Computations of the model parameters of generating unit elements based on measurements

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Abstract
The paper presents the method and results of the parameter estimation of the mathematical model of the electromachine excitation system as well as the steam turbine and its governor. The presented method can also be used for determining the parameters of mathematical models of other elements of generating units as well as of distributed sources. The excitation system computations were based on real dynamic waveforms obtained from possible to perform in Rybnik Power Plant measurements of the generator steady state disturbed with different test disturbances. The turbine computations were based on the simulated dynamic waveforms which occurred after appropriately selected and possible for realisation in a power plant test disturbances of the steady state of the generating unit operation. In both cases the problem of parameter estimation was brought to the minimisation of the objective function determined by the vector of the deviations between the approximated and approximating waveforms computed on the basis of the system model described by the searched parameters.

Keywords: power systems, optimisation, dynamic models

Introduction

Reliable computations of the power system operation under failure-free and failure conditions require well equipped mathematical models of the particular pieces of the generating unit described by the real parameters. The models of generators, excitation systems and turbine governors are well known but not as the same as their parameter values. The parameter values used for dynamic analysis are usually provided by equipment manufacturers or calculated from design data. But the long-lasting exploitation of generating units as well as consecutive repair and modernisation works change those parameter values so that they cannot be the reliable basis for further use. Hence it is necessary to perform research targeted at development of the efficient method for determining true parameter values.

Also when analysing the operation of a power system with a large number of distributed sources, the lack of reliable model parameters of these sources and of high power generating units is the main problem. Such investigations concerning, among others, transient states are necessary when connecting successive distributed sources (for instance wind farms) to a power system.

This paper proposes such a method and presents the results of computations of the excitation system as well as the steam turbine and its governor mathematical model parameters.

1. Mathematical models of the considered systems

The considered electromachine excitation system model contains models of the voltage regulator (Fig. 1a), three phase exciter (Fig. 1b) and diode rectifier (Fig. 1c), where: U – generator terminal voltage, U_{ref} – regulator reference voltage, U_R – regulator output voltage, I_{ww} – exciter field current, U_e – exciter output voltage, I_{fd} – generator exciting current, E_{fd} – generator field voltage, Fex_s – function determining the diode rectifier operating range, K_1, K_2, T_1, T_i, T_2, T_3, T_4 – voltage regulator model gains and time constants, K_3, T_5 – the additional voltage regulator model gain and time constant, T_6 – the exciter model time constant, K_4, K_C, T_7 – gains and time constant of the field voltage forming system model.

The assumed model of the steam turbine (Fig 2b) with its governor (Fig. 2a) standardized by IEEE was applied to the investigations performed [5].

The meaning of the symbols used in the model of Fig. 2a and 2b is as follows:

- K_5, T_8, T_9, T_{10} – gain coefficient and time constants in the turbine control system, respectively,
- K_6, T_{11}, K_7, T_{12}, K_8, T_{13} – gain coefficients and time constants in: the control room and high-pressure part (6, 11), the interstage superheater and medium-pressure part (7, 12), the low-pressure part (8, 13), respectively,
- $\Delta\omega$ – signal of the synchronous generator angular speed deviation,
- P_0 – turbine input power,
- P_d – power transmitted by the steam flow at the turbine inlet,
- P_m – turbine mechanical power.

Fig. 3 shows the block diagram of the electromachine excitation system as well as the turbine and its governor model with the input and output signals used for parameter estimation process.

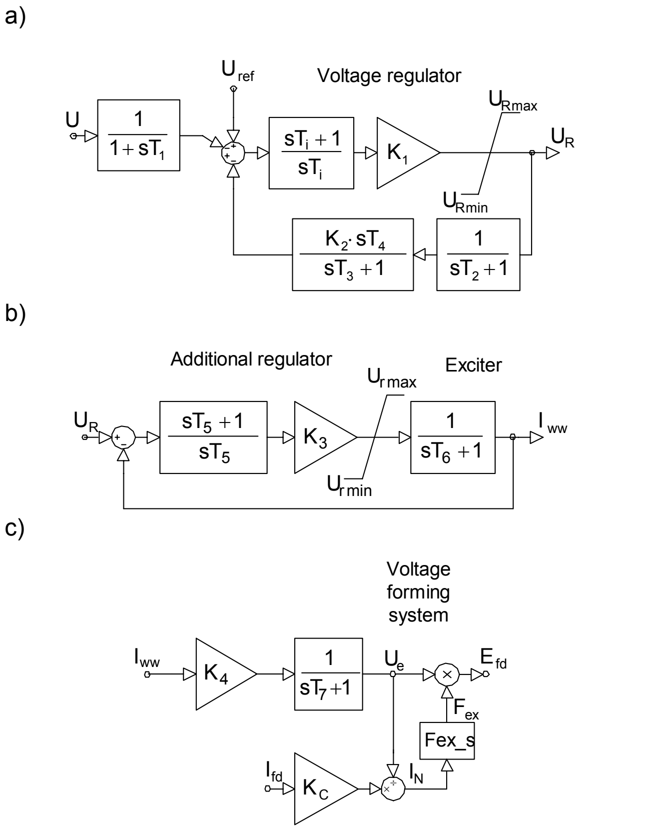


Fig.1 Excitation systems structural model – voltage regulator, additional voltage regulator and exciter as well as voltage forming system structural model

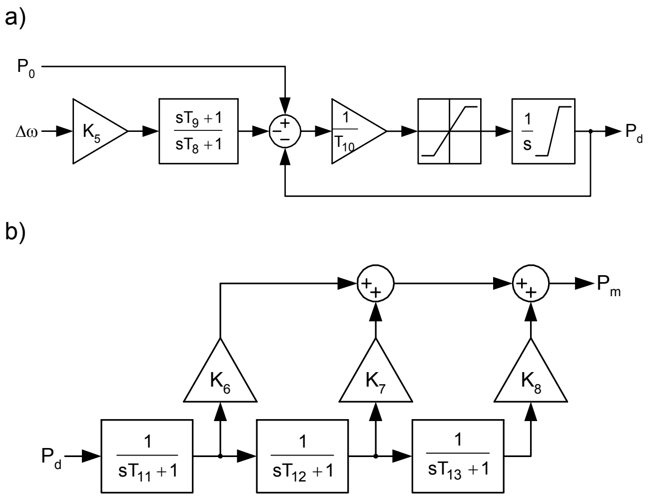


Fig.2 Steam turbine with its governor structural model

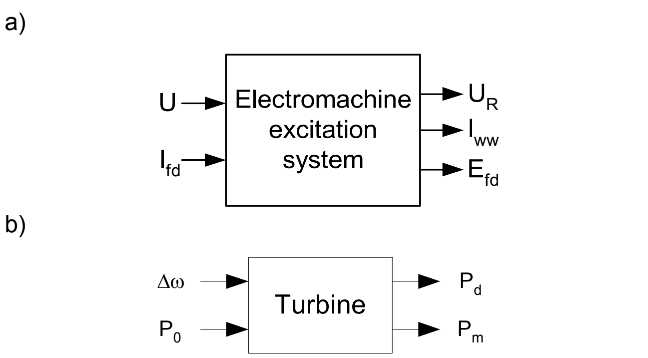


Fig.3 Input and output signals of the electromachine excitation system (a) and steam turbine (b) models

2. Assumptions for parameter estimation of the excitation system model as well as the turbine and its governor

Estimation of the assumed mathematical model of the excitation system and the steam turbine with its governor was carried out in an iterative process in such a way that the dynamic waveforms computed on the basis of these parameters approximated the measured (excitation system) or simulated (turbine) waveforms with a definite accuracy [1], [2], [4].

The excitation system was analysed separately. The influence of the generator on it was modelled by using the terminal voltage U and generator field current I_{fd} waveforms as the input signals of the excitation system. In order to improve effectiveness of the excitation system parameter computations, the estimation process was divided into three stages.

At the first stage, the voltage regulator model parameters: gains K_1 i K_2 and time constants T_1, T_i, T_2, T_3 i T_4 were determined (Fig. 1a). It should be noted that the values of these parameters were known since they were the digital regulator settings fixed by the user during the block starting. Computations at this stage allowed verifying the correctness of the assumed measurement method and the measurement accuracy. At this stage the generator terminal voltage was an input signal, while as the regulator output voltage was the output one (Fig. 1a).

At the second stage, the additional voltage regulator and exciter parameter values were determined (gains K_3 as well as time constants T_5 and T_6) (Fig. 1b). The voltage regulator output voltage was an input signal and the exciter field current was an output signal (Fig. 1b).

At the third stage, the field voltage forming system parameter values were determined (gains K_4 and K_C as well as time constant T_7) (Fig. 1c). During this stage the exciter and generator field current waveforms were input signals, while the generator field voltage was an output signal (Fig. 1c).

The objective functions minimised at particular computation stages were:

$$\varepsilon_1(\boldsymbol{P}_1)=\sum_{i=1}^{n}\left|U_{Ri(m)}-U_{Ri(a)}(\boldsymbol{P}_1)\right|^2 \tag{1}$$

$$\varepsilon_2(\boldsymbol{P}_2)=\sum_{i=1}^{n}\left|I_{wwi(m)}-I_{wwi(a)}(\boldsymbol{P}_2)\right|^2 \tag{2}$$

$$\varepsilon_3(\boldsymbol{P}_3)=\sum_{i=1}^{n}\left|E_{fdi(m)}-E_{fdi(a)}(\boldsymbol{P}_3)\right|^2 \tag{3}$$

where: U_{Ri}, I_{wwi}, E_{fdi} – regulator output voltage, exciter field current and generator field voltage values at i-th time instant, $\varepsilon_1(\boldsymbol{P}_1)$, $\varepsilon_2(\boldsymbol{P}_2)$, $\varepsilon_3(\boldsymbol{P}_3)$ – error values. The approximating waveforms are inexplicit functions of the vector $\boldsymbol{P}_1$, $\boldsymbol{P}_2$, $\boldsymbol{P}_3$ respectively, whose elements are the searched parameters of the excitation system regulator model. The index m denotes the values measured, while the index a the approximating values.

In the parameter estimation process of the model of the turbine and its governor there were used the dynamic waveforms obtained from simulations (due to the lack of the waveforms from measurements). Those dynamic waveforms of the selected quantities of the generating unit obtained after test disturbances of the steady state should be the result, first of all, reaction of the turbine and its governor to the disturbance. The external power system and power system stabilizer should not influence them (the system stabilizer should be switched off during the test). However, the excitation system will influence the waveforms because only automatic voltage control is accepted by the plant personnel during the tests. In order to meet the above assumptions, a load rejection was chosen to be the test disturbance. The opening of the generator main circuit breaker at the instant of the disturbance occurrence will disconnect the generating unit with the network and eliminate the influence of the external power system. The generator initial active power different from zero ($P_0 \neq 0$) will ensure the reaction of the turbine and its governor [3], [6].

The turbine and its governor were also analysed separately. In order to improve effectiveness of the turbine and its governor parameter computations, the estimation process was divided into two stages.

At the first stage, the governor model parameters: gain K_5 and time constants T_8, T_9 and T_{10} were determined (Fig. 2a). At this stage signal of the synchronous generator angular speed deviation waveform was an input signal, while the power transmitted by the steam flow at the turbine inlet was the output signal (Fig. 2a).

At the second stage, the turbine model parameter values were determined (gains K_6, K_7, K_8 as well as time constants T_{11}, T_{12} and T_{13} – Fig. 2b). The power transmitted by the steam flow at the turbine inlet waveform was an input signal and the turbine mechanical power was an output signal (Fig. 2b).

The objective functions were formulated on the basis of the deviations of the turbine output quantities, that is the deviations between the measured (simulated) and approximated values of the power transmitted by the steam flow at the turbine inlet (for the first stage) and the turbine mechanical power (for the second stage):

$$\varepsilon_4(\boldsymbol{P}_4) = \sum_{i=1}^{n} \left| P_{d\,i(m)} - P_{d\,i(a)}(\boldsymbol{P}_4) \right|^2 \quad (4)$$

$$\varepsilon_5(\boldsymbol{P}_5) = \sum_{i=1}^{n} \left| P_{mi(m)} - P_{mi(a)}(\boldsymbol{P}_5) \right|^2 \quad (5)$$

where: P_{mi}, P_{di} – instantaneous values of the mechanical power and the power transmitted by the steam flow at the turbine inlet, $\varepsilon_4(\boldsymbol{P}_4)$ and $\varepsilon_5(\boldsymbol{P}_5)$ – error values. The approximating quantities are functions of the vector $\boldsymbol{P}$ whose elements are the searched parameters of the model of the turbine with its governor.

3. Computation results

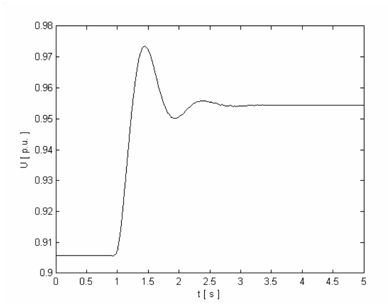
Computations of the electromachine excitation system parameters were performed basing on the dynamic signals measured during a step change in the AVR reference value by +/-5% when the generator was not loaded ($P_0 = 0$, $Q_0 = 0$). No load caused that the external power system did not influence the generator and the turbine. The above mentioned analysis and computations were performed while the voltage controller was operating (automatic excitation control).

The parameter estimation of the turbine with its governor was performed by applying to the model inputs (Fig. 2a and 2b) the simulated dynamic waveforms obtained from the simulated load rejection test in q axis. The following initial values of the generator load were assumed: P_0 = 0.2 and Q_0 = -0.0723 (in p.u.).

The method assumed for parameter estimation of the excitation system as well as the turbine and its governor mathematical models consists in reconstruction of the dynamic waveforms obtained on the basis of the test disturbances mentioned above by means of the system model expressed by the searched parameters. The optimisation algorithm changing the model parameters brings the approximating waveforms closer to the approximated ones which will be obtained, for instance, from the measurements taken in the power plant during the appropriately selected time period. Computations of the system parameters are realised as the minimisation of the objective function expressed by the vector of the deviations between the approximating and approximated waveforms of the selected quantities (approximation input signals) within the appropriately chosen time period. The optimisation was performed with use of the large-scale, trust-region, reflective Newton gradient algorithm.

The computation results of the electromachine excitation system parameter approximation are given in Table 1. The waveforms (measured and approximated ones) obtained from the excitation system are presented in Figs. 4, 5 and 6. Fig. 7 presents the dynamic waveforms of the generator angular speed deviation signal, the power transmitted by the steam flow at the turbine inlet and the turbine mechanical power (initial and final waveforms) at the load rejection in q axis. The estimation results are given in Table 2.

a)



b)

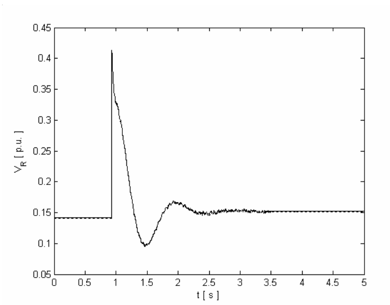
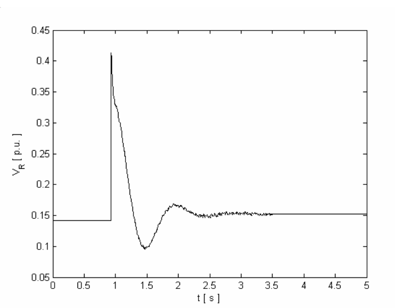


Fig.4 Waveforms of the generator terminal (a) and regulator output (b) voltage (measured and approximated) during the step change in AVR voltage reference value by +5%

a)



b)

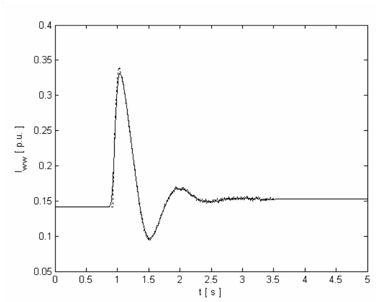
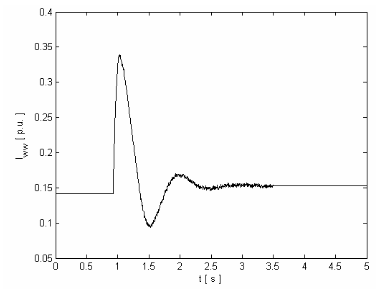
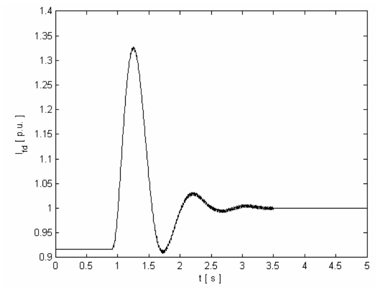


Fig.5 Waveforms of the regulator output voltage (a) and exciter field current (b) (measured and approximated) during the step change in AVR voltage reference value by +5%

a)



b)



c)

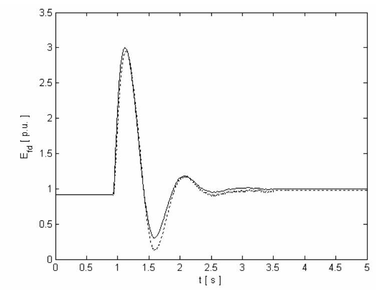
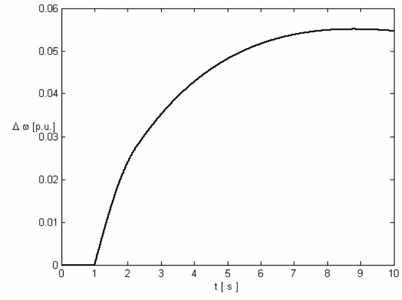


Fig.6 Waveforms of the exciter (a) and generator field current (b) as well as generator field voltage (c) (measured and approximated) during the step change in AVR voltage reference value by +5%

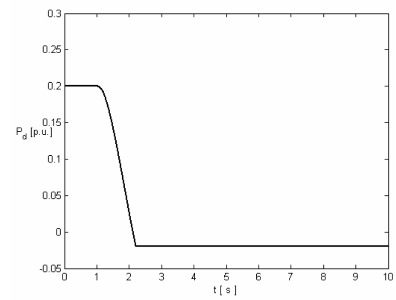
Parameter and its value							
voltage regulator				exciter		rectifier	
K_1	6	K_2	0.0245	K_3	3.43	K_4	12.525
T_1	0.02	T_2	0.05	T_5	0.1	K_C	1.312
T_i	3	T_3	0.25	T_6	0.071	T_7	0.0869
		T_4	1				

Tab.1 Electromachine excitation system parameter values

a)



b)



c)

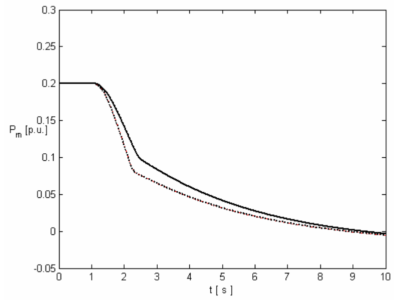


Fig.7 Waveforms of the generator angular speed deviation (a), the power transmitted by the steam flow at the turbine inlet (b) and turbine mechanical power (c) – approximated and approximating (initial and final) signals at load rejection in q axis

			Value		Error [%]
Parameter			sym.	comp.	-
governor		K_5	12	11.970	0.247
		T_8	0.45	0.4462	0.844
		T_9	0.02	0.0217	-8.500
		T_{10}	0.07	0.0730	-4.285
turbine	HP	T_{11}	0.06	0.0599	0.166
		K_6	0.5	0.4995	0.100
	MP	T_{12}	4	3.9999	0.002
		K_7	0.2	0.2099	-4.950
	LP	T_{13}	0.3	0.3012	-0.400
		K_8	0.3	0.2908	3.070
Non-estimated parameters:					
U_0	0.04		P_{max}	1	
U_c	-1		P_{min}	-0.02	

Tab.2 Parameter estimation results of the turbine and its governor model

Conclusion

From the obtained computation results of the excitation system as well as the turbine and its governor model parameters, the following conclusions can be drawn:

- Measurement of the selected dynamic waveforms in a power plant is a sufficient basis for identification of true values of the models mentioned above.
- The excitation system model proposed represents the electromechanical excitation system installed in the Rybnik Power Plant.
- The proposed approach of dividing the excitation system mathematical model into three submodels makes the analysis much easier.
- Possibility of measuring the greater number of signals, especially the internal ones, and using them in computations improves significantly the parameter estimation process (smaller errors) and allows separating the submodels; if only the input and output signals of the model, i.e. the deviation of the generator angular speed and turbine mechanical power are taken into account in the parameter estimation process of the turbine and its governor, the estimation results can be incorrect – the system output waveforms will be approximated correctly, whereas the parameters computed will differ significantly from the real ones.
- Separation of the governor and turbine submodels in the model assumed improves significantly the results of computing their parameters.

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