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01 November 2016

Subject: **Steady State Calculations for Round Rotor Synchronous Machine Models**

This memo compares the steady state calculations of the available generator models to represent round rotor machines, namely the models GENROU, GENROE and GENTPJ. The comparison is based on the OEM data and the simulation results strictly using the parameters provided by the OEM. No adjustments to the model parameters were attempted to try to improve the simulation results.

This memo demonstrates that the use of exactly the same parameters on these different models lead to different steady state (initial conditions) values. As such, the conversion of GENROU or GENROE models into the GENTPJ model, using exactly the same parameters as currently available in GENROU/GENROE, will lead to somewhat different results.

Although not discussed in this memo, similar arguments can be made regarding the conversion of the GENSAE model (essentially, this is the GENROE model with one of the two windings in the q-axis eliminated, similarly to what is done with the GENTPJ model to represent salient pole units). The GENSAL model is the only model that applies saturation only to the d-axis and also derive the saturation from a different variable, unrelated to the other models. Kestrel agrees that the GENSAL model should be phased out in favor of the GENSAE and/or the GENTPJ models.

This conversion into the GENTPJ model of a validated generator model (GENROU, GENROE or GENSAE), leading to changes in the simulated dynamic response of the unit, contradicts the intention behind NERC Std. MOD-026 and possibly contradicts its requirements.

The GENSAE and GENROE models should also be available for use, particularly if the suggestion to add the Kis factor to these models (and also GENROU) is accepted. Another possibility to be considered is the inclusion of a Potier reactance value for the calculation of the flux used as an input to the calculation of the saturation level of the machine, in these models.

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Introduction

This memo will provide a brief description of four key elements in the modeling of synchronous machines for transient stability simulations that are relevant to the discussion about the use of the GENROU, GENROE, GENTPF and GENTPJ models to represent round rotor units. Most of the results presented in this memo extend to the representation of salient pole units (GENSAE and GENTPF/GENTPJ models), but with a significant exception for the GENSAL model.

These four key elements are:

1. The fundamental equations (Park equations) behind these models. These models are developed from fundamental equations that initially ignore the effects of magnetic saturation and differences in these fundamental equations lead to differences between these models even if magnetic saturation is neglected;
2. The way the magnetic saturation is represented or characterized in these models. Due to practical considerations, all available models (GENROU, GENROE, GENTPF, GENTPJ) use the open circuit saturation curve to characterize the magnetic saturation of the machine. A key difference between these models is the mathematical function used to represent the open circuit saturation curve: a quadratic function is used in the GENROU, GENTPF and GENTPJ models, while a geometric function is used in the GENROE model.
3. Related to item 2 and the use of the open circuit saturation curve to represent the magnetic saturation of the machine for different operating conditions (on-load conditions), an important aspect is the flux or (equivalently, at least in steady state) voltage that will be used together with the open circuit saturation curve to determine the magnetic saturation at a given operating point. The GENROU and GENROE models use the sub-transient flux ψ" as the input for the saturation function calculation. This sub-transient flux, in steady state, corresponds to the voltage magnitude behind the sub-transient reactance X" (these models consider $X''_d = X''_q$). The GENTPF and GENTPJ models use the flux equivalent to $E_l + K_{is}|I_t|$ where E_l is the voltage behind the leakage reactance. The only difference between the GENTPF and GENTPJ models is the parameter K_{is} that was introduced in the GENTPJ model. It can be adjusted to add a component proportional to the magnitude of the generator terminal current to the flux/voltage used as the input for the saturation function calculation.
4. The way the magnetic saturation is incorporated into the models. The GENROU and GENROE models represent the saturation effect as an additional component of the field current (and an equivalent approach for the q-axis). The GENTPF and GENTPJ models apply a saturation factor to the model inductances, based on the saturation of the magnetizing inductance L_{ad} in the d-axis and L_{aq} in the q-axis).

The ratings for the generator considered in this memo are presented in Table A1. The generator model parameters are presented in Table A2. This generator data is used as the OEM data for the equipment is available. The examples presented in the current version of the NERC notification could not be used in this memo due to incomplete data.

General Description of the Models

Element 1 – Fundamental Equations

The GENROU and GENROE models share the same overall structure (block diagram) and the only difference between these models is related to the representation of the magnetic saturation.

In their most fundamental aspect, related to the fundamental equations of the Park's model, the GENROU and GENROE models consider the mutual coupling between windings (on each axis) to be numerically identical when expressed in per unit. Thus, the flux linkages of the fundamental model for the GENROU and GENROE models can be expressed as

$$\begin{bmatrix} \psi_d \\ \psi_{fd} \\ \psi_{kd} \end{bmatrix} = \begin{bmatrix} L_\ell + L_{ad} & L_{ad} & L_{ad} \\ L_{ad} & L_{fd} + L_{ad} & L_{ad} \\ L_{ad} & L_{ad} & L_{kd} + L_{ad} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{fd} \\ i_{kd} \end{bmatrix}$$

$$\begin{bmatrix} \psi_q \\ \psi_{kq1} \\ \psi_{kq2} \end{bmatrix} = \begin{bmatrix} L_\ell + L_{aq} & L_{aq} & L_{aq} \\ L_{aq} & L_{kq1} + L_{aq} & L_{aq} \\ L_{aq} & L_{aq} & L_{kq2} + L_{aq} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{kq1} \\ i_{kq2} \end{bmatrix}$$

The fundamental equations for the GENTPF/GENTPJ models are shown in [1]. The key difference regarding the GENROU/GENROE models is the consideration of different mutual inductances between all windings. The flux linkages for the fundamental model associated with the GENTPF and GENTPJ models are expressed as

$$\begin{bmatrix} \psi_d \\ \psi_{fd} \\ \psi_{kd} \end{bmatrix} = \begin{bmatrix} L_\ell + L_{ad} & L_{afd} & L_{akd} \\ L_{afd} & L_{ffd} & L_{fkd} \\ L_{afd} & L_{fkd} & L_{kkd} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{fd} \\ i_{kd} \end{bmatrix}$$

$$\begin{bmatrix} \psi_q \\ \psi_{kq1} \\ \psi_{kq2} \end{bmatrix} = \begin{bmatrix} L_\ell + L_{aq} & L_{akq1} & L_{akq2} \\ L_{akq1} & L_{kkq1} & L_{akq12} \\ L_{akq2} & L_{akq12} & L_{kkq2} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{kq1} \\ i_{kq2} \end{bmatrix}$$

In a separate document [2], it was shown that the different fundamental equations of these models result in differences in the dynamic response of the models when considering the same operational data (synchronous, transient and sub-transient reactances and open-circuit transient and sub-transient time constants) for these models, even when the effects of magnetic saturation are disregarded.

Element 2 – Saturation Function

The GENROU model uses a quadratic function to represent the open circuit saturation curve, while the GENROE model applies a geometric function. The GENTPF and GENTPJ models use the quadratic function to represent the open circuit saturation curve, the same curve used by the GENROU model.

Figure 1 presents the generator open circuit saturation curve represented by these two functions, quadratic and geometric, as well as the points given in the OEM curve. It can be seen that the geometric curve offers a better approximation to the OEM data. One key difference between the quadratic and geometric functions is the fact that the quadratic function crosses the air-gap line for a terminal voltage greater than zero (approximately 14.5 kV in Figure 1) and then the magnetic saturation is neglected for all values of voltage (flux) below that point. The geometric function is defined to be asymptotic to the air-gap line for low values of voltage (flux).

Element 3 – Input Variable for the Saturation Function

By definition, the sub-transient reactance is greater than the leakage reactance. Thus, the GENROU/GENROE models use a different variable (voltage behind sub-transient reactance) than the GENTPF/GENTPJ models (voltage behind leakage reactance, with or without the use of the Kis factor), when estimating the saturation level for a given operating condition.

Figure 2 presents the V-curves calculated for the GENROU, GENROE and GENTPJ/GENTPF models, as well as points obtained from the OEM curves. Figure 3 corresponds to a zoom of Figure 2 for the curves associated with 100% (rated) power output (generator rated at 0.90 pf, thus 90% of 203 MVA or 182.7 MW). The results for the GENTPJ and GENTPF models are identical as the parameter Kis is set to zero, per the proposed instructions to convert the data into the GENTPJ model.

None of the models provide a very close match to the OEM data. In particular, all models resulted in field current values lower than the OEM data for the over-excited conditions, which could lead to a somewhat optimistic model regarding the reactive power output capability of the unit if an over-excitation limiter is represented in the simulation. This is one of the primary justifications for the search of improved models for system simulations.

It can be seen that, in this example, the results from the GENTPJ/GENTPF models are comparable to the results for the GENROE model for the over-excited points, while better approximating the results of the GENROU model for under-excited conditions. This is related to the flux (voltage) used as the input to the saturation function as well as the use of the quadratic or geometric saturation functions to represent the saturation.

To compare these results, 40 points (P and Q initial generator output, always at rated terminal voltage) were defined, as shown in the capability curve for the machine in Figure 4. These points are numbered from under-excited to over-excited conditions for a given power output level, as indicated.

Figure 5 presents the calculated fluxes (or voltages) used as the input for the saturation functions on the different models. Since the Kis parameter is set to zero, the GENTPJ/GENTPF model uses the voltage behind the leakage reactance (0.137 pu), while the GENROU and GENROE models use the voltage behind the sub-transient reactance (0.16 pu). For the sake of comparison, the OEM provides a value for the Potier reactance [3] of 0.182 pu.

With the smaller inductance, the GENTPJ/GENTPF models have smaller voltage drops between the terminal bus voltage and the internal voltage (flux) used as the input for the saturation function. The GENTPJ model tends to use a lower value of internal voltage than GENROU/GENROE for the over-excited conditions and a larger value of internal voltage than GENROU/GENROE for the under-excited conditions, as shown in Figure 5. Also, referring to Figure 1, it can be seen that the quadratic saturation function will result in less saturation than the geometric function for all values of voltage (flux) less than 16.5 kV (nominal voltage, 1.0 pu). Magnetic saturation would be disregarded by the quadratic function for values lower than approximately 14.5 kV (approximately 0.88 pu). Conversely, the quadratic function would result in more saturation than the geometric function for all values of voltage (flux) between 1.0 pu and 1.2 pu. Figure 5 shows that the calculated values for the internal voltage were in the range of approximately 0.90 pu to 1.10 pu.

Thus, for under-excited conditions, the GENTPJ/GENTPF model tends to have a higher value for the internal voltage/flux used in the saturation function calculation, but the use of the quadratic saturation function leads to an under-estimate of the saturation (as compared to the OEM data and the geometric curve), so the results of the GENTPJ/GENTPF model tends to approximate the results of the GENROU model (also quadratic function) for the under-excited conditions.

On the over-excited region, the GENROU/GENROE models start with a higher value for the internal flux, due to the larger value for the sub-transient reactance, compared to the leakage reactance used in the GENTPJ/GENTPF models. Then, the use of the quadratic saturation function for points above 1.0 pu will result in a larger saturation function value. Thus, the GENROU model tends to estimate more saturation and thus more field current than the GENROE model for these conditions, despite the fact that these models start with the same internal voltage/flux for the saturation function. The GENTPJ/GENTPF models start from a lower estimate for the internal voltage/flux, but then combine that effect with the increased estimate for the saturation provided by the quadratic saturation function (for values between 1.0 and 1.2 pu) to make the GENTPJ/GENTPF results approximate those given by the GENROE model for the over-excited conditions. The GENROU model, in this case, resulted in the largest estimates for the field current, although all models are under-estimated field current as compared to the OEM data.

It should be noted that Kestrel has had good experience by using the OEM-provided value for the Potier reactance as the sub-transient reactance in the GENROE model for the calculation of field current in steady state. In other words, the use of a voltage (flux) behind the Potier reactance seems to provide good results, combined with the geometric function.

It should also be noted that the Kis factor introduced in the GENTPJ model is, somehow, an approximation to the Potier reactance, at least for the over-excited conditions. A positive value of Kis will increase the value for the internal voltage (flux) used as the input for the saturation function. This idea can also be applied to the GENROU and GENROE models, though.

Element 4 – Input Variable for the Saturation Function

The GENROU/GENROE models apply saturation as an additional component to the calculation of the field current (d-axis) and, in an equivalent manner, as an additional element added to the q-axis equations. The GENTPF/GENTPJ models apply saturation to the magnetizing inductances L_{ad} and L_{aq}, generating saturated values for the machine inductances that are used in the model.

These are quite distinct ways of representing the effect of the magnetic saturation, both on the steady state calculations and the dynamic response of these models. The impact of these models on the steady state calculation of the generator field current has already been described. It should be noted, though, that GENTPJ/GENTPF will have different initial rotor angle position as compared to GENROU or GENROE, due to differences in the way the saturation is represented.

Figure 6 shows the calculated initial rotor angle position (relative to the generator terminal bus voltage angle) for the V-curve points shown in Figure 4. These differences might not be very significant in this particular example, but it has to be noted that moving from one model to the other with exactly the same parameters might result in differences not only on the estimated field current, but also on the initial rotor angle position, which might have significant impact on certain calculations such as critical clearing time or other determinations of stability limits.

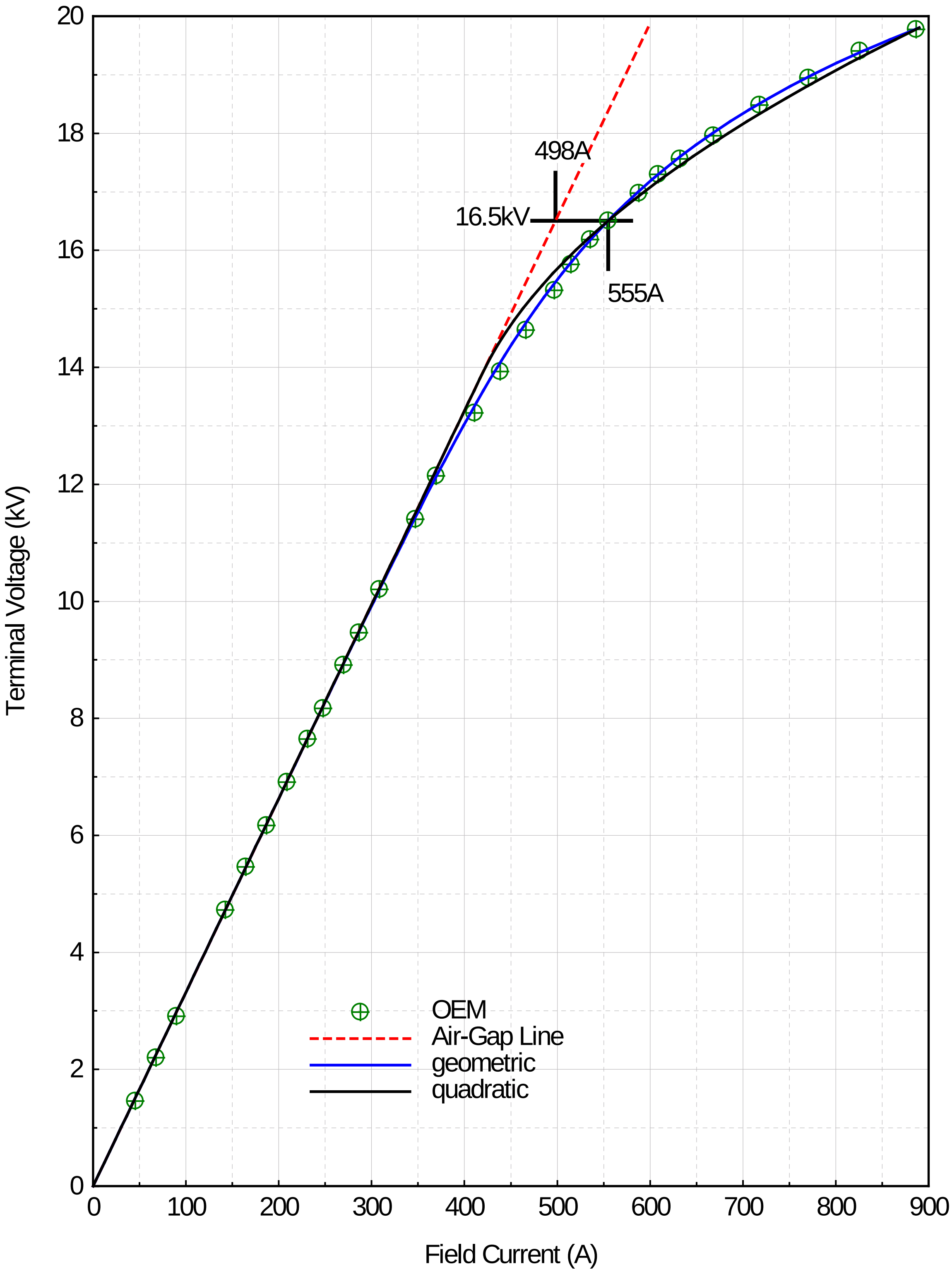

Figure 1 – Generator Open Circuit Saturation Curve

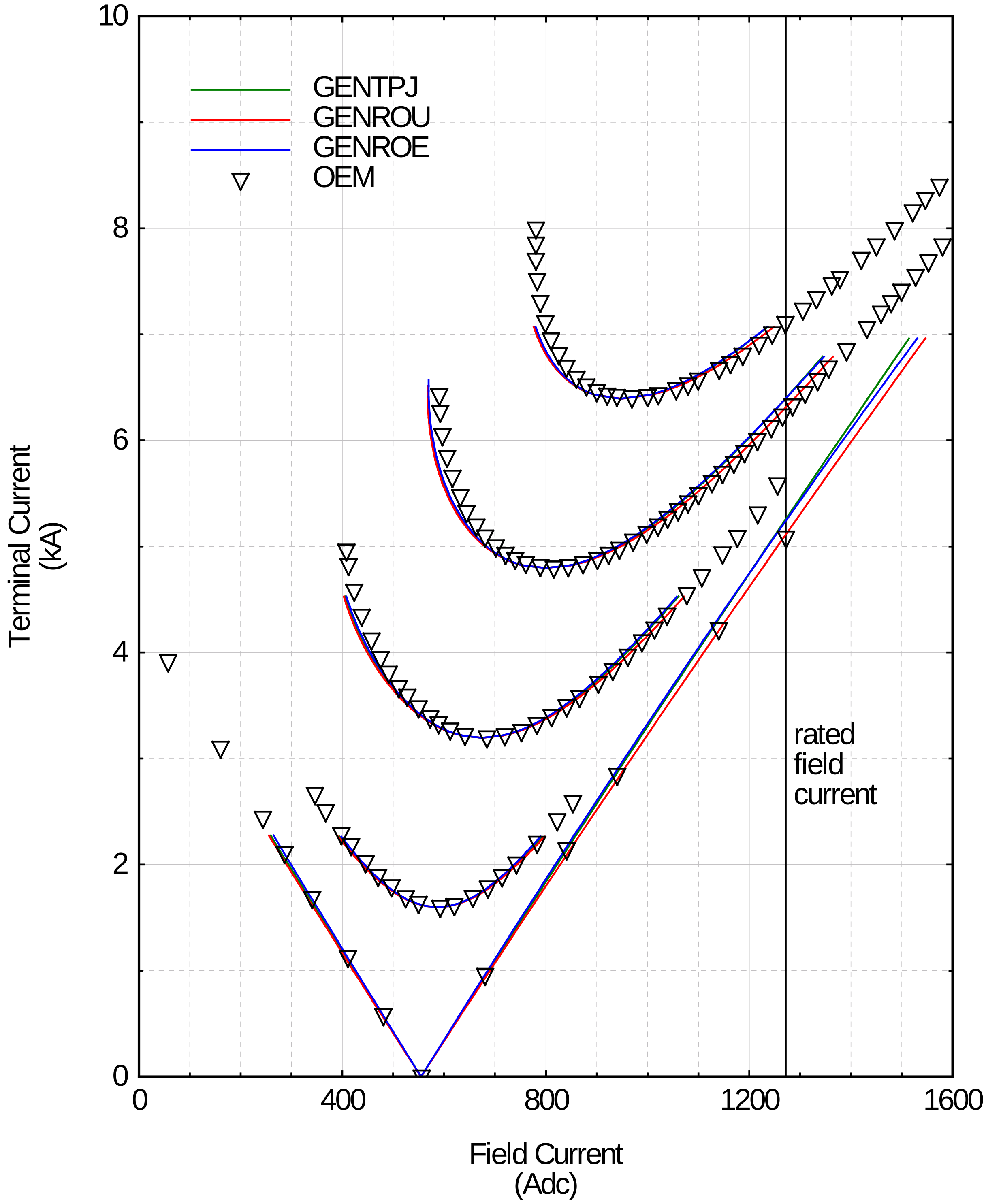

Figure 2 – Generator V-Curves for Nominal Terminal Voltage

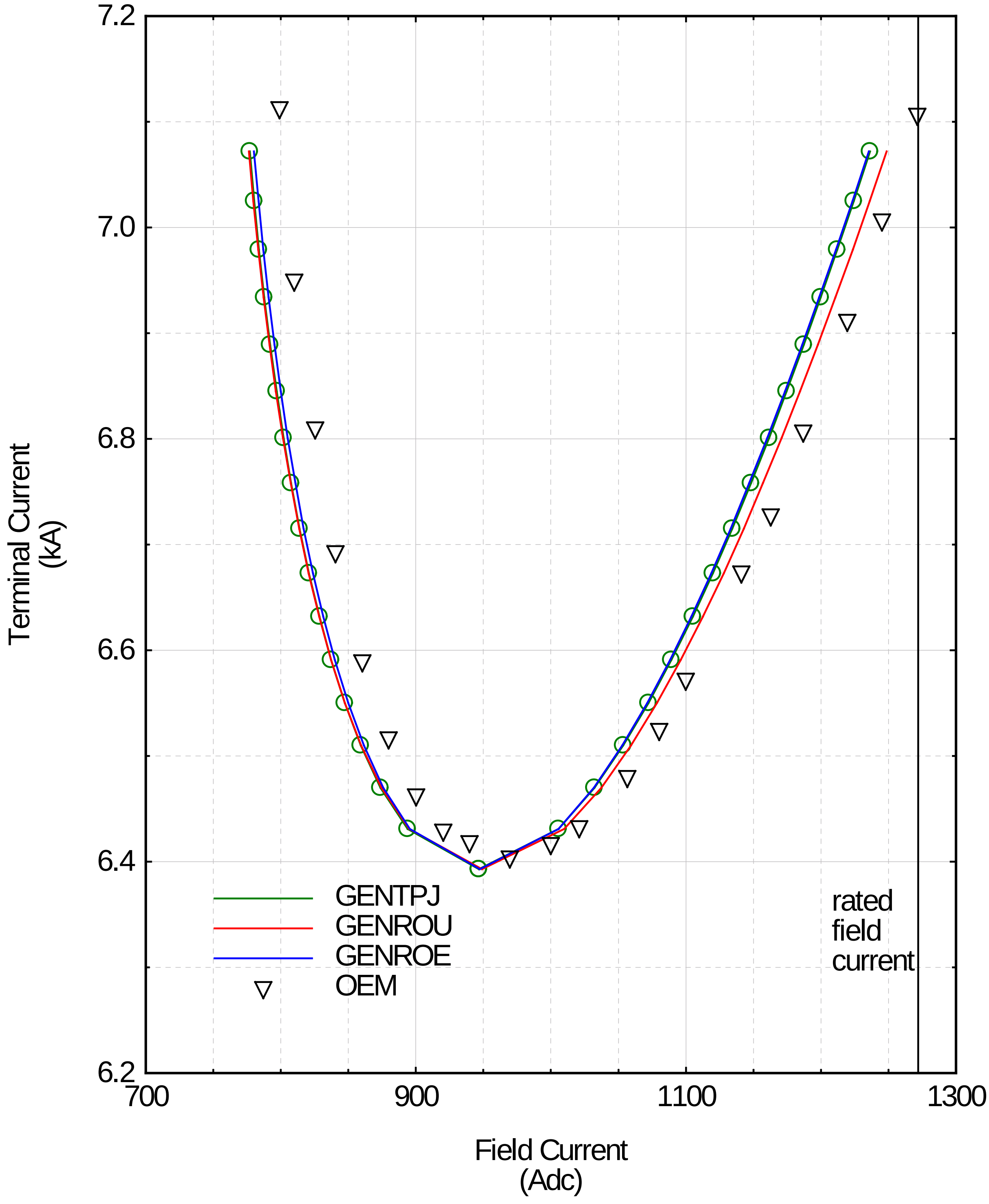

Figure 3 – Generator V-Curve for 100% (rated) Power Output and Nominal Terminal Voltage

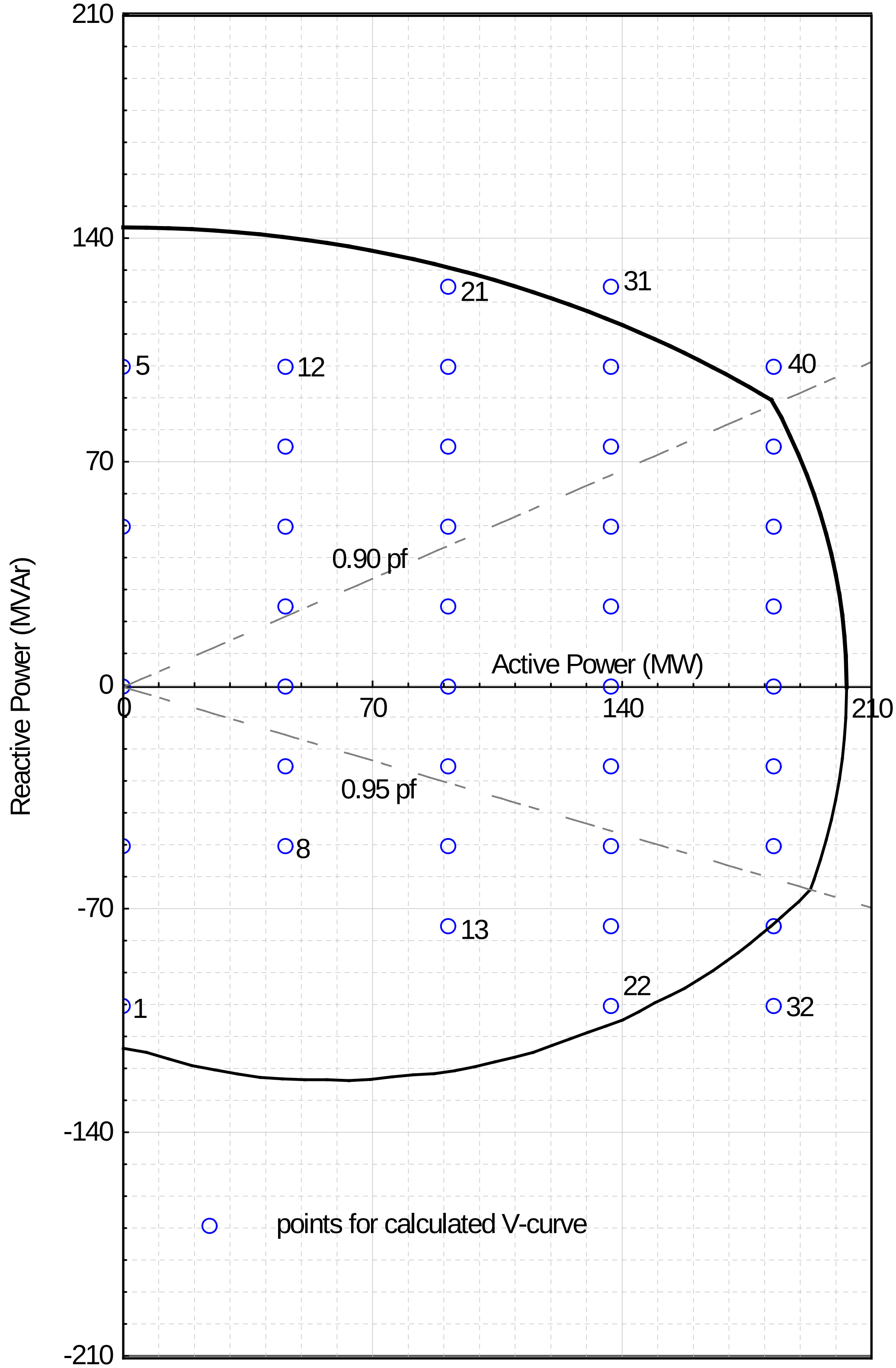

Figure 4 – Generator Capability Curve and Points Used for V-Curve Calculations

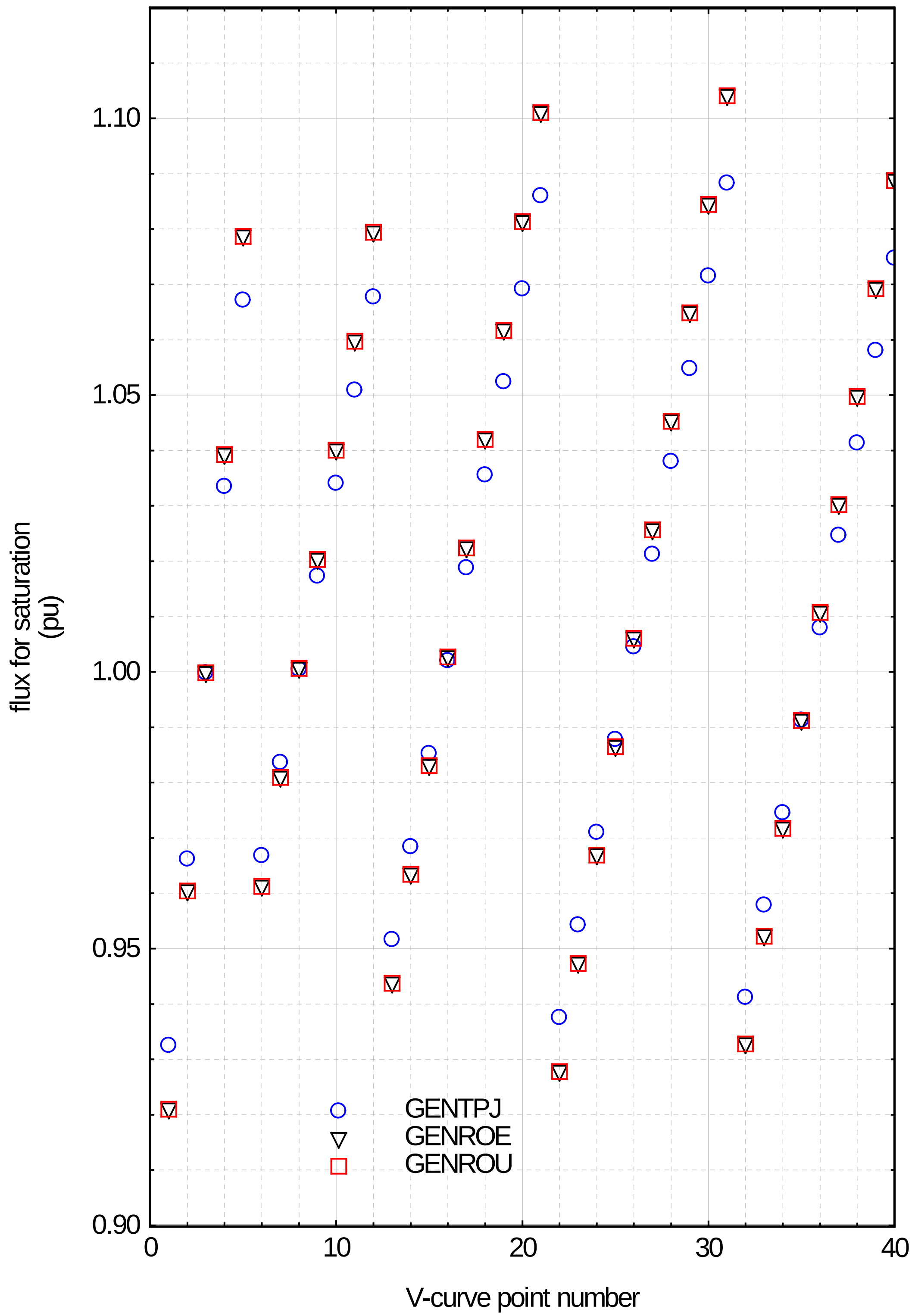

Figure 5 – Calculated Input Flux (Voltage) for the Saturation Function

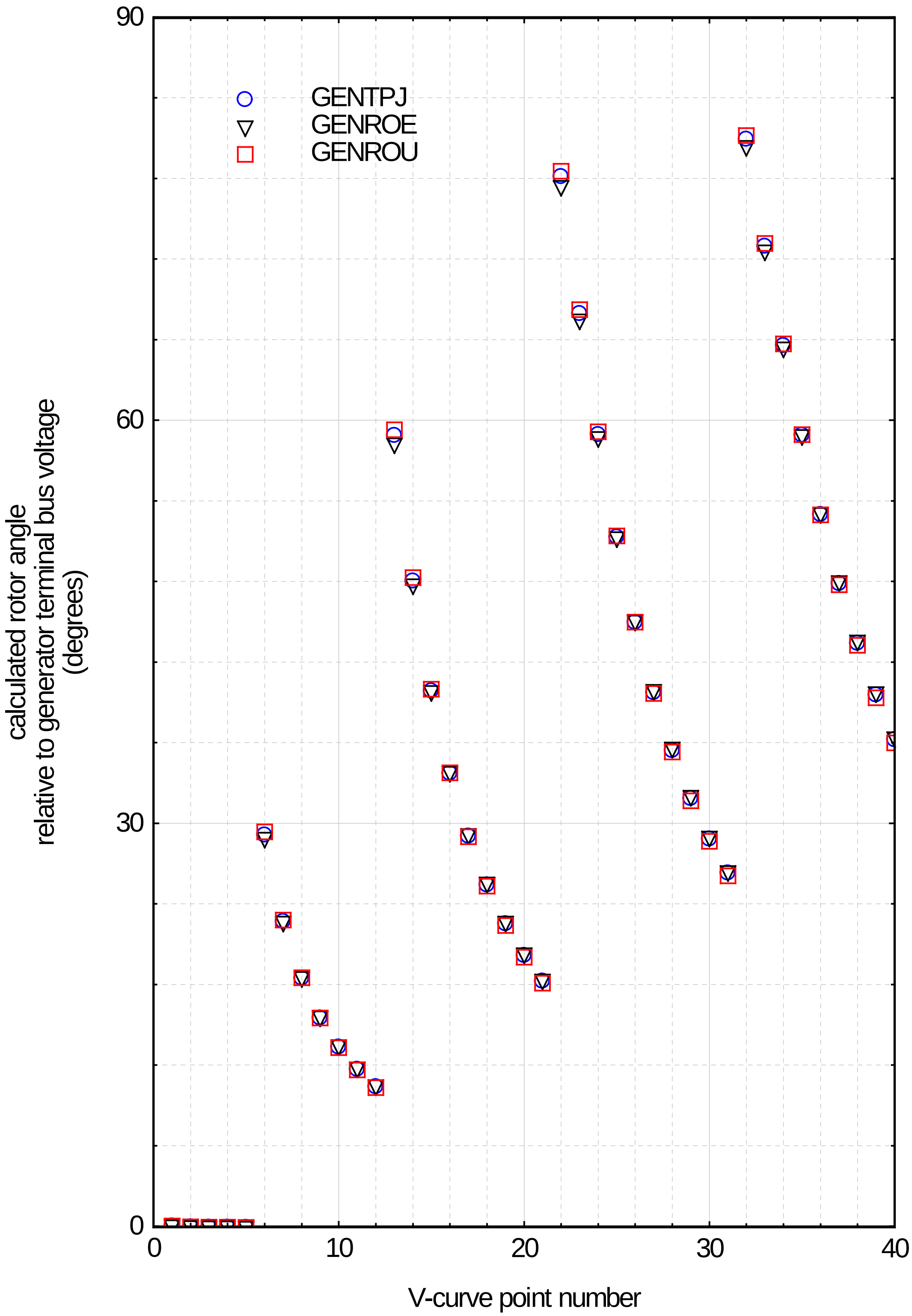

Figure 6 – Calculated Initial Rotor Angle Position Relative to Terminal Bus Voltage Angle

Conclusions

The GENTPF model is not new, its fundamental equations were published in 1968 and the model was available in the WECC (BPA) software since at least the 1980s, if not earlier.

The GENTPJ model was proposed recently and modifies the GENTPF model by adding the Kis factor to the calculation of the internal voltage (flux) used as the input for the saturation function. This Kis factor can be adjusted to increase the internal voltage/flux and thus the amount of magnetic saturation considered for a given operating condition. This could be used to approximate the larger value of the Potier reactance, often used by the OEM in their calculations of field current.

This Kis factor can also be adjusted to somewhat compensate for the deficiency of the quadratic saturation function that under-estimates and even completely neglects the magnetic saturation for values of the internal voltage/flux lower than 1.0 pu. On the other hand, the use of geometric (or an exponential) function to represent the saturation function is actually a better approach, providing a much closer approximation for the available OEM data for the open circuit saturation curve.

Other models, such as GENROU and GENROE, could also use the same approach of adding a heuristic factor such as Kis to their calculation of the saturation function.

Although this memo presents evidence associated with a single machine/vendor data, it is clear that changing the generator model using exactly the same parameters will lead to differences in the calculated results, both in the steady state and the dynamic responses. This approach, currently recommended by WECC and being considered by NERC, should be avoided particularly for machines that have validated models.

References

1. D. W. Olive, "*Digital Simulation of Synchronous Machine Transients*", IEEE Trans. on PAS, vol. 87, no. 8, August 1968, pp. 1669-1675
2. L. Lima, "*Generator Models Comparison Results – Synchronous Generator Models*", Kestrel Power Engineering memo (electronic distribution), version 1.1, September 2016.
3. E. W. Kimbark, *Power System Stability: Synchronous Machines*, Dover, 1968 (unabridged re-publication of the original 1956 John Wiley & Sons edition).

Table A1 Generator Ratings and Base Values

Description	Parameter	Value	Units
Generator Base MVA	MBASE	203	MVA
Turbine Maximum Continuous Rating	MCR	183	MW
Generator Stator Base Voltage	Etbase	16.5	kV
Generator Stator Base Current	Itbase	7.103	kA
Generator Rated Speed	rpm	3600	rpm
Rated Power Factor	pf	0.9	
Rated Field Current (rated MVA and pf)	IfgRated	1272	Adc
Rated Field Voltage (rated MVA and pf)	EfgRated	224	Vdc
Calculated No-Load Field Current	Ifgnlcalc	555	Adc
Generator Base Field Current	IfgBase	498	Adc
Generator Base Field Voltage	EfgBase	87.7	Vdc
Generator Base Field Resistance	RfgBase	0.176	Ω
Generator Base Field Temperature	TfgBase	100	°C
Generator Stator Base Impedance	Zbase	1.341	Ω

Table A2. Generator Model

Generator Model GENROU: Round Rotor Generator Model PSS/E Model

Description	Parameter	Value	Units	CON
d-axis OC transient time constant	T'do (>0)	9.697	s	J
d-axis OC sub-transient time constant	T"do (>0)	0.048	s	J+1
q-axis OC transient time constant	T'qo (>0)	1.164	s	J+2
q-axis OC sub-transient time constant	T"qo (>0)	0.087	s	J+3
Inertia	H	6.29	MW.s/MVA	J+4
Damping	D	0	pu	J+5
d-axis synchronous reactance	Xd	1.685	pu	J+6
q-axis synchronous reactance	Xq	1.641	pu	J+7
d-axis transient reactance	X'd	0.214	pu	J+8
q-axis transient reactance	X'q	0.388	pu	J+9
subtransient reactance [2]	X"d=X"q	0.16	pu	J+10
leakage reactance	Xl	0.137	pu	J+11
saturation factor at 1.0 pu Et	S(1.0)	0.114	pu	J+12
saturation factor at 1.2 pu Et	S(1.2)	0.489	pu	J+13

armature resistance [1]	Ra	0.0006	pu	
Potier reactance [3]	Xp	0.182	pu	

Notes:

1. The armature resistance is not part of the dynamic generator model, but entered in the power flow generator data as Rsorce
2. The subtransient reactance X" should also be entered in the power flow generator data as Xsorce
3. The Potier reactance is not part of any of the dynamic simulation models currently available, but was provided as part of the OEM data and was probably used by the OEM to calculate the V-curve points and related calculations of the generator field current.