ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 2004
Seria: ELEKTRYKA z.188 Nr kol. 1627

Andrzej BOBOŃ, Jerzy KUDŁA
Katedra Maszyn i Urządzeń Elektrycznych

USE OF DYNAMIC RESPONSES TO LOAD REJECTION TEST FOR ESTIMATION OF SYNCHRONOUS GENERATOR PARAMETERS

Summary. The paper presents a parameter estimation methodology for a synchronous generator mathematical model based on load rejection test results. A standard mathematical model of the synchronous generator containing one equivalent damper circuit in the d axis and two damper circuits in the q axis in the rotor (so called (2,2)-type model) is considered. The parameters in d axis are estimated from the d-axis load rejection, while the parameters in q axis are determined from the q-axis load rejection. The parameter estimation process consists of minimising the sum of squared differences between the measured test signals and the simulation results obtained when using the estimated parameter values. Calculations are made for the 200 MW generator.

WYKORZYSTANIE PRZEBIEGÓW DYNAMICZNYCH DO ESTYMACJI PARAMETRÓW GENERATORA SYNCHRONICZNEGO PODCZAS TESTU ZRZUTU MOCY

Streszczenie. W artykule przedstawiono metodykę estymacji parametrów elektromagnetycznych modelu matematycznego generatora synchronicznego na podstawie wyników testów zrzutu mocy. Rozpatrzono klasyczny model matematyczny generatora zawierający jeden zastępczy obwód tłumiący w osi d i dwa obwody tłumiące w osi q (tzw. model typu (2,2)). Parametry w osi d wyznaczono na podstawie testu zrzutu mocy w osi d, zaś parametry w osi q – na podstawie testu zrzutu mocy w osi q. W procesie estymacji parametrów przeprowadzono minimalizację błędów średniokwadratowych pomiędzy sygnałami pomiarowymi a sygnałami wyznaczonymi na podstawie modelu matematycznego. Wyniki estymacji parametrów przedstawiono dla turbogeneratora 200 MW.

1. INTRODUCTION

Computer programs used in simulations of power system transients provide powerful tools for predicting the power system behaviour in normal and emergency operating conditions. The accuracy of simulations depends on structures of mathematical models implemented in computer programs as well as on the quality of their parameters. The accuracy of the synchronous generator model is one of the most important factor influencing the accuracy of final computational results.

The parameter estimation method of the synchronous generator mathematical model from the dynamic responses measured in the machine windings is presented in this paper. Determination of the machine parameters was made using the data obtained from the

conditions close to the normal operating conditions of the machine. The main test used in the estimation process is the load rejection test consisting in disconnection of the main circuit-breaker. The parameter estimation process consists in minimising an objective function defined as the squared differences between the measured test signals and the results of simulations performed when using the estimated parameter values. Calculations are made for the 200 MW generator using the Matlab/Simulink/Optimization Toolbox program.

2. ELECTROMAGNETIC STATE EQUATIONS OF THE SYNCHRONOUS GENERATOR DURING THE LOAD REJECTION TEST

A synchronous machine mathematical model is expressed by the stator and rotor equations of electrical circuits and the equations of the mechanical motion. In this model, electrical circuits of the armature winding (stator) and the field winding (rotor) are treated as lumped parameter circuits. Other electrical circuits of the machine with damping properties are formed by solid parts of the rotor and are modelled by distributed parameters. In the mathematical model, these circuits are represented by a certain number of equivalent circuits with lumped parameters.

A standard Park's model of the synchronous generator, often used in computer programs for power system simulations, is considered. This model contains one equivalent damper circuit in d-axis and two damper circuits in q-axis of the rotor (so-called (2,2)-type model) [7] as shown in Fig. 1.

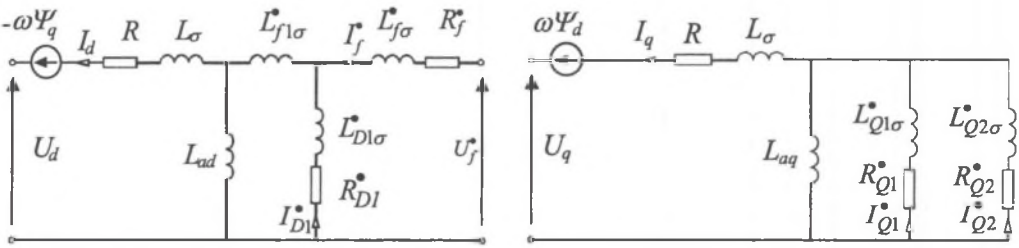

Fig. 1. Equivalent circuits in d and q axis of the synchronous machine
Rys. 1. Schematy zastępcze maszyny synchronicznej w osi d i q

Electromagnetic transient states of the generator initiated by the opening of the main circuit-breaker in the stator circuit, are described by the following differential equations of rotor circuits (in p.u.):

$$[U]=\frac{1}{\omega_N}\frac{d}{dt}[\Psi]+[R][I] \tag{1a}$$

$$[\Psi]=[L][I] \tag{1b}$$

Where

$$[U]=\begin{bmatrix} U^\bullet_f \\ 0 \\ 0 \\ 0 \end{bmatrix},\quad [\Psi]=\begin{bmatrix} \Psi^\bullet_f \\ \Psi^\bullet_{D1} \\ \Psi^\bullet_{Q1} \\ \Psi^\bullet_{Q2} \end{bmatrix},\quad [I]=\begin{bmatrix} I^\bullet_f \\ I^\bullet_{D1} \\ I^\bullet_{Q1} \\ I^\bullet_{Q2} \end{bmatrix},\quad [R]=\begin{bmatrix} R^\bullet_f & 0 & 0 & 0 \\ 0 & R^\bullet_{D1} & 0 & 0 \\ 0 & 0 & R^\bullet_{Q1} & 0 \\ 0 & 0 & 0 & R^\bullet_{Q2} \end{bmatrix}$$

$$[L]=\begin{bmatrix} L_{ad}+L^{\bullet}_{f\sigma}+L^{\bullet}_{f1\sigma} & L_{ad}+L^{\bullet}_{f1\sigma} & 0 & 0 \\ L_{ad}+L^{\bullet}_{f1\sigma} & L_{ad}+L^{\bullet}_{D1\sigma}+L^{\bullet}_{f1\sigma} & 0 & 0 \\ 0 & 0 & L_{aq}+L^{\bullet}_{Q1\sigma} & L_{aq} \\ 0 & 0 & L_{aq} & L_{aq}+L^{\bullet}_{Q2\sigma} \end{bmatrix}.$$

The subscripts "*f*", "*D*" and "*Q*" indicate quantities corresponding to the field winding as well as to the d and q axis damper electrical circuits, respectively. The superscript "•"(dot) indicates rotor quantities referred to the stator side.

Stator voltages in the d and q axis are calculated from the following relations:

$$\begin{aligned} U_d &\approx -\omega\Psi_q, \qquad \Psi_q = L_{aq}\left(I^{\bullet}_{Q1}+I^{\bullet}_{Q2}\right) \\ U_q &\approx \omega\Psi_d, \qquad \Psi_d = L_{ad}\left(I^{\bullet}_{D1}+I^{\bullet}_{f}\right). \end{aligned} \tag{2}$$

$$U_q \approx \omega\Psi_d,$$

3. METHODOLOGY OF THE PARAMETER ESTIMATION PROCESS

The parameter estimation is based on the test results during a load rejection transient process initiated by the opening of the main circuit-breaker connecting the generator to the power system [1, 3, 4, 5, 6]. The generator parameters are chosen in such a way that the circuit-model response calculated for these parameters is the best match to the test response.

The load rejection test is performed under such operating conditions of the generator that ensure elimination or minimization of the influence of the Automatic Voltage Regulator (AVR) and the turbine with its governor (Fig. 2). Hence, in the parameter estimation process only the synchronous generator model can be used.

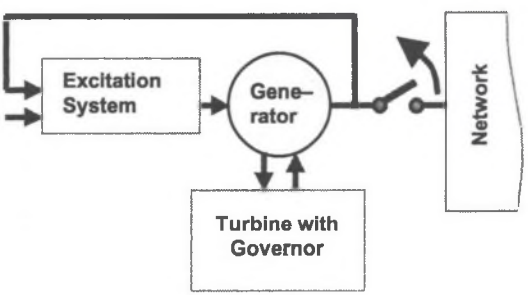

Fig. 2. Load rejection test
Rys. 2. Test zrzutu mocy

To eliminate the influence of the AVR, the excitation system should be manually controlled during the load rejection test (i.e. field voltage should be maintained constant). To minimize the influence of the turbine and its governor, the generator should be loaded with relatively small active power and, if possible, the turbine should be tripped simultaneously with opening the circuit-breaker (for the q-axis load rejection).

Equations (1) describe the transient processes appearing during the load rejection test for arbitrary operating conditions of the machine before this test. If the saturation phenomena and cross-coupling effects associated with them are neglected, then d and q axes of the model are

electrically and magnetically perpendicular to each other and are coupled through the rotational voltages only. By choosing appropriate operating conditions of the generator before the test, we can cause transients to appear only in one axis, which makes the estimation process easier for realization.

In this paper synchronous generator electromagnetic parameters are determined on the basis of two tests: so-called d- and q-axis load rejection tests.

d-axis load rejection test

The electromagnetic parameters in d axis are estimated using the results of the d-axis load rejection test. Before opening the main circuit-breaker the generator is loaded with a negative reactive power (-0,2 to –0,3 p.u.) and a minimum active power consumed by plant's auxiliaries. In this case the stator current has d-axis component only (Fig. 3a). It can be therefore assumed with a good accuracy that after opening the circuit breaker, the angular velocity does not change while, as the result of generator transient processes, the terminal voltage and the field current change.

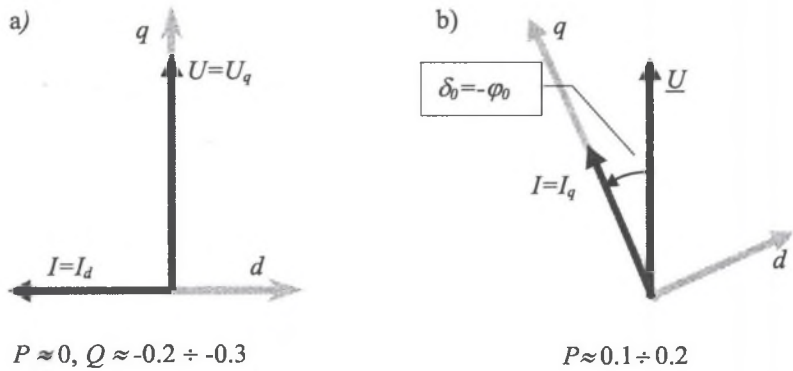

Fig. 3. Load conditions of the generator before the load rejection test in d axis (a) and q axis (b)
Rys. 3. Warunki pracy generatora przed wykonaniem testu zrzutu mocy w osi d (a) i w osi q (b)

q-axis load rejection test

The electromagnetic parameters in q axis are estimated using the results of the q-axis load rejection test. Before opening the main circuit-breaker the generator should be loaded with a small active power (0.1 to 0.2 p.u.) and such a reactive power for which the power angle is equal to the power factor angle (Fig. 3b). In this case the stator current has q-axis component only. After opening the generator circuit breaker changes the d-axis component of the stator voltage in the transient state.

4. INITIAL VALUES FOR THE SIMULATION OF TRANSIENT PROCESSES

In the parameter estimation process the generator differential equations are solved multiple times in order to match transient responses obtained from them to the field test responses. This involves the necessity of determining initial values for the rotor flux linkages and the rotor currents using the continuity principle of the rotor flux linkages. These linkages are determined from the equations describing the machine steady state before the field test.

Steady-state conditions for d-axis load rejection test

The generator steady-state equations before the d-axis load rejection test are of the following form:

$$U_{do} = I_{do} R \approx 0 ,$$
$$U_{qo} = \omega \Psi_{do} = \omega \left(I_{do} L_d + I_{fo}^{\bullet} L_{ad} \right). \tag{3}$$

In the steady-state conditions specified by the active power $P_0 \approx 0$, the reactive power Q_0 and the terminal stator voltage U_0 one obtains

$$I_{do} = \frac{Q_o}{U_o}, \qquad I_{qo} = 0 , \qquad I_{fo}^{\bullet} = \frac{1}{\omega L_{ad}} \left(U_o - I_{do} L_d \right). \tag{4}$$

Steady-state conditions for q-axis load rejection test

The generator steady-state equations before the q-axis load rejection test are of the following form:

$$U_{do} = -\omega \Psi_{qo}, \qquad \Psi_{qo} = L_q \, I_{qo} ,$$
$$U_{qo} = \omega \Psi_{do} + R \, I_{qo} , \qquad \Psi_{do} = L_{ad} \, I_{fo}^{\bullet} . \tag{5}$$

The generator operating conditions before the q-axis load rejection test are specified by the terminal stator voltage U_0, the active power P_0 and the reactive power Q_0 chosen in such a way that the power angle becomes equal to the power factor angle (Fig. 4). Using the phasor diagram from Fig. 4 and equations (4) the following equations can be written

$$U_o^2 = \left(\omega L_q I_o \right)^2 + U_{qo}^2 ,$$
$$P_o = U_o \, I_o \cos \varphi_o = U_{qo} \, I_o , \tag{6}$$

from which the voltage component U_{qo}, the current I_o and then the field current can be determined.

The stator currents I_{do}, I_{qo} and the field current $I_{fo}^{\bullet}$, depend on the estimated electromagnetic parameters therefore they must be calculated before each solution of the differential equations for the actual values of parameters.

5. ESTIMATION OF THE PARAMETERS

In the parameter estimation process, waveforms of the stator terminal voltage and the field current are taken into account. It is usually enough to use the terminal voltage. Then the field current is used to assess the parameter estimation quality and the correctness of the assumed mathematical model. When more accurate generator models are employed, which use for example rotor difference inductances, the field current signal is necessary for parameter estimation purposes.

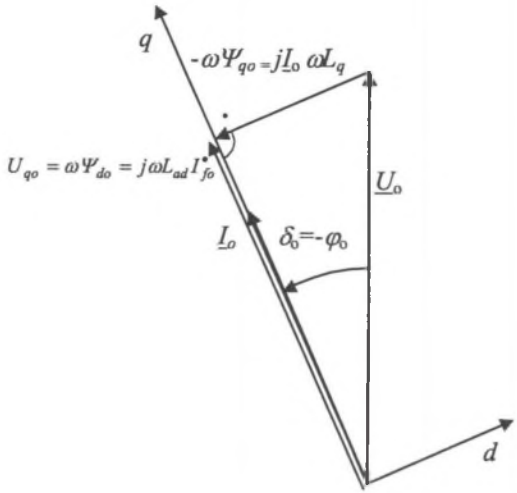

Fig. 4. Phasor diagram of the generator when the current phasor is along the rotor q-axis (the stator resistance is neglected)

Rys. 4. Wykres fazorowy generatora w przypadku gdy prąd stojana ma tylko składową w osi q (pominięto rezystancję stojana)

The objective function to be minimised is defined as a sum of the squared differences between the test results and the simulation results obtained using the derived (estimated) values of the parameters (in p.u.):

- for the d-axis load rejection test

$$\varepsilon_d(\boldsymbol{P}) = \sum_{i=1}^{n}\left(U_{i(m)} - U_{i(a)}(\boldsymbol{P})\right)^2 + \sum_{i=1}^{n}\left(I_{fi(m)} - I_{fi(a)}(\boldsymbol{P})\right)^2 \tag{7a}$$

- for the q-axis load rejection test

$$\begin{aligned}\varepsilon_q(\boldsymbol{P}) &= \sum_{i=1}^{n}\left(U_{di(m)} - U_{di(a)}(\boldsymbol{P})\right)^2 = \\ &= \sum_{i=1}^{n}\left(U_{i(m)}\sin\left(\delta_{i(m)}\right) - U_{i(a)}(\boldsymbol{P})\sin\left(\delta_{i(a)}(\boldsymbol{P})\right)\right)^2\end{aligned} \tag{7b}$$

where $U_i = U_{qi}$ is the instantaneous value of the stator voltage in d axis, I_{fi} is the instantaneous value of the field current, δ_i is the instantaneous value of the load angle and $\boldsymbol{P}$ is the vector of unknown parameter values. The subscript m (measurement) is used to denote the test results while the subscript a (approximation) is used to denote simulation results.

To minimize the objective functions (6a) and (6b) a gradient algorithm for local optimisation from the Matlab Optimization Toolbox was used [8]. Gradient algorithms optimize locally the objective function so the choice of the initial parameter values is important. As the starting point the values provided in the manufacturer's catalogue or the typical values quoted in literature [7] can be used. The parameter estimation is improved when the maximum and minimum values of parameters are also given. This limits the search area while making sure that the estimated values have physical sense.

6. RESULTS OF THE ELECTROMAGNETIC PARAMETER ESTIMATION

The estimation of electromagnetic parameters was performed for the 200 MW turbogenerator. The generator ratings are: S_n=235,3 MV·A, P_n=200 MW, U_n=15,75 kV, I_n=8625 A, $\cos\varphi_n$=0,85.

The terminal voltage responses, used for the parameter derivation purposes, were calculated for the load rejection test using the mathematical model of the generator. In the future studies these test results will be substituted by real signals measured in a power plant.

It was assumed that for the parameter estimation purposes the field voltage and the rotor speed remained constant. The d-axis load rejection test was performed for the generator loaded initially with the active power P_o=0 and the reactive power Q_o=-0,2 (p.u), whereas the q-axis load rejection test was performed for P_o=0,1 and Q_o=-0,0438 (p.u). For each parameter to be estimated, the upper and lower limits on the parameter values from the assumed range were selected.

The estimation results are given in Tables 1 and 2. In these tables, apart from the final estimation values, the initial, minimum, maximum, exact values used to simulate the test results and the percentage error values of the parameters are also presented.

In numerical calculations, the following parameters of the optimizing procedure from the Matlab/Optimization Toolbox program [8] was assumed:

TolX = 1·10-1 – termination tolerance on P (parameters),
TolFun = 1·10-1 – termination tolerance on the function value,
MaxFunEvals = 1000 – maximum number of the evaluation of the objective function.

Table 1

Results of the d-axis parameter estimation for 200 MW turbogenerator

Parameter [p.u.]	Objective function ε_d				Initial value	Limiting values		True value
	$\sum_{i=1}^{n}\lvert\Delta U_{qi}\rvert^2+\sum_{i=1}^{n}\lvert\Delta I_{fi}\rvert^2$		$\sum_{i=1}^{n}\lvert\Delta U_{qi}\rvert^2$					
	Final value	Error [%]	Final value	Error [%]		Min	Max	
L_{ad}	1,663	0	1,66307	0,004	1,4	0,01	2	1,663
$L^*_{fl\sigma}$	-0,0151	0,002	-0,0122	18,98	-0,03	-0,1	-0,002	-0,0151
$L^*_{Dl\sigma}$	0,00153	0,011	0,00010	93,46	0,0025	0,0001	0,006	0,00153
R^*_{Dl}	0,00127	0	0,00116	8,629	0,002	0,0001	0,006	0,00127
$L^*_{f\sigma}$	0,1151	0,001	0,12856	11,7	0,15	0,0001	0,31	0,1151
R^*_f	0,001284	0	0,00142	10,54	0,002	0,0001	0,006	0,00128

Table 2

Results of the q-axis parameter estimation for 200 MW turbogenerator

Parameter [p.u.]	Final value	Initial value	Limiting values		True value	Error [%]
			Min	Max		
L_{aq}	1,662	1,4	0,1	2	1,622	0
$L^{*}_{Q1\sigma}$	0,39198	0,25	0,001	1	0,392	0,004
R^{*}_{Q1}	0,003119	0,0041	0,0001	0,01	0,00312	0,002
$L^{*}_{Q2\sigma}$	0,010494	0,025	0,0001	0,1	0,0105	0,054
R^{*}_{Q2}	0,126827	0,225	0,001	1	0,1267	0,101

The parameters in d axis were determined when taking into account both the stator voltage and the field current as the output signals. When the stator voltage was used only, then the different set of parameters were obtained (Table 1).

The set of estimated electromagnetic parameters should be supplemented by the parameters which were not estimated: $R = 0{,}0018$ [p.u.], $L_{\sigma} = 0{,}15$ [p.u.].

The waveforms of the q-axis stator voltage and the field current for the d-axis load rejection test are presented in Fig. 5. There are compared the curves calculated for the estimated, true and initial parameters when taking into consideration the objective function containing both the stator voltage and the field current. The curves calculated for the estimated and true parameters are practically the same.

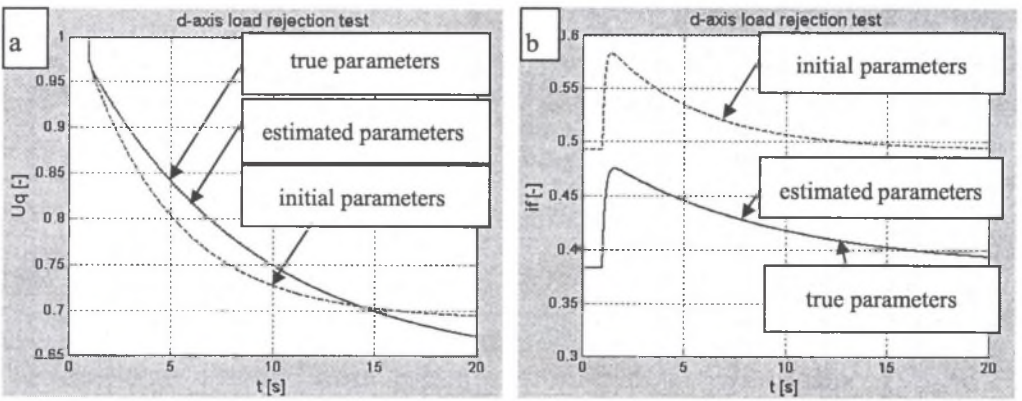

Fig. 5. Comparison of stator q-axis voltage (a) and field current (b) responses following the d-axis load rejection for the estimated, true and initial parameters

Rys. 5. Porównanie przebiegów napięcia w osi q (a) i prądu wzbudzenia (b) podczas testu zrzutu mocy w osi d dla parametrów początkowych, dokładnych i estymowanych

When only the q-axis stator voltage is included in the objective function, then small discrepancies between the field current curves calculated for the estimated and true parameters are observed, as shown in Fig. 6.

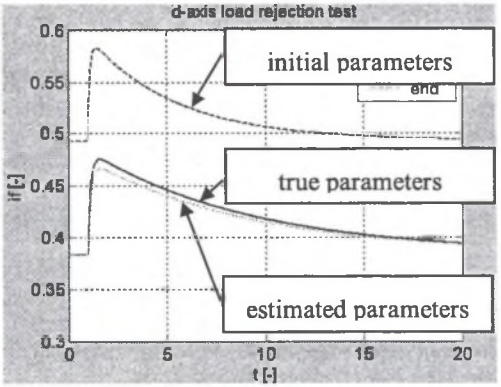

Fig. 6. Comparison of field current responses following the d-axis load rejection when the field current is not included in the objective function

Rys. 6. Porównanie przebiegów prądu wzbudzenia podczas testu zrzutu mocy w osi d, w przypadku gdy prąd wzbudzenia nie jest włączony do funkcji celu

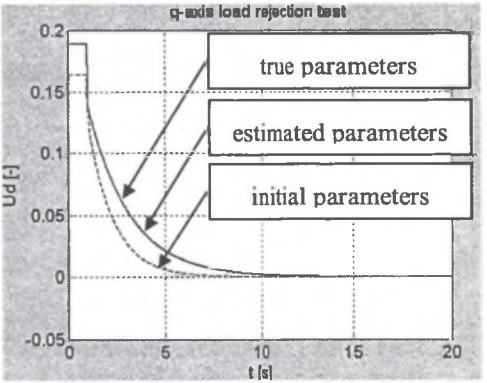

Fig. 7. Comparison of stator d-axis voltage responses following the q-axis load rejection for the estimated and initial parameters

Rys. 7. Porównanie przebiegów napięcia w osi d podczas testu zrzutu mocy w osi q dla parametrów początkowych i estymowanych

The comparison of the d-axis stator voltage waveforms calculated for the estimated, true and initial parameters for the q-axis load rejection test is presented in Fig. 7. Similarly as in Fig. 5, the voltage curves calculated for the estimated and true parameters are close to each other.

7. CONCLUDING REMARKS

The results of parameter estimation for the considered generator model lead to the following conclusions:

- simulated responses, performed using the derived values of parameters, were practically the same as the actual (true) test responses,
- stator voltage should be included in the objective function to obtain correct results, however in the case of more accurate mathematical models the field current should also be taken into account,
- optimization algorithm from the MATLAB/Simulink/Optimization Toolbox takes into account the specified upper and lower limits of parameters, hence ensuring that the final values have physical sense. Reducing the spread between the upper and lower limits reduces the search area of the optimization algorithm, hence speeding up the calculations,
- values chosen from the literature data for the starting point for parameter estimation as well as their upper and lower limitations and parameters of the optimizing procedure enable obtaining the good results in a relatively short time,
- tolerance limits TolFun oraz TolX influence the estimation results. Too high values may result in large estimation errors while too small values increase unnecessarily the number of iterations. Therefore it is useful to assess, by trial-and-error method, the optimum values of tolerances.

REFERENCES

1. Boboń A., Kudła J., Białek J.: Estymacja parametrów modeli matematycznych generatorów synchronicznych na podstawie testów zrzutu mocy. XI Międzynarodowa Konferencja Naukowa "Aktualne Problemy w Elektroenergetyce", Gdańsk-Jurata, czerwiec 2003.
2. Białek J., Boboń A., Kudła J., Paszek S.: Wykorzystanie pakietu Matlab/Simulink/Optimization Toolbox do estymacji parametrów modelu matematycznego zespołu wytwórczego. XI Międzynarodowa Konferencja Naukowa "Aktualne Problemy w Elektroenergetyce", Gdańsk-Jurata, czerwiec 2003.
3. Bobon A., Kudła J.: Metoda estymacji parametrów generatorów synchronicznych na podstawie przebiegów dynamicznych podczas testów zrzutu mocy. Seminarium naukowo-techniczne "Vybrane problemy elektrickych stroju a pohonu 2003", 19-21 maj 2003, Lomnice k. Tisnova.
4. Bortoni E.C., Jardini J.A.: Identification of synchronous machine parameters using load rejection test data. IEEE Transaction on Energy Conversion, vol.17, No.2, June 2002, p.242-247.
5. de Mello F.P., Ribeiro J.R.: Derivation of Synchronous Machine Parameters from Tests. IEEE Transactions on Power Apparatus and Systems, Vol. Pas 96, no.4 July/August 1977, p. 1211-1218.
6. Feltes J.W., Orero S., Fardanesh B., Uzunovic E., Zelingher S., Abi-Samra N.: Deriving Model Parameters from Field Test Measurements. IEEE Computer Applications in Power, Oct., 2002, p. 30-36.
7. Kundur P.: Power System Stability and Control. EPRI Power System Engineering Series, McGraw-Hill, Inc., 1994.
8. Optimization Toolbox User's Guide. Mathworks, Inc., 1990-2001.

Recenzent: Dr hab. inż. Mieczysław Ronkowski,
Profesor Politechniki Gdańskiej

Wpłynęło do Redakcji dnia 17 maja 2004 r.