GENQEC Generator Dynamic Model

(A combination of GENQSC and GENESC)

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July 22, 2019
1. **Objective**

   This document provides the detail of a high-accuracy generator dynamic model to be used for power system analysis. It is provided as a reference for the implementation of the model in power system stability analysis software.

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] and 2002 [2]. The GENQEC model function block diagram is given in Fig. 1 on the next page. The derivation process is given in [3] and [4]. The parameters used in the GENQEC model conform to the “standard” generator model parameters provided by the generator manufacturers.

3. **Improvement over Previous and Existing Generator Dynamic Models**

   - Better steady-state 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 for replacing the old generator dynamic models [4]
   - Innovative method to consider the influence of the magnetic saturation on generator rotor winding field current [3]
   - Simple application of magnetic saturation function to 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 modeling [3]

4. **Highlights of the GENQEC Dynamic Model**

   - One model applies to both round-rotor and salient-pole generators
   - Considers saturation effect on both rotor and stator inductance terms
   - Single model with selectable quadratic or exponential saturation function, combines the GENQSC and GENESC models proposed earlier
   - Same magnetic saturation factor applies to both d-axis and q-axis stator inductance terms
   - Uses generator open-circuit saturation characteristics with a simple field current compensation factor to achieve high accuracy of rotor field current
   - Generator field current compensation factor can be derived or tested from the generator zero-power-factor load characteristics
   - 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] and [5]
5. GENQEC Application Details

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

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

\[ i_{dw} = i_d |_{-1}^{+1} \]: represents generator stator current loading factor on d-axis, only used numerically.

\[ 0 \leq K_w < 1; K_w i_{dw} I_f \] represents the portion of \( I_f \) only contributes to the rotor leakage flux.

Figure 1: GENQEC Model Structure
5.2 Saturation functions

GENQEC model structure was derived without involving the saturation function 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 quadratic and exponential saturation function. These two 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) 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 per unit field current is on X-axis.

![Figure 2: Definition of Saturation Factors for Generator Data (source: Siemens/PTI PSS/E PAGV2)](image)

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

a) Quadratic Saturation (use flag 1 in generator model parameters set )

Define: $= \sqrt{1.2 * S_{1.2}/S_{1.0}}; A = (\alpha - 1.2)/(\alpha - 1)$; and $B = S_{1.0}/(1 - A)^2$
Saturation factor $S_a$ with $\psi_{ag}$ as input:

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

(1)

b) Exponential Saturation (use flag 0 in generator model parameters set)

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

Saturation factor $S_a$ with $\psi_{ag}$ as input:

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

(2)

5.3 Rotor field current compensation factor $K_w$

Refer to Fig. 3 for the second-order generator equivalent circuit represented in the $L_{air}$ reciprocal system, from which the function block diagram given in Fig. 1 was derived; and Fig. 4 for typical generator saturation characteristics provided by generator manufacturers.

Figure 3: Second-order Generator Equivalent Circuit for GENQEC Model
The compensation factor $K_w$ (in the current branch “$K_w i_{d0} i_{fd}$” of Fig. 3) is used to account for the increased rotor leakage fluxes when generator is loaded with stator current. This is demonstrated by the zero-power-factor characteristics provided by the manufacturers (also can be obtained by field testing). The slope difference between the OCC and the zero-power-factor line inherently reflects the rotor current compensation factor. 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 zero-power-factor line due to the current in the stator winding. 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.

The compensation factor $K_w$ is ideally determined from the linear region of the zero-power-factor load characteristics 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. Two methods are proposed here for obtaining the value of $K_w$. The latter was used for comparison results presented in [3].

a) Derived from Zero Power Factor Characteristics:

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. With adjustable
reactive load (reactor/capacitor), the generator terminal voltage is increased gradually (in steps) while keeping the stator current at 1.0 pu.

Take measurements on the 0-pf curve at low voltage level (<0.5 pu). Accurate field current measurement is needed. Provided that good open-circuit saturation characteristic (OCC) measurement results are also available, the field current compensation factor $K_w$ can be calculated.

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 considered. 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 $K_w$ compensation factor derived from the 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 was not considered.)

b) Fitted from Measurements of Online Operating Points:

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- and q-axis current components can be calculated without using generator model parameter $X_q$. If rotor angle measurement is not possible, accurate generator model parameters are essential to have good fitting results 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:

$$I_{fd} = \left[\frac{1+S_a}{\omega}(V_q + R_a i_q) + L_d i_d + S_a L_i i_d\right] / (1 - K_w i_{dw})$$ (3)

With base values of the generator known (very importantly the field current base), per unit field current can be compared from that calculated from the model using above equation. Adjusting $K_w$ to compare the per-unit field current values calculated from model and with that measured. 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 Use GENQEC to Represent Different Types of Generators

(Reactance and inductance may be used interchangeably 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” model parameters provided by the manufacturer or validated from field tests.

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:

- $L^* = L'_q = L_q$ 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 Special Consideration of Initialization

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. The saturation factor at that particular operating point can be obtained based on the air-gap potential (flux) calculated from generator terminal conditions and the leakage reactance. The rest of the initialization process is similar to the method currently being in use, with the initial values of all the quantities strictly conforming to the relations given in Fig. 1 and Fig. 3.

References