GENQEJ Saturation Function Problem Inherited from GENTPJ

Analysis of the Kis Factor in Generator Dynamic Model Saturation Functions

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GENTPJ Model: A Disputable Improvement

1991

IEEE Std 1110

Standard 2nd-order equivalent circuit block diagram established.

GENROU / GENSAL

Conventional flux-based saturation, use a potential behind inductance or reactance as input.

2009

GENTPJ

Stator-current-dependent term added to saturation input; retired from WECC in 2022 due to deficiency in dynamic performance.

2020

GENQEC

WECC-approved. Improves field current via linear compensation; conventional saturation input retained.

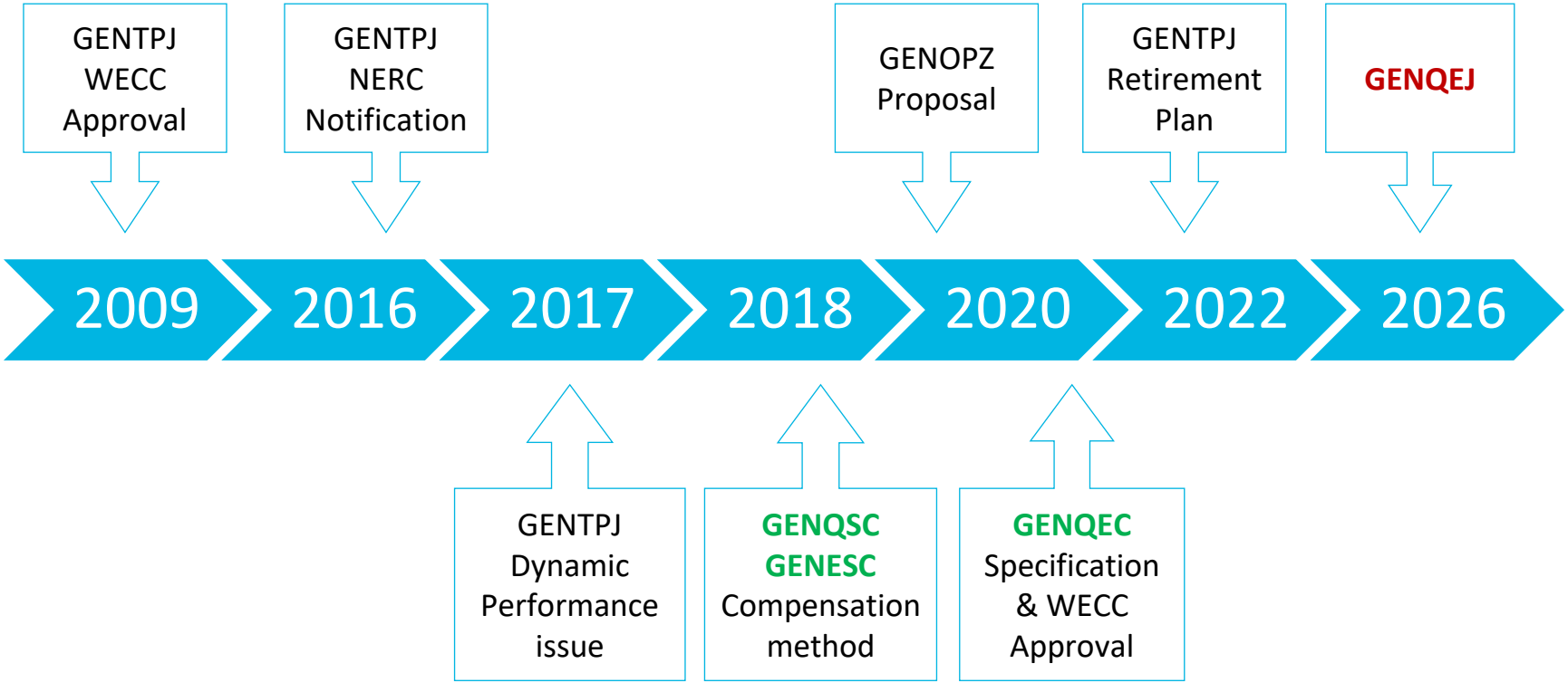
2025

GENQEJ

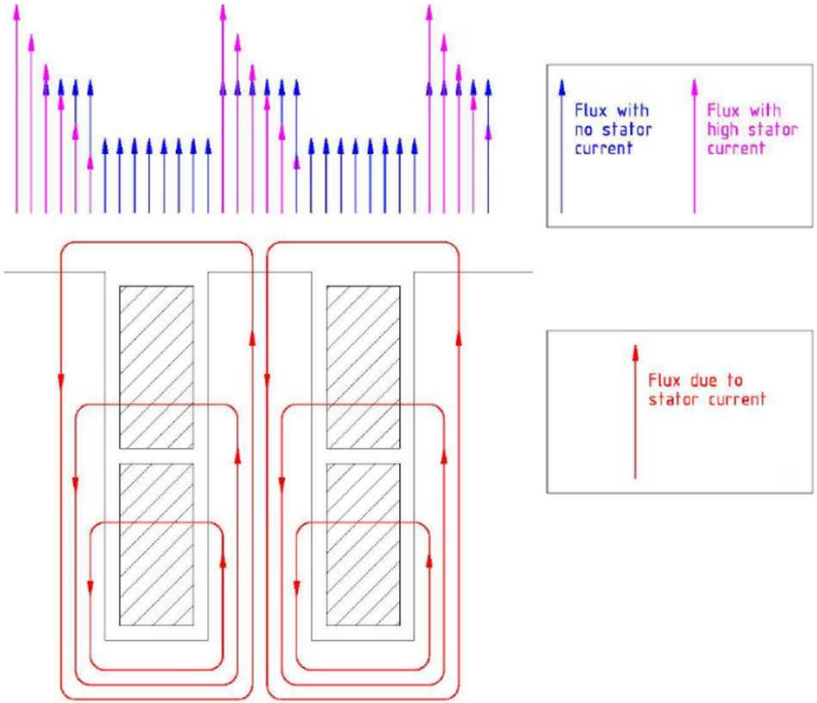
Removes the compensation (the “C”,) in GENQEC model, and reuses GENTPJ’s saturation approach.

The dispute is about mathematical representation of physical phenomenon, not about machine equations.

Development from GENTPJ to GENQEJ



The Physical Concept Justification for K_{is}



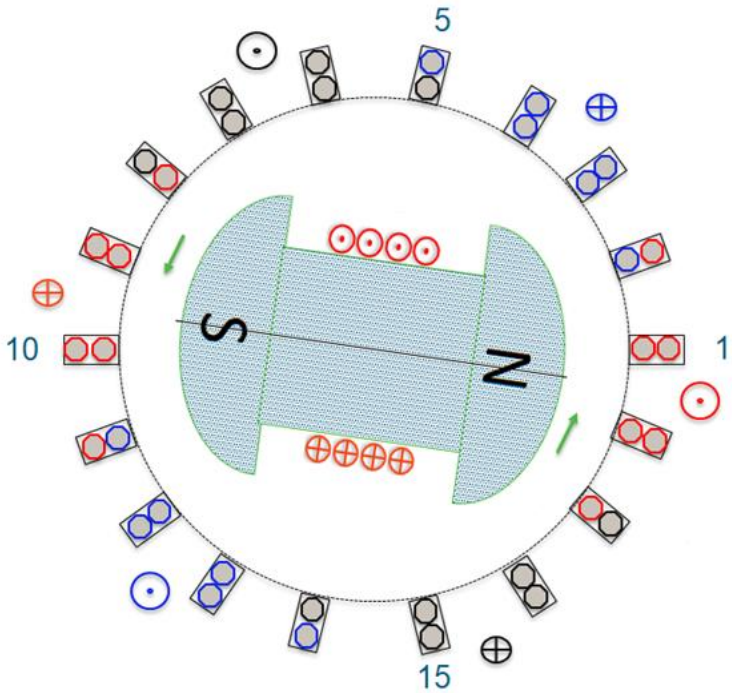
"Stator current increases the degree to which saturation affects the flux crossing the air gap."

— cited justification, being referred to for over a decade [8]

Does this explanation hold across all operating conditions—considering the instantaneous stator current value interacting with the air-gap flux ?

No !

Consistency Check: 0-PF Saturation Characteristic

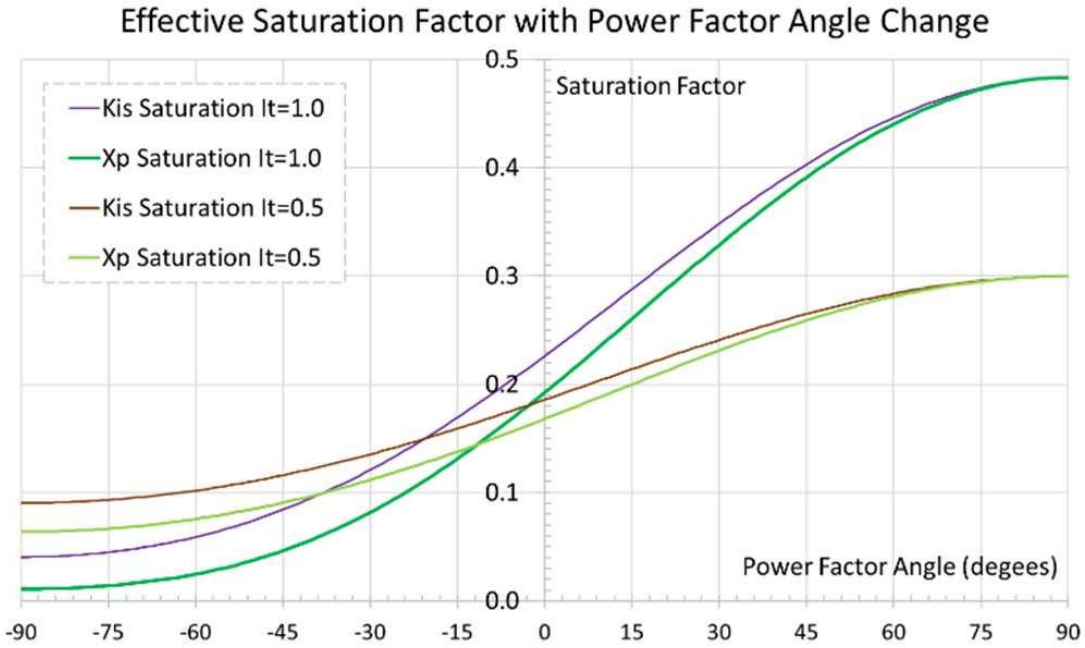


	Potier Reactance	$K_{is} \cdot I_t$ Saturation
Lagging 0-PF	↑ Saturation	↑ Saturation
Leading 0-PF	↓ Saturation	↑ Saturation ⚠ wrong direction

- Stator conductors carry AC. At peak rotor flux at a given tooth, current in the stator conductors adjacent to the tooth depends on power-factor angle and stator winding distribution.
- *At rated current, 0-PF lagging—exactly where load saturation is most pronounced for deriving Potier Reactance [IEEE 115]—the conductor current at that tooth is close to zero.*

The stator current effect illustration on slide 4 does not work!

Comparison With Potier Reactance



Agreement

Tuned at the 0-PF lagging points, where Potier reactance is determined.

Divergence

Largest under under-excited (leading PF) conditions—exactly where the directional error from Slide 11 manifests.

$K_{is}I_t$ has fundamental difference(s) from Potier Reactance.

What should determine saturation?

Air-gap Flux

$$S = f(\psi_{ag})$$

Classical assumption: flux or potential behind leakage reactance, transient reactance, sub-transient reactance, Potier reactance.

Physical concept well-established.

GENTPJ - modified Saturation

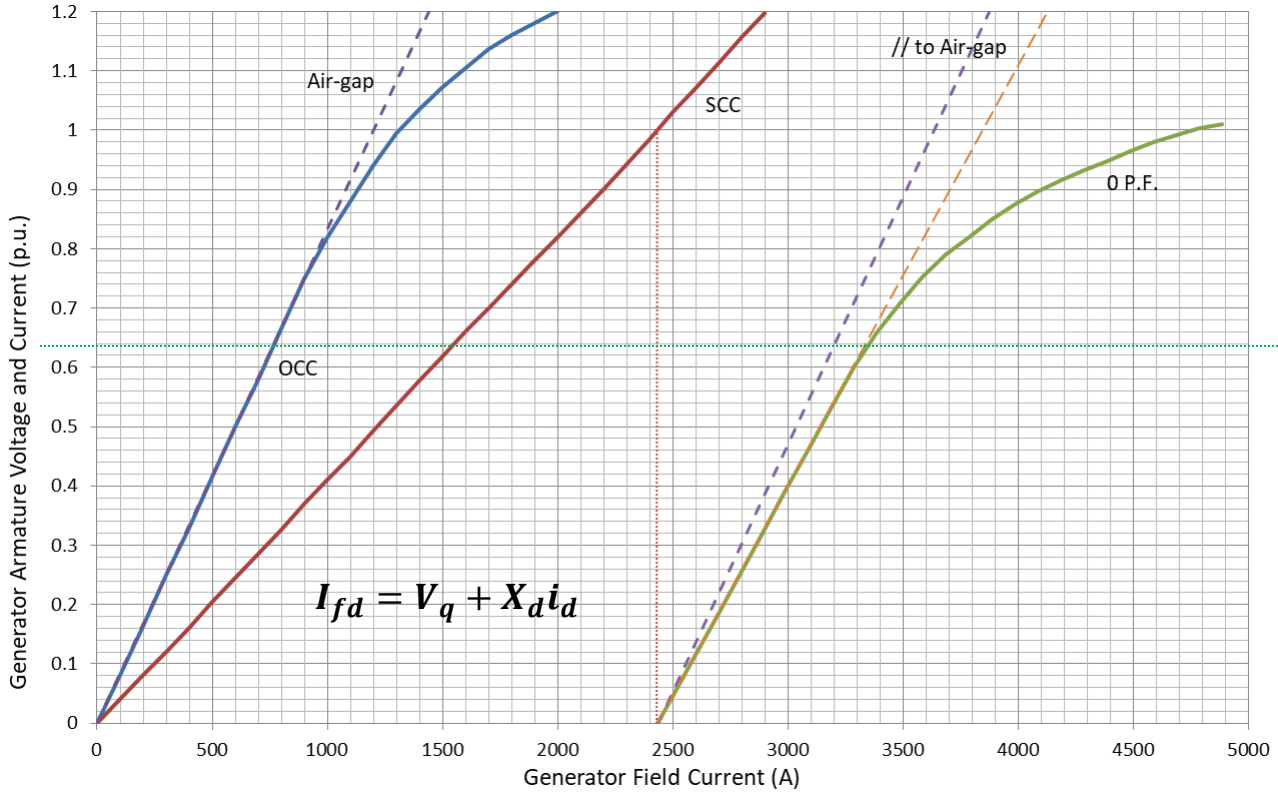
$$S = f(\psi_{ag} + K_{is} I_t)$$

GENTPJ / GENQEJ:
Direction-blind $K_{is}I_t$ term by construction, added to potential behind leakage reactance.

A more mathematical solution than physical ?

ψ_{ag} is the amplitude of a vector/phasor, $K_{is}I_t$ is a scaler regardless of $\dot{I}_t$ direction

Linear Relations of Generator Equations



$$I_{fd} = (1 + S_d)V_q + X_d i_d$$

$$X_d i_d = I_{fd} - (1 + S_d)V_q$$

$$X_d i_d = f(i_d)$$

Linear relationship should be reflected in measurement data when saturation effect is accurately represented.

Evidence From Field Data (Step 1):

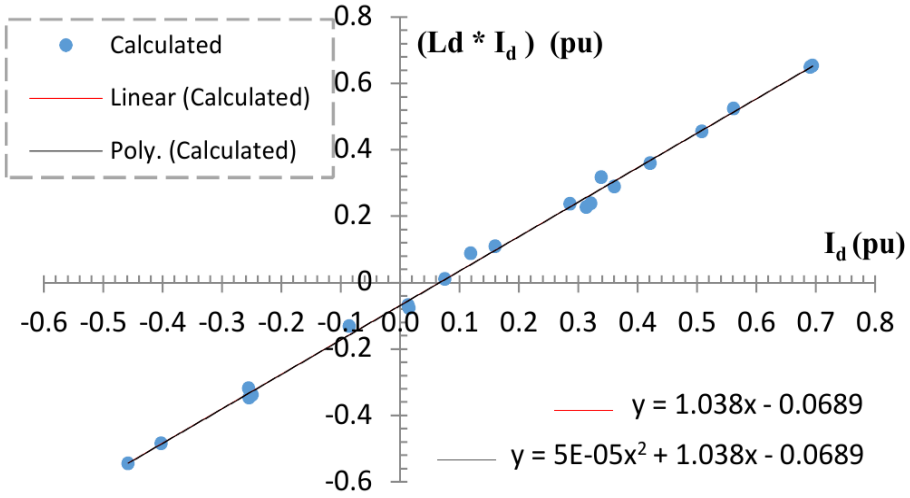


Fig. 7. Adjusting K_{is} Saturation for Ideal Synchronous Inductance

Setup

Salient-pole Unit 1, online measurement data (21 points) [18]. If saturation is properly represented, $(L_d \cdot I_d)$ vs. I_d should be linear through the origin with slope equals to the unsaturated L_d.

What happens with K_{is}

Best-fit K_{is} = 0.0824 gives a good linear fit—but with a nonzero intercept (−0.0689 pu). The plotted linear inductance relationship has no physical reason for a constant offset.

→ **Inconsistency of the modified saturation function: an offset with dimension of impedance,**
- the impact of the $K_{is}I_t$ added to GENTPJ/GENQEJ saturation function

Evidence From Field Data (Step 2):

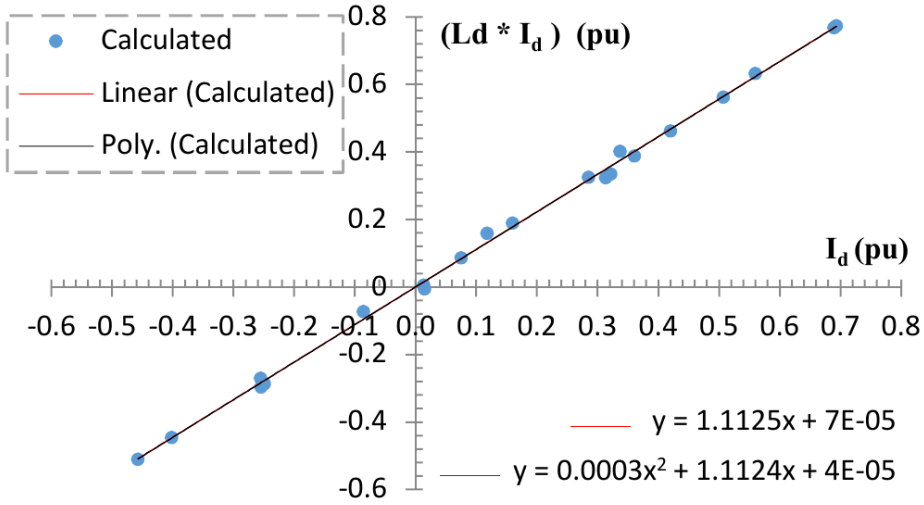


Fig. 8. Adjusting I_{fd_base} for Ideal Synchronous Inductance

The mathematical solution

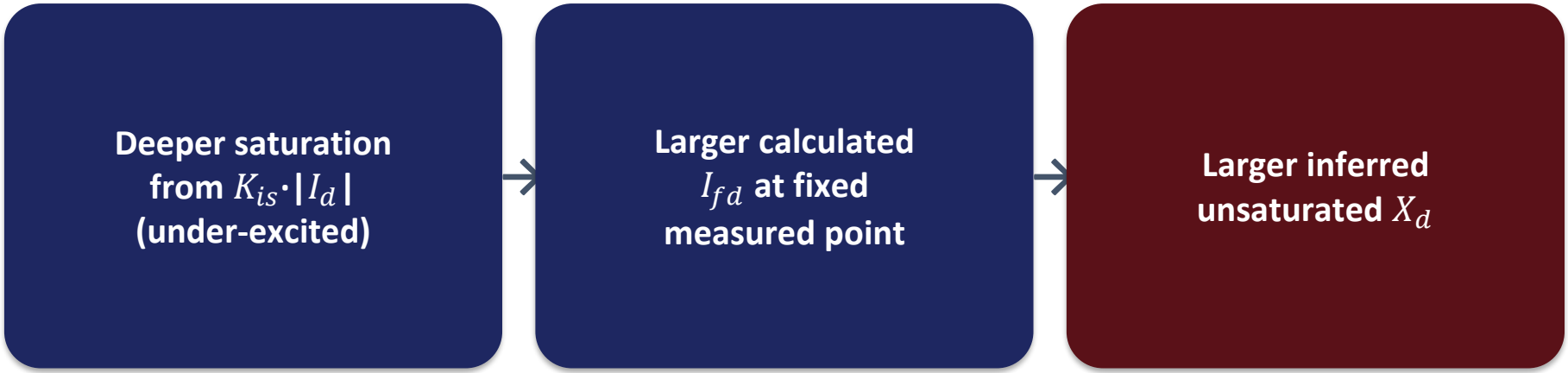
Reduce I_{fd_base} from 468.9 A to 440 A. The offset disappears and the fit looks excellent.

The cost

I_{fd}_base of 468.9 A was derived from this generator's own open-circuit test together with S1.0/S1.2 saturation coefficients. Changing it silently alters the saturation characteristic itself. Accordingly, the fitted L_{afd} would be larger in real measure.

→ Reducing I_{fd_base} numerically increases the per-unit rotor-to-stator mutual reactance. The L_{ad} reciprocal per unit system which the generator models are based on has been altered.

Consequence 1: Larger X_d in Stator Decrement test



Why: at fixed measured (V_t, I_t, I_{fd}), a deeper saturation contribution means a larger X_d must reconcile the steady-state field-current equation. This is consistent with reported validation results for GENQEJ [8].

Model Consistency Check: Unsaturated X_d

Non-reciprocal $I_{fdbase} = L_{adu(pu)} i_{fdbase}$ (reciprocal)

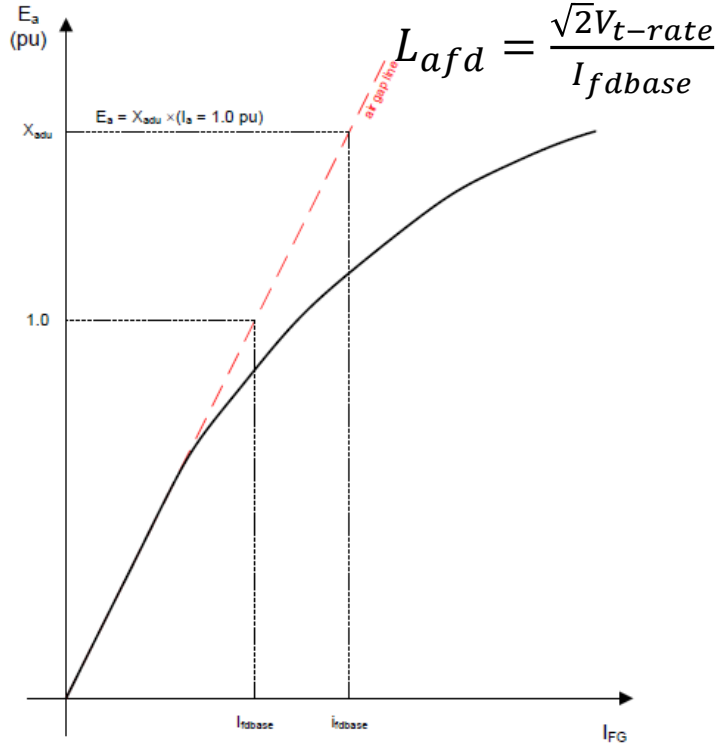
⬇ I_{fdbase} reflects ⬆ L_{afd} in real measure.

The increase of L_{afd} is inversely proportional to the decrease of I_{fdbase}.

In real measurement units $L_{afd} i_{fdbase} = L_{fda} i_{sbase}$ to meet the L_{ad} − reciprocal relation:

$$L_{afd}\, I_{fdbase} = L_{afd} L_{adu(pu)} i_{fdbase}$$
$$= L_{adu(pu)} L_{fda} i_{sbase} = \left[L_{adu(pu)}\right]^2 L_s i_{sbase}$$

$L_{adu(pu)}$ should remain unchanged.



IEEE Std 115-2019 Figure 32

Consequence #2: Continuous, Different Rate of Change

Why |It| breaks smoothness

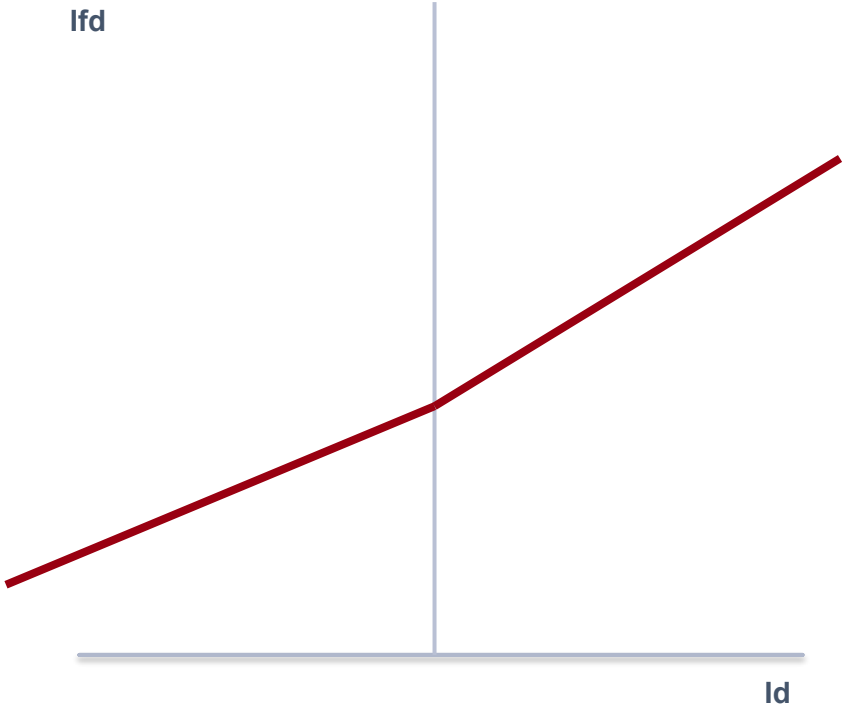
For a saturation function $f_{sat}(x)$ differentiable up to at least 2nd order, on a VEE curve measurement with constant V and P, the 1st order derivative of GENTPJ-modified saturation function with reference to reactive stator current $(I_t \sin\varphi)$, is

$$\frac{\partial f_{sat}(x + K_{is} I_t)}{\partial (I_t \sin\varphi)} = \frac{\partial f_{sat}(x + K_{is} I_t)}{\partial (x + K_{is} I_t)} \frac{\partial (x + K_{is} I_t)}{\partial (I_t \sin\varphi)}$$

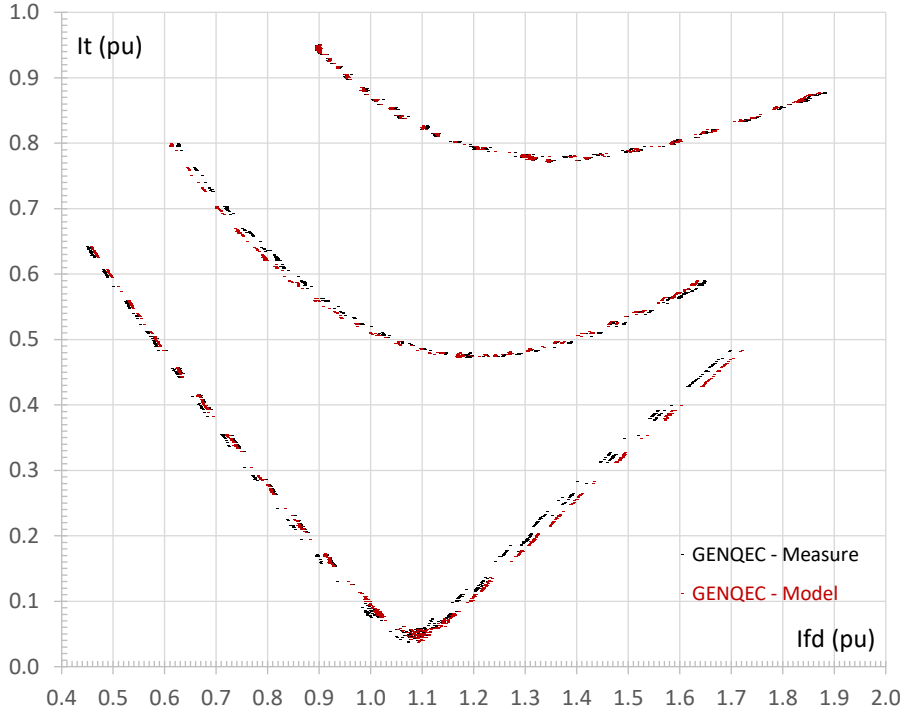
On zero power factor line, $\cos\varphi = 0,\ \sin\varphi = \pm 1$

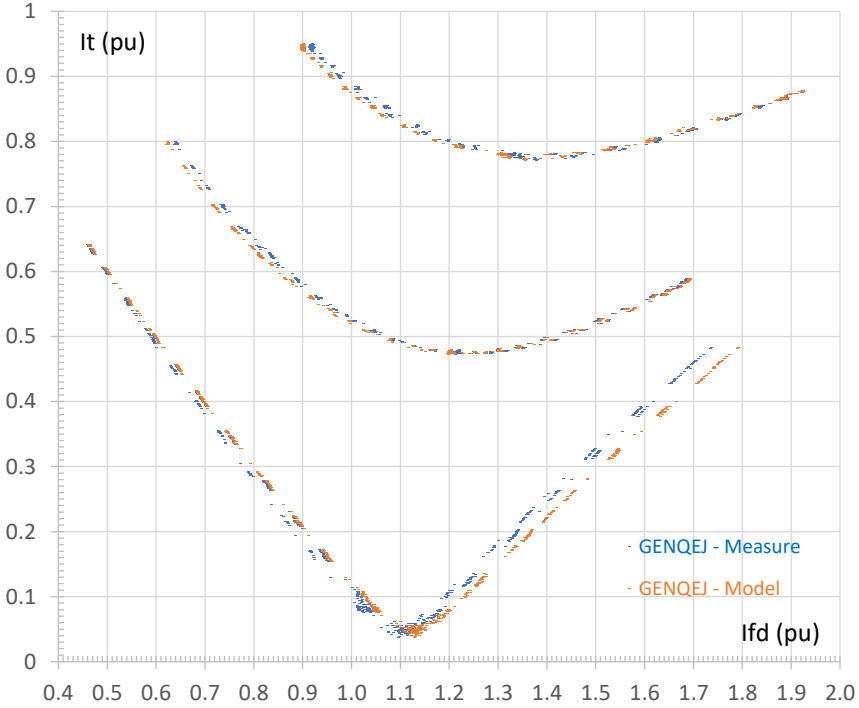
$$\frac{\partial f_{sat}(x + K_{is} I_t)}{\partial (I_t \sin\varphi)} = \frac{\partial f_{sat}(x + K_{is} I_t)}{\partial (x + K_{is} I_t)} \left[\frac{\partial (x)}{\partial (I_t \sin\varphi)} \pm K_{is} \right]$$

with $K_{is} > 0$, GENTPJ and GENQEJ saturation functions return different saturation factors at I_t minimum value, depending on from which side I_t approaches its minimum.



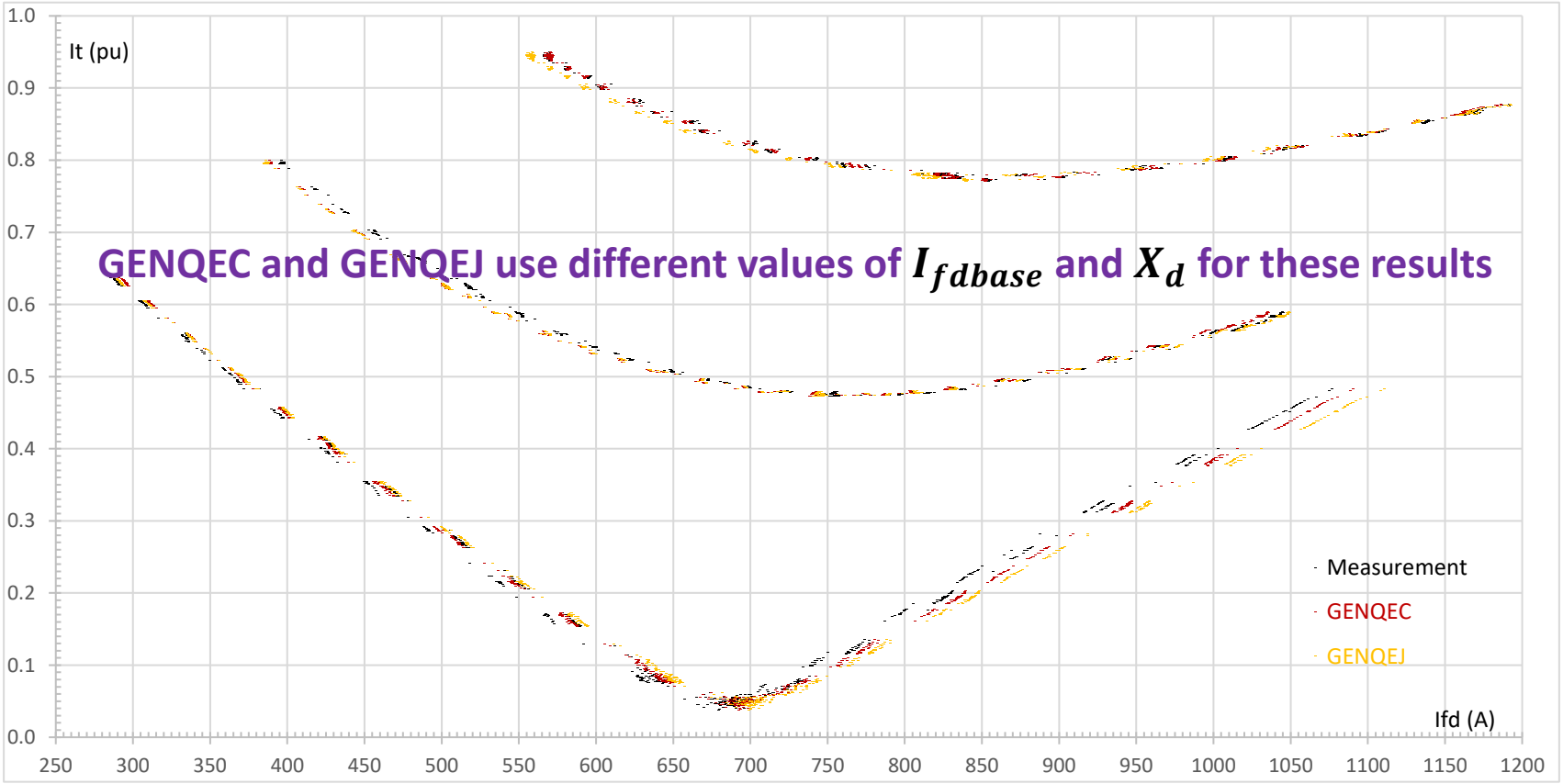
VEE Curve Measurement, different I_{fdbase}



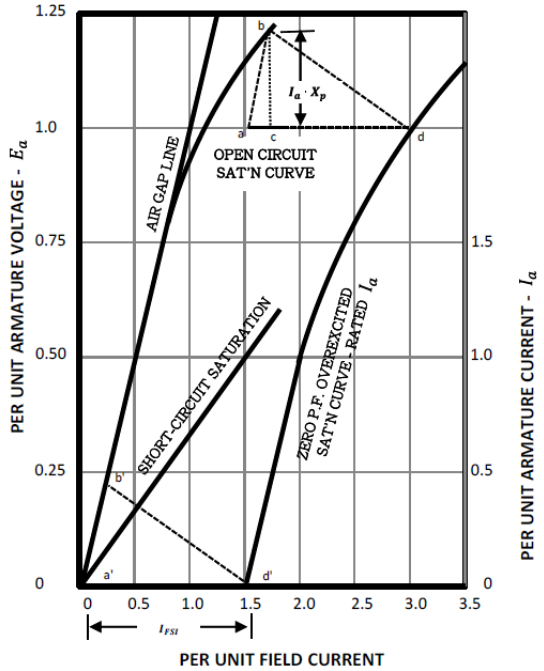


Source Data: Courtesy of Greg Brooks and Carlos Flores of US Army Corps of Engineers, provided on 2024-06-14

VEE Curve, I_{fd} in Real Measurement



Leakage Inductance in Synchronous Machine Model



$$X_{du} = \frac{I_{FSI}}{I_{FG}}$$

$$X_\ell = X_{du} - X_{adu}$$

$$L_{adu} = \frac{V_{LL}}{\sqrt{3} \cdot 2\pi f \cdot I_{fG}} \text{ in Henries}$$

$$L_{afd}\, I_{fdbase} = \left[L_{adu(pu)}\right]^2 L_s i_{sbase}$$

L_{du} can be calculated from X_{du} in per unit and in Henries.

L_l in per unit is the difference between L_{du} and $L_{adu(pu)}$.

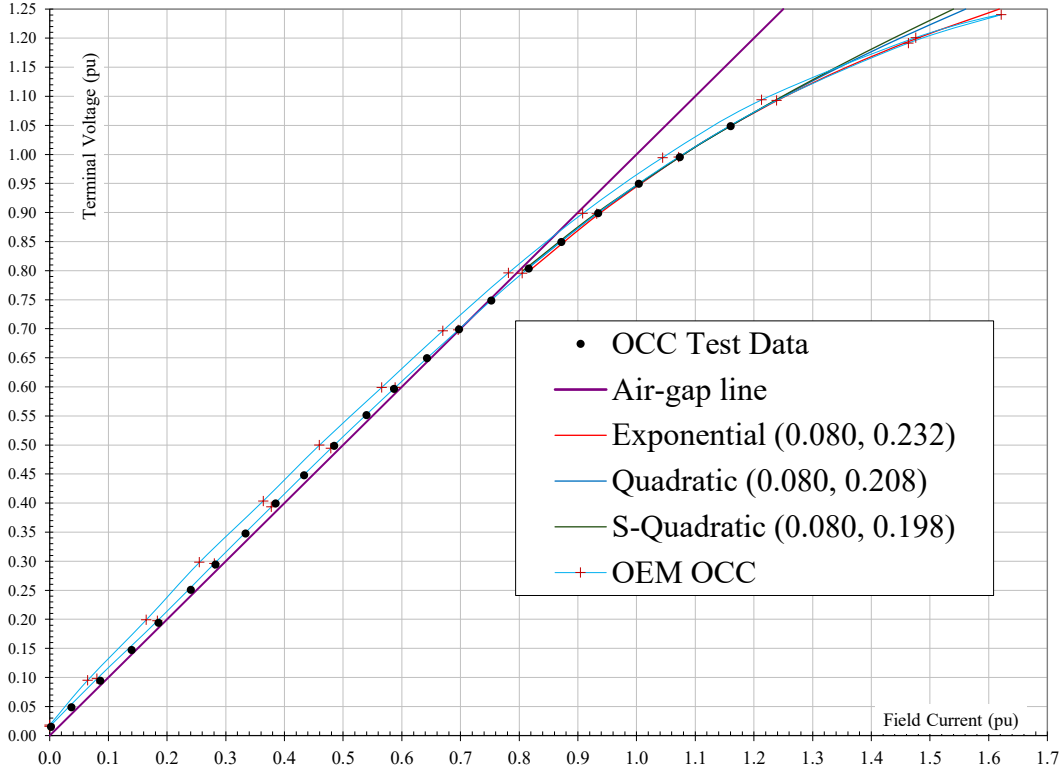
X_l should not be changed without evidence/proof

IEEE Std 115-2019 Figure 16, Section 10.3, Section 6.2.1

Saturation Function Model Accuracy

With OCC Measurements Limited Range

- Fitted $S_{1.2}$ has significant variations across the three saturation function types
- A significant potion of the saturation functions fitted based on 1.0 pu and 1.05 pu voltage points are only “projections” based on assumed mathematic function
- The assumptions of the saturation function will not have a solid foundation without measurement point at higher voltage level(s)



Conclusions for GENTPJ Saturation Modifications

- Departs from Potier Reactance and conventional saturation methods
- Lacks corresponding physical interpretation of the Kis factor
- Alters relationship between generator's physical quantities at certain operating points
- Introduces biased results in generator model parameter validation, for more conservative dynamic simulation results
- Impacts on all generator inductance parameters through the adjustment to rotor field current base value and saturation factor(s)

Thank You !