Parameter Identification of Six-Order Synchronous Motor Model Based on Grey Box Modeling

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Abstract. As the "heart" of power system, synchronous generator's accurate model parameters are the basis of power system simulation, operation analysis and fault diagnosis. These parameters also have a very important impact on the operation analysis of power grid. This paper introduces the mathematical model of the sixth-order synchronous generator and establishes the incremental model for its identification. The methods of grey box modeling and nonlinear least square are used to identify the parameters of the sixth-order synchronous generator. When a single - phase short - circuit fault occurs in the power system, the response data of the generator is simulated in the PSASP software. When a program for synchronous machine parameter identification is written, the result will verify the validity of this approach.

Keywords: Synchronous machine · Parameter identification · Least square method

1 Introduction

Synchronous generator is the core of power system. The establishment of accurate synchronous generator model is crucial to accurate calculation and the analysis of power system dynamic characteristics. At present, most power system analysis and calculation can only be based on data provided by the manufacturer or user manual. However, as the manual data can't consider the influence of actual working conditions, the results are often inconsistent with actual working conditions, which seriously affects the accuracy and reliability of system analysis and calculation. Therefore, it is of great practical significance to study the modeling of real-time synchronous generator set [1, 2].

Through the GPS with the Phasor Measurement unit and the wide-area Measurement System (Wide Area Measurement System of WAMS), wide-area generator power Angle and bus voltage can be monitored in real time. Phasor's observation of the real running state of the power grid provides a key to the safe and stable operation of power grid in the measurements. It has been widely used in the monitoring of normal and abnormal state of power system, auxiliary decision-making of accident handling and dynamic process

X. Jiang and P. Li (Eds.): GreeNets 2020, LNICST 333, pp. 45–52, 2020.
https://doi.org/10.1007/978-3-030-62483-5_6

control. Using the synchronous phasor measurement information provided by the wide-area measurement system can improve the accuracy and reliability of the power system simulation model, and the reliability and economic benefit of its operation, which has far-reaching significance for the power system to adapt to the development [3, 4].

Therefore, this paper carries on the Matrix modeling to the sixth-order Synchronous Motor Mathematical Model. Based on the measurement information of synchronous phasor, grey box modeling and least square method are used to identify the parameters of synchronous motor. Finally, the validity of parameter identification is proved.

2 Mathematical Modeling of Six-Order Synchronous Motor

2.1 Mathematical Model of Six-Order Synchronous Motor

According to the choice of different state vectors, different identification models (i.e. state equations) can be constructed. The sixth order model of synchronous generator is selected in this paper, which is as follows.

Generator electrical model of d axis:

$$\begin{cases} T_{d0}' \cdot \frac{dE_q'}{dt} = E_f - E_q' - \frac{x_d - x_d'}{x_d' - x_d''}(E_q' - E_q'') \\ T_{d0}'' \cdot \frac{dE_q''}{dt} = E_q' - E_q'' - (x_d' - x_d'')i_d + T_{d0}'' \cdot \frac{dE_q'}{dt} \\ u_q = E_q'' - x_d'' \cdot i_d \end{cases} \tag{1}$$

Generator electrical model of q axis:

$$\begin{cases} T_{q0}' \cdot \frac{dE_d'}{dt} = -E_d' - \frac{x_q - x_q'}{x_q' - x_q''}(E_d' - E_d'') \\ T_{q0}'' \cdot \frac{dE_d''}{dt} = E_d' - E_d'' + (x_q' - x_q'')i_q + T_{q0}'' \cdot \frac{dE_d'}{dt} \\ u_d = E_d'' + x_q'' \cdot i_q \end{cases} \tag{2}$$

Rotor motion equation:

$$\begin{cases} \frac{d\delta}{dt} = \omega - 1 \\ M \cdot \frac{d\omega}{dt} = T_m - T_e - D(\omega - 1) \end{cases} \tag{3}$$

Where E_d'', E_q'', E_d', E_q' are subtransient and transient potient of d_q axis; x_d', x_q', x_d'', x_q'' are substransient, transient and synchronous reactance of d_q axis, T_{d0}'', T_{q0}'', T_{d0}', T_{q0}' are subtransient and transient open circuit time constant of d_q axis, E_f is exciting voltage, δ is generator power angle, ω is nominal angular, M is inertia time constant, D is damping coefficient, T_m, T_e is mechanical and electromagnetic torque.

2.2 Incremental State Model of Six-Order Synchronous

The matrix form of six-order synchronous motor's state incremental equation can be obtained by converting the mathematical model of the synchronous motor into an incremental equation and then expressing it in matrix form [5, 6].

From formula (1), the matrix expression of the d-axis increment equation can be obtained as follows:

$$\begin{cases} \begin{pmatrix} \Delta \dot{E}_q' \\ \Delta \dot{E}_q'' \end{pmatrix} = \begin{pmatrix} -\frac{1}{T_{d0}'}\frac{x_d-x_d''}{x_d'-x_d''} & \frac{1}{T_{d0}'}\frac{x_d-x_d'}{x_d'-x_d''} \\ -\frac{1}{T_{d0}'}\frac{x_d-x_d'}{x_d'-x_d''}+\frac{1}{T_{d0}''} & \frac{1}{T_{d0}'}\frac{x_d-x_d'}{x_d'-x_d''}-\frac{1}{T_{d0}''}\frac{x_d'}{x_d''} \end{pmatrix} \cdot \begin{pmatrix} \Delta E_q' \\ \Delta E_q'' \end{pmatrix} + \begin{pmatrix} 0 & \frac{1}{T_{d0}'} \\ \frac{x_d'-x_d''}{T_{d0}''x_d''} & \frac{1}{T_{d0}'} \end{pmatrix} \cdot \begin{pmatrix} \Delta u_q \\ \Delta E_{fd} \end{pmatrix} \\ \Delta i_d = \begin{pmatrix} 0 & \frac{1}{x_d''} \end{pmatrix} \begin{pmatrix} \Delta E_q' \\ \Delta E_q'' \end{pmatrix} - \begin{pmatrix} -\frac{1}{x_d''} & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta u_q \\ \Delta E_{fd} \end{pmatrix} \end{cases} \tag{4}$$

In the identification process, the input vector is $[\Delta u_q, \Delta E_{fd}]$, the state variable is $\left[\Delta E_q' \ \Delta E_q''\right]$, Output is Δi_d, The parameter to be identified is $\alpha = [x_d, x_d', x_d'', T_{d0}', T_{d0}'']^T$.

From formula (2), the matrix expression of the q axis increment equation can be obtained as follows:

$$\begin{cases} \begin{pmatrix} \Delta \dot{E}_d' \\ \Delta \dot{E}_d'' \end{pmatrix} = \begin{pmatrix} -\frac{1}{T_{q0}'}\frac{x_q-x_q''}{x_q'-x_q''} & \frac{1}{T_{q0}'}\frac{x_q-x_q'}{x_q'-x_q''} \\ \frac{1}{T_{q0}''}-\frac{1}{T_{q0}'}\frac{x_q-x_q''}{x_q'-x_q''} & \frac{1}{T_{q0}'}\frac{x_q-x_q'}{x_q'-x_q''}-\frac{1}{T_{q0}''}\frac{x_q'}{x_q''}) \end{pmatrix} \cdot \begin{pmatrix} \Delta E_d' \\ \Delta E_d'' \end{pmatrix} + \begin{pmatrix} 0 \\ -\frac{1}{T_{q0}''}\frac{x_q'-x_q''}{x_q''} \end{pmatrix} \cdot (\Delta u_d) \\ \Delta i_q = \begin{pmatrix} 0 & -\frac{1}{x_q''} \end{pmatrix} \cdot \begin{pmatrix} \Delta E_d' \\ \Delta E_d'' \end{pmatrix} + \frac{1}{x_q''} \cdot \Delta u_d \end{cases} \tag{5}$$

In the identification process, the input vector is Δu_q,State the amount of $[\Delta E_d' \ \Delta E_d'']$, Output is Δi_q. The quantity to be recognized is $\alpha = \left[x_q, x_q', x_q'', T_{q0}', T_{q0}''\right]^T$.

From formula (3), the matrix expression of generator rotor increment equation can be obtained as follows:

$$\begin{cases} \begin{pmatrix} \Delta \dot{\omega} \\ \Delta \dot{\delta} \end{pmatrix} = \begin{pmatrix} -\frac{D}{M} & 0 \\ 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta\omega \\ \Delta\delta \end{pmatrix} + \begin{pmatrix} -\frac{1}{M} \\ 0 \end{pmatrix} \cdot \Delta T_e \\ \Delta\delta = \Delta\delta \end{cases} \tag{6}$$

In the identification process, the input vector is ΔT_e, The output is $\Delta\delta$, The quantity to be recognized is $\alpha = [M, D]^T$.

3 The Principle and Process of Parameter Identification of Synchronous Motor

3.1 The Principle of Parameter Identification

Parameter identification problem is to determine the mathematical model of a system or a process by observing its input-output relationship. Parameter identification based on grey box modeling is selected by the rules in a class of models which are best suited to the data [7, 8].

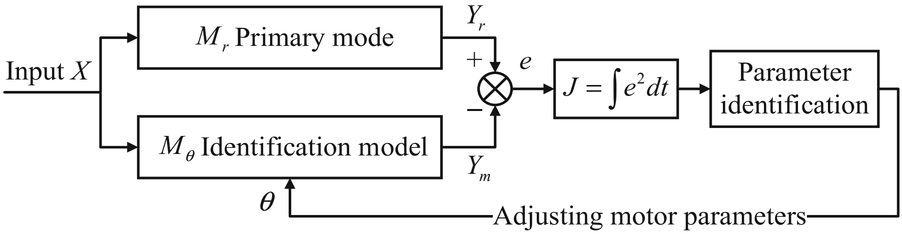

Fig. 1. The process and principle of synchronous motor parameter identification based on grey box modeling

The basic process of synchronous generator identification is shown in Fig. 1 which uses the input and output data provided by the dynamic process of the test system. The structure and parameters of the adjustment model of the synchronous motor mathematical model are constantly adjusted. The results of the model are as close as possible. The X is the input vector, Y_r is the output vector of the prototype system, Y_m is the output vector of the model, and e is the error vector, θ is the model parameter vector.

In order to evaluate the model of parameter identification, an equivalent criterion J is defined to measure error e. Under the action of an input signal X, the error between the actual system output and the model output is e. After the calculation identification criteria, the model parameters will be corrected and repeated until the error e is small enough.

3.2 The Process of Parameter Identification

1. Let the differential equation of the continuous system be as shown in Eq. (7).

$$\begin{aligned} \dot{X}(\alpha) &= A(\alpha)X(\alpha) + B(\alpha)U \\ Y(\alpha) &= C(\alpha)X(\alpha) + D(\alpha)U \end{aligned} \tag{7}$$

   Where $X(\alpha)$ is a state vector, $Y(\alpha)$ is an output observation vector, U is a known input vector, $A(\alpha)$, $B(\alpha)$, $C(\alpha)$, $D(\alpha)$ are matrix contains parameters that need to be identified.
2. Give the initial value of each state vector and quantity to be identified.
3. Calculate the dynamic process curve Y_m of the output vector according to the incre mental model of parameter identification by fourth order runge-kutta method.
4. The value of objective function $J(\Delta\alpha)$ is calculated from the measured data of simulation and the data of identification model. The objective function is shown in Eq. (8).

$$J(\Delta\alpha)_{\alpha_0} = \int_{T_0}^{T} [Y_r - Y_M(\alpha_0) - (\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0}\Delta\alpha]^T W[Y_r - Y_M(\alpha_0) - (\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0}\Delta\alpha]dt \tag{8}$$

5. In order to use the least square method, the partial derivatives of the output vector Y_m are obtained for the identification parameters. The process of finding the partial derivative is shown in Eq. (9).

$$(\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0} = C(\alpha)(\frac{\partial X_M}{\partial \alpha^T})_{\alpha_0} + (\frac{\partial C(\alpha)}{\partial \alpha^T})_{\alpha_0} X_M(\alpha_0) + (\frac{\partial D(\alpha)}{\partial \alpha^T})_{\alpha_0} U \tag{9}$$

Where $(\frac{\partial C(\alpha)}{\partial \alpha^T})$, $(\frac{\partial D(\alpha)}{\partial \alpha^T})$ can be obtained directly, α_0 is the initial value of quantity to be identified. $\frac{\partial X_M}{\partial \alpha^T}$ is expected to solve the following differential Eqs. (10).

$$\Delta\alpha = [\int_{T_0}^{T} (\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0}^T W (\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0} dt]^{-1} \cdot \int_{T_0}^{T} (\frac{\partial Y_M}{\partial \alpha^T})_{\alpha_0}^T W (Y_r - Y_M(\alpha_0)) dt \tag{10}$$

6. Calculate $J(\hat{\alpha})$ by Eqs. (11).

$$\hat{\alpha} = \alpha_n + \Delta\alpha \tag{11}$$

7. If $J(\hat{\alpha}) < J(\alpha_n)$, $\alpha_{n+1} = \hat{\alpha}$, $k = 1$, turn to step 9. Otherwise, continue.
8. Take $k = k + 1$ and move on to step 5.
9. If $\max\limits_{1 \le j \le m} \left(\frac{\Delta\alpha_n^j}{\alpha_n^j} \right) < \varepsilon$, Where $\Delta\alpha_n^j$ is the jth component of $\Delta\alpha_n$, Take α_{n+1} as the identification result, otherwise $n = n + 1$, go back to step 2.

4 Simulation Examples and Identification Results

In this paper, the integrated power system simulation program (PSASP) is applied to carry out dynamic digital simulation test with EPRI-7 node system as an example. The wiring diagram of the system is shown in Fig. 2. The process and principle of the synchronous motor parameter identification are based on grey box modeling. The method described above is applied to identify the parameters of generator G1.

The synchronous generator uses a detailed six - order model. The electrical damping of the damping winding has been taken into account in detail in this model. Only when the mechanical damping is very small, can D can be zero.

The disturbance data is based on the single-phase short-circuit grounding fault data on the line. At 0.02 s, the fault occurs on the line between bus b4-500 and bus b3-500. At 0.1 s, the fault is eliminated and the data interval is 0.01 s (Fig. 2).

The simulation results show that when using the line fault by the measurement of the generator voltage, current and Angle information, time-domain nonlinear least squares method can identify respectively d shaft generator and q axis and the rotor equations of motion parameters. Test results show that the algorithm has strong robustness, and the method is used to identify the effectiveness of the synchronous generator parameters (Table 1 and Figs. 3, 4).

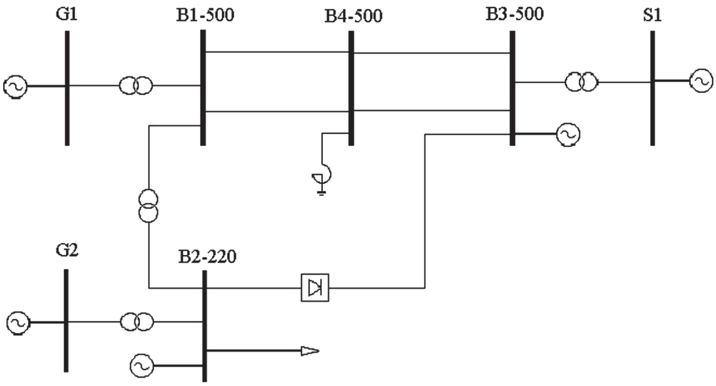

Fig. 2. EPRI (China) Seven lines diagram of node system

Table 1. Parameter identification results

Name of parameter	Set Value	Given initial value	Results of identification	Given initial value	Results of identification
x_d(pu)	0.162	0.150	0.1714	0.3564	0.1711
x_d'(pu)	0.0199	0.016	0.0197	0.044	0.0197
x_d''(pu)	0.0154	0.013	0.0154	0.0339	0.0154
x_q(pu)	0.162	0.14	0.1667	0.324	0.1627
x_q'(pu)	0.0398	0.032	0.0357	0.08	0.0385
x_q''(pu)	0.0154	0.013	0.0153	0.0308	0.0153
T_{d0}'(s)	8.62	6.79	8.5436	18.96	8.5436
T_{d0}''(s)	0.05	0.05	0.0492	0.11	0.0492
T_{q0}'(s)	2.2	1.77	2.1482	4.4	2.1314
T_{q0}''(s)	0.07	0.05	0.0727	0.14	0.00726
M	8	5	7.9757	24	7.9757

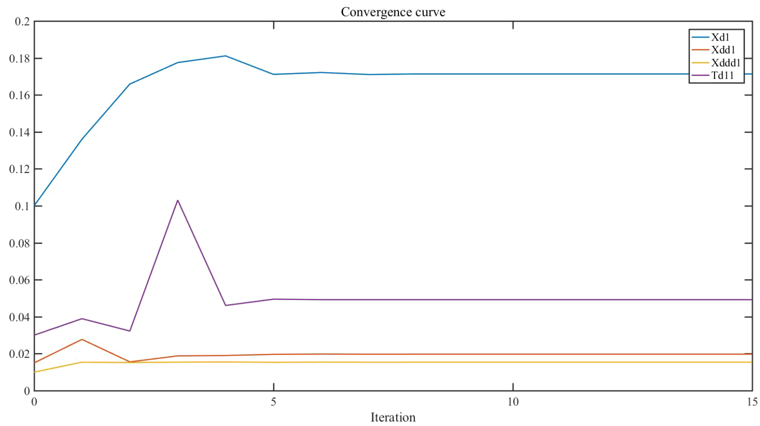

Figure 3 The convergence curve of $x_d x_d^{'} x_d^{''}\ T_{d0}^{''}$ parameters

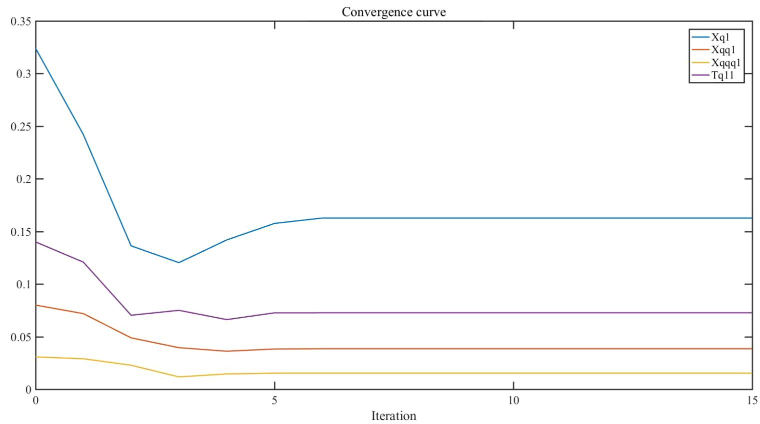

Fig. 4 The convergence curve of $x_q x_q^{'} x_q^{''}\ T_{q0}^{''}$ parameters

Acknowledgment. This work is supported by the National Science Foundation of China under Grant (51677057), Local University Support plan for R & D, Cultivation and Transformation of Scientific and Technological Achievements by Heilongjiang Educational Commission (TSTAU-R2018005) and Key Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Ministry of Education (MPSS2019-05).

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