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IDENTIFICATION OF MODEL PARAMETERS OF STEAM TURBINE AND GOVERNOR

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This paper presents methodology of identification of dynamic models of steam turbine, governor, boiler and its regulators required for investigation and dynamics analysis of stability of power systems. According to the methodology, structure and parameters of dynamic model of generating units are estimated taking into consideration operating mode of turbine and boiler. Measured and simulated regime parameters' curves are presented. Correlation factors of measured and calculated regime parameters for evaluation of identification accuracy are estimated. Expressions for recalculation of model parameters to one apparent generating unit's power are presented, too.

Introduction

The viability of a power system strongly depends on stability conditions. Disturbance influence on static and dynamic stability may cause emergency conditions in the power system. So, the main target is to predict such situations and to plan the power system and its operation regimes when operating conditions stable over the whole range will be met.

Studies of power system stability and electromechanical transient processes are needful for connection of large generating units to the power system, their load control and power reserve forecasting, disconnection of lines for maintenance schedule, automatic protection design and supervisory control coordination.

Precision of steady-state and transient stability analysis of the power system depends on the accuracy of usable models for power system elements. Incorrect determination of stability margins may cause emergency conditions in the power system; however, if determined stability conditions are smaller than actual ones, power system operation would be uneconomical.

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The influence on transient processes depends mostly on generating units, their excitation systems and operation of turbine speed governors. Usually, the generating units' data presented by the manufacturer are used in studies of power system transient processes. If such data are not available, field tests should be performed for estimation (identification) of dynamic models and their parameters. Dynamic models and parameters are identified from the field test data by using special identification techniques.

Identification technique

The object's static and dynamic characteristics, static and dynamic nonlinearities and characteristics' sensitivity to operating parameters must be accounted while identifying the dynamic object. The model structure is composed by using theoretical studies, and the parameters from test data are estimated. Usually, power system dynamic model structures are known and can be described by linear or nonlinear differential equations. The task of identification is to determine numerical values of the model parameters.

The response of linear system output can be described by the sum of responses to separate input signals. According to the input signal type, the object's response can be described as transient function $h(t)$, impulse function $g(t)$, transfer function – frequency response function $W(j\omega)$, autocorrelation function $R_{xy}(\tau)$ and spectral density function $S_{xy}(\omega)$. All these characteristics are interdependent, but the object dynamic parameters are estimated in different way because of noises, inaccurate and insufficient test data [4].

The parametric identification methods are used for identification of dynamic models in transient investigation of the power system. Nonparametric identification methods, e.g. correlation or spectral density analysis may be used for estimation of generalized parameters.

Identification at frequency domain method is based on Fourier transformation. The task of identification in time domain is determination of transient function between input and output signals. If the object's input and output signals are stationary processes and are measured discretely, the object's model can be written as

$$y(t) = G(q,\theta)\,u(t) + H(q,\theta)\,e(t)\,, \tag{1}$$

where q – shift operator; θ – transfer function parametric vector; $e(t)$ – sequence of random unrelated data [5, 6].

Parametric identification methods. Generalized parametric model is described by expression

$$A(q)\,y(t) = \frac{B(q)}{F(q)}u(t) + \frac{C(q)}{D(q)}e(t), \tag{2}$$

where $y(t)$ – output signal, $u(t)$ – input signal, $e(t)$ – signal error or noise, q – shift operator and $A(q)$, $B(q)$, $C(q)$, $D(q)$ and $F(q)$ – polynomials [6].

Partial cases of the model (2) can be used, assuming that some of the polynomials *A*(*q*), *B*(*q*), *C*(*q*), *D*(*q*) and *F*(*q*) are equal to 1 (Table 1). If the discrete parametric identification method is used, the polynomials of identified model (2) are transformed into continuous time model polynomials. Relationship between parameter vectors of discrete and continuous time functions depend on *z* and *s* operators.

The parameters θ_g and θ_h of discrete generalized parametric model partial cases response functions $G(z, \theta_g)$ and $H(z, \theta_h)$ are identified using sampled input and output signals $u(t)$ and $y(t)$. The main transient function $G(z, \theta_g)$ of identified discrete model is converted into continuous time domain transfer function $\hat{W}(s, \hat{\theta})$. The parametric vector $\hat{\theta}$ of the continuous time model is determined from the expression

$$\hat{\theta} = \underset{\theta}{\arg\min} \sum_{i=0}^{n-1} \left(y(t+1) - \hat{y}(t+1), \theta \right)^2 . \qquad (3)$$

Table 1. **Most frequent cases of partial parametric model**

Model structure	Polynomials
FIR (finite impulse response)	$B(q)$
ARX	$A(q)$, $B(q)$
ARMAX	$A(q)$, $B(q)$, $C(q)$
ARMA	$A(q)$, $C(q)$
ARARX	$A(q)$, $B(q)$, $D(q)$
ARARMAX	$A(q)$, $B(q)$, $C(q)$, $D(q)$
OE (output error)	$B(q)$, $F(q)$
BJ (Box-Jenkins)	$B(q)$, $F(q)$, $C(q)$, $D(q)$

The identified model must meet three similarity conditions:

- The autocorrelation of output signals of measured and simulated identified transfer function must verge towards 1, and the least square criterion must be as small as possible:

$$\left. \begin{aligned} R &= \operatorname{corr}\left(y(t), \hat{y}(t) \right) \to 1, \\ S &= \sum_{i=0}^{n-1} \left(y(t+i) - \hat{y}(t+i) \right)^2 \to 0; \end{aligned} \right\} \qquad (4)$$

  where $y(t)$ – measured output signal; $\hat{y}(t)$ – simulated output signal of the identified transfer function $\hat{W}(s,\hat{\theta})$ when the input of the transfer function is measured signal $u(t)$; R – autocorrelation coefficient, S – least square coefficient.
- Degree $\hat{d}$ of determined transfer function $\hat{W}(s,\hat{\theta})$ polynomials must be equal or close to the degree d_0 of polynomial of the known transfer function $W(s,\theta_0)$:

$$d_0 - 1 \le \hat{d} \le d_0 + 1\,. \tag{5}$$

- Members of parameter vector $\hat{\theta}$ the identified continuous time transfer function $\hat{W}(s,\hat{\theta})$ with $\hat{d} = d_0$ must be equal or close to the members of parameter vector θ_0 of known transfer function $W(s,\theta_0)$:

$$P = \sum_{i=1}^{d} (\theta_{0i} - \hat{\theta}_i)^2 = \sum_{i=0}^{d_\alpha} (\alpha_{0i} - \hat{\alpha}_i)^2 + \sum_{j=0}^{d_\beta} (\beta_{0j} - \hat{\beta}_j)^2, \tag{6}$$
$$\text{when } \alpha \in A_0,\ \hat{\alpha} \in \hat{A}_0,\ \beta \in B_0,\ \hat{\beta} \in \hat{B}_0\,;$$

  where d_α – degree of polynomials $A_0(s,\alpha)$ and $\hat{A}(s,\hat{\alpha})$, d_β – degree of polynomials $B_0(s,\beta)$ and $\hat{B}(s,\hat{\beta})$.

Parameter θ_0 values of the transfer function of a real object are not known. The standard deviation $s_{\hat{\theta}_i}$ or dispersion $s^2_{\hat{\theta}_i}$ of the i^{th} parameter can be calculated for the k^{th} experiment:

$$\overline{P} = \frac{1}{n} \sum_{k=1}^{n} \sum_{i=1}^{d} (\theta_{0i} - \hat{\theta}_{in})^2\,, \tag{7}$$

where n – number of experiments, $\hat{\theta}_{in}$ – value of the i^{th} parameter according to the k^{th} experiment data.

Time domain identification methods are useful for identification of power system dynamic models from variation of measured operating parameters with time. Identification in time domain can be used for the sampled passive field test data or active field test data, when the investigated system is perturbed by artificial trigger.

Regimes of turbine operation

Considering P. Kundur [2], there are four different unit control strategies or modes of operation: boiler-following (turbine leading), turbine-following (boiler leading), integrated or coordinated boiler-turbine control and sliding pressure control.

Under the boiler-following mode of control, changes in generation are initiated by turbine control valves. The boiler controls respond to resulting changes in steam flow and pressure by changing steam production. A difference between steam production and steam demand results in a change in boiler pressure. The throttle pressure deviation from its setpoint value is used as an error signal by the combustion controls to regulate fuel and air input to the furnace.

Under the turbine-following mode of control, changes in generation are initiated by changing input to the boiler. The MW demand signal is applied to the combustion controls. The turbine control valves regulate boiler pressure; fast action of the valves maintains essentially constant pressure.

The integrated or coordinated boiler-turbine control provides an adjustable blend of both boiler-following and turbine-following modes of control. The improvement in unit response is achieved through integrated control, which is a compromise between fast response and boiler safety.

In the sliding pressure mode of control, the throttle pressure setpoint is made as a function of unit load rather than a constant value. The control valves are left wide open (provided the turbine pressure is above a minimum level), and the turbine power output is controlled by controlling throttle pressure through manipulation of the boiler controls. It is thus essentially a turbine-following mode of operation.

Turbines of different power plants work in different regimes, for example, regime for the turbine of the Ignalina NPP is selected considering the number of the units in operation: in case of one operating unit, turbine operates in turbine-following (constant pressure mode); in case of two generating units – one turbine operates in constant pressure mode and the other – in boiler-following (constant active power mode). In Kaunas CHPP (Lithuanian power system) and the others CHPP, turbine is operating in turbine-following mode which means – regime of the heat production and active power is produced according to a strictly fixed plan.

Model of the steam turbine

In order to maintain the modes of operation, a specific feature of the boiler should be considered. TGOV5 model from Siemens PSS™E library [3] was used (Fig. 1). Model TGOV5 is made like a classical turbine model which considers fuel flow regulation to the boiler, boiler's response to frequency change and steam loss.

Output of mechanical power is determined with the regard of the boiler response to speed deviation. This model is suitable for the investigation of long-lasting processes (up to 30 seconds and more). Parameters of the model should be chosen carefully and all working regimes of the turbine can be presented – turbine leading, turbine following and sliding pressure regime.

Model input channels are speed deviation $\Delta\omega$, frequency deviation Δf and power P. The variation of fixed power signal P_0 during transitional process depends on model parameters that describe boiler operation. Model is suitable for modeling of primary and secondary frequency control. Classical turbine model is made of transfer functions of servomotor, steam box and imitated high, middle and low pressure parts. Speed signal variation $\Delta\omega$ is adjusted by the transfer function of phase correction at the input. The task for turbine servomotor is adjusted considering load deviation from fixed power signal P_0 and valve position μ. Servomotor time constant is T_3. The valve position and steam pressure before steam box of the control valves determines steam flow value.

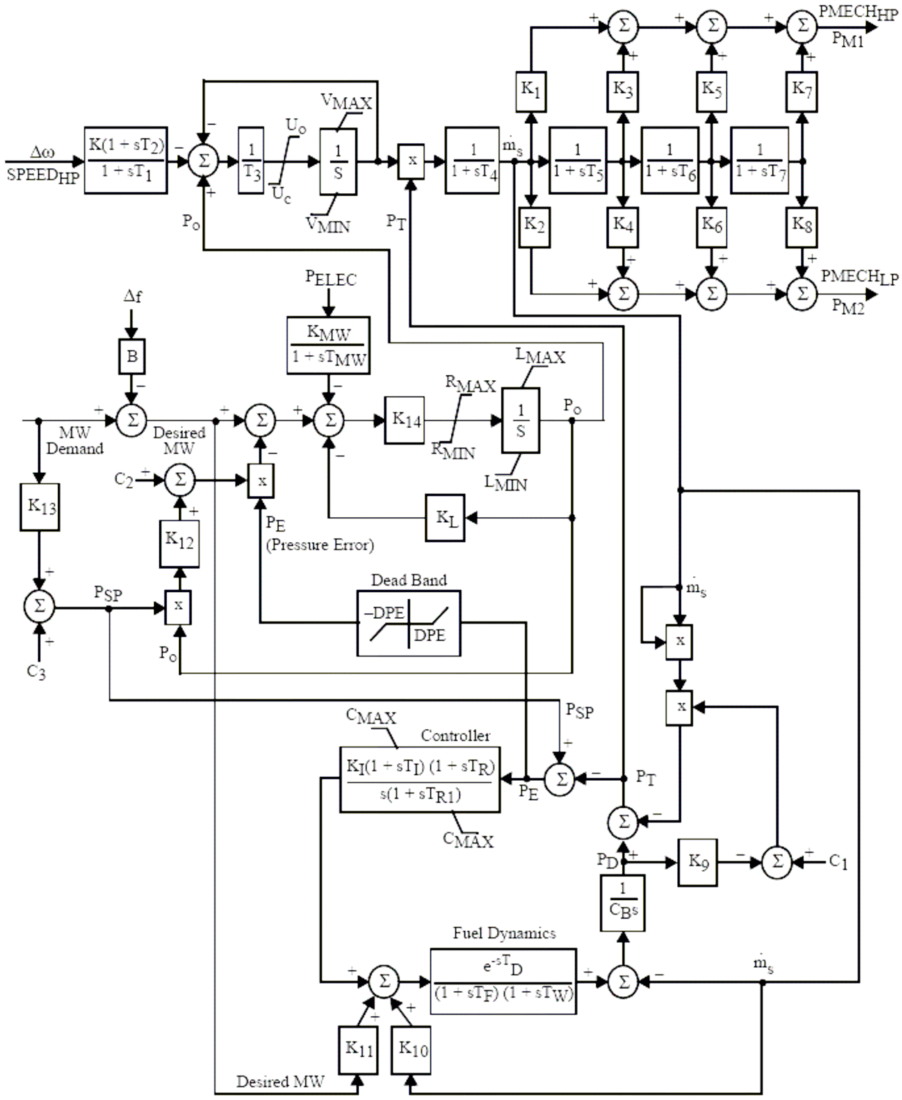


Fig. 1. Steam turbine, speed governor and boiler model TGOV5 [3].

Turbine and governor parameters in per-unit system

If parameters of the turbine and generator in manufacturer's data sheets are presented in per-unit system, the generator's parameters are presented on the basis of total power (S_{GN}) and turbine parameters are presented on the basis of turbine rated active power (P_{TN}) which usually equals to the active power of generator (P_{GN}). Sometimes, turbine's power differs from generator active power.

For the power system stability studies, only one power value of the generating unit is presented, that is a total generator power S_{GN}:

$$S_{GN} = \left|P_{GN} + jQ_{GN}\right| = \left|\frac{P_{GN}}{\cos\phi_N} \cdot e^{j\phi_N}\right| = \frac{P_{GN}}{\cos\phi_N}, \qquad (8)$$

where Q_{GN} , $\cos\varphi_N$ – rated power and rated power factor of the generator.

Parameters of the turbine and boiler need to be recalculated in such a way that variation of the parameters based on the system power S_B would coincide with the parameters calculated according to conditions of the turbine and boiler.

Turbine's rated power in per unit P_{TN*SN} based on total unit power S_{GN} is equal

$$P_{TN*SN} = \frac{P_{TN}}{S_{GN}} = \frac{P_{TN} \cdot \cos\phi_N}{P_{GN}} = P_{TN*PGN} \cdot \cos\phi_N . \qquad (9)$$

Droop of the turbine speed governor R_{*SN}, based on the total power S_{GN} , should bring the same variation in active power ΔP_T when the droop is R_{*TN}, on the basis of the rated power P_{TN}:

$$\Delta P_T = \Delta P_{T*N} \cdot P_{TN} = \frac{\Delta f_*}{R_{*TN}} \cdot P_{TN} , \qquad (10)$$

$$\Delta P_T = \Delta P_{T*SN} \cdot S_{GN} = \frac{\Delta f_*}{R_{*SN}} \cdot S_{GN} = \frac{\Delta f_* \cdot P_{GN}}{R_{*SN} \cdot \cos\phi_N} . \qquad (11)$$

Assuming that right sides of both equations (10) and (11) are equal, we get:

$$\frac{P_{TN*}}{R_{*TN}} = \frac{P_{GN}}{R_{*SN} \cdot \cos\phi_N} , \qquad (12)$$

or

$$R_{*SN} = R_{*TN} \frac{P_{GN}}{P_{TN} \cdot \cos\phi_N} = R_{*TN} \frac{1}{P_{TN*PGN} \cdot \cos\phi_N} = \frac{R_{*TN}}{P_{TN*SN}} = R_{*TN} \frac{S_{GN}}{P_{TN}} . \qquad (13)$$

Gain of the turbine governor K_{*SN} is equal to the inverted R_{*SN}:

$$K_{*SN} = \frac{1}{R_{*SN}} = \frac{1}{R_{*TN}} P_{TN*PGN} \cdot \cos\phi_N = \frac{1}{R_{*TN}} P_{TN*SN} = K_{*TN} \cdot \frac{P_{TN}}{S_{GN}} . \qquad (14)$$

Power of every turbine in per units, when generator's total power is S_{GN}, is expressed on the base of rated turbine power:

$$P_{Ti} = P_{Ti*SN} \cdot S_{GNi} = P_{Ti*N} \cdot P_{TNi} , \qquad (15)$$

$$P_{Ti*SN} = P_{Ti*N} \cdot \frac{P_{TNi}}{S_{GNi}} = P_{Ti*N} \cdot P_{TN*SNi} = P_{Ti*N} \cdot P_{TN*PGNi} \cdot \cos\phi_{Ni} \,. \qquad (16)$$

This expression is applicable in order to establish limits of turbine model: power and speed of power variation V_{i*SN}:

$$V_{i*SN} = V_{i*N} \cdot \frac{P_{TNi}}{S_{GNi}} = V_{i*N} \cdot P_{TN*SNi} = V_{i*N} \cdot P_{TN*PGNi} \cdot \cos\phi_{Ni} \,, \qquad (17)$$

where V_{i*N} – is the value of the power variation in per units on rated power P_{TNi}.

When turbine pressure is constant, pressure in per units $p_{T*} = 1.0$.

Different values of rated power correspond different values of valve position in per unit μ_{*TN}, μ_{*SN}, because droops of turbine regulation R_{*TN}, R_{*SN} and inverse values of governing factors K_{*TN}, K_{*SN} are also different.

Pressure and variation of pressure in the case of different rated power remain the same. Factors of the pressure loss (c_1) and factors dependent from pressure variation (K_9) will be directly proportional to the square of rated power:

$$c_{1*SN} = c_{1*TN} \cdot \left(\frac{S_{GN}}{P_{TN}}\right)^2 = \frac{1}{P_{TN*SN}^2} \cdot c_{1*TN} \,, \qquad (18)$$

$$K_{9*SN} = K_{9*TN} \cdot \left(\frac{S_{GN}}{P_{TN}}\right)^2 = K_{9*TN} \cdot \frac{1}{P_{TN*SN}^2} \,. \qquad (19)$$

Gain of fuel controller K_I and factor of the pressure control C_2 are determined according to:

$$K_{I,SN} = K_{I,TN} \cdot \frac{P_{TN}}{S_{GN}} = K_{I,TN} \cdot P_{TN*SN} \,, \qquad (20)$$

$$C_{2,SN} = C_{2,TN} \cdot \frac{P_{TN}}{S_{GN}} = C_{2,TN} \cdot P_{TN*SN} \,. \qquad (21)$$

Similarly, the values of the fuel flow range C_{max}, C_{min} are determined.

Identification of turbine and boiler parameters of the Lithuanian power plant generating unit from sampled data

When the input signal order is relatively high, identification task becomes very complicated, and parameters identification by blocks is the best solution. First of all, parameters of turbine and boiler should be estimated, and then fuel system, pressure control and frequency and power control blocks are identified. Identification technique must be adjusted according to the sampled data obtained during the field tests.

Turbine parameters of the Lithuanian power plant were estimated according to the manufacturer's data, and a dynamic model was created for the calculations with PSS™E. An accomplishment of the literature survey [1] of the identification test methods of the synchronous generator let us suggest that operators of the large power systems require performing modelling, testing and models' validation tasks. The results should be accurate, and variation in calculated regime parameters should correspond to the measured values. There was also mentioned that requirements differ according to unit power and total power of the controlled network.

Investigative generation unit consists of K-300-240 type turbine, its governor, PK-41 type boiler and its regulator. During the first test a generation variation was set up in that sequence: – 10 MW + 15 MW – 15 MW + 15 MW – 15 MW – 15 MW + 15 MW. Variation of measured operating parameters is presented in Fig. 2.

In order to determine the value of steam pressure loss factor the second test data were used. Variation of measured operating parameters during the test is presented in Fig. 2. The variation of turbine power, boiler's output pressure and turbine input pressure are presented in Fig. 3.

During the first test measurement period was 3 seconds, and during the second test measurement period decreased to 1 second.

Measured operating parameters were processed in Matlab environment and output error (OE) parametric identification model was used. First of all,

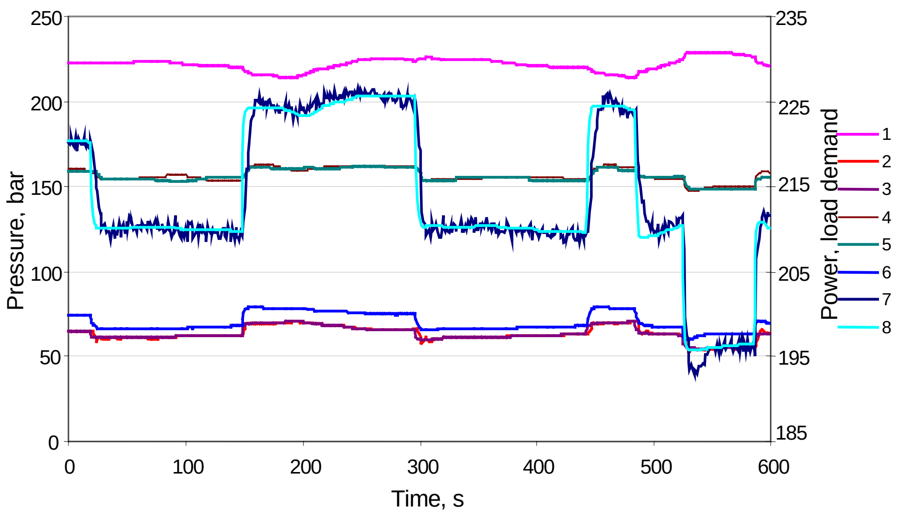


Fig. 2. Variation of measured parameters: *1* – turbine pressure, *2* – fuel flow, *3* – boiler governor, *4* – steam flow in line B, *5* – steam flow in line D, *6* – valve position, *7* – turbine power and *8* – load demand during the first test.

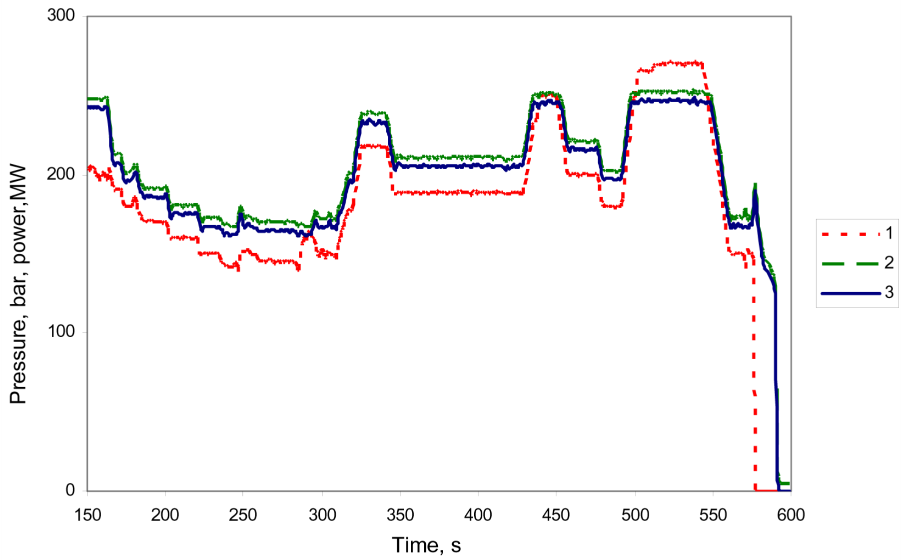


Fig. 3. Variation of measured parameters: *1* – turbine power, *2* – boiler's output pressure, *3* – turbine input pressure during the second test.

time constant values T_1 and T_2 for phase correction transfer function were determined according to the transfer function:

$$W_1 = K \cdot \frac{(1 + sT_2)}{1 + sT_1} . \tag{22}$$

The turbine speed signal of rectangular shape was inputted into the model, and the output signal was load demand variation. The measured and simulated output signals are presented in Fig. 4. The identified time constants are: $T_1 = 0.5$ second and $T_2 = 1.239$ second.

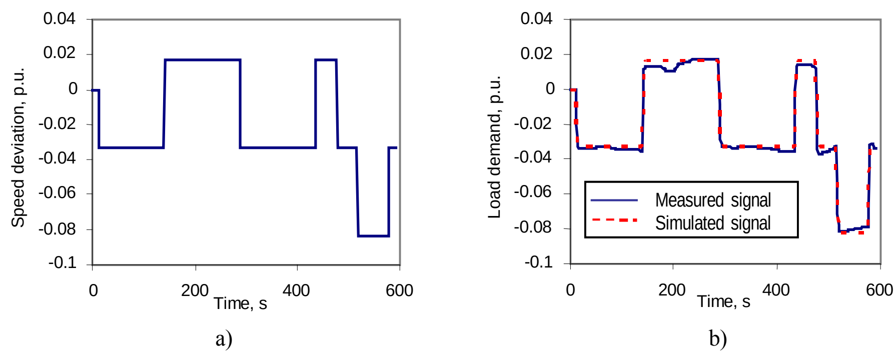


Fig. 4. Transient processes of a) speed deviation (input) and b) load demand (output).

Operation of servomotor is described by the first order transfer function:

$$W_2 = \frac{1}{1+sT_3}. \tag{23}$$

During the identification process, load signal was inputted into the model, the output was servomotor valve position. Signals are shown in Fig. 5. Simulated output signal is compared with the measured signal. It is presented in Fig. 5b).

Steam flow to the steam block is for the input, turbine power for the output in order to identify the values of the power part of the turbine high pressure cylinder K_A, steam box of control valves and time constants of the intermediate-pressure steam reheater T_{GD} and T_P. Steam flow to the steam block is calculated by multiplying valve position and measured turbine pressure values. Ignoring crossover piping and low pressure inlet volume, turbine transfer function is described as

$$W_3 = \frac{1+K_A \cdot T_P}{(1+sT_{GD})(1+sT_P)}, \tag{24}$$

where $T_{GD} = T_4$, $T_P = T_5$ in Fig. 6.

Correlation in all these cases exceeds 0.95. The correlation factor depends on noise level, settling-off of the regime parameters in the case of imited frequency variation and value of the identified signal interval. Measured and identified signals are presented in Fig. 6.

In the case of identifying the values of the parameters of PI type fuel flow controller – integration time constant is $1/K_I$, proportional gain $K_I T_I$, phase correction time constants T_R and T_{R1}, turbine pressure signal in per units is given to input of the model and signal of the fuel flow controller – to the output. Transfer function of the fuel flow controller is

$$W_4 = \frac{K_I(1+sT_I)(1+sT_R)}{s(1+sT_{R1})}. \tag{25}$$

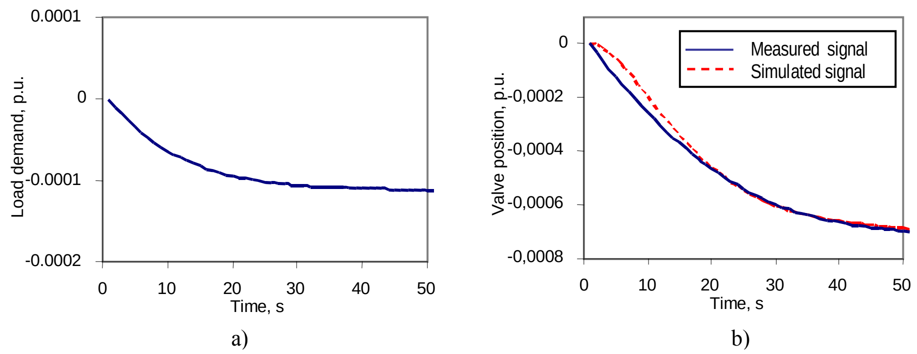
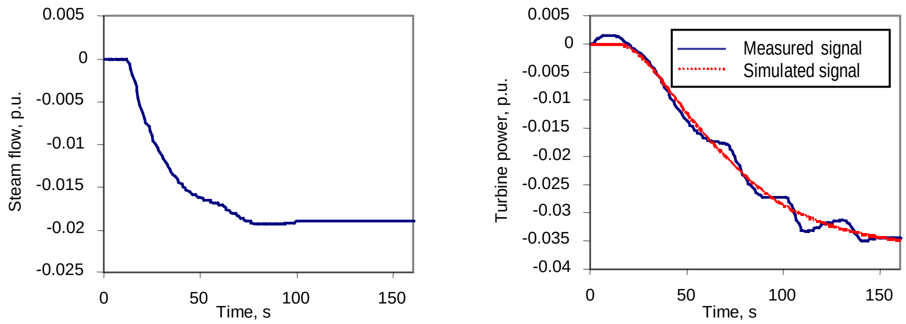


Fig. 5. Transient processes of a) load demand (input) and b) valve position (output).



a) b)

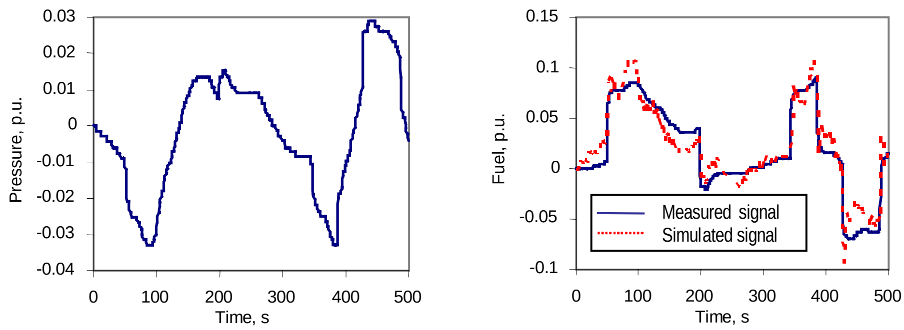
Fig. 6. Transient processes of a) steam flow (input) and b) turbine power (output).

Parameters of the fuel flow controller were identified according to the entire measuring data set, not only by a fragment, because time constants T_{I}, T_{R}, T_{R1} and gain K_{I} influence the whole measuring process. The whole measuring set was provided to input and output of the model, and the time constants and the gain were determined. Variation of the identified and simulated signals is shown in Fig. 7.

During the determination of the boiler parameters, fuel flow variation is provided to input, heat flow delivered to the boiler with fuel was provided to output of the model (Fig. 8). Fuel and heat to boiler flow dynamics is described by transfer function:

$$W_5 = \frac{e^{-sT_D}}{(1+sT_F)(1+sT_W)}, \tag{26}$$

where T_D, T_F, T_W – are delay time of fuel supply, time constant of heat release from the fuel to water walls, and time constant of heat release from the water walls to the water and steam.



a) b)

Fig. 7. Transient processes of a) pressure difference (input) and b) fuel (output).

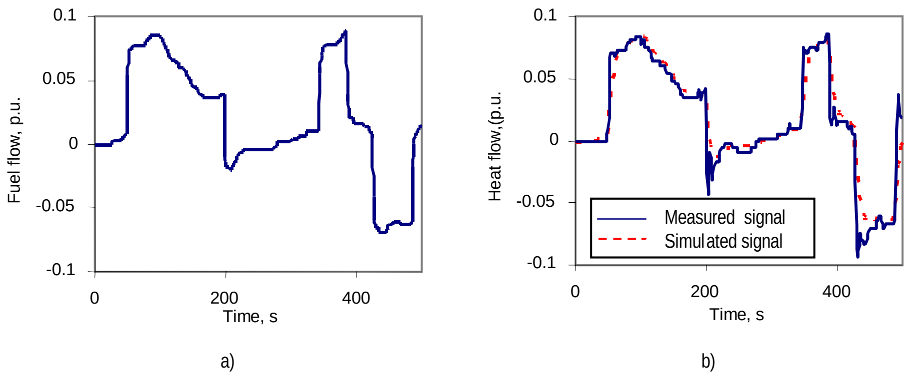


Fig. 8. Transient processes of a) fuel flow (input) and b) heat flow (output).

Correlation factor value of the estimated and measured signals exceeds 0.95. An entire measured signal for identification of these time constants was used.

In the case of identification of steam pressure losses between the boiler and turbine factor C_1 value a square of the steam flow was provided to input and boiler and turbine steam pressure difference in per units – to output. Pressure loss is determined subtracting turbine steam pressure from the boiler steam pressure. Usually loss factor does not exceed 5 percent. In our case it is equal to 1.8 percent (0.01812). Input and output signals for the identification of the loss factor are depicted in Fig. 9.

Boiler thermal time constant C_B was identified when a special heat to boiler signal (steam flow signal subtracted from fuel flow signal in per units) is provided to input while boiler steam pressure variation – to the output. The value of the C_B is determined as 100 s.

Data of the identified fifth turbine of the Lithuanian power plant are given in Table 2.

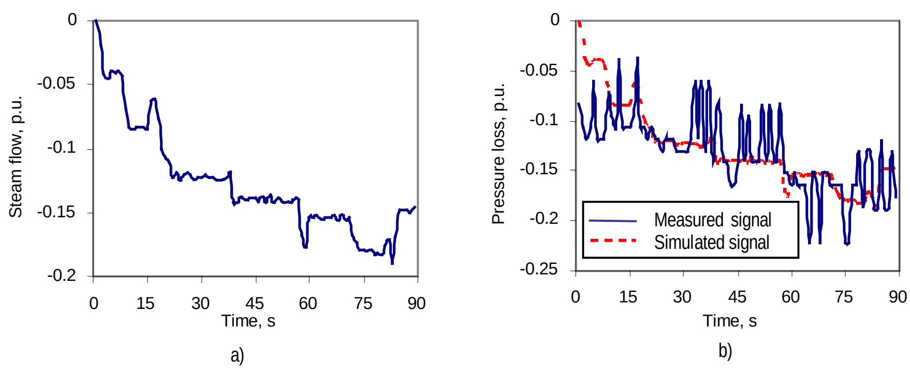


Fig. 9. Steam flow squared signal a) and steam pressure loss signal b) variation.

Table 2. **Identified data of the fifth turbine of the Lithuanian power plant**

Parameters	Identified values
T_1, *s*	0.5
T_2, *s*	1.239
T_3, *s*	0.482
K	1
T_4, *s*	0.329
T_5, *s*	4.23
K_I	0.04
T_I, *s*	50
T_R, *s*	20
T_{R1}, *s*	5
T_D, *s*	0
T_F, *s*	0
T_W, *s*	1
C_B, *s*	100
C_1	0.01812

It is worth to mention that in order to identify parameters of the turbine model more accurately, measuring frequency should be at least 10 Hz, because actual 1 Hz measuring frequency does not always ensure sufficient accuracy.

It is useful to coordinate experiments for dynamic data acquisition with the experiments provided at the initial unit's commitment or after the unit's reconstruction.

Conclusions

The methodology described here enables identification of parameters of generating units dynamic models from experimental data with suitable accuracy. Correlation factor of measured and calculated regime parameters exceeded 0.95 in all investigated cases.

Experiments for acquisition of data for models and identification of their parameters should be coincided with the unit's commitment experiments. Measuring frequency of turbine model identification data should be at least 10 Hz.

Presented expressions of recalculation of turbine and boiler and its regulators to another basis power are useful for submission of dynamic model data in power system stability calculations.

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