GENQEC

Generator Dynamic Model Specification

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Revision History

Version	Date	Description
Draft	March 4, 2019	Proposed dynamic model GENQSC (Quadratic Saturation) and GENESC (Exponential Saturation) draft specification. Request For Comments (RFC).
R0	July 22, 2019	Single dynamic model GENQEC combined GENQSC and GENESC. Use a flag to switch saturation function type between Quadratic and Exponential saturation.
R1	September 23, 2019	Revised to differentiate Quadratic and Scaled Quadratic saturation functions. Added details of GENQEC model initialization steps.
R2	June 26, 2020	Revised Fig.1 and Fig. 3 symbols for clarity. Added reference [6], the latest IEEE Standard 1110.
R3	September 9, 2020	Revised Fig.1 to remove i_{dw} and related limits. Limit the maximum effect of field current compensation to +/- 0.4 on $(K_w i_d)$.

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1. Objective

This document describes the detail of a generic generator dynamic model capable of achieving high field current accuracy across a wide range of generator operating conditions. It is provided as a reference for the implementation of the model in power system stability analysis software, also for comments and feedback from other professionals in power system field.

2. GENQEC Dynamic Model Structure

The structure of the GENQEC model is derived based on the standard second-order generator equivalent circuit given in the IEEE standard 1110, version 1991 [1], 2002 [2] and 2019 [6]. The GENQEC model function block diagram is given in Fig. 1 on the next page. The derivation process of the block diagram is given in [3] and [4]. The parameters used in the GENQEC model conform to the "standard" generator model parameters usually provided by the generator manufacturers.

3. Improvement over Previous and Existing Generator Dynamic Models

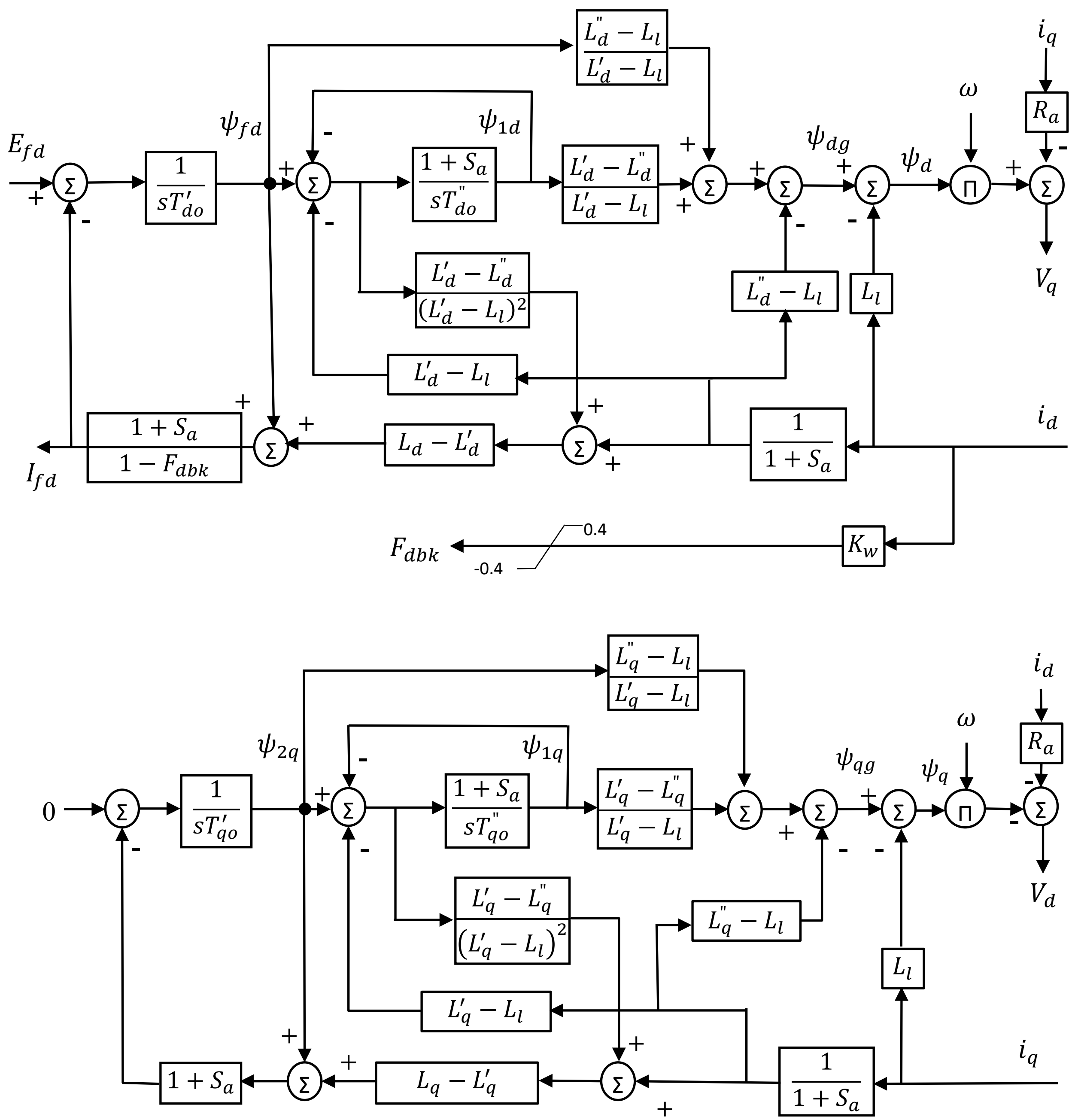
- Better steady-state field current accuracy than all the second-order generator dynamic models currently used in commercial software [3]
- Better dynamic response than the latest NERC-approved generator model recommended to replace the old generator dynamic models [4]
- Innovative method to consider and process the influence of magnetic saturation on generator rotor winding field current [3]
- Simple application of magnetic saturation function to both d-axis and q-axis stator winding inductance terms [5]
- Practical method for obtaining the newly-introduced compensation factor for high accuracy rotor field current in the model [3]

4. Highlights of the GENQEC Dynamic Model

- Very first generator dynamic model with full equivalent circuit representation (in Fig. 3) and model block diagram representation [3] [4]
- One model applicable to both round-rotor and salient-pole synchronous generators
- Applies saturation effect on all rotor and stator inductance terms
- Selectable saturation functions (exponential, quadratic, and scaled-quadratic)
- Same magnetic saturation function output applies to both d-axis and q-axis stator inductance terms [5]
- Uses generator open-circuit saturation characteristics with a field current compensation factor to achieve high accuracy of rotor field current [3]
- Field current compensation factor can be calculated from generator zero-power-factor load characteristics, or fitted from online steady-state VEE curve measurements
- Proven high-accuracy and good performance in calculation and simulation results compared with actual test data on a number of in-service generators [3] [4] [5]

5. GENQEC Application Details

5.1 Model structure (non-reciprocal, commonly-used per-unit system in power system studies)



$$S_a = saturation\ function\left(\sqrt{\psi_{dg}{}^2 + \psi_{qg}{}^2}\right)$$

K_w: Compensation factor related to additional rotor winding leakage flux when stator current is present. It is focused on steady-state operating conditions for improving rotor field current accuracy.

Figure 1: GENQEC Model Structure

5.2 Saturation functions

GENQEC model structure was first derived without involving the saturation function type used to represent the generator Open Circuit Characteristics (OCC). When implementing the dynamic model in computer software, the saturation function can be selected using a flag in the model parameter set, to switch between the exponential, scaled-quadratic and quadratic saturation functions. These three commonly used saturation functions are described below.

Given generator model parameters $S_{1.0}$ and $S_{1.2}$ on the generator open-circuit characteristic (OCC) illustrated in Fig. 2, shown as S(1.0) and S(1.2) respectively, the saturation function (in non-reciprocal per-unit system commonly used in power system study) needs to pass 3 points, [0, 0], [(1+$S_{1.0}$), 1.0] and [(1+$S_{1.2}$), 1.2], with the rest as closely as possible matching the OCC (calculated or tested). The slope of the air-gap line is 1.0 in this non-reciprocal per-unit system when the X-axis represents per unit field current.

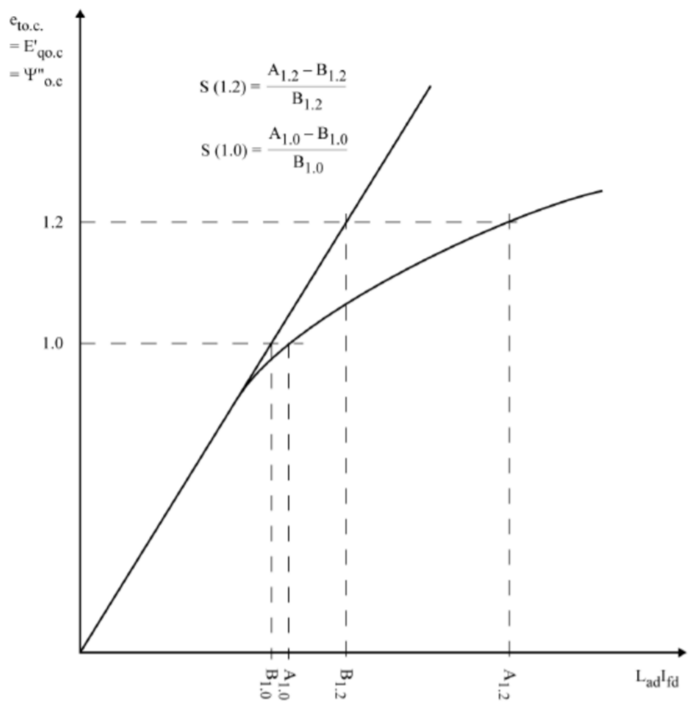


Figure 2: Definition of Saturation Factors in Generator Data (source: Siemens/PTI PSS/E PAGV2)

Let $\psi_{ag} = \sqrt{{\psi_{dg}}^2 + {\psi_{qg}}^2}$, representing the air-gap flux, the saturation factor S_a for GENQEC model at any given operating point can be calculated according to the chosen saturation type:

a) Exponential Saturation (use Flag=0 in generator model parameters set)

Define: $A = \ln(S_{1.2}/S_{1.0}) / \ln(1.2)$; and $B = S_{1.0}$ (1)

Saturation factor S_a with ψ_{ag} as input:

$$S_a = B(\psi_{ag})^A$$

b) Scaled Quadratic Saturation (use Flag=1 in generator model parameters set)

Define: $\alpha = \sqrt{1.2 * S_{1.2}/S_{1.0}}$; $A = (\alpha - 1.2)/(\alpha - 1)$; and $B = S_{1.0}/(1 - A)^2$

Saturation factor S_a with ψ_{ag} as input:

$$S_a = \begin{cases} 0 & when\ \psi_{ag} < A \\ B(\psi_{ag} - A)^2/\psi_{ag} & when\ \psi_{ag} \geq A \end{cases} \tag{2}$$

c) Quadratic Saturation (use Flag=2 in generator model parameters set)

Define: $\alpha = \sqrt{S_{1.2}/S_{1.0}}$; $A = (\alpha - 1.2)/(\alpha - 1)$; and $B = S_{1.0}/(1 - A)^2$

Saturation factor S_a with ψ_{ag} as input:

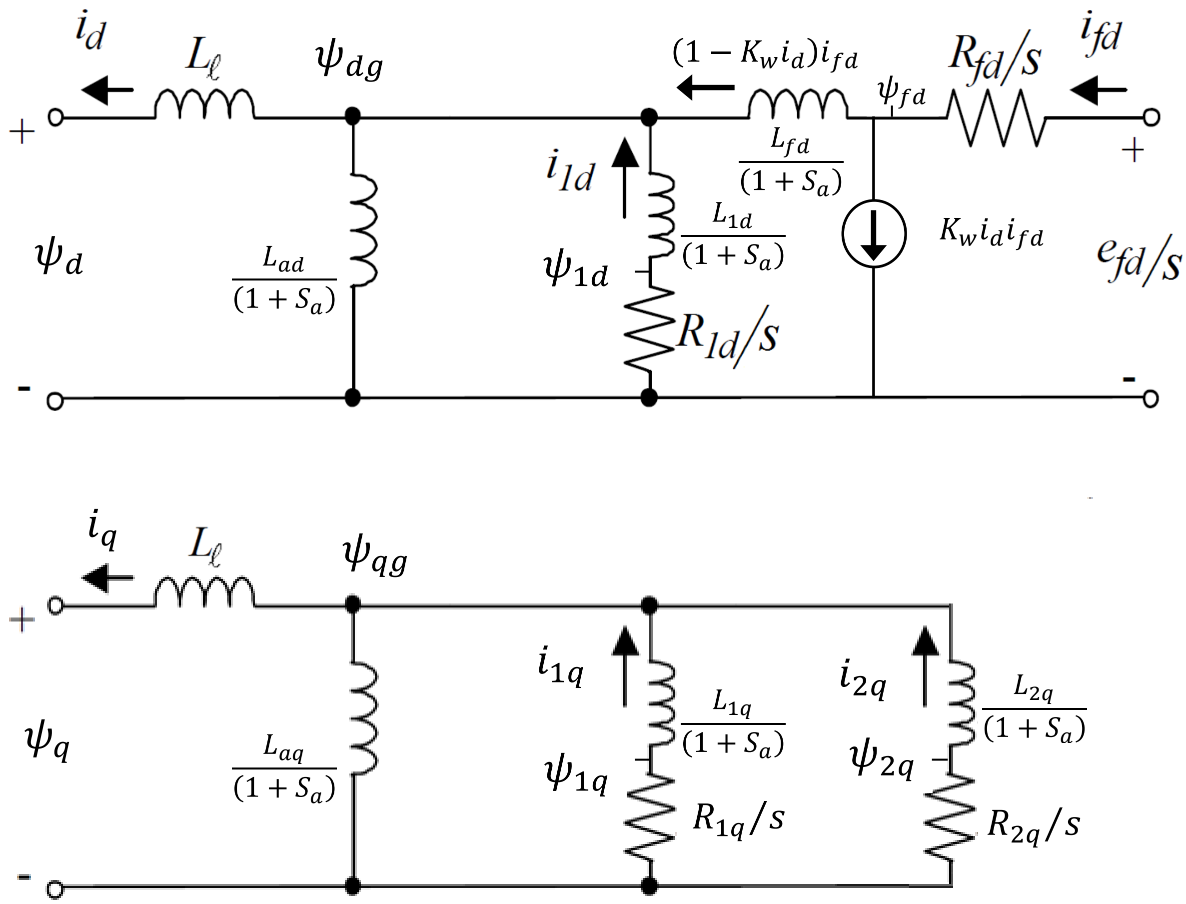
$$S_a = \begin{cases} 0 & when\ \psi_{ag} < A \\ B(\psi_{ag} - A)^2 & when\ \psi_{ag} \geq A \end{cases} \tag{3}$$

d) Other value of Flag in generator model parameter set

Only 0, 1 and 2 are recognized as valid Flag values. Other values of the Flag in generator model data set will be deemed invalid, and a value of zero will be assumed. This makes the exponential saturation function as default for GENQEC model.

5.3 Rotor field current compensation factor K_w

Refer to Fig. 3 for the GENQEC generator equivalent circuit represented in the L_{ad} - base reciprocal per unit system, from which the function block diagram given in Fig. 1 was derived. These equivalent circuits are based on the standard second-order generator equivalent circuits given as model 2.2 in Table 1 of [1] [2] and [6]. GENQEC model modified the IEEE Model 2.2 equivalent circuits in two aspects: 1) Saturation effect on stator and rotor inductance terms except stator winding leakage, and 2) Rotor winding leakage flux change caused by the d-axis stator current. With the first one, saturation of the mutual inductance is dominant, and the rotor leakage inductances are also considered to saturate for the consistency of generator model parameters. The second aspect is evidenced in the comparison between OCC and zero-power-factor load characteristics described below.

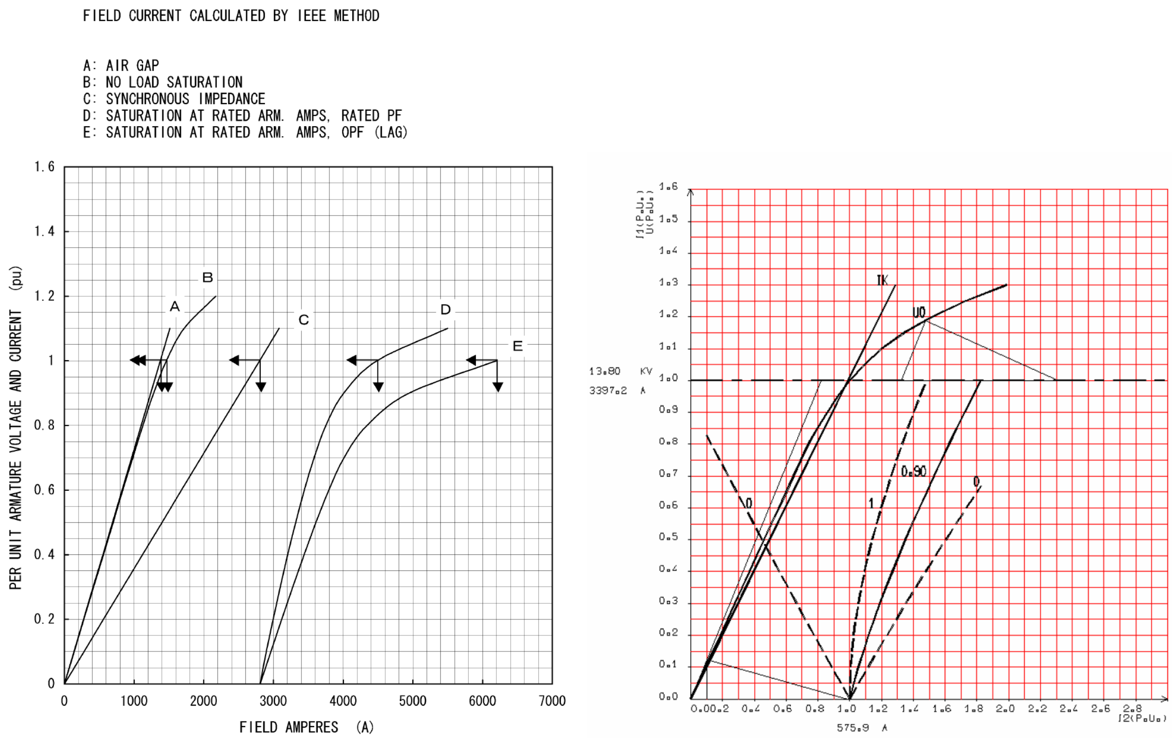


S_a represents the saturation factor at the given operating point

Figure 3: Second-order Generator Equivalent Circuit for GENQEC Model

Fig. 4 shows the typical generator saturation characteristics provided by two generator manufacturers. In most of the cases these curves are calculated generator characteristics by the manufacturers. Some of these curves can be tested onsite during commissioning or parameter validation testing.

The compensation factor K_w (in the current branch "$K_w i_{dw} i_{fd}$ " of Fig. 3) is used to account for the increased rotor winding leakage fluxes when generator is loaded with lagging stator current (also decreased rotor leakage fluxes with leading i_d). This is demonstrated by the zero-power-factor characteristics provided by the manufacturers. The slope difference between the OCC and the zero-power-factor line inherently reflects the rotor current compensation factor K_w. At low terminal voltage level before the magnetic saturation happens, for the same amount of incremental air-gap flux, bigger amount of rotor field current increase is required on the lagging zero-power-factor line due to the flux created by the stator winding current. This is apparent in the linear region with terminal voltage lower than 0.5 pu, long before the magnetic circuit saturates at higher flux level.



(a) Round-rotor (source: Toshiba) (b) Salient-pole (source: Andritz)

Figure 4: Typical Generator Saturation Characteristics Provided by Manufacturers

The compensation factor K_w is ideally determined from the linear region of the zero-power-factor load characteristics in comparison with the air-gap line, without involving the magnetic saturation. As an alternative when the zero-power-factor characteristics are not available, the compensation factor can be “fitted” from the generator on-line measurement results such as VEE curve measurements which covers the full range of generator operating conditions. Two methods are proposed here for obtaining the value of K_w.

a) <u>Derived from Zero Power Factor Characteristics:</u>

The zero-power-factor (0-pf) saturation curve starts from the point on short-circuit saturation characteristic (SCC) when the stator current reaches 1.0 per unit. It is often calculated by machine manufacturer and provided as part of the generator technical specification. 0-pf characteristic of small capacity generators can be tested in the field during commissioning using adjustable reactive load (reactor/capacitor).

Note the well-known Potier reactance, which addresses the additional rotor field winding flux, is obtained from the 0-pf characteristics in the saturated area. K_w is calculated in the linear region of the 0-pf curve.

In per unit, the OCC starts at the origin with slope 1.0. The 0-pf line starts at a slope less than 1 with additional rotor winding flux leakage. The slope at which the 0-pf line starts is (1- K_w) with 1.0 per unit stator current right on the d-axis.

Occasionally the 0-pf leading characteristic is also provided by the manufacturer, such as chart (b) in Fig. 4. In those operating conditions, air-gap flux goes from stator to rotor, and the generator terminal voltage reflects a negative q-axis voltage. Theoretically the slope of the manufacturer-provided leading 0-pf would be (K_w -1).

Considering the fact that generator is mainly operated in over-excited conditions, it is more realistic to rely on the lagging 0-pf results for deriving K_w. As an example, on a salient-pole generator where the manufacturer provided the calculated leading and lagging 0-pf characteristics shown in Fig. 4 (b), there is a small difference between the compensation factor K_w derived from those two. The results of K_w based on the lagging 0-pf line are good and the results based on the average of the two K_w values are also satisfactory. (In this example, the manufacturer-provided curves were used in the “graphical solution” fashion, and the possible data error and measurement error were not considered.)

b) <u>Fitted from Measurements of Online Operating Points:</u>

Online measurement results can be used to fit the field current compensation factor K_w. Ideally, the generator rotor position needs to be measured when using this method so that d-axis and q-axis current components can be calculated without using generator q-axis reactance X_q. If rotor angle measurement results are not available, accurate generator model parameters are essential to have good fitting result of K_w.

From the upper half of Fig. 1, the steady-state per unit generator field current in GENQEC model can be calculated as:

$$I_{fd} = \left[\frac{(1+S_a)}{\omega}(V_q + R_a i_q) + L_d i_d + S_a L_l i_d\right] / (1 - K_w i_{dw}) \tag{4}$$

With generator base values known and the on-line measurements of terminal voltage, active and reactive power, and rotor field current, the field current base value can be determined first. (It corresponds to zero output power at 1.0 pu terminal voltage on air-gap line.) The per unit rotor field current can be compared from that calculated from the model using above equation. Adjusting K_w to compare the per-unit field current calculated from model with the value converted from the field measurement. A satisfactory K_w value is relatively easy to find when efforts are made to minimize the modeling error for over-excited generator operating conditions at high load. Some results of fitted K_w using measured generator rotor angles are given in [3]. The results on a number of generators show that a K_w fitted from a high-load operating point is generally good for the rest of the operating points including under-excited conditions.

5.4 Using GENQEC to Represent Different Types of Generators

(Reactance and inductance may be used interchangeably in the description below, since they have the same values when provided by the manufacturer.)

a) Round-rotor generator (Model 2.2 in IEEE Std 1110, second-order standard model)

Rotor d-axis: Rotor field winding and one damper winding

Rotor q-axis: Two damper windings

- Use "standard" generator model parameters including all synchronous, transient and sub-transient model parameters on d-axis and q-axis.

b) Salient-pole generator (Model 2.1 in IEEE Std 1110, second-order standard model)

Rotor d-axis: Rotor field winding and one damper winding

Rotor q-axis: One damper winding only

- Set $L_q = L'_q$; and T'_{qo} to an extremely big number such as 999. The rest of the parameters are "standard" generator model parameters.

c) Generator without damper or only one q-axis damper winding (model 1.0 & 1.1 in IEEE Std 1110)

It is possible to extend the use of GENQEC model to lower-order by setting:

- $L''_q = L'_q = L_q$ and $L''_d = L'_d$;
- T'_{qo}, T''_{qo}, and T''_{do} all to extremely big numbers, such as 999.

This effectively reduces the model to first-order, as type 1.0 in IEEE 1110.

Model type 1.1 (only one damping winding on q-axis) is also possible by using actual L''_q and T''_{qo} values on top of the model type 1.0 parameters settings.

Note that GENQEC model has not been tested for representing first-order generator models. Above conclusion was drawn based on theoretical analysis.

5.5 GENQEC Model Initialization Steps

As a dynamic model with the magnetic saturation effect on stator inductance items considered, the initialization of GENQEC model will use the saturated generator q-axis synchronous reactance to determine the internal rotor angle during initialization. Phasor diagrams for typical lagging and leading reactive load of generator operating conditions are shown in Fig. 5 and Fig. 6.

Starting from generator terminal measurements, stator voltage and current, the latter may be calculated from active power P and reactive power Q, an air-gap potential E_l can be calculated using stator leakage inductance (reactance). This is Step ❶ in Fig. 5 and Fig. 6. The air-gap potential E_l is resulted from a same-value air-gap flux, ψ_{ag} , so a saturation factor S_a can be calculated using the selected function in GENQEC per equation (1), (2) or (3). Saturated q-axis mutual reactance is the unsaturated value divided by $(1+S_a)$. That is

$$X_{aq-s} = X_{aq}/(1 + S_a)$$

Use this value to determine the q-axis position as step ❷ in Fig. 5 and Fig. 6.

ψ_{ag} is drawn in the phasor diagrams 90° leading E_l. The space and time phasors are overlaid in the same diagram, shown as step ❸ in Fig. 5 and Fig. 6. Note that the d-axis components of the ψ_{ag} drawn in Fig. 5 and Fig. 6 is $V_q + R_a\, i_q + X_l\, i_d$, which is exactly the ψ_{dg} in Fig. 1 and Fig. 3. It is obvious that the q-axis components of ψ_{ag} equals to the ψ_{qg} in Fig. 1 and Fig. 3.

The air-gap flux ψ_{ag} can be considered as being generated from a virtual equivalent magneto-motive-force (MMF) in the same direction as ψ_{ag}, $(1 + S_a)\psi_{ag}$ in per unit value. This step ❹ in Fig. 5 and Fig. 6 completes the inclusion of saturation effect on all affected terms. Note that the q-axis component of the equivalent MMF is exactly $X_{aq}i_q$, where X_{aq} is unsaturated mutual reactance.

The d-axis component of the virtual equivalent MMF generates the d-axis flux behind leakage reactance, ψ_{dg}, as seen in Fig. 1 and Fig. 3. This d-axis component is the combined result from the effective contribution of rotor field winding current and d-axis stator winding current through the mutual reactance X_{ad}. The latter is $X_{ad}i_d$.

Note that X_{ad}-base reciprocal system is used in the equivalent circuits in Fig. 3, the non-reciprocal per unit generator field current in Fig. 1, from the per unit system commonly used in power system simulation software needs to meet 3 conditions: (a) base value of field current shall yield base value of field winding flux; (b) base value of field current shall create rated air-gap terminal voltage; and (c) base value of field voltage shall produce base value of field current. In the non-reciprocal per unit system, the per-unit I_{fd} is the $X_{ad}I_{fd}$ in the X_{ad}-base reciprocal system. In Fig. 3, the effective field current contributing to the electro-magnetic interaction is $(1 - K_w i_{dw})I_{fd}$, represented in the commonly-used per unit system.

Draw phasor $X_{ad}i_d$ on d-axis, step ❺ in Fig. 5 and Fig. 6. From the phasor diagrams we have:

$$(1 + S_a)\psi_{dg} = (1 + S_a)\left(V_q + R_a i_q + X_l i_d\right) = (1 - K_w i_{dw})I_{fd} - X_{ad}i_d$$

It is equivalent to the relation given in equation (4). I_{fd} is determined in step ❻. From here, field current, field voltage and rotor winding flux initial values are determined.

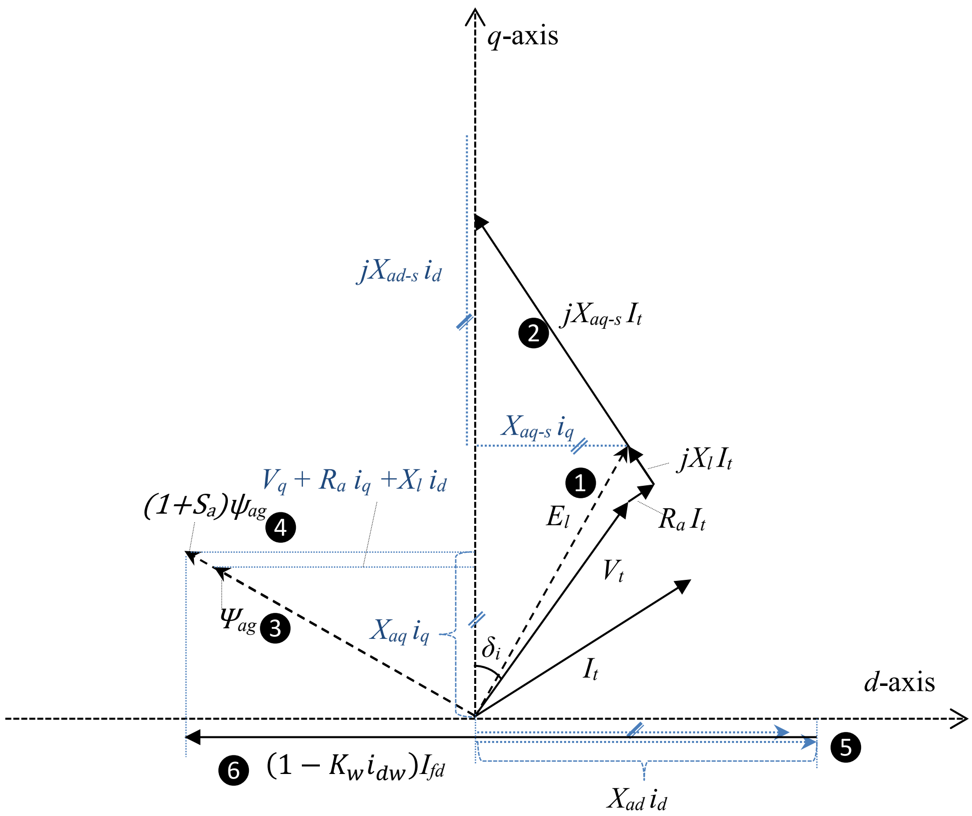


Figure 5: Phasor Diagram of Generator Operated under Lagging Power Factor

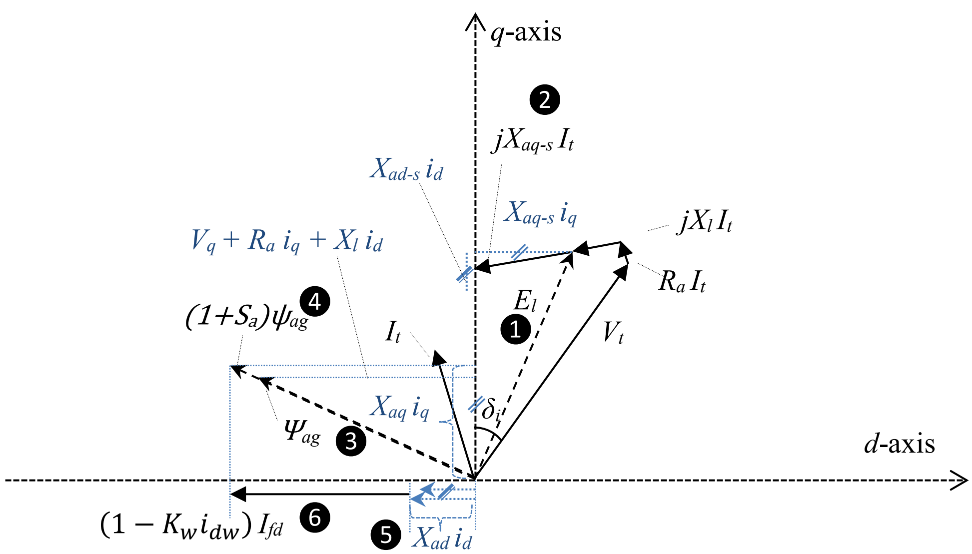


Figure 6: Phasor Diagram of Generator Operated under Leading Power Factor

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