White Paper on GENQEC Model in Power System Studies

WECC PPMVDWG

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Introduction

The WECC Modeling and Validation Subcommittee (MVS) approved the GENQEC synchronous generator model on December 3, 2020, after the implementation and benchmark among the commonly used power system analysis software (PSLFTM, PSS®E, PowerWorld Simulator and DSA Tools™/TSAT [1]). The GENQEC keeps the parameter compatibility with the earlier second-order generator dynamic models such as GENROU, GENSAI, with major improvements in saturation treatment. Compared with currently used generator model GENTPJ in North America, GENQEC model has proven dynamic performance improvement through theoretical analysis and simulation results. The steady-state accuracy improvement on modeled field current has been proven using field test data from over one hundred generators with capacity ranging from 4 MVA to 835 MVA.

This white paper is intended to serve as a technical reference for those interested to validate synchronous generator model parameters using GENQEC model. The method is based on the improvement to generator decrement test in [2].

The GENQEC model

GENQEC model structure

GENQEC model was developed from the second-order generator equivalent circuits given in the IEEE Standard 1110. The full derivation process of the block diagram is given in [3] [4] and provided in Appendix A of this White Paper. The most distinctive difference of the GENQEC model from all previous generator models is that it uses a completely new method to include saturation effect in positive sequence generator model to achieve good accuracy. The root of the GENQEC model could be traced to the zero-power-factor characteristics, on which the Potier Reactance is derived. A machine dependent compensation factor, $K_w$, is introduced in GENQEC model. The meaning of $K_w$ is illustrated in Figure 1 below, and more detail of this compensation factor is explained in [5].

Table 1 compares the major difference between GENQEC and several commonly available second-order models [6]. The improvement of GENQEC over the previous models can be seen from various aspects of the new implementation method of magnetic saturation and generator field current compensation.
Fig. 1 Generator Saturation Characteristics, Potier Reactance and Kw in GENQEC Model

Table 1. Characteristic Comparison of second-order Generator Dynamic Models

<table>
<thead>
<tr>
<th>Characteristic of Model</th>
<th>GENQEC</th>
<th>GENTPJ</th>
<th>GENROU</th>
<th>GEN SAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Magnetic saturation impacts all inductances</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>#2 Magnetic saturation impacts Time Constants</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>#3 +Id (+Mvar) cause additional increase of If</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>#4 -Id (-Mvar) cause extra decreases of If</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>#5 D-axis and Q-axis degree of magnetic saturation</td>
<td>Same</td>
<td>Different</td>
<td>Different</td>
<td>No Q-axis saturation</td>
</tr>
</tbody>
</table>
**GENQEC model application to different types of generators**

**GENQEC model parameters**

GENQEC model uses classical representation of the standard generator parameters. Refer to Appendix A for parameter derivation from its $X_{ad}$-base reciprocal equivalent circuit representations.

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SatFlag, Saturation function selection flag (0-Exponential; 1-Scaled quadratic; 2-Quadratic)</td>
</tr>
<tr>
<td>$T'_{do}$ (sec), d-axis transient rotor time constant</td>
</tr>
<tr>
<td>$T''_{do}$ (sec), d-axis sub-transient rotor time constant</td>
</tr>
<tr>
<td>$T'_{qo}$ (sec), q-axis transient rotor time constant</td>
</tr>
<tr>
<td>$T''_{qo}$ (sec), q-axis sub-transient rotor time constant</td>
</tr>
<tr>
<td>H (&gt;0), Inertia constant</td>
</tr>
<tr>
<td>D (pu), Damping factor</td>
</tr>
<tr>
<td>$X_d$, d-axis synchronous reactance</td>
</tr>
<tr>
<td>$X_q$, q-axis synchronous reactance</td>
</tr>
<tr>
<td>$X_{d}'$, d-axis transient reactance</td>
</tr>
<tr>
<td>$X_{q}'$, q-axis transient reactance</td>
</tr>
<tr>
<td>$X_{d}''$, d-axis sub-transient reactance</td>
</tr>
<tr>
<td>$X_{q}''$, q-axis sub-transient reactance</td>
</tr>
<tr>
<td>$X_l$, stator leakage reactance</td>
</tr>
<tr>
<td>S(1.0), saturation factor at 1.0 pu flux</td>
</tr>
<tr>
<td>S(1.2), saturation factor at 1.2 pu flux</td>
</tr>
<tr>
<td>$K_w$ (0 &lt; $K_w$ &lt; 0.4), rotor field current compensation factor</td>
</tr>
</tbody>
</table>

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

- Rotor d-axis: Rotor field winding and one equivalent damper winding
- Rotor q-axis: Two equivalent damper windings
  - Use “standard” generator model parameters including all synchronous, transient and sub-transient model parameters on d-axis and q-axis.

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

- Rotor d-axis: Rotor field winding and one equivalent damper winding
- Rotor q-axis: One equivalent 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.
Determine $K_w$

Since GENQEC model was developed from the second-order generator equivalent circuits given in the IEEE Standard 1110. All parameters are standard generator parameters which can be achieved by using the testing method given in IEEE Standard 115. Only $K_w$ in GENQEC needs special attention. This chapter introduced a simple and practical method to obtain the compensation factor $K_w$ for GENQEC model.

$K_w$ was defined as the slope difference between the linear regions of the zero-power-factor line (0-P.F.) and the open circuit characteristics (OCC), as seen in Fig. 1. The consideration of applying the $K_w$ factor can be found in [5], and the GENQEC equivalent circuits are given in Appendix A. This session will focus on determining the $K_w$ factor in practice, from field measurement data through calculation.

From GENQEC model block diagram, in steady state when $\omega = 1$, the $K_w$ factor can be obtained from the below relation when a constant, unsaturated generator synchronous inductance $L_d$ is known.

$$L_d i_d = (1 - K_w i_d) I_{fd} - (1 + S_a)(V_q + R_a i_q) - S_a L_l i_d$$

(1)

Where,

$L_d$: Generator d-axis synchronous inductance (also will be determined from this method)

$i_d$: D-axis component of generator stator current (calculated from measurements, P, Q, Vt, etc.)

$i_q$: Q-axis component of generator stator current (calculated from measurements, P, Q, Vt, etc.)

$I_{fd}$: Generator rotor field winding current (measured data)

$V_q$: Q-axis component of generator terminal voltage (calculated from measurement, Vt, P, Q, etc.)

$R_a$: Stator winding resistance (from OEM)

$L_l$: Stator winding leakage inductance (from OEM)

$S_a$: A factor representing the degree of magnetic saturation at a given operating point, calculated based on OCC, between the air-gap flux and the stator-rotor combined magneto-motive-force.

Linear regression is used to eliminate the random measurement error which may exist in the field data. It is suggested to use not less than 15 points of online measurement data including terminal voltage $V_t$, active power P, reactive power Q, and field current $I_{fd}$, for using this method to calculate $K_w$.

A pair of characteristic saturation factors, i.e., S1.0 & S1.2, used to represent the generator open-circuit saturation characteristics, is needed. The saturation function type needs to be specified by setting the SatFlag in the GENQEC model parameter. Due to the sensitivity of the rotor angle measurement to the mechanical reference signal on the rotor shaft (especially for salient-pole machines), it is recommended to use generator’s q-axis synchronous inductance, $L_q$, to calculate generator internal rotor angle when using this method. (The generator q-axis synchronous inductance can be validated using measurement
results with larger rotor angles where the measured values are less-susceptive to the mechanical reference.) Generator stator winding leakage inductance $L_l$ (and resistance $R_a$, if known), are also needed in the calculation.

The unsaturated $L_d$ in equation (1) is a constant per its definition, so the linear function at the left-hand side of equation (1) with reference to $i_d$ should be reflected in the values calculated for all the measurement points on the right-hand of equation (1). In other words, the calculated values of the right-hand side of equation (1) shall conform to a distribution along a linear line in a plot with $i_d$ on X-axis. The only undetermined variable $K_w$ in equation (1) can be chosen in equation (1) such that we can use linear regression with all the online measurement points on the right-hand side of equation (1) to form a most-suitable linear line.

More detailed explanation about this method is illustrated with example steps below.

**Step 1. Gather parameters and field measurements for calculation**

First step is to gathering generator information needed for calculating $K_w$. That includes the data from manufacture and field measurement. Those data are listed as an example in table 2 and 3 below.

**Table 2. 83.5 MVA Salient-pole Generator Parameters**

<table>
<thead>
<tr>
<th>Sbase (MVA)</th>
<th>Vt base (kV)</th>
<th>$L_l$</th>
<th>$L_q$</th>
<th>$S_{1.0}$</th>
<th>$S_{1.2}$</th>
<th>$R_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>83.5</td>
<td>13.8</td>
<td>0.15</td>
<td>0.7</td>
<td>0.19</td>
<td>0.55</td>
<td>0.004</td>
</tr>
</tbody>
</table>

**Table 3. 83.5 MVA Salient-pole Online Measurement Data**

<table>
<thead>
<tr>
<th>No.</th>
<th>Active Power (MW)</th>
<th>Reactive Power (Mvar)</th>
<th>Terminal Voltage (kV)</th>
<th>Field Current (A)</th>
<th>No.</th>
<th>Active Power (MW)</th>
<th>Reactive Power (Mvar)</th>
<th>Terminal Voltage (kV)</th>
<th>Field Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.44</td>
<td>-38.62</td>
<td>13.26</td>
<td>255</td>
<td>34</td>
<td>40.02</td>
<td>-19.49</td>
<td>13.55</td>
<td>495</td>
</tr>
<tr>
<td>2</td>
<td>-0.45</td>
<td>-32.44</td>
<td>13.40</td>
<td>305</td>
<td>35</td>
<td>40.48</td>
<td>-15.29</td>
<td>13.59</td>
<td>529</td>
</tr>
<tr>
<td>3</td>
<td>-0.57</td>
<td>-29.61</td>
<td>13.47</td>
<td>330</td>
<td>36</td>
<td>40.11</td>
<td>-10.74</td>
<td>13.63</td>
<td>560</td>
</tr>
<tr>
<td>4</td>
<td>-0.49</td>
<td>-25.25</td>
<td>13.50</td>
<td>361</td>
<td>37</td>
<td>40.11</td>
<td>-4.92</td>
<td>13.67</td>
<td>604</td>
</tr>
<tr>
<td>5</td>
<td>-0.61</td>
<td>-20.91</td>
<td>13.54</td>
<td>395</td>
<td>38</td>
<td>40.21</td>
<td>-0.53</td>
<td>13.7</td>
<td>650</td>
</tr>
<tr>
<td>6</td>
<td>-0.73</td>
<td>-13.58</td>
<td>13.50</td>
<td>442</td>
<td>39</td>
<td>40.09</td>
<td>5.52</td>
<td>13.76</td>
<td>699</td>
</tr>
<tr>
<td>7</td>
<td>-0.75</td>
<td>-12.12</td>
<td>13.61</td>
<td>465</td>
<td>40</td>
<td>40.23</td>
<td>9.98</td>
<td>13.78</td>
<td>744</td>
</tr>
<tr>
<td>8</td>
<td>-0.78</td>
<td>-4.75</td>
<td>13.67</td>
<td>526</td>
<td>41</td>
<td>40.29</td>
<td>14.4</td>
<td>13.82</td>
<td>784</td>
</tr>
<tr>
<td>9</td>
<td>-0.67</td>
<td>-0.2</td>
<td>13.71</td>
<td>565</td>
<td>42</td>
<td>40.08</td>
<td>20.49</td>
<td>13.87</td>
<td>844</td>
</tr>
<tr>
<td>10</td>
<td>-0.82</td>
<td>5.75</td>
<td>13.75</td>
<td>621</td>
<td>43</td>
<td>40.1</td>
<td>26.58</td>
<td>13.92</td>
<td>908</td>
</tr>
<tr>
<td>11</td>
<td>-0.91</td>
<td>10.22</td>
<td>13.79</td>
<td>664</td>
<td>44</td>
<td>40.29</td>
<td>31.27</td>
<td>13.95</td>
<td>961</td>
</tr>
<tr>
<td>12</td>
<td>-1</td>
<td>14.7</td>
<td>13.83</td>
<td>712</td>
<td>45</td>
<td>40.24</td>
<td>42.19</td>
<td>14.04</td>
<td>1090</td>
</tr>
</tbody>
</table>
Step 2. Determine field current base value

Before the measured field current can be converted to per unit, a field current base value is needed. Typically, the field current base value is obtained from open-circuit saturation test results when the measured terminal voltage is plotted against the field current. In the absence of the good open-circuit test data, the field current base value can be determined as below:

Reorganizing equation (1), noting that

\[ I_{fd} = \frac{I_{fd, meas}}{I_{fd, base}} \]

where \( I_{fd, meas} \) is the measured field current in amperes and \( I_{fd, base} \) is the field current base in amperes, we have:

\[
\frac{1-K_{wd}}{I_{fd, base}} = \frac{(1+S_d)\left(V_q + R_{alq} \right) + S_d L_{ld} I_d + L_{ld} I_d}{I_{fd, meas}} \quad (2)
\]

The right-hand side of Equation (2) is calculated from measurement data for each operating point and plotted against \( i_d \). The \( K_w \) on the left-hand side of (2) is also one factor to be determined in this expression, and it is independent from \( i_d \) in the right-hand expression. The most important observation from (2) is that \( I_{fd, base} \) can be determined with \( i_d=0 \) when the left-hand side of (2) becomes \( 1/I_{fd, base} \).

Using polynomial trend plot based on the calculated values of the right-hand expression of (2) against \( i_d \), let \( i_d=0 \), the field current base value obtained from the online measurements for this unit is 492.5A.
Step 3. Linear regression on $L_d$ to determine $K_w$

Linear regression method is applied to the calculated values of the right-hand side of equation (1) with reference to $i_d$. Since $K_w$ is also undetermined, the criterion used is to decide the most-straight line of $(L_d i_d)$ by adjusting $K_w$.

Fig. 2 shows the calculated $y = L_d i_d$ as a function of $i_d$ when $K_w$ is set to zero, where linear and second-order polynomial trend lines are plotted. Fig. 3 shows the calculated $L_d i_d$ when $K_w$ is set to a value of 0.4, also with linear and second-order polynomial trend lines plotted. It can be observed that the polynomial trendline curves upwards with $K_w=0$ but downwards with $K_w=0.4$. Based on the involvement of $K_w$ in equation (1), it is reasonable to expect that between 0 and 0.4 there exists a $K_w$ value which could make the polynomial trendline closely overlays with the linear one. By gradually adjusting $K_w$ value, it is found that $K_w=0.2235$ gives the best match between the second-order polynomial and linear trendlines, as can be seen in Fig. 4. The two trend lines are virtually overlapping each other. The trendline equations in Fig. 4 also provide the ideal $L_d$ value with the chosen $K_w$.

Statistically with all the measurement points considered, this $L_d=0.982$ with $K_w=0.2235$ will have the best modeling results with least error.

Once this pair of $L_d$ and $K_w$ having the least linear regression error on $L_d$ is found, the corresponding differences (or errors) of the modeled field current for each measurement points are also known from the calculation.

![Fig. 2. Online measurements calculated $L_d i_d$ with $K_w = 0$](image-url)
Fig. 3. Online measurements calculated $L_d i_d$ with $K_w = 0.4$

Fig. 4. Online measurements calculated $L_d i_d$ with $K_w = 0.2235$
Step 4. (Optional) VEE Curve Results Comparison with Determined $L_d$ and $K_w$

Previous three steps illustrated a whole process of obtaining $K_w$, as well as $L_d$. The step 4 using VEE curve can be used as an option to double check the $K_w$ value. The Fig 5 and Fig 6 below are the VEE curve plots using $K_w$ achieved from step 3 for the same generator in the example.

![Fig. 5. Measured and modeled field current comparison with reference to reactive power](image1)

![Fig. 6. Measured and modeled field current comparison with reference to stator current](image2)
Existing generator model migration to GENQEC

Generator models based on the second-order equivalent circuits can be simply converted to GENQEC once the Kw is determined. These second-order equivalent-circuit based models include GENROU, GENROE, GENSAL and GENSAE. It is not recommended to perform direct parameter mapping from GENTPJ to GENQEC, because of the possible modification of GENTPJ to the model parameters when converted from the earlier models.

In the parameter conversion, the parameters in GENQEC are mapped one-to-one directly from the earlier second-order generator models, except those parameters explicitly marked below.

Round-rotor generator (GENROU, GENROE to GENQEC)

Salient-pole generator (GENSAL, GENSAE to GENQEC)

(For GE PSLF™ program, the quadratic saturation model in GENROU and GENSAL may need to use SatFlag = 2 when converting to GENQEC. Using SatFlag=2 will still keep the same compatibility level between the Siemens/PTI PSS®E and GE PSLF using the previous models.)
Appendix A

GENQEC model block diagram and its equivalent circuit representation

Nomenclature

\( i_d \): D-axis component of generator stator current
\( i_q \): Q-axis component of generator stator current
\( V_q \): Q-axis component of generator stator voltage
\( I_{fd} \): Generator rotor field winding current
\( E_{fd} \): Generator rotor field winding voltage
\( R_q \): Generator stator winding resistance
\( L_d \): Generator direct-axis synchronous inductance,
\( (L_d = L_{ad} + L_t) \)
\( L_q \): Generator quadrature-axis synchronous inductance
\( S_a \): A factor representing the degree of magnetic saturation at a given operating point, reflected in the generator’s open-circuit saturation characteristics
\( K_w \): A factor in the GENQEC model to compensate \( I_{fd} \) for the field winding leakage variation associated with \( i_d \)
\( L_t \): Stator winding leakage inductance
\( L_{ad} \): Stator to rotor winding d-axis mutual inductance
\( L_{fd} \): Rotor field winding leakage inductance
\( L_{1d} \): Rotor d-axis damper winding leakage inductance
\( R_{1d} \): Rotor d-axis damper winding resistance
\( R_f \): Rotor field winding resistance
\( \psi_d \): Stator winding d-axis total flux
\( \psi_{1d} \): Rotor d-axis damper winding total flux
\( \phi_{1d} \): Rotor field winding total flux
\( L_{11d} = L_{ad} + L_{1d} \): Rotor d-axis damper winding inductance
\( L_{ffd} = L_{ad} + L_{fd} \): Rotor field winding self-inductance

GENQEC D-axis Saturation

GENQEC model considers the magnetic saturation primarily on the mutual inductance between the generator rotor and stator windings, as shown in Fig. A-1. The inclusion of magnetic saturation on rotor windings’ leakages is for the benefit of using the classical representation of the generator “standard” parameters, as can be seen from the derivation process given below.

\[
\begin{align*}
\psi_d &= -\frac{L_{ad} i_d - S_d L_{ad} i_d}{(1+S_d)} + \frac{L_{ad}(1-K_w i_d) L_{fd}}{(1+S_d)} + \frac{L_{ad} i_{1d}}{(1+S_d)} \quad (A-1) \\
\psi_{1d} &= -\frac{L_{ad} i_d}{(1+S_d)} + \frac{L_{f_{1d}}}{(1+S_d)} + \frac{L_{1d} i_{1d}}{(1+S_d)} \quad (A-2) \\
e_{f_{1d}} &= s \psi_{1d} + R_{f_{1d}} i_{1d} \quad (A-4) \\
0 &= s \psi_d + R_{1d} i_{1d} \quad (A-5)
\end{align*}
\]

To convert to the commonly used per unit system in power system stability studies, we use base values denoted with an overbar accent, which have below relations with the \( L_{ad} \)-base reciprocal per unit system:

\[
\begin{align*}
\bar{\psi}_d &= \psi_d \quad (A-6) \\
\bar{i}_d &= i_d \quad (A-7) \\
\bar{\psi}_{1d} &= \psi_{1d} \quad (A-8) \\
\bar{i}_{1d} &= i_{1d} \quad (A-9) \\
\overline{I_{fd}} &= L_{ad} I_{fd} \quad (A-10)
\end{align*}
\]
\[
\bar{\psi}_{fd} = \frac{l_{ad}}{l_{ffd}} \psi_{fd} \quad (A-11)
\]
\[
\bar{E}_f = \frac{l_{ad}}{R_{fd}} e_{fd} \quad (A-12)
\]

Using (A-6), (A-7), (A-9) and (A-10), Eq. (A-1) can be re-written as:
\[
(1 + S_d)\bar{\psi}_{fd} = -L_{ad}\bar{i}_d - S_d L_{1d}\bar{i}_d + (1 - K_w l_i)\bar{I}_{fd} + L_{ad}\bar{i}_{1d} \quad (A-13)
\]

Apply (A-7), (A-9), (A-10) and (A-11) to (A-2), we have:
\[
(1 + S_d)\bar{\psi}_{fd} = -\frac{l_{ad}^2}{l_{ffd}} i_d + (1 - K_w l_i)\bar{I}_{fd} + \frac{l_{ad}^2}{l_{ffd}} \bar{i}_{1d} \quad (A-14)
\]

In generator’s second-order model, the classical representation of d-axis transient inductance \(L_d\) (a standard parameter) is defined as: \(L_{ad}\) in parallel with \(L_{fd}\), then added to the stator leakage \(L_i\); i.e., \(L'_d = \frac{l_{ad} l_{fd}}{l_{ad} + l_{fd}} + L_i\). Consider the definition of \(L_d\) and \(L_{ffd}\), below relation exists:
\[
L_d - L'_d = \frac{l_{ad}^2}{l_{ffd}} \quad (A-15)
\]

Eq. (A-14) can be re-written as:
\[
(1 + S_d)\bar{\psi}_{fd} = (1 - K_w l_i)\bar{I}_{fd} + (L_d - L'_d)(\bar{i}_{1d} - \bar{i}_d) \quad (A-16)
\]

Using (A-7) to (A-10), Eq. (A-3) can be re-written as:
\[
(1 + S_d)\bar{\psi}_{1d} = -L_{ad}\bar{i}_d + (1 - K_w l_i)\bar{I}_{fd} + L_{1d}\bar{i}_{1d} \quad (A-17)
\]

Apply (A-10), (A-11) and (A-12) to Eq. (A-4),
\[
\frac{R_{fd}}{l_{ad}} \bar{E}_f = s \frac{l_{ffd}}{l_{ad}} \bar{\psi}_{fd} + \frac{R_{fd}}{l_{ad}} \bar{I}_{fd} \quad (A-18)
\]

After simplification,
\[
\bar{E}_f = s \frac{l_{ffd}}{R_{fd}} \bar{\psi}_{fd} + \bar{I}_{fd} \quad (A-19)
\]

Generator’s d-axis open-circuit transient time constant is defined as \(T'_{do} = \frac{l_{ffd}}{R_{fd}}\) according to its classical representation. We have:
\[
\bar{E}_f = s T'_{do} \bar{\psi}_{fd} + \bar{I}_{fd} \quad (A-20)
\]

Eq. (A-5) can be re-written using Eqs. (A-8) and (A-9),
\[
0 = s \bar{\psi}_{1d} + R_{1d} \bar{i}_{1d} \quad (A-21)
\]

The relations given in Eqs. (A-13), (A-16), (A-17), (A-20) and (A-21) can be expressed using the classical representation of the standard generator model parameters, with mathematical derivations shown below.

Subtract Eq. (A-17) from Eq. (A-16), we have:
\[
(1 + S_d)(\bar{\psi}_{fd} - \bar{\psi}_{1d}) = (L'_d - L_d)\bar{i}_d - (L_d - L'_d + L_{1d})\bar{i}_{1d} \quad (A-22)
\]

From Eq. (A-21), \(\bar{i}_{1d} = -s \bar{\psi}_{1d} \frac{R_{1d}}{R_{1d}}\). Define the generator d-axis open-circuit sub-transient time constant \(T'_d = \frac{L_d - L_{1d} + L_{1d}}{R_{1d}}\), the above equation becomes:
\[
(1 + S_d)(\bar{\psi}_{fd} - \bar{\psi}_{1d}) = (L'_d - L_d)\bar{i}_d + s T'_{do} \bar{\psi}_{1d} \quad (A-23)
\]

When the generator d-axis sub-transient inductance \(L'_d\) is defined using its classical representation, \(L'_d = \frac{l_{ad} l_{fd} l_{1d}}{l_{ad} + l_{fd} + l_{1d}} + L_i\). It can be proven that \(\frac{1}{L_d - L'_d} = \frac{L_d - L_{1d}}{(L_d - L_i)^2}\).

Accordingly, from Eq. (A-21),
\[
\bar{i}_{1d} = -s T'_{do} \bar{\psi}_{1d} \frac{R_{1d}}{L_d - L_{1d} + L_{1d}} = -\frac{L'_d - L_d}{(L_d - L_i)} s T'_{do} \bar{\psi}_{1d} \quad (A-24)
\]

Note that the above parameters of \(T'_{do}, T'_d, L'_d\) and \(L_d\) are all defined according to the classical representation of the standard parameters of second-order generator model described in Chapter 4 of Prabha Kundur’s Power System Stability and Control [7].

From Fig. A-1, the \(L_{ad}\) –base reciprocal per unit system representation, we can see,
\[
\frac{(\psi_{1d} - \psi_{do}) (1 + S_d)}{L_{1d}} + \frac{(\psi_{fd} - \psi_{do}) (1 + S_d)}{L_{fd}} = \bar{i}_d + \frac{\psi_{do} (1 + S_d)}{l_{ad}} \quad (A-25)
\]
It can also be written as

\[
\frac{\psi_{1d}}{L_{1d}} + \frac{\psi_{fd}}{L_{fd}} = \frac{i_d}{1+S_d} + \psi_{dg} \left( \frac{1}{L_{ad}} + \frac{1}{L_{fd}} + \frac{1}{L_{1d}} \right) = \frac{i_d}{1+S_d} + \psi_{dg} \left( \frac{1}{L_{ad} - L_{1d}} \right) \tag{A-26}
\]

Also from Fig. A-1, \( \psi_{dg} = \psi_d + L_i i_d \). Substitute \( \psi_{dg} \) into (A-26),

\[
\frac{(L_a - L_i)\psi_{1d}}{L_{1d}} + \frac{(L_a - L_i)\psi_{fd}}{L_{fd}} = \psi_d + L_i i_d + \frac{(L_a - L_i)i_d}{1+S_d} \tag{A-27}
\]

The relation below can be easily obtained:

\[
\frac{L_a - L_i}{L_{1d}} = \frac{L_{ad} L_{fd}}{L_{ad} L_{fd} + L_{ad} (L_{1d} + L_{1d} L_{fd})} \tag{A-28}
\]

In addition, the second term on the left-hand side of Eq. (A-27) can be changed to commonly-used per-unit system:

\[
\frac{L_a - L_i}{L_{1d}} \psi_{fd} + \frac{L_{ad} L_{fd}}{L_{ad} L_{fd} + L_{ad} L_{1d} L_{fd}} \frac{L_{ad} L_{fd}}{L_{ad} L_{fd}} \psi_{fd} = \frac{L_a - L_i}{L_{1d}} \psi_{fd} \tag{A-29}
\]

Substitute Eqs. (A-28) and (A-29) into Eq. (A-27), also noting \( \psi_d = \psi_{ad} \) and \( i_d = i_{ad} \),

\[
\frac{L_a - L_i}{L_{1d}} \psi_{ad} + \frac{L_a - L_i}{L_{1d}} \psi_{ad} = \psi_{ad} + L_i i_{ad} + \frac{(L_a - L_i)i_d}{1+S_d} i_d \tag{A-30}
\]

We can use Eqs. (A-16), (A-20), (A-23), (A-24) and (A-30) to construct a block diagram, shown in the top half of Fig. A-2, the complete GENQEC model block diagram. The overbar notation is dropped, considering only the commonly used per unit system exists in stability analysis. GRNQEC model structure is similar to the previous GENROU/GENSAE model except the implementation of the magnetic saturation and field current compensation factor \( K_w \).

**GENQEC Q-axis Saturation**

From Fig. A-3 GENQEC q-axis equivalent circuit, following the same derivation process (omitted here), we can obtain the lower half of the block diagram shown in Fig. A-2.

GENQEC dynamic model can be completely represented either using its equivalent circuits in Figs. A-1 and A-3, or using the block diagram in Fig. A-2 (with network interfaces added.)

**Figure A-2: GENQEC Model Block Diagram**

**Fig. A-3 GENQEC Q-axis equivalent circuit**

**References:**


