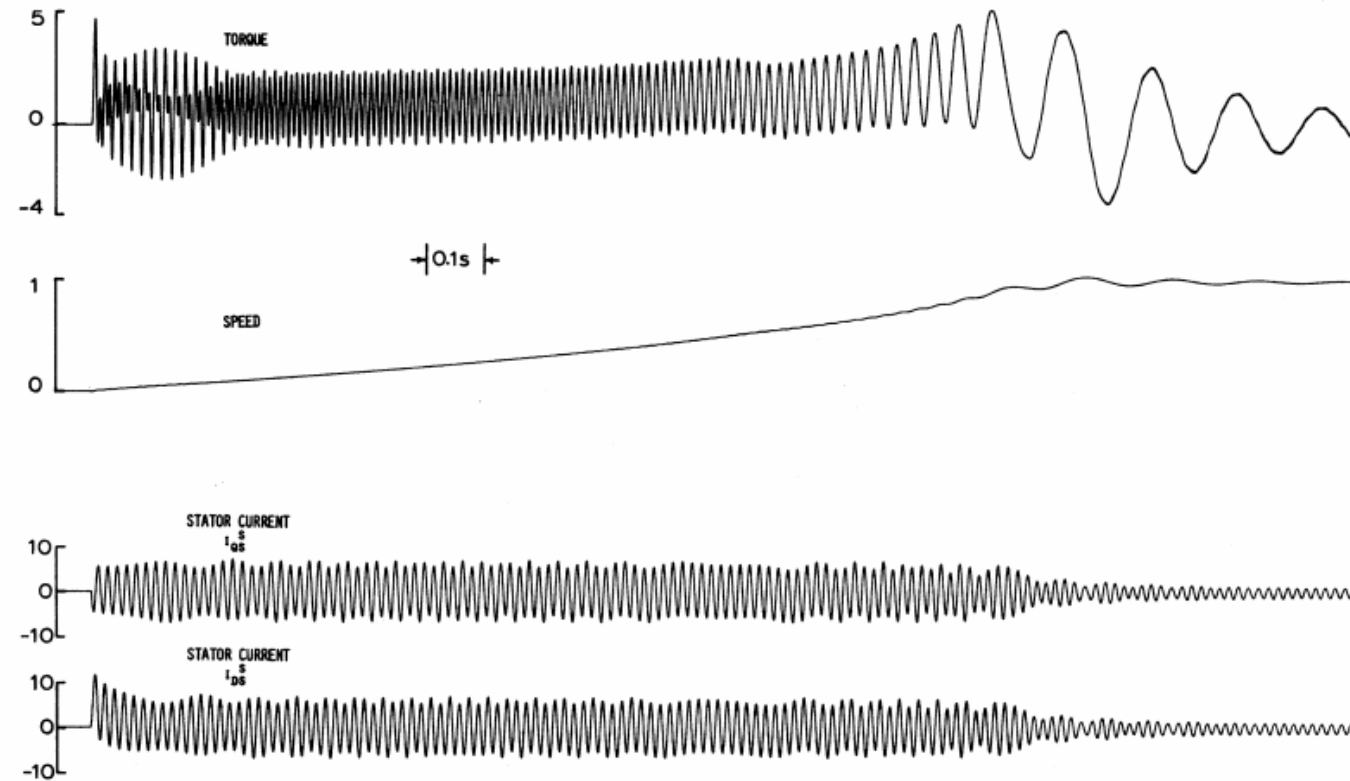


Figure 1 Free acceleration characteristics of a synchronous machine with $p\psi^r$ and $\Delta\omega_r$ terms included

Krause, P.C.; Nozari, F.; Skvarenina, T.L.; Olive, D.W., "The Theory of Neglecting Stator Transients," *Power Apparatus and Systems, IEEE Transactions on*, vol.PAS-98, no.1, pp.141,148, Jan. 1979

Sub-Synchronous Resonance



- The mechanical system of the generator turbine will have mechanical resonant frequency (or frequencies)
- For large generators like big coal plants these can be on the order of 18 – 25 Hz.
 - Note: a generator operator needs to be cognizant of this as they startup a generator. When the generator goes through this resonant speed it can create mechanical oscillations.
- Typically the electrical system resonant frequencies are much higher than this, so it's not a concern
- However
 - Series capacitors near a generator can push electrical system resonance lower into this range
 - Can lead to resonant interaction between electrical and mechanical system damaging the mechanical shaft.

What if we want to model phenomena that are 100 Hz or faster?

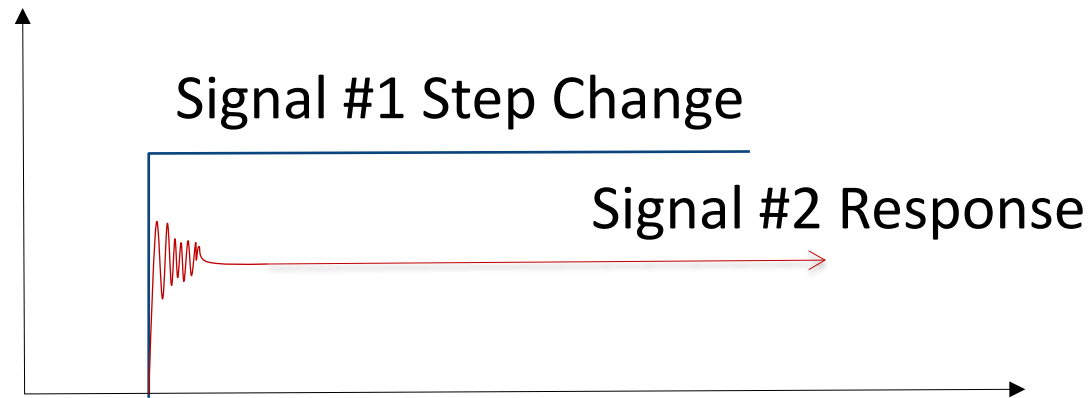


- Would require you to model the standing waves that happen on transmission lines
- This means the “power flow equations” can’t be directly used anymore
- The speed of light comes into play
- You are simulating phenomena that last on the order of a few milliseconds
- Software that simulates this is commonly referred to as “Electro-Magnetic Transients Programs” or EMTP
- This is NOT what we’re going to talk about

How do we handle Ultra-Fast Transient Effects?

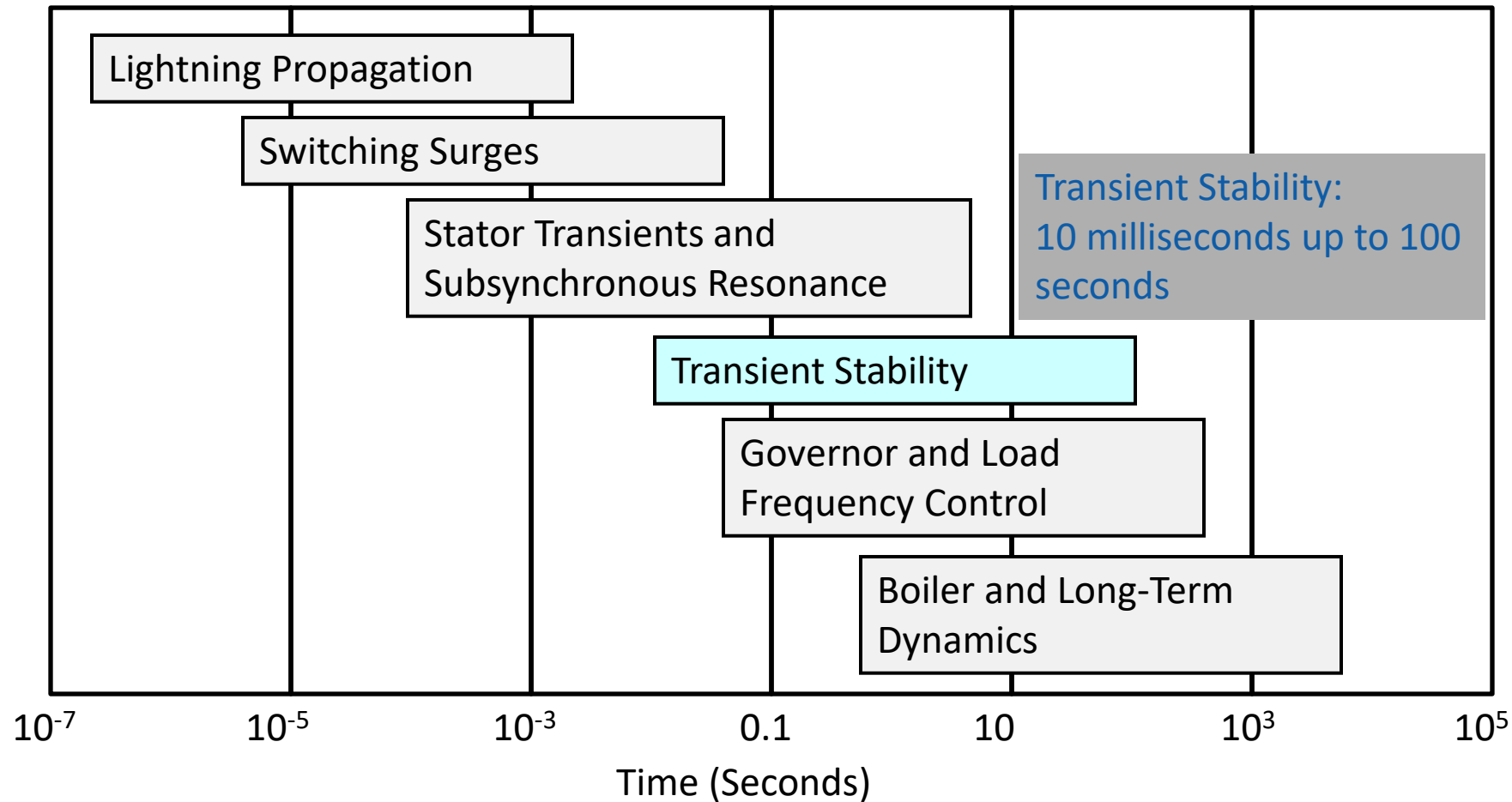


- Consider following response of Signal #2 to a change in Signal #1



- Just replace all the complexity of this and replace it with an algebraic equation
 - $\text{Signal2} = 0.6 * \text{Signal1}$

Time Scale of Dynamic Phenomena



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Power Flow

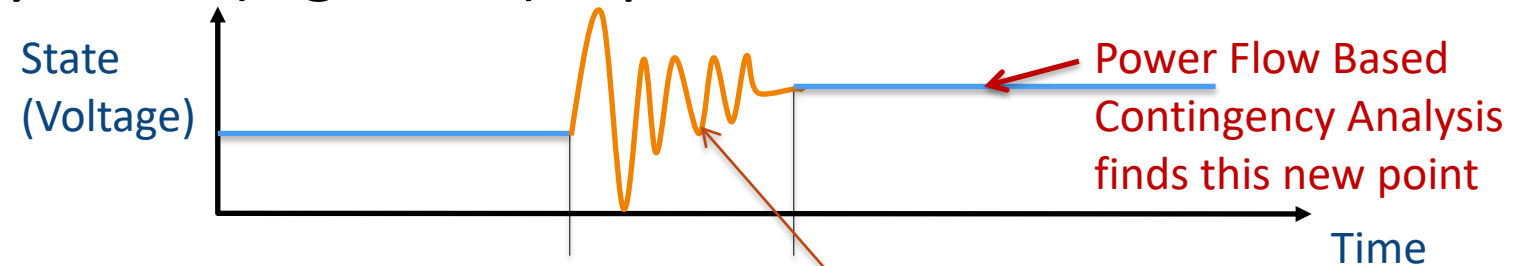


- The power flow is used to determine a quasi steady-state operating condition for a power system
 - Goal is to solve a set of algebraic equations
 - $\mathbf{g}(\mathbf{y}) = \mathbf{0}$ [$\mathbf{y}$ variables are bus voltage and angle]
 - Models employed reflect the steady-state assumption, such as generator PV buses, constant power loads, LTC transformers.

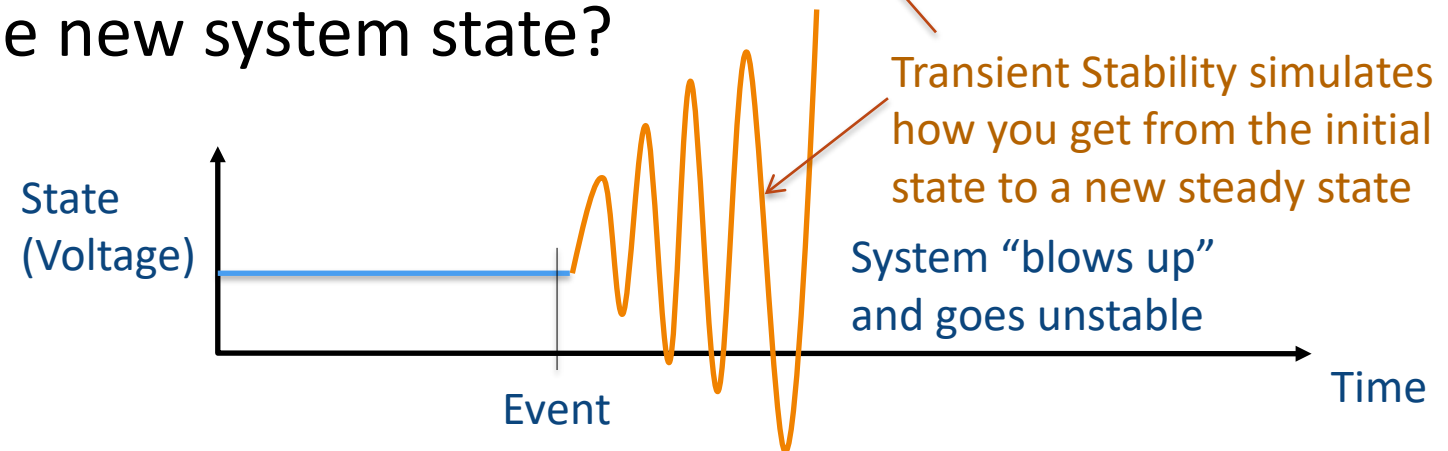
Contingency Analysis



- Contingency re-solves the power flow equations after a change (say opening a line)
- You get a new steady-state (algebraic) equation solution



- But what if system goes unstable before you get to the new system state?



Power Flow vs. Transient Stability



- Transient stability is used to determine whether following a contingency the power system returns to a steady-state operating point
 - Goal is to solve a set of differential and algebraic equations,
 - $\frac{dx}{dt} = f(x, y)$ [y variables are bus voltage and angle]
 - $g(x, y) = 0$ [x variables are dynamic state variables]
 - Starts in steady-state, and hopefully returns to a new steady-state.
 - Models reflect the transient stability time frame (up to dozens of seconds)
 - Slow Values → Treat as constants
 - Some values assumed to be slow enough to hold constant (LTC tap changing)
 - Ultra Fast States → Treat as algebraic relationships
 - Synchronous machine stator current dynamics, voltage source converter dynamics (DC transmission, portions of wind turbine models)

Transient Stability Solution Process



- Commercial Software typically uses explicit integration
 1. Start with solved Power Flow (similar to $\mathbf{g}(\mathbf{x}, \mathbf{y}) = \mathbf{0}$)
 - The “Initial” or “Boundary” Conditions
 - Gives $\mathbf{y}_0 \rightarrow$ initial values for all the $\mathbf{y}$ variables (Voltage, Angle)
 2. Derivatives at “steady state” are zero by definition, thus use the equation $\frac{d\mathbf{x}}{dt} = \mathbf{0} = \mathbf{f}(\mathbf{x}_0, \mathbf{y}_0)$ and solve for $\mathbf{x}_0$
 3. Use numerical integration to simulate going forward in time
 - Many ways to do this (half of an entire class in graduate school was dedicated to this), but let’s just consider the Forward Euler’s method because it’s simple to explain
 - Important user choice is the Time Step Δt that will be used in numerical integration

Transient Stability Numerical Integration



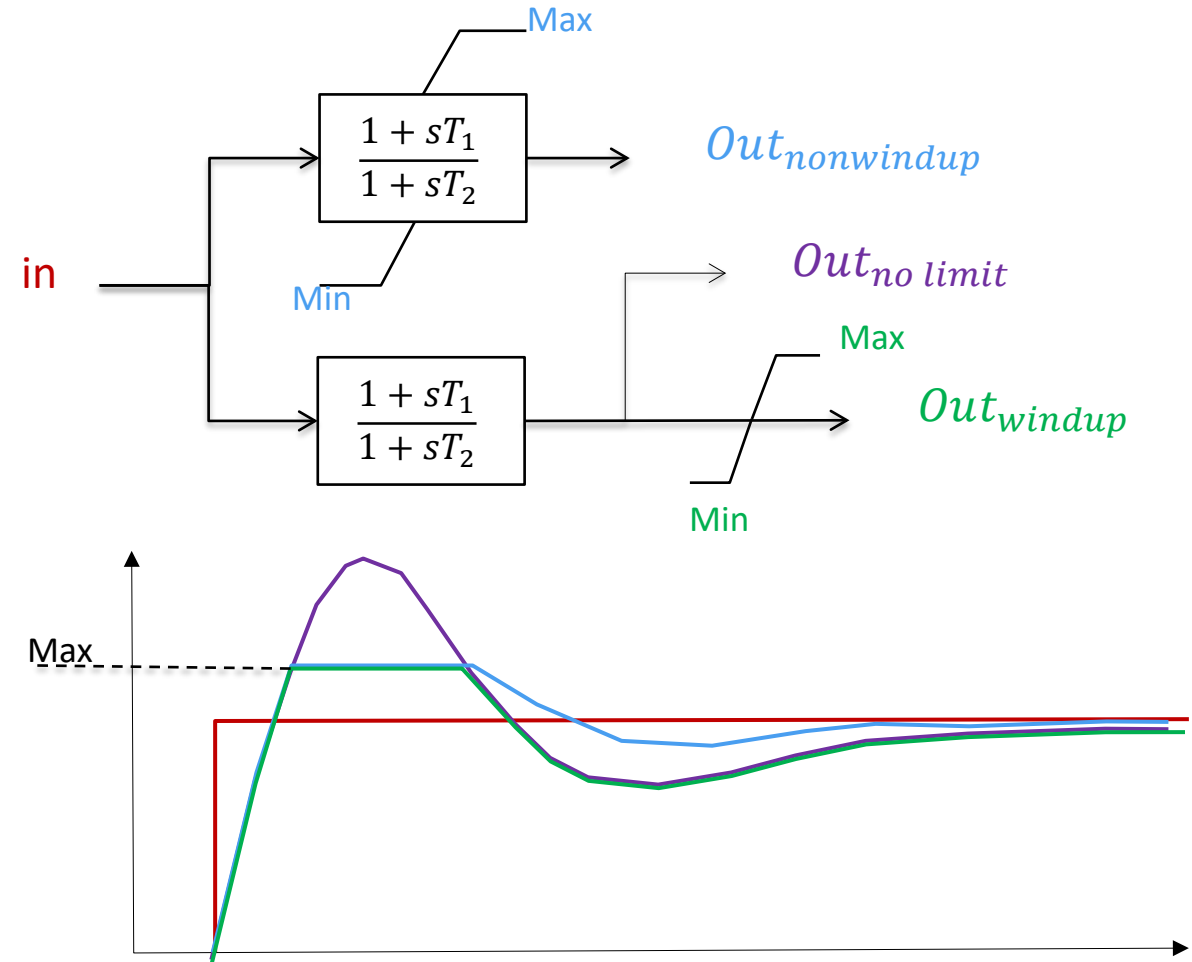
- Already have initial $\mathbf{x}_0$ and $\mathbf{y}_0$
- Initialize $t = 0$ and $k = 0$
- Choose a Time Step Δt that will be used in numerical integration

1. Calculate new $\mathbf{x}$: $\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta t * \mathbf{f}(\mathbf{x}_k, \mathbf{y}_k)$
 - called the “integration time step”
 - Many ways to do this. This is a “Forward Euler”
2. Calculate new $\mathbf{y}$: Solve $\mathbf{g}(\mathbf{x}_{k+1}, \mathbf{y}_{k+1}) = \mathbf{0}$
 - Called solving the “network boundary equations”
 - Very similar to power flow equation, but use complex currents instead
3. Increment time t : $t_{k+1} = t_k + \Delta t$
4. Increment k : $k = k + 1$
5. Go back to 1 repeat

Other Tricks in Integration



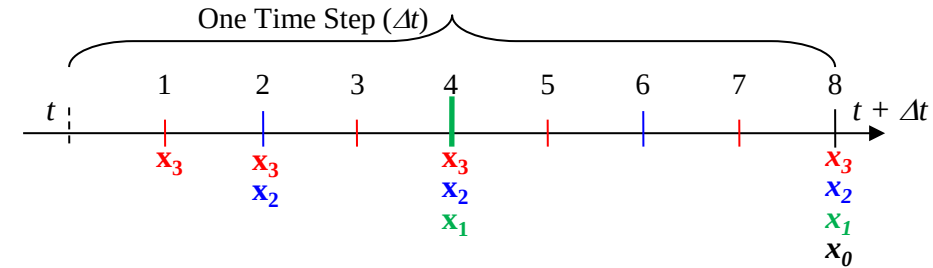
- Non-windup versus Windup Limits
 - Think an old “windup” clock with a spring. Eventually, the spring reaches a point where it can no longer “windup” anymore
 - A “non-windup” limit must be enforced between step 1 and 2 so that the state never goes past its limit



Sub-Interval Integration



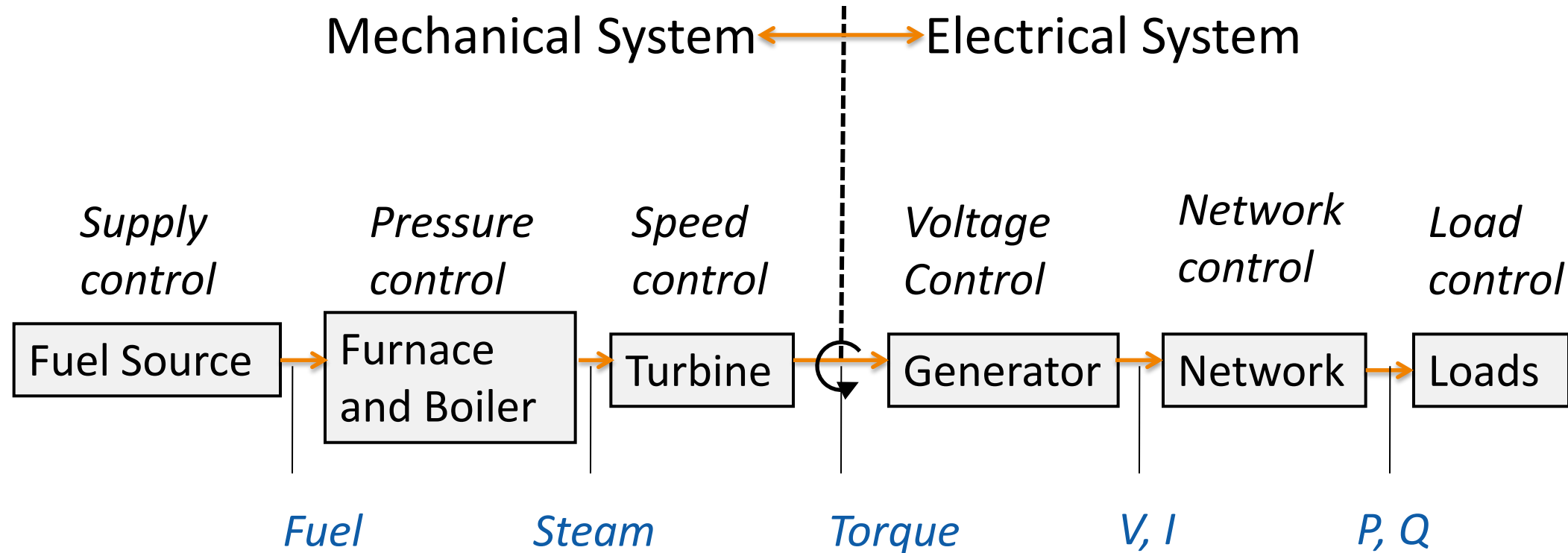
- Chop-up the time step into pieces so that you can use a smaller time step only for states that require this.



Subinterval	x_3 updates	x_2 updates	x_1 updates	x_0 updates
1	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	Assume constant	Assume constant	Assume constant
2	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	$x_2 = x_2 + \frac{\Delta t}{4} * f(x, y)$	Assume constant	Assume constant
3	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	Assume constant	Assume constant	Assume constant
4	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	$x_2 = x_2 + \frac{\Delta t}{4} * f(x, y)$	$x_1 = x_1 + \frac{\Delta t}{2} * f(x, y)$	Assume constant
5	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	Assume constant	Assume constant	Assume constant
6	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	$x_2 = x_2 + \frac{\Delta t}{4} * f(x, y)$	Assume constant	Assume constant
7	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	Assume constant	Assume constant	Assume constant
8	$x_3 = x_3 + \frac{\Delta t}{8} * f(x, y)$	$x_2 = x_2 + \frac{\Delta t}{4} * f(x, y)$	$x_1 = x_1 + \frac{\Delta t}{2} * f(x, y)$	$x_0 = x_0 + \frac{\Delta t}{1} * f(x, y)$

Physical Structure

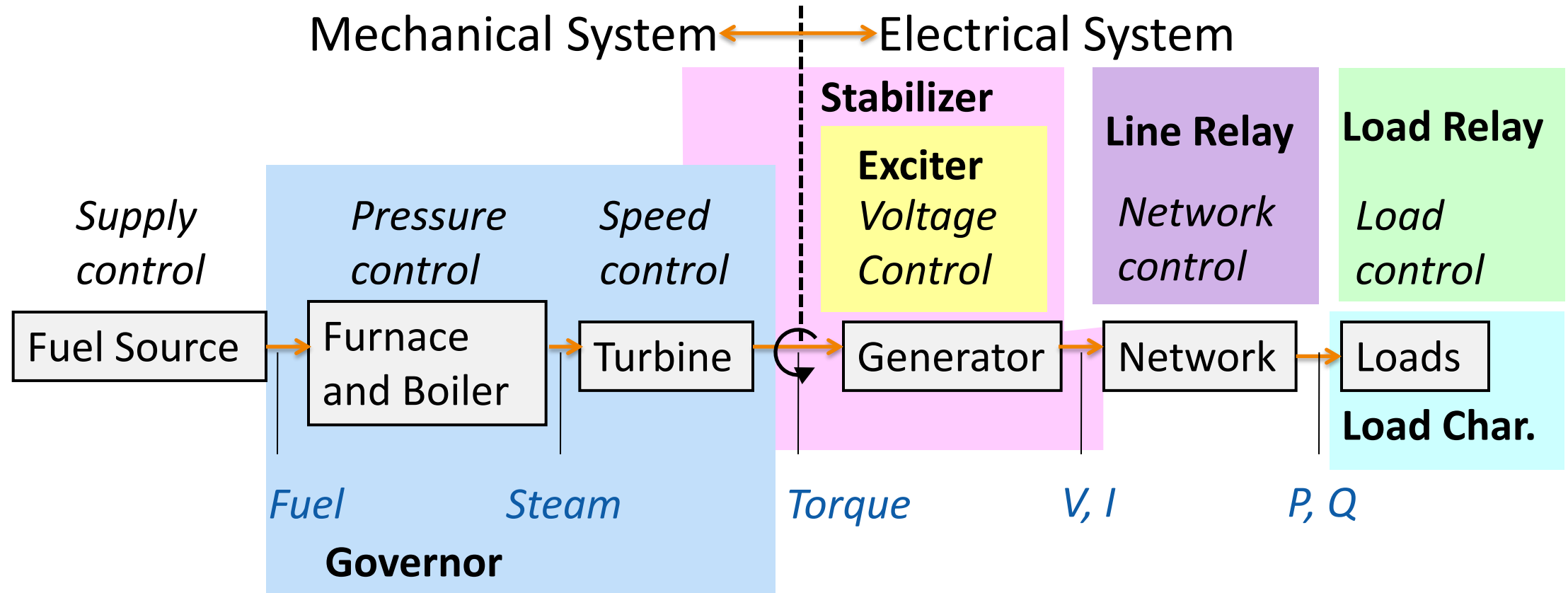
Power System Components



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Physical Structure

Power System Components

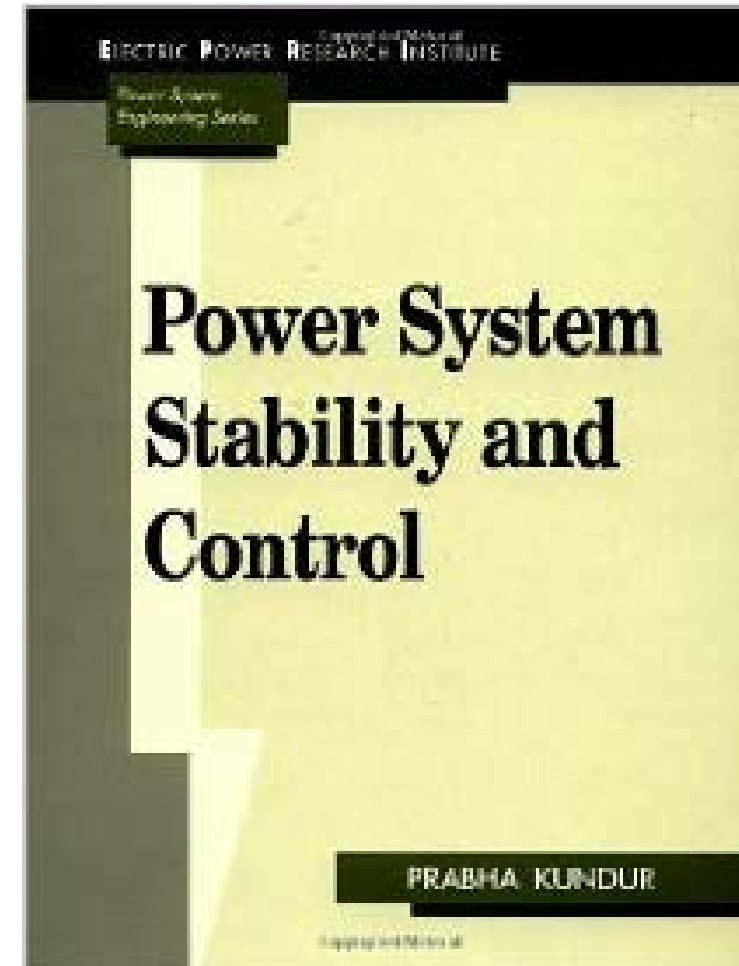


P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Transient Stability Modeling



- The most comprehensive book on this type of analysis is the by Prabha Kundur and is called *Power System Stability and Control* published in 1994
- Book is too detailed for a classroom textbook, but it is a really great as a reference book once you're working



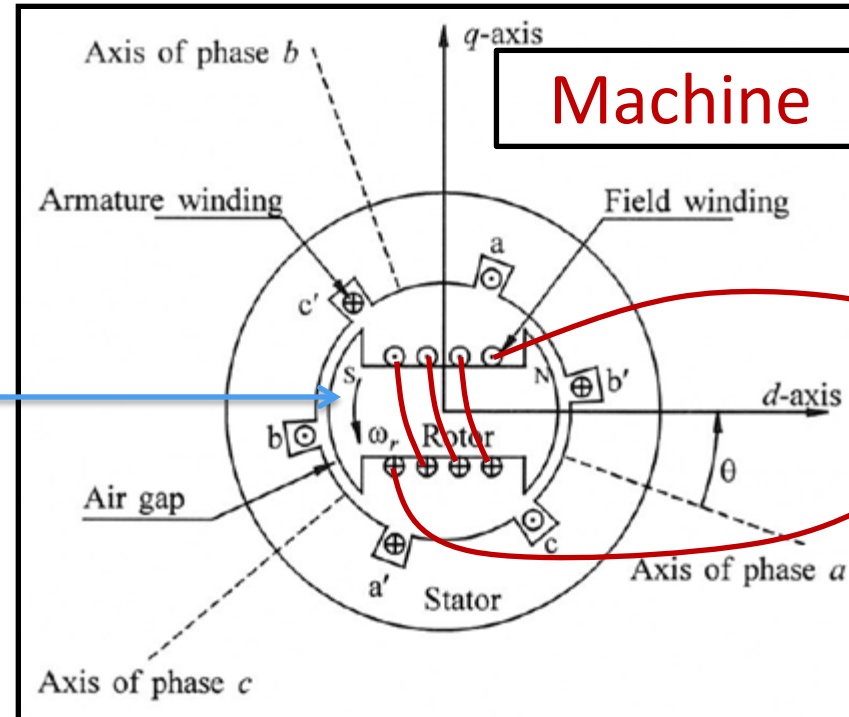
Synchronous Machine



- Basics of Synchronous Machine Model
 - Exciter applies DC current to rotor making it an electromagnet
 - Turbine/Governor spins rotor
 - Spinning magnet creates AC power

**Turbine/
Governor**

Creates a
mechanical torque
to spin the rotor



Exciter

Creates a DC voltage
to apply to Rotor
Winding, resulting in
an electromagnet

Mechanical Modeling a Generator



- Start with Newton's second law
 - Force = Mass * Acceleration
 - $F = M \frac{dv}{dt}$ and $\frac{dx}{dt} = v$
- We have a rotational system though, so instead we end up with something a little different
 - Torque = Moment of Inertia * Angular Acceleration
 - $T = J \frac{d\omega}{dt}$ and $\frac{d\delta}{dt} = \omega$

Per Unit Systems (again and always)



- You were introduced to per unit systems for the power flow
- This concept is everywhere in transient stability analysis
- It can be VERY confusing to everyone, but is a vital part of how these software tools are written and how data is provided by manufacturers
- You need to be very careful when entering data into any software package to make sure you're handling per unit correctly
 - ω_0 = synchronous speed
 - $\omega_0 = 2\pi f_0 = 2(3.14159) * 60 = 376.99$
 - H = Inertia Constant
 - Torque Base = MVA_{Base} / ω_0
 - ω = treated as *per unit speed deviation* $\rightarrow \omega = \frac{\omega_{actual} - \omega_0}{\omega_0}$

Generator Swing Equation



- Anyway, after a lot of additional algebra, software tools model the swing equations as follows with values in per unit

$$- 2H \frac{d\omega}{dt} = \frac{P_{mech}}{1+\omega} - T_{elec} \quad \text{and} \quad \frac{d\delta}{dt} = \omega$$

- If you use a more complete model of the rotor of a generator, then the T_{elec} term has some inherent damping in it
- In academic settings, as we'll introduce in a moment, the rotor modeling has no inherent damping in it (which makes your results really oscillate)
 - To overcome this, folks often add an extra $D\omega$ term as follows

$$2H \frac{d\omega}{dt} = \frac{P_{mech} - D\omega}{1 + \omega} - T_{elec}$$

- This term should NOT be used to model the damping in the more accurate rotor models such as GENROU, GENSAL, GENTPF, GENTPJ, etc.

Modeling the Generator Rotor



- This can be a few weeks worth of lectures in a graduate level course
 - We're going to take 4 slides, so don't worry about the details here
- Physical Structure Terms
 - Positional Winding Terms
 - Stator (Stationary portion of generator)
 - Rotor (Rotating portion of generator)
 - Functional Winding Terms
 - Armature Winding (three-phase AC winding that carries the power)
 - Normally this is on the Stator
 - Field Winding (DC current winding)
 - Normally this is on the Rotor
 - Amortisseur Winding (or damper winding)
 - An extra winding that provides start-up torque and damping
 - Basically a winding that causes a force that attempts to bring machine to synchronous speed (60 Hz)
 - Armature Poles
 - Following slide shows two dots for each (A, B, C) phase → one "in" and one "out"
 - This represents a 2 pole machine
 - If you just repeated this 4 additional times for each phase then you'd have an "8 pole" machine
 - More poles means the machine doesn't need to spin as fast to create 60 Hz

Modeling the Generator Rotor



- d = Direct Axis
 - Spinning axis directly in line with the “North Pole” of the field winding
- q = Quadrature Axis
 - Spinning axis 90 degrees out of phase with the direct axis
- Rotor Angle (δ)
 - Angle between Direct axis and Phase A axis

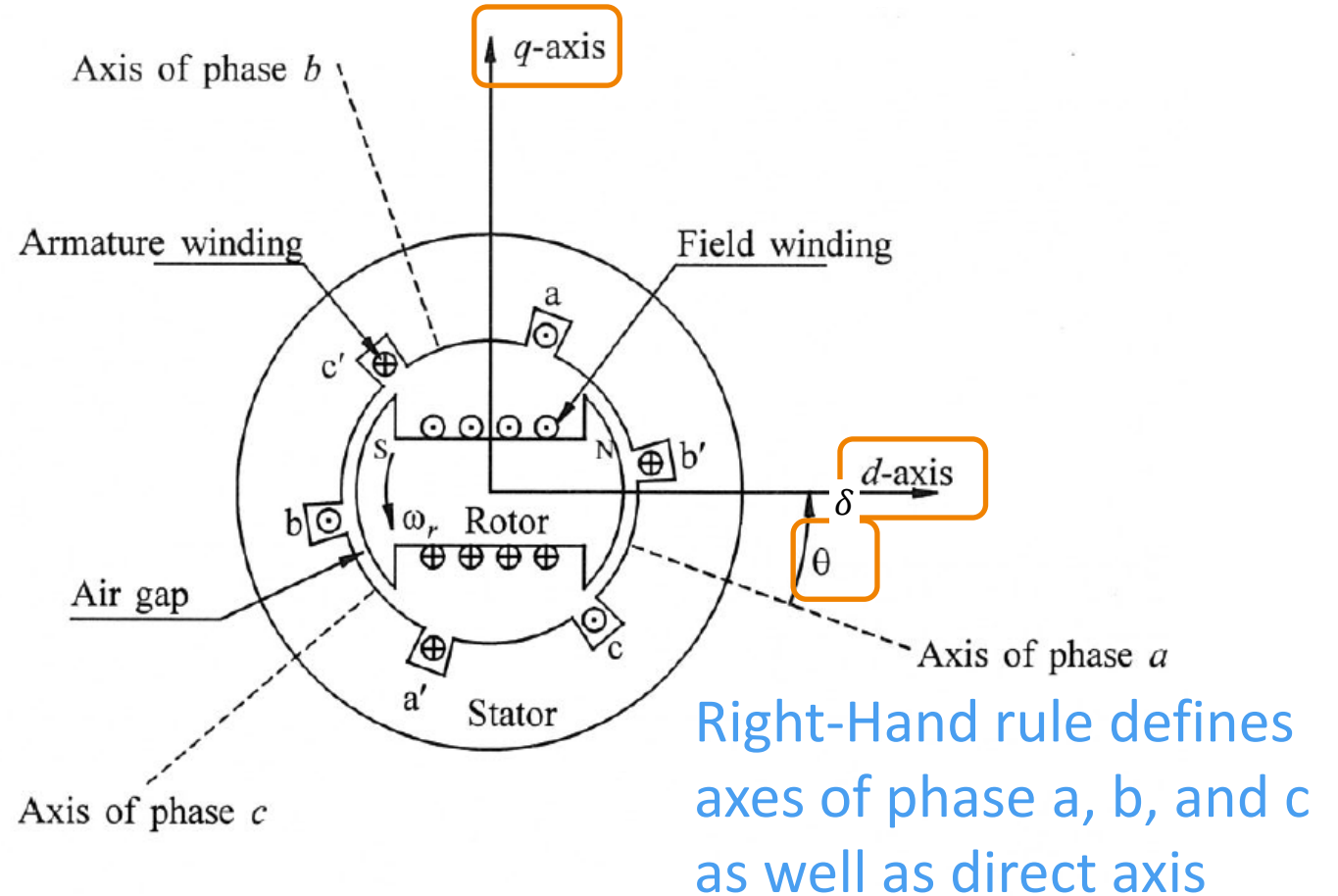


Figure 3.1 Schematic diagram of a three-phase synchronous machine

Deriving Equations for Rotor



- Algebra and trigonometry end up being extremely complex
 - Results give inductances between phases that are a function of the cosine of rotor angle
 - A simplification is done to transform the abc phase quantities into another reference frame
 - Called the dq0 transformation
 - Might hear “Park’s Transformation” after Robert H. Park who did something very similar in 1929

$$I_{dqo} = T I_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$I_{abc} = T^{-1} I_{dqo} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \frac{\sqrt{2}}{2} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_o \end{bmatrix}$$

dq0 Transformation



- This is a very similar idea as symmetrical components when discussing fault analysis (different matrix conversion though)
- We can say thanks to engineers who figured this all out for us 80 years ago!
- We end up with 14 equations that go through conversion similar to following
- Also do some more “magic” per unit assignment to make things clean-up more

$$\begin{aligned}\psi_a = & -i_a[L_{aa0}+L_{aa2}\cos 2\theta]+i_b[L_{ab0}+L_{aa2}\cos(2\theta+\frac{\pi}{3})] \\ & +i_c[L_{ab0}+L_{aa2}\cos(2\theta-\frac{\pi}{3})]+i_{fd}L_{afd}\cos\theta \\ & +i_{kd}L_{akd}\cos\theta-i_{kq}L_{akq}\sin\theta\end{aligned}$$

$$\begin{aligned}\psi_b = & i_a[L_{ab0}+L_{aa2}\cos(2\theta+\frac{\pi}{3})]-i_b[L_{aa0}+L_{aa2}\cos 2(\theta-\frac{2\pi}{3})] \\ & +i_c[L_{ab0}+L_{aa2}\cos(2\theta-\pi)]+i_{fd}L_{afd}\cos(\theta-\frac{2\pi}{3}) \\ & +i_{kd}L_{akd}\cos(\theta-\frac{2\pi}{3})-i_{kq}L_{akq}\sin(\theta-\frac{2\pi}{3})\end{aligned}$$

$$\begin{aligned}\psi_c = & i_a[L_{ab0}+L_{aa2}\cos(2\theta-\frac{\pi}{3})]+i_b[L_{ab0}+L_{aa2}\cos(2\theta-\pi)] \\ & -i_c[L_{aa0}+L_{aa2}\cos 2(\theta+\frac{2\pi}{3})]+i_{fd}L_{afd}\cos(\theta+\frac{2\pi}{3}) \\ & +i_{kd}L_{akd}\cos(\theta+\frac{2\pi}{3})-i_{kq}L_{akq}\sin(\theta+\frac{2\pi}{3})\end{aligned}$$

dq0

$$\psi_d = -L_d i_d + L_{afd} i_{fd} + L_{akd} i_{kd}$$

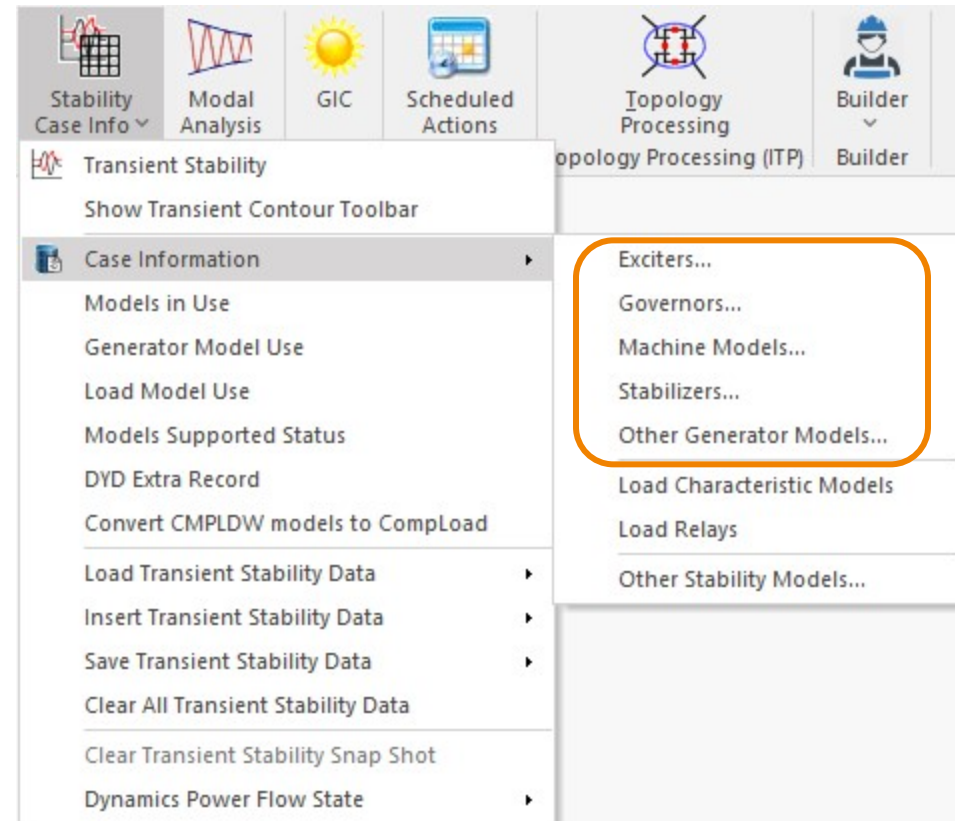
$$\psi_q = -L_q i_q + L_{akq} i_{kq}$$

$$\psi_0 = -L_0 i_0$$

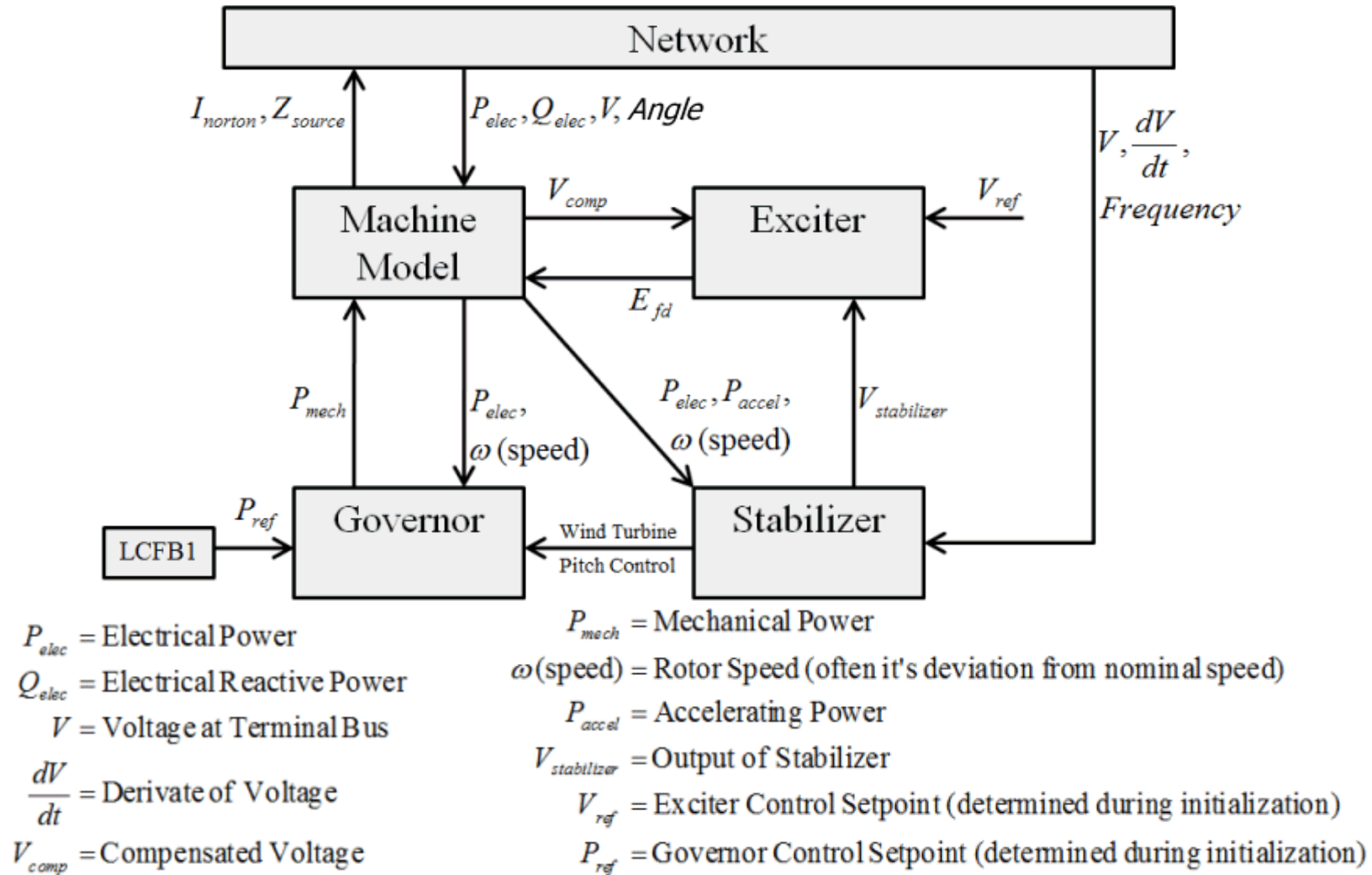
Generator Models



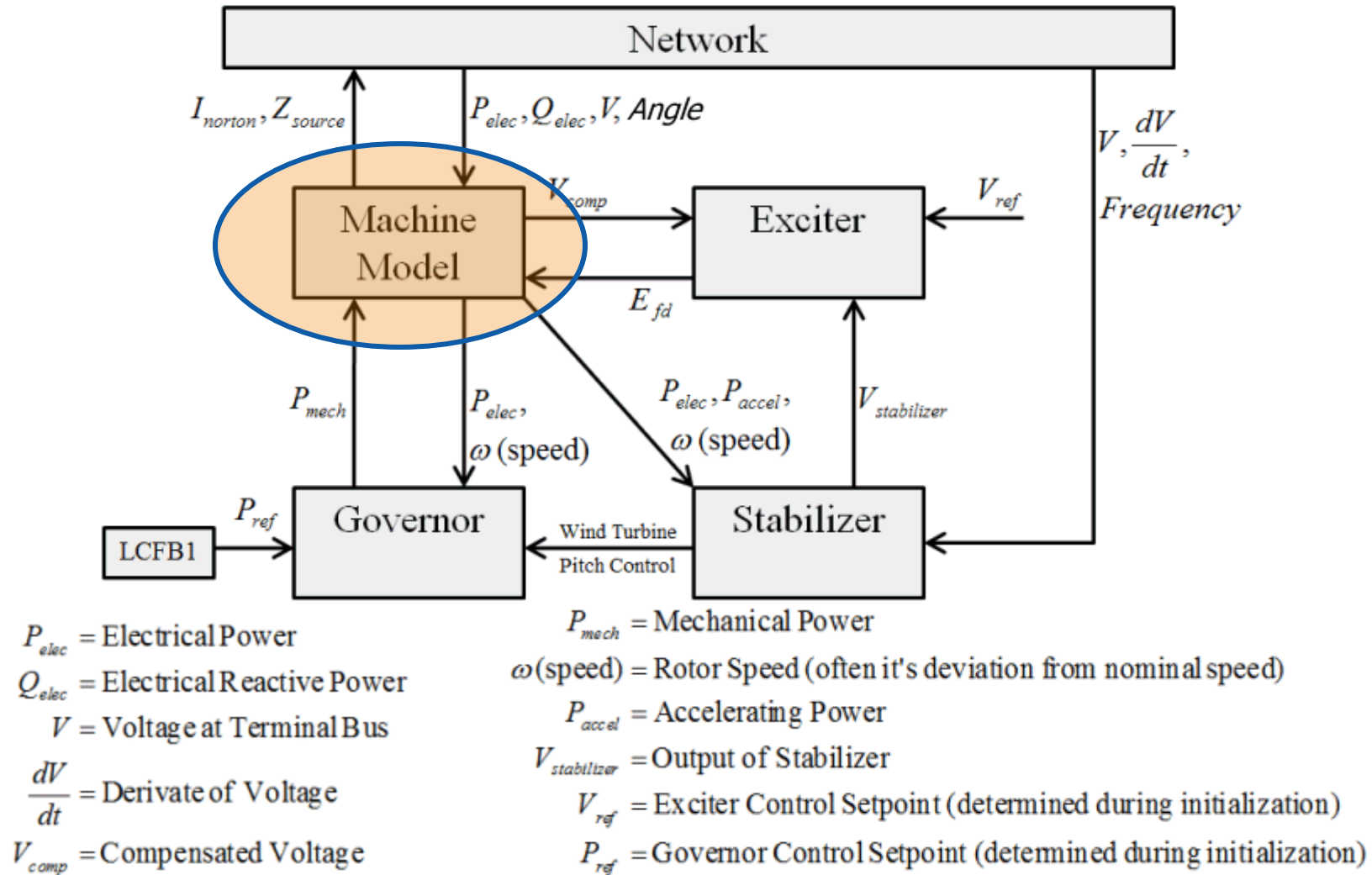
- Generators can have several classes of models assigned to them
 - Machine Models
 - Exciter
 - Governors
 - Stabilizers
- Others also available
 - Excitation limiters, voltage compensation, turbine load controllers, and generator relay model



Generator Models



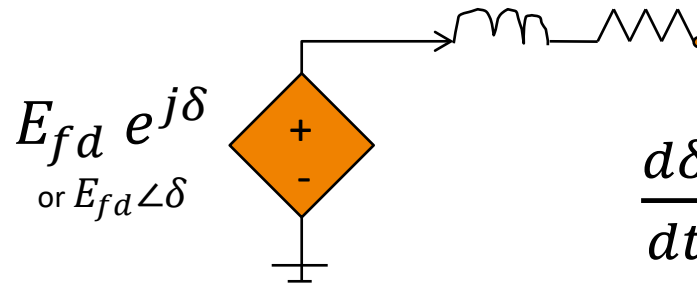
Machine Models



Machine Models



- The Classical Model (GENCLS)- very simplified
- Represents the machine dynamics as a fixed voltage magnitude behind a transient impedance $R_a + jX_d'$.



- Only 2 states equations for ω and δ

$$\frac{d\delta}{dt} = \omega$$

$$\frac{d\omega}{dt} = \frac{1}{2H} \left[\frac{P_{mech} - D\omega}{1 + \omega} - T_{elec} \right]$$

- Used in academic settings because of its simplicity but is not recommended for actual power system studies

More Realistic Models



- PowerWorld Simulator has many more realistic models that can be easily used
 - Many books and papers discuss the details
- Salient pole – GENSAL machine model
- Round rotor – GENROU model
- Generator with Transient Saliency – GENTPF and GENTPJ models
 - These models are becoming required in WECC (Western US and Canada)

GENROU Model



Generator Information for Present

Bus Number: 3 Find By Number
Bus Name: Bus 3 Find By Name
ID: 1 Find ...
Area Name: 1 (1)
Labels: no labels
Generator MVA Base: 100.00
Fuel Type: UN (Unknown) | [PW=0] [EPC=0]
Unit Type: UN (Unknown) | [PW=0] [EPC=0]

Status:
☐ Open
☒ Closed
Energized:
☐ NO (Offline)
☒ YES (Online)
View Bus Dialog

Power and Voltage Control Costs OPF Faults Owners, Area, etc. Custom Stability

Machine Models Exciters Governors Stabilizers Other Models Step-up Transformer Terminal and State

Insert Delete Gen MVA Base: 100.0 Show Block Diagram Create VCurve

Type: Active - GENROU ☒ Active (only one may be active) Set to Defaults

Parameters

H: 3.00000	Xl: 0.15000	XComp: 0.00000
D: 0.00000	Tdop: 7.00000	
Ra: 0.00000	Tqop: 0.75000	
Xd: 2.10000	Tdopp: 0.04000	
Xq: 0.50000	Tqopp: 0.05000	
Xdp: 0.20000	S1: 0.00000	
Xqp: 0.50000	S12: 0.00000	
Xdpp: 0.18000	RComp: 0.00000	

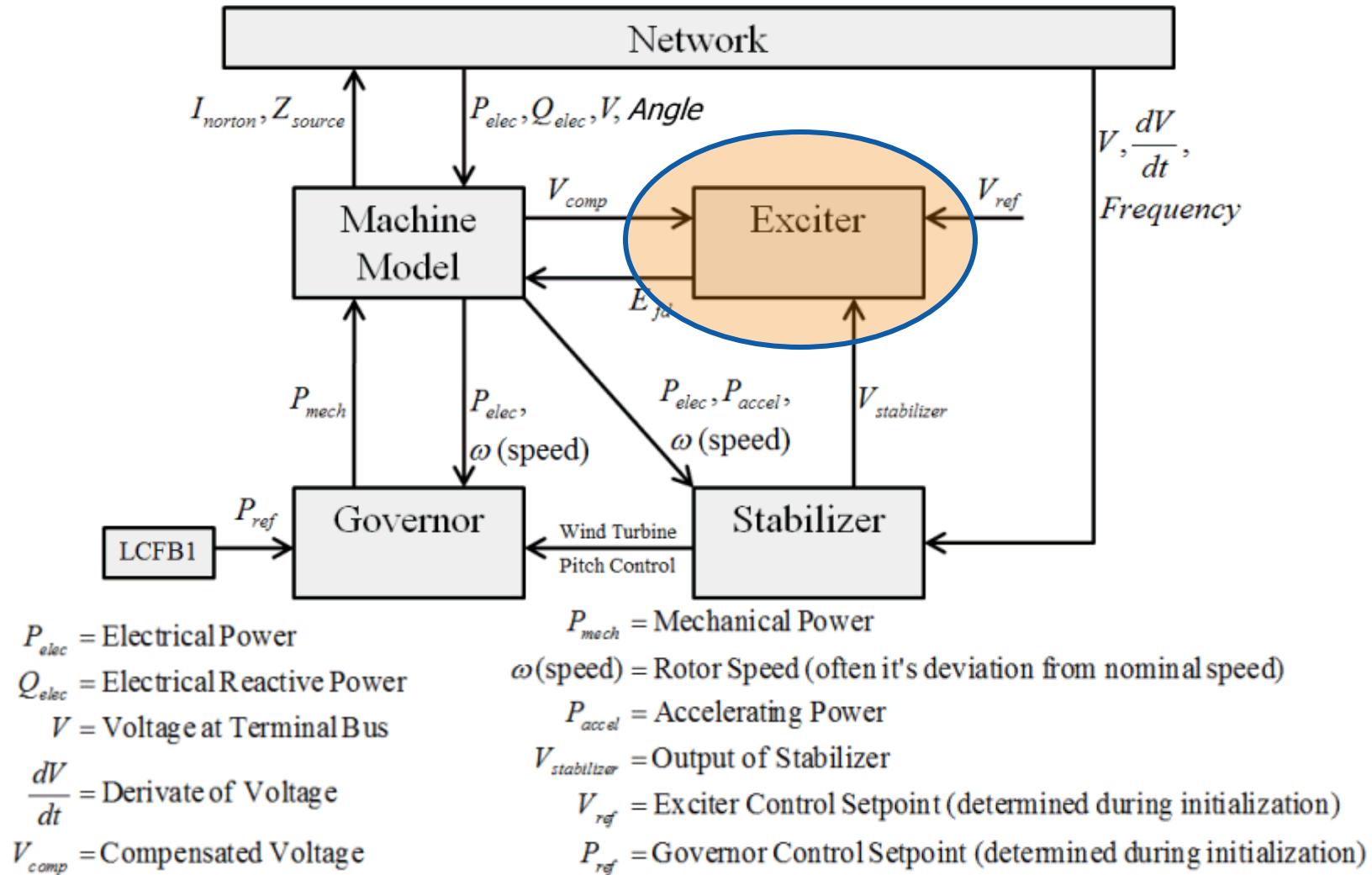
OK Save Save to Aux Cancel Help Print

The GENROU model provides a very good approximation for the behavior of a synchronous generator over the dynamics of interest during a transient stability study (up to about 10 Hz). It is used to represent a solid rotor machine with three damper windings.

The “d” and “q” values here are referring back to the Direct and Quadrature discussion from earlier

More than 2/3 of the machines in the 2006 North American Eastern Interconnect case (MMWG) are represented by GENROU models.

Exciter Models



Types of Exciters



- Three distinctive types
 - Type DC excitation systems
 - Direct current generator with a commutator as source of excitation system power
 - Original exciters (1920s- 1960s)
 - Type AC excitation systems
 - Usually means you place a synchronous motor on the same shaft as the generator
 - Use the AC voltage created by this motor to feed a rectifier and feed back to the DC voltage to the generator field
 - Type Static (ST) excitation systems
 - Similar to AC, except power is supplied through transformers or auxiliary generator windings and rectifiers
 - Source might be the output of generator itself, or an auxiliary feed from somewhere else

Excitation System Models



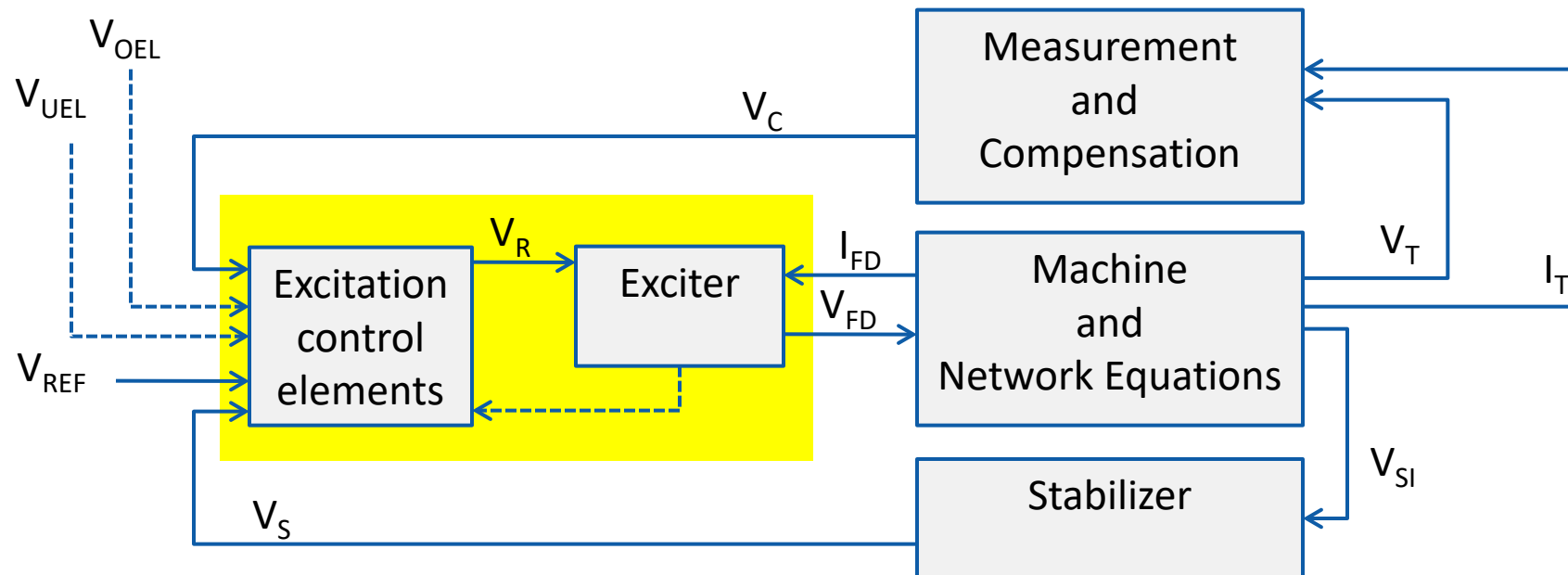
- Models must be suitable for modeling severe disturbances as well as large perturbations
- Generally, these are reduced order models that do not represent all of the control loops
 - For example, there may be an entire control system ensuring that a particular variable doesn't exceed a limit
 - This control system is replaced by an algebraic equation that says ($V_r < V_{rmax}$)
 - Again, Fast Variable $\rightarrow$ Algebraic Equations
- These models do not generally represent delayed protective and control functions that may come into play in long-term dynamic performance studies

IEEE Standard 421.5, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, Aug. 1992

Excitation System Models



- Excitation subsystems for synchronous machines may include voltage transducer and load compensator, excitation control elements, exciter, and a power system stabilizer



Exciter Models in General



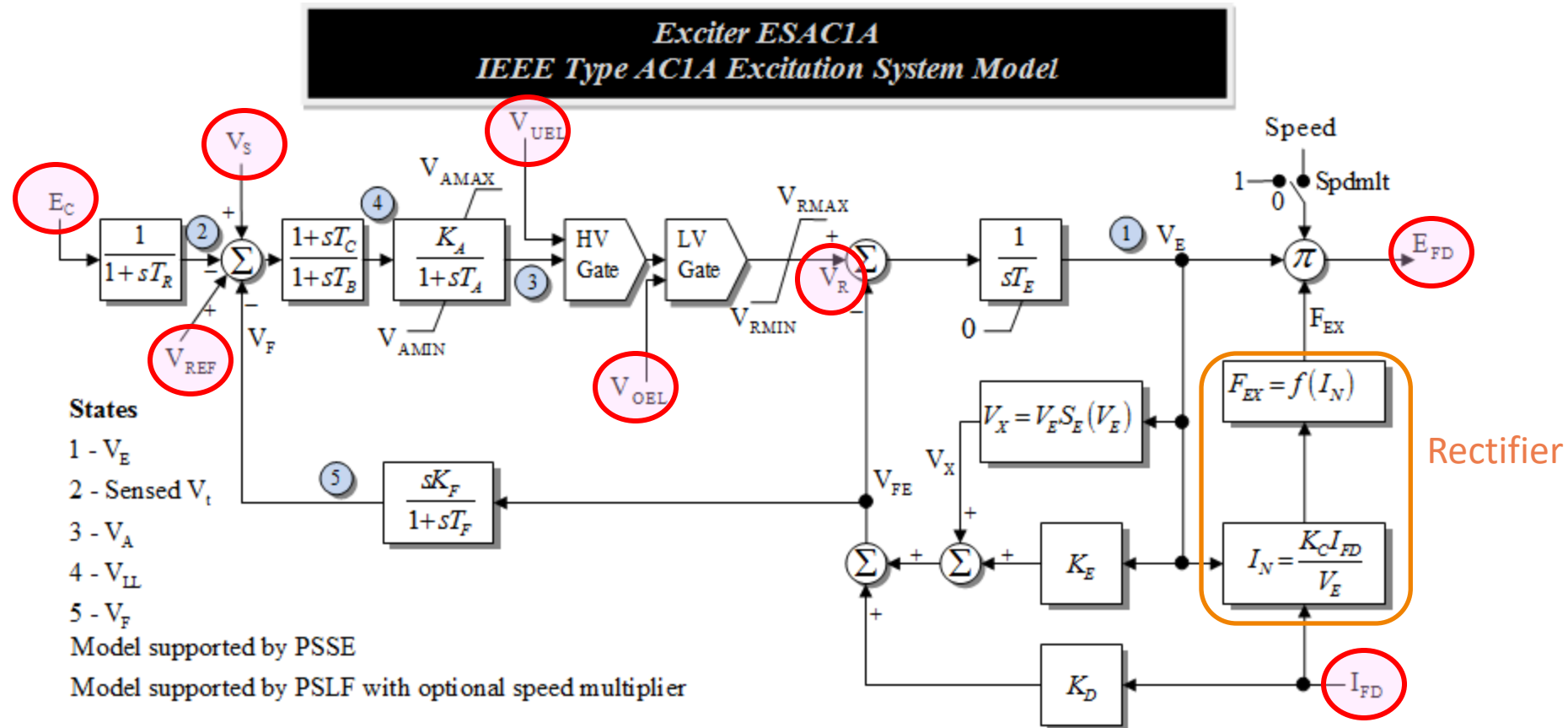
- V_{REF} is the voltage regulator reference signal
 - Is calculated to satisfy the initial operating conditions.
 - In Simulator this will be called the *Exciter Setpoint (Vref)*
 - This represents the “knob” that the generator operator turns to move the voltage higher or lower
- E_{fd} is the field voltage
 - Adjusting the DC field voltage changes the DC field current and thus impacts the terminal AC voltage of generator
 - If E_{fd} were a constant, the machine would not have voltage control.
 - The exciter systematically adjusts E_{fd} in attempt to maintain the terminal voltage equal to the reference signal.
- I_{fd} is the field current

Comments on Typical Exciter



- E_c is the “compensated voltage”
 - Typically this is just the generator terminal voltage
 - Could regulate a point some impedance away (such as half way through the step-up transformer)
 - $E_c = V_t - X_{comp} * I_t$
- Typical optional feedback signals
 - V_s is from the stabilizer
 - V_{UEL} is from an under excitation limiter
 - V_{OEL} is from an over excitation limiter

Typical Exciter Block Diagram

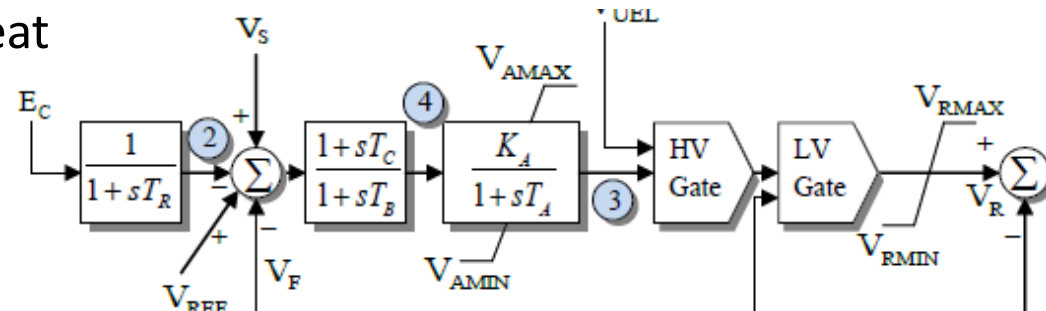
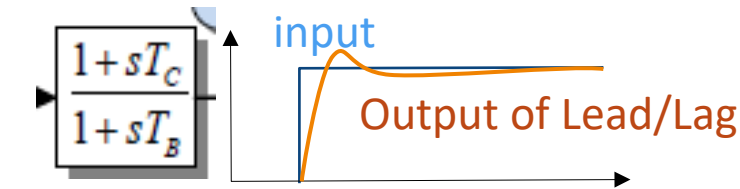
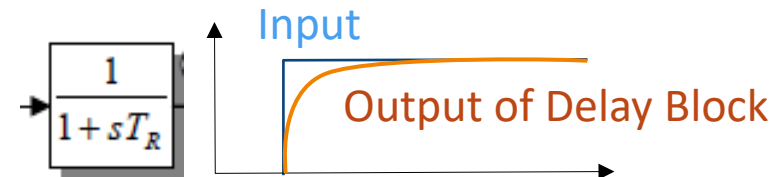
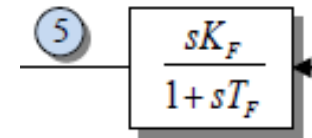


Laplace Transforms! s = Laplace Operator

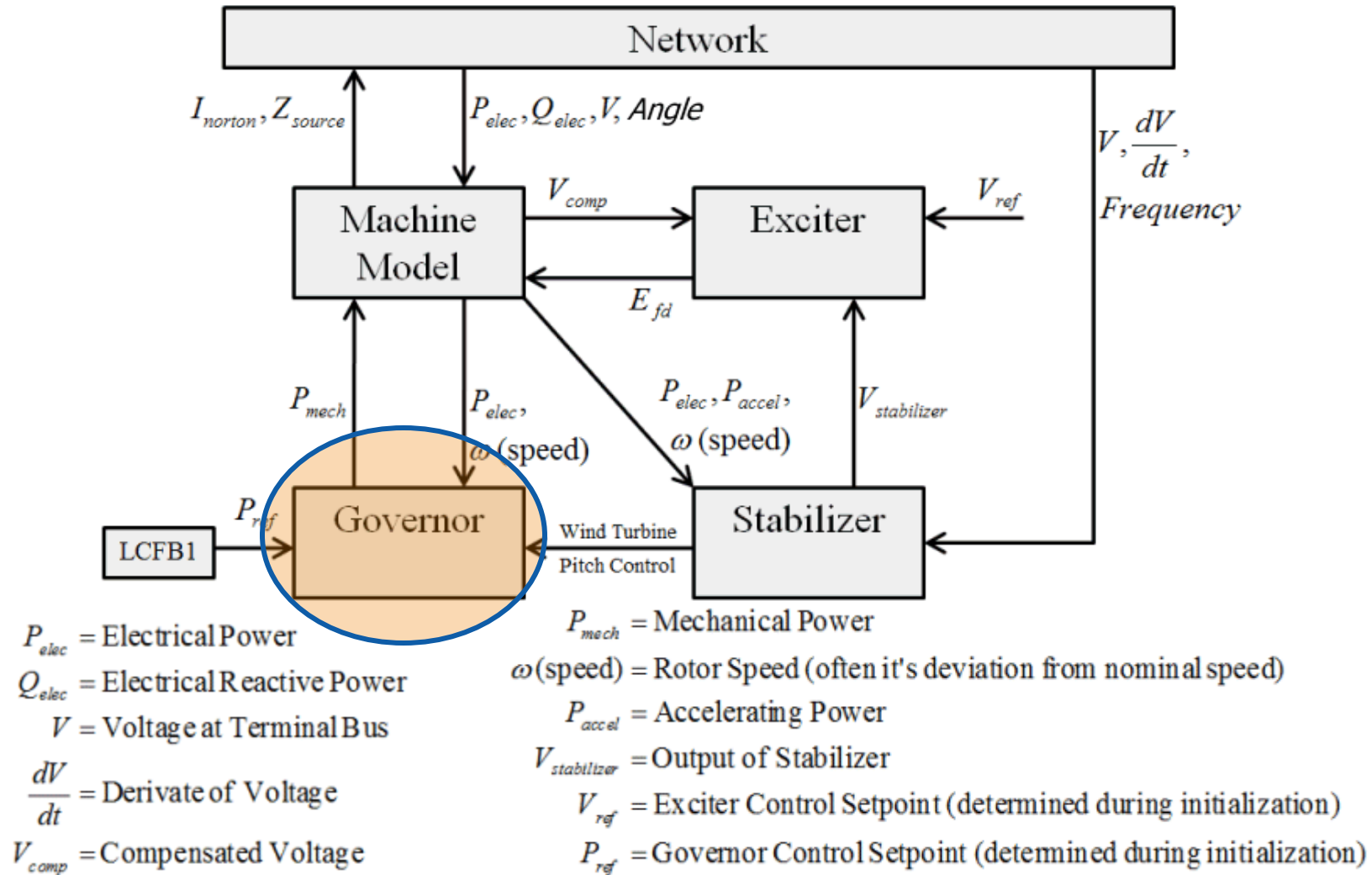
Example “Back-Solving” for Initial States



- Derivative Block Output (V_F)
 - Output at steady state is zero (definition of “steady” state)
- Stabilizer Signal (V_S)
 - Output at steady state is also zero (again by definition)
- Delay Block for signal (E_C)
 - Represents measurement delay
- Assume you know (V_R)
 - (V_{UEL}) and (V_{OEL}) are zero at steady state
 - State 4 is then V_R/K_A
 - Output summation is same as state 4 (treat “s” as zero at steady state)
- Calculation of V_{REF}
 - $V_{REF} = E_C + V_R/K_A$



Governor Models



Prime Movers and Turbine Models



- Steady-state speed of a synchronous machine determined by the speed of the prime mover that drives its shaft
- Prime mover thus provides a mechanism for controlling the synchronous speed
 - Diesel engines
 - Gasoline engines
 - Steam turbines
 - Hydroturbines
- Prime mover output affects the mechanical torque to the shaft (T_M)

What is a Governor?



- A governor senses the speed (or load) of a prime mover and controls the fuel (or steam) to the prime mover to maintain its speed (or load) at a desired level
- Essentially, a governor ends up controlling the energy source to a prime mover so that it can be used for a specific purpose
- Consider driving a car → you act as a governor to control the speed under varying driving conditions

Woodward, “Governing Fundamentals and Power Management,” Technical Manual 26260, 2004. [Online]. Available: <http://www.woodward.com/pubs/pubpage.cfm>

Speed Governor Models



- To automatically control speed and hence frequency, need to be able to sense speed or frequency in such a way that it can be compared with a desired value to take a corrective action.
- This is what a speed governor does.
- For example, if a load is removed from the generator, excess power is being supplied to the turbine and the generator will speed up. The steam valve position P_{SV} will decrease and eventually stop the increase in speed.

Droop

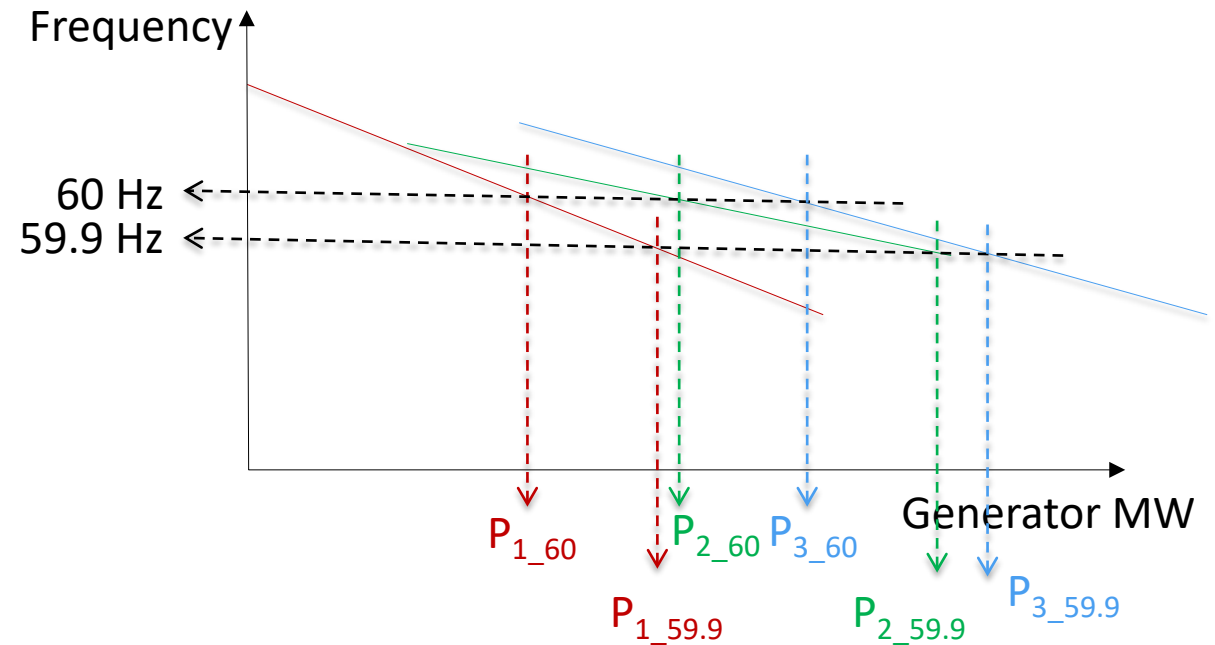


- Droop is a decrease in speed setting as load increases.
- **Without droop**, a load increase causes the engine to slow down. The governor will increase its fuel until the speed has recovered.
- However, all the generators will respond trying to bring the frequency back up and they will end up “fighting” with each other.
- This becomes inherently unstable
- Multiple generator operation
 - Can not allow them all to try to maintain a specified frequency.

Droop Visualization



- Sudden loss of generation somewhere else in the system (or a sudden *increase* in load)
- Causes frequency to drop
- Generators recover to a new setpoint based on the slope defined by the “Droop”

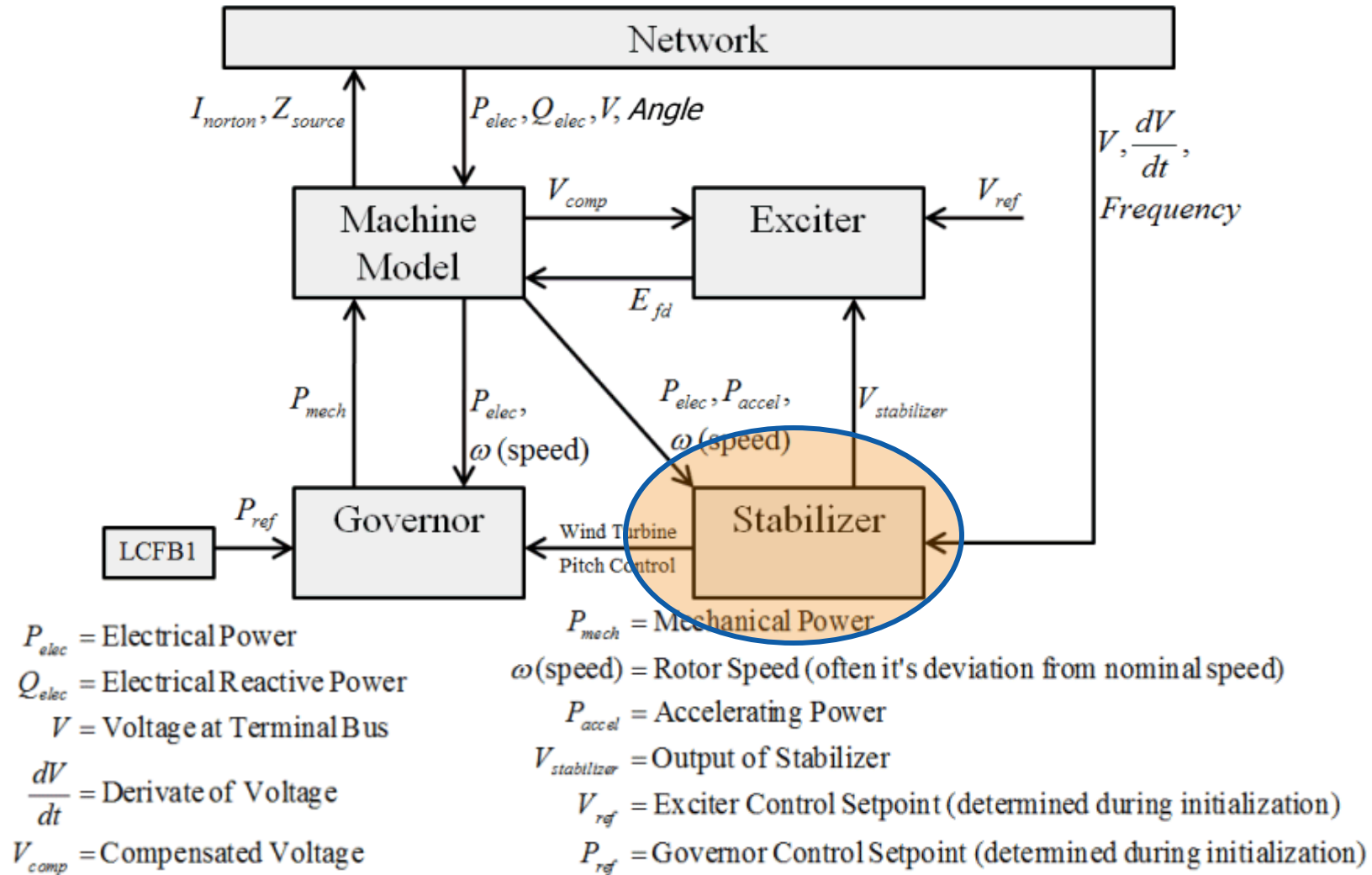


Return to Nominal Frequency



- Transient Stability Simulations normally do NOT bring the frequency back to nominal (60 Hz)
- The AGC control which act on the order of minutes normally do this
- LCFB1 model is a special model which can also do this

Stabilizer Models

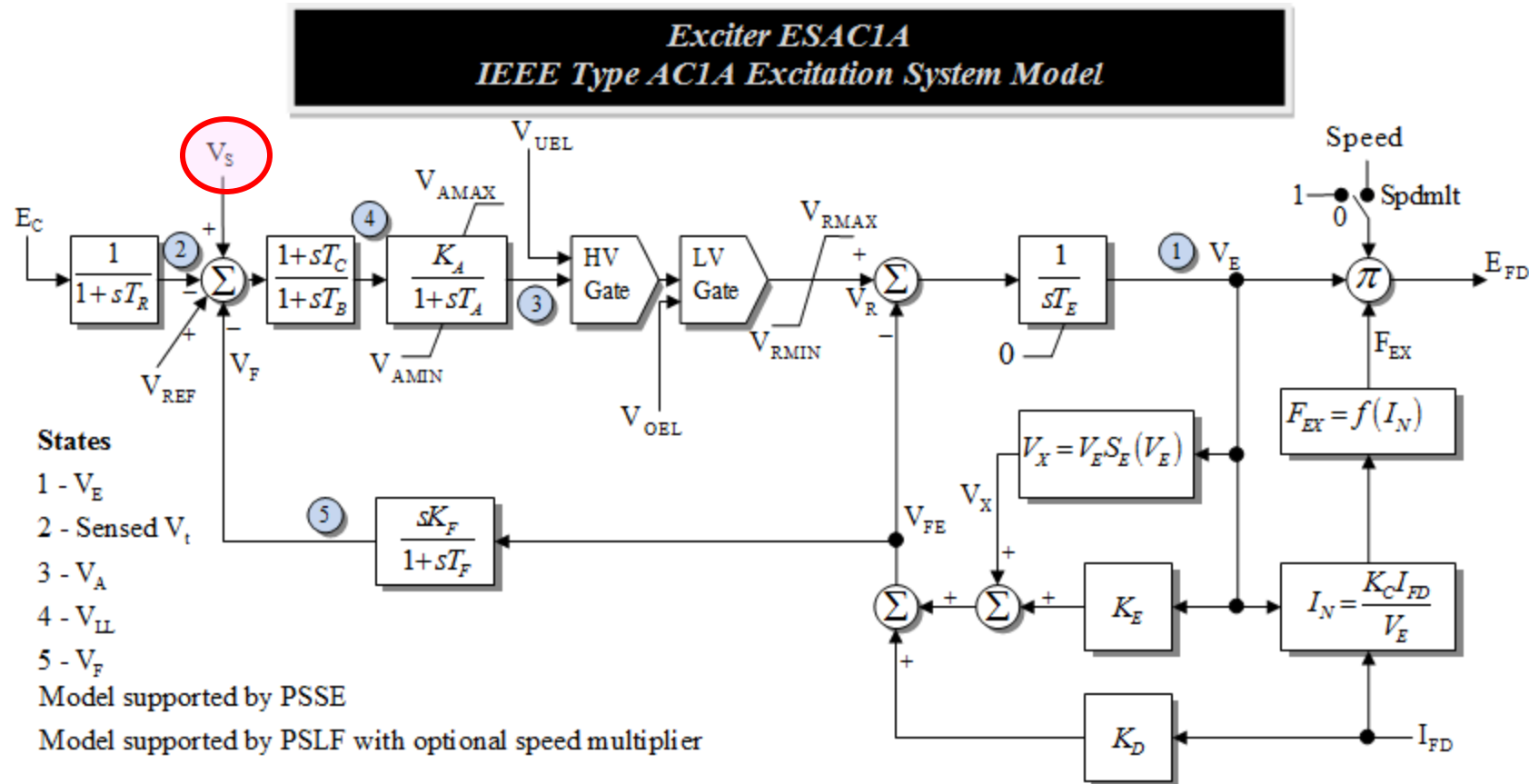


Power System Stabilizers (PSS)



- Stabilizing signals are derived from machine speed, terminal frequency, or power
- Should be activated only when low-frequency oscillations develop
- The design is still done on the basis of a Single Machine Infinite Bus (SMIB) system
- Then, the model parameters are tuned on-line in order to suppress local and inter-area modes
- Output signal goes into exciter

Stabilizer Feedback to Exciter



Wind Generator Models



- Wind Turbines do not have an “exciter”, “governor”, or “stabilizer” built in
- However, modeling is very analogous
 - Wind Machine Model = Machine Model
 - Wind Electrical Model = Exciter
 - Wind Mechanical Model = Governor
 - Wind Pitch Control = Stabilizer
 - Wind Aerodynamic Model = Stabilizer
- Simulator will show wind models listed as though they are Exciters, Governors, and Stabilizers
 - Obviously you not should use a synchronous machine exciter in combination with a wind machine model and wind governor!

Load Characteristic Models

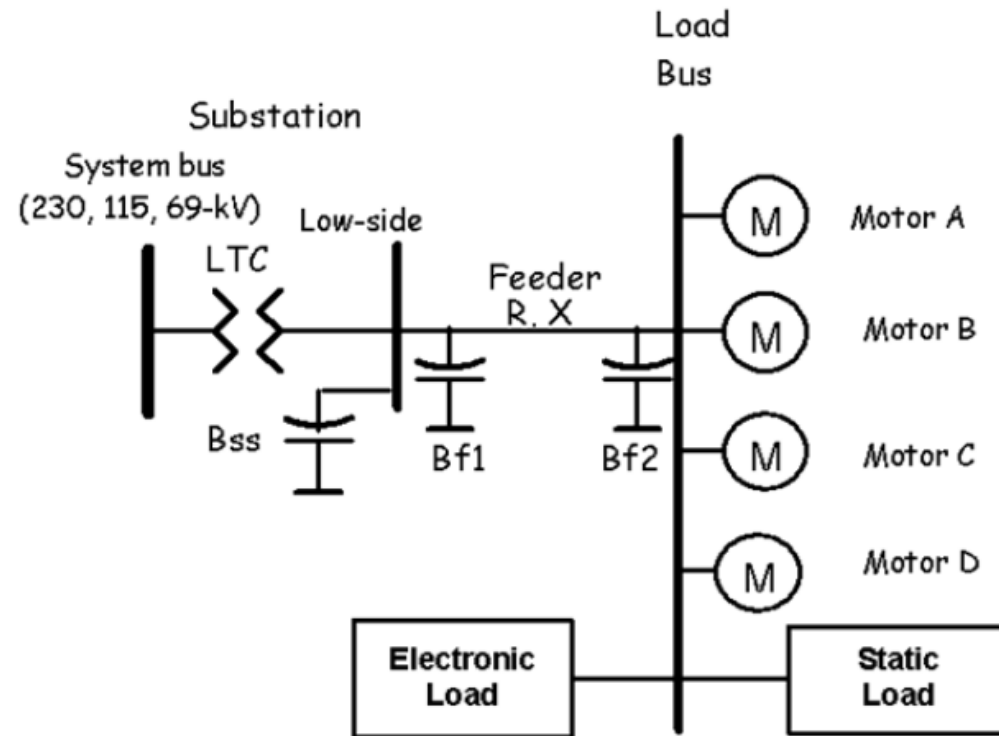


- Load fall into two categories in a transient stability
 - Static Load Model
 - Normally a function of voltage and/or frequency
$$P = P_{load} (a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}) (1 + a_7 \Delta f)$$
$$Q = Q_{load} (a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}) (1 + a_8 \Delta f)$$
 - Discharge Lighting (Fluorescent Lights)
 - Voltage Dependent.
 - Dynamic Load Models
 - Induction Motors
- Load Characteristic Models end up being combinations of all these
 - “Complex” load models include all of them in various proportions

Load Characteristic Models: CMPLDW



- CMPLDW Load Characteristic Models end up being combinations of all these models in the following manner:



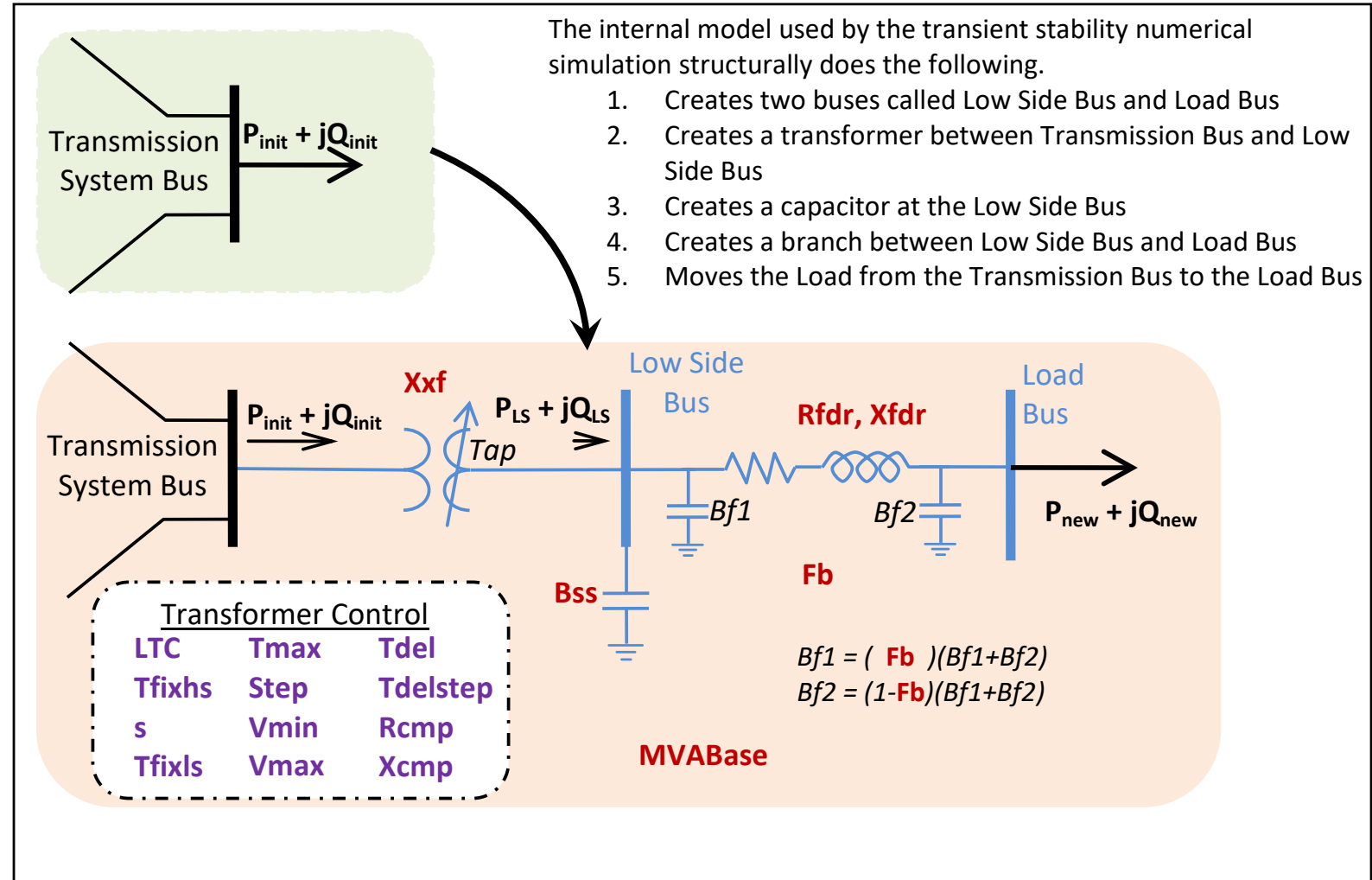
Load Characteristic Models: CMPLDW



- Data management issue
 - Up to 130 parameters
 - Number of parameters can differ depending on the type of motor used
 - Pushing the limits of how much data can be reasonably managed
- Group together models with the same parameters
- Create new objects in Simulator
 - Load Model Groups
 - Load Distribution Equivalent Types
 - More details on these new object in next training section

Load Characteristic Models: CMPLDW

- Basic idea:



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