Improved Treatment of Saturation in a Synchronous Machine Model: GENTPW

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Background

- Quincy Wang (B.C. Hydro) and Jamie Weber (PowerWorld) have been discussing GENTPW model
  - Quincy was having trouble with the dynamic response of some particular machine tests
  - GENTPJ was not capturing some dynamic behavior
- Steve Yang and Dmitry Kosterev at BPA sponsored work on running tests with a modified new synchronous machine model GENTPW
  - Can it better match machine tests in both steady state and dynamic response?
  - Saurav Mohapatra did this work at PowerWorld Corporation

Summary of GENTPW model

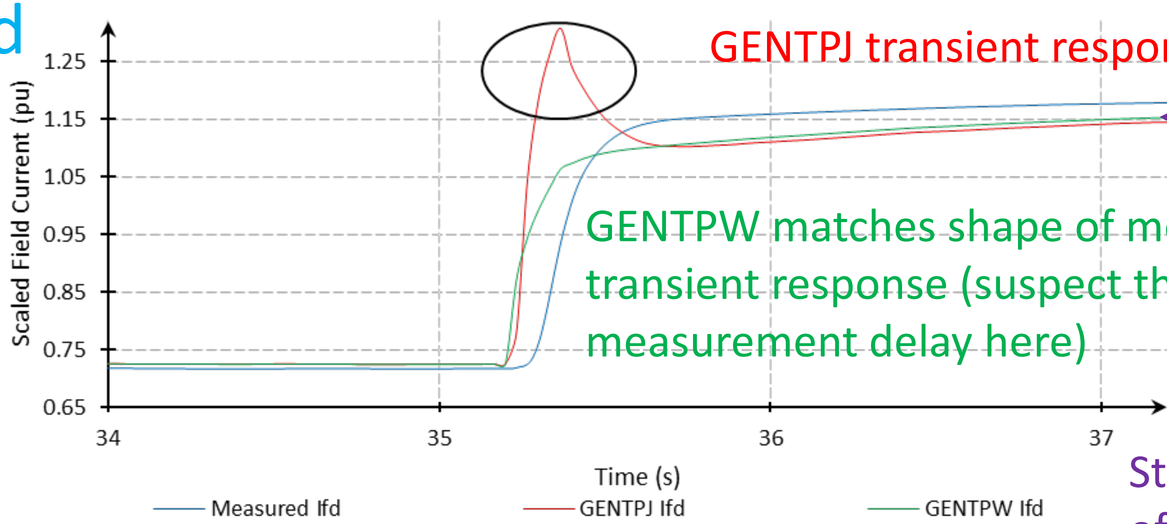
- GENTPW model is available in PowerWorld Simulator Version 20
  - Intended to be used for synchronous machines that are either round rotor or salient pole
  - Has same parameter list as GENTPJ
- Changes the dynamic equations
  - Applies similar concept for saturation used in network boundary equation of GENTPF/GENTPJ
  - Applies concepts directly to the original GENROU model
- Changes the saturation function
  - Additional scaling between d/q axis saturation is applied to *input* to saturation function

Summary of GENTPW Test Results

- Steady state characteristics of GENTPW are very similar to GENTPJ
  - GENTPJ was desirable because it better matched steady state tests and measurements for field current and field voltage
  - We won't present a bunch of plots showing these are the same at steady state.
- Dynamic response of GENTPW better matches test data as compared to GENTPJ
  - Notably better trend of field current transient during Mvar trip tests
  - Next slide shows this
- WECC interconnection dynamic simulation shows a similar trend

Dynamic Response: Reactive Power Trip Tests

Measured
GENTPJ
GENTPW



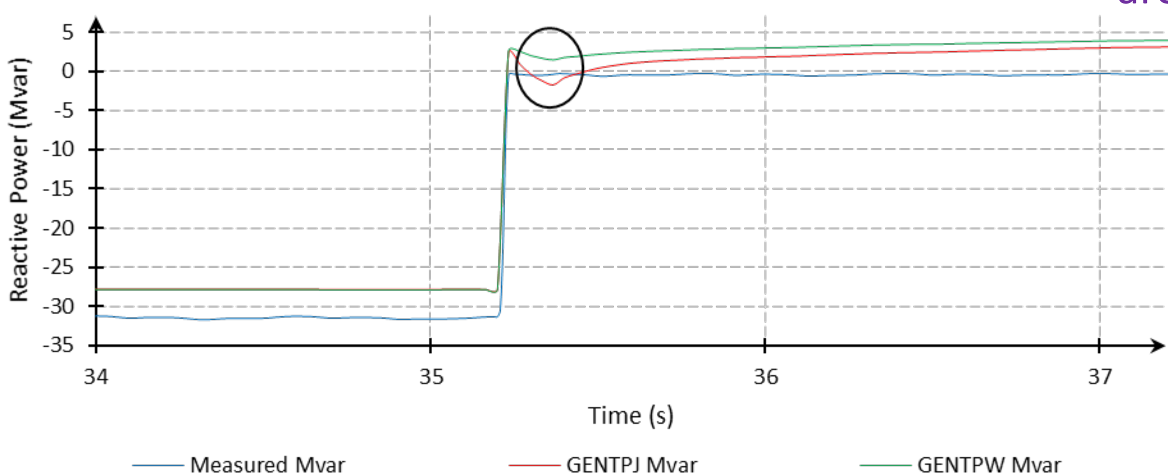
GENTPJ transient response doesn't match

GENTPW matches shape of measured transient response (suspect there is measurement delay here)

Steady State Response of GENTPW and GENTPJ are very similar

Trip to 0.0 Mvar

Initial Mvar



Applying Saturation to the Dynamic Equations

- Bringing treatment of network equations of GENTPF/GENTPJ into the dynamic equations
  - From machine design and analysis, these are the reactance values that saturate: X_{md}, X_{fd}, X_{1d}, and X_{mq}, X_{1q}, X_{2q}
  - Assume leakage reactance does NOT saturate: X_l
  - In transient stability, we use transformed constants: X_d, X_d', X_d'', and X_q, X_q', X_q''
  - GENTPF/GENTPJ used following in network boundary equations

$$X''_{dsat} = \frac{X''_d - X_l}{Sat_d} + X_l \qquad X''_{qsat} = \frac{X''_q - X_l}{Sat_q} + X_l$$

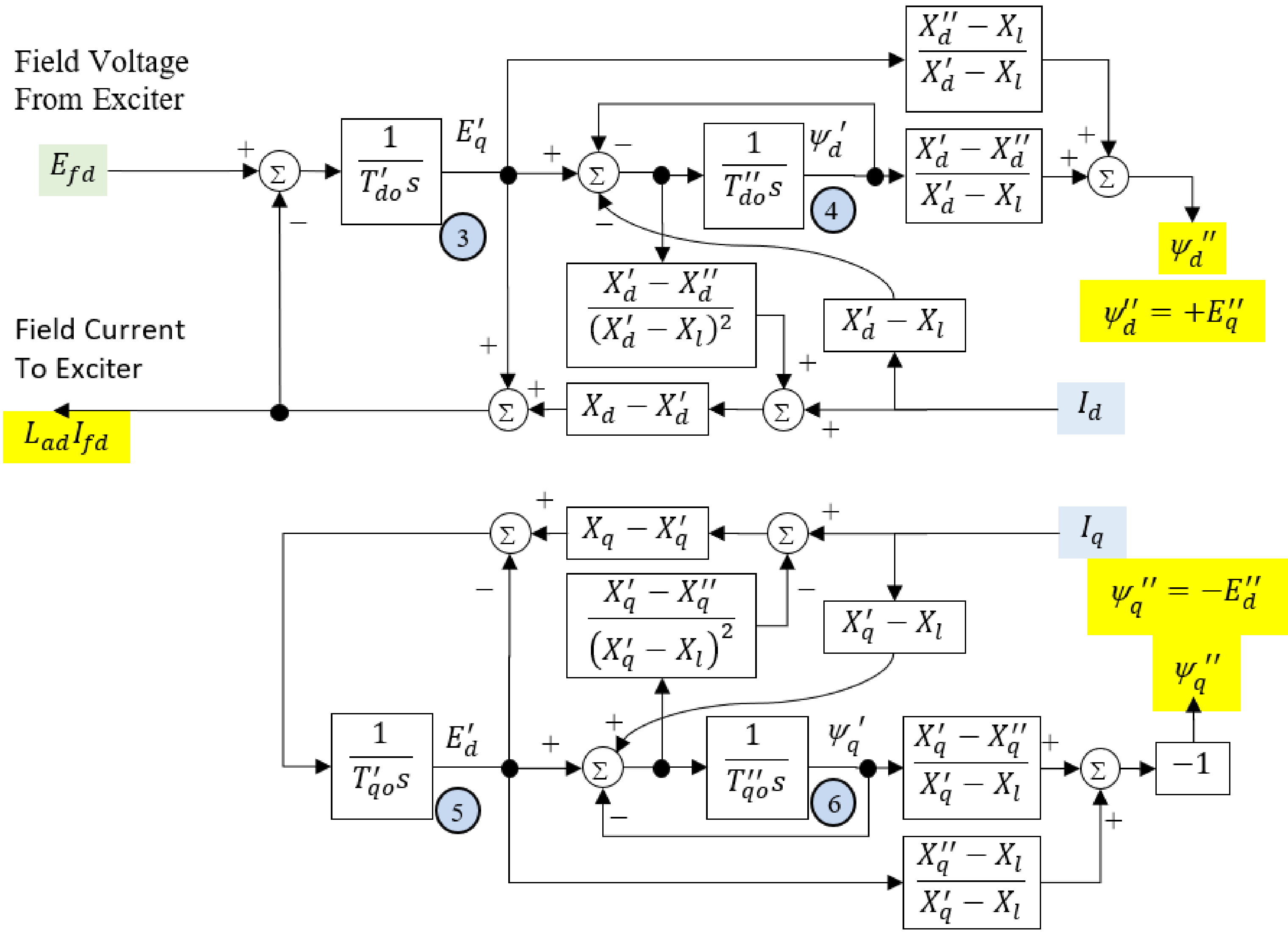
  - Bottom line is that we think the dynamic behavior of GENPTF/GENTPJ could be improved for Quincy

GENTPW – Extend concept used in GENTPJ algebraic network equations

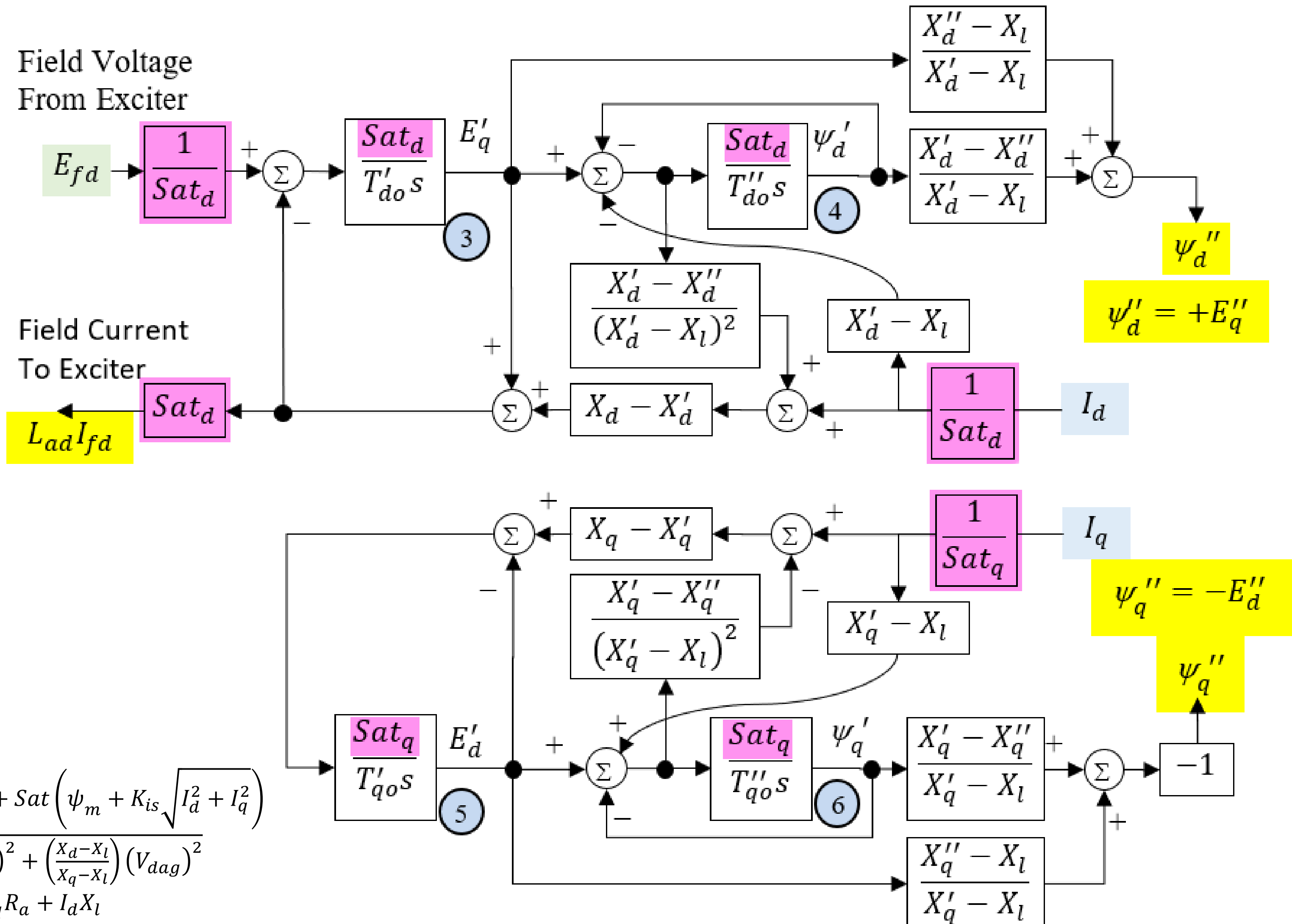
	d-axis	q-axis
Reactance Values	$X''_{dsat} = \frac{X''_d - X_l}{Sat_d} + X_l$ $X'_{dsat} = \frac{X'_d - X_l}{Sat_d} + X_l$ $X_{dsat} = \frac{X_d - X_l}{Sat_d} + X_l$	$X''_{qsat} = \frac{X''_q - X_l}{Sat_q} + X_l$ $X'_{qsat} = \frac{X'_q - X_l}{Sat_q} + X_l$ $X_{qsat} = \frac{X_q - X_l}{Sat_q} + X_l$
Time Constants (are a function of reactance values)	$T'_{dosat} = \frac{T'_{do}}{Sat_d}$ $T''_{dosat} = \frac{T''_{do}}{Sat_d}$	$T'_{qosat} = \frac{T'_{qo}}{Sat_q}$ $T''_{qosat} = \frac{T''_{qo}}{Sat_q}$
Exciter Interface Signals	$E_{fdsat} = \frac{E_{fd}}{Sat_d}$ $X_{mdsat} I_{fd} = (X_{dsat} - X_l) I_{fd} = \frac{X_d - X_l}{Sat_d} I_{fd}$	

White paper referenced on last slide has more detailed analysis of why this is appropriate

GENROU Block Diagram Without Saturation



GENTPW Block Diagram
After a bunch of Algebra



$$Sat_d = Sat_q = 1 + Sat\left(\psi_m + K_{is}\sqrt{I_d^2 + I_q^2}\right)$$

$$\psi_m = \frac{1}{1+\omega}\sqrt{(V_{qag})^2 + \left(\frac{X_d - X_l}{X_q - X_l}\right)(V_{dag})^2}$$

$$V_{qag} = V_{qterm} + I_q R_a + I_d X_l$$

$$V_{dag} = V_{dterm} + I_d R_a - I_q X_l$$

Network and Torque Equations

- GENTPW uses identical formulation as GENPTJ/GENTPF

$$X''_{dsat} = \frac{X''_d - X_l}{Sat_d} + X_l$$

$$X''_{qsat} = \frac{X''_q - X_l}{Sat_q} + X_l$$

<u>Network Interface</u>

$$V_{dterm} = V_d - R_a I_d + X''_{qsat} I_q$$

$$V_{qterm} = V_q - X''_{dsat} I_d - R_a I_q$$

<u>Torque Equation</u>

$$\psi_q = \psi_q'' - I_q X''_{qsat}$$

$$\psi_d = \psi_d'' - I_d X''_{dsat}$$

$$T_{elec} = \psi_d I_q - \psi_q I_d$$

$$\dot{\delta} = \omega * \omega_0$$

$$\dot{\omega} = \frac{1}{2H}\left(\frac{P_{mech} - D\omega}{1+\omega} - T_{elec}\right)$$

Note: $X''_{dsat} <> X''_{qsat}$, so you must implement equations directly in software and not use circuit equation as was done for GENROU

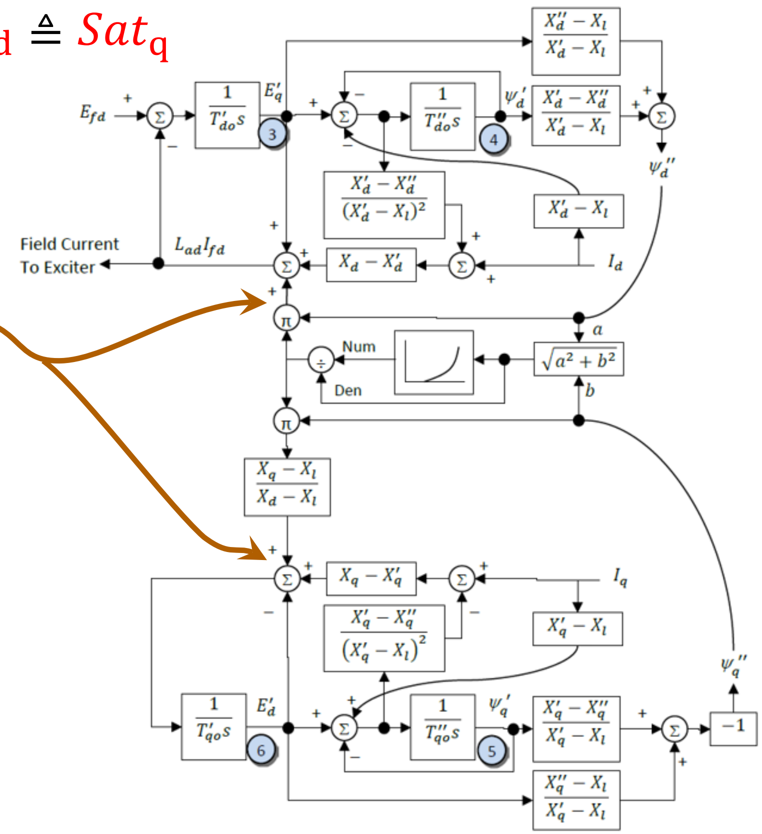
- For GENROU, this is simplified by assuming $X''_d = X''_q$ and not saturating this reactance

Saturation Assumption in GENROU

- Same degree of saturation on d and q-axis

$$\frac{X_q - X_l}{X_d - X_l} = \frac{\mathrm{X_{mq}}}{\mathrm{X_{md}}} \triangleq \frac{\mathrm{X_{mqsat}}}{\mathrm{X_{mdsat}}} = \frac{\mathrm{X}_{mq}\ Sat_d}{Sat_\mathrm{q}\ \mathrm{X}_{md}} \Rightarrow Sat_\mathrm{d} \triangleq Sat_\mathrm{q}$$

- This is same assumption used in GENROU
  - Saturation Term in GENROU is done with *addition* of flux
  - We want ratio of fluxes to remain $\frac{X_{mq}}{X_{md}}$.
  - Thus the additional terms must be scaled by factor which was used
- In GENTPW saturation is applied by using multiplication on the reactance terms
  - Scaling on output not needed



Limitation – Only have open-circuit magnetization saturation curve

- Same Assumption as GENROU:

$$\frac{X_q - X_l}{X_d - X_l} = \frac{X_{mq}}{X_{md}} \triangleq \frac{X_{mqsat}}{X_{mdsat}} = \frac{X_{mq}\ Sat_d}{Sat_q\ X_{md}} \Rightarrow Sat_d \triangleq Sat_q$$

- DOES mean that both X_{md} and X_{mq} saturate to the same extent
- DOES NOT require that ψ_{md} and ψ_{mq} contribute equally towards the degree of saturation
  - More discussion on next two slides

Scaled Saturation Function – What should be the input variable?

- Input Variable= $\|\bar{\psi}_{\mathrm{m}}\|$
- Trick used when only d-axis saturation curve is available
  - Widely researched and now accepted as the right way

$$\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}}\psi_{\mathrm{mq}}$$

$$= X_{\mathrm{md}}I_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}}X_{\mathrm{mq}}I_{\mathrm{mq}}$$

$$= X_{\mathrm{md}}\left[I_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{mq}}}{X_{\mathrm{md}}}}I_{\mathrm{mq}}\right]$$

$$\bar{I}_{\mathrm{m}} \triangleq I_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{mq}}}{X_{\mathrm{md}}}}I_{\mathrm{mq}}$$

This choice means that $\bar{\psi}_{\mathrm{m}} = X_{\mathrm{md}}\bar{I}_{\mathrm{m}}$

X_{md} shows up as a linear factor relating $\bar{\psi}_{\mathrm{m}}$ and $\bar{I}_{\mathrm{m}}$

Hence, d-axis saturation curve can be used for both axes

INCORRECT

$$\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + j\psi_{mq}$$

$$\bar{I}_{\mathrm{m}} \triangleq I_{\mathrm{md}} + \mathrm{j}\frac{X_{\mathrm{mq}}}{X_{\mathrm{md}}}I_{\mathrm{mq}}$$

OR

$$\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}\psi_{\mathrm{mq}}$$

$$\bar{I}_{\mathrm{m}} \triangleq I_{\mathrm{md}} + \mathrm{j}I_{\mathrm{mq}}$$

- References dating back from **1991, 1998, 2013**

A. L Pierrat, E Dejaeger, MS Garrido, “Models unification for the saturated synchronous machines,” - *International conference on Evolution and modern and Modern Aspects of Synchronous Machines*, **1991**

B. E. Levi, “State-space d-q axis models of saturated salient pole synchronous machines,” in *IEE Proceedings - Electric Power Applications*, vol. 145, no. 3, pp. 206-216, May **1998**. doi: 10.1049/ip-epa:19981786

C. F. Therrien, L. Wang, J. Jatskevich and O. Wasynczuk, "Efficient Explicit Representation of AC Machines Main Flux Saturation in State-Variable-Based Transient Simulation Packages," in *IEEE Transactions on Energy Conversion*, vol. 28, no. 2, pp. 380-393, June **2013**.

Scaled Saturation Function – What should be the input variable?

- $x = \|\bar{\psi}_{\mathrm{m}}\|$, where $\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}}\psi_{\mathrm{mq}}$
- Compare with : $\bar{\psi}_{\mathrm{ag}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\psi_{\mathrm{mq}}$
  - One of the **INCORRECT** transformations (reference B)
  - E. Levi, "State-space d-q axis models of saturated salient pole synchronous machines," in *IEE Proceedings - Electric Power Applications*, vol. 145, no. 3, pp. 206-216, May **1998**.
- If $X_{\mathrm{mq}} < X_{\mathrm{md}} \Rightarrow \sqrt{\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}} > 1$

  i.e. Contribution of ψ_{mq} towards saturation is amplified

INCORRECT

$$\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + j\psi_{mq}$$
$$\bar{I}_{\mathrm{m}} \triangleq I_{\mathrm{md}} + \mathrm{j}\frac{\mathrm{X_{mq}}}{\mathrm{X_{md}}}I_{\mathrm{mq}}$$

OR

$$\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}\psi_{\mathrm{mq}}$$
$$\bar{I}_{\mathrm{m}} \triangleq I_{\mathrm{md}} + \mathrm{j}I_{\mathrm{mq}}$$

- Pierrat, Levi, Wasynczuk: Machines background
  - Determining rotor position accurately is VERY important for controlling machines
  - Drove the work to calculate I_{fd} accurately during saturation

Algebra to get input to Saturation Function

- $\bar{\psi}_{\mathrm{m}} \triangleq \psi_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{md}}}{X_{\mathrm{mq}}}}\psi_{\mathrm{mq}} = \psi_{\mathrm{md}} + \mathrm{j}\sqrt{\frac{X_{\mathrm{d}}-X_l}{X_{\mathrm{q}}-X_l}}\psi_{\mathrm{mq}}$
- $\psi_{\mathrm{md}} = \psi_{dag} = \frac{V_{dag}}{1+\omega}$ (air gap flux on d axis)
- $\psi_{\mathrm{m}q} = \psi_{\mathrm{qag}} = \frac{V_{qag}}{1+\omega}$ (air gap flux on q axis)
- $\psi_{\mathrm{m}} = \sqrt{\left(\psi_{\mathrm{dag}}\right)^2 + \left(\sqrt{\frac{X_{\mathrm{d}}-X_l}{X_{\mathrm{q}}-X_l}}\psi_{qag}\right)^2} = \sqrt{\left(\frac{V_{dag}}{1+\omega}\right)^2 + \left(\sqrt{\frac{X_{\mathrm{d}}-X_l}{X_{\mathrm{q}}-X_l}}\frac{V_{qag}}{1+\omega}\right)^2}$
- $\psi_{\mathrm{m}} = \frac{1}{1+\omega}\sqrt{\left(V_{dag}\right)^2 + \frac{X_{\mathrm{d}}-X_l}{X_{\mathrm{q}}-X_l}\left(V_{qag}\right)^2}$

Saturation Function Input

- We continue to add the K_{is} to include additional saturation as the stator current increases
  - $Sat_d = Sat_q = 1 + Sat\left(\psi_m + K_{is}\sqrt{I_d^2 + I_q^2}\right)$
  - $\psi_m = \frac{1}{1+\omega}\sqrt{\left(V_{qag}\right)^2 + \left(\frac{X_d - X_l}{X_q - X_l}\right)\left(V_{dag}\right)^2}$
- Air Gap Voltage Terms can be calculated from circuit equation
  - $V_{qag} = V_{qterm} + I_q R_a + I_d X_l$
  - $V_{dqg} = V_{dterm} + I_d R_a - I_q X_l$

GENTPW Status

- GENTPW is available and released in PowerWorld Simulator Version 20.
  - We believe this model combines the improvements made in GENTPJ with some dynamic behavior that may have been lost
- What you should NOT do
  - All these synchronous machine models (GENROU, GENTPJ, GENTPW) are slightly different
  - Input parameters (X_d, X'_d, X''_d, X_q, X'_q, X''_q, and X_l) are specifically tuned using test data for ONE model type
  - You should not just switch model types and copy parameters over!
- When you should use GENTPW
  - When you do a generator test in the next decade, look at using GENTPW
  - Our expectation is you will have very good success using the manufacture specified reactances with this model

GENTPW Documentation

- This presentation is posted in a knowledge base article on PowerWorld’s website
  - https://www.powerworld.com/files/GENTPW_Presentation.pdf
- Also, a very detailed white-paper is included there that explains how to implement this model in software
  - Initialization is more difficult, but doable
  - Network Boundary Equation is identical to GENTPF/GENTPJ, so nothing new there (that’s still the hard part!)
  - https://www.powerworld.com/files/GENTPW_Software_Implementation.pdf