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10.1515/acsc-2015-0005

Archives of Control Sciences
Volume 25(LXI), 2015
No. 1*, pages 65–86*

Dynamic model of nuclear power plant steam turbine

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The paper presents the dynamic multivariable model of Nuclear Power Plant steam turbine. Nature of the processes occurring in a steam turbine causes a task of modeling it very difficult, especially when this model is intended to be used for on-line optimal process control (model based) over wide range of operating conditions caused by changing power demand. Particular property of developed model is that it enables calculations evaluated directly from the input to the output, including pressure drop at the stages. As the input, model takes opening degree of valve and steam properties: mass flow and pressure. Moreover, it allows access to many internal variables (besides input and output) describing processes within the turbine. The model is compared with the static steam turbine model and then verified by using archive data gained from researches within previous Polish Nuclear Power Programme. Presented case study concerns the WWER-440 steam turbine that was supposed to be used in Żarnowiec. Simulation carried out shows compliance of the static and dynamic models with the benchmark data, in a steady state conditions. Dynamic model also shows good behavior over the transient conditions.

Key words: nuclear power plant, steam turbine, modeling, control.

1. Introduction

One of authors motivations to undertake the research at the field of Nuclear Power Plants (NPP) is to restore the scientific potential of Polish researchers and engineers within this important area. The first approach to building the NPP in Żarnowiec took place in 1982-1990. The concept of research and construction works within this project were governed by the Central Research and Development Programme 5.3. "Nuclear Power" (CRDP5). Once the first nuclear programme was canceled in 1990, there was little motivation to proceed and to conduct researches in the area of modeling, estimation and control intended for nuclear energy sector. Current "Polish Nuclear Power Programme" [14] provides for the launch of the first NPP about year 2024 and creates research and educational opportunities for Polish Universities. Paper authors take part

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This work was supported by the National Centre for Research and Development under Strategic Research Project No. SP/J/10/176450/12. The authors wish to express their thanks for the support.

Received 25.06.2014.

in a research team whose research focus on solving the problems related to modeling, diagnostic and control of NPP e.g. [3, 12, 15, 16, 17, 20].

This paper presents a dynamic, multivariable, nonlinear model of NPP steam turbine based on the approach [18] and compares it with the modified static one presented in [12]. The steam turbines are one of the most important devices of the power generating systems [13]. The necessity of having the appropriate steam turbine model in order to simulate the processes occurring within the turbine as well as the outputs is obvious. There are variety of different levels of the model complexity with respect to the purpose (e.g. design works, simulations, predictions, control, diagnostics) and its kind (linear or nonlinear, static or dynamic) [1, 2, 6, 7, 10, 18]. The common practice is to use the static models or linear dynamic ones in process of control design of the steam turbine. Generally, in case of steam turbine (as well as e.g. synchronous generator, nuclear reactor and steam generator) the control structures are defined as SISO systems which are based on and limited to basic controllers such as PID that are valid only over specified operational point (steady state). However, the most advanced control methods that enable for optimal dynamic control, such us e.g. MPC [7], require dynamic, input-output models which describe the processes occurring within the steam turbine with high accuracy [1]. In return, these offer economically efficient control with improved control accuracy (comparing with aforementioned basic control methods) over wide range of operating conditions.

Dynamic model presented in the paper, as an opposite to the most steam turbine models (which are calculated backwards [5, 8, 11, 19]), enables for calculations evaluated directly from the input (opening degree of valve and steam properties: mass flow and pressure) to the output and hence can be used for on-line control purposes under varying inputs. The model is implemented in Matlab environment supplemented with X-Steam toolbox [9].

The paper is organized as follows: Sec. 2 describes the static model of the NPP steam, then Sec. 3 presents the theoretical fundamentals of steam turbine dynamic modeling and finally delivers steam turbine model. Farther, in Sec. 4 the dynamic model is confronted with the static one. The turbine which was to be used in NPP Żarnowiec (WWER-440/213) serves as the case study while Żarnowiec Reports [4, 18] are the source of benchmark data. Finally, Sec. 5 concludes the paper and presents on-going and future researches at this field.

2. Static model

NPP steam turbine structure consists of parts dependent on level of pressure. It is common to define three pressure levels: high, intermediate and low (HP, IP and LP). The presence of each section is not necessary so a turbine with only HP and LP sections can be made. The number of sections depends on construction and output power of the designed turbine. It is possible to design e.g. turbine with one HP part and two parallel LP parts. In order to improve properties of steam between sections a process of reheating can be applied. The position of reheater is not specified directly so it can be placed between any parts of steam turbine or even between each of them [13].

Example steam turbine scheme that is described in following sections, is shown in Fig. 1, however described in the paper model can be also used with other variants. According to the scheme, the whole turbine is divided into two parts: High Pressure Turbine (HP-turbine) and Low Pressure Turbine (LP-turbine). Every turbine part consists a number of turbine stages dependent on construction and design. There are vents (Vent) at some of the turbines stages. Very important is the position of the vents. In case of CRDP5, e.g. two vents can be placed at stages of HP-turbine and three vents can be placed at stages of LP-turbine [4]. Each turbine is preceded by so called dead space (DS) where slackness of the steam takes place. Steam in proposed model is superheated to improve its properties. In order to allow it, a moisture separator and reheater between HP-turbine and LP-turbine are placed. Described model consists of separated submodels of devices such as dead space, reheater, moisture separator, stage with vent and stage without it. Each submodel was created as input-output model. As the inputs, the model takes pressure, temperature and mass flow of fresh steam. A set of parameters and nominal values which are mostly gained from factory data is also needed for purposes of model building and its simulation. It was assumed that the value of input steam enthalpy is kept constant and the value of steam enthalpy in the vent is the same as the value of steam enthalpy at the next stage. Where needed, enthalpy and vapor fraction were calculated with usage of XSteam toolbox [9] function for Matlab. In the static model the influence of dead space in LP-turbine was neglected because of the character of reheater [18].

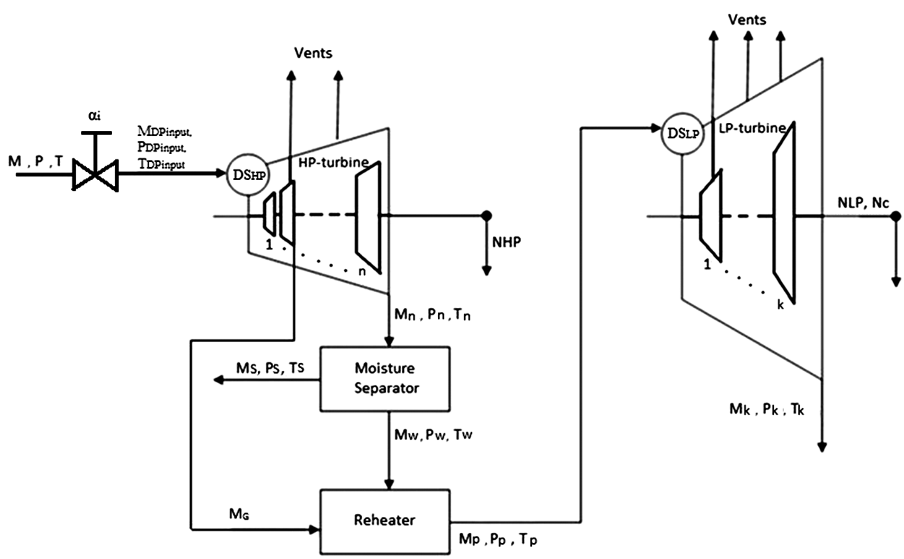

Figure 1: Example scheme of steam turbine with steam superheating between the stages.

Dead space

Accordingly to the scheme in Fig. 1 the dead space (DS_{HP}) was modeled. This submodel uses mass flow $M_{DPinput}$, steam pressure $P_{DPinput}$ and temperature $T_{DPinput}$ as the inputs. With assumption of accumulation of steam and that this process has adiabatic nature a dependence for mass flow was derived (1). Dead space output pressure is equal to the input pressure, because of assumption of no pressure drop in this area (2). For the temperature a proportion including nominal values of these variables for appropriate dead space was assumed (3). Model output results with: mass flow $M_{DPoutput}$, temperature $T_{DPoutput}$ and pressure $P_{DPoutput}$.

$$M_{DPoutput} = M_{DPinput} \tag{1}$$

$$P_{DPoutput} = P_{DPinput} \tag{2}$$

$$T_{DPoutput} = \frac{T_{DPinput}}{T_{DPinput}^{nominal}} T_{DPoutput}^{nominal} \tag{3}$$

where $T_{DPinput}^{nominal}$, $T_{DPoutput}^{nominal}$ are dead space nominal temperatures [K].

Stage with vent

In case of turbine stages mass flow M_i, steam pressure P_i and steam temperature T_i of i-th stage were used as the input data in order to receive M_{i+1}, P_{i+1}, T_{i+1} and mass flow of the j-th vent $M_{Vent\,j}$. Mass flow at the stages with a vent was based on full Stodola-Flügel cone law (4). At stages without the vents the output mass flow is equal to the input, assuming no leaks. As for the stage with the vent, mass flow of the vent is given by (5). Pressure was calculated in proportion to its nominal values (6),while for most stages the temperature can be calculated according to (7). In order to calculate the temperatures at the first $T_{LPfirst}$ and second $T_{LPsecond}$ stage of LP-turbine (8) and (9) were used (with usage of first and second stage of LP-turbine pressure $P_{LPfirst}$, $P_{LPsecond}$ calculated using (6)).

$$M_{i+1} = \sqrt{\frac{T_i^{nominal}}{T_i} \frac{(P_i)^2 - (P_{i+1})^2}{(P_i^{nominal})^2 - (P_{i+1}^{nominal})^2}} M_{i+1}^{nominal} \tag{4}$$

$$M_{Vent\,j} = \frac{M_{i+1}}{M_{i+1}^{nominal}} M_{Vent\,j}^{nominal} \tag{5}$$

$$P_{i+1} = \frac{P_i}{P_i^{nominal}} P_{i+1}^{nominal} \tag{6}$$

$$T_{i+1} = T_{coef1} P_{i+1}^{pow_{coef1}} P_{i+1}^{pow_{coef2}} \tag{7}$$

$$T_{LPfirst} = T_{coef2} + T_{coef3} \frac{P_{LPfirst}}{P_{LPfirst}^{nominal}} T_{LPfirst}^{nominal} \tag{8}$$

$$T_{LPsecond} = T_{coef4} + T_{coef5} \frac{P_{LPsecond}}{P_{LPsecond}^{nominal}} T_{LPsecond}^{nominal} \tag{9}$$

where: $M_{i+1}^{nominal}$ – nominal output mass flow of i-th turbine stage [kg/s]; $P_i^{nominal}$ – nominal input pressure of i-th turbine stage [MPa]; $P_{i+1}^{nominal}$ – nominal output pressure of i-th turbine stage [MPa]; $T_i^{nominal}$ – nominal input temperature of i-th turbine stage [K]; $M_{Vent\,j}^{nominal}$ – nominal mass flow of j-th vent [kg/s], T_{coef1}, T_{coef2}, T_{coef3}, T_{coef4}, T_{coef5} – temperature coefficients, $\mathrm{pow}_{\mathrm{coef1}}$, $\mathrm{pow}_{\mathrm{coef2}}$ – exponential coefficients of temperature, $P_{LPfirst}^{nominal}$ – nominal pressure of the first LP-turbine stage, $P_{LPsecond}^{nominal}$ – nominal pressure of the second LP-turbine stage, $T_{LPfirst}^{nominal}$ – nominal temperature of the first LP-turbine stage, $T_{LPsecond}^{nominal}$ – nominal temperature of the second LP-turbine stage.

Moisture separator

Moisture separator which separates water and steam was modeled with the usage of nominal values of output vapor fraction. Based on mass flow $\mathrm{M}_{MSinput}$ and input x_{in} and output x_{out} vapor fractions, mass flow $\mathrm{M}_{MSoutput}$ and water mass flow MS were calculated (10 and 11). Input vapor fraction was calculated using XSteam function while the output vapor fraction was assumed to be 0.9999.

$$M_{MSoutput} = \frac{x_{in}}{x_{out}} M_{MSinput} \tag{10}$$

$$M_S = M_{MSinput} \left(1 - \frac{x_{in}}{M_{MSoutput}} \right) \tag{11}$$

where: x_{in} – input vapor fraction of moisture separator, x_{out} – output vapor fraction of moisture separator.

Steam pressure $\mathrm{P}_{\mathrm{MSoutput}}$ and water pressure are equal to the input pressure, while output temperatures of steam ($\mathrm{T}_{\mathrm{MSoutput}}$) and water ($T_S$) are equal to the input temperature.

Reheater

Reheater is responsible for improvement of steam properties after its exploitation of steam in HP-turbine. The mass flow $M_{Routput}$ at the outlet of the reheater depends mainly on inlet mass flow M_{Rinput} ($M_{MSoutput}$), time constant and change of the pressure (12). Because of the value of this constant the dynamic of the dead space (and dead space itself in the static model) placed directly after the reheater was neglected.

$$M_{Routput} = \frac{M_{Rinput}}{M_{wp}^{nominal}} M_w^{nominal}. \tag{12}$$

Pressure $P_{Routput}$ was assumed to be a proportion of input pressure P_{Rinput} to nominal pressure values (13). Regarding the temperature $T_{Routput}$, a similar proportion with the correction coefficients a_T , b_T was given (14).

$$P_{Rinput} = \frac{P_{Routput}}{P_w^{nominal}} P_w^{nominal} \tag{13}$$

$$T_{Routput} = \left(a_T \frac{P_{Routput}}{P_p^{nominal}} + b_T \right) T_p^{nominal} \tag{14}$$

where: $M_{wp}^{nominal}$ – nominal input steam mass flow of reheater [kg/s]; $M_w^{nominal}$ – nominal output steam mass flow of reheater [kg/s]; $P_p^{nominal}$ – nominal input steam pressure of reheater [MPa]; $P_w^{nominal}$ – nominal output steam pressure of reheater [MPa]; $T_p^{nominal}$ – nominal output steam temperature of reheater [K]; a_T, b_T – temperature coefficients of reheater (from factory data).

Effective power

Data collected from each submodel (output and input pressures, temperatures, mass flows), allow to calculate a steam turbine power. Pressure and temperature values were used to gain values of enthalpies of each turbine stage. Those allow to gain knowledge about changes of enthalpies required to calculate the power of each stage, N_i. With the data set which includes: stage mass flow M_i, change of enthalpy dh_i and nominal value of NPP power N_{TN}, efficiency of stage $\mu_i^{nominal}$, power coefficient of stage $k_i^{nominal}$, it was possible to determine the theoretical power of each of the stages (15). That lead to theoretical power of turbine which is a sum of power of each of the turbine stages N_C with n stages (16). N_C is finally multiplied by nominal effective efficiency of the whole turbine equal E_E giving the effective output power.

$$N_i = \frac{k_i^{nominal}}{\mu_i^{nominal}} \frac{M_i}{M_i^{nominal}} \frac{h_i}{h_i^{nominal}} N_{TN} \tag{15}$$

$$N_C = \sum_{t=1}^{n} N_i \tag{16}$$

where: $\mu_i^{nominal}$ – efficiency of i-th stage, $k_i^{nominal}$ – power coefficient of i-th stage, $M_i^{nominal}$ – nominal mass flow of i-th stage $h_i^{nominal}$ – theoretical enthalpy drop of i-th stage.

3. Dynamic model

Dynamic model of Nuclear Power Plant (NPP) Steam Turbine presented in this paper takes: pressure on the inlet of steam turbine p_1 (before control valve) and degree of opening of control valve α_i as the inputs. Input pressure is generated by the NPP Steam

Generator. The degree of control valve opening is defined as percentage of opened area of the valve. Because of the technical operating area of steam turbine, where technical minimum operating point is 30 percent of nominal power, valve opening degree value range is from 30 up to 100 percent [4]. Dynamic model of NPP steam turbine consists a number of submodels. Each submodel represents individual device or a separate part of the turbine. The control valve was modeled using (17-19). Output mass flow m_i of the control valve is calculated based on the valve pressure (17): input p_i and output p_{i+1V} (18), which is dependent on the valve characteristic. For the purposes of this paper a linear characteristic of the valve dependent on valve opening degree α was assumed. Because of the character of the presented model, a dynamic of control valve actuator was modeled with usage of the first degree inertia (19) [18].

$$m_i = m_i^{nominal} \left(\frac{V_a \left(\frac{\alpha}{\alpha^{nominal}}\right)^{\frac{H_i-1}{H_i}}}{\sqrt{1 - V_b \left(\frac{\alpha}{\alpha^{nominal}}\right)^{\frac{H_i-1}{H_i}}}} \sqrt{\left(\frac{p_{i+1V}}{p_i}\right)^{\frac{2}{H_i}} - \left(\frac{p_{i+1V}}{p_i}\right)^{\frac{H_1-1}{H_i}}} \right) \tag{17}$$

$$p_{i+1V} = p_i \frac{\alpha}{\alpha_n} \tag{18}$$

$$\alpha = k_p \alpha_i - T \frac{d\alpha}{dt} \tag{19}$$

where: $m_i^{nominal}$ – nominal input mass flow of the control valve, H_i – adiabatic exponent, $\alpha^{nominal}$ – nominal valve opening degree, k_p – inertia gain, V_a, V_b – valve mass flow coefficients.

Dead space

Next submodel concerns a HP-part dead space DS_{HP} (LP-part dead space is neglected because of dominating dynamic of reheater). It was modeled according to (20-21). Dead space has very significant contribution to the dynamic character of presented NPP steam turbine model. Submodel is based on time derivative (20) of the pressure within dead space which determines an input for the first stage of steam turbine. Derivative time constant τ_i (21) was proven [18] to be a constant value within the range from 43 up to 100 percent of the steam turbine power.

$$\frac{m_i}{m_i^{nominal}} - \frac{m_{i+1}}{m_{i+1}^{nominal}} = \tau_i \frac{d}{dt}\left(\frac{p_{DS}}{p_{DS}^{nominal}}\right) \tag{20}$$

$$\tau_i = \frac{V_i}{H_i m_i^{nominal} v_i} \tag{21}$$

where: $m_i^{nominal}$ – nominal input mass flow, $m_{i+1}^{nominal}$ – nominal output mass flow, H_i – adiabatic exponent, $p_{DS}^{nominal}$ – nominal output pressure of dead space, V_i – accumulation volume of dead space, v_i – specific volume of steam.

Group of stages

Approach used in the presented model is concentrated on the steam turbine vents. Because of that, instead of modeling each steam turbine stage, groups of stages were made. Process of merging the stages takes place either between vents or between vent and outlet of each steam turbine part. Described approach gives groups of stages for High Pressure (HP) part of steam turbine and groups of stages for Low Pressure (LP) part of steam turbine. Each group is described with its individual exponents which were calculated as average of the original values from factory data [4]. For HP part of the steam turbine a dependence of mass flow m_{iHP}, pressure p_{iHP} and temperature T_{iHP} based on simplified Stodola's cone law for each group of stages was used (22). For each group of stages in LP part a proportion of stage mass flow m_{iLP} and reheater mass flow m_p is given (23). Pressure in groups of stages of HP part results from time derivatives of dead space p_{DS} (20) and vents p_{iV} (41). Pressure of stage groups p_{iLP} (except last group of stages) in the LP part can be calculated as proportional to pressure of reheater p_p (24). In order to calculate temperatures in groups of stages, (25) and (26) were used. For groups of stages in HP part and for the first group in LP part (25) is valid (with p_{LHP} – which, depending on the stage, could be calculated with (24) or formulas for HP part stage pressure). For the rest of LP part groups (except the last group) (26) was used.

$$m_{iHP} = m_{iHP}^{nominal}\left(\frac{p_{iHP}}{p_{iHP}^{nominal}}\sqrt{\frac{T_{iHP}^{nominal}}{T_{iHP}}}\right) \tag{22}$$

$$m_{iLP} = m_{iLP}^{nominal}\frac{m_p}{m_p^{nominal}} \tag{23}$$

$$p_{iLP} = p_{iLP}^{nominal}\frac{p_p}{p_p^{nominal}} \tag{24}$$

$$T_{iHP} = T_{iHP}^{nominal}\left(T_{a1} + T_{b1}\sqrt{T_{c1}\frac{p_{LHP}}{p_{LHP}^{nominal}} - 1}\right) \tag{25}$$

$$T_{iLP} = T_{iHP}^{nominal}\left(T_{a2} + T_{b2}\sqrt{\frac{p_{iLP}}{p_{iLP}^{nominal}}}\right) \tag{26}$$

where: $m_{iHP}^{nominal}$ – nominal mass flow of i-th group of stages, $p_{iHP}^{nominal}$ – nominal pressure of group of i-th stages of HP part, $T_{iHP}^{nominal}$ – nominal temperature of i-th group of stages, $m_p^{nominal}$ – nominal mass flow of reheater, $p_p^{nominal}$ – nominal average pressure of reheater, T_{a1}, T_{b1}, T_{c1}, T_{a2}, T_{b2} – temperature coefficients, $p_{iLP}^{nominal}$ – nominal pressure of group of i-th stages of LP part, $p_{LHP}^{nominal}$ – nominal pressure of group of i-th stages of HP part and first stage of LP part.

HP-part and LP-part outputs

Outlets of HP- and LP- parts were calculated. Calculations concerning HP part: outlet mass flow m_{HPout} which is proportional to the mass flow of last HP group of stages (27), outlet pressure p_{HPout} (28) proportional to pressure of the last HP group of stages and outlet temperature T_{HPout} (29).

$$m_{HPout} = m_{HPout}^{nominal} \frac{m_{iHP}}{m_{iHP}^{nominal}} \tag{27}$$

$$p_{HPout} = p_{HPout}^{nominal} \frac{p_{iHP}}{p_{iHP}^{nominal}} \tag{28}$$

$$T_{HPout} = T_{HPout}^{nominal} \left(T_{a3} + T_{b3} \sqrt{T_{c3} \frac{p_{HPout}}{p_{HPout}^{nominal}} - 1} \right) \tag{29}$$

where: $m_{iHP}^{nominal}$ – nominal mass flow of i-th group of stages, $m_{HPout}^{nominal}$ – nominal outlet mass flow of HP part, $p_{iHP}^{nominal}$ – nominal pressure of group of i-th stages, $p_{HPout}^{nominal}$ – nominal outlet pressure of HP part, $T_{HPout}^{nominal}$ – nominal outlet temperature of HP part, T_{a3}, T_{b3}, T_{c3} – temperature coefficients.

For the LP part the same values were calculated: outlet mass flow m_{LPout} (30) dependent on reheater mass flow m_p, outlet pressure p_{LPout} (31) with usage of reheater pressure p_p and outlet temperature (32).

$$m_{LPout} = m_{LPout}^{nominal} \frac{m_p}{m_p^{nominal}} \tag{30}$$

$$p_{LPout} = p_{LPout}^{nominal} \left(P_{a1} + P_{b1} \frac{p_p}{p_p^{nominal}} + P_{c1} \left(\frac{p_p}{p_p^{nominal}} \right)^2 \right) \tag{31}$$

$$T_{LPout} = T_{LPout}^{nominal} \left(T_{a4} + T_{b4} \sqrt{T_{c4} \frac{p_{LPout}}{p_{LPout}^{nominal}} - 1} \right) \tag{32}$$

where: $m_{LPout}^{nominal}$ – nominal outlet mass flow of LP part, $m_p^{nominal}$ – nominal mass flow of reheater, $p_{LPout}^{nominal}$ – nominal outlet pressure of LP part, P_{a1}, P_{b1}, P_{c1} – temperature coefficients (approximation of outlet pressure in function of reheater pressure), $p_p^{nominal}$ – nominal average pressure of reheater, $T_{LPout}^{nominal}$ – nominal outlet temperature of LP part, T_{a4}, T_{b4}, T_{c4} – temperature coefficients (approximation of outlet temperature in function of outlet pressure of LP part).

Effective power

For the purpose of calculating the effective power of steam turbine, in each group of stages an enthalpy drop was calculated. The above can be calculated with (33-37).

Enthalpy drop h_{iHP} in the HP part groups of stages can be calculated as in (33), the last group of HP part h_{HPlast} as in (34), where p_{p1} is an input pressure of reheater (49). For LP-part the equations: (35) (the first group of stages - h_{1LP}), (36) (middle groups of stages h_{iLP}) and (37) (last group of stages – h_{Plast}) are valid, where p_{p2} in (35) is an output pressure of reheater (49).

$$h_{iHP} = h_{iHP}^{nominal} \left(\frac{T_{i+1HP}}{T_{i+1HP}^{nominal}} \frac{1 - \left(\frac{p_{i+2HP}}{p_{i+1HP}} \right)^{\frac{H_{i-1}}{H_i}}}{1 - \left(\frac{p_{i+2}^{nominal}}{p_{i+1}^{nominal}} \right)^{\frac{H_{i-1}}{H_i}}} \right) \tag{33}$$

$$h_{HPlast} = h_{HPlast}^{nominal} \left(\frac{T_{i+1HP}}{T_{i+1HP}^{nominal}} \frac{1 - \left(\frac{p_{p1}}{p_{i+1HP}} \right)^{\frac{H_{i-1}}{H_i}}}{1 - \left(\frac{p_{p1}^{nominal}}{p_{i+1HP}^{nominal}} \right)^{\frac{H_{i-1}}{H_i}}} \right) \tag{34}$$

$$h_{1LP} = h_{1LP}^{nominal} \left(\frac{T_{i+1HP}}{T_{i+1HP}^{nominal}} \frac{1 - \left(\frac{p_{p1}}{p_{i+1HP}} \right)^{\frac{H_{i-1}}{H_i}}}{1 - \left(\frac{p_{p1}^{nominal}}{p_{i+1HP}^{nominal}} \right)^{\frac{H_{i-1}}{H_i}}} \right) \tag{35}$$

$$h_{iLP} = h_{iLP}^{nominal} \left(\frac{T_{iLP}}{T_{iLP}^{nominal}} \frac{1 - \left(\frac{p_{i+1LP}}{p_{iLP}} \right)^{\frac{H_{i-1}}{H_i}}}{1 - \left(\frac{p_{i+1LP}^{nominal}}{p_{iLP}^{nominal}} \right)^{\frac{H_{i-1}}{H_i}}} \right) \tag{36}$$

$$h_{LPlast} = h_{LPlast}^{nominal} \left(\frac{T_{iLP}}{T_{iLP}^{nominal}} \frac{1 - \left(\frac{p_{LPout}}{p_{iLP}} \right)^{\frac{H_{i-1}}{H_i}}}{1 - \left(\frac{p_{LPout}^{nominal}}{p_{iLP}^{nominal}} \right)^{\frac{H_{i-1}}{H_i}}} \right) \tag{37}$$

where: $h_{iHP}^{nominal}$ – nominal drop of enthalpy of i-th group of stages of HP part, $h_{HPlast}^{nominal}$ – nominal drop of enthalpy of last group of stages of HP part, $h_{1LP}^{nominal}$ – nominal drop of enthalpy of the first group of stages of LP part, $h_{iLP}^{nominal}$ – nominal drop of enthalpy of the i-th group of stages of LP part, $h_{iLPlast}^{nominal}$ – nominal drop of enthalpy of last group of stages of LP part, $T_{i+1HP}^{nominal}$ – nominal temperature of i-th group of stages of HP part, $T_p^{nominal}$ – nominal temperature of reheater, $T_{iLP}^{nominal}$ – nominal temperature of i-th group of stages of LP part, $p_{iLP}^{nominal}$ – nominal pressure of i-th group of stages of LP part, $p_{i+1LP}^{nominal}$ – nominal pressure of $i+1$-th group of stages of LP part, $p_{i+2}^{nominal}$, $p_{i+1}^{nominal}$ – nominal pressure of $i+2$-th and $i+1$-th groups of stages of HP part, H_i – adiabatic exponent of i-th group of stages, $p_{p1}^{nominal}$ – nominal input pressure of reheater, $p_{p2}^{nominal}$

– nominal output pressure of reheater, $p_{LPout}^{nominal}$ – nominal outlet pressure of LP part.

Vents

For every vent a mass flow is calculated according to (38) based on i-th group of stages for steam turbine HP part ($m_{Vent\,jHP}$) and (39) for LP part ($m_{Vent\,jLP}$). Additionally, for the chosen vent the heating mass flow for reheater m_g is calculated (40). Moreover, vents in the HP part of steam turbine can be described as time derivative (41) of pressure with time constant τ_i (42).

$$m_{Vent\,jHP} = m_{Vent\,jHP}^{nominal} \frac{m_{iHP}}{m_{iHP}^{nominal}} \tag{38}$$

$$m_{Vent\,jLP} = m_{Vent\,jLP}^{nominal} \frac{m_p}{m_p^{nominal}} \tag{39}$$

$$m_g = m_g^{nominal} \frac{m_{iHP}}{m_{iHP}^{nominal}} \tag{40}$$

$$\frac{m_{iHP}}{m_{iHP}^{nominal}} - \frac{m_{i+1HP}}{m_{i+1HP}^{nominal}} = \tau_i \frac{d}{dt}\left(\frac{p_{iV}}{p_{iV}^{nominal}}\right) \tag{41}$$

$$\tau_i = \frac{V_i}{H_i m_{iHP}^{nominal} v_j} \tag{42}$$

where: $m_{Vent\,jHP}^{nominal}$, $m_{Vent\,jLP}^{nominal}$ – nominal j-th vent mass flow of HP and LP part, $m_{iHP}^{nominal}$, $m_{i+1HP}^{nominal}$ – nominal mass flow of i-th and $i+1$-th groups of stages, $m_p^{nominal}$ – nominal mass flow of reheater, $m_g^{nominal}$ – nominal heating mass flow, $p_{iV}^{nominal}$ – nominal pressure of i-th group of stages of HP part, V_i – i-th accumulation volume, v_{j-1} – specific volume of steam in j-th vent, H_i – adiabatic exponent of i-th group of stages, $m_{iHP}^{nominal}$ – nominal mass flow of i-th stage of HP part.

Moisture separator

Moisture separator was modeled based on (43) for mass flow of condensate m_s with usage of reheater mass flow m_p and mass flow of the last group of stages of HP part m_{HPlast}. For condensate temperature approximation (as the function of pressure in last group of stages of HP part) given by (44) was used.

$$m_s = m_s^{nominal}\left(S_a \frac{m_{HPlast}}{m_{HPlast}^{nominal}} - S_b \frac{m_p}{m_p^{nominal}}\right) \tag{43}$$

$$T_s = T_s^{nominal}\left(T_{sa} \frac{p_{HPlast}}{p_{HPlast}^{nominal}} + T_{sb}\right) \tag{44}$$

where: $m_s^{nominal}$ – nominal mass flow of condensate, $m_{HPlast}^{nominal}$ – nominal mass flow of the last group of stages of HP part, $m_p^{nominal}$ – nominal mass flow of reheater, $T_s^{nominal}$ – nominal temperature of condensate, T_{sa}, T_{sb} – temperature coefficients (approximation of temperature in function of pressure of last group of stages of HP part), $p_{HPlast}^{nominal}$ – nominal pressure of the last group of stages of HP part.

Reheater

The dynamic of reheater, which is placed between the two parts of steam turbine (HP and LP), can be described as time derivative of reheater pressure p_p (45) with time constant τ_p (46). Input mass flow of reheater m_{p1} is dependent on mass flow in the last group of stages of HP steam turbine part m_{HPlast} in accordance with (47) and the output mass flow of reheater m_{p2} can be calculated using (48). Output temperature of reheater T_p can be defined by approximated function of reheater pressure p_p (50). As a part of reheater model, a temperature of heating steam T_g after reheating can be calculated with usage of pressure p_{HPlast} in last group of stages of HP part (51).

$$\frac{m_{p1}}{m_p^{nominal}} - \frac{m_{p2}}{m_p^{nominal}} = \tau_p \frac{d}{dt}\left(\frac{p_p}{p_p^{nominal}}\right) \tag{45}$$

$$\tau_p = \frac{V_p}{H_{pavr} m_p^{nominal} v_{pavr}} \tag{46}$$

$$\frac{m_{p1}}{m_{pn}} = \frac{m_{HPlast}}{m_{HPlast}^{nominal}} \tag{47}$$

$$\frac{m_{p2}}{m_p^{nominal}} = \frac{p_p}{p_p^{nominal}} \sqrt{\frac{T_p^{nominal}}{T_p}} \tag{48}$$

where

$$\frac{p_{p1}}{p_{p1}^{nominal}} = \frac{p_{p2}}{p_{p2}^{nominal}} = \frac{p_p}{p_p^{nominal}} \tag{49}$$

$$\frac{T_{p1}}{T_{p1}^{nominal}} = \frac{T_{p2}}{T_{p2}^{nominal}} = \frac{T_p}{T_p^{nominal}} = A_{Tp} + B_{Tp}\frac{p_p}{p_p^{nominal}} - C_{Tp}\left(\frac{p_p}{p_p^{nominal}}\right)^2 \tag{50}$$

$$T_g = T_g^{nominal}\left(T_{ga}\frac{p_{HPlast}}{p_{HPlast}^{nominal}} + T_{gb}\right) \tag{51}$$

where: $m_p^{nominal}$ – nominal mass flow of reheater, $p_p^{nominal}$ – nominal average pressure of reheater, V_p – reheater accumulation volume, v_{pavr} – average specific volume of steam in reheater, H_{pavr} – average adiabatic exponent of reheater, $m_{HPlast}^{nominal}$ – nominal mass flow in the last group of stages of HP part, $T_p^{nominal}$ – nominal reheater temperature, $T_{p1}^{nominal}$ – nominal reheater input temperature, $T_{p2}^{nominal}$ – nominal reheater output temperature,

A_{Tp}, B_{Tp}, C_{Tp} – temperature coefficients of reheater, $T_g^{nominal}$ – nominal temperature of heating steam after reheating, T_{ga}, T_{gb} – temperature coefficients of heating steam approximating function, $p_{HPlast}^{nominal}$ – nominal pressure in the last group of stages of HP part, $p_{p1}^{nominal}$ – nominal input pressure of reheater, $p_{p21}^{nominal}$ – nominal output pressure of reheater.

Effective power

In order to calculate the effective power of whole NPP steam turbine a component power of each group of stages was calculated. Accordingly to the above component powers N_{iHP} of HP part were calculated (52) with usage of output mass flow of i-th group of stages m_{iHP}, its enthalpy drop h_{iHP} and power coefficient of i-th group k_{iHP}. Because LP part of steam turbine is strongly related with reheater and its temperature T_p, the power NLP of whole LP part was calculated using with one power coefficient k_{LP} (53). Effective power of whole NPP steam turbine N_T for n groups of stages is defined by (54) as a summation of all power components.

$$\frac{N_{iHP}}{N_T^{nominal}} = \frac{m_{iHP}}{m_{iHP}^{nominal}} \frac{h_{iHP}}{h_{iHP}^{nominal}} k_{iHP} \tag{52}$$

$$\frac{N_{LP}}{N_T^{nominal}} = \frac{m_p}{m_p^{nominal}} \frac{h_{LP}}{h_{LP}^{nominal}} k_{LP} \tag{53}$$

where

$$\frac{h_{LP}}{h_{LP}^{nominal}} = \frac{T_p}{T_p^{nominal}}$$

$$k_{LP} = 1 - \left(k_1^{nominal} + k_2^{nominal} + \cdots + k_n^{nominal}\right)$$

$$\frac{N_T}{N_T^{nominal}} = \sum_{i=1}^{n} \frac{N_{iHP}}{N_T^{nominal}} + \frac{N_{LP}}{N_T^{nominal}} \tag{54}$$

and where: $N_T^{nominal}$ – nominal effective power of steam turbine, $m_{iHP}^{nominal}$ – nominal mass flow of i-th group of HP steam turbine part, $h_{iHP}^{nominal}$ – nominal enthalpy drop of i-th group of stages (HP part), $h_{LP}^{nominal}$ – nominal enthalpy drop of LP part steam turbine, $m_p^{nominal}$ – nominal mass flow of reheater, $T_p^{nominal}$ – temperature of reheater, $k_n^{nominal}$ – n-th power coefficient of HP part.

4. Results of the simulations

Results presented in this paper were based on simulation of a case study of Nuclear Power Plant Żarnowiec which was going to be built in Poland in the 20th century [4, 18]. Nuclear Power Plant Żarnowiec was to consist of four blocks with nuclear reactors

WWER-440/213, 4 CK 465 (Zamech, Elblag, Poland) turbine sets and electrical power generators. With respect to generator GTHW-600 (Dolmel, Wrocław, Poland) estimated gross electrical power of one block was 465MW, what gives summary power of the complete plant with four blocks equal 1375 MW. Thermal power of reactor was going to be 1375 MW.

The benchmark steam turbine (Fig. 1) is divided into two parts: High Pressure part (HP) and Low Pressure part (LP). In this case HP part consists of ten stages and LP part consists of six stages. As for the vents there are five vents in the whole steam turbine, two vents in HP part (3rd and 6th HP stage) and three vents in LP part (2nd, 4th and 5th LP stage). Each part of steam turbine is preceded by so called dead space (only one of two dead spaces was considered in both models). Presented steam turbine has a mechanical moisture separator and reheater placed between two parts (HP and LP) of the turbine in order to improve properties of steam from the outlet of HP part for increasing efficiency of the LP part. Two models of the above steam turbine were presented in this paper. Despite the fact that static model gives an opportunity of calculating process values for all sixteen stages, only the mutual process variables of the two presented models could be compared. Due to the aforementioned as a result of simulation for each group of stages a set of process values were calculated, such as: mass flow, pressure and temperature. For vents values of mass flow was received. In addition for whole steam turbine an effective power and its components such as effective power of HP steam turbine part and effective power of LP steam turbine part were calculated. Simulation was conducted over 125 seconds with five different levels of constraint as the percentage degree of valve opening (called further an input signal) and constant input pressure (equal to nominal input pressure 4.161 [MPa]). Input signal presented in Fig. 2. was divided into five ranges (25 second each) with initial conditions defined as for the nominal operating point.

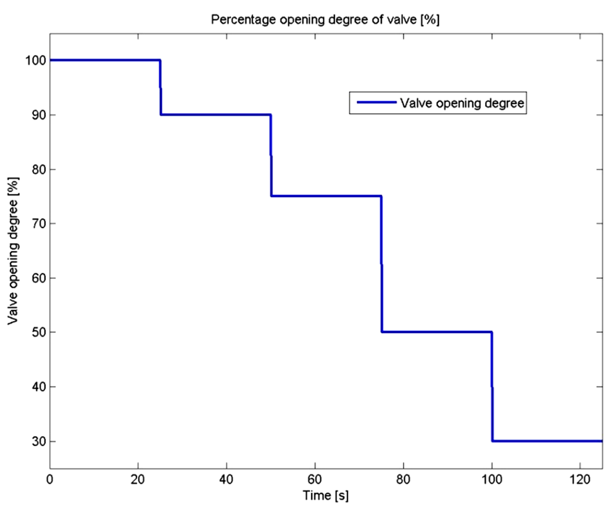

Figure 2: Input signal for simulation.

As a results of simulation a comparison of presented models is given. First comparison was made for the steady state in five different operating points. Its results are presented in Tab. 1 for 100% and 90% of valve opening degree and in Tab. 2 for 75%, 50% and 30% of valve opening degree.

Table 4: Comparison of static and dynamic turbine model in steady states

Valve opening degree [%]		100 [%]			90 [%]		
Values	Units	Static	Dynamic	Difference [%]	Static	Dynamic	Difference [%]
1st group of stages (HP) mass flow	[kg/s]	748.6380	748.6480	-0.0013	673.7742	673.7261	0.0071
1st group of stages (HP) pressure	[MPa]	4.1610	4.1611	-0.0017	3.7449	3.7188	0.6973
1st group of stages (HP) temperature	[K]	525.5360	525.8538	-0.0605	519.3742	518.6160	0.1460
2nd group of stages (HP) mass flow	[kg/s]	668.4283	668.3740	0.0081	604.9810	601.4856	0.5778
2nd group of stages (HP) pressure	[MPa]	2.7285	2.7291	-0.0208	2.4557	2.4413	0.5853
2nd group of stages (HP) temperature	[K]	501.6950	500.3610	0.2659	496.0791	494.3991	0.3387
3rd group of stages (HP) mass flow	[kg/s]	615.4799	615.4823	-0.0004	556.8916	553.8871	0.5395
3rd group of stages (HP) pressure	[MPa]	1.6729	1.6730	-0.0068	1.5056	1.4980	0.5076
3rd group of stages (HP) temperature	[K]	476.6709	474.5446	0.4461	471.6176	469.7557	0.3948
Mass flow after reheater	[kg/s]	503.2516	504.4837	-0.2448	455.4292	454.0836	0.2955
Pressure after reheater	[MPa]	0.6449	0.6448	0.0215	0.5804	0.5766	0.6595
Temperature after reheater	[K]	483.6500	483.4922	0.0326	478.4749	477.2397	0.2582
1st group of stages (LP) mass flow	[kg/s]	503.2516	504.4837	-0.2448	455.4292	454.0836	0.2955
1st group of stages (LP) pressure	[MPa]	0.2344	0.2343	0.0215	0.2110	0.2096	0.6595
1st group of stages (LP) temperature	[K]	398.4600	397.9376	0.1311	393.6785	394.1187	-0.1118
2nd group of stages (LP) mass flow	[kg/s]	472.7260	472.6974	0.0061	428.0293	425.4728	0.5973
2nd group of stages (LP) pressure	[MPa]	0.0762	0.0762	0.0215	0.0686	0.0681	0.6595
2nd group of stages (LP) temperature	[K]	365.9684	364.2427	0.4715	363.2687	360.5590	0.7459
3rd group of stages (LP) mass flow	[kg/s]	449.6012	449.8966	-0.0657	406.1419	404.9499	0.2935
3rd group of stages (LP) pressure	[MPa]	0.0287	0.0287	0.0215	0.0258	0.0257	0.6595
3rd group of stages (LP) temperature	[K]	342.9334	340.4453	0.7255	340.6963	338.0549	0.7753
4th group of stages (LP) mass flow	[kg/s]	421.9665	423.7879	-0.4317	381.0146	381.4496	-0.1142
4th group of stages (LP) pressure	[MPa]	0.0048	0.0048	0.0172	0.0043	0.0044	-2.0687
4th group of stages (LP) temperature	[K]	310.4080	305.2698	1.6553	308.8128	303.8018	1.6226
1st vent mass flow	[kg/s]	51.7580	51.7587	-0.0013	46.5822	46.5789	0.0071
2nd vent mass flow	[kg/s]	52.8960	52.8917	0.0081	47.8751	47.5985	0.5778
3rd vent mass flow	[kg/s]	31.7087	31.7863	-0.2448	28.6955	28.6107	0.2955
4th vent mass flow	[kg/s]	22.8020	22.8008	0.0052	20.6461	20.5229	0.5964
5th vent mass flow	[kg/s]	26.0915	26.1086	-0.0657	23.5694	23.5003	0.2935
Effective power of HP part	[MW]	182.6582	195.1546	-6.8414	163.2573	173.4965	-6.2718
Effective power of LP part	[MW]	288.8760	276.0943	4.4246	258.7294	245.2975	5.1915
Effective power of steam turbine	[MW]	471.5343	471.2489	0.0605	421.9867	418.7940	0.7566

Table 5: Comparison of static and dynamic turbine model in steady states (continuation)

Valve opening degree [%]	75 [%]			50 [%]			30 [%]		
Values	Static	Dynamic	Difference [%]	Static	Dynamic	Difference [%]	Static	Dynamic	Difference [%]
1st group of stages (HP) mass flow	561.4785	561.4274	0.0091	374.3190	374.2816	0.0100	224.5914	224.5683	0.0103
1st group of stages (HP) pressure	3.1208	3.0639	1.8219	2.0805	1.9965	4.0376	1.2483	1.1684	6.4035
1st group of stages (HP) temperature	509.0446	506.9555	0.4104	487.4988	484.3402	0.6479	462.9043	460.7554	0.4642
2nd group of stages (HP) mass flow	509.0065	501.2281	1.5281	346.4102	334.1491	3.5395	213.0389	200.4889	5.8910
2nd group of stages (HP) pressure	2.0464	2.0144	1.5640	1.3643	1.3162	3.5213	0.8186	0.7718	5.7078
2nd group of stages (HP) temperature	486.6596	484.7317	0.3962	466.9906	465.6553	0.2859	444.5023	444.7902	-0.0648
3rd group of stages (HP) mass flow	468.3062	461.5635	1.4398	318.3573	307.7063	3.3456	195.5234	184.6232	5.5749
3rd group of stages (HP) pressure	1.2547	1.2378	1.3460	0.8365	0.8107	3.0843	0.5019	0.4751	5.3257
3rd group of stages (HP) temperature	463.1366	461.8897	0.2692	445.4066	445.7643	-0.0803	425.1002	425.3861	-0.0673
Mass flow after reheater	383.0936	378.4232	1.2191	260.5678	252.3297	3.1616	160.2885	151.4019	5.5441
Pressure after reheater	0.4837	0.4758	1.6284	0.3225	0.3120	3.2336	0.1935	0.1847	4.5291
Temperature after reheater	470.7124	467.9259	0.5920	457.7747	452.6093	1.1284	447.4246	440.5474	1.5371
1st group of stages (LP) mass flow	383.0936	378.4232	1.2191	260.5678	252.3297	3.1616	160.2885	151.4019	5.5441
1st group of stages (LP) pressure	0.1758	0.1729	1.6284	0.1172	0.1134	3.2336	0.0703	0.0671	4.5291
1st group of stages (LP) temperature	386.5062	387.9824	-0.3819	374.5524	376.1535	-0.4275	364.9894	363.8976	0.2991
2nd group of stages (LP) mass flow	359.9854	354.5796	1.5017	243.7898	236.4310	3.0185	148.1778	141.8625	4.2620
2nd group of stages (LP) pressure	0.0572	0.0562	1.6284	0.0381	0.0369	3.2336	0.0229	0.0218	4.5291
2nd group of stages (LP) temperature	358.7255	354.6883	1.1254	349.1773	343.6143	1.5932	338.1584	332.7410	1.6020
3rd group of stages (LP) mass flow	340.5880	337.4763	0.9136	230.1422	225.0266	2.2228	140.3171	135.0197	3.7753
3rd group of stages (LP) pressure	0.0215	0.0212	1.6284	0.0144	0.0139	3.2336	0.0086	0.0082	4.5291
3rd group of stages (LP) temperature	336.9297	334.2455	0.7966	329.0066	327.0598	0.5917	319.8526	320.0042	-0.0474
4th group of stages (LP) mass flow	319.2820	317.8917	0.4355	215.4024	211.9677	1.5945	131.0778	127.1841	2.9705
4th group of stages (LP) pressure	0.0036	0.0039	-8.1142	0.0024	0.0032	-33.3989	0.0014	0.0028	-93.9641
4th group of stages (LP) temperature	306.1260	301.6709	1.4553	300.4713	298.3548	0.7044	293.9362	295.9826	-0.6962
1st vent mass flow	38.8185	38.8150	0.0091	25.8790	25.8764	0.0100	15.5274	15.5258	0.0103
2nd vent mass flow	40.2802	39.6646	1.5281	27.4131	26.4429	3.5395	16.8588	15.8657	5.8910
3rd vent mass flow	24.1378	23.8436	1.2191	16.4178	15.8987	3.1616	10.0994	9.5395	5.5441
4th vent mass flow	17.3639	17.1033	1.5008	11.7592	11.4044	3.0177	7.1474	6.8428	4.2612
5th vent mass flow	19.7652	19.5846	0.9136	13.3557	13.0589	2.2228	8.1430	7.8355	3.7753
Effective power of HP part	134.4548	141.6612	-5.3597	87.4010	90.4511	-3.4897	50.8883	51.4665	-1.1362
Effective power of HP part	214.0170	200.4360	6.3458	140.8756	129.2744	8.2350	83.6639	75.4996	9.7584
Effective power of steam turbine	348.4718	342.0972	1.8293	228.2766	219.7255	3.7459	134.5522	126.9661	5.6380

In both tables the same process variables for static and dynamic models are shown with a measure of a difference between each model (where static model was taken as a reference model) given by percentage difference calculated as:

$$Difference\% = \frac{Static\ model\ value\ -\ Dynamic\ model\ value}{Static\ model\ value} 100\%$$

The farther from the nominal operating point the bigger percentage difference is. It can be seen in Tab. 1 and Tab. 2 that if operating point is closer to the nominal point as it is within the range from 100% to 75% of input signal, the percentage differences between variables values of both models are around 2%. When the difference between actual operating point and nominal operating point is bigger (like for 50% of input signal and less), the differences between variables values of both models are greater than before and are around 5% in most process variables but never exceed 10%. Exceptions, e.g. value of pressure of the 4th group of LP stages, can be observed. The differences appear due to the errors caused by round-off of small values. What is more, calculations for static model are based on nominal values which used in this case were precise up to the fourth decimal place what gives less precise results in case of smaller values. It is caused completely by numeric methods and its errors in case of processing of partial floating point values which are close to zero.

Beside the comparison of steady state conditions for presented models a comparison under changing input conditions was conducted and the results are presented in Figs 3-12. Figs 3-5 show outlet mass flow, outlet pressure and outlet temperature of HP part of steam turbine. The similar sets of variables are presented for LP part of steam turbine in Figs 6-8. The effective power of whole steam turbine is presented in Fig. 9 while its components: HP part effective power in Fig. 10 and LP part effective power in Fig. 11. Additionally, as a significant variable for the LP part in dynamic model a temperature of steam after reheating is presented in Fig. 12. Each figure includes simulation results of process variables (both models) and percentage difference between both models.

As it can be seen in Fig. 3 and 4 for both presented models the output trajectory of mass flow and pressure of high pressure part of steam turbine is similar. The difference between each is close to zero in steady states. As expected the bigger differences only appear in case of transient conditions and in time it is getting closer to zero as it is in steady states.

Output temperature of high pressure part of steam turbine of presented models give bigger differences than mass flow and pressure described above. Also in steady states it can give greater difference between both models. Temperature is approximated based on pressure so the value of temperature is dependent on precision of approximation in whole operating area.

For output mass flow of low pressure part of steam turbine the difference between each model is close to zero except the transient states. It can be seen that dynamic of output mass flow in low pressure part of steam turbine is slower than in high pressure part. It is caused by the dynamic of reheater.

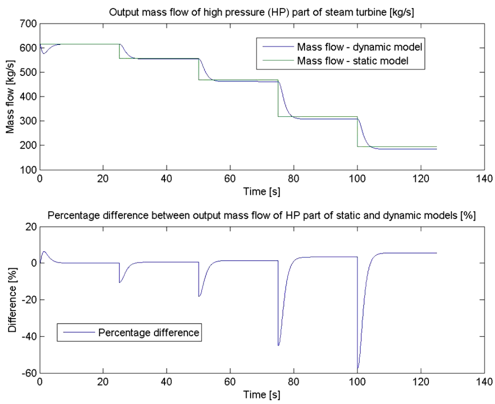

Figure 3: Comparison between mass flow of HP steam turbine part of dynamic and static models.

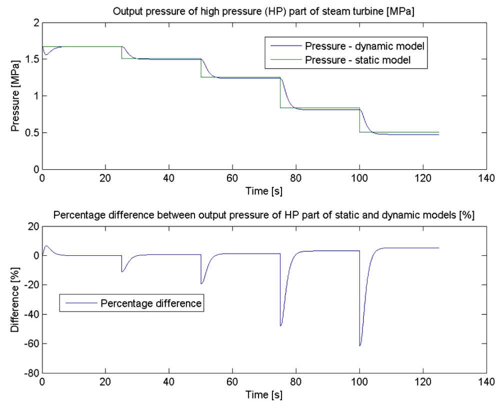

Figure 4: Comparison between pressure of HP steam turbine part of dynamic and static models.

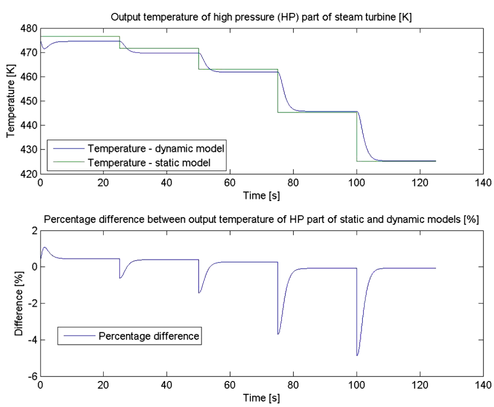

Figure 5: Comparison between temperature of HP steam turbine part of dynamic and static models.

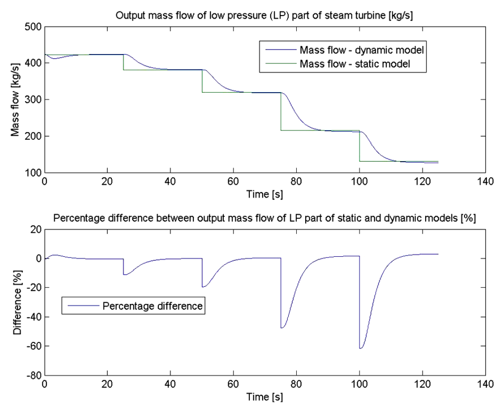

Figure 6: Comparison between mass flow of LP steam turbine part of dynamic and static models.

Differences between output pressure in low pressure part of steam turbine is caused by the order of magnitude of its values. Once again errors caused by round-off of small values generates crucial differences between models.

The differences of temperature in low pressure part of steam turbine between both presented models are not only caused by precision of approximation used in order to calculate temperature but also in function used to do so. Temperature is calculated as a function of pressure so bigger difference in pressure values effects differences in temperature results.

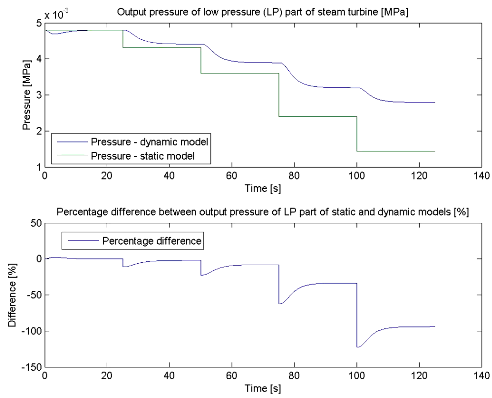

Figure 7: Comparison between pressure of LP steam turbine part of dynamic and static models.

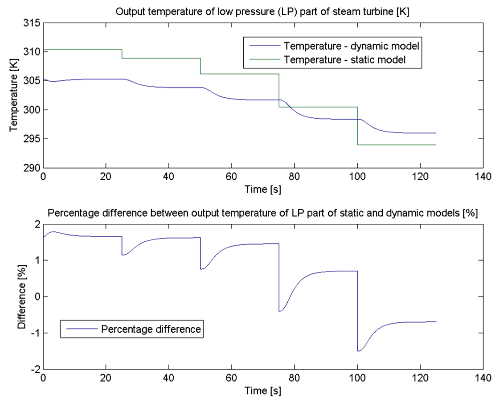

Figure 8: Comparison between temperature of LP steam turbine part of dynamic and static models.

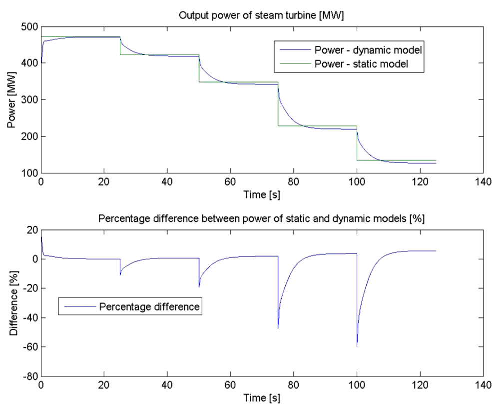

Figure 9: Comparison between effective power of steam turbine of dynamic and static models.

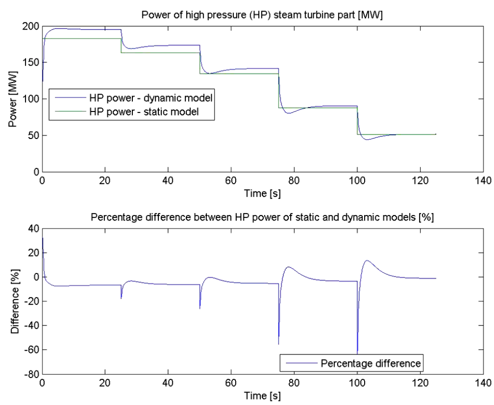

Figure 10: Comparison between effective power of steam turbine HP part of dynamic and static .

Difference of output effective power of steam turbine in steady states is close to zero. In transient states difference in time is getting closer to zero as expected.

Even though the differences of effective powers in both parts of steam turbine are quite big alike in non steady and steady states a sum of these values gives difference of whole turbine power close to zero.

As it was mentioned before the dynamic of reheater has great influence on elements placed after it. As for the temperature after reheater not only transportation delay of response can be observed but also difference between dynamic and static model in Fig. 12 can be seen. It is once more caused by approximation of the temperature in function

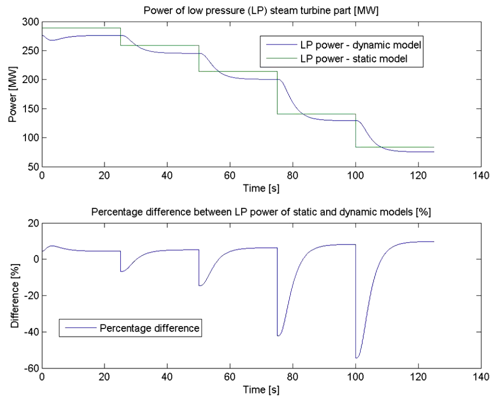

Figure 11: Comparison between effective power of steam turbine LP part of dynamic and static models.

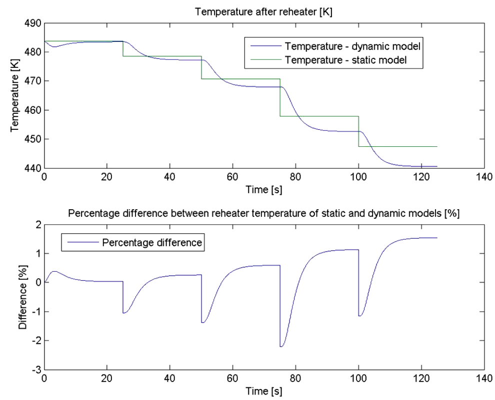

Figure 12: Comparison between temperature of reheated steam of dynamic and static models.

of the pressure. As it can be seen in the figures above, the percentage differences of characteristic values in steady states are around 5%. In case of effective power of LP part where difference is around 10% it can be explained with simplification of dynamical model where this value is based on properties of steam after reheater only.

5. Summary and concluding remarks

Steam turbine model presented in the paper is dynamic, multivariable and nonlinear. The model is in the form which enables calculations evaluated directly from the input (opening degree of the valve and pressure of the steam) to the output and allows access to 52 model variables (not only input and output but also internal variables), hence can be used for purposes of on-line optimal control under varying inputs. The model is confronted with the static one. The case study, based on the steam turbine which was to be used in NPP Żarnowiec, delivers simulation results that compares static and dynamic models with changing inputs conditions. As expected, in steady states the outputs of both models have similar values, however they significantly differ over transient conditions. These differences might be very significant in model based optimal on-line control (e.g. MPC) which is the subject of current authors research.

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