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Sebastian Berhausen · Łukasz Majka ·
Adrian Nocoń · Piotr Pruski

Synchronous Generators and Excitation Systems Operating in a Power System

Measurement Methods and Modeling

Springer

Stefan Paszek
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

Andrzej Boboń
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

Sebastian Berhausen
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

Łukasz Majka
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

Adrian Nocoń
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

Piotr Pruski
Faculty of Electrical Engineering
Silesian University of Technology
Gliwice, Poland

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Preface

The monograph presents measurement methods and most essential results of analyses concerning the parameter estimation of mathematical models of synchronous generators and excitation systems operating in a power system.

The following theoretical and practical issues are considered:

1. Different mathematical models of the synchronous generators and excitation systems working in the power system are discussed in detail. The most important equations describing particular models and the simplifying assumptions are given.
2. The sensitivity analysis of the generating unit simulation waveforms to the change in the model parameters is performed. On its basis, the assessment of the possibility of estimating particular parameters of generating unit mathematical models is made.
3. The parameter estimation algorithms for mathematical models of synchronous generators and excitation systems are described. The objective functions are presented, and the algorithms used for searching the extrema of these functions are discussed. The best searching algorithms for the function extremum are selected.
4. The user interface of the parameter estimation program for generating unit element mathematical models developed in the MATLAB–Simulink environment is presented.
5. The problem of processing, scaling and filtering the measurement signals is presented.
6. The designed and constructed device which enables, among others, determining the generator load angle in steady and transient states is described. Moreover, the pseudorandom signal (PRBS) generation module implemented in this device is presented. This signal is used for parameter estimation of synchronous generator models.
7. The laboratory measurements and the measurements taken in selected power plants are described. The exemplary parameter estimation results of the generating unit element mathematical models obtained from those measurements are

given. A pseudorandom signal PRBS applied to the voltage regulation system during the generator normal work was used in the laboratory measurements. This method can also be used for parameter estimation of high power synchronous generators working in system power plants.

8. The procedures for determination of the tested synchronous generator model parameters in a laboratory and model parameters of selected generating unit elements in power plants by means of the computer program developed by the authors of the monograph are presented. Parameter determination of the GENROU (type XT), RL (2, 2) and (3, 3) synchronous generator models as well as the electromachine and static excitation system models is described in detail.

In the summary, the conclusions drawn from the analyses, the possibilities of using the results obtained and the perspective of further investigations are presented.

The measuring methods developed, the devices constructed, the results obtained and the conclusions drawn can be used for simulation investigations aiming at the assessment of causes and results of system failures associated with the transient states of a power system, assessment of the system angular stability, optimization of the installation place and parameters of power system stabilizers as well as assessment of the influence of connecting new generating units on the power system.

Gliwice, Poland

Stefan Paszek
Andrzej Boboń
Sebastian Berhausen
Łukasz Majka
Adrian Nocoń
Piotr Pruski

Contents

About the Authors

Stefan Paszek, Prof. Ph.D., D.Sc., Eng., received the Ph.D. and D.Sc. degrees from the Faculty of Electrical Engineering of the Silesian University of Technology, Gliwice, Poland, in 1986 and 1999, respectively. In 2012, he received the title of professor. He is currently Director of the Institute of Electrical Engineering and Computer Science of the Silesian University of Technology. His publications may be found at https://www.researchgate.net and https://scholar.google.pl. His research interests include: power system analysis in transient states, power system angular stability, optimization and polyoptimization of power system stabilizers and voltage regulators of synchronous generators, estimation of parameters of generating unit models in power system.

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Andrzej Boboń, Ph.D., Eng., has been working at the Silesian University of Technology since 1973. He obtained the degree of Ph.D. in 1982. His areas of scientific interest include research on AC electrical machines, in particular analysis of steady and transient states, estimation of parameters of mathematical models of machines and analysis of electromagnetic fields in machines. He also investigates stability and generally operation of synchronous generators operating in the power system.

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Sebastian Berhausen, Ph.D., Eng., obtained Ph.D. degree in Electrical Engineering in Silesian University of Technology (Gliwice, Poland), Faculty of Electrical Engineering, in 2012. At present he is employed as Assistant Professor in Institute of Electrical Engineering and Computer Science of the same university. His scientific interests include: estimation of electromagnetic parameters of synchronous generators operating in power system, optimization algorithms, simulations of synchronous generators under symmetrical and asymmetrical operational conditions using circuit and field-circuit models based on Finite Elements Method (FEM). List of his publications may be found at https://www.researchgate.net.

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Łukasz Majka, Ph.D., Eng., from 2011 an employee of the Department of Electrical Engineering and Computer Science as an Assistant Professor. His interests focus on modeling components and phenomena of the power system. In cooperation with Energotest-Gdańsk, he performed numerous measurements at strategic power plants in Poland, including those presented in this book. He also deals with measurements of electrical quantities in industrial installations, including signal processing and analysis of transients in the power system, especially for modeling and simulation purposes. He is a graduate of two industrial internships. He is the author and co-author of over 50 scientific publications.

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Adrian Nocoń, Ph.D., Eng., received the Ph.D. degree at the Faculty of Electrical Engineering of the Silesian University of Technology, Gliwice, Poland, in 2006. Assistant Professor in Department of Electrical Engineering and Computer Science. Author or co-author of 86 publications, including three monographs and one academic textbook. His publications may be found at https://www.researchgate.net and https://scholar.google.com. Author or co-author of many projects for industry. His research interests include: power system analysis in transient states, power system angular stability, optimization and polyoptimization of power system stabilizers and voltage regulators of synchronous generators, estimation of parameters of generating unit models in power system.

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Piotr Pruski, Ph.D., Eng., completed his Master's studies at the Faculty of Electrical Engineering of the Silesian University of Technology in Gliwice with distinction in 2009. He defended his doctoral dissertation at his home department, also with distinction, in 2014. He is currently Assistant Professor in Department of Electrical Engineering and Computer Science. His research interests include analysis of the power system operation in symmetrical and asymmetrical transient states, power system angular stability, asymmetrical faults in power systems, optimization algorithms, digital signal processing and programming. Author or co-author of 82 publications, including three monographs. His publications may be found at https://www.researchgate.net and https://scholar.google.com

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Principal Symbols

a, b	Delay angle and conduction angle of thyristors in a static excitation system
$\boldsymbol{A}_{\mathrm{R}}$, $\boldsymbol{A}_{\mathrm{R1}}$, $\boldsymbol{A}_{\mathrm{R2}}$, $\boldsymbol{B}_{\mathrm{Rref}}$, $\boldsymbol{B}_{\mathrm{Rr}}$, $\boldsymbol{B}_{\mathrm{RU}}$, $\boldsymbol{C}_{\mathrm{R}}$, $\boldsymbol{E}_{\mathrm{R2}}$, $\boldsymbol{C}_{\mathrm{R1}}$, $\boldsymbol{C}_{\mathrm{R2}}$, $\boldsymbol{D}_{\mathrm{RZ}}$	Matrices in state equations, output equations and limits of excitation systems
$\cos\varphi_{\mathrm{N}}$	Generator rated power factor
$\boldsymbol{C}$	Park transformation matrix
$\underline{E}''_0$	Initial value of the generator voltage phasor behind the subtransient reactance
E_{fd}	Generator field voltage
E_{fd0}	Initial value of the field voltage
E_{fdN}	Generator rated field voltage
E_{fdmax}	Maximum value of the generator field voltage
E_{fdB}	Excitation winding reference voltage for values expressed in relative units
E'_{d}	Generator voltage in the d-axis behind the transient reactance X'_{q}
E'_{d0}	Initial value of the generator voltage in the d-axis behind the transient reactance X'_{q}
E'_{q}	Generator voltage in the q-axis behind the transient reactance X'_{d}
E'_{q0}	Initial value of the generator voltage in the q-axis behind the transient reactance X'_{d}
$\underline{E}'_{\mathrm{Q0}}$	Voltage phasor in the q-axis behind the generator reactance X_{q}
f	Frequency
f_{N}	Generator rated frequency
f_{pass}	Higher cutoff frequency of the filter
f_{s}	Sampling frequency of measurement waveforms
f_{stop}	Lower cutoff frequency of the filter

F_{EX}	Output signal from the rectifier of the EXAC1 excitation system
$\boldsymbol{I}$	Unit matrix
I_B	Stator reference current for values expressed in relative units
I_N	Generator rated current
I_{N1}	Load current of the excitation system rectifier
I_d, I_q	Generator stator current in the d- and q-axes
I_{d0}, I_{q0}	Initial value of the generator stator current in the d- and q-axes
I_{fd}	Field current
I_{fd0}	Initial value of the field current
I_{fdN}	Rated field current
I_{fdB}	Excitation winding reference current for values expressed in relative units
I_T	Generator stator current
$\underline{I}_T$	Generator stator current phasor
$\underline{I}_{T0}$	Initial value of the generator stator current phasor in steady state
I_{fe}	Field current of the electromachine excitation system exciter
$K(t)^g_{x_i}$	Semi-relative sensitivity of the output waveform g to changes in the value of the ith parameter x_i
K_A, K_B, K_C, K_F	Gains of the excitation system
L_B	Stator reference inductance for values expressed in relative units
L_{ad}, $L^{\bullet}_{lf}$, $L^{\bullet}_{lkd1}$, $L^{\bullet}_{lkd2}$	Magnetizing inductance, excitation winding leakage inductance, leakage inductances of the rotor damping circuits in the generator d-axis
L_{aq}, $L^{\bullet}_{lkq1}$, $L^{\bullet}_{lkq2}$	Magnetizing inductance, leakage inductances of the rotor damping circuits in the generator q-axis
L_d, L_q	Synchronous inductance in the generator d- and q-axes
T_e	Generator electromagnetic torque
n	Rotational speed of the generator rotor
n_N	Rated rotational speed of the generator rotor
n_d, n_q	Number of the equivalent damping circuits in the generator rotor d- and q-axes
P	Generator active power
$\boldsymbol{P}$, $\boldsymbol{P}_d$, $\boldsymbol{P}_q$, $\boldsymbol{P}_1$, $\boldsymbol{P}_2$, $\boldsymbol{P}_3$	Vector of the searched parameters of the generating unit element model
P_m	Turbine mechanical power
P_0	Initial value of the generator active power

P_N	Generator rated active power
Q_0	Initial value of the generator reactive power
R_a	Generator stator winding resistance
$R_f^\bullet$, $R_{kd1}^\bullet$, $R_{kd2}^\bullet$	Excitation winding resistance, resistances of the rotor damping circuits in the generator d-axis
s	Laplace differential operator
$\underline{S}_0$	Initial complex power of the generator
S_1, S_2, S_3, S_4	Sensitivity factors
S_{10}, S_{12}	Saturation coefficients of the generator model
S_N	Rated apparent power of the generator
$STFT(g)$	Short-time Fourier transform of the signal $g(t)$ with window function
t	Time
Δt	State equation integration step for generating unit element models
t_0	Time instant of disturbance occurrence
t_s	Analysis beginning time
t_e	Analysis ending time
T_A, T_B, T_C, T_E, T_F, T_{F2}, T_R	Time constants of the excitation system model
T'_{do}	Transient time constant in the d-axis at the open generator stator winding
T''_{do}	Subtransient time constant in the d-axis at the open generator stator winding
T'_{qo}	Transient time constant in the q-axis at the open generator stator winding
T''_{qo}	Subtransient time constant in the q-axis at the open generator stator winding
T_m	Mechanical time constant
V_B	Stator reference voltage for values expressed in relative units
V_{RMAX}, V_{RMIN}, V_{1MAX}, V_{1MIN}, I_{eemax}, I_{eemin}	Limits in the excitation system model
V_{in}	Spectrum of the signal measured at the power plant
V_{out}	Spectrum of the filtered measurement signal
V_d, V_q	Generator stator voltage in the d- and q-axes
V_{d0}, V_{q0}	Initial values of the generator stator voltage in the d- and q-axes
V_{ref}	Reference voltage of the generator voltage regulator
V_{ref0}	Initial value of the generator voltage regulator reference voltage
V_r	Output voltage of the generator voltage regulator

V_{r0}	Initial value of the generator voltage regulator output voltage
V_{PSS}	Power system stabilizer output signal
V_T	Generator terminal voltage
$\underline{V}_T$	Generator terminal voltage phasor
V_{T0}	Initial value of the generator terminal voltage
$\underline{V}_{T0}$	Initial value of the generator terminal voltage phasor
V_{TN}	Generator rated voltage
$w(t)$	Fourier transform window function
w_k	Weighting coefficients in the expression for mean square error $\varepsilon(\boldsymbol{P})$
X''	Generator subtransient reactance
X_{ad}, X_{aq}	Magnetizing reactance in the generator d- and q-axes
X_d	Generator reactance in the d-axis
X_d'	Generator transient reactance in the d-axis
X_d''	Generator subtransient reactance in the d-axis
X_l	Generator stator leakage reactance
$\boldsymbol{X}_R$, $\boldsymbol{X}_{R1}$, $\boldsymbol{X}_{R2}$	Vectors of the excitation system state variables
X_q	Generator reactance in the q-axis
X_q'	Generator transient reactance in the q-axis
X_q''	Generator subtransient reactance in the q-axis
Z''	Generator subtransient impedance
Z_B	Absolute value of the stator reference impedance for values expressed in relative units
$Z_e = R_e + j\,X_e$	PS equivalent impedance
Z_{fB}	Absolute value of the excitation winding reference impedance for values expressed in relative units
α	Generator stator voltage phasor position angle
$\varepsilon(\boldsymbol{P})$	Minimized mean square error of the deviations between the measured waveforms and the waveforms calculated on the basis of mathematical models of generating unit elements
δ	Generator power (load) angle
δ_0	Initial value of the generator power (load) angle
δ_g	Thickness of the air gap between the generator stator and rotor
ϑ	Angle determining the generator rotor instantaneous position
ϑ_0	Initial angle of generator rotor instantaneous position (for $t = 0$)

ϑ_G	Generator rotor instantaneous position angle measured by the appropriate position sensor
τ	Signal sampling period
φ_0	Initial value of the generator power factor angle
$\Delta\omega$	Change in the generator rotor angular speed
ω	Electric angular speed of the generator rotor
ω_B	Reference angular speed for values expressed in relative units
ω_N	Generator rated angular speed
$\underline{\Psi}''$	Generator subtransient flux linkage phasor
$\underline{\Psi}''_0$	Initial value of the generator subtransient flux linkage phasor
Ψ_B	Stator reference magnetic flux linkage for values expressed in relative units
Ψ_d, Ψ_q	Generator flux linkage in the d- and q-axes
Ψ''_d, Ψ''_q	Generator subtransient flux linkage in the d- and q-axes
Ψ''_{d0}, Ψ''_{q0}	Initial value of the generator subtransient flux linkage in the d- and q-axes
Ψ_{kd0}, Ψ_{kq0}	Initial value of the flux linkage of the generator damping windings in the d- and q-axes
Ψ_m^{sat}	Resultant magnetizing flux of the generator taking into account magnetic core saturation
Ψ_{md}, $\Psi^\bullet_f$, $\Psi^\bullet_{kd1}$, $\Psi^\bullet_{kd2}$	Instantaneous values of flux linkages of the stator and rotor electric circuits in the machine d-axis referred to the stator side
Ψ_{mq}, $\Psi^\bullet_{kq1}$, $\Psi^\bullet_{kq2}$, $\Psi^\bullet_{kq3}$	Instantaneous values of flux linkages of the stator and rotor electric circuits in the machine q-axis referred to the stator side
Ψ_{md}^{sat}, Ψ_{mq}^{sat}	Instantaneous values of saturated magnetizing fluxes in the d- and q-axes
$\Delta\Psi_m$	Resultant saturation correction of the magnetizing flux
$\Delta\Psi_{md}$, $\Delta\Psi_{mq}$	Flux corrections expressing differences between the values of magnetizing flux components in the d- and q-axes, when taking into account and omitting the saturation phenomenon

Dot ($^\bullet$) means referring the rotor quantities to the generator stator side.
Subscript (gen) means a quantity in the generator relative units.
Subscript (reg) means a quantity in the regulator relative units.