Control-Oriented Modelling of the Primary Circuit and its Controllers of a PWR Nuclear Power Plant

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Abstract: A simple concentrated parameter non-linear model of the primary circuit of a pressurized water nuclear power plant is developed that describes the reactor, the steam generator, the tubes of the primary circuit and the pressurizer. The dynamic model includes the description of the reactor power controller and the primary pressure controller as well. The complex logic network and the control mode changes of the reactor power controller are represented by state charts using Simulink StateFlow. The parameters of the plant, and that of the reactor power controller are determined by optimization using data measured in the Paks Nuclear Power Plant under load changing transients.

Keywords: dynamic modelling, control oriented models, nuclear plants, reactor control modelling, process parameter estimation

1. INTRODUCTION

Many nuclear power plants were designed in the '70s and built in the '80s. These plants typically had 30–40 years of planned lifetime, and nowadays need to be refurbished in order to have their lifetime extended. A refurbishment of the instrumentation and control (I&C) systems in the plant also provides a possibility for a modernization of the control loops in order to obtain increased efficiency or even a power uprate. However, the development of a formal, control-oriented mathematical model of the controller and the controlled process is always the necessary first step, whether it will be the recreation of original functionality using modern equipment, or a redesign of the existing controller. There are several reasons for this:

- The modern advanced controller design techniques are *model-based*, i.e. they need a mathematical model and exact requirements in order to be able to develop the controller.
- Even if the functionality of a controller does not change, the implementation using a modern digital distributed control system (DCS) hardware necessitates the reformulation of the controller specification. For the sake of clarity and unambiguity this has to be given as a formal mathematical model.
- The performance and the operation of the refurbished/redesigned controller has to be verified before the implementation process would begin. Having an executable mathematical model (such as a MATLAB Simulink model), one can use *simulation and testing* for verification purposes.

In our previous work (Fazekas et al., 2007) a simplified model of a VVER-type nuclear power plant was presented. The reactor of this model was extended with temperature effects (Fazekas et al., 2009) and with xenon poisoning (Gábor et al., 2011). The part of the model was a one region pressurizer consisting of the mixed water-steam together with the vessel, which had heat capacity and heat loss. Additional research was conducted towards the analysis of the pressure controller of the pressurizer by Varga et al. (2006), and a new controller were designed and implemented (Szabó et al., 2008). The accurate stabilization of the primary loop pressure that provided by the new controller made the safe increase of the average thermal power possible in the Paks Nuclear Power Plant in 2005.

After the implementation of this controller, some pressure peaks occurred in the system during the load-following operation. We found that the model can not describe these pressure peaks adequately, therefore a better two-region pressurizer model was developed in (Gábor et al., 2010), which has proven that the disturbances from the electrical network in the secondary circuit have influence on the water temperature changes in the primary circuit.

In this paper we describe the advanced model of the primary circuit of a PWR nuclear power plant, supplemented by a steam generator model and a steam collector model, as well as the model of controllers in the primary circuit. This model will serve as a basis for designing a supervisory controller that coordinates the power and pressure controllers during load following transients.

2. MODEL OF THE PRIMARY CIRCUIT

The Paks Nuclear Power Plant has four pressurized water reactor (PWR) units. The schematic block diagram of the plant with the main controllers is shown in Fig. 1. The red circles indicate the location of measurement points, while the blue rectangles denote the connections of the control signals to the system.

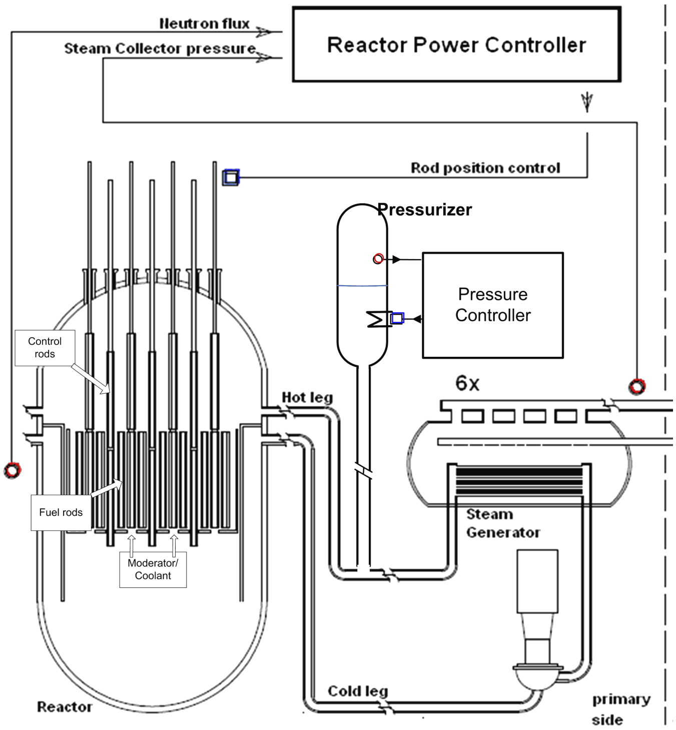


Fig. 1. Pressurized Water Reactor with Controllers (adapted from (Bátai, 1997))

The primary circuit of the power plant consists of the *reactor*, the *pressurizer*, the *tubing* of the primary circuit, and six *steam generators*. The secondary circuit includes the *secondary side of the steam generators*, the *steam collectors* and the *turbines*. However, there is only one average cooling loop and one average steam generator in the model. The two main collectors were also closed up to one average unit and so were the two turbines. The modelling domain is in the 80–100 % of the nominal power range with normal operation load changes.

2.1 The Reactor

The reactor is part of the primary circuit. It generates thermal energy gained from nuclear fissions occurring in the active zone. The reactor consists of two homogeneous regions in this simplified model. The first is the mixed fuel and clad and the other is the coolant in the active zone. From control point of view the reactor model has to be a lumped model that is able to describe the short time transients —e.g. effects of control rod movements (time scale of seconds)— as well as the medium time transients —e.g. the transient length during a load change operation (time scale of minutes to tens of minutes). The long term transients, like the fuel depletion and the changing of the boron concentration were neglected. For these reasons the reactor model assumes the point kinetic equation with one average group of precursor nuclei. Some control oriented work where this type of model is used can be found in (Accorsi et al., 1999; Arab-Alibeik and Setayeshi, 2005; Marseguerra et al., 2004) and (Gábor et al., 2011).

The nomenclature for the equations can be found in Table A.1 in the Appendix. The zero subscript (i.e. $_0$) in every parameter notation refers to the reference value of that parameter at the nominal power, in steady state.

2.2 Neutron physics

As mentioned above, the point kinetic equation system describes the reactor physics:

$$\frac{dN(t)}{dt} = \beta\frac{N(t)}{\Lambda}(\rho(T_f, T_m, z, X) - 1) + C(t)\frac{\beta}{\Lambda} \quad (1)$$

$$\frac{dC(t)}{dt} = \lambda_C(N(t) - C(t)), \quad (2)$$

where (1) describes the change of neutron concentration and (2) stands for the concentration change of the precursor nuclei. Note that the concentrations are transformed into dimensionless form. The thermal power of the reactor is proportional to the neutron flux:

$$P_r(t) = N(t)P_{r0} \quad (3)$$

The following equations describe the concentration of iodine and xenon nuclei for the poisoning calculation:

$$\frac{dI(t)}{dt} = Y_I\phi(t) - \lambda_I I(t) \quad (4)$$

$$\frac{dX(t)}{dt} = Y_X\phi(t) - \lambda_X X(t) + \lambda_I I(t) - \sigma_X X(t)\phi(t) \quad (5)$$

Instead of the concentration, new states were introduced (i.e. $I = n_I/\Sigma_f$ and $X = n_X/\Sigma_f$) in the above equations.

The fuel and moderator temperatures, the rod position and the xenon concentration take effect on the neutron concentration through the reactivity $\rho(T_f, T_m, z, X)$ (see (1)), where:

$$\rho(T_f, T_m, z, X) = \alpha_f(T_f(t) - T_{f0}) + \alpha_m(T_m(t) - T_{m0}) + \\ + \rho_r(z) - \frac{\sigma_X}{\beta}(X(t) - X_0) \quad (6)$$

$$\rho_r(z) = p_2(z(t) - z_0)^2 + p_1(z(t) - z_0) \quad (7)$$

$$\frac{dz(t)}{dt} = \chi(t)v_r. \quad (8)$$

Equation (7) describes the rod reactivity while (8) stands for the control rod position. The velocity of the control rod v_r is constant. The Reactor Power Control system (RPC) is responsible for the actuating of the control rods. The χ control signal of the RPC has three discrete states:

$$\chi(t) = \begin{cases} +1 & \text{“More”} \\ -1 & \text{“Less”} \\ 0 & \text{“Stop”} \end{cases}$$

Without the RPC there is the opportunity to run the simulation of the reactor model by taking the rod position as input: $z = z(t)$.

2.3 The fuel and the moderator

In order to compute the reactivity, the temperature of the fuel and moderator have to be determined using the energy balance equations over the control volume belonging to the fuel and the moderator. The latter will be presented in the next subsection. The energy balance equation for the fuel temperature is:

$$\frac{dT_f(t)}{dt} = \frac{1}{C_f}\left(P_r(t) - P_{fm}(t)\right) \tag{9}$$

$$P_{fm}(t) = k_{fm}(T_f(t) - T_m(t)). \tag{10}$$

Equation (10) describes the heat transfer with constant heat transfer coefficient between the fuel and the moderator.

2.4 The Tubes of the Primary Circuit

The thermal power released in the reactor core is transported to the secondary circuit via the primary circuit tubing. Four control volumes were formed to model one average loop as follows:

- the water in the active zone belongs to the control volume "m",
- the water in the upper plenum and in the hot legs (the pipes between the reactor outlet points and the steam generator inlet points) belongs to "hl",
- the water in the steam generator primary side belongs to "sg",
- the water in the cold leg (the pipes between the steam generator outlet points and the reactor inlet points), in the downcomer and in the lower plenum belongs to the control volume "cl".

The mass flow was assumed to be constant in each control volume and the in- and outflow from the system were neglected. So only the energy balance equation was used to calculate the average temperature of each control volume:

$$\begin{aligned}
\frac{dT_m(t)}{dt} &= \frac{1}{C_m}\left(mc_{p,m}(T_{m,in}(t) - T_{m,out}(t)) + P_{fm}(t)\right)\\
\frac{dT_{hl}(t)}{dt} &= \frac{1}{C_{hl}}\left(mc_{p,hl}(T_{hl,in}(t) - T_{hl,out}(t))\right)\\
\frac{dT_{sg}(t)}{dt} &= \frac{1}{C_{sg}}\left(mc_{p,sg}(T_{sg,in}(t) - T_{sg,out}(t)) - P_{sgs}(t))\right)\\
\frac{dT_{cl}(t)}{dt} &= \frac{1}{C_{cl}}\left(mc_{p,cl}(T_{cl,in}(t) - T_{cl,out}(t))\right)\\
P_{sgs}(t) &= k_{sgs}(T_{sg}(t) - T_s(t))
\end{aligned}$$

where C_i is the constant heat capacity of the control volume. The notation for these equations are listed in Table A.2 in the Appendix.

The outlet temperatures of the heated or cooled pipes in the reactor and in the steam generator is computed by:

$$T_{m,out}(t) = \frac{P_{fm}(t)}{2c_{p,m}m} + T_m(t) \tag{11}$$

$$T_{sg,out}(t) = \frac{P_{sgs}(t)}{2c_{p,sg}m} + T_{sg}(t) \tag{12}$$

Since the hot leg and cold leg pipes are not heated, the outlet temperatures of these pipes are equal to the average temperatures of the control volumes. It follows from the connectivity of the systems that some inlet and outlet water temperatures are equal see Fig. 2).

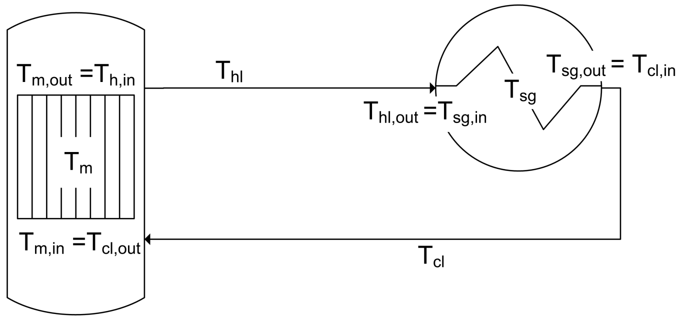


Fig. 2. Connections of the primary circuit tubing and the inlet and outlet temperatures

2.5 The Pressurizer and its Controller

The main functions of the pressurizer is to maintain the specified pressure (124 bar absolute pressure) during the operation. The pressure is controlled by the power of the heaters, located in the lower water region.

A two-region dynamic model that is based on first engineering principles is described in this section. The original detailed description can be found in (Gábor et al., 2010). The modelling goal is to adequately describe the behaviour of the pressurizer during the normal operating mode together with load changes in the approx. 80–100 % reactor thermal power range, which causes pressure peaks about ±3 bars maximum.

In order to have a low order dynamic model of the pressurizer the following simplification assumptions were made:

A1 the mass change caused by the phase transition is neglected in the water region,
A2 the mechanical work is neglected,
A3 the steam is in saturated state,
A4 the two regions share the same pressure that belongs to the saturated state of the steam,
A5 the water density change is neglected in the pressurizer,
A6 the mass change in the pressurizer is caused by the temperature change of the primary circuit coolant.

One input of the model is the m_{PR} mass flow rate between the hot leg and the pressurizer. The value of this mass flow is computed using the temperatures of the primary circuit control volumes. As the temperature increases (decreases), the volume of the coolant expands (contracts), which causes the water level to change in the pressurizer (assumption [A6]). The compressibility of the water is neglected, thus the density only depends on the temperature:

$$m_{PR}(t) = -\sum_i V_i \frac{d\rho(T_i)}{dT_i}\frac{dT_i(t)}{dt}. \tag{13}$$

The other input is the T_{HL} hot leg temperature. The outputs are the collapsed water level in the pressurizer l_{PR} and the pressure p_{PR}.

The Pressure Controller is also included in the model. The input of the controller is the pressure (the measurement noise is simulated by adding a white noise to the computed pressure before feeding the controller) and the output of the controller is the electric power of the heaters. The variables including the model in- and outputs can be found in Table A.3.

The mass balance equations for the two regions are

$$\frac{dM_w(t)}{dt} = m_{PR}(t) - m_{s,PR}(t) \quad (14)$$

$$\frac{dM_s(t)}{dt} = m_{s,PR}(t) \quad (15)$$

Using assumption [A1] the term $m_{s,PR}$ is neglected in the mass balance equations.

Instead of using these mass balance equations for the regions, the mass of water and steam in the pressurizer is computed as

$$M_w(t) = M_{w,0} + M_{PC,0} - \sum_i V_i \rho(T_i) \quad (16)$$

$$M_s(t) = (V_{PR} - \frac{M_w(t)}{\rho(T_w)})\rho(T_s) \quad (17)$$

Equation (16) states that the water, which is not in the primary circuit tubing, belongs to the pressurizer water region, i.e. the water expands to the pressurizer vessel. Equation (17) states that the V_{PR} volume of the vessel is constant, divided into the water volume ($V_w = M_w/\rho T_w$) and steam volume ($V_s = M_s/\rho T_s$).

Energy balance equations The dynamic energy conservation law gives rise to the following model equations:

$$\frac{d(h_w M_w)}{dt} = h_{w,x} m_{PR} - h_{s,x} m_{s,PR} + +K_{PR}(T_w - T_s) - P_{w,loss} + P_{w,heat} \quad (18)$$

$$\frac{d(h_s M_s)}{dt} = h_{s,x} m_{s,PR} + +K_{PR}(T_w - T_s) - P_{s,loss} \quad (19)$$

where

$$h_{w,x} = \begin{cases} h_{w,HL} & \text{if } m_{PR} > 0 \\ h_w & \text{if } m_{PR} < 0, \end{cases}$$

$$h_{s,x} = \begin{cases} h_s & \text{if } m_{s,PR} > 0 \\ h_w & \text{if } m_{s,PR} < 0, \end{cases}$$

where $m_{PR} > 0$ means that the water flows from the hot leg to the pressurizer, and there is evaporation if $m_{s,PR} > 0$ and condensation otherwise. According to assumption [A2] the mechanical work terms are neglected.

The water level is calculated using the average area of the vessel:

$$l_{PR} = \frac{M_w}{\rho(T_w) A_{PR}} \quad (20)$$

The mass transfer due to the evaporation and condensation is derived from the fact that the vessel has a constant volume ($V_w + V_s = V_{PR}$) and

$$\frac{dV_w}{dt} + \frac{dV_s}{dt} = 0. \quad (21)$$

from which —after one substitutes the relationship among the volume, the mass and density— we get:

$$\frac{1}{\rho_w}\frac{dM_w}{dt} - \frac{M_w}{\rho_w^2}\frac{d\rho_w}{dt} + \frac{1}{\rho_s}\frac{dM_s}{dt} - \frac{M_s}{\rho_s^2}\frac{d\rho_s}{dt} = 0. \quad (22)$$

Using (14) and (15) and ignoring the density change of the water (see the [A5] assumption), the equation can be transformed into:

$$\frac{m_{PR} - m_{s,PR}}{\rho_w} + \frac{m_{s,PR}}{\rho_s} - \frac{V_s}{\rho_s}\frac{d\rho_s}{dt} = 0. \quad (23)$$

According to assumption [A3] $\rho_s = \rho_s(h_s)$, so the mass flow is given by:

$$m_{s,PR} = -m_{PR}\frac{\rho_s}{\rho_w - \rho_s} + V_s \frac{\rho_w}{\rho_w - \rho_s}\frac{d\rho_s}{dh_s}\frac{dh_s}{dt}. \quad (24)$$

For computing the system pressure and the temperature of the regions, assumption [A3] is also used. In saturated state there is a relationship between the specific enthalpy and pressure: $p = p(h_s)$, and same as between the specific enthalpy and temperature: $T_s = T(h_s)$ and $T_w = T(h_w)$.

2.6 The Secondary Side of the Steam Generator

The purpose of the steam generator is to transfer the reactor produced heat into dry, saturated steam for the turbines. The location of the steam generator in the primary circuit can be seen in Fig. 2.

The water flows trough the steam generator in slim pipes, while the generation of the steam happens in the space among the pipes. During the steam production the water and steam in the secondary side are always in saturated state. In this section the description of this mixture on the secondary side is presented.

The saturated mixture of water and steam has an energy and mass storing ability. If a pressure change occurs then not only the stored energy but through the changing of the phase ratio the stored mass is changing too. The following equations for this type of energy and mass storage can be found also in (Czinder, 2000). The notation can be found in Table A.4 in the Appendix.

Model equations The secondary side of the steam generator is modelled as a lumped parameter system. Only one control volume is considered, but this volume can be distributed into two sub-volumes, namely the water and steam volume. The sum of these volumes is obviously constant.

The mass and energy balance equation is given by:

$$\frac{dM}{dt} = m_f - m_s \quad (25)$$

$$\frac{dU}{dt} = P_{sgs}/6 + m_f h_f - m_s h'', \quad (26)$$

where P_{sgs} appears in (11). The heating power was divided by six because only one "average" steam generator was modelled. From these equations and the constant volume assumption one can compute the equations for the water volume and pressure changes (Czinder, 2000).

The equation for the volume of water is given by:

$$\frac{dV_w}{dt} = \frac{1}{\rho_w - \rho_s}\left(m_f - m_s - (V_s\frac{d\rho_s}{dp} + V_w\frac{d\rho_w}{dp})\frac{dp_{sg}}{dt}\right). \quad (27)$$

Note, that not only the inlet and outlet mass flow can change the volume of the water, but —because of the compressibility of the mixture— the pressure affects it as well. As the mixture is in saturated state, the densities can be computed as a function of the pressure. The $\frac{d\rho_w}{dp}$ and $\frac{d\rho_s}{dp}$ derivatives were assumed to be constants.

The pressure can be computed as:

$$\frac{dp_{sg}}{dt} = \frac{(1-\frac{\rho_s}{\rho_w})\frac{P_{sgs}}{h''-h'} + m_f(\frac{\rho_s}{\rho_w}\frac{h''-h_f}{h''-h'} - \frac{h'-h_f}{h''-h'}) - m_s}{V_w a(p_{sg}) + (V-V_w)b(p_{sg})}. \quad (28)$$

The denominator represents the energy capacity of the water and steam part separately. The two terms in the denominator $a(p_{sg})$ and $b(p_{sg})$ were introduced, as they only depend on the saturated pressure in the following form:

$$a(p) = \frac{1}{h''-h'}(1-\frac{\rho_g}{\rho_v})(\rho_v \frac{dh'}{dp} - 1) + \frac{\rho_g}{\rho_v}\frac{d\rho_v}{dp} \quad (29)$$

$$b(p) = \frac{1}{h''-h'}(1-\frac{\rho_g}{\rho_v})(\rho_g \frac{dh''}{dp} - 1) + \frac{d\rho_g}{dp} \quad (30)$$

Instead of computing them in each time step, they were fitted with linear function and the fitted parameters were used in the model.

One of the inputs is the heating power, which can be computed from the saturated steam temperature. From the saturated sate follows that the saturated temperature is the function of the pressure $T_s = T_s(p_{sg})$.

There is a Steam Generator Level Controller, which is responsible for the constant water level. It was assumed that this controller is ideal, so the feed water mass flow is equal to the generated steam. Finally the feed water specific enthalpy was assumed to be constant.

2.7 The Simplified Model of the Secondary Circuit

The Steam Collector The steam generator is connected to the turbine through the main steam collector. The main steam collector was modelled as a steam container. The mass balance equation is

$$\frac{dM_c(t)}{dt} = 3m_s(t) - m_{tu}(t)/2, \quad (31)$$

where M_c is the mass of steam in the collector, m_s is the steam mass flow from one steam generator and m_{tu} is the mass flow to the two turbines.

Using $M_c = \rho_c V_c$, and that the saturated steam the density depends on the pressure: $\rho_c = \rho_c(p)$, we get an equation for the collector pressure:

$$\frac{dp_c(t)}{dt} = \frac{m_g(t) - m_{tu}(t)}{\frac{d\rho_c}{dp_c}V_c}, \quad (32)$$

This collector pressure is one of the inputs of the Reactor Power Controller.

The mass flow between the steam generator and steam collector can be computed using Bernoulli's law. After the linearisation of this equation around the nominal mass flow we get:

$$m_g(t) = m_{g0} + K(p_{gf}(t) - p_c(t) - \Delta p_{gc0}), \quad (33)$$

where m_{g0} is the nominal mass flow when the nominal pressure difference between the steam generator and the steam collector is Δp_{gc0}. K is a constant, which was determined from the measured data.

The Turbine The turbine consumes the produced steam and transforms it to mechanical energy. The mass flow to the turbine is considered as a boundary condition and must be given in every time during the simulation. The power of the turbine is assumed to proportional to the swallowed steam mass flow.

2.8 Parameter Estimation of the Primary Circuit Model

The unknown parameters of the described model were determined using parameter estimation methods. As the system has a lot of unknown parameters, the parameters of the decomposed system were estimated first. Passive measured data were used from the 1st unit of the Paks NPP under closed-loop control, where the excitation was provided only by the load changes.

The described model is non-linear in its variables and in some of the parameters. Constraints were constructed for the values of parameters, therefore the Pattern search/Nelder-Mead search method of MATLAB was used. It is an optimization-based parameter estimation method based on the Nelder-Mead simplex method (Nelder and Mead, 1965).

After the parameters of each subsystem were determined, the model was tested against measured data for validation purposes. Because of the limited space the detailed method and its results are not presented here, they can be found in (Gábor, 2011).

3. THE REACTOR POWER CONTROLLER

3.1 The Aim of the Reactor Power Controller

The Reactor Power Controller (RPC) is part of a larger entity, the Unit Power Controller (UPC). The main purpose of the UPC is to guarantee the balance of power between the primary and secondary circuits in the power range at different operational states of the unit (Bátai, 1997). In other words, it provides a controlled and appropriate heat transfer for the thermal energy produced in the primary circuit. The UPC is composed of two controllers: the already mentioned RPC and the Turbine Power Controller (TPC). The technological equipment of the primary and secondary circuits can be separated from control point of view: the boundary is the Steam Collector, which realizes the energy link between the two sides.

3.2 Operation of the Reactor Power Controller

The RPC performs the power control of the primary or steam generation side. Its main input parameters are the *neutron flux* that characterizes well the power of the active zone in the reactor, and the *fresh steam pressure* in the Steam Collector. The actuator of the controller is the *6th rod group* (the so-called Control Group) of the Reactor Rod Controller (RRC) system that allows rapid changes to the reactor power.

The TPC implements the power control of the secondary or steam consumptive side. Its main input parameters are the *rotational speed* of the turbine, the *fresh steam pressure* in the steam generator, and the amount of electric power produced by the Generator. The actuators of the controller are the *valves of the electro-hydraulic steam controller* that control the amount of steam flow to the turbine.

In normal operation the reactor power is kept constant by the Neutron Flux Control loop (denoted as KRRN) of the RPC, based on the neutron flux measurements of the reactor unit. At the same time the fresh steam pressure control is performed by the TPC with one turbine-side intervention. The purpose of this mode of operation is the compensation for the burn-up of the nuclear fuel.

The other important mode of operation is the so-called *following* mode. In this mode the pressure of the steam collector is kept constant by the Steam Collector Pressure Control loop (denoted as KRRT) of the RPC using reactor-side intervention, based on the fresh steam pressure measurement signals. At the same time the electric power is controlled by the two TPCs based on the effective electric power measurements in the generator. Due to keeping the steam collector constant, the reactor power follows the changes in the power of the secondary circuit. This mode of operation is usual for the units taking part in secondary-side frequency control, where the aim is to follow the secondary-side power changes performed according to the so-called *droop curve*. The other practical application of the "following" mode is during the load changing of a reactor unit. The Turbine Power Controller has an automatic power control functionality, and in this mode of operation the performance of the unit can be changed in a controlled and automatic way using the TPC.

The above described control methods are applicable during the so-called boric campaign, i.e. until the conditions of manoeuvrability by control rods still fully hold. This is possible while the position of the control rods can be kept in the operational region, which is 1500–2250 mm at the nominal power level.

Modes of Operation and Their Characteristics The previous section outlined the main two modes of operation of the Reactor Power Control system. In this section we present the complete set of modes and their characteristics. After that we define the transitions between the modes (with their conditions and effects). The name and description of each mode of operation is the following:

N.Aut: This is the first main automatic control mode, the *N-mode*. Its purpose is to keep the neutron flux on a preset (in a previous manual mode) constant reference level, using reactor-side intervention by moving the control rods. During this mode the controller reacts to the decrease of the neutron flux (e.g. due to burn-up) by increasing the reactor power (moving the rods upward), and to the increase of the neutron flux by decreasing the reactor power (moving the rods downward). In the current RPC of the Paks NPP this mode is realized by a dedicated control loop called the KRRN.

N.Kezi: This is a manual control mode. In this mode the outputs of the controller are inhibited, thus it cannot issue movement commands. Group-wise movement of the control rods can be initiated using the manual group control switches located on the operator's panel.

T.Aut: This is the other main automatic control mode, the *T-mode*. Its task is to keep the steam pressure in the Steam Collector on a pre-set (in a previous manual mode) constant reference level, using reactor-side intervention by moving the control rods. During this mode the controller reacts to the decrease of the fresh steam collector tube by increasing the reactor power, and to the increase of the pressure by decreasing the reactor power. In the current RPC of the Paks NPP it is realized by a dedicated control loop called the KRRT.

T.Kezi: This is another manual control mode, completely identical to the **N.Kezi** mode, except that the controller is in T-mode instead of N. The outputs of the controller are inhibited, and group-wise movement of the control rods can be initiated using the manual group control switches located on the operator's panel.

Sz.Aut: This is the third automatic control mode. The operation range and dynamics of the **Sz.Aut** mode are identical to the **T.Aut** mode, except that it is forbidden to issue upward movement command to the control rods. Therefore, in this mode the controller does not react to the decrease of the pressure at all.

Transition Between Modes of Operation The five control modes of the Reactor Power Control system, and the possible transitions between them are shown in Fig. 3, in the form of a state chart diagram. (The implementation of this discrete event system model was done in MATLAB Simulink StateFlow. However, here we can include only a simplified diagram due to space constraints.) The modes are represented by rounded rectangles, sub-modes by circles, and the mode transitions by arrows. The modes are identified by labels written in the circles and the transitions by numbers in boxes written on the arrows.

Note, that Fig. 3 has a hierarchical structure: modes include sub-modes. The semantics of the mode hierarchy and of the mode transitions conform to the StateFlow semantics. Default states in each level of the hierarchy are designated by arrows ending in tiny black circles. The diagram contains additional states compared to the description in the previous section, called as **N.Aut.Tiltas**, **T.Aut.Tiltas**, and **N.Kezi.Tiltas**. These are not separate modes of operation, but parts of the main modes **N.Aut**, **T.Aut**, and **N.Kezi,** respectively. They indicate that power increase is forbidden (see in detail below).

The execution of mode transitions depends on the state of the input signals of the RPC, and mode changes may change some output signals of the RPC. The inputs and outputs of the RPC are listed in Tables 1 and 2. The type of the inputs is "M" for measured and "M/C" for measured and controlled signals.

In normal operation of a reactor unit the default mode is **N.Au**t. The set of transitions between modes as indicated by the numbers in Figure 3 are the following:

(1) **N.Aut** $\rightarrow$ **T.Aut**: When the actual pressure exceeds the reference pressure (stored at the time of entering the **N.Aut** mode) by +2 bars, the RPC switches from **N.Aut** mode to **T.Aut** mode. This action is called

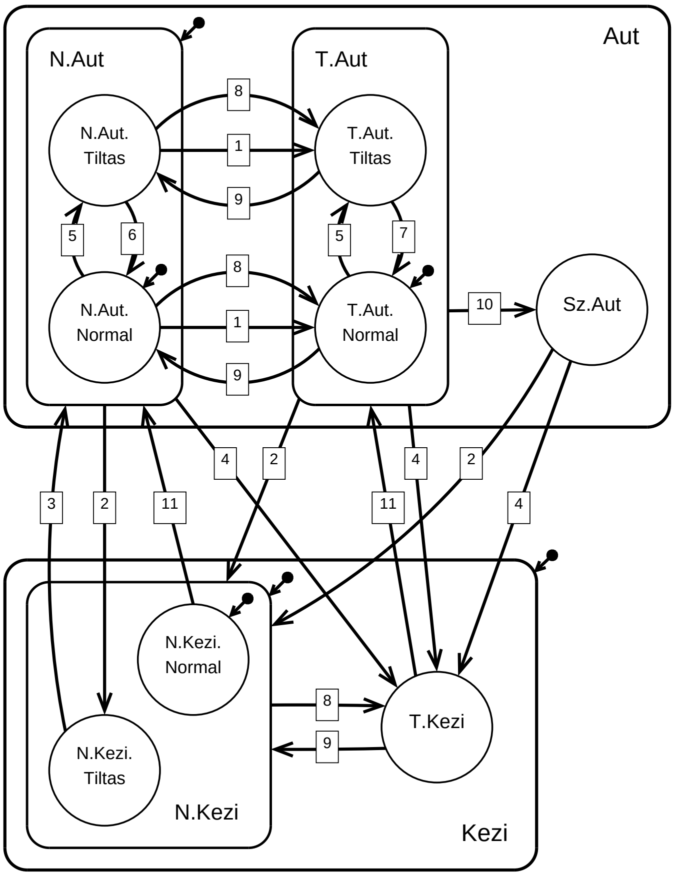


Fig. 3. RPC Modes of Operation and Mode Transitions

Table 1. Input signals to the RPC

Name	Type	Description
Neutron flux	M/C	Proportional to the thermal power in the reactor active zone
Fresh steam pressure	M/C	Pressure of the fresh steam in the Steam Collector
Kezi/Aut	M	Manual/automatic operating mode switch in the Main Control Room
N, T, SZ	M	N, T, or SZ operating mode selector buttons in the Main Control Room
EP-3, EP-4	M	Emergency protection signals from the Reactor Protection System (RPS)
Inhibitions	M	Period time $T < 40$ s or neutron flux $N > 100$ % from the Neutron Monitoring System

the *automatic N-T transition*. After the transition the RPC begins to restore the pressure to the previously set reference value by reactor-side intervention. The mode of operation will not change automatically afterwards, thus the N-T transition is a single and unidirectional operation.

(2) **{N,T,Sz}.Aut** → **N.Kezi**: In case of an emergency protection signal (EP-3 or higher) sent by the Reactor Protection System —any EP signal that gives a direct downward movement command to the the drive logic of the Reactor Rod Control system— the RPC switches automatically to the manual control mode **N.Kezi** from any automatic (**Aut**) mode. The emergency protection signal remains active until the reactor power is reduced appropriately.

Table 2. Output signals from the RPC

Name	Description
Drive control commands	Actuation commands to the drive control logic of the RRC. These commands are immediate (their effect has negligible delay). They trigger a constant-speed upward or downward movement of the appropriate control rods.
At least 2 channels in automatic mode	Signal to the RPS and the Plant Information Center (PIC).
T.Aut mode	Signal to the TPC to inhibit its pressure control function.
Mode of operation and commands	Mode of operation and command signals to the protection systems and the Unit Computer.

(3) **N.Kezi** → **N.Aut**: After an emergency protection signal (EP-3 or higher) sent by the RPS is deactivated, the RPC stores the new, reduced neutron flux value as the reference value and switches back to mode **N.Aut**.

(4) **{N,T,Sz}.Aut** → **T.Kezi**: In case of switching from any automatic (**Aut**) to manual mode the **T.Kezi** mode of operation will be activated. The operation is identical in both manual modes, i.e. the outputs of the regulation system are inhibited, no actuation command can be issued, group movements of the control rods can be performed by the manual group switches (moving up or down) on the operator panel.

(5) The effect of interlocks prohibiting power increase: signals from the RPS such as the EP-4 signal or the "Increase prohibition" signal (that is active when the neutron flux exceeds 100 % or the period time is less than 40 s), activate the transitions denoted by number $\boxed{5}$ in Fig. 3. While the RPC is in one of the "Tiltas" sub-modes upward rod movement commands are inhibited.

(6) **N.Aut.Tiltas** → **N.Aut.Normal**: This transition, i.e. the release of the interlock takes place when the signals prohibiting power increase become inactive.

(7) **T.Aut.Tiltas** → **T.Aut.Normal**: Differently from the previous one, in this mode the interlock is latched, thus the release does not takes place immediately after the signals prohibiting power increase become inactive. Instead, the interlock remains further active until the pressure reaches the reference value, i.e. the demand for power increase disappears.

(8) **N.Aut** → **T.Aut**: N-T mode transition manually initiated by an operator.

(9) **T.Aut** → **N.Aut**: T-N mode transition manually initiated by an operator.

(10) **T.Aut** → **Sz.Aut**: T-Sz mode transition manually initiated by an operator.

(11) **{N,T}.Kezi** → **{N,T}.Aut**: Manual (**Kezi**) to automatic (**Aut**) mode transition initiated by an operator according to the arrows denoted by number 11 in Figure 3.

In the following sections we present the two main control loops and their models.

The N-Mode of the Controller The purpose of the KRRN (N-Mode) controller is to keep the neutron flux on a preset reference value by moving the control rods. The conceptual schematics of the controller is shown in Figure 4.

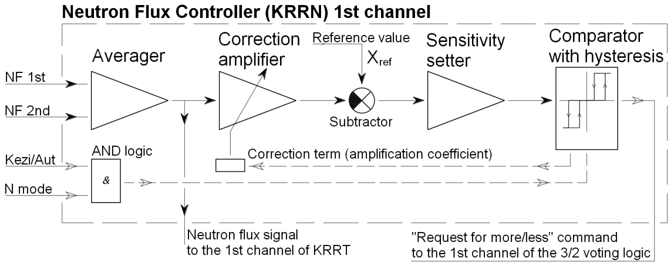


Fig. 4. Structure of the N-mode (KRRN) control loop

Operation of the N-mode (KRRN) Control Loop The neutron flux signals from multiple analogue measurements enter the analogue inputs of the control loops in pairs for each channel. The signal pairs are processed by an *Averager* circuit that produces their arithmetic mean. The mean neutron flux signal is amplified by a *Correction amplifier* circuit, which has a variable amplification coefficient. The amplification coefficient is determined by the actual value of the neutron flux at the time the RPC enters the **N.Aut** mode. The amplified mean neutron flux signal is lead to a *Subtractor* circuit, where its value is subtracted from a constants X_{ref} value. The difference is processed by a *Sensitivity setter* circuit that creates and appropriate signal level for the *Comparator with hysteresis* circuit. The *Comparator with hysteresis* switches on and off at static signal levels. Its outputs form a "Request for more" (move up) command or "Request for less" (move down) command. The movement commands are issued in three separate channels and are processed by 3/2 voter circuits. The comparison level of the *Comparator*, i.e. the static precision of the control loop is determined jointly by the *Sensitivity setter* and the *Comparator* circuits.

The operation of the control loop is simple: when the difference between the actual reactor power and the reference value exceeds 1 %, the output of the *Comparator* will be non-zero. If the power is less than the reference, the output will be 1, otherwise −1. These values form an upward movement command for the control rods if the actual power is less than the reference, and a downward movement command otherwise. The output of the *Comparator* and so the output of the controller will be non-zero until the actual and reference power become equal again. The N-mode is a simple proportional controller, but the whole control loop (including the integrating property of the actuators, the control rod drive mechanics) realizes a PI (proportional-integral) controller.

The controller has no dedicated reference input. It stores the last valid measurement data and uses it as a reference value on entering an **Aut** mode. The storage of the reference value is accomplished using the *Correction amplifier* circuit. Another important role of the variable amplification coefficient is to adjust the sensitivity of the control loop to the reactor power, thus making the loop adaptive.

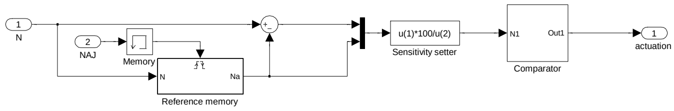
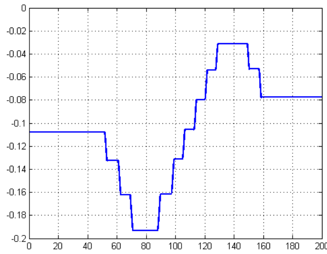
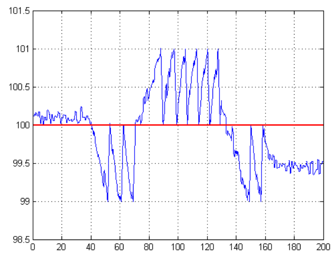


Fig. 5. MATLAB Simulink implementation of the N-mode controller

The MATLAB Simulink implementation of the controller is shown in Fig. 5. This model was validated by simulation. During the testing a noise was added to the temperature, the magnitude and behaviour of which was determined by measured data. Furthermore, a Gaussian noise with 0 mean and 0.001 variance was added to the temperature, representing the signal noise in the measurements. The results of simulation are presented in Figure 6. The results confirm that the N-mode controller could maintain the constant reference signal. The movement of the control rods started exactly when the difference of the actual and reference power exceeded $+/-1$ %, and lasted until the difference was not 0. So the implemented controller operated as required during the simulations.



(a) Rod movement (m/s)



(b) Power $(\%/s)$

Fig. 6. Simulation of the N-mode controller

The T-Mode of the Controller The conceptual schematics of the KRRT (T-mode) controller is shown in Fig. 7. This control loop realizes two modes of operation in the RPC: these are the **T.Aut** and **Sz.Aut** modes. In the next two sections we examine the two modes in detail separately.

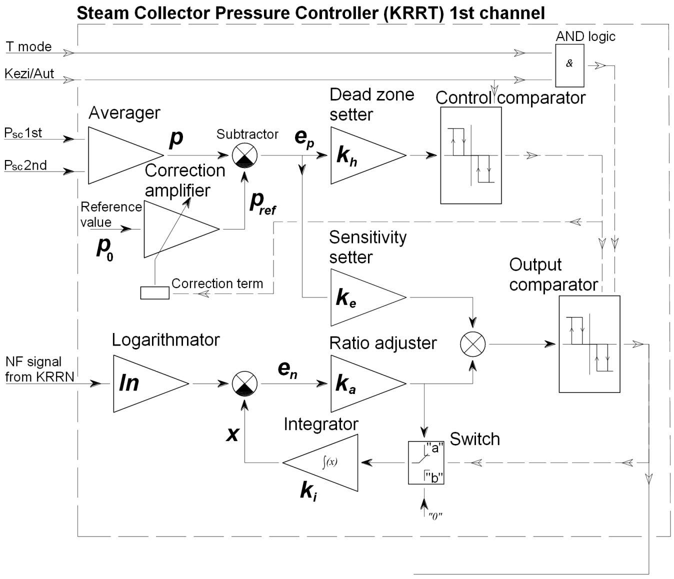


Fig. 7. Structure of the T-mode (KRRT) control loop

Operation of the T-mode (KRRT) Control Loop The measured value that is at the same time controlled by the RPC is the pressure in the Steam Collector. The pressure signals are obtained from multiple analogue measurements, and their arithmetic mean is produced by an *Averager* circuit, similarly to the KRRN control loop. The T-mode realizes a proportional controller.

The controller switches to **T.Aut** mode when the operator issues an “Aut” command and the e_p pressure difference approx. equals 0, i.e. the input of the *Control Comparator* is zero. The zero output of the *Control Comparator* stops the adjustment of the $k_r(t)$ amplification coefficient of the *Correction amplifier*, and the reference pressure is set to the actual pressure value at the time the RPC enters the **T.Aut** mode. The amplification stays at constant $k_r(t_v)$ value during the **T.Aut** mode.

When the input p pressure changes, a $p(t) - p_{ref}$ error arises at the analogue inputs of the *Control Comparator* and *Output Comparator* circuits. If the difference exceeds 0,33 bars, then first the *Control Comparator* switches, and as the difference reaches 0,5 bars the *Output Comparator* switches as well. According to the difference this will effectuate the upward or downward movement of the 6th group of the control rods.

However, the pressure of the fresh steam reacts to the movement of the control rods with a considerable delay (minutes). Thus, control is impossible based solely on fresh steam pressure. The solution applied in the RPC is the use of an auxiliary parameter, which is the logarithm of the neutron flux. This auxiliary parameter is processed by a predictor loop composed of an *Integrator*, a *Subtractor*, a *Ratio adjuster*, and a *Switch*. The task of the predictor loop is to determine a prediction of the pressure based on the undelayed neutron flux value. The prediction compensates the pressure delay by decreasing the $p(t) - p_{ref}$ error.

The *Switch* has two states: state “a” and “b”. If the output of the controller is zero, the *Switch* is in state “a”. In this state the input of the *Integrator* is 0, so it will hold its value obtained at the time the *Switch* turned into state “a”. If the output of the controller is non-zero, the *Switch* will turn into state “b”, where the input of the integrator will be the output of the *Ratio adjuster* amplifier k_a.

The dynamics of the control loop, i.e. the amount and frequency of rod movement is determined by the relation between the amplification of the *Ratio adjuster* circuit in the predictor loop and the integration time. The parameters of the controller are set in such a way that 1 output impulse at 100 % reactor power should result in 2 % power change. The implementation of control according to this characteristics is made possible by the use of the *Logarithmator* circuit.

The KRRT controller does not have a dedicated reference input, similarly to the KRRN controller. The reference pressure value is stored in a previous manual control mode, accomplished the same way using the *Correction amplifier* circuit. However, in the KRRT controller the *Correction amplifier* does not take part in the control.

Operation of the KRRT Control Loop in Sz.Aut *Mode* The *Sz.Aut* is an automatic control mode used at the end of the fuel campaign, when it is no longer allowed to increase the reactor power. This mode of operation is implemented as part of the KRRT control loop, as an extended sensitivity (+2 bars), asymmetric (upward control rod movement is prohibited) variant of the T-mode controller. In order to increase the sensitivity, the difference of the measured and the reference pressure is amplified less, therefore a larger error signal (2 bars instead of 0.5 bars) can initiate actuation.

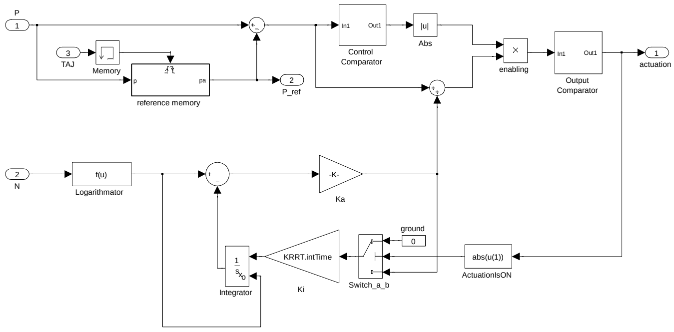


Fig. 8. MATLAB Simulink implementation of the T-mode controller

3.3 Controller Parameters

N-mode controller parameters The N-mode controller is a P-type hysteresis controller with three parameters: the threshold and cut-off point of the *Comparator with hysteresis* and the gain of the *Sensitivity setter* coefficient. The *Sensitivity setter* is assumed to transform the incoming mean neutron flux into percentage of the reference value. The threshold of the *Comparator with hysteresis* must be 1 and the cut-off point 0, since the N-mode controller is known to actuate when the difference between the actual and reference reactor power exceeds 1 % of the actual reactor power.

T-mode controller parameters The T-mode controller has a more complicated structure, with numerous parameters. We can assume from the control requirements, that the thresholds and cut-off points of the *Control comparator* and the *Output comparator* are both 0.5 and 0. The task is to obtain the reference value without error, and the actual pressure cannot exceed the reference more than 0.5 bar.

There are two other parameters, the values of which cannot be determined based on the documentation. The roles of these parameters from our analysis using the implemented primary circuit model:

The effect of the k_a amplifier: the value of the k_a amplifier affects the duration of the rod movements. This is due to the following: if we the value of k_a is increased, the sum reaching the *Output comparator* will be decreased faster, so the *Output comparator* will reach its cut-off point sooner. If the actuation whose duration was decreased that way was not enough, then the *Output comparator* will reach its threshold again (at the time, the sum in the *Integrator* will not be enough to compensate the pressure difference). Therefore, the k_a amplifier also affects the number of controller actuations during a load changing transient. Moreover, if we decrease the value of k_a, the controller will reach the desired power with fewer but longer lasting actuation steps.

The effect of k_i: the value of the integration time k_i affects the time between two actuations during a load changing transient. This is due to the following: if the integration time is increased, the *Integrator* (which is in state *"a"* after an actuation) can only decrease the sum reaching the *Output comparator* slowly and this will delay the re-opening of the *Output comparator*. It is also true, that by decreasing the value of k_i the time between the actuations can be decreased.

To determine the values of the above described unknown parameters, we needed to solve a two-dimensional optimization problem. The goal was to find a configuration where the simulated and measured controller actuations show the same behaviour. Since this task would have been very difficult to solve for a hybrid non-linear system even with numerical methods, we used a heuristic approach.

Simulation results have shown that the system is very sensitive to the values of these parameters, so the search space became very limited. Assuming that the two parameter values are independent, it was easy to find a good configuration on an intuitive way.

We obtained a configuration that gave the simulation results shown in Fig. 9. In this case the operation of the simulated system matches the measured data, since the controller actuation timing and duration are quite similar.

Note, that the measured system was switched to manually controlled mode **T.Kezi** at 2000 s of the investigated time frame (but the simulation remained in mode **T.Aut**). This happened in order to avoid a known behaviour of the T-mode controller resulting significant overshoots in the reactor power. These overshoots could reach 103 % of the nominal reactor power which is forbidden because of safety reasons. As it can be seen in Fig. 9 the simulated system shows some overshoots after simulation time 2000 s. This can be interpreted as a reproduction of the above described undesired behaviour of the T-mode controller.

4. CONCLUSION

An advanced model of the primary circuit of a VVER nuclear power plant and its reactor power controller system was described in this paper. The model was implemented in MATLAB Simulink environment partially using Simulink StateFlow based on engineering knowledge, operational experience, and measurement data from the Paks Nuclear Power Plant.

The developed models of the process and of the controllers were validated by simulation results fitting the measured data from the 1st unit of Paks NPP. The main contribution of our work is an identified model of the primary circuit that is valid for normal operation at and close to nominal load. The model is suitable for describing the main dynamic phenomena and it is appropriate for controller design. The other important result is the MATLAB Simulink StateFlow implementation and detailed description of the Reactor Power Controller of the Paks NPP.

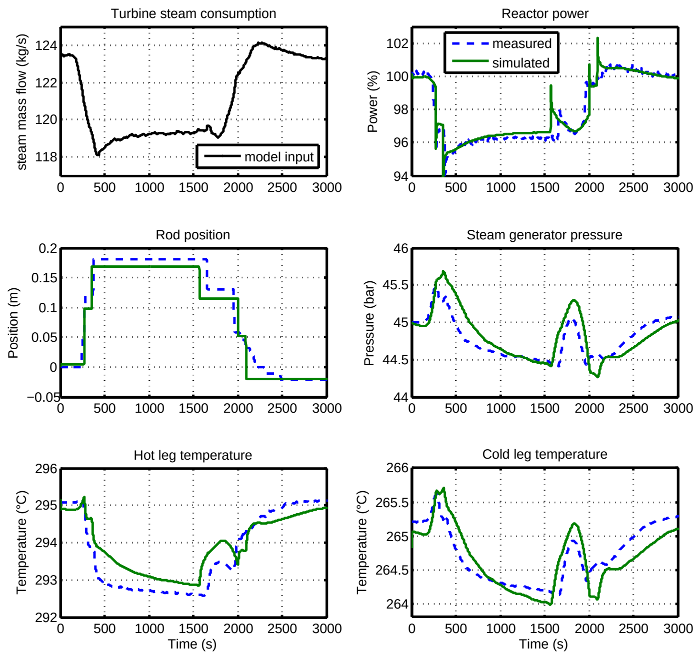


Fig. 9. Operation of the T-mode controller

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Appendix A. NOTATIONS

Table A.1. Nomenclature for the reactor model

Notation	**Units**	**Description**
Inputs		
$\chi(t)$	$-$	Control rod movement direction
$T_m(t)$	$^\circ C$	Moderator temperature
Outputs		
$P_r(t)$	kW	Reactor power
States		
$n(t)$	$1/cm^3$	Neutron density
$\phi(t)$	$1/cm^2s$	Neutron flux ($\phi(t) = n(t)v$
$N(t)$	$-$	Neutron density in relative unit n/n_0
$P_{fm}(t)$	kW	Heating power of the fuel rods
$c(t)$	$1/cm^3$	precursor nuclei density
$C(t)$	$-$	precursor nuclei density in rel. unit c/c_0
$n_I(t)$	$1/cm^3$	Iodine concentration
$n_X(t)$	$1/cm^3$	Xenon concentration
$I(t)$	$1/cm^2$	n_I/Σ_f
$X(t)$	$1/cm^2$	n_X/Σ_f
$\rho(t)$	$\$$	reactivity
$T_f(t)$	$^\circ C$	Fuel temperature
Constants		
n_0	$1/cm^3$	Initial, equilibrium neutron density
c_0	$1/cm^3$	initial equilibrium precursor density
P_0	kW	Nominal reactor power
α_f	$\$/^\circ C$	Doppler coefficiant
α_m	$\$/^\circ C$	Moderator temp. coefficiant
p_1, p_2	$\frac{\$}{m}, \frac{\$}{m^2}$	Control rod reactivity coefficiants
k_{fm}	$kW/^\circ C$	Heat transfer coeff. times the surface of fuel rods
v	m/s	Velocity of thermal neutrons
v_r	m/s	Velocity of control rods
β	-	Delayed neutron ratio
Λ	s	Generation time
Σ_f	cm^{-1}	Fuel macroscopic fission cross-section
λ_C	s^{-1}	Precursor nuclei average decay constant
λ_I	s^{-1}	Iodine decay constant
λ_X	s^{-1}	Xenon decay constant
σ_X	cm^2	Xenon microscopic absorption cross-section
Y_I	-	Iodine yield
Y_X	-	Xenon yield

Table A.2. Nomenclature for the primary circuit tubing model

Notation	Units	Description
Inputs		
$P_{fm}(t)$	kW	Heating power of the fuel rods
$T_s(t)$		saturated temp. on the secondary side of the s.g.
Outputs		
$T_i(t)$	$^\circ C$	temperatures of control volumes
$P_{sgs}(t)$	kW	Heating power of the s.g.
Other notations		
c_p	$kJ/kg/^\circ C$	specific heat capacity
k_{sgs}	$kW/^\circ C$	heat transfer coeff. times the surface of the s.g. wall
m	kg/s	mass flow
ρ	kg/m^3	density
V_i	m^3	volume of control volumes
Subscripts		
$\{m, hl, sg, cl\}$		moderator, hot leg, steam generator, cold leg respectively
$\{in, out\}$		inlet and outlet medium property

Table A.3. Nomenclature for the pressurizer model

Notation	Unit	Description
Inputs		
$T_i(t)$	$^\circ C$	water temp. in p.c. tubing
$T_{hl}(t)$	$^\circ C$	water temp. in hot leg
Outputs		
$l_{PR}(t)$	m	water level
$P_{heat}(t)$	kW	heaters power
$p_{PR}(t)$	bar	pressure
States		
$h_{s,PR}(t)$	$^\circ C$	steam specific enthalpy
$h_{w,PR}(t)$	$^\circ C$	water specific enthalpy
$M_{s,PR}(t)$	kg	mass of steam
$M_{w,PR}(t)$	kg	mass of water
$m_{s,PR}(t)$	kg/s	condensation/evaporation mass flow
$m_{PR}(t)$	kg/s	mass flow from the hot leg
Other notations		
A	m^2	area
K_{PR}	$kW/^\circ C$	heat transfer coeff. times the area
$P_{w/s,loss}$	kW	heat loss
ρ	kg/m^3	density
Subscripts		
$i = \{m, hl, sg, cl\}$		refers to the p.c. control volumes
$\{w, s\}$		water/steam region property

Table A.4. Nomenclature for the steam generator model

Notation	Unit	Description
Inputs		
$h_f(t)$	kJ/kg	feed water specific enthalpy
$m_f(t)$	kg/s	feed water mass flow
$m_s(t)$	kg/s	steam mass flow
$T_{sg}(t)$	$^\circ C$	primary side temperature of SG
Outputs		
$p_{sg}(t)$	bar	pressure
$V_w(t)$	m^3	water volume
Other notations		
$a(p)$	kg/m^3bar	pressure dependent relative storage parameter of water
$b(p)$	kg/m^3bar	pressure dependent relative storage parameter of steam
h	kJ/kg	specific enthalpy
h'	kJ/kg	specific enthalpy of water
h''	kJ/kg	specific enthalpy of steam
M	kg	Mass
p	bar	pressure
T_s	$^\circ C$	Saturated temperature
u	kJ/kg	specific inner energy
U	kJ	Inner energy
V	m^3	Volume
Subscripts		
$\{w, s\}$		water/steam region property