Study on Analysis Model for Transient Phenomena of Brushless Synchronous Generator

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Brushless excitation synchronous generators have been widely used because of their ease of operation and maintenance. Until now, in the analyses of transient phenomena, the brushless AC exciter and the permanent magnet generator (PMG) have been conventionally considered to be modeled transfer functions. In this paper, a new model for the brushless synchronous generator is proposed that can simulate the transient phenomena in the field circuit more accurately. The authors verified the model by comparison with the actual measurement of the excitation response of a 400 MVA-class turbogenerator with brushless excitation.

Keywords: brushless synchronous generator, transient phenomena, EMTP analysis

1. Introduction

Large-capacity synchronous machines are conventionally used in power utilities. The increase of single-unit capacity in recent years is remarkable, and Toshiba has manufactured many sets of 900–1200 MVA-class 2-pole turbogenerators for customers around the world. As single-unit capacity increases, its influence on the grid system makes a larger contribution in the case of a network fault. Therefore, it is desired to improve the accuracy of the equivalent circuit model for simulating the transient phenomena, including the excitation system.

Currently, the types of excitation system mainly used for turbogenerators are the static excitation system (Fig. 1) and the brushless excitation system (Fig. 2), and chosen between them in accordance with the features and requirements (1–2). The authors have conducted various kinds of studies on transient phenomena in generator systems, including the field winding. This is a common issue for both the static excitation system and the brushless excitation system (3–6).

The study of transient phenomena in the static excitation system is relatively simple, because the excitation voltage is directly applied to the generator’s field winding by using the voltage-phase control of a thyristor rectifier. On the other hand, it is more difficult to study transient phenomena in the brushless excitation system because the AC exciter (ACex) and the permanent magnet generator (PMG) should be taken into consideration. In past analyses of transient phenomena, ACex and PMG have been conventionally expressed as modeled transfer functions combined with the generator’s field winding.

For this issue, the authors have developed a new model (the “total brushless model”) in which each ACex and PMG is considered to be a small generator. The authors studied the results of the transient analysis by comparing them to the results obtained from a conventional model (7–9). Furthermore, the authors verified the total brushless model by comparing it to the actual measurement of the excitation response of a 400 MVA-class turbogenerator with a brushless excitation system. By using the total brushless model, we studied on the excitation response quickness and the stability of the generator. In this paper, those results are reported below.
2. Analytical Model

The equivalent circuit model of the synchronous machine used in this analysis study is the Park model (synchronous machine model 59 in EMTP-ATP (the Electromagnetic Transients Program, Alternative Transients Program)) shown in Fig. 3. The subject of analyses in this paper is shown in Figs. 4 and 5. Figure 4 shows the generator and its field circuit, and Fig. 5 shows the system configuration of the brushless excitation system with a PMG. The grid was modeled as an infinite bus. In addition, descriptions of the symbols in Fig. 5 are shown in the Appendix.

For this paper, the authors studied a 400 MVA-class turbo-generator (2P, 60 Hz) with a 1520 kVA brushless AC exciter.

3. Models for Analyses of Brushless Excitation System

3.1 Transfer Function Model

For transient analyses of the brushless excitation system, a transfer function model has been conventionally used for the field control part, with the generator modeled by the equivalent circuit shown in Fig. 3. It is because of difficulties in the analytical modeling of this system; the AC ex and PMG are connected to the main generator on the same rotor axis, and generate the excitation power by using the driving power from the shaft. It is especially difficult to use the complex models in analyses that consider transient DC components such as an EMTP because of problems in the convergence of solutions in calculations in steps of several microseconds. Figure 6 shows an example of the transfer function model of a feedback-compensation type brushless excitation system. (Legends for Fig. 6 are shown in the Appendix.) There are several models that interpret the characteristics of an AC ex and rotating rectifiers.

For the transfer function model in this paper, the model in Fig. 6, combined with the standard AC ex model in Fig. 7, was adopted. (Legends for Fig. 7 are also shown in the Appendix.)

3.2 Total Brushless Model

As a new approach, the authors developed an analytical model (“total brushless model”) that includes an AC ex, rotating rectifier, and PMG, as shown in Fig. 8. In the total brushless model, each AC ex and PMG is considered to be a small generator model mounted on the same shaft.

In the next section, the authors describe the comparison of results of transient analyses between the conventional transfer function model and the total brushless model. A detailed explanation of Fig. 8 is shown in the Appendix.

4. Effects of Modeling Difference in Results of Analyses of Ground Fault and Mismatched Synchronizing

4.1 Ground Fault Case

4.1.1 1-Line-to-Ground Fault

Figures 9–11 show
the analysis results of the generator’s power, field current, and field voltage in the case of single-line-to-ground (1LG) fault that occurs outside of the power station. (A 1LG fault outside of the generator transformer corresponds to a line-to-line short-circuit fault for the generator.) In these figures, solid lines show the results from the total brushless model, whereas dotted lines show the results from the transfer function model.

4.1.2 2-Line-to-Ground Fault  Similar to the previous section, Figs. 12–14 show the analysis results in the case of a 2-line-to-ground (2LG) fault that occurs outside of the power station. (A 2LG fault outside of the generator transformer corresponds to a three-phase short-circuit fault for the generator.)

4.1.3 3-Line-to-Ground Fault  Similar to the previous sections, Figs. 15–17 show the analysis results in the case of a 3-line-to-ground (3LG) fault that occurs outside of the power station.

According to the data above, for the analysis of ground fault transient phenomena, there is no significant difference between the results obtained from the two models. There is only a slight difference in the generator field voltage for a short time period after the fault. The field current of the generator is increased by the armature reaction of the fault current. Therefore, the armature current of the ACex increases, and the armature voltage of the ACex drops. Thus the field voltage of the generator is initially reduced, but raised again by the automatic voltage regulator (AVR). The transfer function model is unable to express this initial behavior, but no significant difference is seen in the results of either model after the AVR increases the voltage. It is understood that a significant difference does not appear in the
results because the generator field current is not significantly affected by the rapid change of the generator field voltage, which can only be simulated by the total brushless model due to the long time constant of the generator.

4.2 Asynchronizing Phenomena  
Close matching of voltage, frequency, and phase-angle between the generator and the grid should be a mandatory requirement for parallel synchronization of the generator into the grid. Automatic synchronizer devices have become popular in recent years. However, there are still some cases for which medium- or small-capacity generators are manually synchronized, and the mismatched synchronizing occurs from an operational error. In those cases of asynchronizing phenomena, it is possible that an overvoltage arises in the field circuit that has a rectifier because the rectifier blocks negative field current. This is shown in Fig. 4.

The basic equations for the Park model shown in Fig. 3 are the following Eqs. (1)–(12):

\[
e_d = \frac{d}{dt} \varphi_d - \omega \varphi_q - R_s i_d \tag{1}
\]
\[
e_{fd} = \frac{d}{dt} \varphi_d + R_s i_d \tag{2}
\]
\[
0 = \frac{d}{dt} \varphi_q + R_s i_q \tag{3}
\]
\[
e_q = \frac{d}{dt} \varphi_q - \omega \varphi_d - R_s i_q \tag{4}
\]
\[
0 = \frac{d}{dt} \varphi_q + R_s i_q \tag{5}
\]
\[
e_0 = \frac{d}{dt} \varphi_0 - R_s i_0 \tag{6}
\]
\[
\varphi_d = x_{ad} i_d + x_{al} i_d - (x_l + x_{al}) i_d \tag{7}
\]
\[
\varphi_{fd} = (x_{ad} + x_{jd}) i_d + x_{al} i_d - x_{ad} i_d \tag{8}
\]
\[
\varphi_{kd} = x_{ad} i_d + x_{al} i_d - x_{ad} i_d \tag{9}
\]
\[
\varphi_q = x_{ad} i_q - (x_l + x_{al}) i_q \tag{10}
\]
\[
\varphi_{dq} = x_{ad} i_q + x_{ql} i_q - x_{ad} i_q \tag{11}
\]
\[
\varphi_0 = -x_{ad} i_0 \tag{12}
\]

For field current at a mismatched synchronized condition in a system composed of one generator and an infinite bus, the following Eq. (13) can be obtained by expanding Eqs. (1)–(12):

\[
i_f = \frac{1}{x_{\prime d}} \left[ i_0 - x_{\prime d} \left( \frac{\Delta e_d}{e_t} - \frac{\Delta e_q}{e_t} \right) e^{-t/T_{d \prime}} \right] + \frac{T_{kd}}{T_{\prime d}} \left( \frac{\Delta e_d}{e_t} + \frac{\Delta e_q}{e_t} \right) e^{-t/T_{\prime d}} \tag{13}
\]

\(e_0\): infinite bus voltage
\(\Delta e_d\): voltage difference in direct axis
\(\Delta e_q\): voltage difference in quadrature axis

The above Eq. (13) is a general formula for cases with voltage and phase-angle mismatches. Hereafter the case of synchronization with a mismatch only in the voltage is studied. In this case, the equation for the generator the field current can be obtained from Eq. (13), resulting in the following:

\[
i_f = i_{f_0} - \frac{x_{\prime d}}{x_{\prime d}} \left( e_{\infty} - e_t \right) e^{-t/T_{d \prime}} \left( 1 - \frac{T_{kd}}{T_{\prime d}} \right) e^{-t/T_{\prime d}} \cos 2\pi f t \tag{14}
\]

The second term inside the brackets of Eq. (14) is negligible because of its fast attenuation. Therefore, the condition that the field current is positive can be shown as Eq. (15).

\[
1 > \begin{cases} \frac{x_{\prime d}}{x_{\prime d}} e_{\infty} - e_t \left( 1 + \frac{T_{kd}}{T_{\prime d}} \right) \quad \text{Eq. (15)} \\
1 + \frac{T_{kd}}{T_{\prime d}} \frac{e_{\infty}}{e_t} \end{cases} \tag{16}
\]

As mentioned above, Eq. (16) was obtained by using an analytical method based on the Park model in Fig. 3. It is a simplified formula that can derive the range in which the field current becomes negative in case of voltage-mismatched synchronization. The overvoltage may occur in the field circuit in this range.

The results of analysis study for the range in which the field current becomes negative after a 25% voltage-mismatched synchronization are shown in Figs. 18–20. These figures show the cases of using the total brushless model (solid lines) and the transfer function model (dotted lines). Figures 18–20 show that the overvoltage in the field circuit occurs when the field current is going to become negative. When the negative current is blocked by the rectifier, the current changing rate is very high at that time, and the overvoltage occurs as the product with a large inductance of the generator field.

It is desirable to use the total brushless model for an analysis like this, because the conventional transfer function model cannot consider the rotating rectifier. The blocking of the field current by the rectifier can be simulated by using the
Analysis Model of Brushless Synchronous Generator  (Daisuke Hiramatsu et al.)

5. Verification Test and Study of Excitation Response and Generator Stability

5.1 Accuracy Confirmation of Total Brushless Model by Verification Test  In order to confirm the accuracy of the analysis results obtained from the total brushless model described in the previous section, the authors performed a verification by comparing the results with actual test measurements of the excitation response of a 400 MVA-class turbogenerator with a brushless excitation system. Response measurements of the field values were taken under the following conditions:

1) Step change of the generator terminal voltage from 50% to 100%, at no-load condition.
2) Step change of the generator terminal current from 50% to 100%, at sustained three-phase short-circuit condition.

The actual test measurements, and the simulation results using the total brushless model, are shown in Figs. 21 and 22. Because the difference between the simulated and measured data is less than 6%, we think that our total brushless model is in good accordance with actual phenomena.

This can be regarded as proof of validity of the developed total brushless model.

5.2 Evaluation of Response of Brushless Excitation System  The response of the brushless excitation system is generally evaluated by nominal response (also called as response ratio) and response time. A brief explanation follows.

- Nominal Response

The rate of increase of the excitation system output voltage determined from the excitation system voltage response curve, divided by the rated field voltage (Fig. 23). This rate, if maintained constant (curve $ac$), would develop the same voltage-time area as obtained from the response (curve $ab$) over the first half-second interval.

A nominal response of 2.0 or higher is often specified in case a quick response is required.

- Response Time

The time in seconds for the excitation voltage to attain 95% of the difference between ceiling voltage and rated field voltage (Fig. 24). An excitation system with a response time of 0.1 second or less is classified as a high initial response.

Figure 25 shows the simulation results of the excitation voltage response for the ceiling condition of a 400 MVA-class turbogenerator with a brushless excitation system. The simulation was conducted using both the total brushless model and the transfer function model. The following observations were obtained from the results:

- Nominal response: The result from the total brushless model is approximately 2.4, which satisfies the requirement of quick response (i.e., nominal response higher than 2.0). By contrast, the transfer function model gives an optimistic result that is not appropriate.
6. Conclusions

The authors studied the analysis models of brushless excitation generators, which have not been reported despite the fact that the single-unit capacity of turbogenerators is rapidly increasing. In the analyses of transient phenomena, the ACex and PMG have been conventionally expressed as modeled transfer functions. The authors developed a new model (the “total brushless model”) in which each ACex and PMG is considered to be a small generator. The following conclusions were obtained from comparisons between the models and actual measurements for a 400 MVA-class brushless turbogenerator.

- Transient phenomena in ground-fault and mismatched synchronization conditions were studied by using the transfer function model and the total brushless model. For ground faults, no significant difference was found in the results from the two models. However, field overvoltage phenomena after mismatched synchronization can only be simulated by the total brushless model. It is important to select a suitable applied model to analyze the transient phenomena.

- The validity of the developed total brushless model was confirmed by the similarities between the actual test measurements and the simulation results of the step response of the field voltage of a 400 MVA-class brushless excitation turbogenerator.

- Adoption of the total brushless model is desirable for the evaluation of the quickness of the excitation voltage response of the brushless system.

The authors are studying further transient phenomena, and are preparing to report on additional observations.

References


Appendix

1. Symbol legends for Fig. 5
(1) Voltage Transformer, (2) Current Transformer,
(3) Shunt for DC Current Measurement,
(4) Excitation Controller, (5) PMG,
(6) Thyristor Rectifier, (7) Field Switch (41E),
(8) Discharge Resistor, (9) AC exciter,
(10) Rotating Rectifier,
(11) Capacitor Voltage Transformer

2. Symbol legends for Figs. 6, 7
$T_R$: Time Constant of Voltage Detector,
$V_{Amax}$: AVR Upper Limiter, $K_A$: AVR Gain,
$V_{Amin}$: AVR Lower Limiter,
$T_A$: Time Constant of AVR Amplifier,
$V_L$: Output Limiter, $K_H$: Aux. Signal Gain,
$K_F$: Anti-Hunt Gain, $K_M$: Thyristor Amplifier Gain,
$T_F$: Anti-Hunt Constant,
$K_H$: Exciter Field Current Feedback Gain,
$K_V$: 1/(ACex Field Winding Resistance),
$K_E$: $V_{eo}/I_{eo}$, ($V_{eo}/I_{eo}$: shown in Fig. 7),
$T_{E2}$: (ACex Open Circuit Time Constant
+0.9 ACex Load Time Constant)/2,
$T_{E1}$: (ACex Open Circuit Time Constant)/2.0,
$V_{CE}$: Ceiling Voltage,
$K$: ($V_{eo} - V_{eo}^\prime$)/$V_{eo}$, ($V_{eo}/V_{eo}^\prime$: shown in Fig. 7),
$T_G$: Adjusted Generator Open Time Constant

3. Details about the total brushless model of Fig. 8
The total brushless model is composed of the following elements:
- Three Park models that represent the main generator, ACex, and PMG,
- Rotating rectifier (diode bridge),
- Thyristor rectifier and AVR for ACex field control.
Analysis calculations were performed by EMTP-ATP, using models for the elements above mentioned. Details of the modeling are as follows:

a) Main generator and ACex
Park model for each main generator and ACex is equivalent to Eqs. (1)–(12) in the body text.
b) PMG
Since the field is given by permanent magnets, the Park model for the PMG is expressed as follows:

$$e_d = -\omega X_{dpl} - R_{dl}i_d$$ \hspace{1cm} (A1)

$$e_q = +\omega X_{qpl} + \omega \varphi_{pm} - R_{ql}i_q$$ \hspace{1cm} (A2)

where $\varphi_{pm}$ is permanent magnet flux by permanent magnets.
c) Rotating rectifier
Each diode is modeled as a switch that closes and opens in accordance with the positive/negative polarity of the applied voltage.
d) Thyristor rectifier and AVR
A thyristor is modeled as a switch that closes and opens in accordance with the firing signal and the positive/negative polarity of the applied voltage. As for the AVR, the model applied is the transfer function model equivalent to Fig. 6 in the body text, with the AC exciter portion removed.
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