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

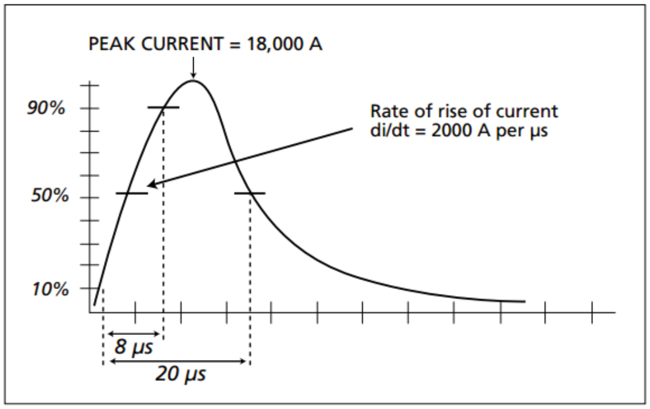
- Overview of power system modeling in general
  - Time Scales
- Overview of the different model types supported by Simulator
  - Generator Models
    - Relationships between the different types of generator models
  - Wind Generator Models
    - Relationships for them
  - Also some discussion of Load 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 in the 10s of kilohertz



Switching Surges

- Closing in a Transmission Line that's presently de-energized
  - 300 km line → ¼ wavelength standing wave will be
    - Wavelength * Frequency = Speed
      - Speed of Light ~ 3E8
      - Wavelength = 300E3 * 4
    - 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).

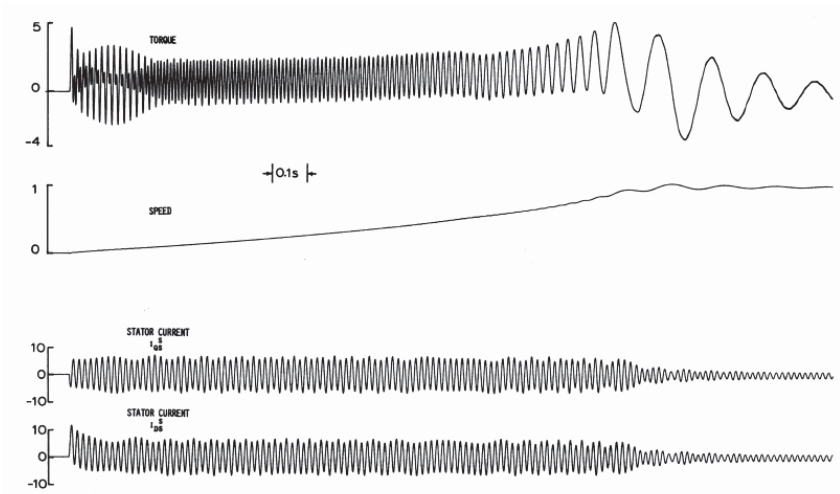


Figure 1 Free acceleration characteristics of a synchronous machine with $p\psi^r$ and $\Delta\omega_r$ terms included

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.

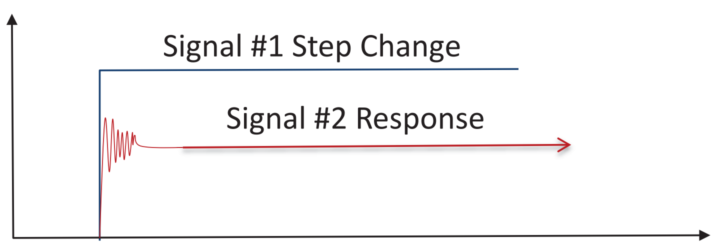
What if we want to model phenomena that are 100 Hz or faster

- 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

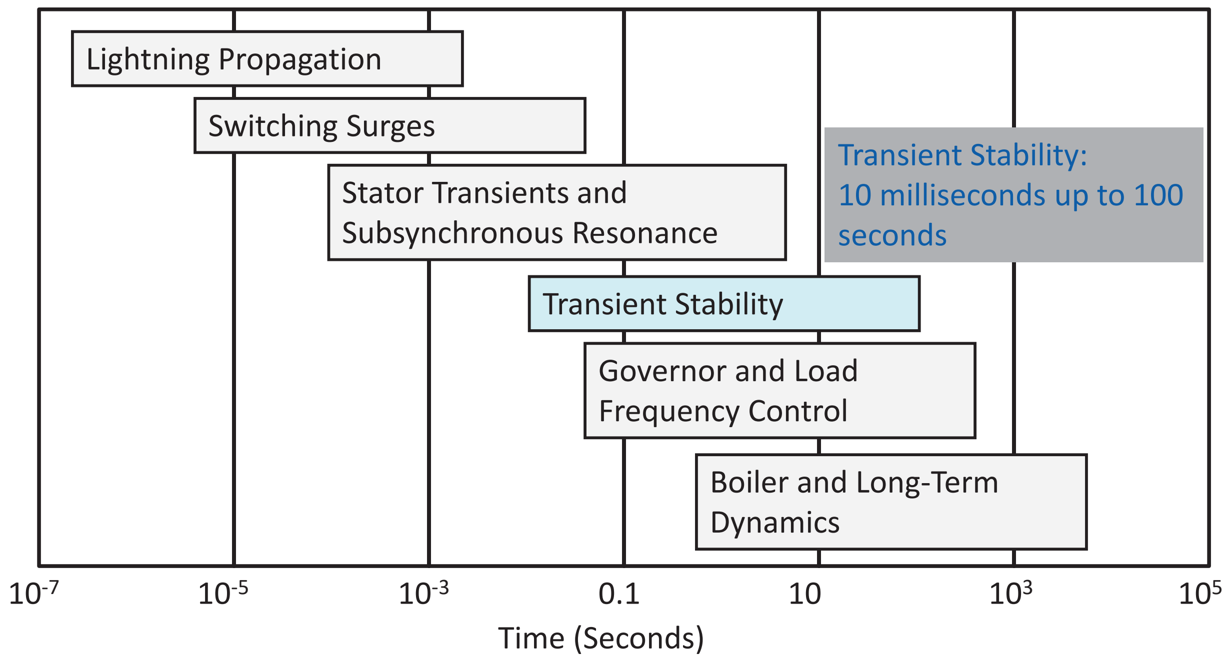
How do we handle Ultra-Fast Transient Effects?

- 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
  – Signal2 = 0.6*Signal1

Time Scale of Dynamic Phenomena



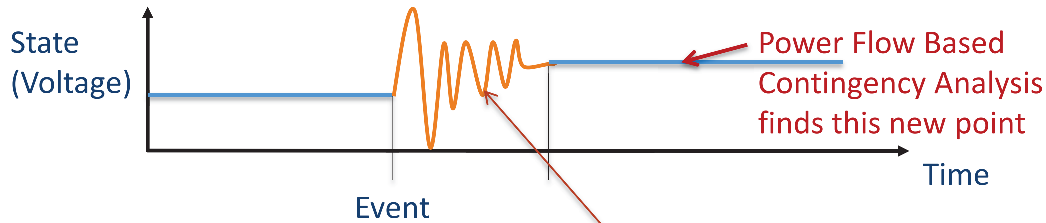
P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Power Flow

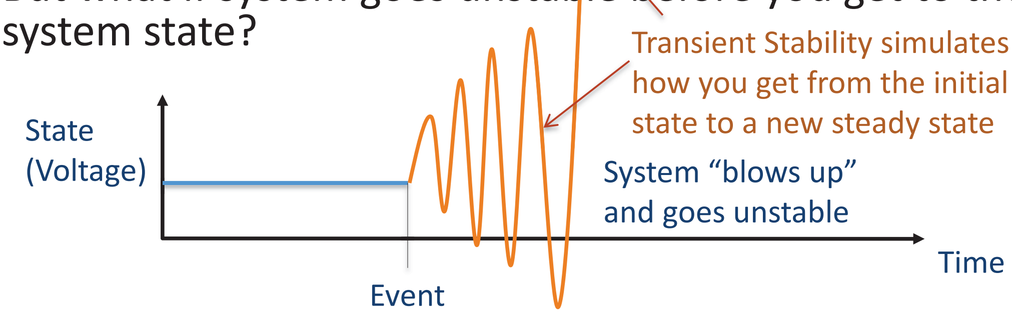
- The power flow is used to determine a quasi steady-state operating condition for a power system
  - Goal is to solve a set of algebraic equations
    - **g(y)** = **0** [**y** variables are bus voltage and angle]
  - Models employed reflect the steady-state assumption, such as generator PV buses, constant 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,
    - d**x**/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 $\boldsymbol{g}(\boldsymbol{x},\boldsymbol{y})=\mathbf{0}$
     - The "Initial" or "Boundary" Conditions
     - Gives $\boldsymbol{y}_0$ → initial values for all the $\boldsymbol{y}$ variables (Voltage, Angle)
  2. Derivatives at "steady state" are zero by definition, thus use the equation $\frac{d\mathbf{x}}{dt}=\mathbf{0}=\boldsymbol{f}(\boldsymbol{x}_0,\boldsymbol{y}_0)$ and solve for $\boldsymbol{x}_0$
  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

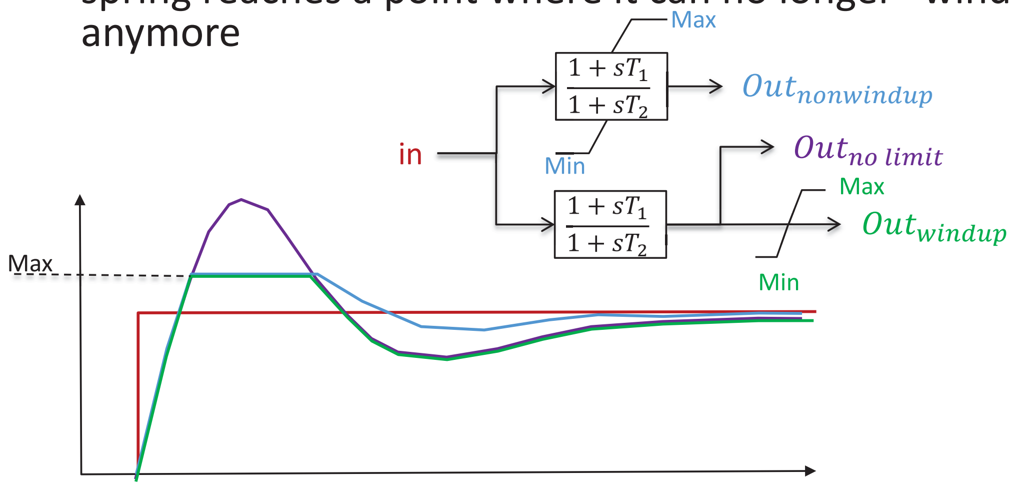
Transient Stability Numerical Integration

- Already have initial $\boldsymbol{x_0}$ and $\boldsymbol{y_0}$
- Initialize $t=0$ and $k=0$
- Choose a Time Step Δt that will be used in numerical integration

1. Calculate new $\boldsymbol{x}$: $\boldsymbol{x}_{k+1}=\boldsymbol{x}_k+\Delta t*\boldsymbol{f}(\boldsymbol{x}_k,\boldsymbol{y}_k)$
   - called the "integration time step"
   - Many ways to do this. This is a "Forward Euler"
2. Calculate new $\boldsymbol{y}$: Solve $\boldsymbol{g}(\boldsymbol{x}_{k+1},\boldsymbol{y}_{k+1})=\mathbf{0}$
   - 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

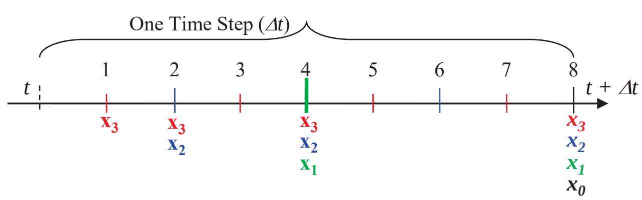
- Non-windup versus Windup Limits
  - Think an old "windup" clock with a spring. Eventually, the spring reaches a point where it can no longer "windup" anymore



  - A "non-windup" limit must be enforced between step 1 and 2 so that the state never goes past its limit

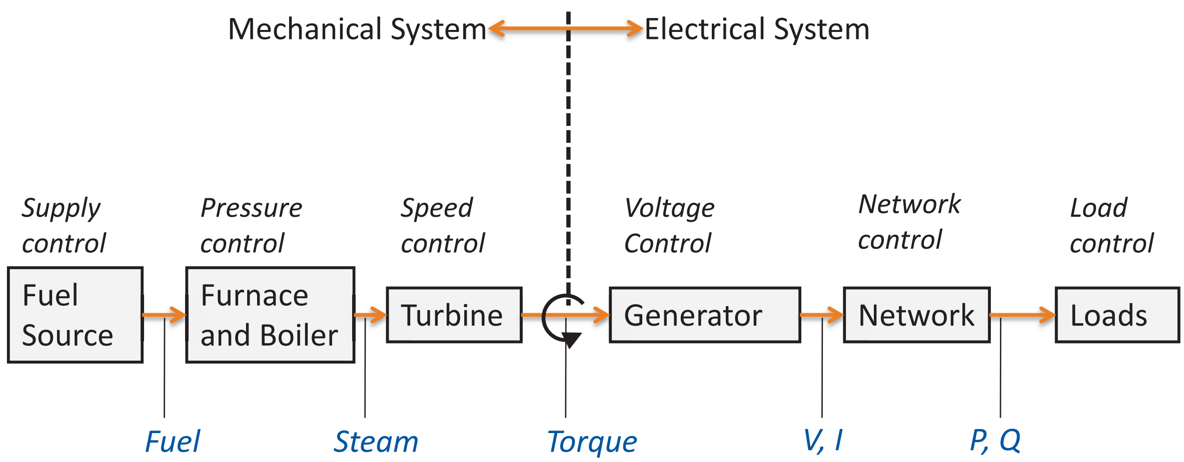
Sub-Interval Integration

- 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



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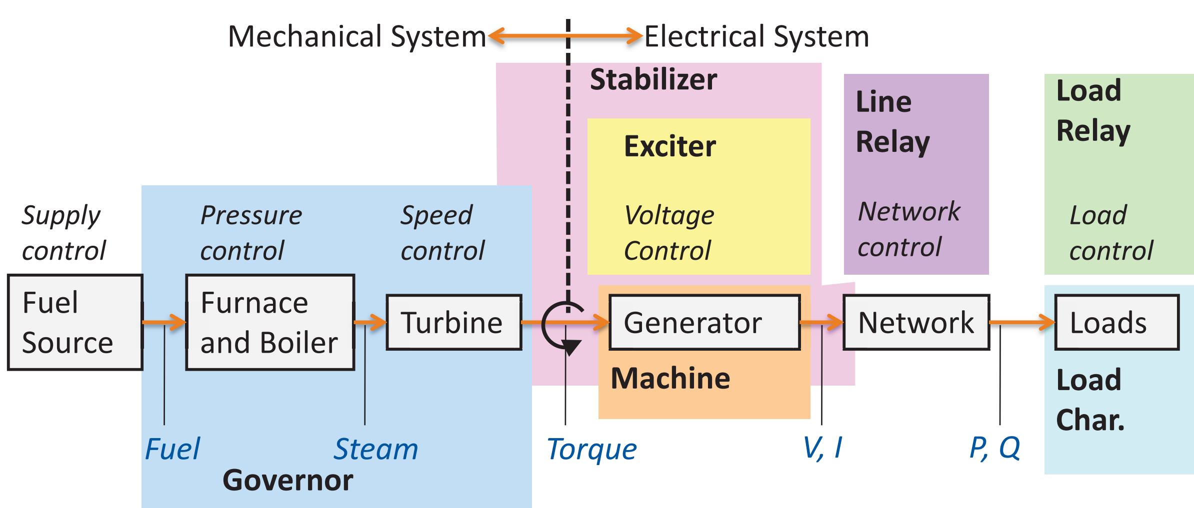
Transient Stability Models
in the Physical Structure



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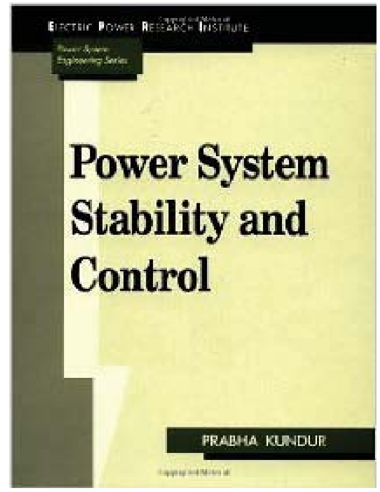
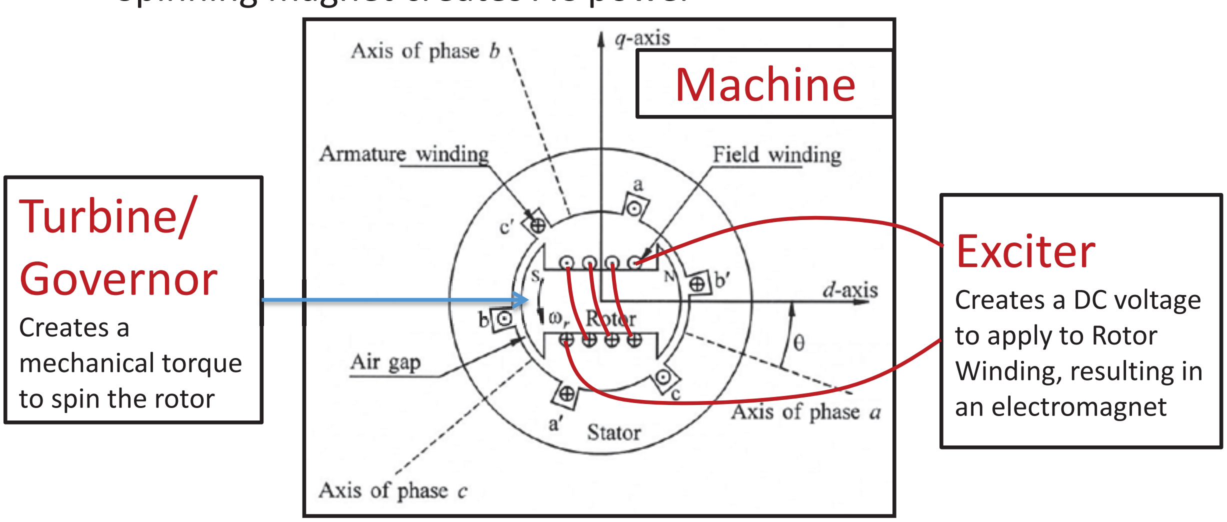
Transient Stability Modeling

- 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



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 = MVABase/ω_0
  - ω = treated as *per unit speed deviation* → $\omega = \frac{\omega_{actual} - \omega_0}{\omega_0}$

Generator Swing Equation

- Anyway, after a lot of additional algebra, software tools model the swing equations as follows with values in per unit
  - $2H\frac{d\omega}{dt} = \frac{P_{mech}}{1+\omega} - T_{elec}$ and $\frac{d\delta}{dt} = \omega$
- 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

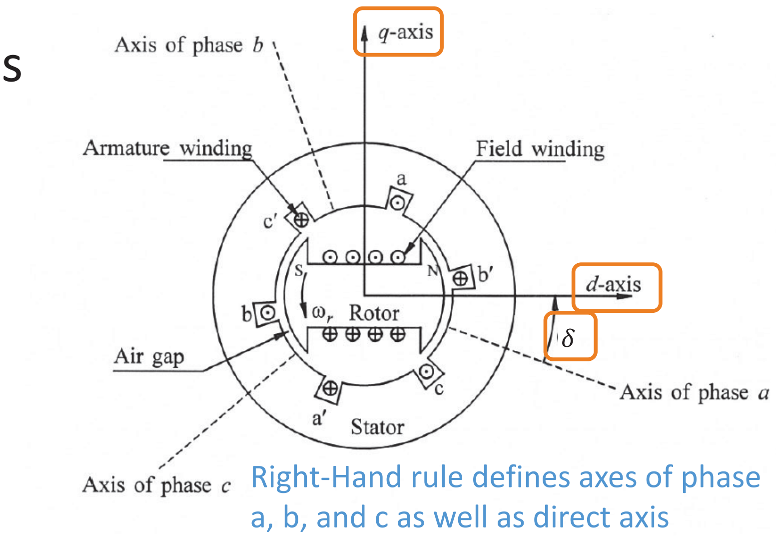


Figure 3.1 Schematic diagram of a three-phase synchronous machine

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 →

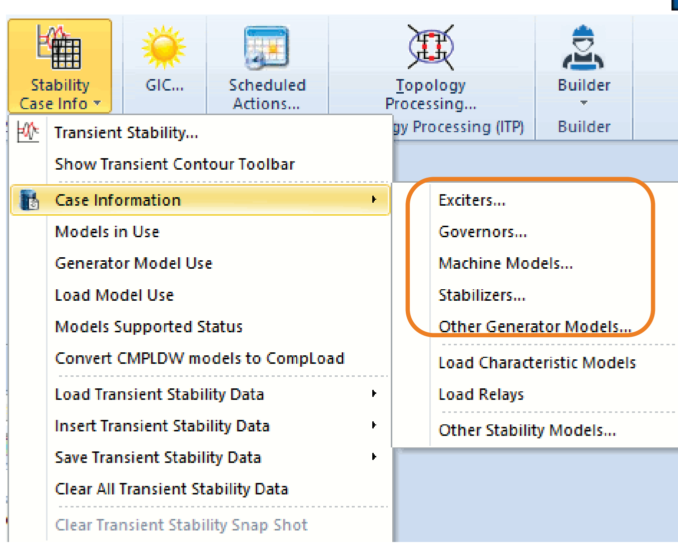
$$\psi_d = -L_d i_d + L_{afd} i_{fd} + L_{akd} i_{kd}$$

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

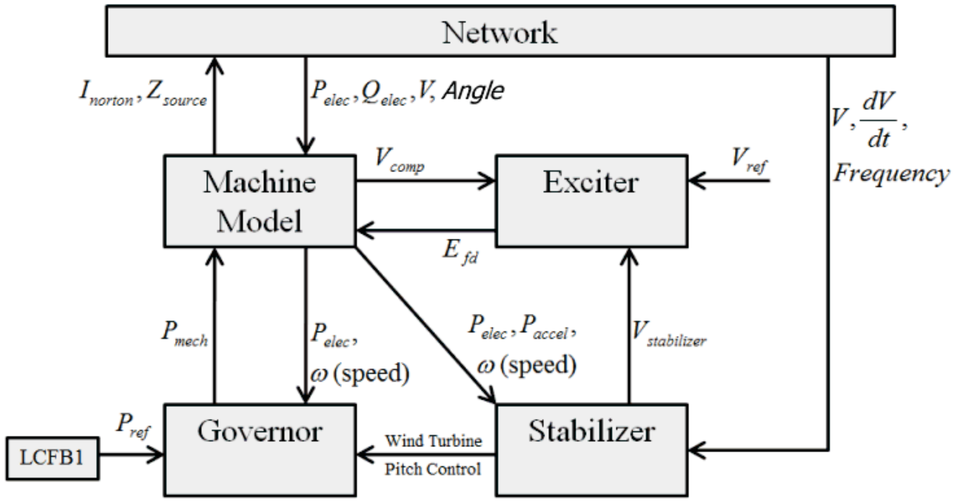
$$\psi_0 = -L_0 i_0$$

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

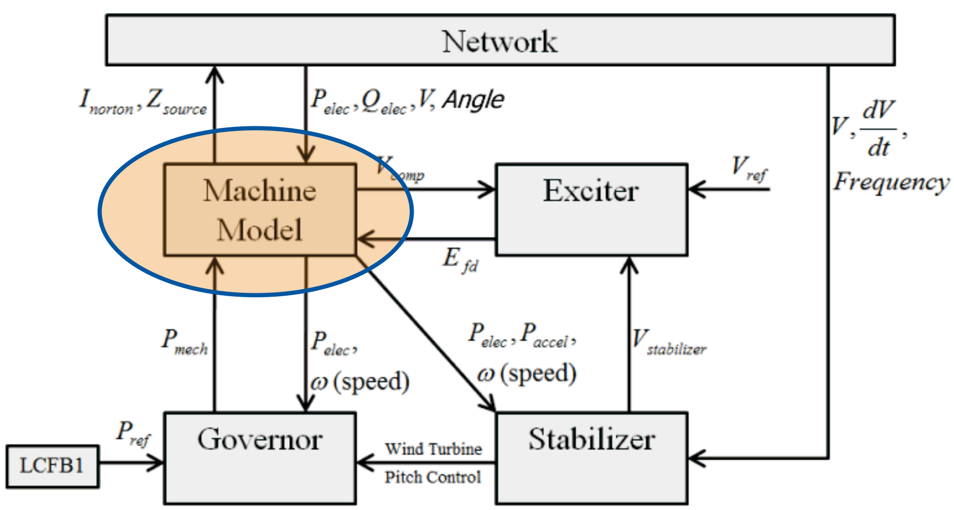


Generator Models



P_{elec} = Electrical Power
Q_{elec} = Electrical Reactive Power
V = Voltage at Terminal Bus
$\frac{dV}{dt}$ = Derivate of Voltage
V_{comp} = Compensated Voltage
P_{mech} = Mechanical Power
ω(speed) = Rotor Speed (often it's deviation from nominal speed)
P_{accel} = Accelerating Power
$V_{stabilizer}$ = Output of Stabilizer
V_{ref} = Exciter Control Setpoint (determined during initialization)
P_{ref} = Governor Control Setpoint (determined during initialization)

Machine Models



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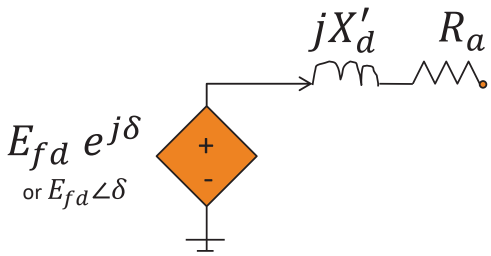
Machine Models

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



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

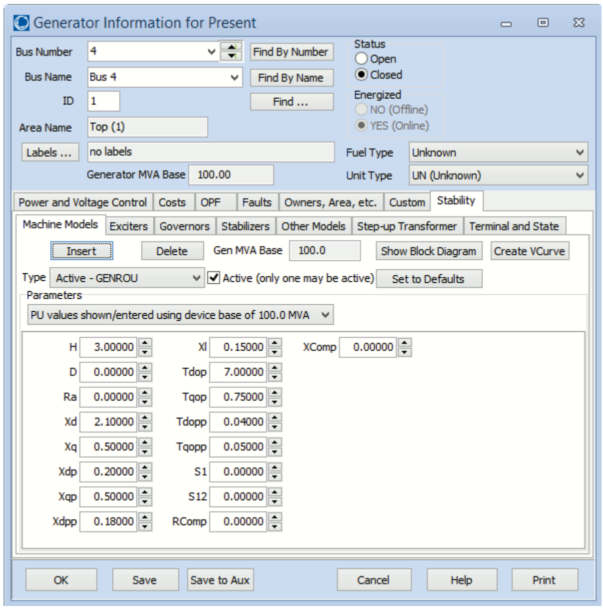
$$\frac{d\omega}{dt} = \frac{1}{2H}\left[\frac{P_{mech} - D\omega}{1+\omega} - T_{elec}\right]$$

- Only 2 states equations for ω and δ
- 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

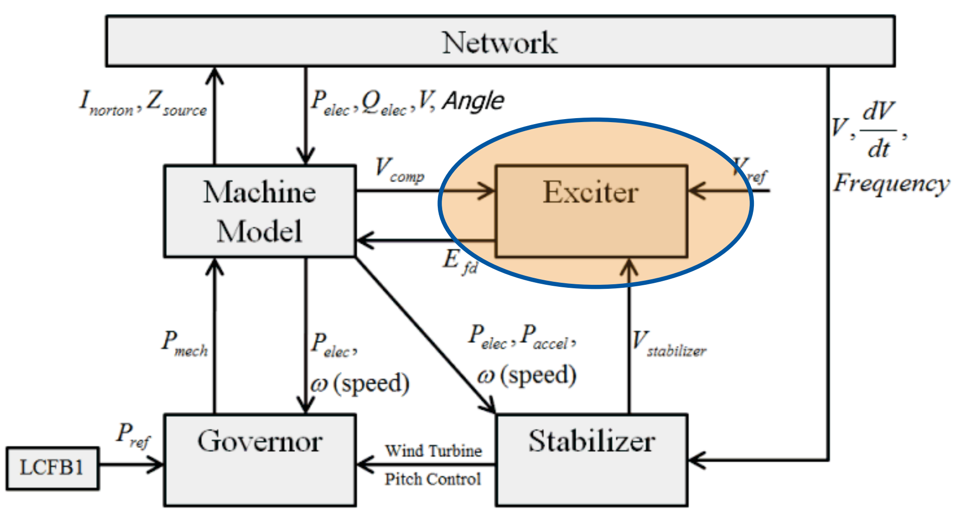


The GENROU model provides a very good approximation for the behavior of a synchronous generator over the dynamics of interest during a transient stability study (up to about 10 Hz).
It is used to represent a solid rotor machine with three damper windings.

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

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

Exciter Models



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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

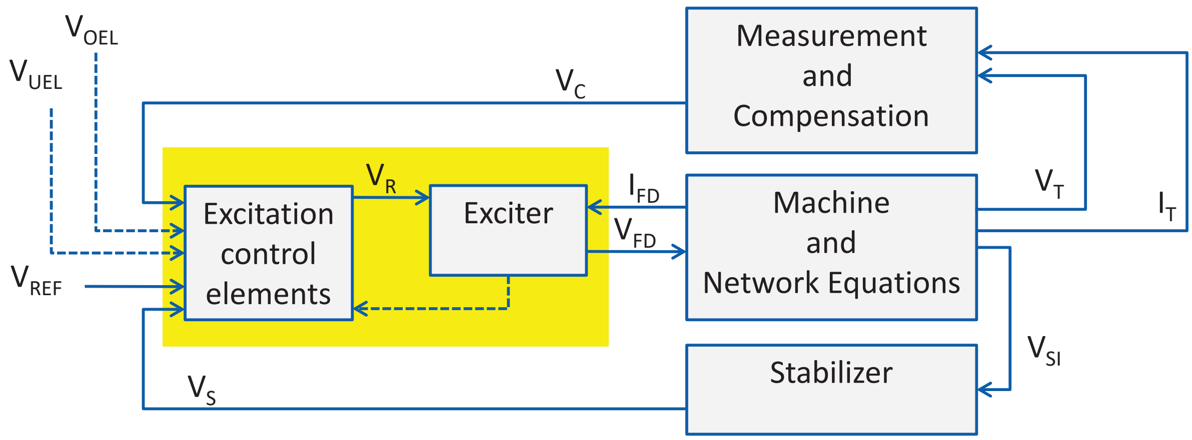
Excitation System Models

- 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 (Vr < Vrmax)
  - Again, Fast Variable → 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



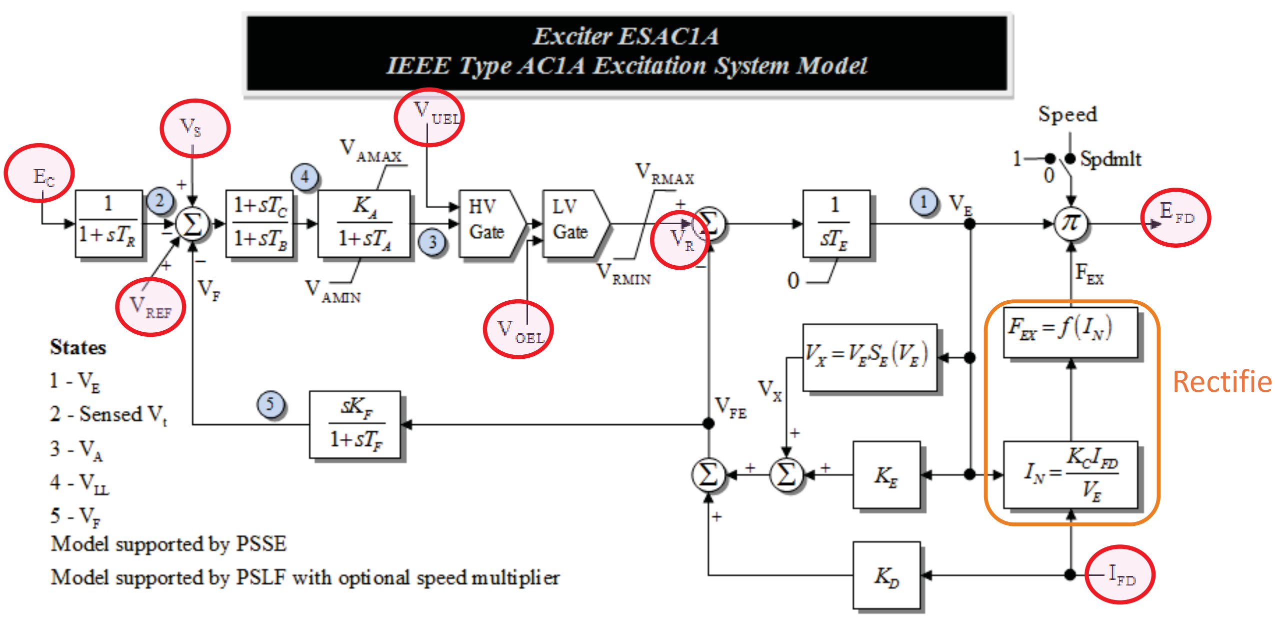
Exciter Models in General

- 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

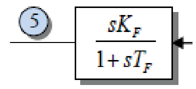
Typical Exciter Block Diagram



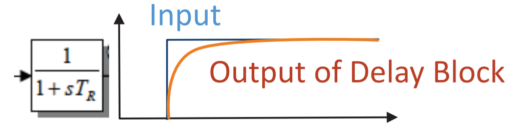
Laplace Transforms! s = Laplace Operator

Example "Back-Solving" for Initial States

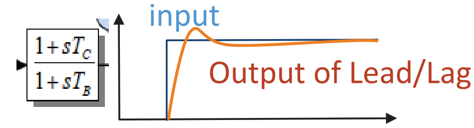
- Derivative Block Output (V_F)
  - Output at steady state is zero (definition of "steady" state)



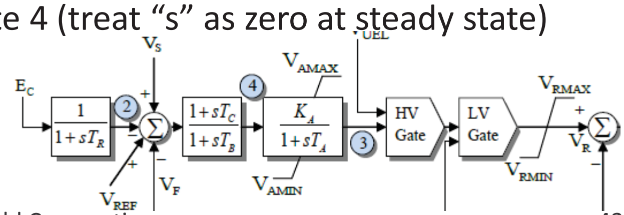
- Stabilizer Signal (V_S)
  - Output at steady state is also zero (again by definition)



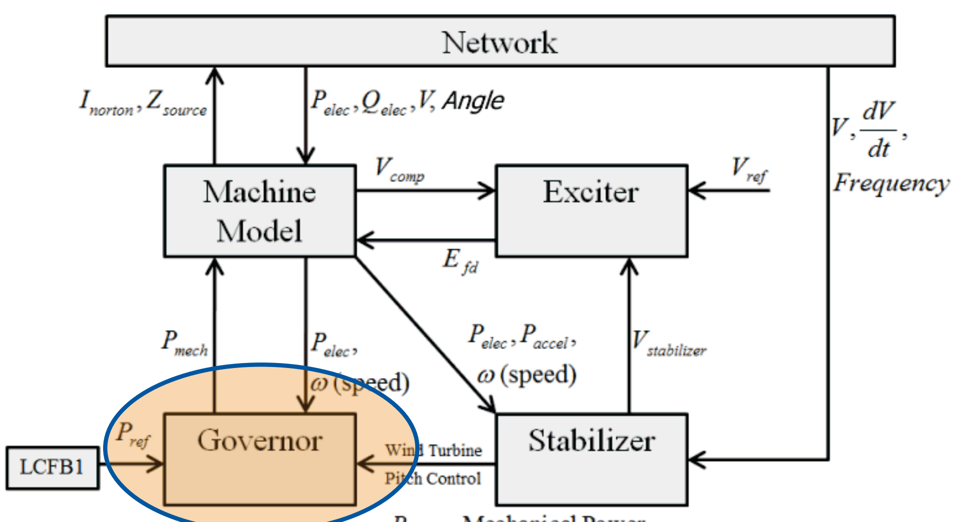
- Delay Block for signal (E_C)
  - Represents measurement delay



- 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



P_{elec} = Electrical Power
Q_{elec} = Electrical Reactive Power
V = Voltage at Terminal Bus
$\frac{dV}{dt}$ = Derivate of Voltage
V_{comp} = Compensated Voltage
P_{mech} = Mechanical Power
ω(speed) = Rotor Speed (often it's deviation from nominal speed)
P_{accel} = Accelerating Power
$V_{stabilizer}$ = Output of Stabilizer
V_{ref} = Exciter Control Setpoint (determined during initialization)
P_{ref} = Governor Control Setpoint (determined during initialization)

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

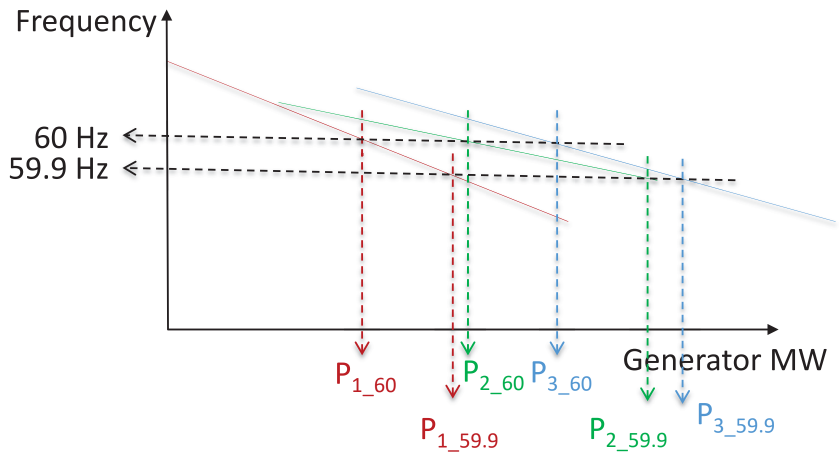
- To automatically control speed and hence frequency, need to be able to sense speed or frequency in such a way that it can be compared with a desired value to take a corrective action.
- This is what a speed governor does.
- For example, if a load is removed from the generator, excess power is being 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

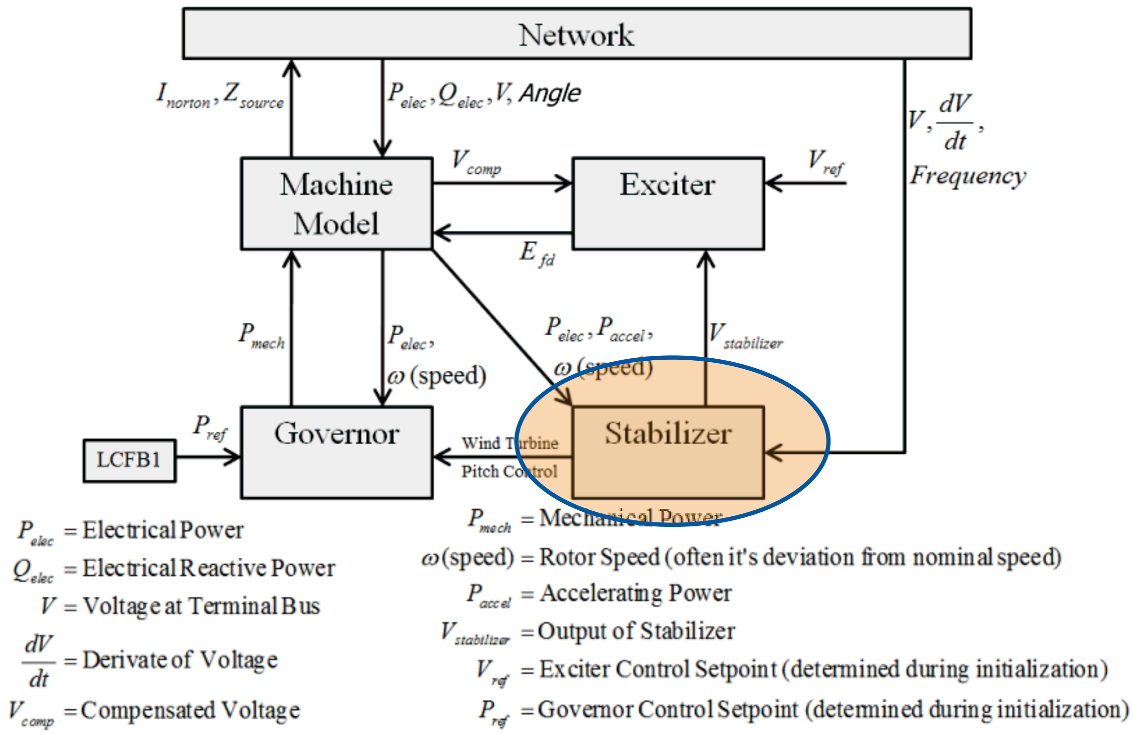
- Sudden loss of generation somewhere else in the system (or a sudden *increase* in load)
- Causes frequency to drop
- Generators recover to a new setpoint based on the slope defined by the "Droop"



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

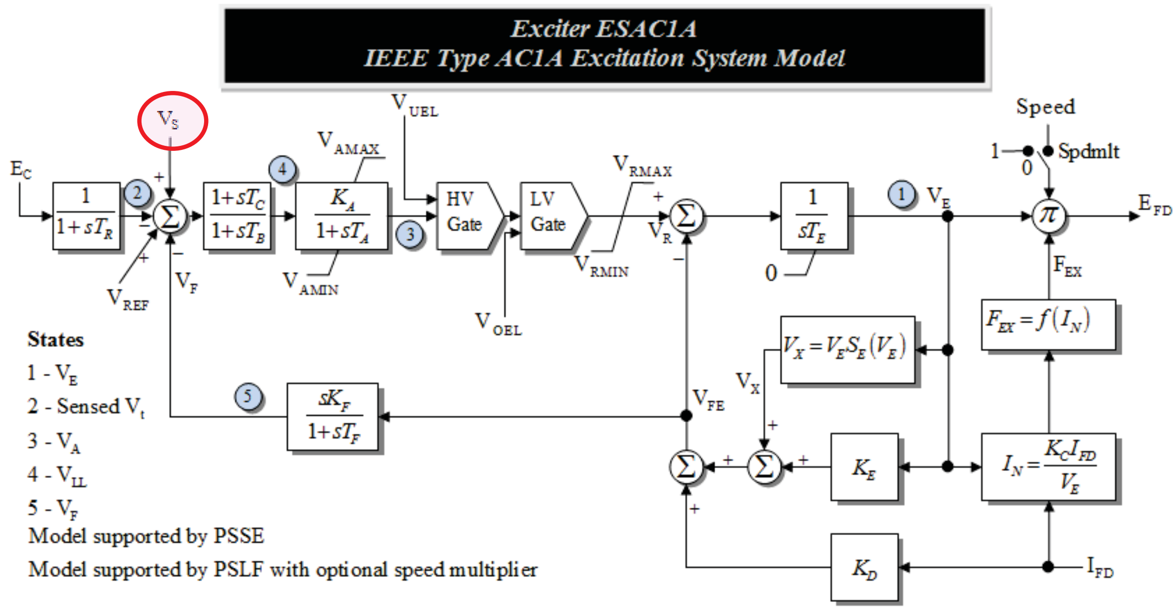
Stabilizer Models



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

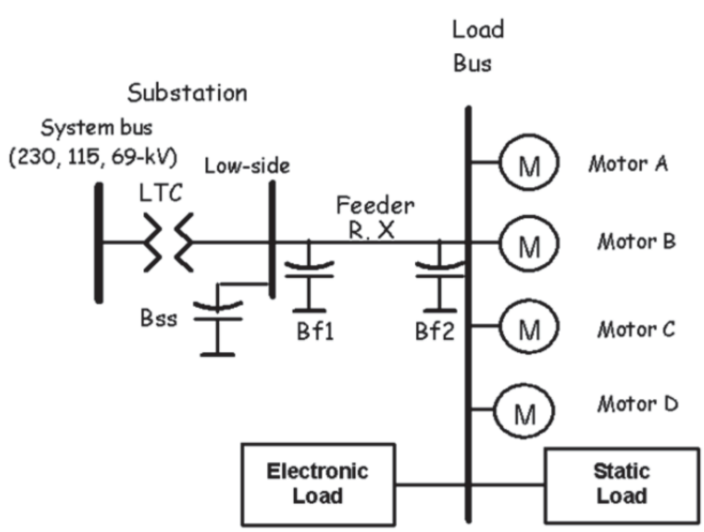
$$P = P_{load}\left(a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}\right)\left(1 + a_7 \Delta f\right)$$

$$Q = Q_{load}\left(a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}\right)\left(1 + a_8 \Delta f\right)$$

    - 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:

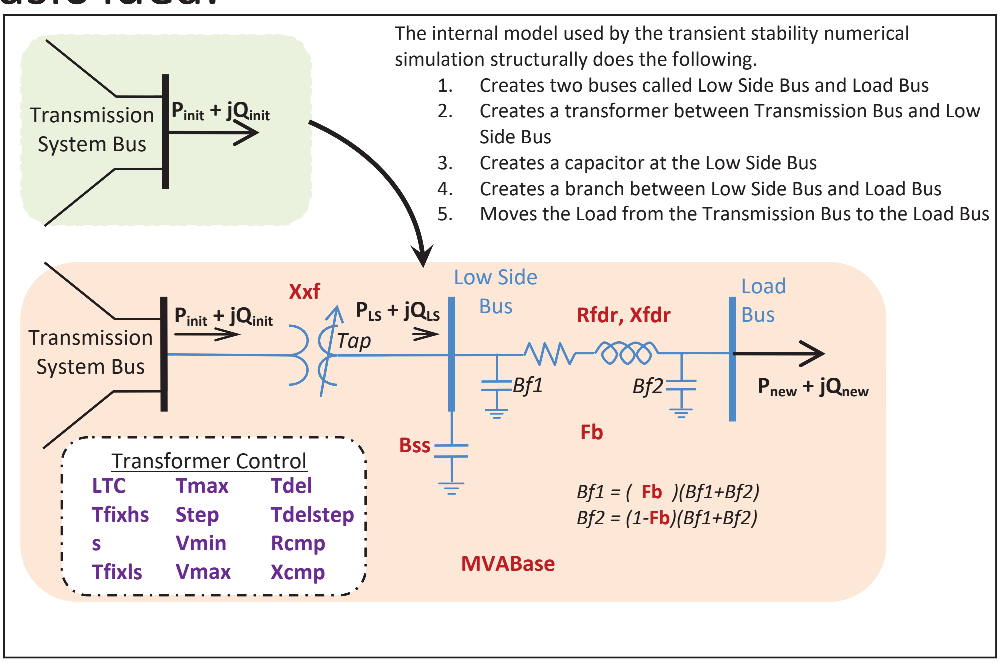


Load Characteristic Models: CMPLDW

- 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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