ECEN 667
Power System Stability

Lecture 10: Synchronous Machine Models, Exciter Models

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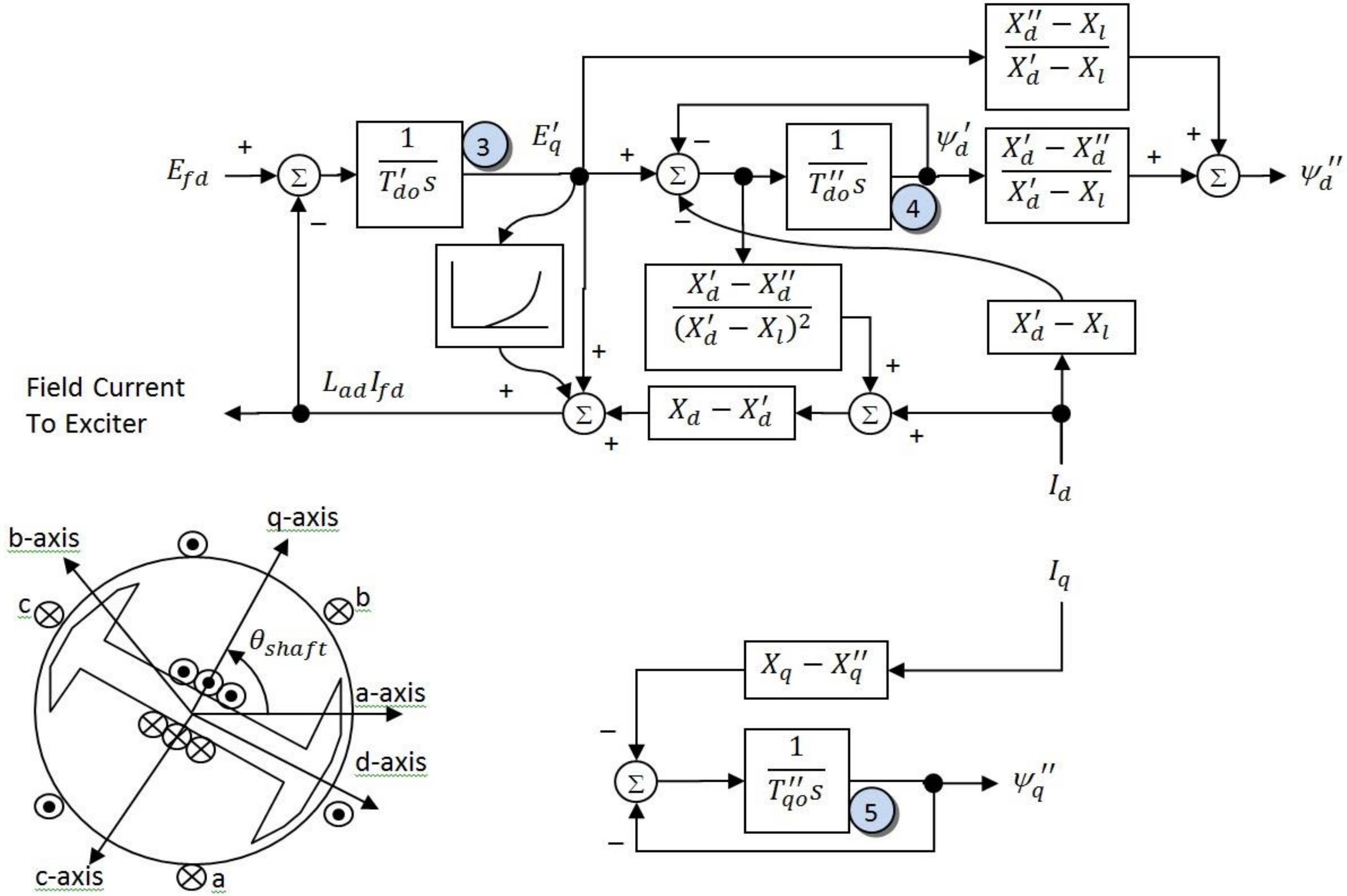
Announcements

- Read Chapter 4
- Homework 3 is posted, due on Thursday Oct 5
- Midterm exam is Oct 17 in class; closed book, closed notes, one 8.5 by 11 inch hand written notesheet allowed; calculators allowed

GENSAL Block Diagram



A quadratic saturation function is used. For initialization it only impacts the E_{fd} value

GENSAL Example

- Assume same system as before with same common generator parameters: H=3.0, D=0, R_a = 0, X_d = 2.1, X_q = 2.0, X'_d = 0.3, X''_d=X''_q=0.2, X_l = 0.13, T'_{do} = 7.0, T''_{do} = 0.07, T''_{qo} =0.07, S(1.0) =0, and S(1.2) = 0.
- Same terminal conditions as before
  - Current of 1.0-j0.3286 and generator terminal voltage of 1.072+j0.22 = 1.0946 $\angle$11.59 °
- Use same equation to get initial δ

$$|E|\angle\delta = \bar{V} + \left(R_s + jX_q\right)\bar{I}$$
$$= 1.072 + j0.22 + (0.0 + j2)(1.0 - j0.3286)$$
$$= 1.729 + j2.22 = 2.81\angle 52.1°$$

Same delta as with the other models

GENSAL Example

- Then as before

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.0723 \\ 0.220 \end{bmatrix} = \begin{bmatrix} 0.7107 \\ 0.8326 \end{bmatrix}$$

And $$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.000 \\ -0.3287 \end{bmatrix} = \begin{bmatrix} 0.9909 \\ 0.3553 \end{bmatrix}$$

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

$$= 1.072 + j0.22 + (0 + j0.2)(1.0 - j0.3286)$$

$$= 1.138 + j0.42$$

GENSAL Example

- Giving the initial fluxes (with ω = 1.0)

$$\begin{bmatrix} -\psi''_q \\ \psi''_d \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.138 \\ 0.420 \end{bmatrix} = \begin{bmatrix} 0.6396 \\ 1.031 \end{bmatrix}$$

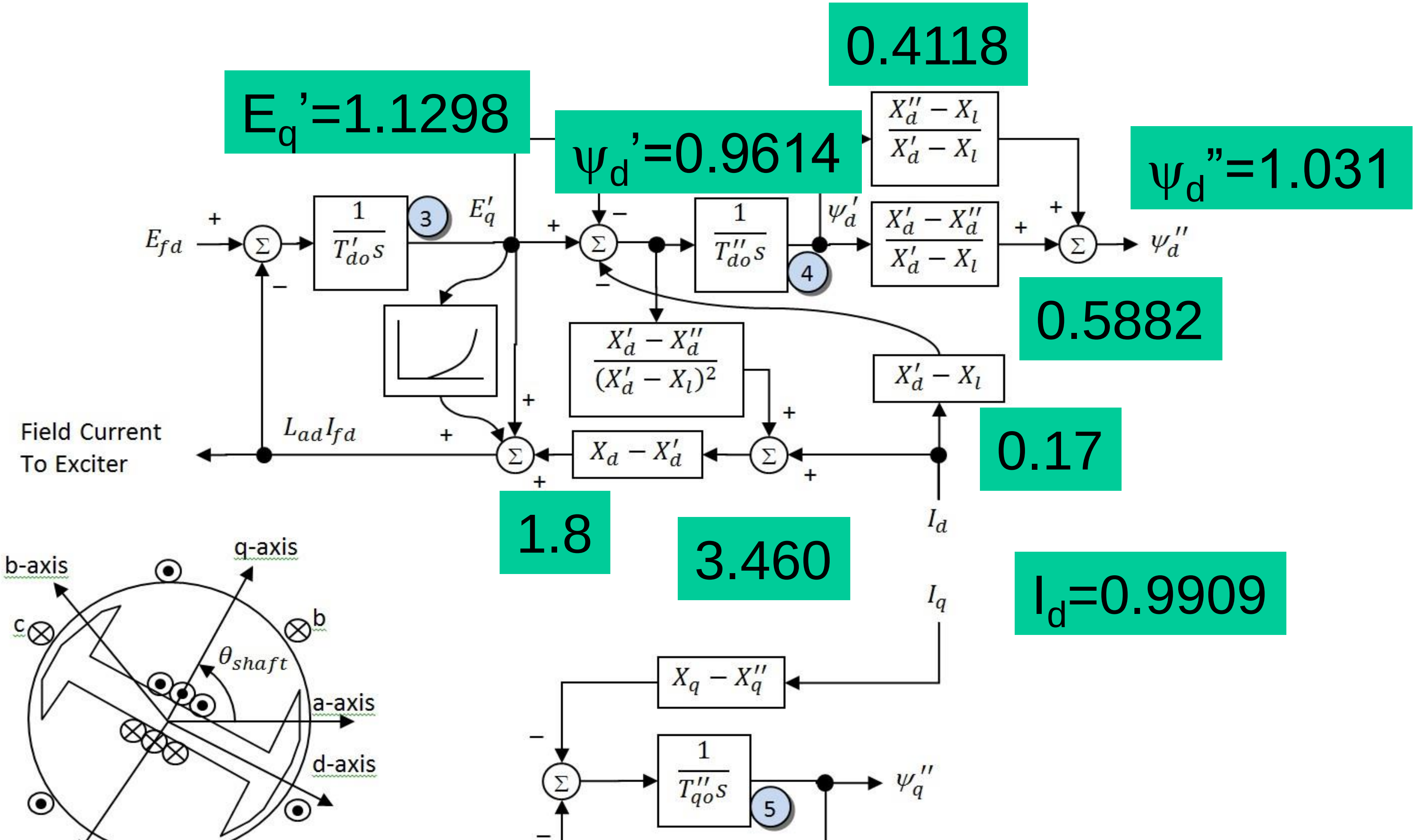
- To get the remaining variables set the differential equations equal to zero, e.g.,

$$\psi''_q = -\left(X_q - X''_q\right) I_q = -(2 - 0.2)(0.3553) = -0.6396$$

$$E'_q = 1.1298, \quad \psi'_d = 0.9614$$

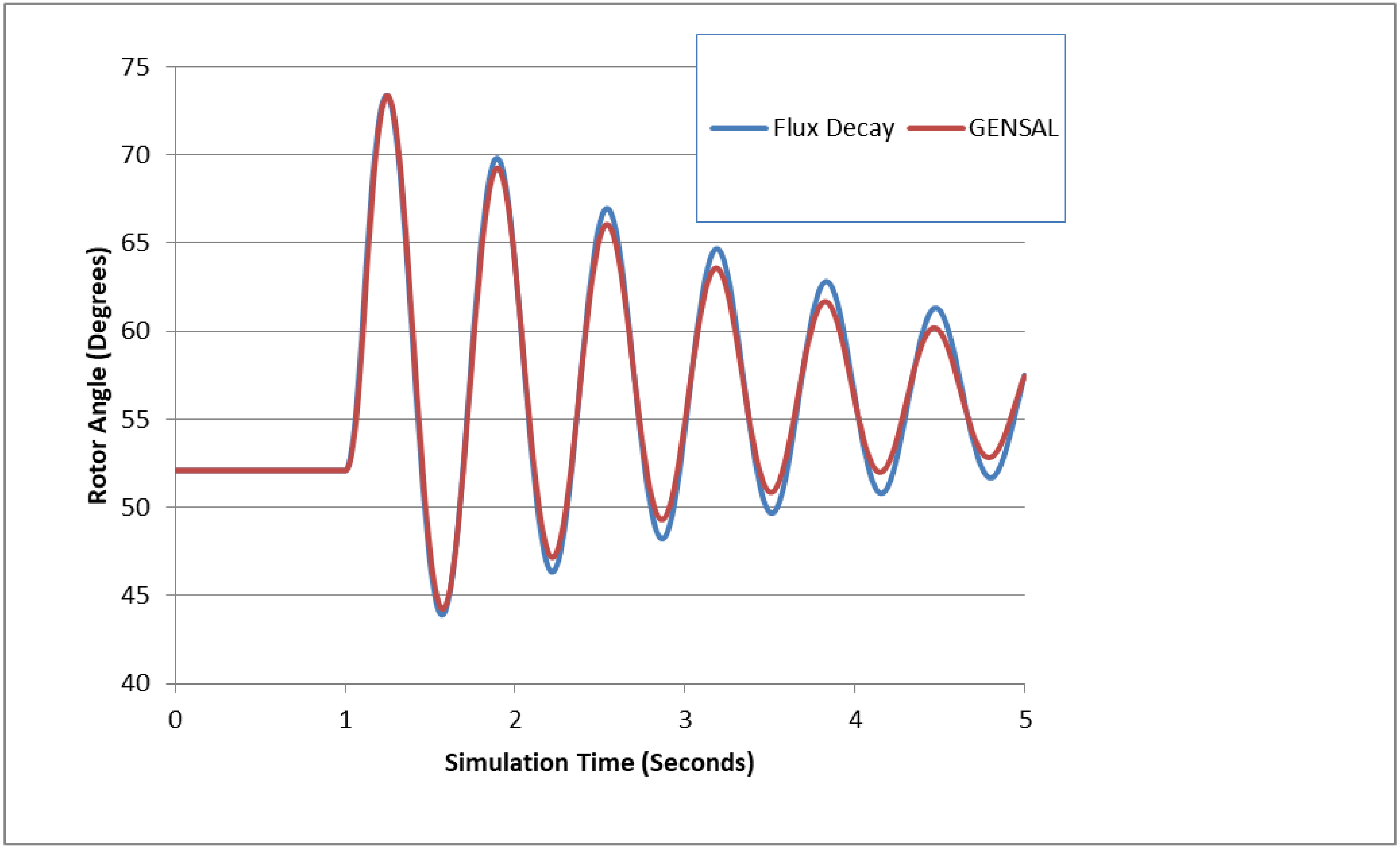
Solving the d-axis requires solving two linear equations for two unknowns

GENSAL Example



E_{fd} = 1.1298+1.8*0.991=2.912

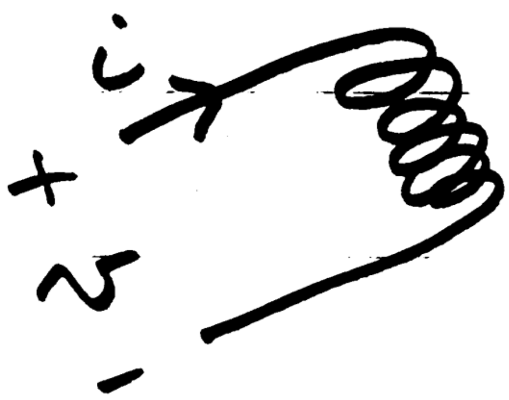
Comparison Between Gensal and Flux Decay



Nonlinear Magnetic Circuits

- Nonlinear magnetic models are needed because magnetic materials tend to saturate; that is, increasingly large amounts of current are needed to increase the flux density

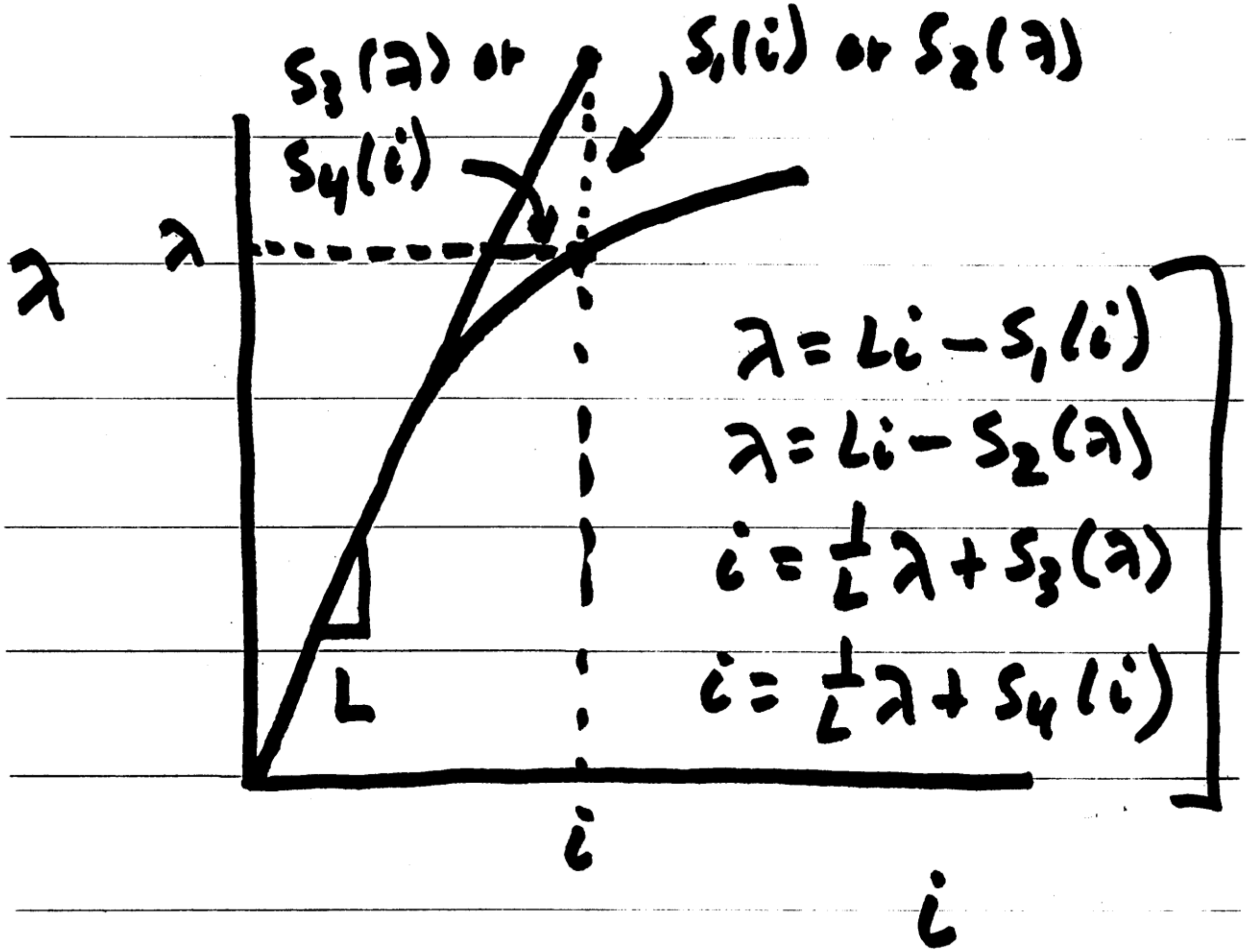
$$R = 0$$



$$v = \frac{d\lambda}{dt} = N\frac{d\phi}{dt}$$

Linear $\lambda = Li$

Saturation



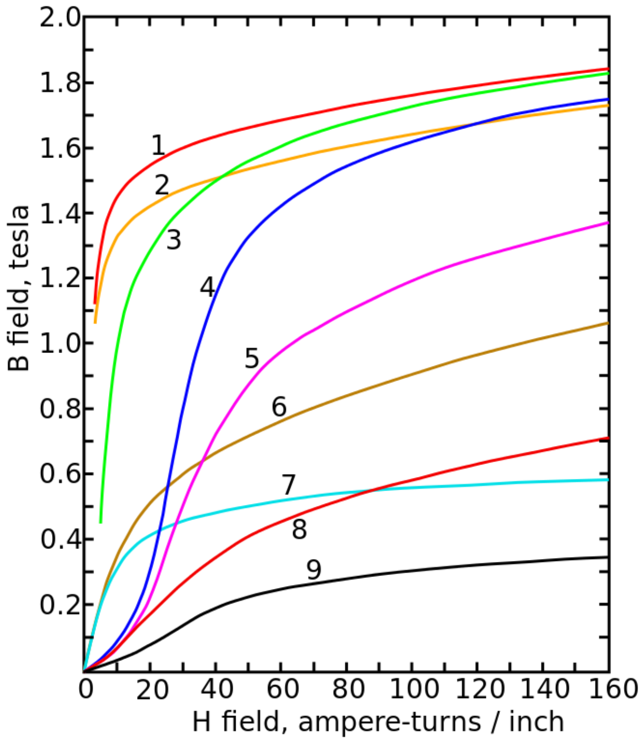
The flux density (B) determines when a material saturates; measured in Tesla (T)

Relative Magnetic Strength Levels

- Earth's magnetic field is between 30 and 70 μT (0.3 to 0.7 gauss)
- A refrigerator magnet might have 0.005 T
- A commercial neodymium magnet might be 1 T
- A magnetic resonance imaging (MRI) machine would be between 1 and 3 T
- Strong lab magnets can be 10 T
- Frogs can be levitated at 16 T (see www.ru.nl/hfml/research/levitation/diamagnetic
- A neutron star can have 1 to 100 MT!

Magnetic Saturation and Hysteresis

- The below image shows the saturation curves for various materials



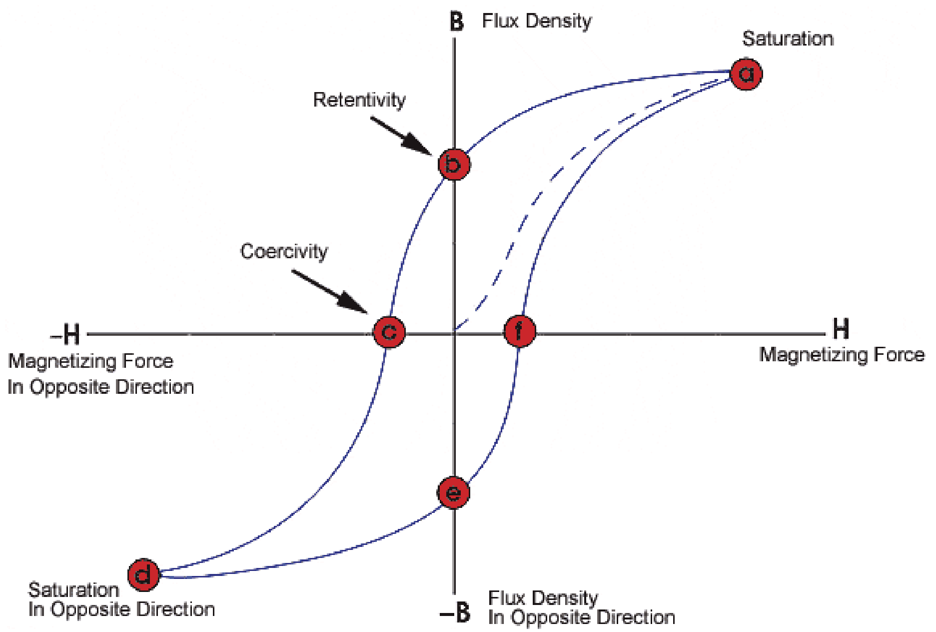
Magnetization curves of 9 ferromagnetic materials, showing saturation. 1.Sheet steel, 2.Silicon steel, 3.Cast steel, 4.Tungsten steel, 5.Magnet steel, 6.Cast iron, 7.Nickel, 8.Cobalt, 9.Magnetite; highest saturation materials can get to around 2.2 or 2.3T

H is proportional to current

Image Source: en.wikipedia.org/wiki/Saturation_(magnetic)

Magnetic Saturation and Hysteresis

- Magnetic materials also exhibit hysteresis, so there is some residual magnetism when the current goes to zero; design goal is to reduce the area enclosed by the hysteresis loop



To minimize the amount of magnetic material, and hence cost and weight, electric machines are designed to operate close to saturation

Image source: www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Graphics/BHCurve.gif

Saturation Models

- Many different models exist to represent saturation
  - There is a tradeoff between accuracy and complexity
- Book presents the details of fully considering saturation in Section 3.5
- One simple approach is to replace

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'}\left(-E_q' - (X_d - X_d')I_d + E_{fd}\right)$$

- With

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'}\left(-E_q' - (X_d - X_d')I_d - Se(E_q') + E_{fd}\right)$$

Saturation Models

- In steady-state this becomes

$$E_{fd} = E_q' + (X_d - X_d')I_d + Se(E_q')$$

- Hence saturation increases the required E_{fd} to get a desired flux
- Saturation is usually modeled using a quadratic function, with the value of Se specified at two points (often at 1.0 flux and 1.2 flux)

$$Se = B(E_q' - A)^2$$

An alternative model is $Se = \dfrac{B(E_q' - A)^2}{E_q'}$

A and B are determined from the two data points

Saturation Example

- If Se = 0.1 when the flux is 1.0 and 0.5 when the flux is 1.2, what are the values of A and B using the $Se = B(E_q^{'} - A)^2$

To solve use the Se(1.2) value to eliminate B

$$B = \frac{Se(1.2)}{(1.2 - A)^2} \rightarrow Se(1.0) = \frac{Se(1.2)}{(1.2 - A)^2}(1.0 - A)^2$$

$$(1.2 - A)^2 Se(1.0) = Se(1.2)(1.0 - A)^2$$

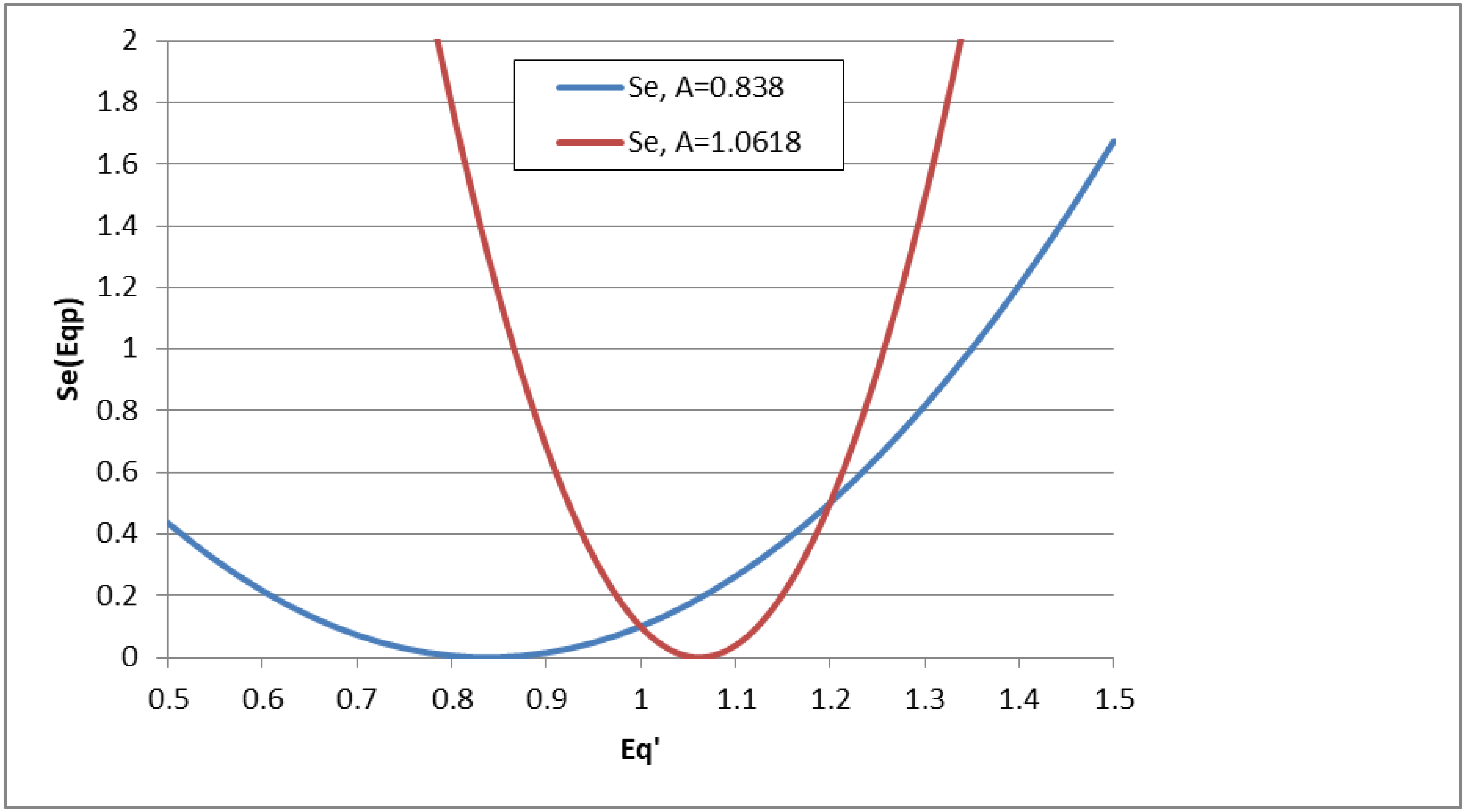
With the values we get

$$4A^2 - 7.6A + 3.56 = 0 \rightarrow A = 0.838 \text{ or } 1.0618$$

Use A=0.838, which gives B=3.820

Saturation Example: Selection of A

When selecting which of the two values of A to use, we do not want the minimum to be between the two specified values. That is Se(1.0) and Se(1.2).



Implementing Saturation Models

- When implementing saturation models in code, it is important to recognize that the function is meant to be positive, so negative values are not allowed
- In large cases one is almost guaranteed to have special cases, sometimes caused by user typos
  - What to do if Se(1.2) < Se(1.0)?
  - What to do if Se(1.0) = 0 and Se(1.2) <> 0
  - What to do if Se(1.0) = Se(1.2) <> 0
- Exponential saturation models have also been used

GENSAL Example with Saturation

- Once E'_q has been determined, the initial field current (and hence field voltage) are easily determined by recognizing in steady-state the E'_q is zero

$$E_{fd} = E'_q\left(1+Sat(E'_q)\right)+\left(X_d - X'_d\right)I_D$$
$$=1.1298\left(1+B\left(1.1298-A\right)^2\right)+\left(2.1-0.3\right)(0.9909)$$
$$=1.1298\left(1+3.82\left(1.1298-0.838\right)^2\right)+1.784=3.28$$

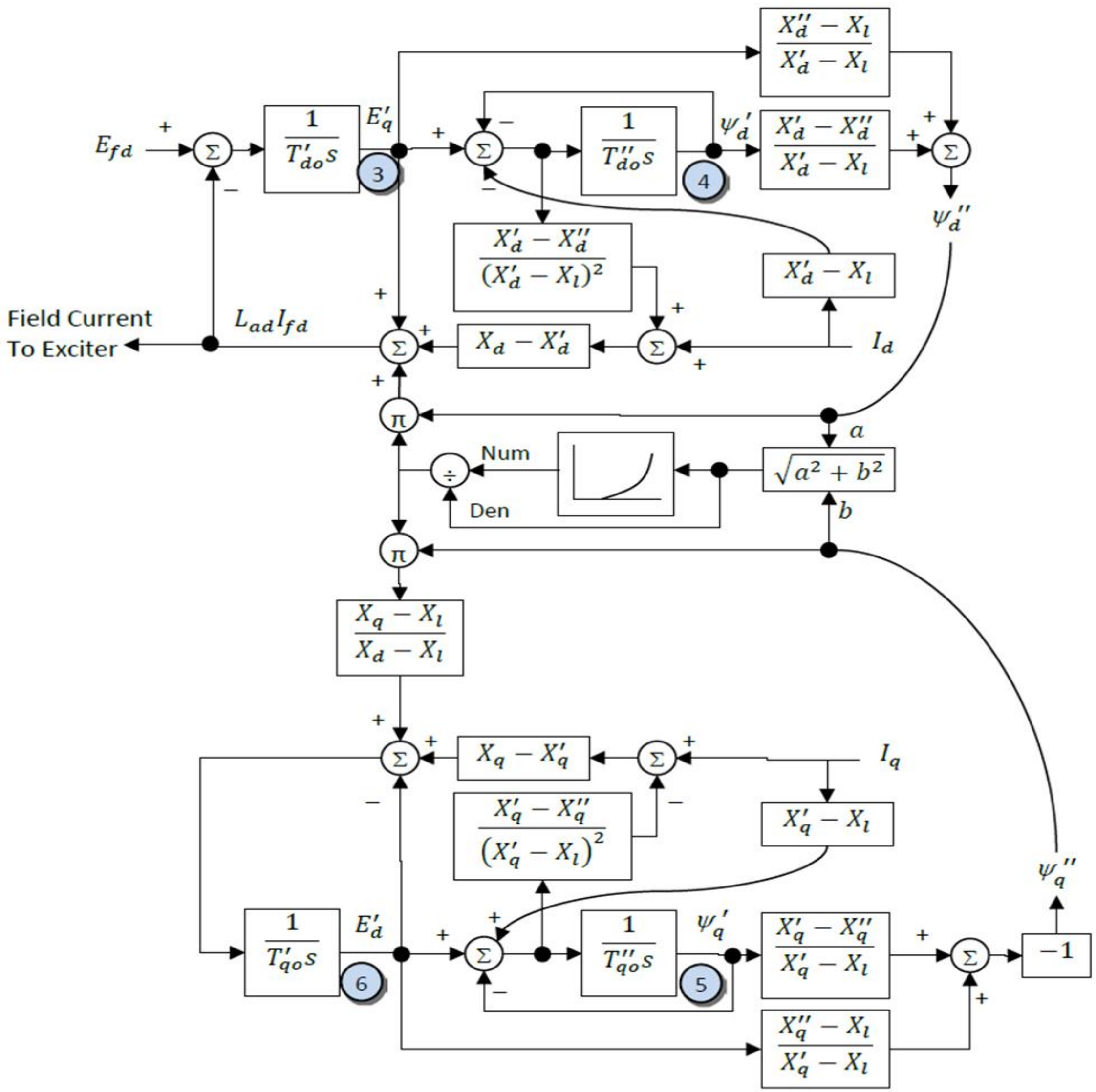
Saturation coefficients were determined from the two initial values

Saved as case B4_GENSAL_SAT

GENROU

- The GENROU model has been widely used to model round rotor machines
- Saturation is assumed to occur on both the d-axis and the q-axis, making initialization slightly more difficult

GENROU Block Diagram



The d-axis is similar to that of the GENSAL; the q-axis is now similar to the d-axis. Note that saturation now affects both axes.

GENROU Initialization

- Because saturation impacts both axes, the simple approach will no longer work
- Key insight for determining initial δ is that the magnitude of the saturation depends upon the magnitude of ψ'', which is independent of δ

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

This point is crucial!

- Solving for δ requires an iterative approach; first get a guess of δ using 3.229 from the book

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

GENROU Initialization

- Then solve five nonlinear equations for five unknowns
  - The five unknowns are δ, E'_q, E'_d, ψ'_q, and ψ'_d
- Five equations come from the terminal power flow constraints (which allow us to define $\boldsymbol{\psi_d}''$ and $\boldsymbol{\psi_q}''$ as a function of the power flow voltage, current and δ) and from the differential equations initially set to zero
  - The $\boldsymbol{\psi_d}''$ and $\boldsymbol{\psi_q}''$ block diagram constraints
  - Two differential equations for the q-axis, one for the d-axis (the other equation is used to set the field voltage
- Values can be determined using Newton's method, which is needed for the nonlinear case with saturation

GENROU Initialization

- Use dq transform to express terminal current as

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \sin\delta & -\cos\delta \\ \cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

These values will change during the iteration as δ changes

- Get expressions for ψ''_q and ψ''_d in terms of the initial terminal voltage and δ
  - Use dq transform to express terminal voltage as

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \sin\delta & -\cos\delta \\ \cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} V_r \\ V_i \end{bmatrix}$$

Recall $X_d''=X_q''=X''$ and ω=1 (in steady-state)

  - Then from $-\psi''_q + j\psi''_d = \left(V_d + jV_q\right) + (R_s + jX'')\left(I_d + jI_q\right)$

$$-\psi''_q = V_d + R_s I_d - X'' I_q$$

$$\psi''_d = V_q + R_s I_a + X'' I_d$$

Expressing complex equation as two real equations

GENROU Initialization Example

- Extend the two-axis example
  - For two-axis assume H = 3.0 per unit-seconds, $R_s=0$, $X_d = 2.1$, $X_q = 2.0$, $X'_d= 0.3$, $X'_q = 0.5$, $T'_{do} = 7.0$, $T'_{qo} = 0.75$ per unit using the 100 MVA base.
  - For subtransient fields assume $X''_d=X''_q=0.28$, $X_l = 0.13$, $T''_{do} = 0.073$, $T''_{qo} =0.07$
  - for comparison we'll initially assume no saturation
- From two-axis get a guess of δ

$$\bar{E} = 1.0946\angle 11.59° + (j2.0)(1.052\angle -18.2°) = 2.814\angle 52.1°$$

$$\rightarrow \delta = 52.1°$$

GENROU Initialization Example

- And the network current and voltage in dq reference

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.0723 \\ 0.220 \end{bmatrix} = \begin{bmatrix} 0.7107 \\ 0.8326 \end{bmatrix}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.000 \\ -0.3287 \end{bmatrix} = \begin{bmatrix} 0.9909 \\ 0.3553 \end{bmatrix}$$

- Which gives initial subtransient fluxes (with R_s=0),

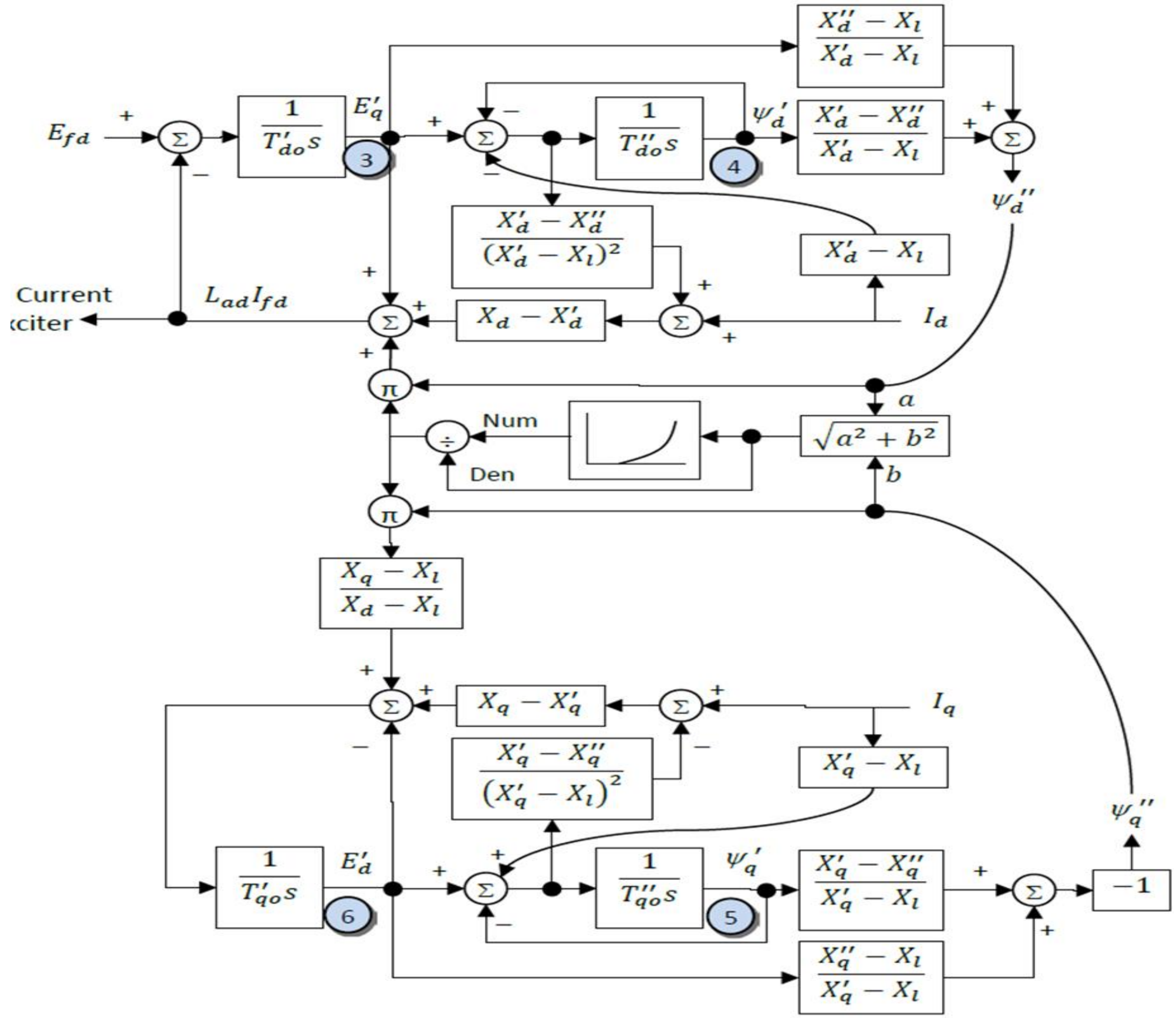
$$\left(-\psi''_q + j\psi''_d\right)\omega = \left(V_d + jV_q\right) + (R_s + jX'')\left(I_d + jI_q\right)$$

$$-\psi''_q\,\omega = V_d + R_s I_d - X''I_q = 0.7107 - 0.28 \times 0.3553 = 0.611$$

$$\psi''_d\,\omega = V_q + R_s I_a + X''I_d = 0.8326 + 0.28 \times 0.9909 = 1.110$$

GENROU Initialization Example

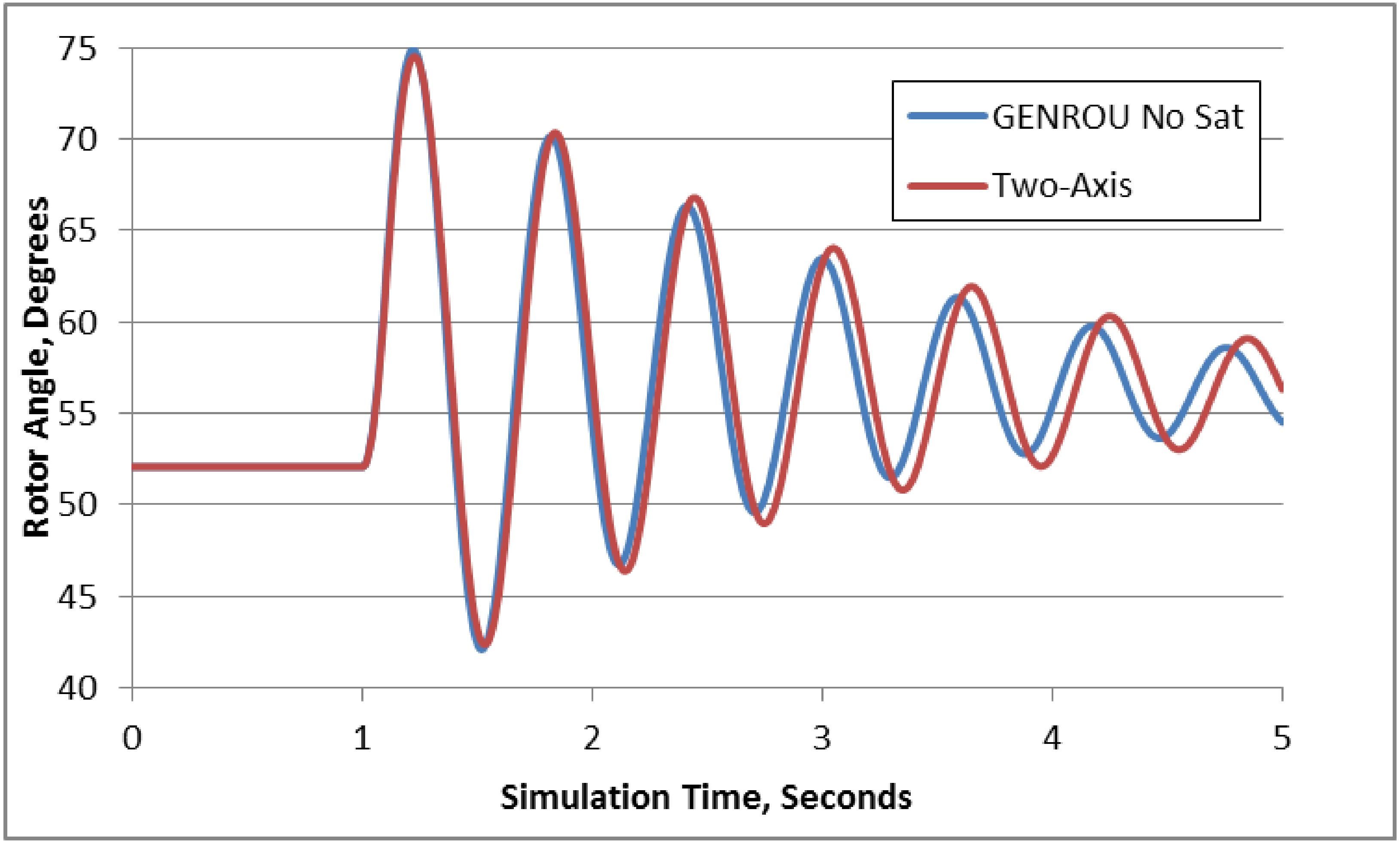
- Without saturation this is the exact solution
- Initial values are:
  $\delta = 52.1°$,
  $E'_q=1.1298$,
  $E'_d=0.533$,
  $\psi'_q=0.6645$,
  and $\psi'_d=0.9614$
- $E_{fd}=2.9133$



Saved as case
B4_GENROU_NoSat

Two-Axis versus GENROU Response

Figure compares rotor angle for bus 3 fault, cleared at t=1.1 seconds



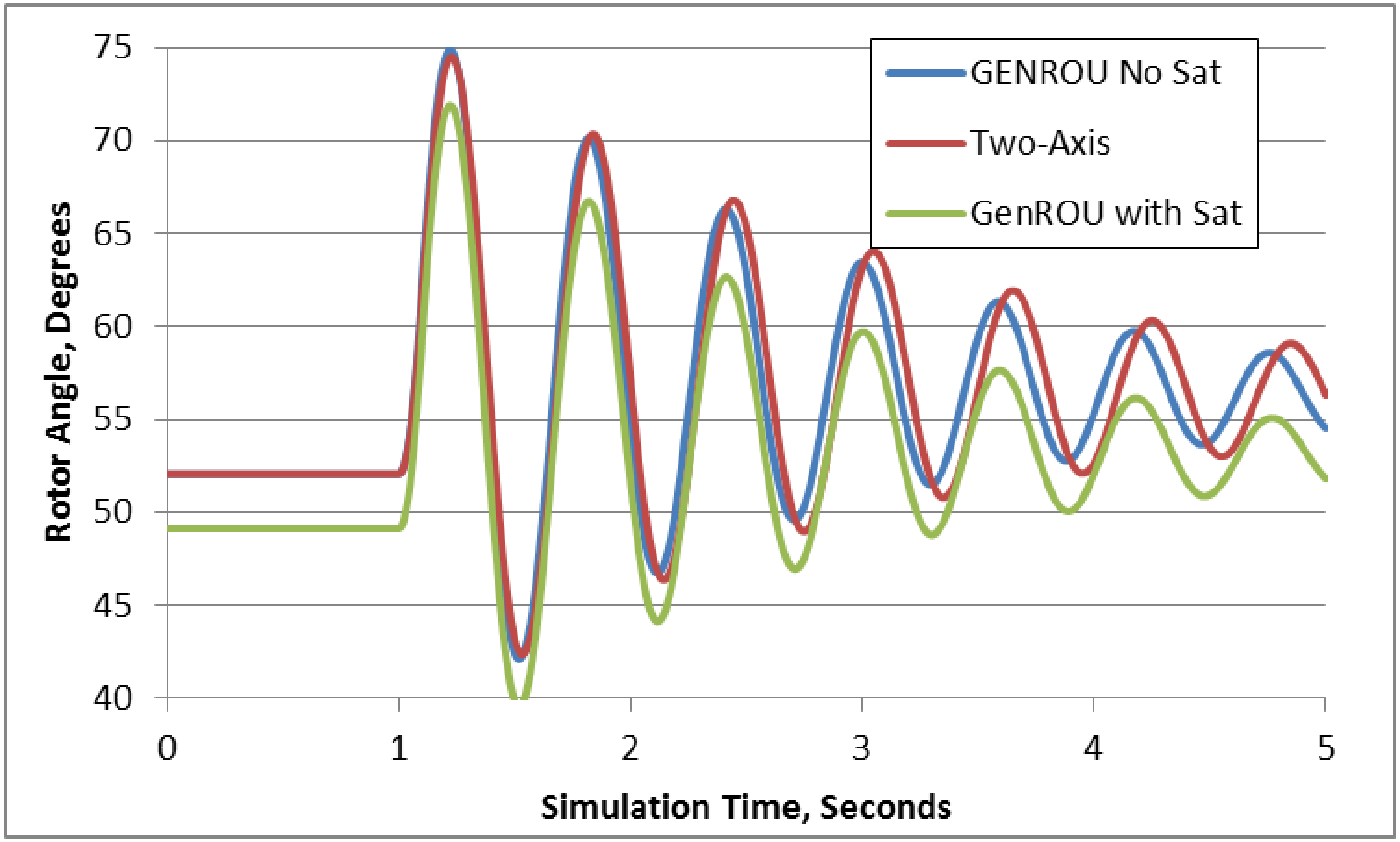
GENROU with Saturation

- Nonlinear approach is needed in common situation in which there is saturation
- Assume previous GENROU model with S(1.0) = 0.05, and S(1.2) = 0.2.
- Initial values are: $\delta = 49.2°$, $E'_q=1.1591$, $E'_d=0.4646$, $\psi'_q=0.6146$, and $\psi'_d=0.9940$
- Efd=3.2186

Saved as case B4_GENROU_Sat

Two-Axis versus GENROU Response

Figure compares rotor angle for bus 3 fault, cleared at t=1.1 seconds

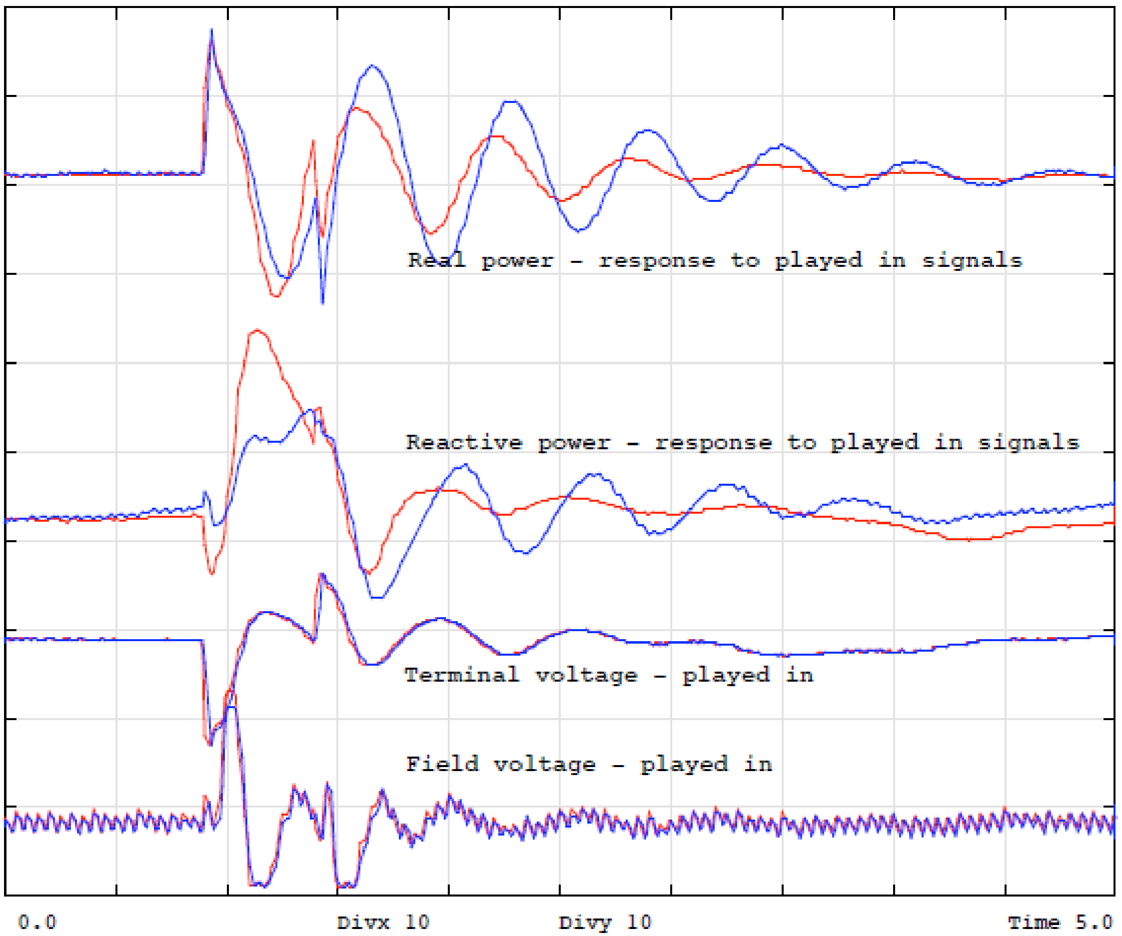


GENTPF and GENTPJ Models

- These models were introduced into PSLF in 2009 to provide a better match between simulated and actual system results for salient pole machines
  - Desire was to duplicate functionality from old BPA TS code
  - Allows for subtransient saliency ($X''_d \neq X''_q$)
  - Can also be used with round rotor, replacing GENSAL and GENROU
- Useful reference is available at below link; includes all the equations, and saturation details

https://www.wecc.biz/Reliability/gentpj-typej-definition.pdf

GENSAL Results



Chief Joseph disturbance playback GENSAL
BLUE = MODEL
RED = ACTUAL

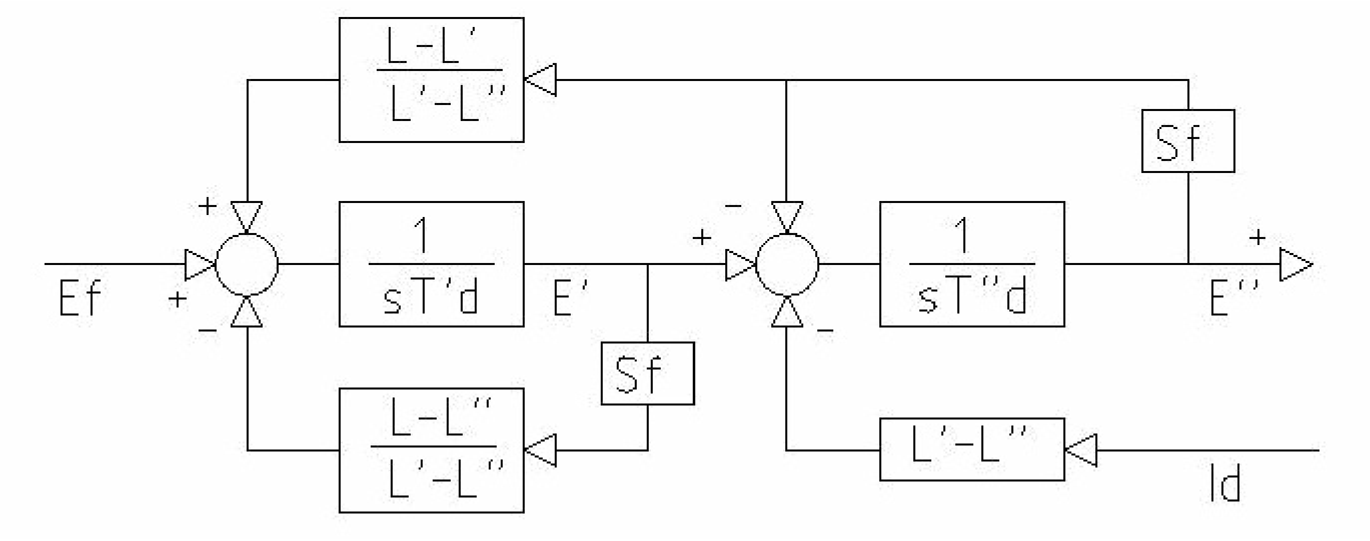
Image source :https://www.wecc.biz/library/WECC%20Documents/Documents%20for %20Generators/Generator%20Testing%20Program/gentpj%20and%20gensal%20morel.pdf

GENTPJ Results

Chief Joseph disturbance playback GENTPJ
BLUE = MODEL
RED = ACTUAL

GENTPF and GENTPJ Models

- GENTPF/J d-axis block diagram
- GENTPJ allows saturation function to include a component that depends on the stator current



Se = 1 + fsat(ψ_{ag} + Kis*It)

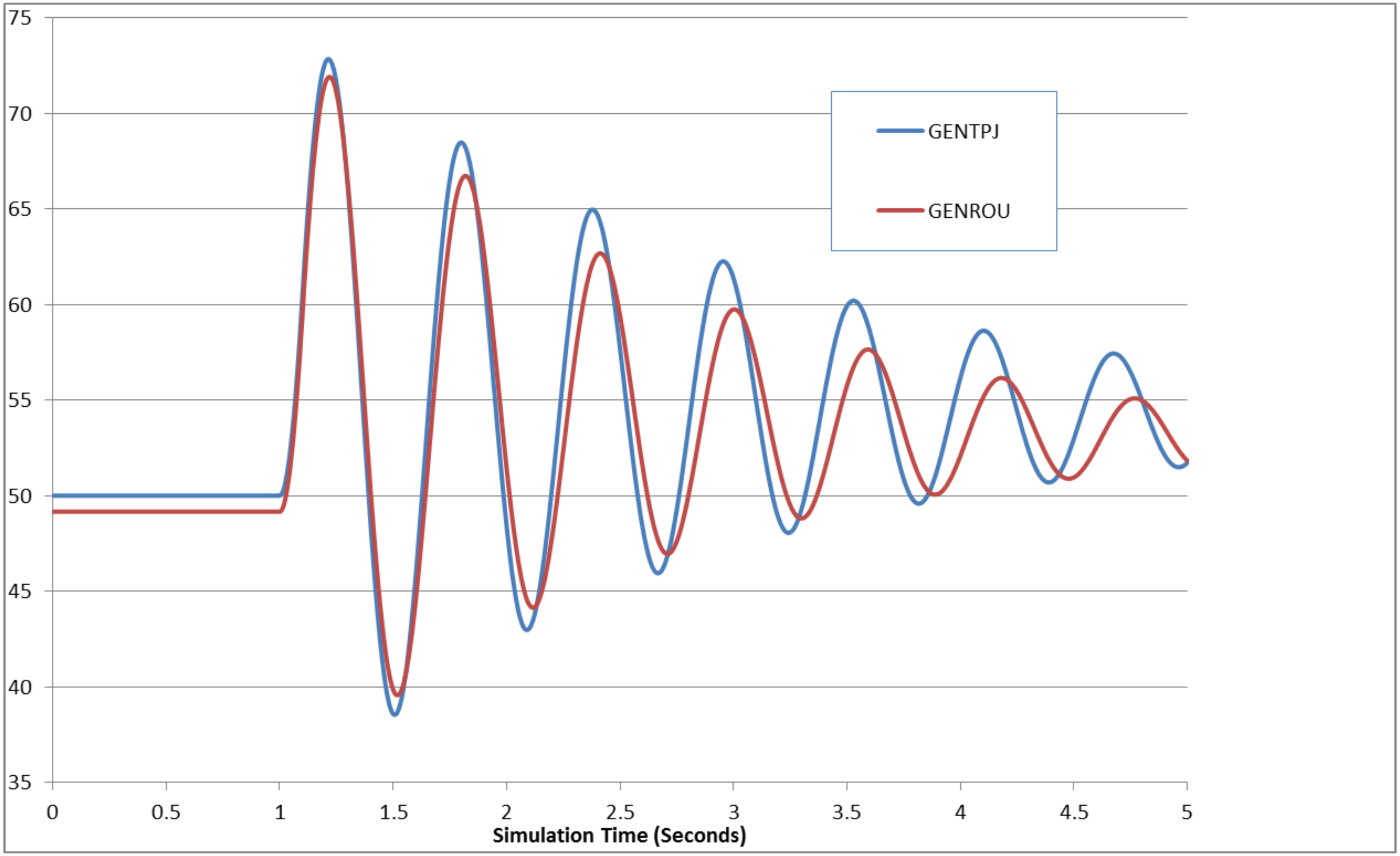
Most of WECC machine models are now GENTPF or GENTPJ

If nonzero, Kis typically ranges from 0.02 to 0.12

Theoretical Justification for GENTPF and GENTPJ

- In the GENROU and GENSAL models saturation shows up purely as an additive term of E_q' and E_d'
  - Saturation does not come into play in the network interface equations and thus with the assumption of $X_q'' = X_d''$ a simple circuit model can be used
- The advantage of the GENTPF/J models is saturation really affects the entire model, and in this model it is applied to all the inductance terms simultaneously
  - This complicates the network boundary equations, but since these models are designed for $X_q'' \neq X_d''$ there is no increase in complexity

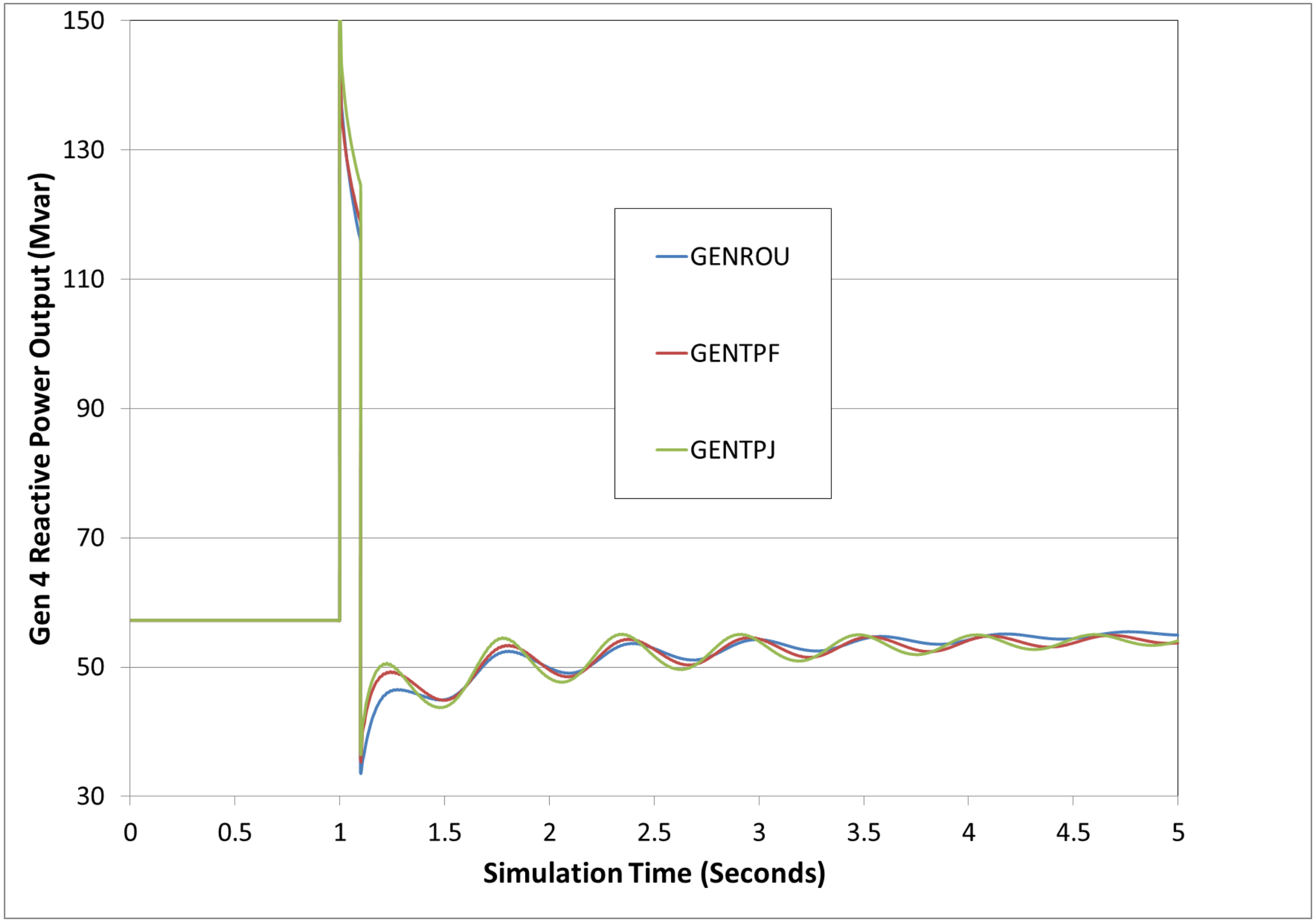
GENROU/GENTPJ Comparison



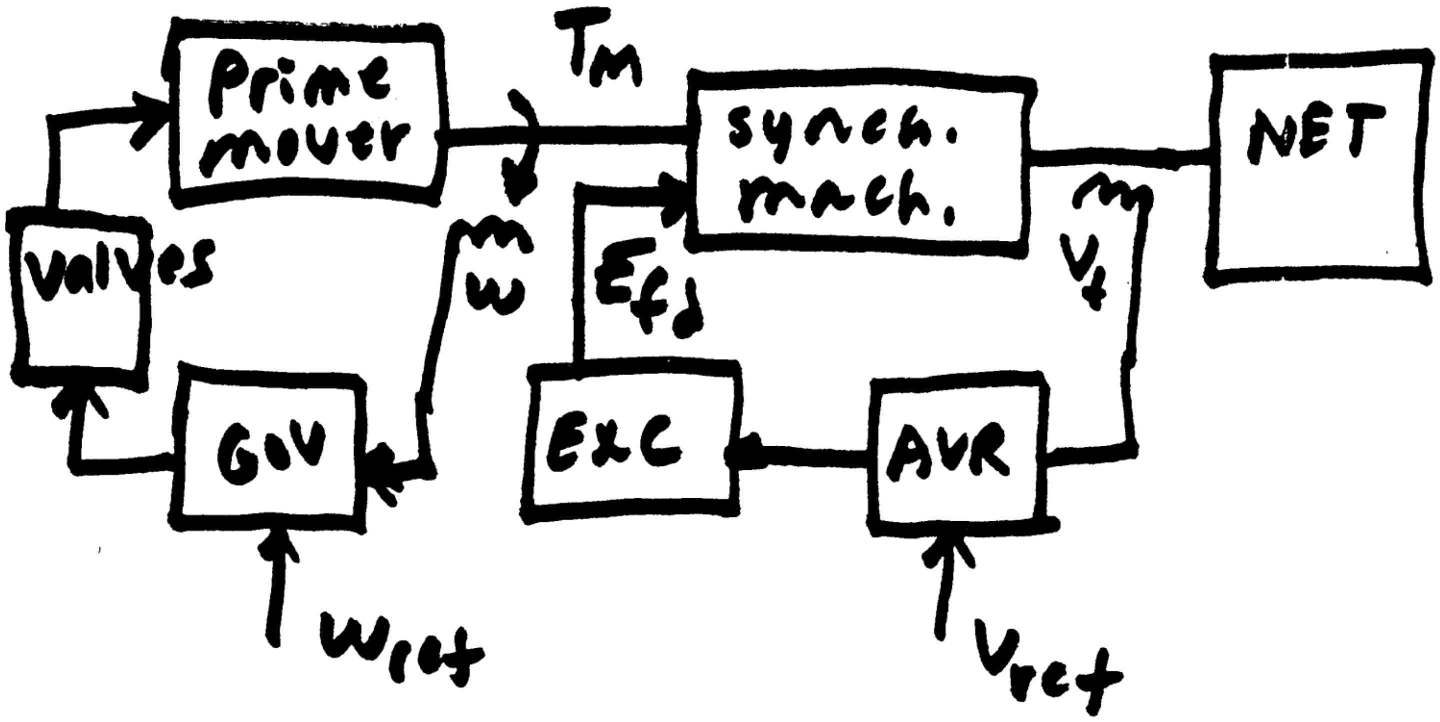
Easy Paper Suggestion (Done by Birchfield in 2017 GM)!

GenRou, GenTPF, GenTPJ

Figure compares gen 4 reactive power output for the 0.1 second fault



Voltage and Speed Control



(P, θ) (Q, V)

Exciters, Including AVR

- Exciters are used to control the synchronous machine field voltage and current
  - Usually modeled with automatic voltage regulator included
- A useful reference is IEEE Std 421.5-2016
  - Just updated from the 2005 edition!
  - Covers the major types of exciters used in transient stability
  - Continuation of standard designs started with "Computer Representation of Excitation Systems," IEEE Trans. Power App. and Syst., vol. pas-87, pp. 1460-1464, June 1968
- Another reference is P. Kundur, *Power System Stability and Control*, EPRI, McGraw-Hill, 1994
  - Exciters are covered in Chapter 8 as are block diagram basics

Functional Block Diagram

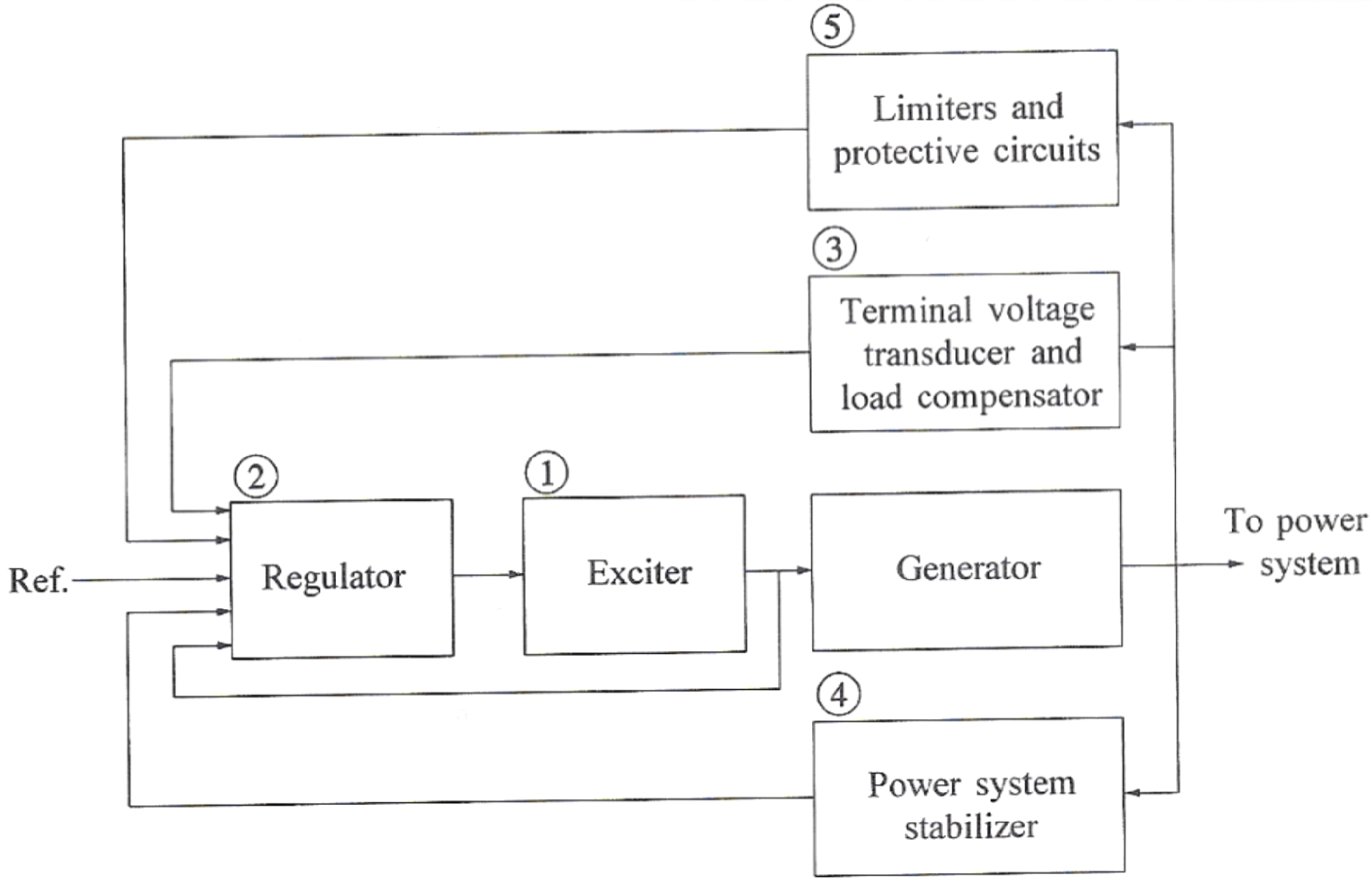


Image source: Fig 8.1 of Kundur, *Power System Stability and Control*

Types of Exciters

- None, which would be the case for a permanent magnet generator
  - primarily used with wind turbines with ac-dc-ac converters
- DC: Utilize a dc generator as the source of the field voltage through slip rings
- AC: Use an ac generator on the generator shaft, with output rectified to produce the dc field voltage; brushless with a rotating rectifier system
- Static: Exciter is static, with field current supplied through slip rings