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Computer-aided determining of parameters of generating unit models based on measurement tests

***Abstract**. The paper presents a computer program for determining parameters of generating unit element models (synchronous generators and their excitation systems, turbines with governors) based on transient waveforms recorded in the generating unit after introducing disturbances of the steady working point.*

Streszczenie.** W artykule przedstawiono program komputerowy przeznaczony do wyznaczania parametrów modeli elementów zespołów wytwórczych (generatorów synchronicznych i ich układów wzbudzenia, turbin z układami regulacji prędkości) na podstawie przebiegów nieustalonych zarejestrowanych w zespole wytwórczym po wprowadzeniu zakłóceń ustalonego punktu pracy. **(Komputerowo wspomagane wyznaczanie parametrów modeli zespołów wytwórczych na podstawie przebiegów pomiarowych)

Keywords: Matlab/Simulink program, generating unit models, parameter estimation.
Słowa kluczowe: Program w środowisku Matlab/Simulink, modele zespołów wytwórczych, estymacja parametrów.

Introduction

Simulation investigations of the power system are an important tool used for estimation of static and dynamic properties as well as prediction of the results of disturbances and system failures. Reliability of these investigations depends mainly on the accuracy of used mathematical models of particular system elements and their parameters. The paper presents a computer program (PARZW) for determining parameters of generating unit element models (synchronous generators and their excitation systems, turbines with governors), based on transient waveforms recorded in the generating unit after introducing disturbances of the steady working point.

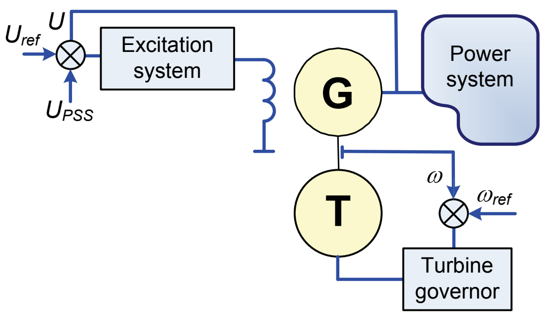

Fig. 1. Elements of the generating unit

Fig. 1 shows the elements of a typical generating unit. One of them is a synchronous generator (G) connected with a power system and driven by a turbine (T). The generator excitation system is controlled by a signal dependent on the generator voltage (U), the reference voltage of the voltage regulator (U_{ref}) and the output signal of the power system stabilizer PSS (U_{PSS}). The turbine is equipped with a governor controlled by a signal dependent on the generator angular (ω) and reference (ω_{ref}) speed.

A general model of the generating unit was developed in the framework of the research realized. Due to blocks of "Configurable Subsystems" used in this model, it is convenient to construct a concrete model of the generating unit (Fig. 2) selecting the models of its particular elements. It is possible to neglect the influence of the excitation system, turbine and PSS in the generating unit model.

Mathematical models of generating unit elements

The following mathematical models of generating unit elements were implemented in the program:

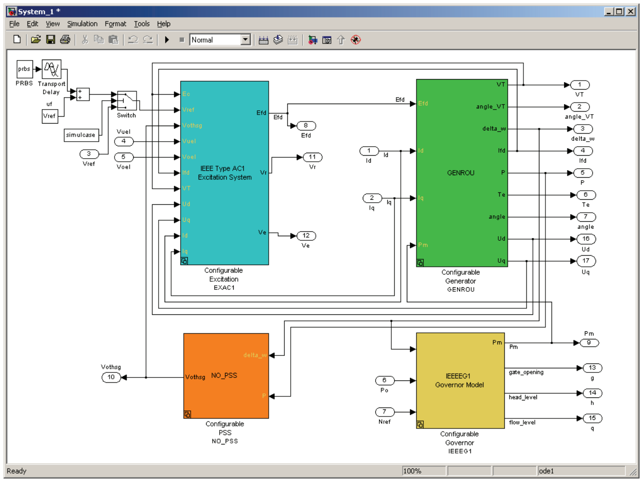

Fig. 2 Structural model of the generating unit in Matlab – Simulink environment

- Synchronous generator models:

○ Approximated models expressed by the standard reactances and time constants of the subtransient, transient and steady state (X_d, X_d', X_d'', T_{do}', T_{do}'', and so on [1, 2, 3, 4]). In these models the stator transformation voltages were neglected, while saturation of magnetic cores was taken into account. There were included one equivalent damping circuit in *d* axis and two equivalent damping circuits in *q* axis (turbogenerator) or one equivalent damping circuit in *q* axis (hydrogenerator). Four kinds of the generator models expressed by the standard parameters: GENROU and GENROE (turbogenerators) as well as GENSAE and GENSAL (hydrogenerators) differing in the way of approximation of the magnetic core magnetization characteristic [3] are implemented in the program. Fig. 3 presents the GENROU turbogenerator model implemented in Simulink.

○ Models expressed by resistances and inductances of the generator electric circuits (R, L_σ, L_{md}, and so on [1, 2]). These models take into account the transformation and rotation voltages in the stator and different number of damping circuits in the rotor. Fig. 4 shows the equivalent circuits of the generator model including two damping circuits in *d* axis and three damping circuits in *q* axis, the so-called model of type (3,3). In these circuits index *d* and *q* denotes the stator circuit parameters in *d* and *q* axis, index

D and *Q* denotes the rotor damping circuit quantities, while index *f* is used for the excitation system quantities.

- Models of the excitation systems with voltage regulators recommended by the IEEE Committee [4, 5]: IEEET1, EXAC1, EXAC2, EXDC2, EXPIC1, EXST1, EXST2, IEEET2, IEEET3 as well as models of static and electromachine (Fig. 5) excitation systems working in the Polish Power System [6].
- Models of the IEEEG1 steam (Fig. 6), HYGOV water and GAST gas turbines and their governors [4, 6, 7].

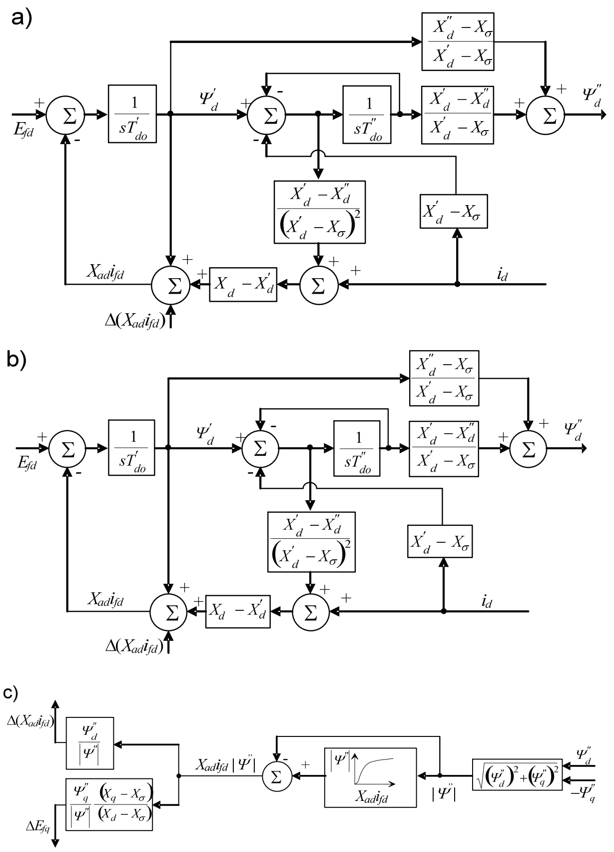

Fig. 3. Model of the synchronous generator GENROU: a) in *d* axis, b) in *q* axis, c) including saturation of magnetic cores

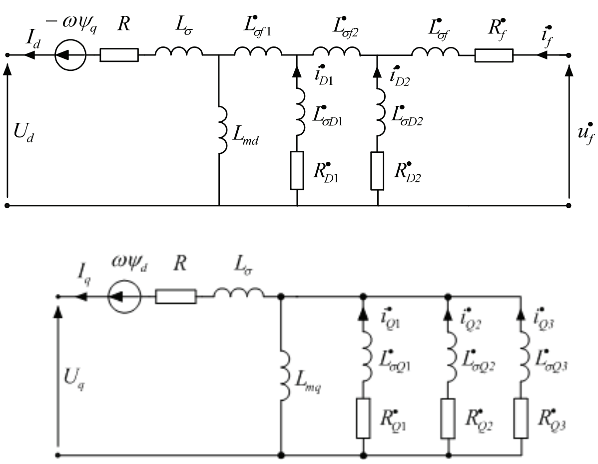

Fig. 4. Equivalent circuits in *d* and *q* axis of the synchronous generator of type (3,3) expressed by resistances and inductances of the generator electric circuits

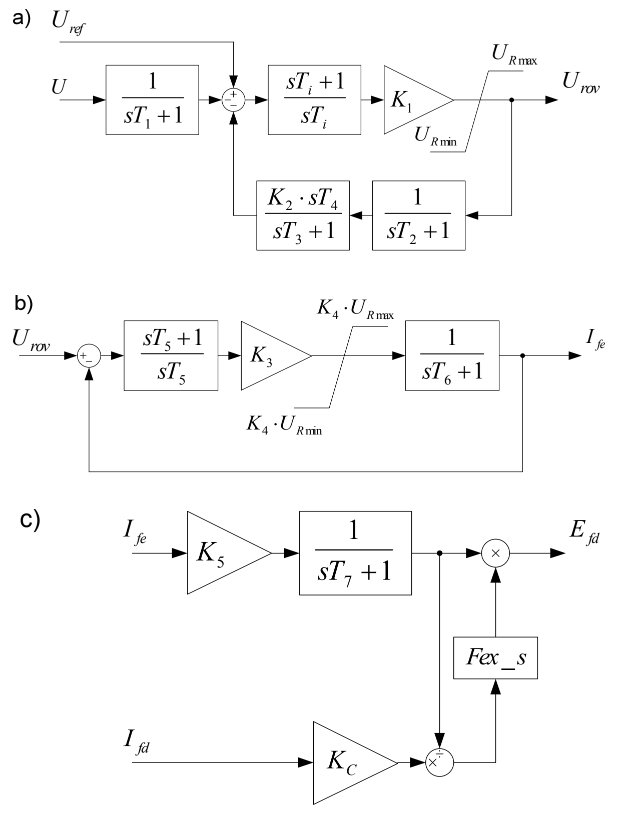

Fig. 5. Structural diagram of the electromachine excitation system installed in Power Plant Rybnik; a) voltage regulator, b) exciter and additional regulator of the excitation system, c) system forming the excitation voltage

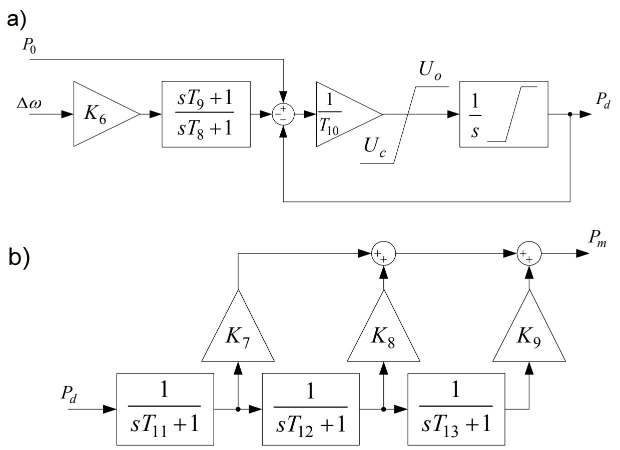

Fig. 6 Model of the IEEEG1 steam turbine with a governor; a) governor, b) turbine

According to the operating conditions of the generating unit, the equation of mechanical motion or equations of the equivalent power system are taken into account in the generating unit model.

Measurement tests

There were selected such measurement tests that they should be safe and easy to realise for a working or being launched generating unit. The exemplary test signals are small disturbances such as a step change or pseudorandom signal (PRBS) of the voltage regulator reference voltage introduced in the synchronous generator excitation system or load rejection of the generator operating under the determined conditions.

Appropriate selection of the test and measured signals makes it possible to separate the tested element of the generating unit by reducing or eliminating the influence of the other unit elements, and thus to simplify estimation of its parameters. For instance, during the no-load or load rejection test of the generator, the influence of the external power system (PS) is eliminated.

The measured waveforms, being the basis for parameter estimation, have to be processed numerically, which is aimed at preliminary processing and filtration of disturbances [8].

Methods for parameter estimation

Parameter estimation of the generating unit particular models is performed with use of the least square method. The mean square error was defined as the difference at particular time instants between the waveforms obtained from measurements and those from computations when using the mathematical models expressed by the parameters searched [9, 10]:

$$\varepsilon_w(\boldsymbol{P}) = \sum_{i=1}^{n} \left(\left| W_{i(m)} - W_{i(s)}(\boldsymbol{P}) \right| \right)^2 \tag{1}$$

where: index m denotes the measured waveform of quantity *W*, index s denotes the simulated waveform of quantity *W* calculated for the parameter vector $\boldsymbol{P}$.

In case of taking into account several waveforms, the mean square error is a sum of the errors defined for particular waveforms when taking into consideration appropriately chosen weight functions w_k:

$$\varepsilon(\boldsymbol{P}) = \sum_{k} w_k \varepsilon_{wk}(\boldsymbol{P}) \tag{2}$$

The following optimization algorithms are used for minimization of the mean square error [6, 11]:

- Gradient algorithm implemented in the package Optimization Toolbox of Matlab program. Gradient algorithms belong to local optimization algorithms, that is why the initial set of parameters should be selected carefully in order to obtain correct results.
- Genetic algorithm which finds the global minimum of the objective function.
- Hybrid algorithm consisting of genetic and gradient algorithms. The hybrid algorithm ensures the highest accuracy of approximation.

Fig. 7 shows the general diagram of the algorithm for parameter estimation of the generating unit elements.

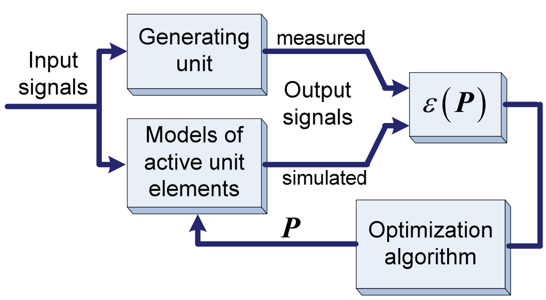

Fig. 7. Algorithm for parameter estimation of the generating unit

Program structure

The program was developed in Matlab/Simulink environment. Its structure includes:

- menu controlled graphical user interface,
- measurement data acquisition module containing procedures for preprocessing and filtering the signals,
- library of mathematical models of the generating unit elements implemented in Simulink,
- parameter estimation module of the generating unit models,
- module for sensitivity analysis of dynamic waveforms to parameter changes of particular models,
- simulation module of generating unit disturbance states,
- database containing the models of generating units and their parameters.

Fig. 8 shows the functional diagram of program PARZW.

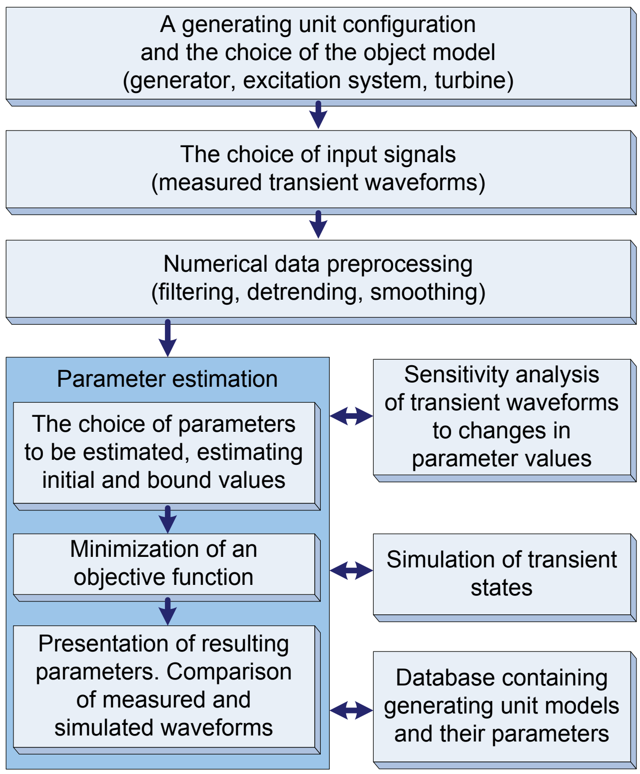

Fig. 8. Functional diagram of program PARZW

Examples of parameter estimation of the generating unit

<u>Parameter estimation of the synchronous generator model of type (3,3)</u>

Estimation of the model of type (3,3) parameters (resistances and inductances of the equivalent circuits shown in Fig. 4) was performed for the 589 MVA synchronous generator. The dynamic waveforms in the machine caused by introducing a small disturbance in the form of -5% change in the field voltage were used for estimation. Before introducing the disturbance, the generator worked in the steady state of the rated load. In the program window presented in Fig. 9 there are shown the stator current waveforms in *d* axis calculated for the initial and final, estimated parameter values as well as the true waveform. At the window bottom part there are given the initial values of the parameters and their upper and lower constraints taken into account by the gradient optimization algorithm. At the bottom row, distinguished with colour, there is given the list of the model final, estimated parameters. The program enables the choice of estimated parameters when assuming that the others are known and the comparison of the waveforms of selected quantities.

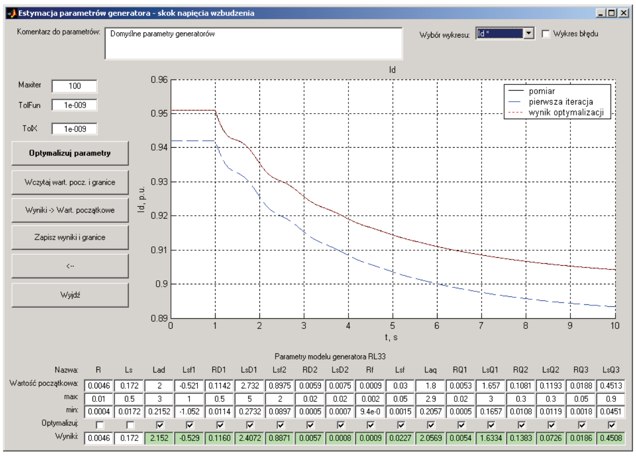

Fig. 9. Results of parameter estimation of the type (3,3) generator for the step change in field voltage by -5%

<u>Parameter estimation in *d* axis of the GENROU generator model</u>

For parameter estimation of the TWW-200-2A generator GENROU model there were used the exemplary (recorded during launching test of the generating block in Power Plant Rybnik [6, 8]), dynamic waveforms of the field voltage (input signal – Fig. 10), exciting current (Fig. 11) and the generator armature voltage (Fig. 12) for a step change of the voltage regulator reference voltage of the no-load generator by +5%. During measurements the generator was operating with the so-called automatic regulation in the excitation system.

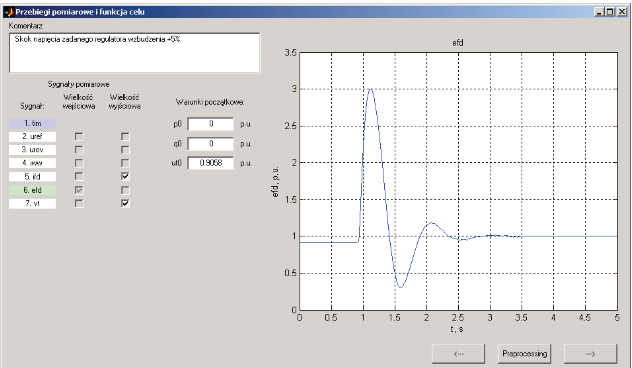

Fig. 10. Program window with the measured waveform of the generator field voltage (input signal for estimation) for a step change of the voltage regulator reference voltage by +5%

<u>Parameter estimation of the excitation system</u>

For calculation of the electromachine excitation system parameters of Fig. 5 there were used exemplary dynamic waveforms of selected quantities measured on the unit in Power Plant Rybnik for a step change of the voltage regulator reference voltage of the no-load generator by +5%. In order to improve the calculation efficiency, the parameter estimation procedure was divided into three substages related to the excitation system submodels of Fig. 5 for which separate calculations were carried out [6]. Fig. 13 shows the waveforms of the field voltage as well as the estimation results of the system forming the excitation voltage.

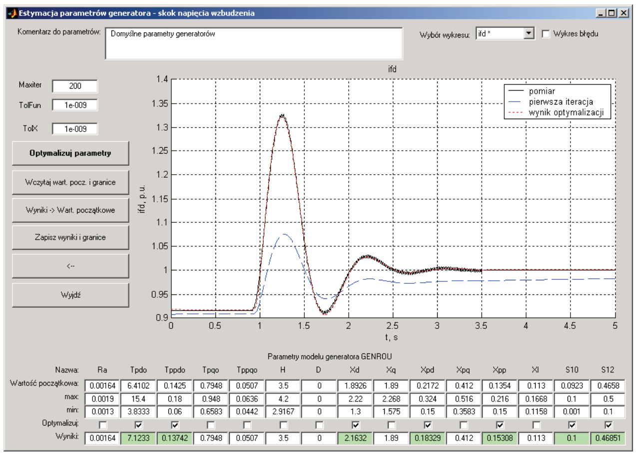

Fig. 11. Generator exciting current (measured, approximated) for a step change of the voltage regulator reference voltage by +5%, the approximating waveforms and results of parameter estimation in *d* axis of the GENROU generator model

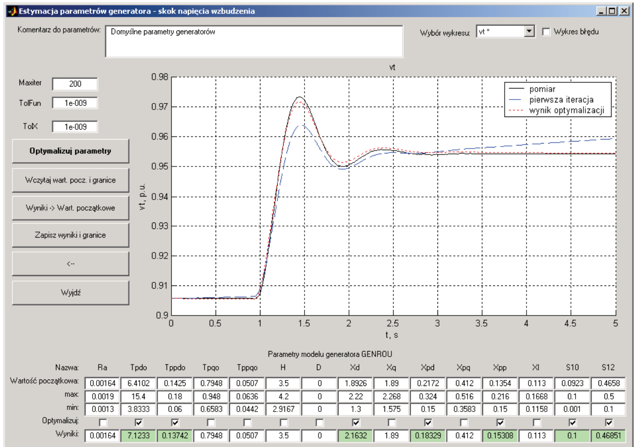

Fig. 12. Generator terminal voltage (measured, approximated) for a step change of the voltage regulator reference voltage by +5%, the approximating waveforms and results of parameter estimation in *d* axis of the GENROU generator model

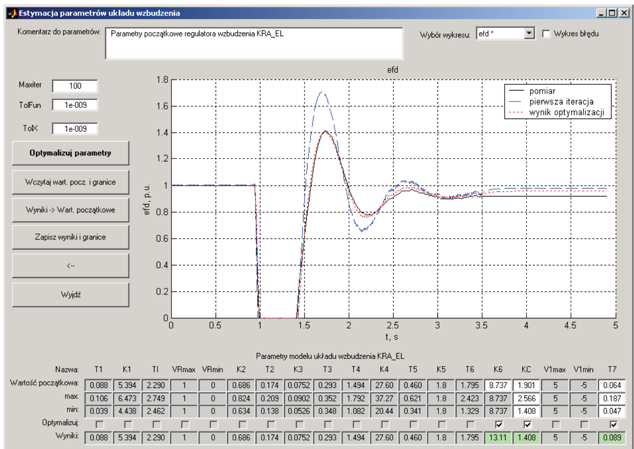

Fig.13. Field voltage (measured, approximated) for a step change of the voltage regulator reference voltage by +5%, the approximating waveforms and results of parameter estimation of the system forming the excitation voltage

<u>Parameter estimation of the turbine</u>

For parameter estimation of the IEEEG1 steam turbine model there were used the exemplary dynamic waveforms for the generator load rejection in *q* axis (P_0 = 0.2 and

Q_0 = -0.0723 in relative units were assumed to be the initial values of the generator load). Parameter estimation of the turbine with its governor was performed by dividing the computational process into two substages [6]. In the model there were distinguished a governor model and a turbine model, for which calculations were carried out separately. Fig. 14 shows the exemplary dynamic waveforms of the power transmitted by the steam flow at the turbine inlet and the parameter estimation results of the steam turbine model.

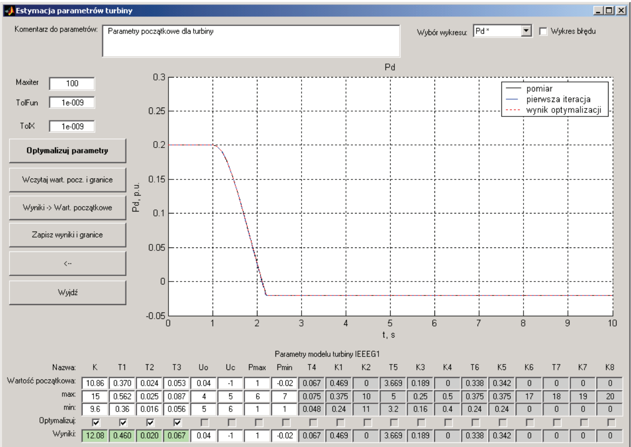

Fig. 14. Power transmitted by the steam flow at the turbine inlet (measured, approximated) for load rejection in *q* axis, the approximating waveforms and parameter estimation results of the steam turbine model

Summary

The computer program PARZW developed in Matlab/Simulink environment (being improved continuously) is a convenient tool for calculating parameters of different models of generating unit elements (synchronous generators, excitation systems, turbines with governors) working in the power system. The basis for estimation is the analysis of dynamic waveforms obtained from appropriate measurement tests carried out on generating units in power plants. The program is equipped with modules of: measured signal filtration, generating unit operation simulation and sensitivity analysis of waveforms to parameter changes as well as enables entering the results in the database of the dynamic parameters of the Polish and European PS.

The program PARZW should be used widely in the future for analysis of PS operation, since the knowledge of the actual parameters of generating units can enable carrying out reliable calculations of static and dynamic states, and in consequence, avoiding occurrence of system failures.

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