Modeling Notification

Use of GENTPJ Generator Model

Distribution Date: November 18, 2016

This Modeling Notification describes using the *GENTPJ* generator model as a replacement of the *GENSAL* model for representation of salient pole generators. The *GENTPJ* model recognizes that the inductance coefficients that characterize a generator are affected by load current to a greater extent than is embodied in the *GENSAL* model. Treatment of magnetic saturation in *GENTPJ* allows it to provide more accurate simulation of required field current than is given by the *GENSAL* model. It is recommended to use the *GENTPJ* model for new modeling of salient pole generators and future (re)verification of salient pole generator models. The *GENTPJ* model may also provide improved calculation of field current in comparison with the *GENROU* model in the simulation of round rotor machines. It is noted that it can be appropriate to use *GENTPJ* in place of *GENROU* in situations where overexcitation limiter action, and hence accurate estimation of field current, is an important factor in system performance.

Primary Interest Groups

Generator Owners, Generation Operators, Transmission Operators, Transmission Planners, Planning Coordinators, Reliability Coordinators, MOD-032 Designees

Background

The *GENROU*, *GENSAL*, *GENTPF*, and *GENTPJ* models represent round rotor and salient pole synchronous machines. The predominant difference between the *GENROU*/*GENSAL* and *GENTPF*/*GENTPJ* models is how they account for saturation.

- The *GENSAL* model uses simplifying approximations that significantly compromise treatment of magnetic saturation. The *GENSAL* model ignores saturation on the q-axis completely. In both the *GENROU* and *GENSAL* models, saturation is a single additive terms. The *GENROE* and *GENSAE* models use the same treatments of saturation as *GENROU* and *GENSAL*; the only difference is that they fit saturation with an exponential rather than quadratic curve.
- The *GENTPJ* and *GENTPF* models use approximations in their treatments of saturation, but are more accurate than *GENSAL* and *GENROU*. In these models, saturation is multiplicative on all inductance terms. *GENROU* and *GENTPF* do not fully recognize the effect of stator current on saturation.
- The *GENTPJ*[1] model recognizes the effect of stator current on saturation by including an additional parameter, K_{is}, which appears in the saturation function as shown in [3] and [5].

The modeling improvements made possible by modern computational power as well as more accurate representation of saturation drive the need for industry to transition from using the *GENROU*[2] and *GENSAL*[3] models to the *GENTPJ* model.

[1] The *GENTPJ* model is identical to the *GENTPF* model when K_{is} equal zero.
[2] Or *GENROE*
[3] Or *GENSAE*

Testing in connection with NERC Reliability Standard MOD-026 has revealed that the *GENSAL*, *GENROU*, and *GENTPF* generator dynamic models may significantly underestimate the field current needed to support rated reactive power output of the generator and, consequently, could introduce significant error into simulations where reactive power support is an issue.

Modeling Notification

All recipients of this Modeling Notification that are using the *GENSAL* salient pole generator model or the *GENROU* round rotor generator model are advised to consider using the *GENTPJ* model for new generators and where generator data is to be newly verified or (re)verified.

The following are recommended:

- Upon (re)verification for compliance with the applicable NERC MOD standards[4], it is recommended that the *GENTPJ* model be used to represent salient pole and round rotor machines rather than using the *GENSAL* or *GENROU* models based on the assumptions made to account for magnetic saturation in the machine.
  - Model parameters can be determined and/or verified by original equipment manufacturer (OEM) specifications, baseline testing, or disturbance-based power plant model verification (PPMV). Typically, using the OEM data and then fitting the K_{is} parameter using measured V-curve data tends to yield good results.
- Generator Owners (GOs) are encouraged to consider timely, prioritized (re)verification of generators currently modeled using the *GENSAL* model, and to use the *GENTPJ* model upon (re)verification of these units. *GENSAL* is considered an obsolete model in the *NERC Library of Standardized Dynamic Models*[5].
  - K_{is} should be estimated from V-curve (I_t vs. I_{fd}) data whenever possible. Use of K_{is} more accurately captures the variation of saturation with machine loading. NOTE: V-curve data may not always be easily measured (e.g., where reactive power maneuvering is not possible because of local operating concerns); therefore, it is not required but should be determined whenever possible for more accurate modeling.
- Where round rotor generator data has been verified in relation to the *GENROU* model, the *GENROU* model should be retained. For new generators and where generator data is to be newly (re)verified, GOs are recommended to use the *GENTPJ* model; however, the *GENROU* may be used so long as a suitable match of simulations to the available measured data is achieved[6].
- Planning Coordinators (PCs) and Transmission Planners (TPs) are recommended to put in place modeling data requirements, per MOD-032-1, that disallow new *GENSAL* models from entering any future base cases used for interconnection-wide studies.

[4] Namely, MOD-026 and MOD-027, as applicable.

[5] *NERC Library of Standardized Powerflow Parameters and Standardized Dynamic Models*", NERC, Atlanta, GA, Oct 2015, Online.

[6] Particularly V-curve test results in conjunction with MVAR rejection and open circuit saturation curve test results.

- TPs, PCs, and GOs are recommended to perform disturbance-based power plant model verification (PPMV) on any units regardless of model to ensure that operational performance to grid events can be matched with a modeled response.

Appendix A: Dynamic Parameter Reference List

Table 1 shows the relationship between the dynamic model parameters of *GENTPJ*, *GENSAL*, and *GENROU*[7]. This is provided as a reference between the models, and is not intended for direct conversion.

Table 1: Model Mapping Table for GENTPJ, GENROU, and GENSAL

GENTPJ Parameters	*GENSAL* Parameters	*GENROU* Parameters
T'_{d0}	T'_{d0}	T'_{d0}
T''_{d0}	T''_{d0}	T''_{d0}
T'_{q0}	0	T'_{q0}
T''_{q0}	T''_{q0}	T''_{q0}
H	H	H
D	D	D
X_d	X_d	X_d
X_q	X_q	X_q
X'_d	X'_d	X'_d
X'_q	X_q	X'_q
X''_d	X''_d	X''_d
X''_q	X''_d	X''_d
X_l	X_l	X_l
S(1.0)	S(1.0)	S(1.0)
S(1.2)	S(1.2)	S(1.2)
K_{is}	0	0

Notes:

- In all models, the unsaturated reactances should be specified.
- A round rotor machine (i.e., *GENROU*) can be modeled using the *GENTPJ* model with:
  - T'_{d0}, T''_{d0}, T'_{q0}, $T''_{q0} > 0$; and
  - X_d, X'_d, X''_d, X_q, X'_q, X''_q, $X_l > 0$.
- A salient pole machine (i.e., *GENSAL*) with single amortisseur circuit on each axis can be modeled using the *GENTPJ* model with:
  - $T'_{q0} = 0$;
  - X_d, X'_d, X''_d, X_q, X''_q, $X_l > 0$; and
  - $X'_q = X_q$
- A salient pole machine (i.e., *GENSAL*) without amortisseur circuits can be modeled using the *GENTPJ* model with[8]:

[7] *GENROE* and *GENSAE* model parameters match *GENROU* and *GENSAL*.
[8] Where applicable due to differences in software.

- $T''_{d0} = T''_{q0} = T'_{q0} = 0$;
- $X''_d = X'_d$ and $X''_q = X'_q = X_q$; and
- X_d, X'_d, X_q, X_l, $T'_{d0} > 0$;

Appendix B: Supporting Background Material

B1. Model Performance

Current in the stator of a synchronous machine affects the saturation of its magnetic circuit in two ways:

1. The armature reaction effect modifies the magnitude and rotational position of the fundamental frequency flux wave linking the stator windings; and
2. The slot leakage magnetomotive force modifies the spatial distribution of flux in the stator teeth.

Both effects modify the degree of saturation in the machine. The legacy generator models (i.e., *GENSAL*, *GENROU*, and *GENTPF*) use a variety of approximations to recognize the first of these effects but neglect the second. The *GENTPJ* model recognizes the first effect in the same way as the legacy models and, in addition, introduces an approximate representation of the second.

The error introduced by neglecting the second stator current effect was assumed to be negligible in the legacy models but has been shown by generator testing over the last ten years to be significant. Figure B1 shows an example of test data values and corresponding values calculated by the *GENSAL*, *GENROU*, and *GENTPJ* models for a 163 MVA hydro generator. The generator was run at 2 MW and at 148 MW. Field current was measured as reactive power output was varied from maximum underexcited to maximum overexcited value[9]. Generator terminal voltage varied significantly as reactive power was varied.

Field current values corresponding to the test points were calculated by presenting the measured values of real power, reactive power, and terminal voltage to the generator models; this ensured that the calculated field current values recognized the variation of voltage at the generator terminals. The same generator parameters were used in all three models, with the addition of the new parameter, K_{is}, for *GENTPJ*.

The black curve shows measured field current in per unit. The blue, green are red curves show:

Blue	- Field current calculated by *GENSAL* model
Green	- Field current calculated by *GENROU* model
Magenta	- Field current calculated by *GENTPF* model
Red	- Field current calculated by *GENTPJ* model with a non-zero value of K_{is}

At no load, when the stator current is purely reactive the currents calculated by the four dynamic models are closely clustered. At high output, however, the models give decidedly different results. The *GENSAL* model underestimates the field current by as much as ten percent or, for a given field current, overestimates the reactive power produced by as much as fourteen percent of the generator rated MVA. The green and magenta curves show that the *GENROU* and *GENTPF* models produce nearly equal estimates of field current that are somewhat better than those of *GENSAL* but still significantly in error. The red curve shows the calculation of field current by the *GENTPJ* model when the parameter, K_{is}, is adjusted to give a fair representation of the effect of stator current. K_{is} can always be adjusted to give exact agreement between test and model at a single operating point; the significant aspect of the saturation modeling in *GENTPJ* is that a constant value of K_{is} gives very close agreement over the broad operational range.

[9] Based on prudent, practical engineering judgment and operating experience.

The relative behavior of the four models shown by Figure B1 has been seen, with differences in detail but close overall similarity, for hydro generators ranging in capacity from small (~20 MW) to large (1000+ MW).

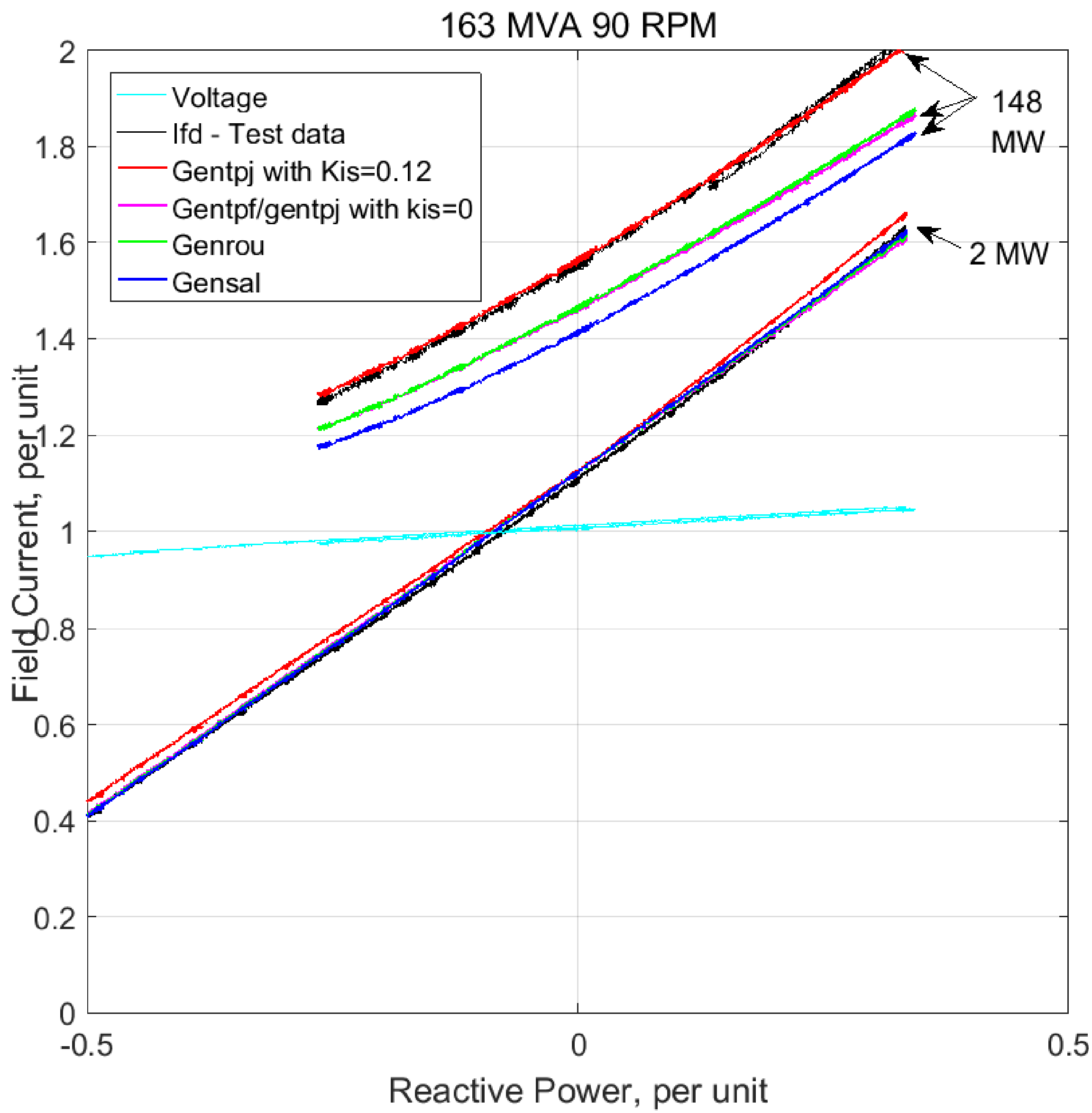

Figure B1. Comparison of Model Performance and Actual Test Data for Low Speed Hydro Unit

While the *GENTPJ* model was developed in connection with the modeling of hydro generators, experience also shows it to be appropriate for representing high speed machines [4]. The relative behavior of the *GENROU* and *GENTPJ* models for a 1,550 MVA 1,800 RPM generator producing 1,448 MW is shown in Figure B2. The same parameters (manufacturer's values) are used for calculation of field current by *GENROU* (green), *GENTPF* (dashed red), and *GENTPJ* (red). The K_{is} parameter was adjusted to achieve good correspondence of calculation with the test data shown by the black curve. As with the hydro generator example, underestimation of field current by the older models is clear.

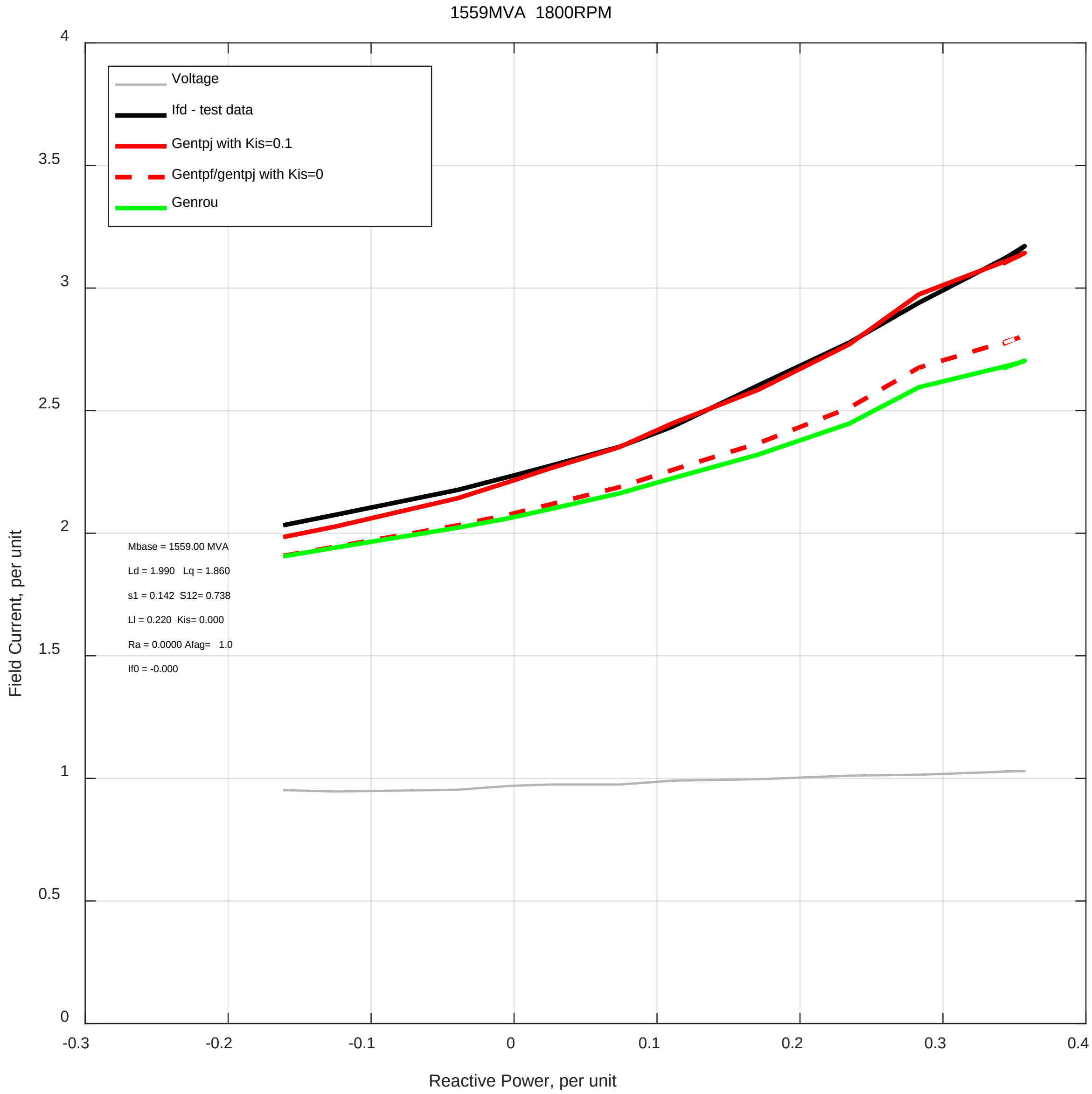

Figure B2. Comparison of Model Performance and Actual Test Data for High Speed Thermal Unit

Experience to date indicates that the underestimation of field current by legacy models is most apparent with hydro generators and of varying degree in high speed machines. As an illustration, Figure B3 shows test and calculated field current for a 234 MVA 3,600 RPM generator. The green curve shows that *GENROU* underestimates field current while *GENTPJ* with appropriately adjusted value of K_{is} gives estimates in close agreement with the test data. The extent of underestimation by *GENROU* in this case is less than in the previous examples; however, the *GENTPJ* model is still a more accurate representation at higher field current.

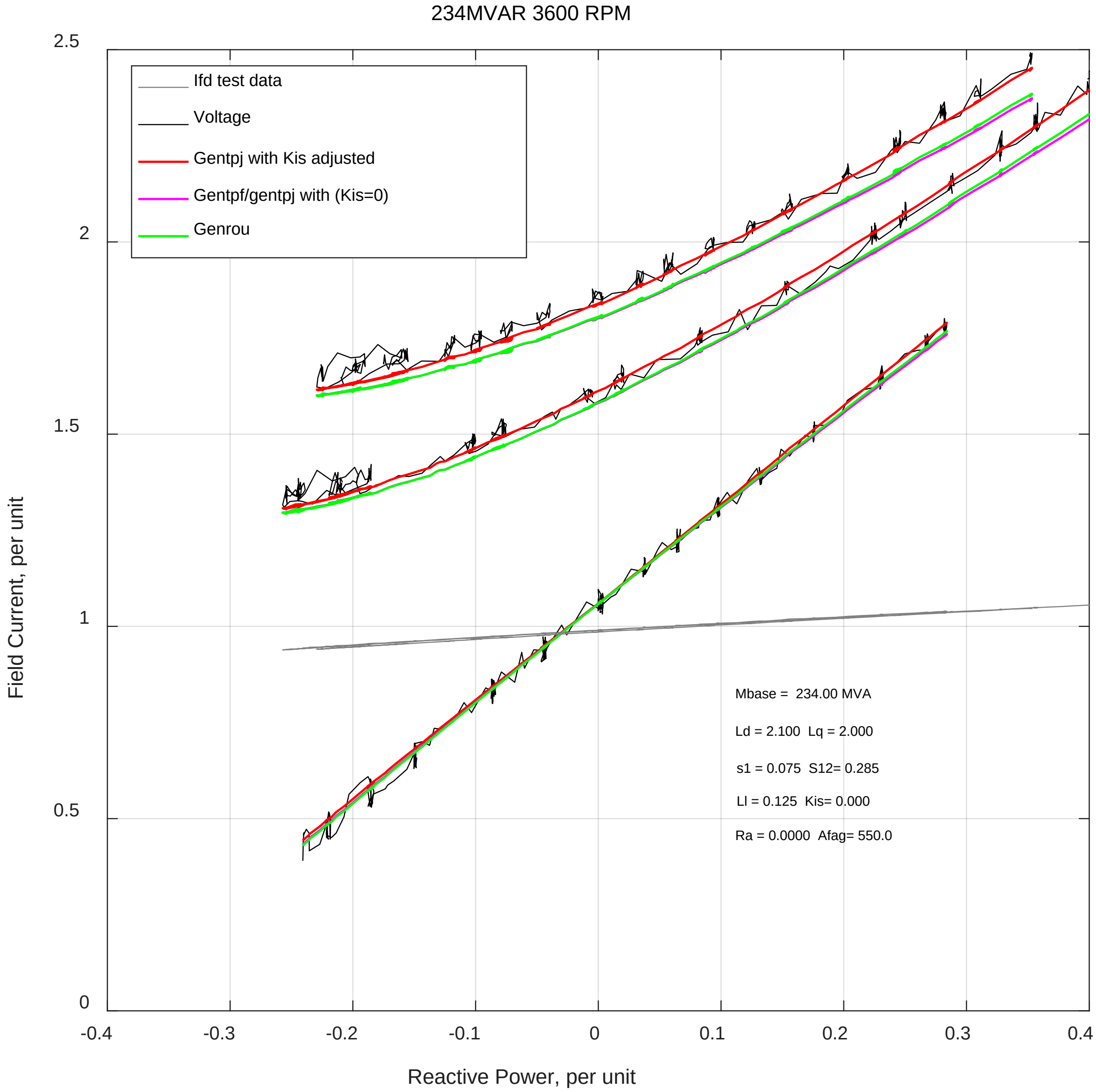

Figure B3. Comparison of Model Performance and Actual Test Data for 3600 RPM Machine

While the difference in results between *GENROU* and *GENTPF* may be small, in most cases there is strong justification to use *GENTPJ* in cases where the value of the stator current saturation parameter, K_{is}, is not known. When K_{is} is unknown *GENTPJ* can be used with $K_{is} = 0$ and then, as values become known from tests or other sources, K_{is} can be updated accordingly. Thus, when benchmark testing is done for compliance with MOD-026 and MOD-027, the resultant modeling should use *GENTPJ*.

B2. Model Internal Details

All of the generator models are interfaced with the electric network solution by means of a voltage source behind a reactance [2, 6, 7]. The exact method of interface however, is a matter of detail[10]. The various models differ mainly in the ways they implement the representation of magnetic saturation.

All of the models describe saturation effects by reference to the open circuit magnetization curve of the generator and, accordingly, all of the models reproduce the open circuit behavior of the machine with the same level of accuracy. For loaded conditions all of the models assume that saturation effects throughout the machine are described by a single saturation function whose shape is that of the open circuit magnetization curve. The differences in the models are in the variable chosen as the input to the saturation function and in the way the resulting saturation function is applied.

- *GENSAL* develops an additive saturation term as a function of the state variable representing direct axis voltage behind direct axis transient impedance. This is a simplification that was necessitated by the limitations of analog computers and was carried over into early digital computer implementations.
- *GENROU* develops an additive saturation term as a function of a "voltage behind subtransient reactance". This mathematically defined voltage is reasonably closely related to the flux linking the machine across the air gap.
- *GENROU* and *GENSAL* recognize variation of the inductance coefficients of the machine implicitly and handle saturation by developing a term to be added on to the field current that is calculated on the basis of the unsaturated inductance coefficients.
- *GENTPF* and *GENTPJ* recognize explicitly that the inductance coefficients of the machine vary in accordance with the saturation function. The input variable to the saturation function is chosen as a mathematically defined voltage behind the leakage reactance of the machine. This voltage is closely related to the flux linking the machine across the air gap. No additive field current term is needed in *GENTPF* and *GENTPJ*.

In *GENTPF* and *GENTPJ*, the input to the saturation function is calculated as

$$E_l + K_{is} I_s$$

where,

E_l: voltage behind stator leakage reactance
I_s: stator current

In *GENTPF*, $K_{is} = 0$ and the contribution of the second stator current effect to saturation is neglected. In *GENTPJ*, K_{is} is non-zero and the contribution of the second stator current effect to saturation is recognized.

The Western Electricity Coordinating Council (WECC) completed conversion to *GENTPJ* from *GENSAL* approximately five years ago. Numerous generator tests have shown that *GENTPJ* provides more accurate

[10] Refer to individual software vendor manual

representation of generator field current versus reactive power, as illustrated in this notification. The need for generator model improvement was identified during model validation studies for the June 14, 2004 Western Interconnection system disturbance, which concluded that the magnetic saturation was not modeled properly leading to the development of *GENTPJ* [1]. This was prior to the applicable NERC MOD Standards taking affect.

B3. Dynamic Simulations

The main effect of changing from legacy models (*GENROU* or *GENTPF*) to *GENTPJ* is that generator field currents corresponding to given generator terminal conditions are increased while the dynamic aspect of generator behavior is little changed.

An illustrative microcosm model (Figure B4) and simulation (Figure B5) help explain this concept. Figure B4 shows the model of a situation where local generation must provide reactive power needed to support nearby load after a transmission outage increases the impedance of the supply path from stronger parts of the grid. Figure B5 shows the response of the generator when one of the two transmission circuits is opened. The red traces are the *GENTPF* model response; the blue traces are the *GENTPJ* model response with K_{is} set to 0.1.

Initially the generator terminal conditions are the same with both the legacy model (*GENTPF*) and with *GENTPJ*. Opening one of the two incoming circuits initiates a voltage drop at the load and a decrease in power inflow from the supporting grid. Loss of the circuit produces an oscillation of real power and greatly increases the reactive power demand on the generator.

The first eight seconds of the plot show that dynamic behavior produced by the two generator models. The active and reactive power response of the two models are similar; however, the *GENTPJ* model requires a significantly greater amount of field current, both in the initial steady-state condition and throughout the transient. Both models produce adequate damping and both call for reactive power output to go to 86MVAR, which is just within the normal capability of the generator.

The importance of the *GENTPJ* model is apparent at the eight second point of the simulation. Higher field current more accurately calculated by the *GENTPJ* model exceeds the pickup setting of the overexcitation limiter; it picks up and at eight seconds times out, taking control of field current. The importance of the *GENTPJ* model, as compared with legacy models, is in capturing the proper relationship between predicted generator excitation requirement and the settings of limiters.

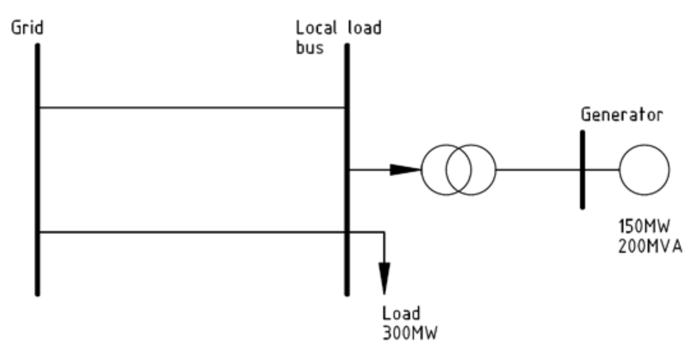

Figure B4. Illustrative Simulation Model

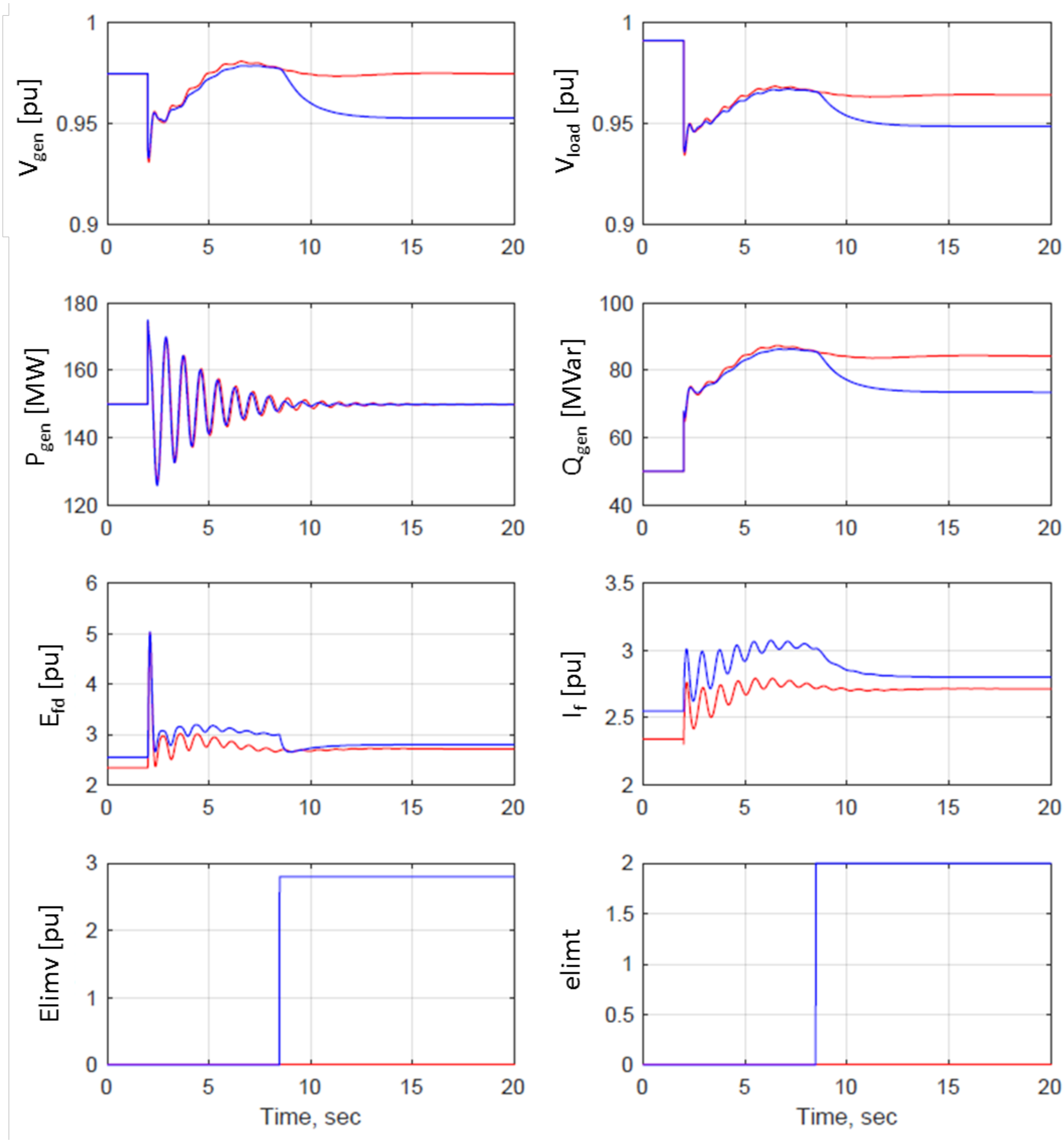

Figure B5. Example of Transient Performance of *GENTPF* and *GENTPJ* Models

References

[1] B. Agrawal, D. Kosterev, “Model Validation Studies for a Disturbance Event That Occurred on June 14 2004 in the Western Interconnection,” *IEEE Power Engineering Society General Meeting,* Tampa, FL, 2007, pp. 1-5.

[2] D. Olive, “Digital Simulation of Synchronous Machine Transients”, IEEE Trans. on Power Apparatus and Systems, vol. PAS-87, no. 8, pp. 1669-1675, Aug 1968.

[3] P. Pourbiek, “Generator Modeling,” WECC Modeling and Validation Work Group Meeting, March 2016.

[4] P. Pourbeik, B. Agrawal, S. Patterson, R. Rhiner, “Modeling of Synchronous Generators in Power System Studies,” CIGRE Science and Engineering, Volume 6, October 2016, pages 21-31. http://www.cigre.org/Menu-links/Publications/CIGRE-Science-Engineering

[5] J. Undrill, “The *GENTPJ* Model”, Western Electricity Coordinating Council, June 2012, Online. Available: https://www.wecc.biz/Reliability/*GENTPJ*-typej-definition.pdf

[6] J. Undrill, "Structure in the Computation of Power System Dynamical Response", IEEE Trans. on Power Apparatus and Systems, vol. PAS-88, no. 1, pp 1-6, Jan 1969.

[7] J. Weber, “Description of Machine Models *GENROU*, *GENSAL*, *GENTPF* and *GENTPJ*,” PowerWorld Corporation, December 2015. Available: http://www.powerworld.com/files/*GENROU-GENSAL-GENTPF-GENTPJ*.pdf.

For more information or assistance with the Modeling Notification, please contact the System Analysis Department (via email) or (404) 446-2560.

North American Electric Reliability Corporation
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
(404) 446-2560 | www.nerc.com