Acta Montanistica Slovaca Ročník **15**(2010), číslo **1**, 24-27

Theoretical-empirical model of the steam-water cycle of the power unit

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The diagnostics of the energy conversion systems' operation is realised as a result of collecting, processing, evaluating and analysing the measurement signals. The result of the analysis is the determination of the process state. It requires a usage of the thermal processes models. Construction of the analytical model with the auxiliary empirical functions built-in brings satisfying results. The paper presents theoretical-empirical model of the steam-water cycle. Worked out mathematical simulation model contains partial models of the turbine, the regenerative heat exchangers and the condenser. Statistical verification of the model is presented.

Key words: *empirical modelling, steam-water cycle, power unit, simulation model, regression.*

Introduction

An analytical modelling with the application of the auxiliary empirical functions admits to obtain the required accuracy with the short computation time, what entails raise of the model usefulness, especially in the operating conditions (Rusinowski et al., 2008). Presented theoretical-empirical model of the steam-water cycle contains the equations as a result of conservation laws and the empirical characteristics describing dependences of the unknown factors on the operating parameters.

A mathematical model of the steam-water cycle contains the following partial models: a model of the turbine, models of the regenerative heat exchangers and a model of a condenser. Empirical functions coefficients values are estimated using the least square method on the basis of the special measurements. In order to verify the model, quality evaluation of the prediction is performed. For this purpose statistical factors like a coefficient of determination and estimator of the model's error are used.

A model of a cycle

A steam-water cycle of an analysed power unit contains 18K370 three-part turbine, low- and high-pressure regeneration system (each involves four heat exchangers), a condenser, a feed water tank and a pump, and an auxiliary turbine.

A model of a turbine

A worked out model of the turbine contains mass and energy balance equations for high-, medium- and low-pressure parts of the turbine [Szapajko, Rusinowski 2008] taking into account leaks in the valves spindles seals and from the external glands, steam mass flow in the balance piston and inter-body steam mass flow (ABB, Zamech) and the model of the steam expansion line for the individual groups of stages.

The course of the steam expansion line for the individual groups of stages is modelled with the utilization of the steam flow capacity equation in form (Perycz, 1992):

$$\dot{G} = A_1 p_{out} \tag{1}$$

where:

$\dot{G}$ – steam mass flow in the group of stages,

p_{out} – steam pressure at the outlet of the group of stages, A_1 – empirical coefficient,

and internal efficiency equation for the adiabatic process in form [Miller 1975]:

$$\eta_i = B_1 + B_2\left(\frac{p_{out}}{p_{in}}\right)^{-1} + B_3\left(\frac{p_{out}}{p_{in}}\right)^{4} \tag{2}$$

where: η_i – internal efficiency for the group of stages, p_{in} – steam pressure at the inlet of the group of stages, B_1, B_2, B_3 – empirical coefficients.

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(Review and revised version 23. 2. 2010)

On account of the slip control, steam pressure at the inlet of the HP part of the turbine is determined by the relation:

$$p_{HP_{in}} = 9{,}2 + 4{,}7 \cdot 10^{-2} N_{el} - 6{,}5 \cdot 10^{-5} N_{el}^2 \qquad (3)$$

where: $p_{HP_{in}}$ – steam pressure at the inlet of the high-pressure part of the turbine,

N_{el} – turbine set electric power.

An objective function in the estimation procedure for each part of the turbine is assumed:

$$\sum_{i=1}^{25} \left[\left(\frac{K_{i,j}^{m} - K_{i,j}^{cal}}{K_{i,j}^{m}} \right)^2 + \left(\frac{p_{i,j}^{m} - p_{i,j}^{cal}}{p_{i,j}^{cal}} \right)^2 \right] \to \min \qquad (4)$$

where: indices m – measurement, cal – calculated, i – number of the special measurement, j – outlet of the group of stages, $j = HP_{out}$ for HP part, $j = A6; A5; A4$ for MP part and $j = A3; A2; LP_{out}$ for LP part, $K = t$ for HP and MP parts, $K = i$ for LP part.

The identification of the steam expansion line for the first two groups of the stages in the LP part is performed analogical to the HP and MP parts on the basis of the steam flow capacity and internal efficiency equations. The pressure at the outlet of the turbine $p_{LP_{out}}$ not only depends on the expansion process in the previous groups, but also on the cooling of the condenser conditions. For its prediction linear function of the steam mass flow at the outlet of the turbine $\dot{G}_{LP_{out}}$ and temperature of the cooling water at the inlet of the condenser $t_{C_{in}}$ has been used:

$$p_{LP_{out}} = -8{,}95 + 0{,}0363 \cdot \dot{G}_{LP_{out}} + 0{,}4034 \cdot t_{c_{in}}$$

(5)

A model of a heat exchanger

The models of the regenerative heat exchangers contains mass and energy balances and empirical dependences describing heat transfer in the exchangers, steam pressure losses between a bleed and an exchanger, and condensate subcooling.

Detailed information about the models of the heat exchangers was presented in (Szapajko, Rusinowski, 2008). Empirical dependences contain five empirical coefficients $D_0 \div D_4$. The quantities determined on the basis of the heat exchanger model are steam mass flow at the inlet of the heat exchanger, heated water temperature, condensate subcooling and pressure in the heat exchanger.

An objective function in the estimation procedure for each heat exchanger is assumed:

$$\sum_{i=1}^{25} \left[\left(\frac{\dot{G}_i^{\,m} - \dot{G}_i^{\,cal}}{\dot{G}_i^{\,m}} \right)^2 + \left(\frac{T_{wi}^{\,m} - T_{wi}^{\,cal}}{T_{wi}^{\,m}} \right)^2 \right] \to \min \qquad (6)$$

where: $\dot{G}_i$ – steam mass flow from the turbine bleed, T_w – heated water temperature.

The minimum of the functions (4) and (6) was found by the Powell's method.

A model of a condenser

Model of the condenser contains mass and energy balances and empirical dependence describing the heat transfer in the exchanger analogical to the model of the regenerative heat exchangers. Relative heat losses in the condenser expresses the relation:

$$\xi_c = \dot{Q}_l / \dot{Q}_{out} \qquad (7)$$

where: $\dot{Q}_{out}$ – heat flux transferred to the cooling water, $\dot{Q}_l$ – heat losses flux.

The relation expresses the heat transfer in the condenser:

$$\phi_c = \frac{t_{c_{out}} - t_{c_{in}}}{t_s(p_{LP_{out}}) - t_{c_{in}}} \qquad (8)$$

where: $t_{c_{out}}$ – cooling water temperature at the outlet of the condenser, t_s – saturation temperature.

An auxiliary empirical function is:

$$\phi_c = 1{,}05 - 4{,}38 \cdot 10^{-5} \dot{G}_{c_{in}}$$

(9)

where: $\dot{G}_{c_{in}}$ – cooling water mass flow.

The system of equations (8) and (9) enables to determine cooling water temperature at the outlet of the condenser.

Additionally, steam specific enthalpy at the outlet of the turbine and condensate mass flow are assigned on the basis of the condenser model.

Quality evaluation of the models

For the statistical evaluation of the obtained models quality, the correlation coefficient R and the mean coefficient of the model's error δ are used. These coefficients are defined as:

$$R = \frac{\sum_{i=1}^{n}(Y_i - \overline{Y})(\hat{Y}_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2 \sum_{i=1}^{n}(\hat{Y}_i - \overline{Y})^2}} \tag{10}$$

$$\delta = \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{n - p - 1}} \tag{11}$$

where: Y_i – measurement, $\overline{Y}$ – mean value, $\hat{Y}_i$ – estimated value, n – number of measurements, p – number of the estimated coefficients, $Y = p, t, i$.

Calculation results

Table 1 presents results of the steam expansion line identification in the turbine. The obtained results are satisfying which close to 1 value of the correlation coefficient and low value of the mean coefficient of the model's error show.

Table 2 presents the values of the empirical functions coefficients used in the model of the heat exchangers and quality evaluation of the prediction coefficients. The obtained results are also satisfying, especially for the most import ant parameters, which are steam mass flow and heated water temperature.

Tab. 1. Calculation results of the steam expansion line model:coefficients estimators and quality evaluation for each group of stages.

No.	**Group of stages**	**Model of the turbine**							
		coefficients estimators				**quality evaluation**			
		A_1	B_1	B_2	B_3	R_p	R_t	R_i	δ_i
1.	HP part	0,07	90,7	-1,98	1667,8	0,999	0,997	0,983	3
2.	MP part								
	- MP_{in}- $A6$	14,9	-4766	2001	13819	0,999	0,998	0,996	2,6
	- $A6 - A5$	8,03	95702	-39352	-272905	0,999	0,994	0,989	1,8
	- $A5 - A4$	4,65	2463	-990,3	-6364	0,999	0,995	0,990	1,6
3.	LP part.								
	- LP_{in}- $A3$	2,77	-71,6	73,33	226,5	0,999	-	0,944	2,4
	- LP_{in}- $A2$	0,81	-112,6	30,3	19926	0,999	-	0,792	5
	- $A1 - LP_{\text{out}}$	0,18	101,4	-6,03	783,2	0,987	-	0,946	3

Tab. 2. Calculation results of the heat exchanger models:coefficients estimators and quality evaluation for each exchanger.

No.	**Heat exchanger**	**Coefficients estimators**					**Quality evaluation**			
		D_0	D_1	D_2	D_3	D_4	$R_{\dot{G}}$	$\delta_{\dot{G}}$	R_T	δ_T
1.	XN1	$5{,}6 \cdot 10^{-3}$	$-6{,}2 \cdot 10^{-4}$	0,978	$-9 \cdot 10^{-5}$	2,89	0,989	0,28	0,987	0,77
2.	XN2	0,087	$-6{,}8 \cdot 10^{-4}$	0,875	$-6{,}3 \cdot 10^{-5}$	1,26	0,992	0,21	0,992	0,70
3.	XN3	0,101	$-9{,}7 \cdot 10^{-4}$	1,121	$4{,}4 \cdot 10^{-5}$	1,46	0,999	0,17	0,993	0,90
4.	XN4	0,234	$-4{,}5 \cdot 10^{-4}$	1,058	$3{,}7 \cdot 10^{-5}$	3,33	0,997	0,25	0,999	0,30
5.	XW1	2,04	$-2{,}1 \cdot 10^{-3}$	1,130	$-5{,}3 \cdot 10^{-5}$	0,96	0,999	0,06	0,979	2,50
6.	XW2	2,9	$-2{,}0 \cdot 10^{-3}$	1,076	$-4{,}1 \cdot 10^{-5}$	0,77	0,999	0,04	0,964	2,82
7.	XW3	6,87	$-1{,}2 \cdot 10^{-3}$	1,1	$-4 \cdot 10^{-5}$	1,09	0,999	0,05	0,999	0,38
8.	XW4	5,49	$-1{,}2 \cdot 10^{-3}$	1,12	$-1{,}26 \cdot 10^{-5}$	0,94	0,999	0,07	0,999	0,40

Table 3 presents results of the quality evaluation obtained for the model of a condenser. These results show high accordance of the model with the special measurements.

Tab. 3. Model of the condenser – quality evaluation.

Quality evaluation					
$R_{\dot{G}}$	$\delta_{\dot{G}}$	R_T	δ_T	R_i	δ_i
0,993	2,7	0,998	0,23	0,890	3,3

For the model of a condenser, obtained results are satisfying. The worst values are for the specific enthalpy at the outlet of the turbine for the sake of high sensitivity of this parameter on the minimal changes of the steam quality.

Conclusion

The partial theoretical empirical models of the turbine, the regenerative heat exchangers and a condenser, using conservation laws and empirical characteristics describing dependence of the unknown factors on the operating parameters provide high accordance with the special measurements. Such models are useful for the maintenance service for the sake of short computation time and high accuracy.

Acknowledgement
The work is co-financed by the science budget resources of the Polish Ministry of Science and Higher Education in years 2007 – 2009 as the research project (Project No. N N512 1268 33).
The work is co-financed by the charter budget resources of the Institute of Thermal Technology, The Silesian University of Technology.

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