Identification of the primary circuit dynamics in a pressurized water nuclear power plant

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Abstract: This paper presents the results of the parameter estimation procedure for the primary circuit dynamics of a VVER-type nuclear power plant. The model structure is a low dimensional lumped nonlinear model published previously in Fazekas et al. [2007a]. The parameter estimation method uses the modular decomposition of the system model for obtaining physically meaningful initial parameter estimates. The final parameter estimates are computed using the integrated model.

1. INTRODUCTION

This paper presents the model identification of the primary circuit dynamics of the Paks Nuclear Power Plant (Paks NPP) located in Hungary. The Paks NPP operates four pressurized water (VVER-440/213 type) reactors with a total nominal electrical power of 1860 MWs. The aim of the present work is to produce a low dimensional (possibly nonlinear) state space model for the primary circuit dynamics that is capable of reproducing the most important dynamic phenomena in the plant under normal operation in a neighborhood of the nominal load (approximately in the 80-100% range). Then, this model can be used to help the re-tuning or even the re-design of the current primary circuit controllers.

It is important to remark that previously, a subsystem of the primary circuit, namely the pressurizer has been modeled and identified (Varga et al. [2006]) using a similar methodology. Based on the results of the modeling and identification, a dynamic inversion based H-infinity controller (Szabó et al. [2005]) has been designed and implemented for the precise pressure control of the primary circuit, that is currently running on three units of the Paks NPP. The new controllers largely contributed to the safe increase of the thermal power by 1-2% on the above mentioned three units.

The dynamic modeling of nuclear power plants is a well-developed area. The usually highly detailed dynamic models are used e.g. for equipment design, safety analysis, operator training or simulation studies (IAEA [2003], Fletcher and Schultz [1995], Vanttola et al. [2005]). However, advanced controller design methods need relatively simple (not very high dimensional) models usually in the form of linear or nonlinear ordinary differential equations. The studies about the integrated control of pressurized water reactors (PWRs) are often based on linear state-space (Banavar and Deshpande [1996]) or input-output models (Na et al. [2005]). However, these models usually do not give insight into the most important physical processes and sub-systems. Therefore, our aim is to identify a relatively simple physical model in input-affine form. The basic structure of the model that we will use has been described in Fazekas et al. [2007a].

2. MODEL OF THE PRIMARY CIRCUIT

2.1 Operation principle

The most important structural components of pressurized water reactors are the *active zone (reactor)*, the *primary circuit* and the *secondary circuit*. The controlled nuclear chain reaction is taking place in the active zone, where the fuel rods made of uranium dioxide and the absorbent control rods are located. The function of the primary circuit is to transfer the heat generated in the active zone towards the secondary circuit. Therefore the water in the primary circuit is circulated at a high flow rate by powerful circulation pumps. In PWRs the water in the primary circuit is not boiling which is achieved by maintaining high pressure (approximately 123 bars) using an electrically heated *pressurizer* unit. The *steam generator* is essentially a huge heat exchanger, where a significant part of the primary circuit heat is transferred to the secondary circuit. This heat is converted to mechanical and finally to electrical energy in the secondary circuit. The water of the secondary circuit in the steam generator is boiling and the vapor going out of the steam generator rotates the turbines that produce electrical energy.

Figure 1 shows the flowsheet of the primary circuit in Paks NPP, where the main equipments and their connections are depicted. The sensors that provide on-line measurements are also indicated in the figure by small full rectangles. The controllers are denoted by double rectangles, their input and output signals are shown by dashed lines. A unique identifier will be used for each of the four main operating units in the subscript of their related variables

and parameters (R - reactor, PC - primary circuit, PR - pressurizer, SG - steam generator).

2.2 Mathematical model

A systematic modeling procedure suggested for constructing process models described in Hangos and Cameron [2001] has been followed to construct a simple dynamic model of the primary circuit. The modeling assumptions and the detailed derivation of the model equations can be found in Fazekas et al. [2007a].

The *state-space model* of the primary circuit is of the following form

$$\frac{dN}{dt} = \frac{p_1 v^2 + p_2 v + p_3 - \beta}{\Lambda} N + \lambda C + S \tag{1}$$

$$\frac{dC}{dt} = \frac{\beta}{\Lambda} N - \lambda C \tag{2}$$

$$\frac{dM_{PC}}{dt} = m_{in} - m_{out} \tag{3}$$

$$\frac{dT_{PC}}{dt} = \frac{1}{c_{p,PC} M_{PC}} \Big[c_{p,PC} m_{in} \left(T_{PC,I} - T_{PC} \right) +$$
$$+ c_{p,PC} m_{out} 15 + W_R - 6 \cdot K_{T,SG,1} \left(T_{PC} - T_{SG} \right) -$$
$$- K_{loss,PC} \left(T_{PC} - T_{out} \right) \Big] \tag{4}$$

$$\frac{dM_{SG}}{dt} = m_{SG,in} - m_{SG,out} \tag{5}$$

$$\frac{dT_{SG}}{dt} = \frac{1}{c_{p,SG}^L M_{SG}} \Big[c_{p,SG}^L m_{SG,in} \left(T_{SGSW} - T_{SG} \right) -$$
$$- \left(c_{p,SG}^V - c_{p,SG}^L \right) m_{SG,out} T_{SG} - m_{SG,out} E_{evap,SG} +$$
$$+ K_{T,SG,2} \left(T_{PC} - T_{SG} \right) + W_{in,SG} \Big] \tag{6}$$

$$\frac{dT_{PR}}{dt} = \frac{1}{c_{p,PR} M_{PR}} \Big[\chi_{m_{PR}>0} c_{p,PC} m_{PR} T_{PC,HL} +$$
$$+ \chi_{m_{PR}<0} c_{p,PR} m_{PR} T_{PR} - W_{loss,PR} +$$
$$+ W_{heat,PR} - c_{p,PR} m_{PR} T_{PR} \Big] \tag{7}$$

The output equations are as follows:

$$W_R = c_\Psi N \tag{8}$$

$$p_{SG} = p_*^T \left(T_{SG} \right) \tag{9}$$

$$\ell_{PR} = \frac{1}{A_{PR}} \left(\frac{M_{PC}}{\varphi(T_{PC})} - V_{PC}^0 \right) \tag{10}$$

$$p_{PR} = p_*^T \left(T_{PR} \right) \tag{11}$$

where p_*^T and $\varphi(T_{PC})$ are quadratic functions describing the saturated vapor pressure and the liquid density, respectively, while m_{PR} is the mass flow rate between the liquid in the primary circuit and the liquid in the pressurizer. The value of the mass flow rate overflowing to the pressurizer (m_{PR}) is positive when the liquid flows into the pressurizer and negative when the liquid flows out from the pressurizer. This switching behavior is represented in Eq. (7) with indicator variables $\chi_{m_{PR}<0}$ and $\chi_{m_{PR}>0}$ where the value of $\chi_{m_{PR}<0}$ is 1 if $m_{PR} < 0$ and its value is 0 otherwise.

The difference between the temperature of the hot and cold legs ($T_{PC,HL}$ and $T_{PC,CL}$, respectively in Fig. 1) is assumed to be constant ($30^o C$) therefore the energy loss caused by the primary circuit (m_{out}) is $c_{p,PC} m_{out} (T_{PC} - T_{PC,CL})$ where $(T_{PC} - T_{PC,CL}) = 15$ in Eq. (4). Furthermore, one has 6 steam generators in the primary circuit that have been lumped to-

gether in the primary to secondary heat transfer form $6 K_{T,SG,1} (T_{PC} - T_{SG})$ in Eq. (4).

The definition of the variables and parameters can be found in Tables 1 and 2.

Table 1. Variables with type (**s**tate, **i**nput, **o**utput, **d**isturbance).

Identifier	Variable	Type
N	R neutron flux	s
C	R quantity of the delayed neutron emitting nuclei	s
v	R control rod position	i
W_R	R reactor power	o
m_{in}	PC inlet mass flow rate	i
m_{out}	PC purge mass flow rate	d
M_{PC}	PC liquid mass	s
$T_{PC,I}$	PC inlet temperature	d
T_{PC}	PC temperature	s
$T_{PC,HL}$	PC temperature in the hot leg	(s)
$T_{PC,CL}$	PC temperature in the cold leg	(s)
M_{PR}	PR liquid mass	o
p_{PR}	PR pressure	o,(s)
T_{PR}	PR temperature	s
ℓ_{PR}	PR liquid level	o,(s)
$W_{heat,PR}$	PR heating power	i
M_{SG}	SG water mass	s
ℓ_{SG}	SG water level	o
T_{SG}	SG steam generator temperature	s
$m_{SG,in}$	SG inlet mass flow rate	i
$m_{SG,out}$	SG steam mass flow rate	d
$T_{SG,SW}$	SG inlet water temperature	d
p_{SG}	SG steam pressure	o

Table 2. Parameters of the primary circuit model with their reliability domain.

Notation	Definition	Domain
c_Ψ	Constant in the power equation	$13.75 \cdot 10^6 \ W/\%$
$E_{evap,SG}$	Evaporation energy (at 260 ^oC)	$1.658 \cdot 10^6 \ J/kg$
(p_1, p_2, p_3)	Rod's parameters	-
S	Source	-
β	Total fraction of delayed neutrons	≈ 0.0064
Λ	Generation time	$\approx 10^{-5} \ s$
λ	Half life of the delayed neutron emitting nuclei	$\approx 0.1 \ 1/s$
$c_{p,PC}$	Specific heat	$\approx 4900 \ J/kg/K$
$K_{T,SG,1}$	Heat transfer coefficient	$\approx 10^7 \ W/K$
$K_{T,SG,2}$	Heat transfer coefficient	$< K_{T,SG,1}$
$K_{loss,PC}$	Energy loss coefficient	-
$W_{in,SG}$	Environmental inlet energy	-
$c_{p,SG}^L$	Specific heat of water	$\approx 4700 \ J/kg/K$
$c_{p,SG}^V$	Specific heat of vapor	$\approx 2800 \ J/kg/K$
$c_{p,PR}$	Specific heat	$> 5080 \ J/kg/K$
$W_{loss,PR}$	Heat loss	$\approx 10^5 \ W$
V_{PC}^0	Volume of primary circuit	$230 - 250 \ m^3$

The system variables can be classified as follows:

- *State variables*: differential variables in the differential equations, N, C, M_{PC}, T_{PC}, T_{PR}, M_{SG}, T_{SG}
- *Input variables*: manipulable variables set by the corresponding controllers (PR-pressure, PC-mass through PR-level, SG-level, R-power controllers), v, m_{in}, $m_{SG,in}$, $W_{heat,PR}$
- *Disturbances*: all other possibly time-dependent variables appearing on the right-hand side of the differential equations, m_{out}, $m_{SG,out}$, m_{PR}, $T_{SG,SW}$, $T_{PC,I}$
- *Output variables*: measurable variables that are regulated by the appropriate controllers, N (W_R), p_{SG}, ℓ_{PR} (M_{PC}), p_{PR}
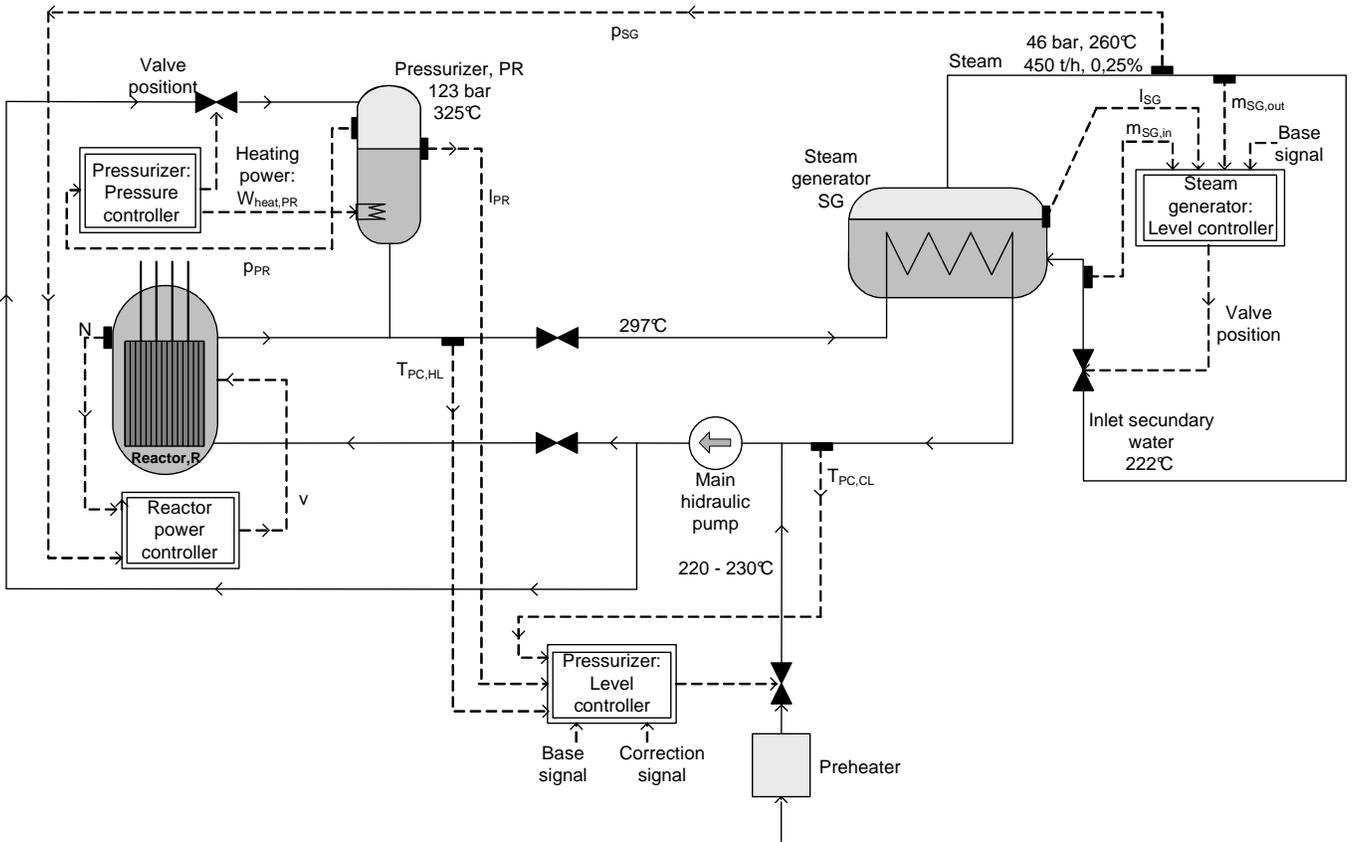
Fig. 1. Structure of the primary circuit

We have to note that during normal operation the amount of liquid in the primary circuit is constant, i.e. $m_{in} = m_{out}$. However, our model contains both variables separately, because this constant mass is maintained by the level controller of the pressurizer.

From a mathematical viewpoint, the above state-space model is a bimodal switching system, where the switching behaviour is generated by the indicator function $\chi_{m_{PR}>0}$ in the pressurizer.

3. MEASUREMENTS AND DATA PROCESSING

Measured data from units 1,3 and 4 of the Paks Nuclear Power Plant were collected for parameter estimation purposes. In order to span a relatively wide operating domain, transient data of increasing and decreasing the power of the units when shifting from day to night load conditions and back have been used.

The measured data are originated from two different systems: the so called unit computer and the Verona system, respectively. The unit computer stores all kinds of data related to the unit. Stored data are non-uniformly sampled: a new value is stored if the difference between the previously stored value and the new value has reached an predefined limit. The Verona system (see Adorján et al. [1985]) is a reactor monitoring system that also stores reactor data. Stored values are uniformly sampled, the sampling time is 10 s.

Since the sampling time of data originating from the unit computer is not uniform, these data have been resampled using linear interpolation and a constant sampling time of 10 s.

The following variables have been measured: N, v, W_R, m_{out}, $T_{PC,I}$, T_{PC}, p_{PR}, T_{PR}, $W_{heat,PR}$, T_{SG}, $m_{SG,in}$, $m_{SG,out}$, $T_{SG,SW}$, p_{SG}.

4. PARAMETER ESTIMATION

4.1 Methods

The identification method is based on the structural decomposition of the model (see Fazekas et al. [2007a], Fazekas et al. [2007b] for the details). First, the reactor unit (Eqs. (1)-(2)) that is nonlinear in its parameters has been identified. The second dynamic sub-system is the liquid in the primary circuit (Eqs. (3)-(4)) that is nonlinear in its physical parameters but linear in its variables. The third dynamic sub-system is the steam generator (Eqs. (5)-(6)) that is also nonlinear in its physical parameters and linear in the variables. The last dynamic sub-system is the pressurizer (Eq. (7)) that is again nonlinear in its parameters and shows a hybrid behaviour depending on the direction of liquid flow from and into the primary circuit.

The parameter estimation has been carried out sequentially and component-wise following the dependencies outlined above. If the dynamic model equation(s) is/are nonlinear in its/their parameters, an optimization-based parameter estimation method, the Nelder-Mead simplex method (Nelder and Mead [1965], Lagarias et al. [1998])

available in MATLAB has been used. The value of the objective function is given by the scaled 2-norm of the difference between the measured and the model-predicted output signals, i.e.

$$e = \sqrt{\frac{\int_0^T (\hat{y}(t) - y(t))^2 dt}{\int_0^T y^2(t) dt}} \qquad (12)$$

where y is the measured output, $\hat{y}$ is the model-predicted (simulated) output signal and T denotes the time-span of the measurement/simulation. To use the simplex method, suitable initial values are needed. They could be found in Perry and Green [1999], ThermExcel [2007] and obtained from engineers from Paks NPP.

4.2 Reactor

The equations describing the operation of the reactor are (1)-(2). The manipulable input in the reactor is v, while the controlled output is N. The measurements in this case were obtained from the Verona system.

During parameter estimation the values of p_1, p_2, p_3 β, Λ are λ are estimated while the value of S is computed from the estimated values of p_1, p_2 and p_3 to maintain the initial steady state. The initial value of variable C is also not known, therefore it is computed from the values of β, λ, Λ and the initial value of variable N to maintain the initial steady state. The value of estimated parameters can be found in Table 3 for the case of unit 1.

Table 3. Results of the parameter estimation
of the decomposed system

Parameter	Unit	unit 1 Time span: 4h
p_1	m^{-2}	$-1.6765 \cdot 10^{-4}$
p_2	m^{-1}	$-4.0610 \cdot 10^{-5}$
p_3	1	$-2.5396 \cdot 10^{-4}$
S	$\%/s$	2554.5
β	1	0.00459
λ	$1/s$	0.05315
Λ	s	$9.9421 \cdot 10^{-6}$
$C(0)$	$\%$	$8.7002 \cdot 10^{-5}$
$c_{p,PC}$	$J/kg/K$	5130.5
$K_{T,SG,1}$	W/K	$9.276 \cdot 10^6$
$K_{loss,PC}$	W/K	$1.9649 \cdot 10^6$
$M_{SG}(0)$	kg	34988
$c_{p,SG}^L$	$J/kg/K$	3922.2
$c_{p,SG}^V$	$J/kg/K$	2910.5
$W_{in,SG}$	W	$-1.1723 \cdot 10^5$
$K_{T,SG,2}$	W/K	$8.2939 \cdot 10^6$
$c_{p,PR}$	$J/kg/K$	4350.7
$W_{loss,PR}$	W	$2.1022 \cdot 10^5$

4.3 Primary circuit liquid dynamics

The operation of this subsystem is described by Eqs. (3)-(4). The input variables in the model are W_R, m_{in}, the measurable disturbances are $T_{PC,I}$, m_{out}, T_{SG}, and the output is T_{PC}. The estimated parameters are $c_{p,PC}$, $K_{T,SG,1}$, $K_{loss,PC}$. Measurements were taken from the Verona system. The inlet liquid mass flow rate measurements were apparently inaccurate, therefore the measurement of purge liquid mass flow rate is applied as the inlet liquid mass flow rate assuming that the mass of the liquid in the primary circuit has a constant value: $M_{PC} = 200000 \ kg$.

During parameter estimation the values of $c_{p,PC}$ and $K_{T,SG,1}$ are estimated while the value of the parameter $K_{loss,PC}$ is computed from the estimated values of $c_{p,PC}$ and $K_{T,SG,1}$ to maintain the initial steady state. The values of the estimated parameters can be found in Table 3 for unit 1.

4.4 Steam generator

Eqs. (5)-(6) describe the dynamics of the steam generator, where the input variable is $m_{SG,in}$, the disturbances are T_{PC}, $T_{SG,SW}$ and $m_{SG,out}$, the controlled output variable is T_{SG} (p_{SG}). The estimated parameters in this subsystem were $K_{T,SG,2}$, $W_{in,SG}$, $c_{p,SG}^L$ and $c_{p,SG}^V$. The measurements came from the Verona system. Since the mass of the water in the secondary side of the steam generator is not measured, only the inlet water and the outlet vapor flow rate are known. It means that the initial water mass $M_{SG}(0)$ must also be estimated. The initial value of its estimation is its normal value $M_{SG}(0) = 32000 \ kg$ known from a technical discussion. The value of estimated parameters can be found in Table 3 for unit 1.

4.5 Pressurizer

The simplified dynamics of the pressurizer is given by Eq. (7). The manipulable inputs are m_{in} and $W_{heat,PR}$, the disturbances are T_{PC} and m_{out}, the controlled output is T_{PR} (p_{PR}). The estimated parameters are $c_{p,PR}$ and $W_{loss,PR}$. The pressurizer measurements were obtained from the Unit computer. The values of the estimated parameters can be found in Table 3 for unit 1.

5. MODEL INTEGRATION AND VALIDATION

In this final step, the previously separately identified subsystems were integrated into one model described by Eqs. (1)-(7). The aim of this step was the proper identification of the connections between the operating units and the fine tuning of the already estimated most influential parameters.

The states and output variables (see Table 1) were computed from the model and compared to the corresponding measured variables. During this simulation the measured input and disturbance variables (see Table 1) were the inputs of the model and the initial values of the state variables of the model were also given from the measurements.

The parameters to be estimated in this final step were determined by sensitivity analysis of the integrated system where the error function was the same as applied to the identification of the integrated system (Eq. (13)). Each parameter value was changed at $\pm 10\%$ of its original value and the change of the error function was investigated. If the value of error function changed more then a predefined limit than we decided that the changed parameter would have to be estimated.

Based on the sensitivity analysis the estimated parameters were $c_{p,SG}^L$, $c_{p,SG}^V$, $K_{T,SG,1}$, $K_{T,SG,2}$, $c_{p,PR}$ and $W_{loss,PR}$.

The heat loss of the liquid in the primary circuit and the inlet energy term of the steam generator were determined such that they maintained their initial steady state. It is important to note that here, we did not apply the constraint that the estimated values must be in their reliability domains. The initial values of estimated parameters were the estimated values of the decomposed system.

During this identification the error function was the average of the error functions for the temperature of the liquid in the primary circuit, the temperature in the steam generator and the temperature in the pressurizer and the error function of the power of the reactor i.e.

$$
e = \frac{1}{4} \left(\sqrt{\frac{\int_0^T (\hat{W}_R(t) - W_R(t))^2 dt}{\int_0^T W_R^2(t) dt}} + \right.
$$

$$
+ \sqrt{\frac{\int_0^T (\hat{T}_{PC}(t) - T_{PC}(t))^2 dt}{\int_0^T T_{PC}^2(t) dt}} +
$$

$$
+ \sqrt{\frac{\int_0^T (\hat{T}_{SG}(t) - T_{SG}(t))^2 dt}{\int_0^T T_{SG}^2(t) dt}} +
$$

$$
\left. + \sqrt{\frac{\int_0^T (\hat{T}_{PR}(t) - T_{PR}(t))^2 dt}{\int_0^T T_{PR}^2(t) dt}} \right) \tag{13}
$$

The result of the curve fitting of this parameter estimation can be seen in Fig. 2, while the values of the estimated parameters can be seen in Table 4.

Table 4. Results of the estimation of the integrated system

Parameter	Unit	unit 1 Time span: 4h
$K_{T,SG,1}$	W/K	$6.3453 \cdot 10^6$
$K_{loss,PC}$	W/K	$3.774 \cdot 10^6$
$c_{p,SG}^L$	$J/kg/K$	7818
$c_{p,SG}^V$	$J/kg/K$	4823
$W_{in,SG}$	W	$3.9813 \cdot 10^7$
$K_{T,SG,2}$	W/K	$3.7268 \cdot 10^5$
$c_{p,PR}$	$J/kg/K$	6460
$W_{loss,PR}$	W	$9.7982 \cdot 10^4$

One can see from Table 3 and 4 that the majority of the estimated parameter values are not in their reliability domains, and there are significant differences between their initial and final values. This is probably explained by the fact that our model has been too simplified, some of the influential mechanisms have been neglected. However, as one can see, these estimated parameters have made a satisfactory curve fitting (see Fig. 2) considering the very simple model structure and the sometimes too high sampling time of important measurements. The difference between the measured and simulated temperatures is always less than $1^o C$.

At the same time, one can see that the real reactor dynamics is faster than the simulated one. The reason of this can be the too simplifying assumption on single-group neutrons and a single type of delayed neutron emitting nuclei. The error between the measured and the simulated temperature of the liquid of the primary circuit
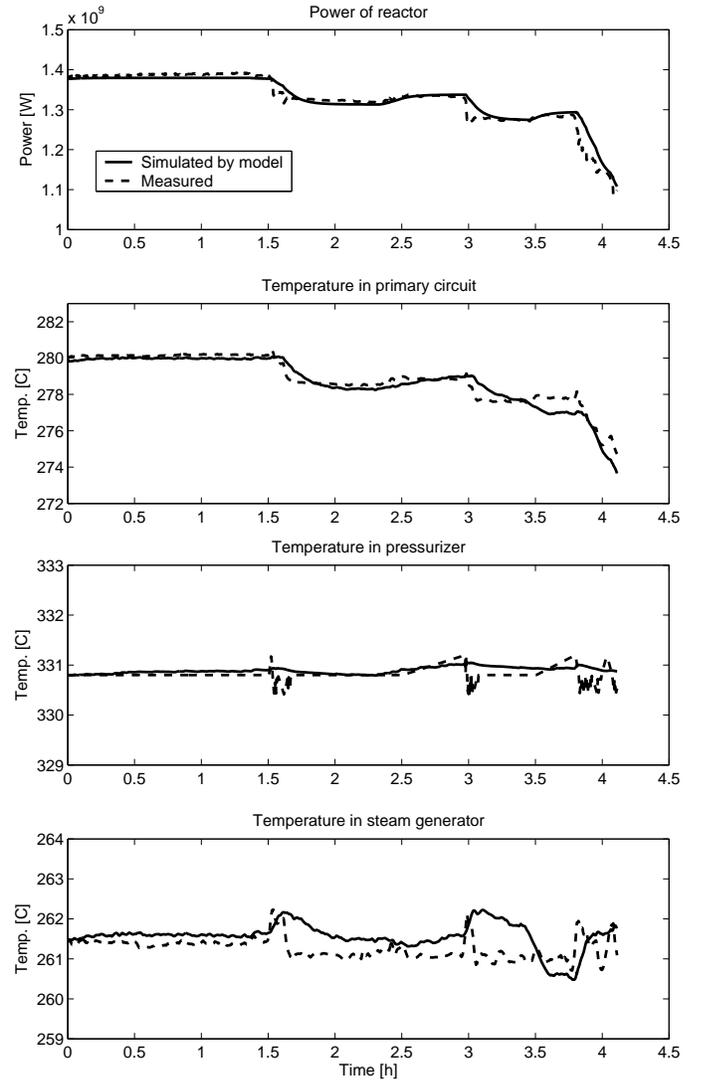

Fig. 2. Measured and simulated temperatures after the parameter estimation of the integration model, for unit 1.

and the liquid of the steam generator could be caused by the ignored tube-wall of the steam generator because it behaves as a heat storage system.

The most important measured inputs of the integrated model can be seen in Fig. 3, in case of unit 1. The position of rods is measured as the difference between the current position of rods and their position in case of operation 100%. (The position of rods is positive when the rods are inserted into the reactor.)

6. RESULT AND CONCLUSION

The parameter estimation procedure of the primary circuit dynamics in a pressurized water nuclear power plant has been described in this paper. The result of the reported work is a low dimensional nonlinear dynamic model with physically meaningful structure that is suitable for controller design. During the identification, we tried to use all the available engineering knowledge and operation experience about the plant. As a result, the values of a part of the estimated parameters are physically meaningful.
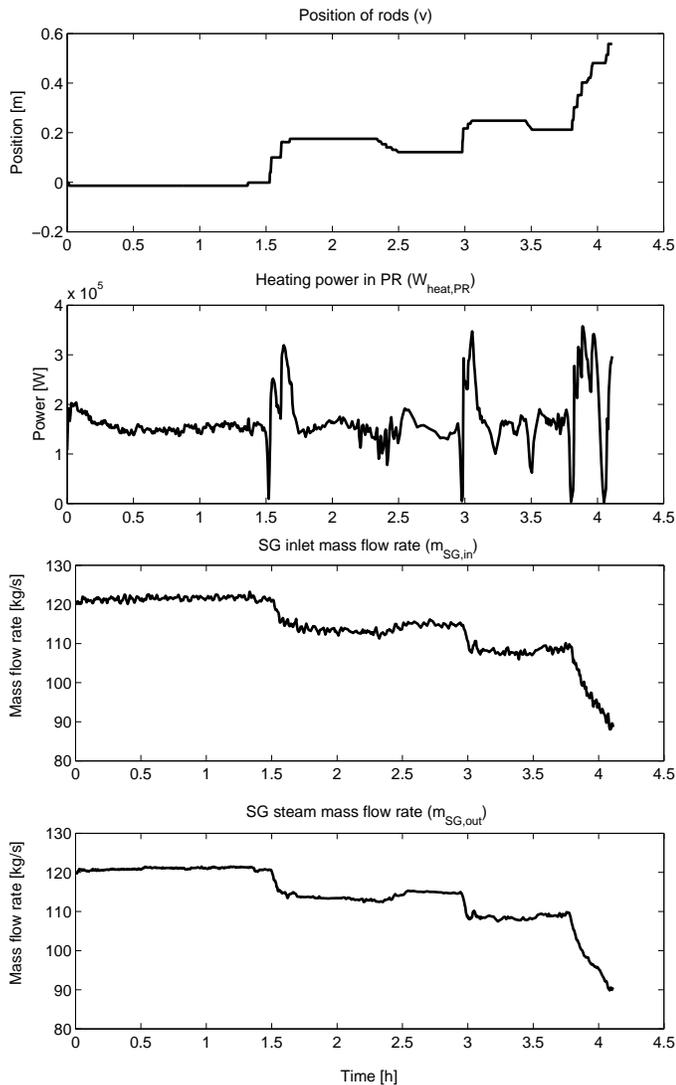
Fig. 3. The most important measured inputs of the integrated model, for unit 1.

The identified model is valid for normal operation in a neighborhood of the nominal load and is suitable for describing basic dynamic phenomena such as load changes between day and night periods and responses to the limited change of the modeled external disturbances. The model is not suitable for describing dynamics under non-standard operating conditions such as faults, but it can be extended with certain fault models in the future.

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