Analysis about modeling MEC7000 excitation system of nuclear power unit

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Abstract. Aiming at the importance of accurate modeling excitation system in stability calculation of nuclear power plant inland and lack of research in modeling MEC7000 excitation system, this paper summarize a general method to modeling and simulate MEC7000 excitation system. Among this method also solve the key issues of computing method of IO interface parameter and the conversion process of excitation system measured model to BPA simulation model. At last complete the simulation modeling of MEC7000 excitation system first time in domestic. By used No-load small disturbance check, demonstrates that the proposed model and algorithm is corrective and efficient.

1. Introduction

The first phase 2 * 1000MW unit of Fangchenggang nuclear power plant is about to put into operation. As the first nuclear power plant in Guangxi, it will have an important impact on the energy structure and stable operation of the whole Guangxi power grid [1-3].

The excitation system of generator as important auxiliary equipment plays an important role in improving electromechanical oscillation damping in large network and the static stability and transient stability of the power grid [4-7]. In the stability analysis of the connected nuclear power unit, the accuracy of the excitation system model and parameters directly affects the accuracy and conclusion of the stability analysis. The excitation system of unit 1 in first phase Fangchenggang Nuclear Power Station is brushless ac excitation system, the excitation regulator for the latest third-generation dual-channel digital excitation regulator MEC7000 of Japan's Mitsubishi Corporation. The excitation system is the first application in China, its parameter testing and modeling work are rarely reported at home and abroad. Therefore, it is meaningful to carry out the measurement modeling of MEC7000 excitation system.

In this paper, model identification, parameter measurement and BPA simulation are described, and the general method of modeling MEC7000 excitation system and the precautions in modeling process are given. Taking the no-load small disturbance check into established BPA simulation model of excitation system, the correctness and feasibility of the modeling method in this paper are validated. The model of MEC7000 excitation system better displays the actual operation state of the equipment, which can provide accurate excitation data for the stable calculation of grid-connected nuclear power.
2. Identification test on excitation system model
The model identification test of excitation system is mainly to verify the correctness of the PID and PSS transfer function block which provided by the equipment manufacturer. The results of the test and comparison are shown in Table 1.

Table 1. Test results of spectrum identification.

| Identify the link                  | amplitude-frequency characteristic error (%) | phase-frequency characteristic error (°) |
|-----------------------------------|---------------------------------------------|----------------------------------------|
| PID ratio link                    | 0.532                                       | 1.072                                  |
| PID lead lag link                 | 0.276                                       | 0.284                                  |
| PSS ratio link                    | 0.273                                       | -0.260                                 |
| PSS first order damp link         | -0.026                                      | 0.088                                  |
| PSS DC blocking link              | 0.455                                       | -0.60                                  |
| PSS lead lag link                 | -0.437                                      | 0.274                                  |
| PSS lowpass filtering link        | 0.119                                       | -0.513                                 |
| Overall PSS                       | 0.428                                       | -0.214                                 |

Note: The formula of the amplitude-frequency characteristic error ($d$) is $d = (P_2 - P_1)/P_1$. The formula of the phase-frequency characteristic error is $b = Q_2 - Q_1$, where $P_2$ and $Q_2$ are the measured amplitude and phase, $P_1$ and $Q_1$ denote amplitude and phase of theoretical calculation in corresponding link.

It can be seen from the data in Table 1 that the value error between the measured frequency characteristics and the theoretical calculation of PID and PSS is less, which indicates that the models of PID and PSS are consistent with transfer function block diagrams provided by the manufacturer.

It is worth noting that parameter values $A_{I_a}$ and $A_{O_a}$ of IO range should be calculated based on the amplitude of incoming white noise signal. Two values are used to set the analog signal’s IO range of excitation regulator, which will affect the accuracy of the test results if the value is unreasonable. If the $A_{I_a}$ value is too small, the amplitude of the input signal will be limited, and the signal cannot be fully inserted into the regulator. If the $A_{O_a}$ value is too small, the dynamic signal analyzer will not be able to fully receive the feedback signal of PID and PSS, which makes test results erroneous.

According to the calculation function and field calculation provided from the manufacturer, the formula of $A_{I_a}$ and $A_{O_a}$ is modified to make it more versatile. The modified formula is as follows:

\[
0.1 = y \times 3000 \times A_{I_a} + b \quad (1) \\
y \times 3000 = 0.1 \times A_{O_a} + b \quad (2)
\]

In the formula above, $y$ denotes the maximum value or minimum value of the input white noise signal, $b$ is the auxiliary parameter.

If the largest value and the minimum value of $y$ are 10V and -10V respectively, there are $A_{I_a}=0.000 \ 000 \ 333$ and $A_{O_a}=300 \ 000$. In the actual settings, the input/output signal is complete as long as the values of $A_{I_a}$ and $A_{O_a}$ are greater than calculated value above.

3. Measurement and calculation of excitation system parameters

3.1. The correlation calculation to no-load characteristics of generator and excitation circuit

(1) No-load characteristics test of generator

Since the generator adopts brushless excitation system, the no-load characteristics of the generator cannot be measured on the spot, so it can only refer to factory test data provided by manufacturers (figure 1).
Figure 1. No-load characteristic curve of generators.

(2) The calculation of excitation circuit’s reference value

In figure 1 the excitation current that corresponds to rated stator voltage in no-load air gap of generator is treated as the reference value of the generator excitation current \( I_{FD0} \), and its value is 2 828.32A. Take ratio that rated excitation voltage divided by rated excitation current in generator nameplate as resistance reference value of generator exciting winding:

\[
R_{FD0} = \frac{U_{FD0}}{I_{FD0}} = \frac{482/8}{2828.32} = 0.059 \Omega
\]

(3) The reference value of the generator excitation voltage \( U_{FD0} \):

\[
U_{FD0} = R_{FD0} \times I_{FD0} = 0.059 \times 2828.32 = 166.87V
\]

(3) The calculation of saturation coefficient in generator excitation circuit

In figure 1, the excitation current that corresponds to rated stator voltage in no-load air gap is \( I_{FD0} = 2828.32A \), and the excitation current is \( I_{FD0,1.2} = 3400A \) when the rated stator voltage is 1.2 times. The excitation current that corresponds to rated stator voltage on the no-load characteristic curve is \( I_{FD0} = 3050A \), and the excitation current is \( I_{FD0,1.2} = 5080A \) when the rated stator voltage is 1.2 times. The saturation coefficient of generator is:

\[
S_{G1.0} = \frac{I_{FD0} - I_{FD0,1.2}}{I_{FD0}} = 0.0784
\]

\[
S_{G1.2} = \frac{I_{FD0,1.2} - I_{FD0,1.2}}{I_{FD0,1.2}} = 0.4941
\]

3.2. No-load and load characteristics test of main exciter

The no-load and load characteristics of main exciter also cannot be obtained from field testing, so that the test data provided equipment manufacturers is adopted (figure 2).

Figure 2. no-load and load characteristics curve of main exciter.
3.3. Model parameter calculation of excitation circuit in main exciter

The mathematical models of exciter and uncontrollable three-phase full wave rectifier are shown in figure 3, where $K_E$ is self-excitation coefficient, $S_E$ is saturation factor, $T_E$ is no-load time constant of main exciter, $V_E$ is output voltage of uncontrolled rectifier (The arc voltage drop is not taken into account), $V_R$ is the output voltage of excitation regulator, $I_{FD}$ is load current of the exciter, $K_D$ is the demagnetizing coefficient of the load current in the exciter, and $E_{FD}$ is the output voltage when arc voltage drop is not taken into account, which is excitation voltage of generator.

$$\frac{\pi}{2} \frac{K_E S_E}{K_D I_{FD}} + V_E \left( \frac{1}{R_{EFB}} \right) = E_{FD}$$

Figure 3. The mathematical models of exciter and uncontrollable three-phase full wave rectifiers.

(1) The Reference Value of Excitation Circuit for Main Exciter

Take the excitation current that corresponds to a per-unit value of excitation voltage on the no-load characteristic curve as the reference value of the excitation current, which can be calculated from figure 2.

$$I_{EFB}=55.62A$$

The reference value of excitation circuit resistance for main exciter is the test value provided by the generator manufacturers.

$$R_{EFB}=0.134\Omega$$

The voltage reference value for main exciter is:

$$U_{EFB}=I_{EFB} \times R_{EFB} = 7.453V$$

(2) The Calculation of Saturation Coefficient for Main Exciter

In the figure 2, the excitation current for main exciter that corresponds to 2 times rated excitation voltage in no-load characteristic curve and in no-load air gap respectively are:

$$I_{EFB0E1}=371A; I_{EFBE1}=321A$$

The excitation current for main exciter that corresponds to 1.5 times rated excitation voltage in no-load characteristic curve and in no-load air gap respectively are:

$$I_{EFB0E2}=260A; I_{EFBE2}=248A$$

We can obtain the saturation factor of the main exciter:

$$S_{E1}=S_{emax}=\frac{(I_{EFB0E1}-I_{EFBE1})}{I_{EFBE1}}=0.154$$

$$S_{E2}=S_{0.75max}=\frac{(I_{EFB0E2}-I_{EFBE2})}{I_{EFBE2}}=0.0484$$

(3) The phase-change reactance coefficient $K_C$.

In figure 3, There is $I_N=K_C \times I_{FD}/V_E$, where $K_C$ denotes phase-change reactance coefficient for uncontrollable three-phase full wave rectifier bridge, which can be calculated by the following formula:

$$K_C = \frac{3\sqrt{3}}{\pi} \frac{X_{dc}^* + X_{2c}^*}{2} \frac{1}{R_{EFB}} \frac{U_N^2}{S_N} = 0.279$$

In the formula, $S_N$, $U_N$, $X_{dc}$ and $X_{2c}$ are the rated apparent power, rated voltage, sub-transient reactance and negative sequence reactance of the main exciter, respectively.

(4) Demagnetization Coefficient $K_D$ of Load Current for main exciter

In figure 2, Take DC output voltage $U_1$ arbitrarily when generator running at rated conditions in load characteristic curve for main exciter, the value is 482V in this paper. This line of voltage intersect
no-load characteristic curve and load characteristics curve at point a and b, So that the excitation current corresponding to point a and b are $I_{f_a}=160A$ and $I_{f_b}=220A$. There is:

$$K_D = \frac{I_{f_b}}{I_{f_a}} - 1 - K_c / \sqrt{3} = 0.214$$

(11)

3.4. The test of direct-axis transient open circuit time constant for generator

The generator is running at rated speed and no-load condition, the generator voltage is reduced from 100% to 0 by cutting the pulsed power supply, and measured generator stator voltage is shown in figure 4, Take the time period that the generator voltage from the rated value down to 0.368 times rated voltage required as the direct-axis transient open circuit time constant, which is 8.208s.

![Figure 4](image)

**Figure 4.** The test of generator no-load time constant.

3.5. Regulatory quality test of generator excitation regulator

Some text. Using the generator voltage 5% step response curve to test, figure 5 for the recorded wave chart when the generator voltage step from 95% to 100%. The voltage overshoot $M_p$, pak time $T_p$, rise time $T_{up}$, regulation time $T_s$ and the number of oscillation $N$ can be calculated from figure 5, and the calculation results are shown in table 2.

![Figure 5](image)

**Figure 5.** Generator voltage 5% step response curve.
Table 2. Regulatory quality of generator excitation regulator.

| $M_p/%$ | $T_p/s$ | $T_{up}/s$ | $T_d/s$ | $N$ |
|---------|---------|------------|---------|-----|
| 36.36   | 0.393   | 0.222      | 1.71    | 1.5 |

3.6. The test of maximum output voltage $V_{RMAX}$ and minimum output voltage $V_{RMIN}$ for excitation regulator

In the automatic excitation mode, adjust the generator voltage to 60% of the rated voltage, and perform the 10% upper step test and the 10% down step test. The no-load step response curve of generator voltage and exciter excitation voltage is shown in figure 6.

In figure 6, take the maximum and minimum exciter excitation voltage to calculate minimum and maximum trigger angle $\alpha$ of silicon controlled, the formula: $\alpha = \arccos \left( \frac{U_{FD}}{1.35 \times U_{ac}} \right)$, where $U_{ac}$ is measured voltage for the auxiliary exciter, $U_{FD}$ is excitation voltage of exciter. The calculation results are shown in table 3.

![Figure 6. 10% step response test.](image)

Table 3. Test results of maximum / minimum trigger angle

| $U_{FD}/V$ | $U_{ac}/V$ | Trigger Angle[°] |
|------------|------------|-------------------|
| -236.8     | 347        | 120.25            |
| 459.6      | 347        | 11.53             |

According to table 3 data, $V_{RMAX}$ and $V_{RMIN}$ can be calculated.

$$V_{RMAX} = 1.35 \times U_{ac} \times \cos(\alpha_{min})/U_{EFB} = 61.58$$

$$V_{RMIN} = 1.35 \times U_{ac} \times \cos(\alpha_{max})/U_{EFB} = -31.66$$

4. Mathematical models and parameters of excitation system for stable calculation

Mitsubishi MEC7000 excitation system model is shown in figure 7. In the BPA simulation, use FM-type brushless excitation system model as the excitation system model to calculate, which is shown in figure 8. The model parameters provided by Mitsubishi manufacturers is in table 4.
Figure 7. The block diagram of Mitsubishi MEC7000 excitation system model.

Figure 8. FM brushless excitation system model.

Table 4. The model parameters of MEC7000 excitation regulator.

| parameters | value | parameters | value |
|------------|-------|------------|-------|
| $T_d$      | 0.004 | $K_2$      | 1873  |
| $K_A$      | 23.55 | $K_f$      | 0.0015|
| $T_{lead}$ | 0.95  | $T_i$      | 20    |
| $T_{lag}$  | 3.309 | $K_E$      | 0.0121|

It should be noted:

1) The value of $K_2$ is 20, but the regulator itself also has a conversion process: $K_2 = 4 \times 1.35 \times U_{ac}$, where $U_{ac}$ is measured output voltage for auxiliary exciter, the value is 347V, so the actual value of $K_2$ is 1873.

2) In figure 7, $K_E$ is the reciprocal of the no-load excitation voltage ($K_E = 1/U_{fe0}$), the measured value of $U_{fe0}$ is 82.8V, so $K_E = 0.0121$. And $K_E$ in figure 8 is the self-excitation of the exciter, the value is 1.

According to the general principle of the modeling for the excitation system, the measured model of figure 7 is required to be equivalent to the BPA model in figure 8, the modules in the red frame and in the blue frame may correspond respectively. The $K_2/R_{fe}$ in figure 7 may be equivalent to the secondary regulator gain $K_B$ in figure 8, but due to the value of $K_2/R_{fe}$ is 14104, which is beyond the maximum input value of $K_B$, so the value cannot be entered in the BPA data card; The $K_f$ in figure 7 can be equivalent to $K_H$ in figure 8, the value of $K_f$ is 0.0015, and the minimum value of $K_H$ is 0.001, and if the approximate number is used, there will be a great influence on the simulation results. Therefore, it is necessary to reduce the value of $K_B$ and increase the value of $K_H$ by further equivalent calculation to ensure the simulation efficiency.

In figure 7 and figure 8, the model in the red frame is converted to the models shown in figure 9 and figure 9, respectively.
Figure 9. The equivalent diagram of the module in the red frame for figure 7.

Figure 10. The equivalent diagram of the module in the red frame for figure 8

Set $K_{B1} = K_2/R_{fe}$, then the equivalent transfer function of figure 9 is:

\[
\frac{E_{FD}}{V_R} = \frac{K_{B1}}{1 + S \cdot T_E} \cdot \frac{1 + K_{B1} \cdot K_f}{1 + K_{B1} \cdot K_f} \cdot KE
\]

(14)

The equivalent transfer function of figure 10 is:

\[
\frac{E_{FD}}{V_R} = \frac{K_R}{1 + S \cdot T_E} \cdot \frac{1 + K_R \cdot K_H}{1 + K_R \cdot K_H} \cdot (S_E + 1)
\]

(15)

In Formula (14) and Formula (15), $K_f$ and $K_H$ are the current feedback gain of the exciter in figure 7 and figure 8 respectively, $KE$ is the reciprocal of the no-load excitation voltage for the generator, and $K_B$ is the secondary regulator gain.

Take the measured parameters into Formula (14), and let Formula (14) is equal to Formula (15), then the $K_B$ and $K_H$ can be obtained, which is shown in table 5.

Table 5. The comparison of $K_B$ and $K_H$ parameter values before and after conversion in BPA.

| Parameter | $K_B$ | $K_H$ |
|-----------|-------|-------|
| The value before conversion | 14 104 | 0.001 5 |
| The value after conversion | 170 | 0.106 5 |
| The limit value of BPA data card | 9 999 (maximum value) | 0.001 (minimum value) |

It can be seen from the data in table 5 that the values of $K_B$ and $K_H$ after model conversion are within the limits of the values. In addition, since the Formula (14) is equal to Formula (15), the simulation results of the two models are consistent.

5. The verification of no-load characteristics with small disturbance for generator

The FM model parameters of BPA converted from measured model of MEC7000 excitation system is obtained according to actual measurement and calculation above. In order to verify the correctness of the measured model and parameters, the BPA program is used to carry out the 5% step response simulation of generator voltage. The simulation results are compared with the measured results, as shown in figure 11 and table 6.
Figure 11. The measured terminal voltage and simulation results for 5% step response simulation.

It can be seen from the data in figure 11 and table 6, the BPA simulation curve is goodness of fit with the field measurement curve, and the errors of the key indicators are within the range specified by The Excitation Modeling Guideline for Southern Power Grid [8]. It shows that the simulation model of the excitation system is in accordance with the operation of the actual equipment and can be used for daily power stability analysis.

Table 6. The comparison of actual measurement and simulation results for 5% step response simulation in no-load generator.

|       | Measured | Simulation results | Deviation | Allow deviation |
|-------|----------|--------------------|-----------|----------------|
| Mp    | 36.36%   | 37.90%             | 1.54%     | ±0.5Mp         |
| Tp    | 0.222    | 0.300              | 0.078     | ±0.1s          |
| Tp    | 0.393    | 0.51               | 0.117     | ±0.2s          |
| Ts    | 1.71     | 1.44               | -0.27     | ±2s            |
| N     | 1.5      | 1.5                | 0         | ∞              |

6. Conclusions

The modeling approach of MEC7000 excitation system is proposed by static model identification, field measurement of excitation system and BPA simulation.

In the process of modeling, the key problems of the input and output interface parameters for the excitation regulator and the conversion process of the excitation system to the BPA simulation model are solved.

The simulation model of MEC7000 excitation system is used to carry out the no-load small disturbance test. The results show that the model is accurate and reliable, and it meets the requirements of stability analysis for grid-connected generators.

In this paper, the simulation and modelling of MEC7000 excitation system is completed for the first time in China. This work not only makes sense for the calculation of nuclear power grid, but also has reference value of related work of domestic type excitation system.

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