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Simulation of control of lowpower-output steam turbines

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Abstract Problems related to power control of low power-output steam turbines are analyzed. These turbines are designed to operate in distributed power generation systems. Principles of automatic control involving a single control valve are presented on the basis of experience gathered with high power-output turbines. Results of simulations of power control for a low power-output turbine are discussed. It has been proven that closing of the control system and an application of a power controller (of optimally selected parameters) improves the object dynamics (shortening of the transition period). At the same time, a lack of such optimization can results in occurrence of undesirable phenomena such as: overshoot in the generator power characteristics, elongation of the response time to disturbance or overshoot of turbine control valves.

Keywords: Steam turbine; Simulation; Power control

Nomenclature

P_G	–	generator (real) power
P_z	–	setpower
p_T	–	pressure of the steam from the boiler
Y_h	–	position of the control valve (inlet signal of the power generator)
E	–	deviation of control signal (error value)
K_p	–	proportional gain

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k	–	amplification
SLSP	–	speed limiter of set power
T_i	–	integration time
t	–	time
V	–	speed

1 Introduction

Control of high-power-output turbosets is a complex problem, in which many difficulties have to be overcome [1–5]. In the case of low power-output turbines, the issues that decide about the quality of the generated electrical power are usually considerably simplified. A change in power is most often obtained by manual control of the regulation valve. In this way, a mass flow rate of the steam delivered to the turbine from the boiler is altered. A low power-output steam turbine (nominal capacity 50 kW), driven by a heat recovery boiler, is subject to analysis [6]. The working medium inlet pressure is equal to 12 bar, and the temperature is 573 K (300°C). The nominal mass flow rate is 0.1 kg/s. This is a condensing turbine and the pressure in the condenser is equal to 0.25 bar. These unconventional nominal data (a relatively low mass flow rate) follow from the requirements imposed by the purchaser.

A schematic view of the turbines shown in Fig. 1, whereas Fig. 2 presents a general view of the whole turboset. A turbine flow part was designed as an unconventional doubled stage of the elektrosystem [7]. A throttle-type control system with one control valve was applied, which is the best solution from the economic viewpoint. Moreover, it simplifies the machine design significantly.

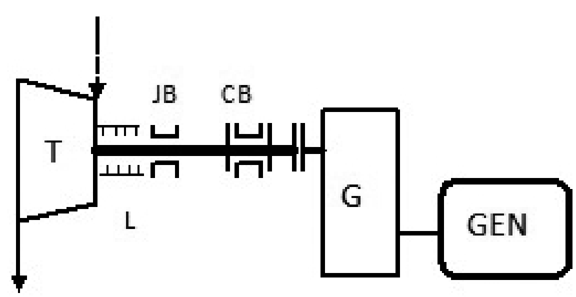

Figure 1: Schematic view of the turbine [6]: T – turbine, L – labyrinth seal, G – gear, GEN – generator, JB – journal bearing, CB – combined (thrust/journal) bearing.

Figure 2: General view of the whole turboset.

The simulation results for the above-mentioned object are presented. The conclusions resulting from the fact that manual control with control valves of the turboset was replaced by an automatic control system are discussed. Proved that the control system performance can be improved by combining the feedback control of a PI controller (proportional-integral controller). An algorithm to select controller settings is presented on the basis of the conducted simulations for the case under analysis.

The simulations presented in this paper refer to a situation when we deal with low power-output turbosets. Thus, it was possible to assume constant pressure of the steam delivered to the turbine. For larger turbosets, an interaction between the boiler and turbine systems should be accounted for. Each overshoot of turbine control valves brings disturbance of the boiler operation, as its control system has to overcome a pressure decrease or increase that follows. This issue [9], however, falls beyond the scope of the present paper.

2 Simulation of operation of the low power-output turboset

Simulations of the turboset operation when it was controlled manually and when it was equipped with a control system were conducted to discuss some selected problems referring to the issues related to power control of the turboset. An application of simulation methods allows one to check if the designed control system operates properly. The experience gathered previously shows that its worth doing to precede many design stages by computer simulations of operation of the devices being designed. Thus, the structure can be optimized and mistakes which could result in a considerable increase in costs during the manufacturing process of the device or control system can be avoided. Thanks to simulation methods, it is also possible to improve performance of the existing systems by a suboptimal selection of parameters of control systems, determined in the simulations. Control properties of the turboset can be defined experimentally or by means of mathematical modelling. In the present paper, a simple model of the turbine, generator and devices involved in the control system was used. The simulation results of the generated model are presented on diagrams depicting alternations in the simulated quantities versus time. In order to test the developed model of control systems (simulation of their operation), a simulation program Scilab version 6.1.0 [8] was used. This code has a built-in tool Xcos, which includes a library of ready functional blocks to build schemes of control systems, and to simulate their operation then. In this section, we will limit to these parameters that refer to control of real power delivered to the energy distribution network. In [1,3,8], schemes of functional blocks used in the model are to be found. Individual devices were modelled on the basis of basic dynamic blocks, and then inserted in the computational code as the so-called 'superblocks' [8]. As this paper is not devoted to the way of modelling, detailed schemes for individual simulations are not presented here. However, in order to illustrate the simulation methodology and calculational methods used in the simulations, the modelling way of the speed limiter of set power (SLSP), which was introduced in further calculations as such a 'superblock', is described below.

The operation of the SLSP consists in slowing down an effectof the step change in the set power on the object. It is carried out with a set speed of the SLSP. The idea of the SLSP modelling consists in generation of a difference signal E between the input signal IN and the output signal OUT by the adder SUM. This difference is amplified 100 times by the block $K1$ and then limited by the $LIMITER$ block to an inconsiderable value. Owing to that, the difference has a constant value in a wide range of E. The difference signal E is transferred to the integration element input $INTEGR$ with amplification set by the block $K2$, correspondingly to the needed input signal gradient. The constant value E causes a linear alternation in the input signal from the element $INTEGR$. Very low values of the difference signal

E are stopped by the block *DEADZONE* to avoid oscillations when the signal E attains values close to zero. The respective values of amplification are given on the scheme depicted in Fig. 3.

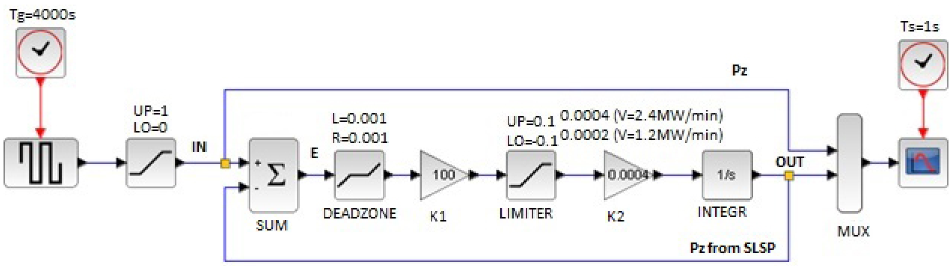

Figure 3: Scheme of the speed limiter of set power (SLSP): Tg – initialization time of the clock, Ts – period of the clock, V – speed setting of setpower, L – lower (left) limit of deadband, R - upper (right) limit of deadband, UP – upper limit of saturation, LO – lower limit of saturation, Pz – setpower. Other markings in the text.

The signal set speed is determined as follows. The operator transmittance of the integration term is expressed as

$$G(s) = \frac{k}{s}\,, \tag{1}$$

where s is the Laplace operator, thus, in the time domain, the above equation takes the form

$$h(t) = kt, \tag{2}$$

where: $h(t)$ – integration term response to the step excitation, k – amplification, t – time.

Equation (2) is an equation of the straight line with a slope resulting from the coefficient k. In the *INTEGR* block, the integration time (the time after which the output signal of the integration term reaches the excitation value), is set with the parameter k, which is equal to the reciprocal of the integration time. Hence, in order to attain a specified set power speed, parameters of the system should be selected in such a way – with respect to the nominal power – that the real value of the set step value is attained after the specified time. As regards Fig 3, the relevant parameters are as follows: at the speed $V = 1.2$ MW/min, the parameter $k = 0.0002$, whereas at the speed $V = 2.4$ MW/min, $k = 0.0004$. The respective plots are shown in Fig. 4, and the values were used in simulations further in the present work (cf. Figs. 6–14).

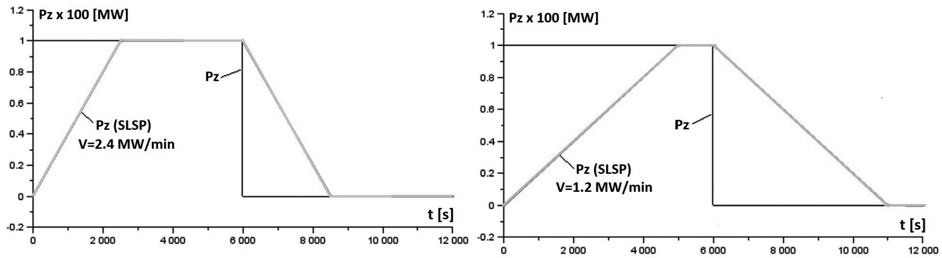

Figure 4: The speed limiter of setpower response to the speed $V = 1.2$ MW/min and 2.4 MW/min; setpower 100 MW (y-axis) changes in 5000 s (for $V = 1.2$ MW/min) or in 2500 s (for $V = 2.4$ MW/min).

The steam required to drive the turbine is generated in a steam generator (boiler). A constant pressure value of the steam delivered to the turboset from the power generator is basically assumed in the considerations presented below. The inflow of the steam to the turbine, and thus, the turboset power, is controlled by a degree of the steam valve opening. The valve can be adjusted manually or with additional devices. A servomotor is a device that directly adjusts a degree of the valve opening. The servomotor is most often controlled manually or with an electrohydraulic transducer, and the latter is controlled with an electric signal coming from the setter of power or from an electronic controller of the turboset. A scheme of the turboset part and automatic system parts that cooperate with it are presented in Fig. 5.

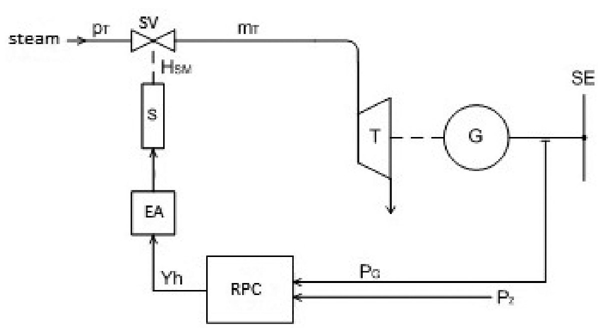

Figure 5: Technological scheme (part) of the power generation turboset: p_T – presure of the steam from the boiler, SV – steam valve, H_{SM} – leap (displacement) of the servomotor spindle, m_T – steam mass flow rate, T – steam turbine, S – servomotor, EA – electrohydraulic actuator, Y_h – set-up signal, RPC– real power controller, P_G – real power generated by the generator G, P_Z – set (real) power, SE – electricity generation system.

3 Results and discussion

An analysis of the system operation starts with the simplest case when the turboset works in an open system and the power is controlled manually via adjustment of the control valve (no power regulator). The system was subject to simulations. The simulations consisted in investigations of the system response (power) to 10% step closing and opening of the control valve. The result of the simulations is presented in Fig. 6. The 10% overshoot of the control valve (the excitation is transferred on the valve motion with slight inertia, the overshoot of the control valve takes place without re-adjustment) results in a change in power by approx. 8% (with respect to the nominal power) but the duration of the transition process is very long (individual interferences were excited every 20 s, and the termination of the transition period is even longer, thus a change in power does not attain the full range of 10%).

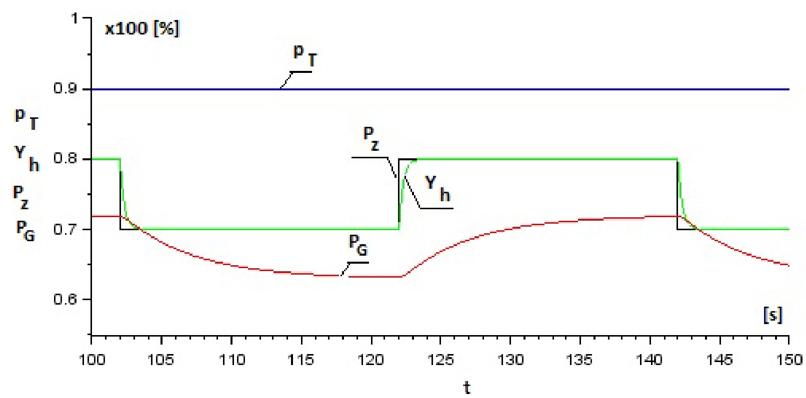

Figure 6: Simulation of manual power control of the turboset: p_T – presure of the steam from the boiler, P_z – set (real) power, P_G – generator power (real), Y_h – position of the control valve.

In Fig. 7 a simulation of the system operation in the situation when the turboset works in the power control system (a closed feedback from the real power, an application of a proportional integral (PI) controller optimally selected settings) is shown. A deviation of control is plotted versus time separately, apart from the quantities shown above.

Comparing the diagrams in Figs. 6 and 7, an improvement in static and dynamic conditions can be easily noticed: a 10% step change in the set value is followed by a 10% change in power, and the time in which the steady

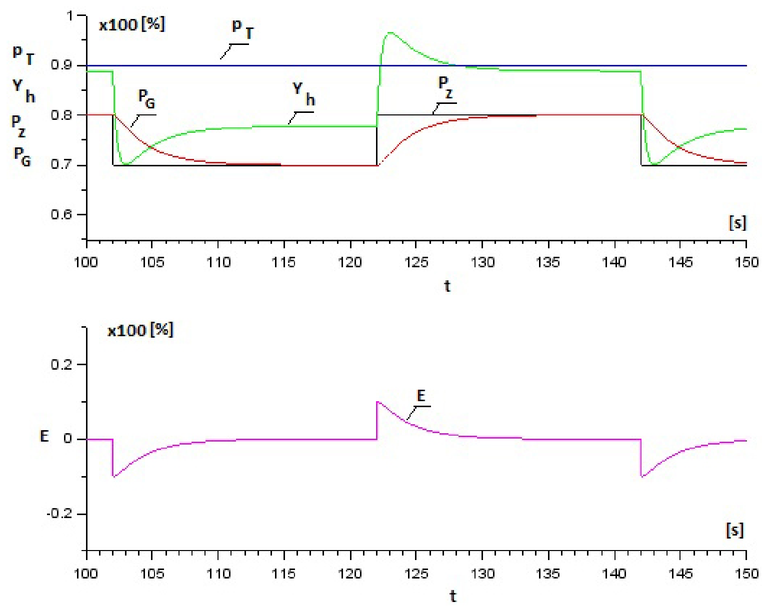

Figure 7: Simulation of manual power control of the turboset: p_T – pressure of the steam from the boiler, P_z – set power, P_G – generator (real) power, Y_h – position of the control valve (inlet signal of the power generator), E – deviation of control signal. Optimal settings of the controller PI ($K_p = 2$, $T_i = 0.4$).

state was attained was shortened considerably and was equal to approx. 5 s. However, the overshoot of the control valve takes place.

Figure 7 shows a result of simulations for optimally selected parameters of the proportional integral (PI) controller ($K_p = 2$, $T_i = 0.4$ s, where K_p is proportional gain and T_i is the integral time). In Figs. 8–14 responses of the system to an analog out interference for other settings of the controller are presented.

Figure 8 depicts a situation when amplification was decreased at optimally selected time of the controller integration. A decrease in the valve overshoot was attained, but the overshoot can be seen on the power diagram, and the time needed by the real power to attain the set power increased up to approx. 9 s (the total control time was approx. 18 s taking into consideration the overshoot on the power diagram).

Figure 9 refers to a situation when the controller integration time was increased for the optimally selected time of amplification. For such settings, the real power (during the transition process, for $t = 20$ s) does not reach the set value.

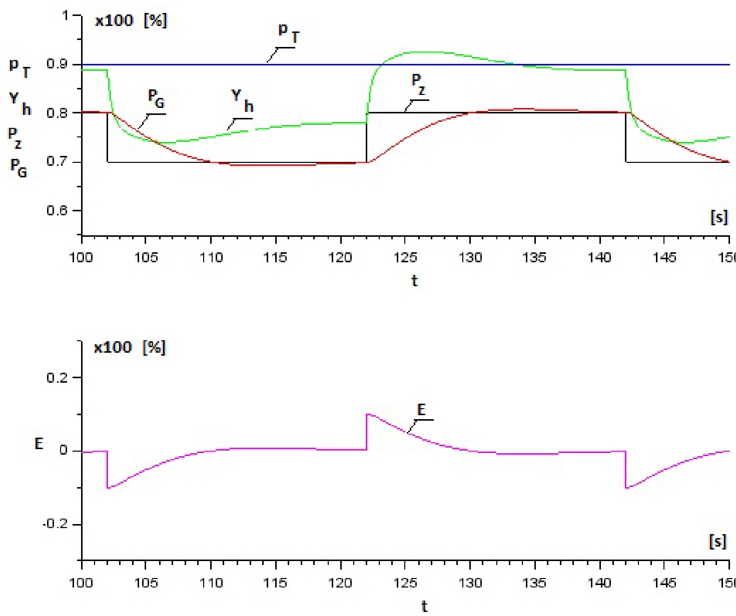

Figure 8: Simulation of power control of the turboset. Settings of the controller PI: $K_p = 1$, $T_i = 0.4$.

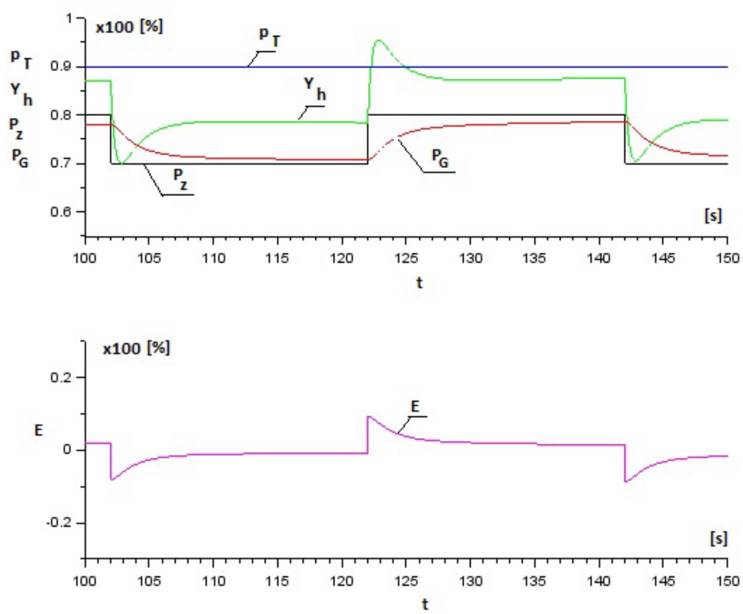

Figure 9: Simulation of power control of the turboset. Settings of the controller PI: $K_p = 2$, $T_i = 0.1$.

Figure 10 represents a situation where the amplification was decreased, and the controller integration time was increased with respect to optimally selected settings of the controller. For such settings, duration of the transition process remains still very long – the real power does not attain the set power, although there is no overshoot of the control valve.

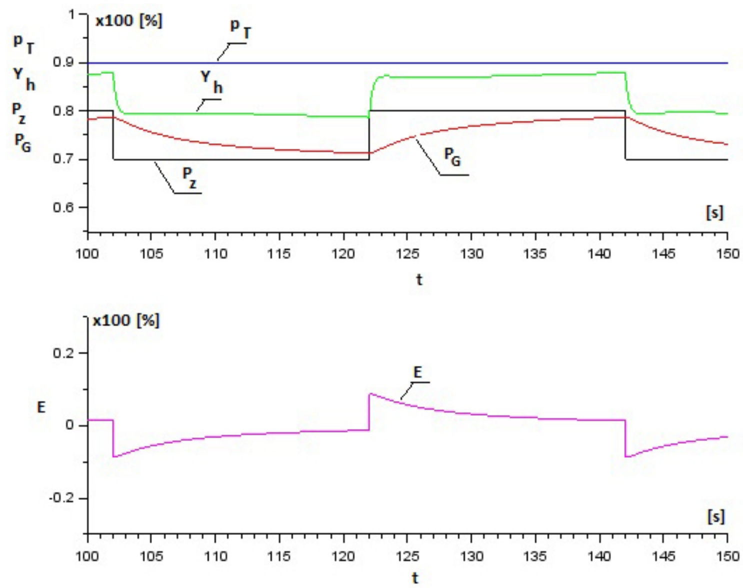

Figure 10: Simulation of power control of the turboset. Settings of the controller PI: $K_p = 1$, $T_i = 0.1$.

Figure 11 shows a situation where the amplification was increased, and the controller integration time was shortened with respect to optimally selected settings of the controller. For such settings of the controller, a diagram of the real power *vs* time is comparable to the optimal curve from Fig. 7, however, considerable overshoot of the control valve occurs here.

Figure 12 refers to a situation where the controller integration time was shortened at the optimally selected amplification. A decrease in the valve overshoot comes at an increase in the control time (approx. 10 s).

The presented diagrams and the given descriptions show in what way the system operation can be optimized by changes in settings of the PI controller by means of simulations.

As mentioned previously, the target real power, controlled with a power regulator, is sometimes attained not in a step-like way but at a certain constant speed, which follows from the performance characteristics of the

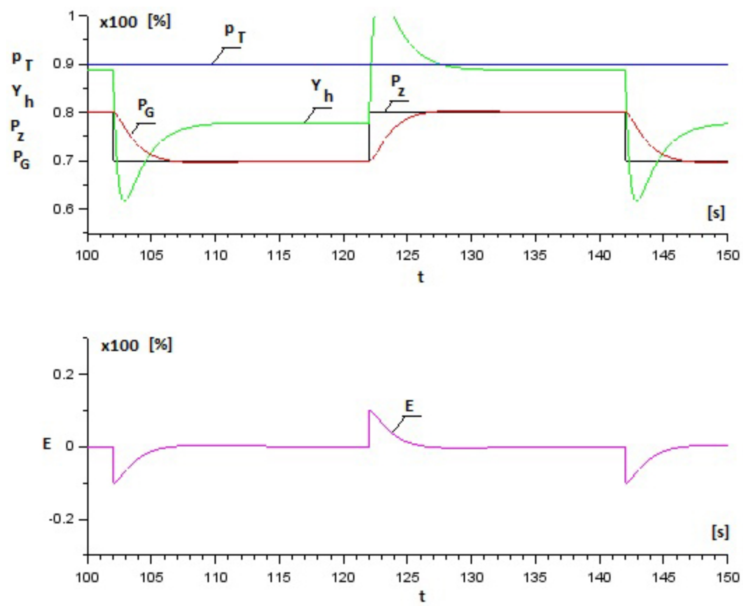

Figure 11: Simulation of power control of the turboset. Settings of the controller PI: $K_p = 3$, $T_i = 0.8$.

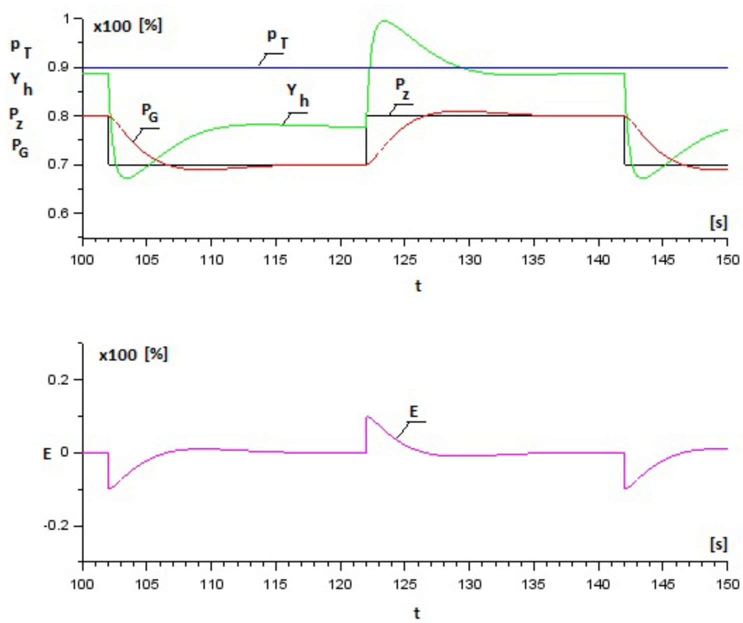

Figure 12: Simulation of power control of the turboset. Settings of the controller PI: $K_p = 2$, $T_i = 0.8$.

object under control after an introduction of a new set power value. In such a situation, 'a leap' of the set value has to be 'transferred' to the system at a given speed. This function is performed by a speed limiter. This device is used to set power with a specified gradient. A result of simulations for an open system (manual control with the speed set in the speed limiter) is shown in Fig. 13, and for a closed system (a set value of the generator with a gradient adjusted in the speed limiter) in Fig. 14.

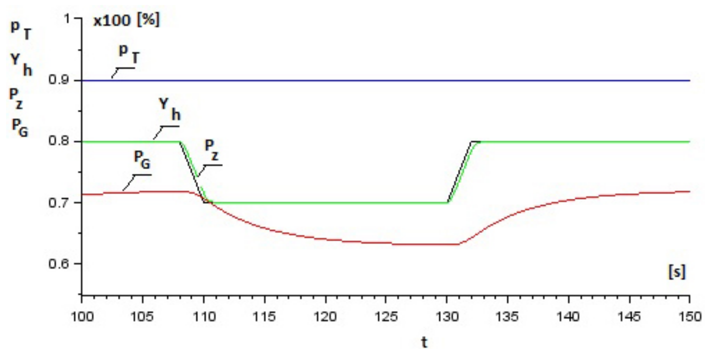

Figure 13: Simulation of manual power control of the turboset at a linear increase in the set signal.

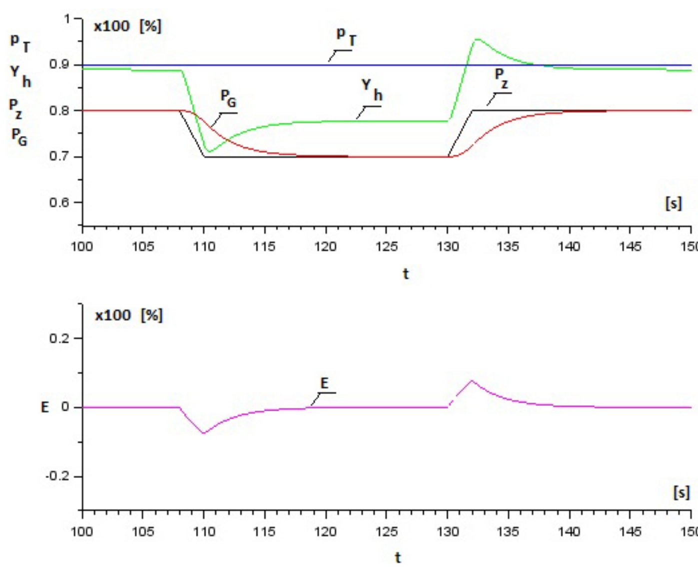

Figure 14: Simulation of power control of the turboset at a linear increase in the set power signal. Optimal settings of the controller PI ($K_p = 2$, $T_i = 0.4$).

As can be seen, it does not matter whether we change the valve position in a step-like or slow-down way in the case of manual control. As regards power control, a linear increase in the set value results in a 'smoother' increase on individual diagrams (it is visible on, e.g., the diagram of the deviation of control). Optimally selected settings of the controller for the step excitation are also optimal in the case when a speed limiter is used.

4 Conclusions

The turbine power can be changed *via* alterations in the mass flow rate of the steam delivered from a steam generator by opening or closing the control valve. In low power-output turbosets, power is usually changed in an open system by manual control of the valve opening. Such control causes that the process of power setting is longer and troublesome due to difficulties resulting from not a very precise adjustment of the set value. It should be noticed that such problems become the more serious the longer machines operate. However, we encounter good static conditions with this kind of control, and the valve is not subject to overshoot. Closing of the control system and an application of a power controller improves considerably the dynamics of machine operation. It is manifested mainly by a significant shortening of the transition process. Attention should be drawn to a proper selection of controller parameters. Non-optimal settings of amplification and integration time can result in deterioration of performance curves (overshoot in the generator power, elongation of the response time to interference, overshoot of control valves The period of transient run can be minimized with respective controller settings (e.g. by shortening of the controller integration time) or can neutralize overshoot (a decrease in the controller amplification). Moreover, the optimization process should be carried out in such a way as to prevent too high overshoot of control valves. In the case the set value grows too slowly, an improvement in dynamic conditions occurs via an application of a speed limiter of set power but only when a close system is used. To conclude, it can be stated that to improve control conditions of small turbosets, it is purposeful to use power controllers and to set the signal not in a leap way but at a certain speed. It is worth doing to precede numerous stages of the design works of control systems by computer simulations of the machines and devices. It allows one to optimize the design and avoid mistakes which could lead to a significant increase in manufacturing costs. Thanks to simulation methods, performance of the existing systems can be improved via a suboptimal selection of parameters of control systems, determined in the simulations.

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