Practical Assessment of Synchronous Generator Dynamic Model Parameters

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Introduction

Accuracy of power system stability investigation and reliability of the study results depends on the accuracy of the used dynamic models of generating units. More accurate models ensure more reliable evaluation of maximum permissible capacities of power flows, loadings of separate generating units and possibilities of transient processes control.

Identification of dynamic models for power system stability and transient studies requires large amount of information about the equipment and its characteristics. The lack of data may make uncertainties in evaluation of dynamic models of generating units as well as simulation of operating conditions of power system.

Dynamic model of synchronous generator

The synchronous generator may be presented by the operator expressions for the direct and quadrature axes:

$$L_d(s) = L_d \cdot \frac{(1 + sT_{d0})(1 + sT_{d1})\ldots(1 + sT_{dn_d+1})}{(1 + sT_{d0})(1 + sT_{d1})\ldots(1 + sT_{dn_d+1})},$$  (4)

$$L_q(s) = L_q \cdot \frac{(1 + sT_{q0})(1 + sT_{q1})\ldots(1 + sT_{qn_q+1})}{(1 + sT_{q0})(1 + sT_{q1})\ldots(1 + sT_{qn_q+1})}. $$  (5)

here $T_{dl}$ is the flux linkage time constant; $T_{d}$ and $T_{q}$ is the short circuit time constants of d and q axes; $T_{d0}$ and $T_{q0}$ is the short circuit time constants of d and q axes; $n_d$ and $n_q$ is the number of circuits of d and q axes.

In practice, two-circuit diagrams of d and q axes are used for modeling of synchronous generators [2].

The producing of synchronous generator dynamic models and the calculation of their parameters need to know the type of generator, and the nominal total power $S_N$, active power $P_N$, nominal power factor of $\cos \phi$, the nominal generator voltages and currents $U_N$ and $I_N$, the field voltage and current $U_f$ and $I_f$ and the power diagram $Q_G = f(P_G)$.

The main generator dynamic parameters are the inductive reactance’s of direct-axis and quadrature-axis, time constants of field winding at open circuit (no load)
and short circuit and rotor inertia. The detailed list of parameters used in dynamic model is presented in Table 1.

Table 1. Parameters of synchronous generator

<table>
<thead>
<tr>
<th>Inductive reactance's and resistances, in p.u., at rated power and voltage S₀ and Uₖ₀</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. d-axis synchronous inductive reactance</td>
<td>xₙd</td>
</tr>
<tr>
<td>2. q-axis synchronous inductive reactance</td>
<td>xₙq</td>
</tr>
<tr>
<td>3. d-axis transient inductive reactance</td>
<td>xₚd</td>
</tr>
<tr>
<td>4. q-axis transient inductive reactance</td>
<td>xₚq</td>
</tr>
<tr>
<td>5. d-axis subtransient inductive reactance</td>
<td>xₚ₀d</td>
</tr>
<tr>
<td>6. q-axis subtransient inductive reactance</td>
<td>xₚ₀q</td>
</tr>
<tr>
<td>7. Leakage reactance</td>
<td>xₙ</td>
</tr>
<tr>
<td>8. Stator resistance</td>
<td>rₙ</td>
</tr>
<tr>
<td>9. Field circuit resistance **</td>
<td>rₓ</td>
</tr>
</tbody>
</table>

Field circuit time constants

| d-axis open circuit transient time constant ** | T₀d |
| q-axis open circuit transient time constant * | T₀q |
| d-axis open circuit subtransient time constant | T₀d₀ |

Total inertia of generator, turbine and exciter

| Inertia constant, s | T₀ |
| Moment of inertia, kgm² (GD²/4) or | J |
| GD², kgm² | |

Open circuit saturation

| Saturation at rated voltage Uₙ | S(1.0) |
| Saturation at voltage 1.2Uₙ | S(1.2) |

Note: * is the parameter not used for salient rotor (hydro) generators; ** – T₀d₀ and rₓ are given at certain temperature of field winding during measurement.

The dynamic parameters of the synchronous generator can be identified according to two types of field tests:

- regime test – the disconnection of the generator loaded by only reactive load;
- frequency response test of the stopped generator.

Evaluation of dynamic model parameters according to regime test data

The dynamic parameters of the generator d-axis can be determined with sufficient accuracy according to the regime test data. During the test of unloaded generator which consumes the reactive power from the network, the terminal voltage and current are registered.

Processing of test data according to the voltage variation, the d-axis parameters xₚ₀d, xₚ₀q, xₚd, Tₚ₀d, Tₚ₀q are determined.

Terminal voltage of the disconnected generator can be expressed as follows

\[ U(t) = U_∞ + \left( U'_0 - U_∞ \right) e^{-\frac{t}{T₀d}} + \left( U''_0 - U'_0 \right) e^{-\frac{t}{T₀d₀}} \]

or

\[ U(t) = U_0 - I₀ \cdot xₚd + I₀ \cdot \left( xₚ₀d - xₚd \right) e^{-\frac{t}{T₀d₀}} + I₀ \cdot \left( xₚ₀d - xₚ₀q \right) e^{-\frac{t}{T₀q}} \]

(6)

(7)

here U₀, I₀, Uₙ₀ is the initial voltage and current and the steady state voltage of the disconnected generator; U₀, Uₙ₀ is the initial values of transient and sub transient voltages; Tₚ₀d, Tₚ₀q is the direct axis open circuit transient and sub transient time constants; xₚ₀d, xₚ₀q, xₚd is the direct axis synchronous, transient and sub transient inductive reactance's.

The variation in voltage when the generator that is loaded with capacitive reactive load was switched off is shown in Fig. 2. The initial value of the sub transient voltage Uₙ₀ can be expressed from the first voltage jump and a sub transient inductive resistance value can be found:

\[ U''_0 = U₀ - I₀ \cdot xₚd \cdot \frac{t}{T₀d₀} \]

\[ xₚd = \frac{U₀ - U''_0}{I₀} \]

At the subsequent voltage curve point (when the short-term voltage component extinct) derived tangent to the line that corresponds settled voltage Uₙ can be determined.

Extrapolating the curve of the exponential transient voltage U₀ to the stoppage time the value of U₀ is determined. According to it, the direct axis transient inductive resistance xₚ₀d value is determined as follows

\[ xₚ₀d = \frac{U₀ - U''_0}{I₀} \]

(10)

The d-axis synchronous inductive resistance value is determined similarly

\[ xₚ₀d = \frac{U₀ - Uₙ₀}{I₀} \]

(11)

Table 2. Typical ratios for the d and q axis generators parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Non-salient pole generator</th>
<th>Salient pole generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>xₚ₀d</td>
<td>0.9 xₚ₀d</td>
<td>(0.6-0.7) xₚ₀d</td>
</tr>
<tr>
<td>xₚ₀q</td>
<td>1.5 xₚ₀q</td>
<td>xₚ₀q</td>
</tr>
<tr>
<td>T₀d₀</td>
<td>0.3 T₀d₀</td>
<td>T₀d₀</td>
</tr>
<tr>
<td>T₀dq</td>
<td>T₀dq</td>
<td></td>
</tr>
</tbody>
</table>

The value of the d-axis sub transient time constant T₀dq is defined by extrapolating the tangent at certain point of the Uₙ₀ curve to the derived U₀ curve.

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The leakage resistance of the stator inductive reactance $x_l$ value is not normally determined with the tests. It can be assessed in accordance with the manufacturers’ data or approximately according to longitudinal resistance $x_d$:

$$x_l \approx 0.08 \times x_d.$$

Appropriate parameters of the $q$ axis can be extrapolated in accordance to typical $d$ and $q$ axis ratios that are presented in Table 2.

**Evaluation of dynamic model parameters according to frequency response test of the stopped generator**

The data of the stopped generator frequency response test allows identifying the main parameters of $d$ and $q$ axes: $x_{d0}$, $x'_{d0}$, $x_{q0}$, $x'_{q0}$, $T_{d0}$, $T_{q0}$, $T''_{d0}$, $T''_{q0}$ and resistances of the stator and rotor $r_s$ and $r_r$.

During the test, stator voltage and current and rotor current instant values were recorded.

During the test data processing complex input reactance of the $d$ and $q$ axes – $Z_d(s)$ and $Z_q(s)$; transfer function stator $sG(s)$ for the different frequencies ($s=j\omega$) are determined. Operator values of the inductances $L_d(s)$ and $L_q(s)$ determine estimating stator resistance:

$$L_d(s) = \frac{Z_d(s) - r_a}{s},$$  \hspace{5mm} (12)

$$L_q(s) = \frac{Z_q(s) - r_a}{s},$$  \hspace{5mm} (13)

here $r_a$ – the active resistance of stator windings, measured during the test at the temperature of windings.

With operator transfer functions and inductance values and expanded with polynomial ratio the dynamic parameters of $L_d$, $T_{d0}$, $T''_{d0}$, $T''_{d}$ and $L_q$, $T_{q0}$, $T''_{q0}$, $T''_{q}$ are determined. Parameters normally used to determine by frequency identification methods [3].

During the rapid changes of measured value, when $s=j\omega \rightarrow j\infty$, marginal values of the inductances $L_d(s)$, $L_q(s)$ will be equal to transient inductance values $L''_d$ and $L''_q$. $L''_d$ and $L''_q$ are expressed following:

$$L''_d = L_d(j\infty) = L_d \cdot \frac{T''_d}{T''_{d0}},$$  \hspace{5mm} (14)

$$L''_q = L_q(j\infty) = L_q \cdot \frac{T''_q}{T''_{q0}}.$$  \hspace{5mm} (15)

Dynamic expressions of the inductances without the damping windings (the second rotor contour, contour with large time constants) will be less complicated and expressed as follows:

$$L'_d = L_d(j\infty) = L_d \cdot \frac{T'_d}{T_{d0}},$$  \hspace{5mm} (16)

$$L'_q = L_q(j\infty) = L_q \cdot \frac{T'_q}{T_{q0}}.$$  \hspace{5mm} (17)

Rotor poles of the hydro units that are made of the steel sheets and the free currents closes through damping windings of rotor transverse axis. Hydro generators that is usually modeled with “2.1” model, now are designed with one contour in the transverse axis [4]. In case when damping windings time constants are smaller than the excitation windings time constants, it is considered that there is no transient inductance or transient time constants, just transient inductance $L''_q$, and the open circuit and short circuit time constants $T''_{q0}$, $T''_{q0}$. Expression of the transient inductance $L''_q$ is similar to the expression of the transient inductance of the turbo generator

$$L''_q = L_q(j\infty) = L_q \cdot \frac{T''_q}{T_{q0}}.$$  \hspace{5mm} (18)

The test of the frequency response for the stopped generator is recommended only when the routine maintenance is completed and the generating unit is off for long time.

In both cases of parameters’ identification according to regime test and frequency response test of the stopped generator, the test temperature $\theta_0$ and the identified time constant $T_{d0b}$ must be taken into account and the value of excitation windings resistance $r_{q0}$ need to be adjusted to the winding temperature of the nominal regime $\theta_N$:

$$T'_{d0} = T_{d0b} \cdot \frac{234.5 + \theta_B}{234.5 + \theta_N},$$  \hspace{5mm} (19)

$$r_t = r_{q0} \cdot \frac{234.5 + \theta_N}{234.5 + \theta_B}.$$  \hspace{5mm} (20)

**Evaluation of inertia constant**

The inertia time constant $T_J$ of the generating unit is determined from the generator tripping test, where the initial speed $\frac{d\Delta\omega}{dt}|_{t=0}$ is measured and the generator is loaded with low active load $\Delta P$,

$$T_J = \frac{\Delta P}{\frac{d\Delta\omega}{dt}|_{t=0}}.$$  \hspace{5mm} (21)

The initial rotor speed should be recorded with sufficiently high sampling frequency, and the time interval should be within 0.01-0.1 s range.

During the test when unit operates under a small resistive load ($S_Q = (0.1 \div 0.3) \times P_G + j0$ MVA) and is turned off by generator switch, a step output change is applied to the rotor $\Delta P = P_G$, which accelerates unit’s rotor. An initial acceleration $d\Delta\omega/dt(t=0)$ is determined from the registered rotor speed change and a time constant of the unit inertia is determined according to (21).

**Evaluation of saturation characteristic**

Generator saturation values of $S(1.0)$, $S(1.2)$ characteristics are determined by the open circuit (no load) characteristic (Fig. 3) [5].
The list of parameters of the dynamic model for analysis of electromechanical transient processes and stability conditions in power systems is presented. The parameters of direct and quadrature axes can be evaluated according to frequency response test applied to the stopped generator. If the parameters are evaluated according to regime test data, only direct axis dynamic parameters can be determined directly and the quadrature axis parameters can be evaluated according to typical ratios.

Conclusions

The identification techniques of synchronous generators dynamic model’s parameters according to the field test data are presented in the paper. The most informative method for evaluation of direct and quadrature axes parameters is frequency response test of a stopped generator. If the parameters are evaluated according to regime test data, only direct axis dynamic parameters can be determined directly and the quadrature axis parameters can be evaluated according to typical ratios.

References


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The paper presents analysis of evaluation methods of synchronous generator dynamic model parameters according to field test data. The list of parameters of the dynamic model for analysis of electromechanical transient processes and stability conditions in power systems is presented. The parameters of direct and quadrature axes can be evaluated according to frequency response test applied to the stopped generator. Regime tests of operating generator can be used for evaluation of direct axis parameters as well as for value of inertia constant. The open circuit characteristic is used for evaluation of saturation characteristic. The methodic of parameters’ evaluation is created and equations for their evaluation according to field test data are presented. Ill. 3, bibl. 5, tabl. 2 (in English; abstracts in English and Lithuanian).