ECEN 667
Power System Stability

Lecture 7: Synchronous Machine Modeling, Part 3

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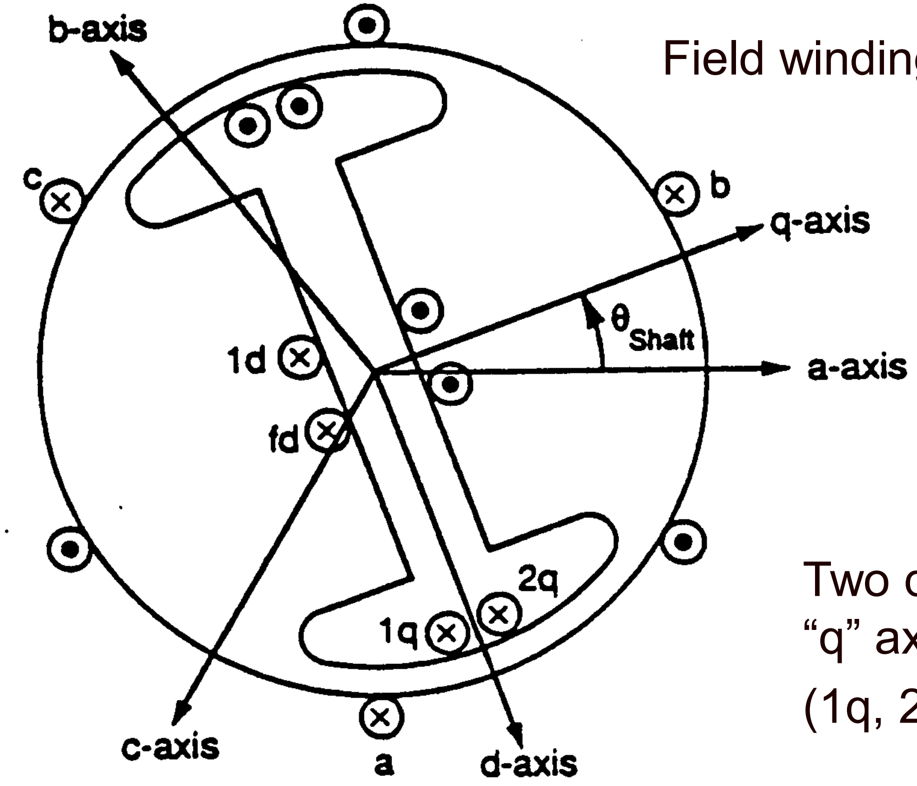
Announcements

- Homework Assignment #2 is due Thursday, Sept. 25th at 8 AM. Email me your solution as a single PDF.
- Read book chapters 3, 4, and 5
- Review the slides and PowerWorld examples

Recall, The Main Diagram

3ϕ bal. windings (a,b,c) – stator



Field winding (fd) on rotor

Damper in
“d” axis
(1d) on rotor

Two dampers in
“q” axis
(1q, 2q) on rotor

Model Without Stator Transients, No Saturation

Network Interface

$$0 = V_d + I_d R_s - X_q'' I_q + (1+\omega)\psi_q''$$
$$0 = V_q + I_q R_s + X_d'' I_d - (1+\omega)\psi_d''$$

Rotor Windings

$$T_{do}' \frac{dE_q'}{dt} = -E_q' - (X_d - X_d')\left[I_d - \frac{(X_d' - X_d'')}{(X_d' - X_{\ell s})^2}\left(\psi_{1d} + (X_d' - X_{\ell s})I_d - E_q'\right)\right] + E_{fd}$$
$$T_{do}'' \frac{d\psi_{1d}}{dt} = -\psi_{1d} + E_q' - (X_d' - X_{\ell s})I_d$$
$$T_{qo}' \frac{dE_d'}{dt} = -E_d' + (X_q - X_q')\left[I_q - \frac{X_q' - X_q''}{(X_q' - X_{\ell s})^2}\left(\psi_{2q} + (X_q' - X_{\ell s})I_q + E_d'\right)\right]$$
$$T_{qo}'' \frac{d\psi_{2q}}{dt} = -\psi_{2q} - E_d' - (X_q' - X_{\ell s})I_q$$

Mechanical equations

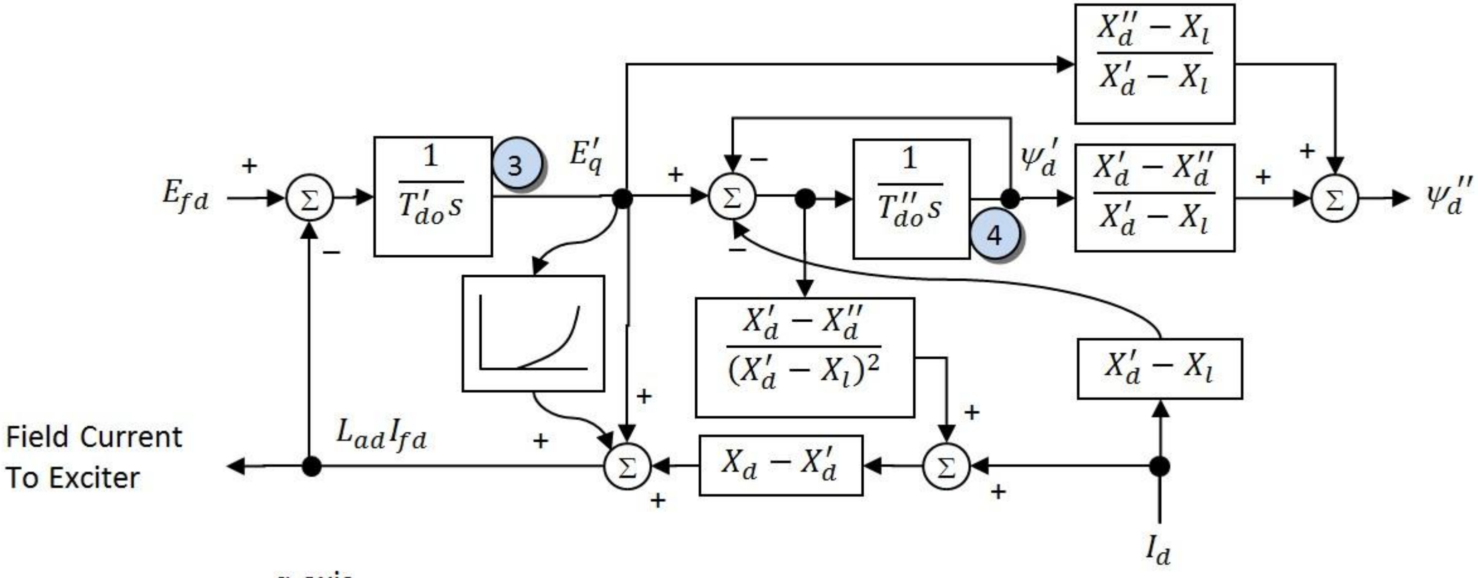
$$\frac{d\delta}{dt} = \omega \cdot \omega_s$$
$$2H\frac{d\omega}{dt} = T_M + (\psi_q'' I_d - \psi_d'' I_q) - T_{FW}$$

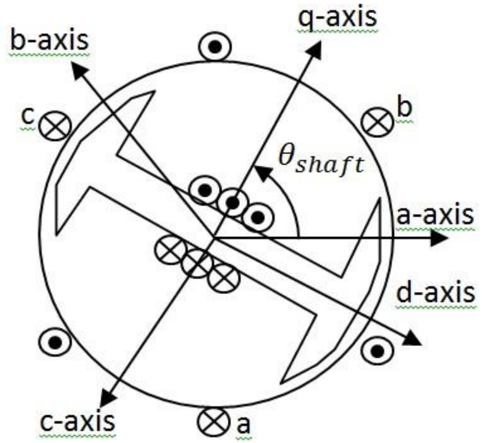
Flux definitions

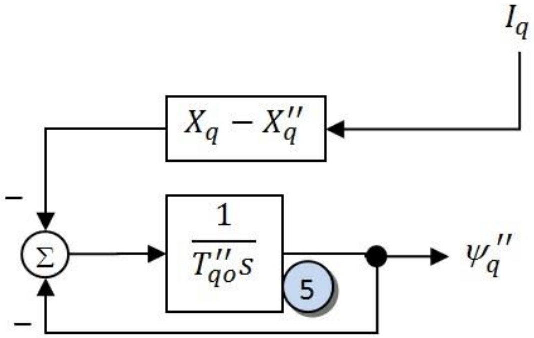
$$\psi_d'' = \frac{X_d'' - X_{\ell s}}{X_d' - X_{\ell s}} E_q' + \frac{X_d' - X_d''}{X_d' - X_{\ell s}}\psi_{1d}$$
$$\psi_q'' = -\frac{X_q'' - X_{\ell s}}{X_q' - X_{\ell s}} E_d' + \frac{X_q' - X_q''}{X_q' - X_{\ell s}}\psi_{2q}$$

GENSAL Definition

- Block diagram shows rotor equations
- Same machine interface equations and mechanical equations as the "model without stator transients" we developed above.
- For initialization, saturation only impacts calculation of E_{fd}

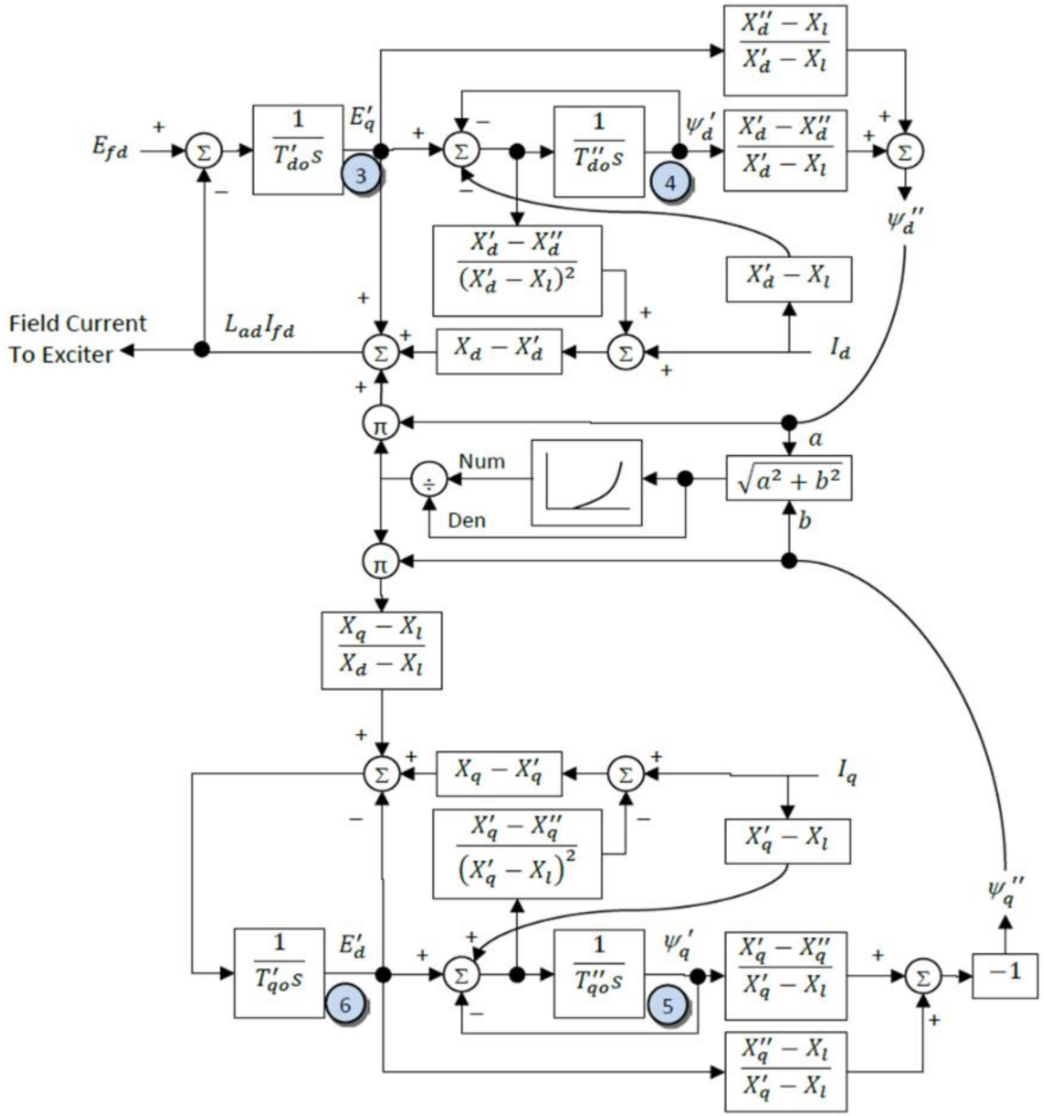






GENROU

- Widely used to model round rotor machines
- Same network interface and mechanical equations as GENSAL
- 6th order – includes both q-axis dampers
- Saturation is assumed to occur on both the d axis and the q axis
- This makes initialization more difficult



GENROU Initialization

1. Recognize that the saturation is independent of δ

$$|\psi''| = |\bar{V} + (R_s + jX'')\bar{I}|$$

2. Finding δ is the key. First get a guess of δ using the unsaturated approach

$$E\angle\delta = \bar{V} + \left(R_s + jX_q\right)\bar{I}$$

3. Then solve 5 nonlinear equations for 5 unknowns.
   - The 5 unknowns are δ, E'_q, E'_d, ψ'_q and ψ'_d
   - 3 of the equations come from differential equations (2 on q-axis and 1 on d-axis)
   - The other 2 equations come from the definition of ψ''_d and ψ''_q as a function of the power flow voltage, current, and δ
   - Use Newton's method

4. Finally, with δ known, convert to V_d, V_q, I_d, I_q and find the rest of the variables and E_{fd} and T_M.

GENROU Initialization Example

- Use the B4 case as before (B4_GENROU_NoSat)
  - H = 3.0, R_s=0, X_d = 2.1, X_q = 2.0, X'_d= 0.3, X'_q = 0.5, T'_{do} = 7.0, T'_{qo} = 0.75, X''_d=X''_q=0.28, X_l = 0.13, T''_{do} = 0.073, T''_{qo} =0.07
- For comparison initially assume no saturation
  - Get our guess of δ the same way we did before: $\delta = 52.1°$
  - This gives network current and voltage in the dq reference frame

$$V_d + jV_q = (V_s \angle \theta_s) e^{-j\left(\delta - \frac{\pi}{2}\right)} = 1.09\angle(11.59° - 52.1° + 90°) = 0.7107 + j0.8326$$

$$I_d + jI_q = (I_s \angle \phi_s) e^{-j\left(\delta - \frac{\pi}{2}\right)} = 1.0526\angle(-18.2° - 52.1° + 90°) = 0.9909 + j0.3553$$

  - And from this we can get initial subtransient fluxes

$$0 = V_d + I_d R_s - X''_q I_q + (1 + \omega)\psi''_q \rightarrow \psi''_q = -0.611$$
$$0 = V_q + I_q R_s + X''_d I_d - (1 + \omega)\psi''_d \rightarrow \psi''_d = 1.110$$

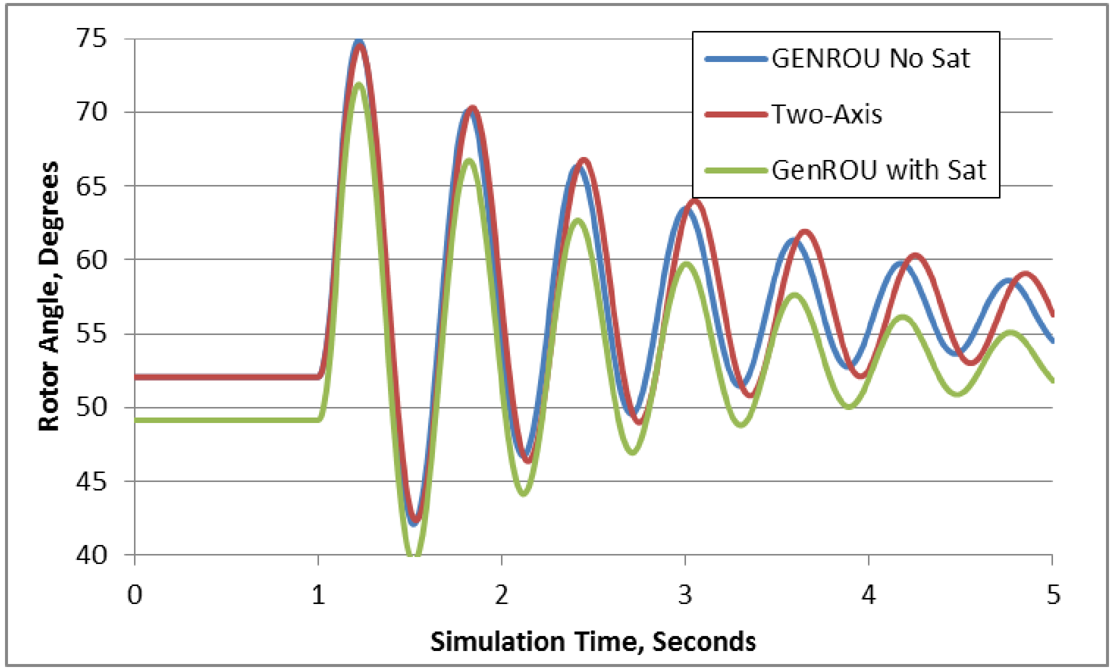
  - Other values will be

$$E'_q = 1.1298, E'_d = 0.533, \psi'_q = 0.6645, \psi'_d = 0.9614, E_{fd} = 2.9133$$

(See the block diagram)

GENROU Initialization Example, with Saturation

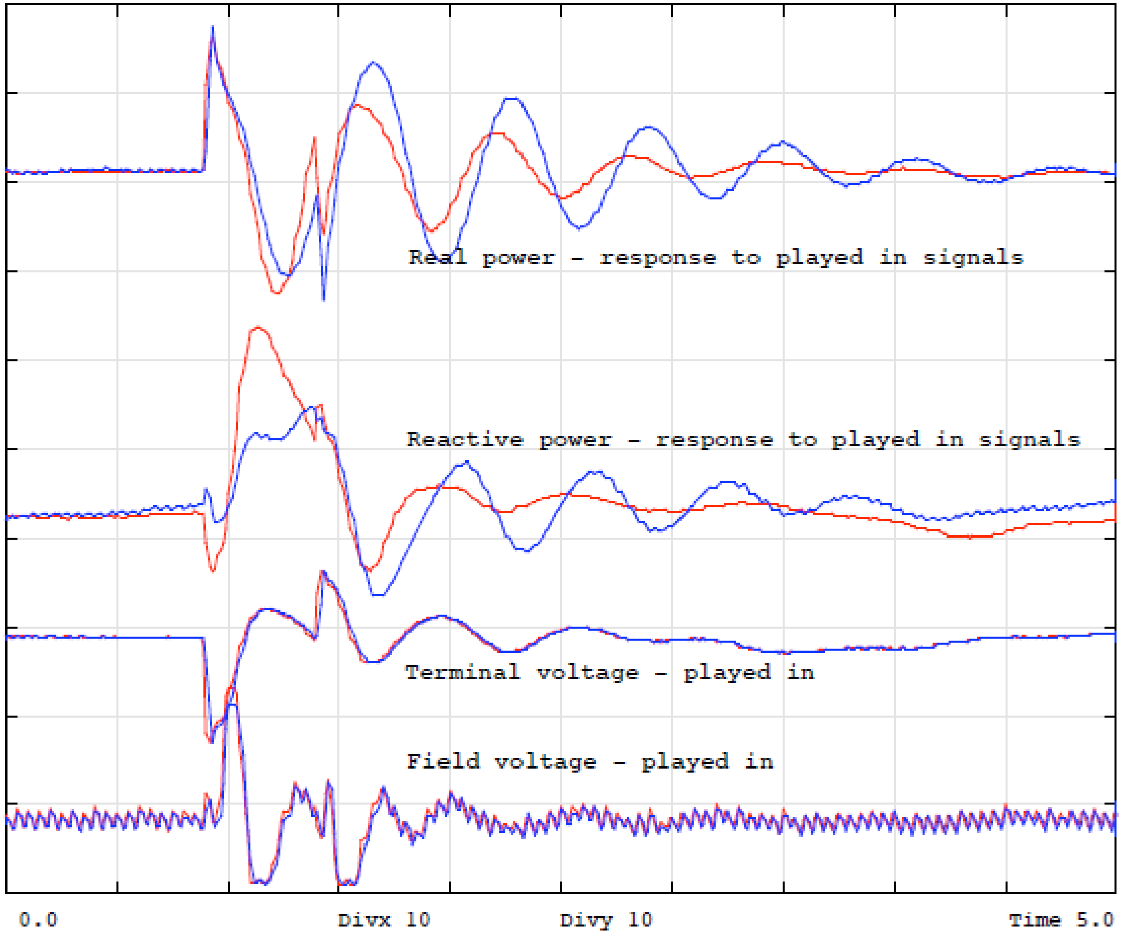
- Assume prior example but with $S(1.0) = 0.05$ and $S(1.2) = 0.2$
- Initial values change to $\delta = 49.2°, E'_q = 1.1591, E'_d = 0.4646, \psi'_q = 0.6146, \psi'_d = 0.9940, E_{fd} = 3.2186$
- Now run the same fault we've been running (B4_GENROU_Sat)



GENTPF, GENTPJ, and GENQEC

- GENTPF and GENTPJ were introduced in 2009 to better match between simulated and actual system results for salient pole machines (replacing GENSAL)
  - Desire was to duplicate functionality from old BPA transient stability code
  - Allows for subtransient salience, such that $X_q'' \neq X_d''$
  - Can also be used for round rotor, hence can replace GENSAL and GENROU
- For more information
- https://www.powerworld.com/knowledge-base/derivation-of-the-gentpjgentpf-model-from-the-genrougensal
- Now these are being replaced by GENQEC, which is becoming the recommended model by WECC for new synchronous machines
- https://www.wecc.org/sites/default/files/documents/meeting/2024/GENQEC%20Model%20Specification%20-%20R3.pdf

Motivation for the Change: GENSAL Results



Chief Joseph disturbance playback

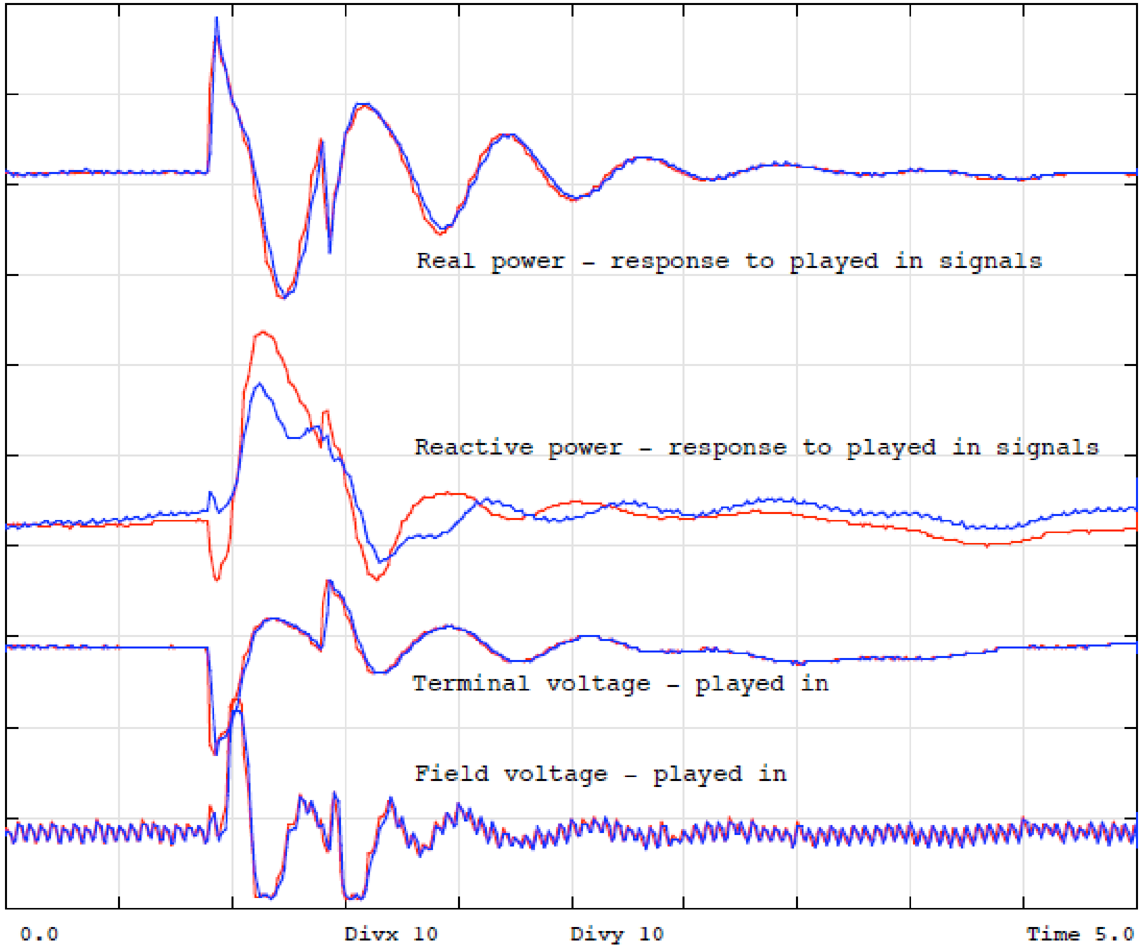
GENSAL BLUE = MODEL

RED = ACTUAL

(Chief Joseph is a 2620 MW hydro plant on the Columbia River in Washington)

Image source :https://www.wecc.biz/library/WECC%20Documents/Documents%20for %20Generators/Generator%20Testing%20Program/gentpj%20and%20gensal%20morel.pdf

Motivation for the Change: GENTPJ Results



Chief Joseph disturbance playback

GENTPJ

BLUE = MODEL

RED = ACTUAL

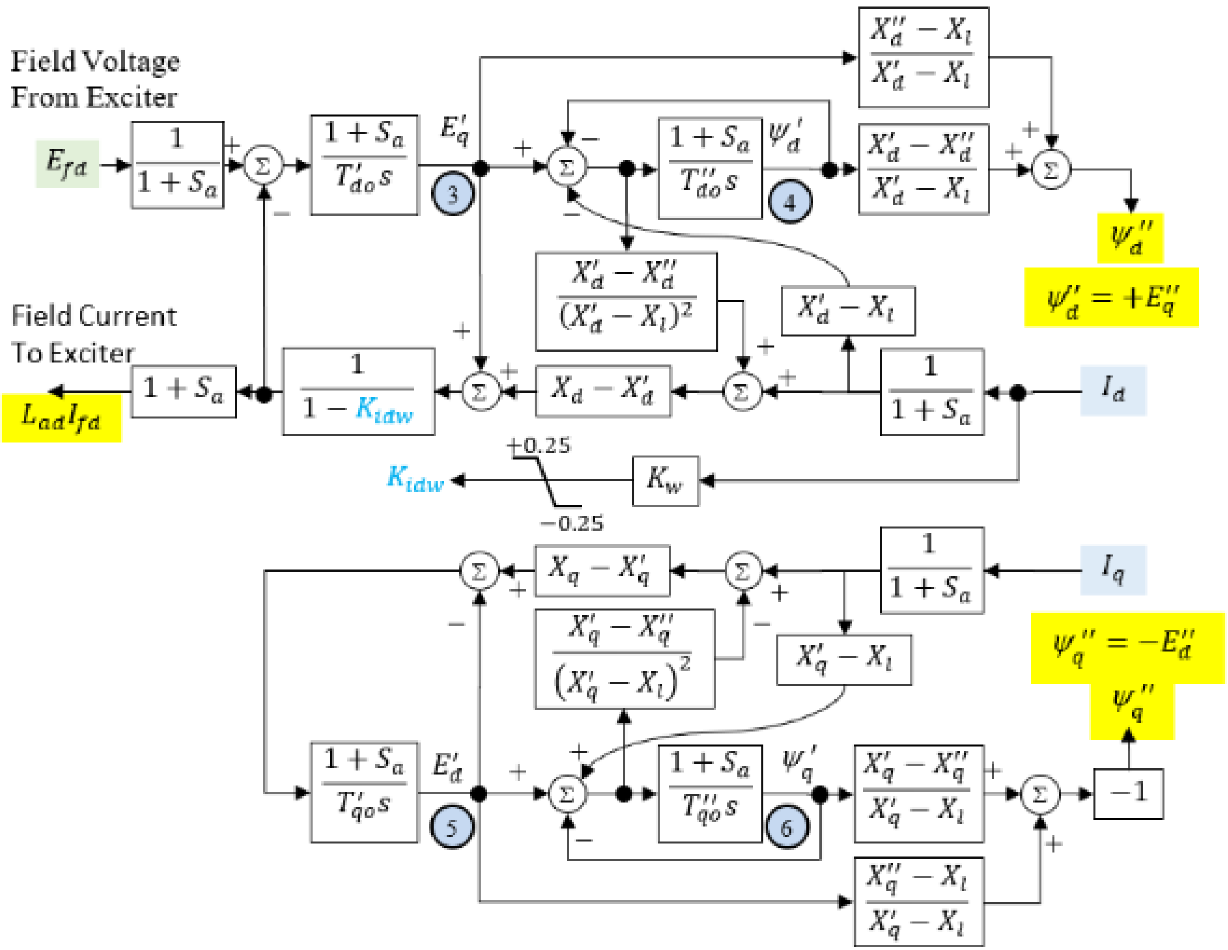
GENQEC Definition

- Saturation terms now appear in lots of places around the rotor equations (notice the S_a terms)

$$S_a = Sat(\psi_{ag})$$
$$\psi_{ag} = \frac{1}{1+\omega}\sqrt{V_{qag}^2 + V_{dag}^2}$$
$$V_{qag} = V_q + I_q R_a + I_d X_\ell$$
$$V_{dqg} = V_d + I_d R_a - I_d X_\ell$$

- We need to consider saturated transient reactances

$$X''_{dsat} = \frac{X''_d - X_\ell}{1+S_a} + X_\ell$$
$$X''_{qsat} = \frac{X''_q - X_\ell}{1+S_a} + X_\ell$$



Subtransient Salience

- Because $X''_{qsat} \neq X''_{dsat}$, there is no exact circuit model for the network interface. We need to use the following equations directly

$$V_d = -(1+\omega)\psi''_q - R_a I_d + X''_{qsat} I_q$$
$$V_q = (1+\omega)\psi''_d - X''_{dsat} I_d - R_a I_q$$

- Combined with the network reference frame transformation based on delta
- For GENQEC, we use the following for electrical torque

$$T_{elec} = \psi_d I_q - \psi_q I_d$$
$$\psi_d = E''_q - I_d X''_{dsat}$$
$$\psi_q = -E''_d - I_q X''_{qsat}$$

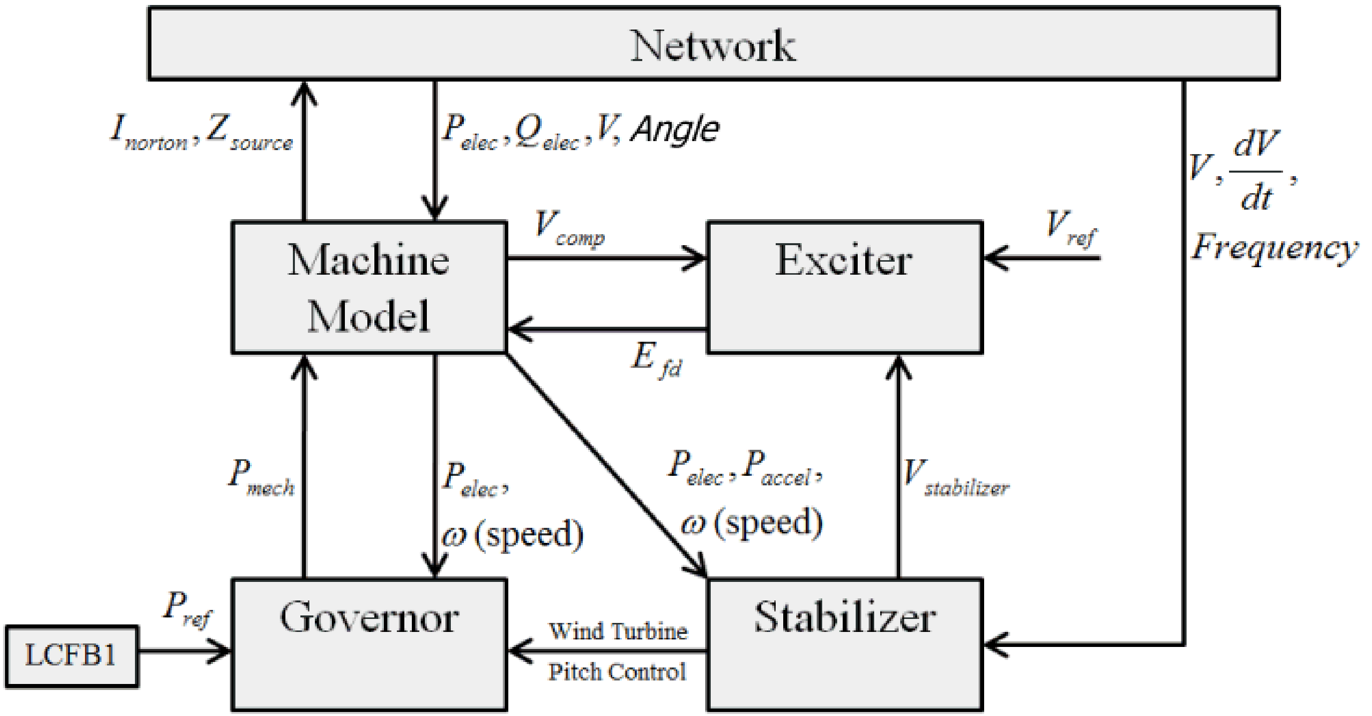
Summary: Synchronous Machine Models

Model Name	Order	Saturation	Other Comments
Classical	2nd	None	
Flux Decay	3rd	None	
Two-Axis	4th	None	
GENSAL	5th	D-axis	
GENROU	6th	D&Q	
GENTPF/J	6th	D&Q	Allows subtransient saliency
GENQEC	6th	D&Q	Allows subtransient saliency

- These models have the same parameter names, but they are not the same
  - Parameters are tuned to a specific model
  - It is not appropriate to just transfer parameters and call that a new model
  - When doing a new generator testing study, that is the time to update the model

Synchronous Machine Controllers

- The machine model itself only models the physical stator and rotor
- Next we will be beginning discussion of various control systems associated with the synchronous machine



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

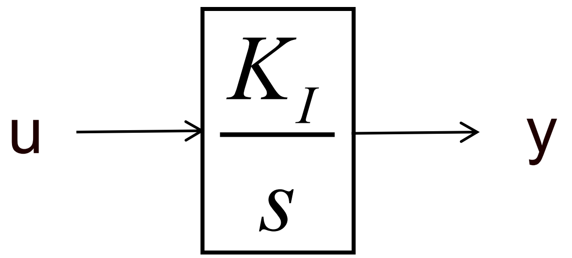
V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

Block Diagram Basics

- The following slides will make use of block diagrams to explain some of the models used in power system dynamic analysis. The next few slides cover some of the block diagram basics.
- To simulate a model represented as a block diagram, the equations need to be represented as a set of first order differential equations
- Also the initial state variable and reference values need to be determined

Integrator Block

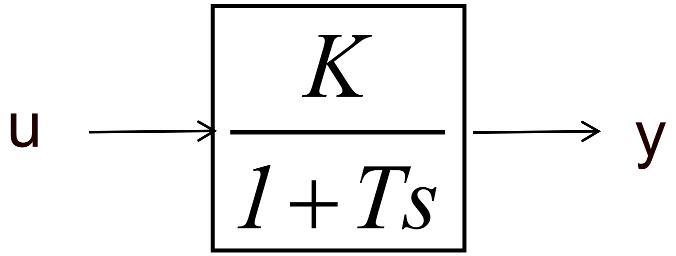


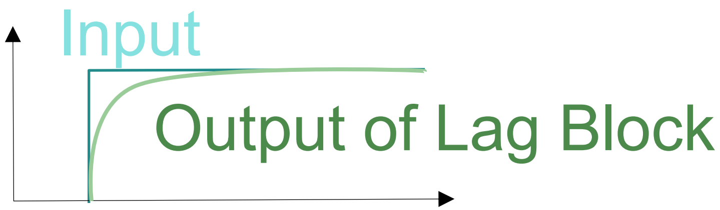
- Equation for an integrator with u as an input and y as an output is

$$\frac{dy}{dt} = K_I u$$

- In steady-state with an initial output of y_0, the initial state is y_0 and the initial input is zero

First Order Lag Block



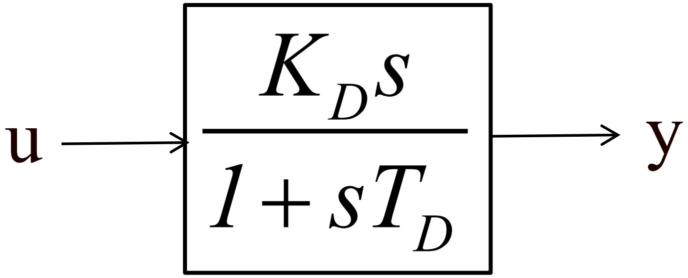


- Equation with u as an input and y as an output is

$$\frac{dy}{dt} = \frac{1}{T}(Ku - y)$$

- In steady-state with an initial output of y_0, the initial state is y_0 and the initial input is y_0/K
- Commonly used for measurement delay (e.g., T_R block with IEEE T1)

Derivative Block



- Block takes the derivative of the input, with scaling K_D and a first order lag with T_D
  - Physically we can't take the derivative without some lag
  - An example is the feedback block in the IEEET1 model
- In steady-state the output of the block is zero
- State equations require a more general approach

State Equations for More Complicated Functions

- There is not a unique way of obtaining state equations for more complicated functions with a general form

$$\beta_0 u + \beta_1 \frac{du}{dt} + \cdots + \beta_m \frac{d^m u}{dt^m} =$$

$$\alpha_0 y + \alpha_1 \frac{dy}{dt} + \cdots + \alpha_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + d^n y / dt^n$$

- To be physically realizable we need n >= m

General Block Diagram Approach

- One integration approach is illustrated in the below block diagram

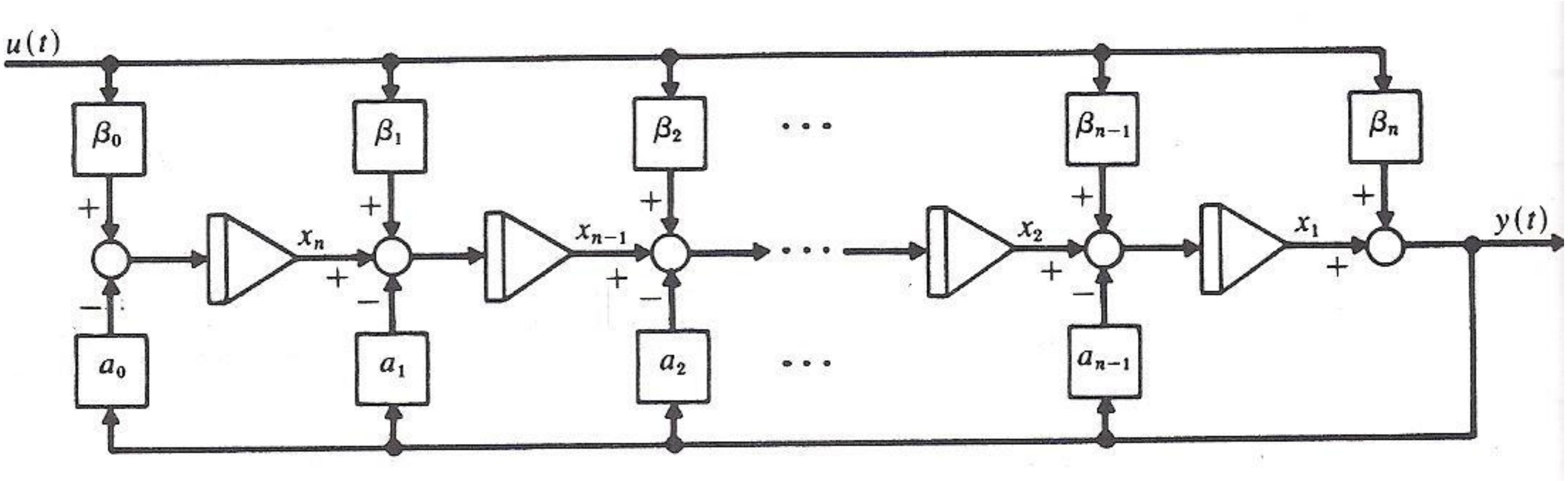
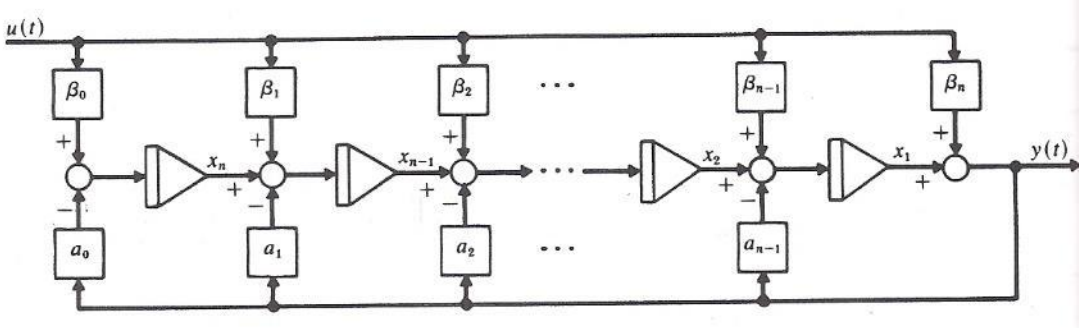


Image source: W.L. Brogan, *Modern Control Theory*, Prentice Hall, 1991, Figure 3.7

Derivative Example

- Write in form

$$\frac{{}^{K_D}\!/_{T_D}\, s}{1/T_D + s}$$



- Hence β_0=0, β_1=K_D/T_D, α_0=$1/T_D$
- Define single state variable x, then

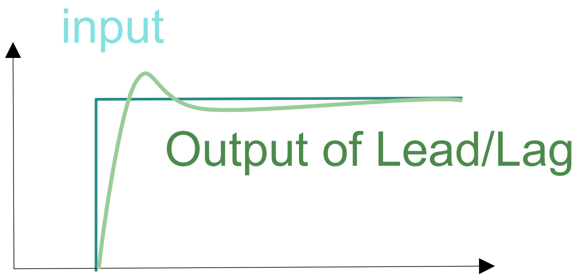
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = -\frac{y}{T_D}$$

$$y = x + \beta_1 u = x + \frac{K_D}{T_D u}$$

Initial value of
x is found by recognizing
y is zero so x = $-b_1u$

Lead-Lag Block

$$u \longrightarrow \boxed{\frac{1+sT_A}{1+sT_B}} \longrightarrow y$$



The steady-state requirement that u = y is readily apparent

- In exciters such as the EXDC1 the lead-lag block is used to model time constants inherent in the exciter; the values are often zero (or equivalently equal)
- In steady-state the input is equal to the output
- To get equations write in form with $\beta_0=1/T_B$, $\beta_1=T_A/T_B$, $\alpha_0=1/T_B$

$$\frac{1+sT_A}{1+sT_B}=\frac{\frac{1}{T_B}+s\frac{T_A}{T_B}}{\frac{1}{T_B}+s}$$

Lead-Lag Block

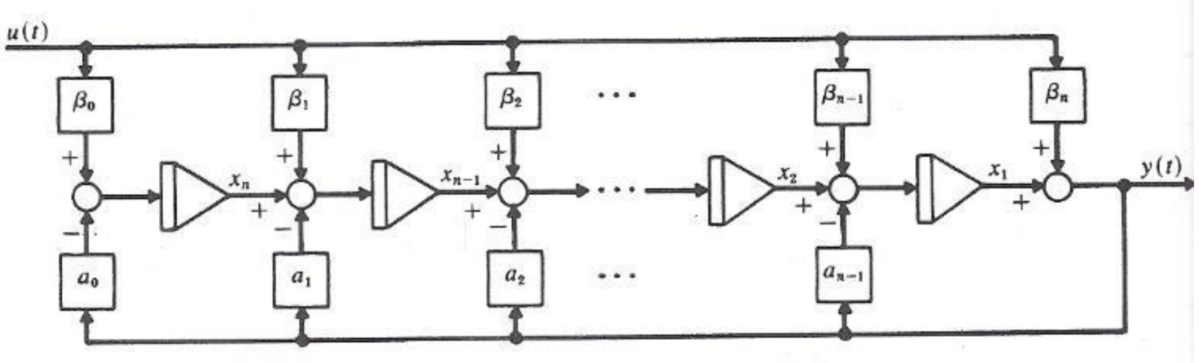
- The equations are with

  $\beta_0=1/T_B$, $\beta_1=T_A/T_B$,
  $\alpha_0=1/T_B$

  then

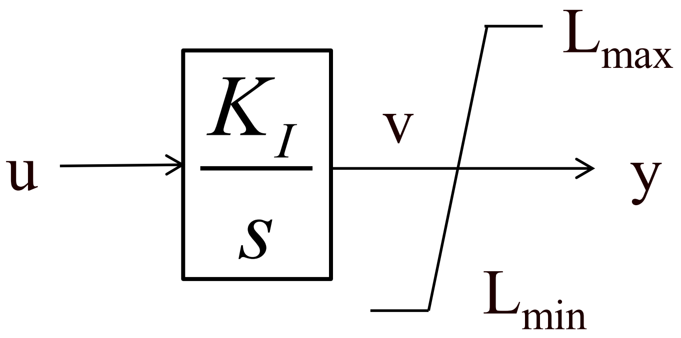
  $$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = \frac{1}{T_B}(u - y)$$

  $$y = x + \beta_1 u = x + \frac{T_A}{T_B} u$$



Limits: Windup versus Nonwindup

- When there is integration, how limits are enforced can have a major impact on simulation results
- Two major flavors: windup and non-windup
- Windup limit for an integrator block



The value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

$$\frac{dv}{dt} = K_I u$$

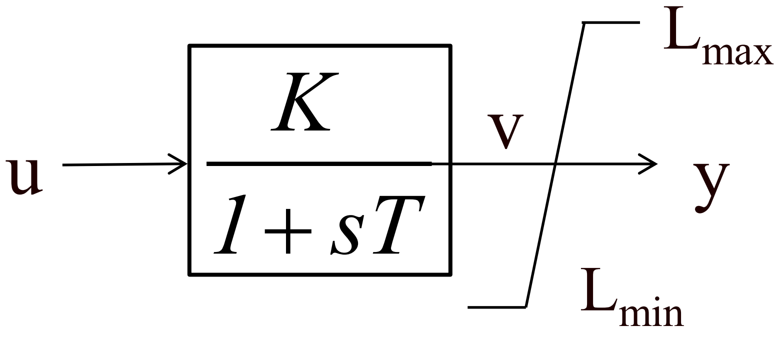
If $L_{min} \le v \le L_{max}$ then $y = v$

else If $v < L_{min}$ then $y = L_{min}$,

else if $v > L_{max}$ then $y = L_{max}$

Limits on First Order Lag

- Windup and non-windup limits are handled in a similar manner for a first order lag



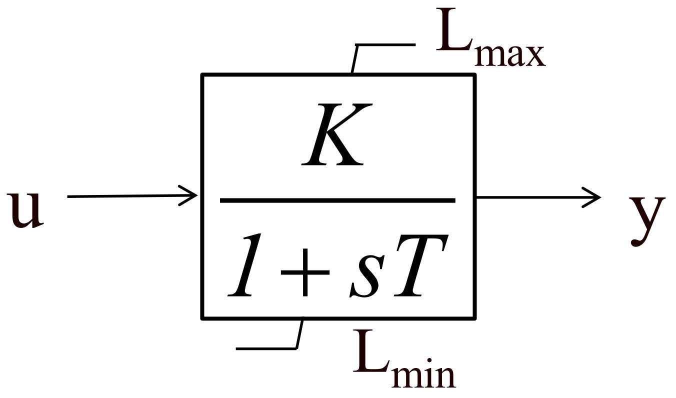
$$\frac{dv}{dt} = \frac{1}{T}(Ku - v)$$

If $L_{min} \le v \le L_{max}$ then $y = v$
else If $v < L_{min}$ then $y = L_{min}$,
else if $v > L_{max}$ then $y = L_{max}$

Again the value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

Non-Windup Limit First Order Lag

- With a non-windup limit, the value of y is prevented from exceeding its limit



$$\frac{dy}{dt} = \frac{1}{T}(Ku - y)$$
(except as indicated below)

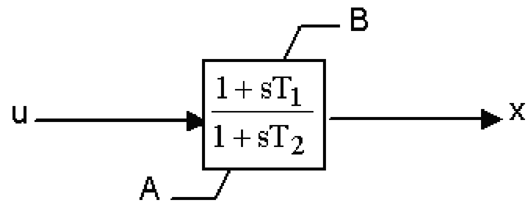
If $L_{min} \leq y \leq L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}(Ku - y)$

If $y \geq L_{max}$ then $y = L_{max}$ and if $u > 0$ then $\frac{dy}{dt} = 0$

If $y \leq L_{min}$ then $y = L_{min}$ and if $u < 0$ then $\frac{dy}{dt} = 0$

Lead-Lag Non-Windup Limits

- There is not a unique way to implement non-windup limits for a lead-lag. This is the one from IEEE 421.5-1995 (Figure E.6)



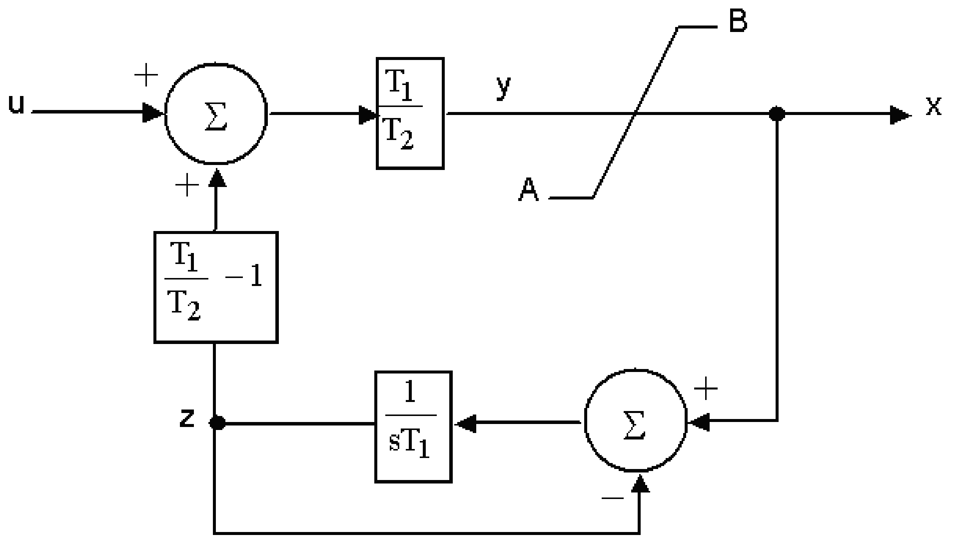
(a) Model

$$T_2 > T_1, T_1 > 0, T_2 > 0$$

If $y > B$, then $x = B$

If $y < A$, then $x = A$

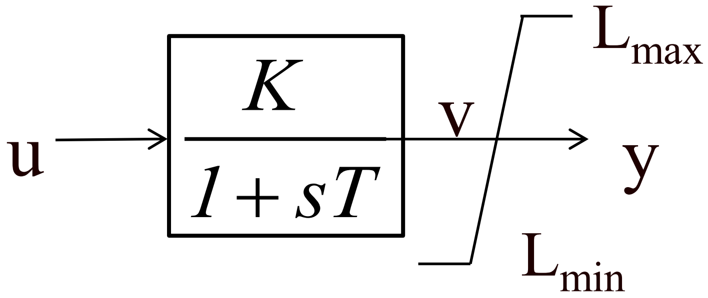
If $B \geq y \geq A$, then $x = y$



(b) Implementation

Ignored States

- When integrating block diagrams often states are ignored, such as a measurement delay with $T_R=0$
- In this case the differential equations just become algebraic constraints
- Example: For block at right, as $T \rightarrow 0$, v=Ku



- With lead-lag it is quite common for $T_A=T_B$, resulting in the block being ignored