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Multi-region fuzzy logic controller with local PID controllers for U-tube steam generator in nuclear power plant

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In the paper, analysis of multi-region fuzzy logic controller with local PID controllers for steam generator of pressurized water reactor (PWR) working in wide range of thermal power changes is presented. The U-tube steam generator has a nonlinear dynamics depending on thermal power transferred from coolant of the primary loop of the PWR plant. Control of water level in the steam generator conducted by a traditional PID controller which is designed for nominal power level of the nuclear reactor operates insufficiently well in wide range of operational conditions, especially at the low thermal power level. Thus the steam generator is often controlled manually by operators. Incorrect water level in the steam generator may lead to accidental shutdown of the nuclear reactor and consequently financial losses. In the paper a comparison of proposed multi region fuzzy logic controller and traditional PID controllers designed only for nominal condition is presented. The gains of the local PID controllers have been derived by solving appropriate optimization tasks with the cost function in a form of integrated squared error (ISE) criterion. In both cases, a model of steam generator which is readily available in literature was used for control algorithms synthesis purposes. The proposed multi-region fuzzy logic controller and traditional PID controller were subjected to broad-based simulation tests in rapid prototyping software – Matlab/Simulink. These tests proved the advantage of multi-region fuzzy logic controller with local PID controllers over its traditional counterpart.

Key words: nuclear power plant, U-tube steam generator, PID control, fuzzy logic, multi-region PID controller, advanced control systems.

1. Introduction

The main objective of steam generator control system designed for pressurised water nuclear reactor is to maintain water level within the NRL (Narrow Range water

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Level) by changing flow rate of feed water from steam condensers and heat exchangers. It is a difficult task due to [6,12]:

- the controlled plant is non-linear and its characteristics depend on thermal power transferred from the primary coolant loop,
- efficiency of commonly used water level controllers is insufficient due to complex thermal and hydraulic processes taking place in the steam generator i.e. rising and falling water level depending on the feed water and the steam flow rates (shrink and swell phenomena).

Insufficient heat transfer between primary and secondary coolant loop may occur when water level in the steam generator goes below minimum lower limit posing a safety hazard to the entire nuclear power station. On the other hand, water level exceeding the upper limit increases the threat of feed water transfer to the steam turbine potentially causing its blades to erode [2].

Incorrectly controlled water level in the steam generator, either dropping below or exceeding permissible limits may cause frequent unforeseen reactor shutdowns entailing unnecessary financial penalties [7]. At the start-up phase water level controllers fail to assure satisfactory control performance, therefore in many nuclear power stations water level during the start-up is controlled manually [7, 12]. This problem may be eliminated by designing a control system which would provide satisfactory control performance both at the stage of reactor start-up and also during daily operation. Outcomes of research into just such a solution, namely multi-region fuzzy logic controller with local PID controllers are presented in this paper.

The research to date into advanced techniques of water level control in steam generators comes to algorithms based on gain scheduling control [1,6,12] artificial neural networks [4,6,11], fuzzy logic [5,6,11,13], adaptive control [8, 11], Model Predictive Control [9,10] and combinations of aforementioned.

Compared to above-mentioned, the proposed multi-region fuzzy logic control system is based on PID controllers which are commonly used across the industry. The multi-region fuzzy controller consists of several local PID controllers tuned for its operating points and one Takagi-Sugeno fuzzy interface module. That fuzzy inference module combines local control signals produced by local PID controllers into one global control signal. The main advantage of proposed control algorithm is simplicity of implementation in modern digital control devices (e.g. programmable controllers – PLC). This stems from the fact that the PID control algorithm is available practically in every programmable controller and fuzzy logic module may be implemented by using simple IF-THEN functions.

Fig. 1 presents analyzed in the paper water level control structure for the steam generator [6,9,12].

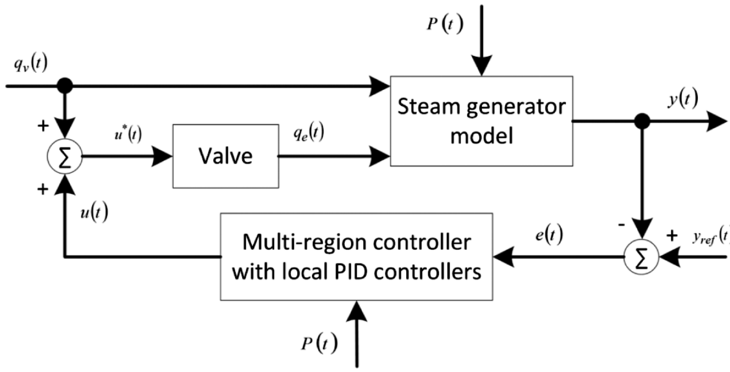

Fig. 1. Steam generator water level control structure.

The following symbols are used, respectively: $q_v(t)$ – steam flow rare, $q_e(t)$ – feed water flow rate, $u(t)$ – multi region fuzzy logic controller control signal, $u^*(t)$ – valve control signal, $y(t)$ – steam generator water level (controlled variable), $y_{ref}(t)$ – steam generator water level reference value, $e(t)$ – steam generator water level control error, $P(t)$ – nuclear reactor thermal power.

The structure of this paper is as follows: sec. 2 describes model of the steam generator used for analysis and synthesis of the proposed multi-region fuzzy logic controller with local PID controllers, sec. 3 presents the process of designing the multi-region fuzzy logic controller including tuning of the local PID controllers as well as the fuzzy logic used for switching between them, sec. 4 compares the multi-region fuzzy logic controller based on the local PID controllers with traditional, single PID controllers tuned for two different operation points. In conclusions, sec. 5, the paper is briefly summarized.

2. Steam generator and feed water control valve models

A mathematical model of U-tube steam generator commonly used in water level control system design [6,8,12] has been applied in this paper also. Accurate models of a steam generator are intricate and complex for synthesis of water level control systems [2,3]. Therefore linear model of steam generator with changeable parameter depending on output thermal power $P(t)$ was used. It is the transfer function with inputs: $Q_e(s)$ [kg/s] – flow rate of feed water, $Q_v(s)$ [kg/s] – flow rate of steam, and output $Y(s)$ [mm] – relative water level:

$$Y(s) = \left(\frac{K_1}{s} - \frac{K_2}{1+\tau_2 s}\right)\left(Q_e(s) - Q_v(s)\right) + \tag{1}$$

$$+ \frac{K_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} s + s^2} Q_e(s)$$

where: s is the Laplace operator.

Parameters K_1, K_2, K_3, τ_1, τ_2, T and Q_v depend on thermal power output and are shown in Tab. 1. All variables from equation (1) are positive. All terms used in model (1) satisfy the following function [6,7]:

- $\frac{K_1}{s}$ – mass accumulation in secondary coolant loop of U-tube steam generator, this term integrates flow rates difference ($Q_e(s) - Q_v(s)$) thus it determines change in water level,
- $-\frac{K_2}{(1+\tau_2 s)}$ – negative heat effect caused by shrink and swell phenomena primarily occurring when either steam or feed water change their flow rate at low-power,
- $\frac{K_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} s + s^2}$ – oscillatory changes of water mass caused by inlet feed water.

System of differential and algebraic equations is derived from model (1) in order to describe the controlled plant in state space. Hence, new state variables X_A, X_B, X_C are introduced:

$$Y(s) = X_A(s) + X_B(s) + X_C(s) \tag{2}$$

$$X_A(s) = \frac{K_1}{s}\left(Q_e(s) - Q_v(s)\right) \tag{3}$$

$$X_B(s) = -\frac{K_2}{1+\tau_2 s}\left(Q_e(s) - Q_v(s)\right) \tag{4}$$

$$X_C(s) = \frac{K_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} s + s^2} Q_e(s) \tag{5}$$

Then, by inverse Laplace transform $\mathcal{L}^{-1}$, the state variables X_A and X_B are transformed into time domain:

$$sX_A(s) = K_1\left(Q_e(s) - Q_v(s)\right) \quad /\mathcal{L}^{-1} \tag{6}$$

$$\frac{dx_A(t)}{dt} = K_1\left(q_e(t) - q_v(t)\right) \tag{7}$$

$$sX_B(s) = -\frac{K_2}{\tau_2}\left(Q_e(s) - Q_v(s)\right) - \frac{X_B(s)}{\tau_2} \quad /\mathcal{L}^{-1} \tag{8}$$

$$\frac{dx_B(t)}{dt} = -\frac{K_2}{\tau_2}\left(q_e(t) - q_v(t)\right) - \frac{x_B(t)}{\tau_2} \tag{9}$$

Next, the ancillary state variable X_D is introduced into state space model:

$$\underbrace{\frac{X_C(s)}{s}\left(\tau_1^{-2}+4\pi^2T^{-2}\right)}_{X_D(s)}+X_C(s)\left(2\tau_1^{-1}\right)+sX_C(s)=K_3Q_e(s) \tag{10}$$

$$X_D(s)=\frac{X_C(s)}{s}\left(\tau_1^{-2}+4\pi^2T^{-2}\right) \tag{11}$$

Then, the state variable X_C (10) is transformed into time domain:

$$sX_C(s)=K_3Q_e(s)-X_C(s)\left(2\tau_1^{-1}\right)-X_D(s)\quad /\mathcal{L}^{-1} \tag{12}$$

$$\frac{dx_C(t)}{dt}=K_3q_e(t)-x_C(t)\left(2\tau_1^{-1}\right)-x_D(t) \tag{13}$$

and finally, the ancillary state variable X_D (11) is transformed into time domain:

$$sX_D(s)=X_C(s)\left(\tau_1^{-2}+4\pi^2T^{-2}\right) \tag{14}$$

$$\frac{x_D(t)}{dt}=x_C(t)\left(\tau_1^{-2}+4\pi^2T^{-2}\right) \tag{15}$$

The above transformations give the system of first order differential equations and the system of algebraic equations, which denote the steam generator model in state space as follows:

$$\begin{cases}\dot{x}_A(t)=K_1\left(q_e(t)-q_v(t)\right)\\ \dot{x}_B(t)=-\dfrac{x_B(t)}{\tau_2}-\dfrac{K_2}{\tau_2}\left(q_e(t)-q_v(t)\right)\\ \dot{x}_C(t)=-x_C(t)(2\tau_1^{-1})-x_D(t)+K_3q_e(t)\\ \dot{x}_D(t)=x_C(t)(\tau_1^{-2}+4\pi^2T^{-2})\\ y(t)=x_A(t)+x_B(t)+x_C(t)\end{cases} \tag{16}$$

Model (16) is linear and non-stationary since its parameters depend on changes in reactor's thermal output. Tab. 1 shows parameters of the model (16) in five selected operating points which are characterized by thermal power of nuclear reactor. Thus, five linear models of steam generator are obtained.

Tab. 1. Parameters of the steam generator model relative to thermal power output [6].

Reactor power [%]	K_1 [mm/kg]	K_2 [mm s/kg]	K_3 [mm/kg]	τ_1 [s]	τ_2 [s]	T [s]	q_v [kg/s]
5	0.058	9.63	0.181	41.9	48.4	119.6	57.4
15	0.058	4.46	0.226	26.3	21.5	60.5	180.8
30	0.058	1.83	0.310	43.4	4.5	17.7	381.8
50	0.058	1.05	0.215	34.8	3.6	14.2	660
100	0.058	0.47	0.105	28.6	3.4	11.7	1435

In order to derive parameters of the steam generator model within intervals between selected five operating points (Tab. 1) and extend its utility the linear interpolation is used. The following intervals are subjected to linear interpolation:

- interval I – 5% < power ≤ 15%,
- interval II – 15% < power ≤ 30%,
- interval III – 30% < power ≤ 50%,
- interval IV – 50% < power ≤ 100%.

Furthermore, linear extrapolation was used for intervals from 0% to 5% and above 100% of thermal power. Fig. 2 presents charts showing known and interpolated parameters relative to reactor's thermal output for intervals I to IV. In Fig. 2 the parameter K_1 was omitted because it is constant across all intervals.

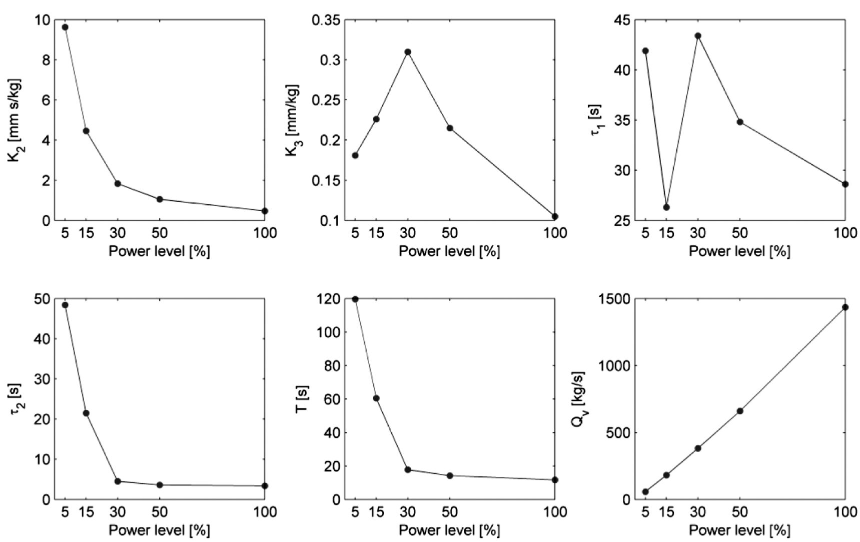

Fig. 2. Parameters of the steam generator model relative to thermal power transferred by primary side.

Fig. 3 and 4 present step responses of the steam generator model both in operating points defined by Tab. 1 as well as in intervals between these points. Parameters of the steam generator model in these intervals are derived through linear interpolation presented on Fig. 2. Fig. 3 shows response of the steam generator model to unit step of feed water Q_e with zero steam flow rate Q_v. While, the Fig. 4 shows response of the model to unit step of steam flow rate Q_v with zero flow rate of feed water Q_e. Families of step response characteristics presented in Fig. 3 and 4 are visualising the impact of change in the reactor's thermal output on the steam generator dynamics.

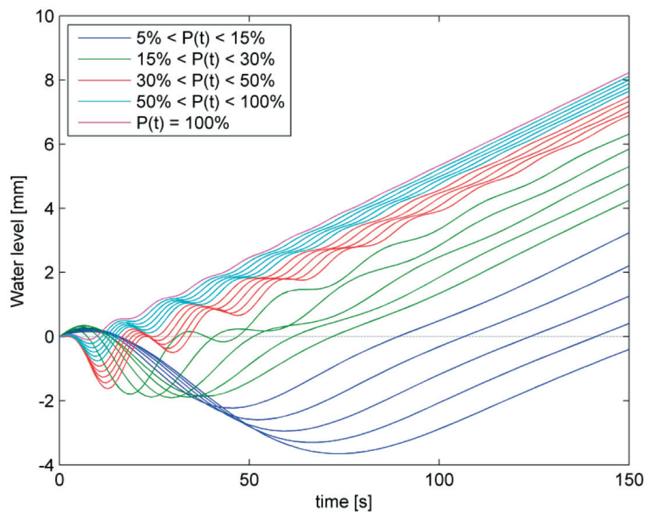

Fig. 3. Family of unit step responses Q_e of the steam generator models.

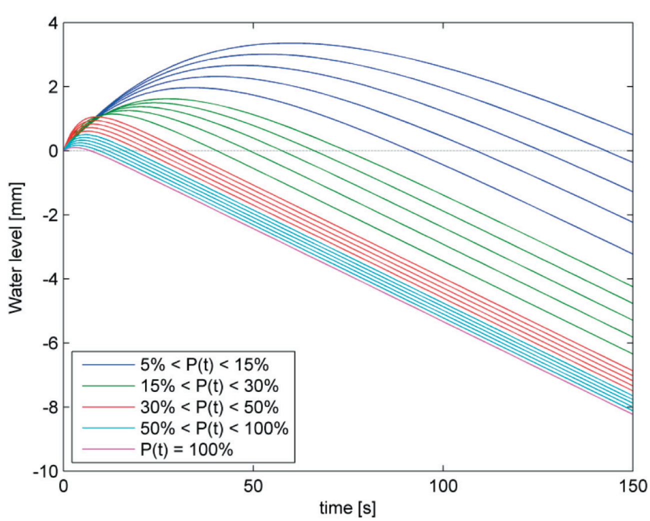

Fig. 4. Family of unit step responses Q_v of the steam generator models.

The feed water control valve, which is an integral part of the steam generator water level control structure (Fig. 1), is modelled with simple transfer function in Laplace domain as follows [12]:

$$\frac{Q_e(s)}{U^*(s)} = \frac{1}{s+1} \tag{17}$$

where: $Q_e(s)$ is Laplace transform of feed water flow rate signal and $U^*(s)$ is Laplace transform of valve control signal.

3. Multi-region fuzzy logic controller with local PID controllers

3.1. Controller structure

The structure of multi-region fuzzy logic controller with local PID controllers, presented in this paper (Fig. 5), is composed of: five local PID controllers; and Takagi-Sugeno fuzzy logic interface module.

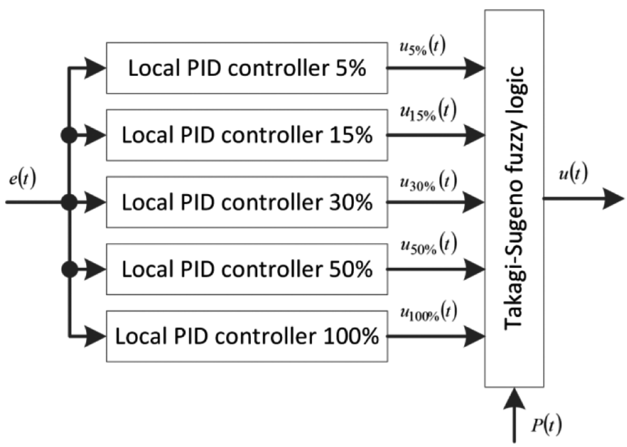

Fig. 5. Structure of the multi-region fuzzy logic controller with local PID controllers.

The local PID controllers has a standard form, which can be described in Laplace domain as follows:

$$PID(s) = K_p + K_i / s + K_d s \tag{18}$$

where: K_p, K_i and K_d are proportional, integral and derivative gains of PID controller,

Takagi-Sugeno fuzzy logic interface module is the second main element of the proposed controller. The main purpose of this module is to softly switch between control signals of local PID controllers and derive single control signal, depending on current thermal power output $P(t)$. Fig. 6 shows five membership functions $\mu_i(P(t))$ used in

Takagi-Sugeno fuzzy logic block (one membership function for each local PID controllers). Proposed fuzzy logic interface is based on typical triangular and trapezoidal membership functions satisfying the partition of unity condition. In the operating points, where parameters of the steam generator are exact (Tab. 1) membership functions are equal 1. When thermal power is below 5% or exceeds 100%, the membership functions are equal 1 as well.

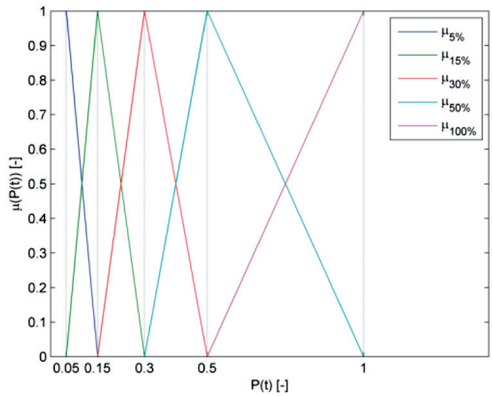

Figure 6. Membership functions used in Takagi-Sugeno fuzzy logic interface module.

Finally, the global control signal $u(t)$ generated by the multi-region fuzzy logic controller (Fig. 1 and 5) is combined from local PID controllers signals by Takagi-Sugeno fuzzy logic interface module. It is done with following weighted mean formula (19):

$$u(t)=\frac{\mu_{5\%}(P(t))\times\mu_{5\%}(t)+\mu_{15\%}(P(t))\times\mu_{15\%}(t)+\ldots+\mu_{100\%}(P(t))\times\mu_{100\%}(t)}{\mu_{5\%}(P(t))+\mu_{15\%}(P(t))+\ldots+\mu_{100\%}(P(t))} \tag{19}$$

3.2. Controller tuning procedure

The local PID controllers parameters are determined based on the solving of static and nonlinear programming problems with single, quadratic objective function in the form of ISE criterion (Integral of the Square value of the Error). It is done in order to minimize the steam generator water level control error e in appropriate operating point i (20). The steam generator operating points are related to the thermal power of nuclear reactor (Tab. 1). Hence, mentioned optimization problem (20) is solved individually for each local PID controller:

$$\min_{Kp,Ki,Kd}\{f_{ISE}^{i}=\int_{t_0}^{t_{end}}\left(e(Kp,Ki,Kd)\right)^2dt\} \tag{20}$$

according to:

$$[0;\,0;\,0]^{\mathrm{T}}\le[K_p;\,K_i;\,K_d]^{\mathrm{T}}\le[10;\,10;\,10]^{\mathrm{T}}$$

where: f_{ISE}^{i} – single-objective function; e – steam generator water level control error; t_0, t_{end} – beginning and end of the analyzed period of time; t – time.

The solver with hybrid structure is proposed to solve presented static mathematical programming problem (20). The value of objective function is evaluated based on the numerical simulation [14], in simulation phase, of the steam generator water level control structure with multi-region fuzzy controller (Fig. 1 and Fig. 5) with steam generator model (16). Notice, that during simulation phase the reference trajectory was a step change from 0 [mm] to +100 [mm] of desired relative water level in steam generator. During optimization phase, the optimization problem (20) is solved by SQP (Sequential Quadratic Programming) algorithm [14] and the optimal values of the decision variables K_p, K_i, K_d are determined.

For the case study purposes, 5 operating points were selected, within wide range of nuclear reactor thermal power. The PID controllers parameters obtained via solving optimization problem (20) for selected operating points are presented in the Tab. 2.

Tab. 2. Optimal parameters of local PID controllers according to ISE criteria in optimization task (20).

Local PID controller	5%	15%	30%	50%	100%
K_p	0.0662	0.13	0.2972	0.5287	1.6833
K_i	0	0	0	0	0
K_d	0	0	0	0	1.4453
$[t_0\ t_{end}]$	[0; 1500]	[0; 1000]	[0;200]	[0;200]	[0;100]
$[K_p; K_i; K_d]_0$	[1; 0; 0]	[0.0662; 0; 0]	[0.13; 0; 0]	[0.2972; 0; 0]	[0.5287; 0; 0]

In Tab. 2, the $[K_p; K_i; K_d]_0$ denote initial condition for optimization procedure [14] that is local PID controllers parameters and t_0, t_{end} denotes time range considered for objective function calculation during optimization problem (20) solving.

4. Simulation tests results

Comparison between PID controllers tuned for 100% and 50% of nuclear reactor thermal power and the proposed multi-region fuzzy logic controller was performed. Test simulations were done with the Matlab/Simulink [14] environment.

Three different tests were proposed to verify controllers effectiveness:

- the positive step of nuclear reactor thermal power from 0% to 100% (start time 10 sec.),
- the negative step of nuclear reactor thermal power from 100% to 5% (start time 110 sec.),

- the thermal power changes according to the rising and falling slopes of the thermal power curve.

Figures (Fig. 8–14),that illustrate obtained simulations results are presented in each subparagraph in following order:

- the reactor power,
- the water level in the steam generator,
- the feed water flow rate.

In all presented figures (Fig. 8–14) the solid line represents multi-region (PID_{MR}) controller, dash-dotted line represents the single, PID controller tuned for 100% thermal power output ($PID_{100\%}$) and dotted line represents typical PID controller tuned for 50% thermal power output ($PID_{50\%}$). The water level in the steam generator was set to relative level according to reference water level denoted as 0 [mm].

During the test simulations the following constraints related to control signal value – $u(t)$ and feed water flow rate $q_e(t)$ were taken into consideration:

$$-500[kg/s] \le u(t) \le 500[kg/s] \tag{21}$$

$$q_e(t) \ge 0 \tag{22}$$

4.1. Positive step change of thermal power from 0% to 100%

Results of positive step change tests are shown in Fig.8 and Fig. 9.

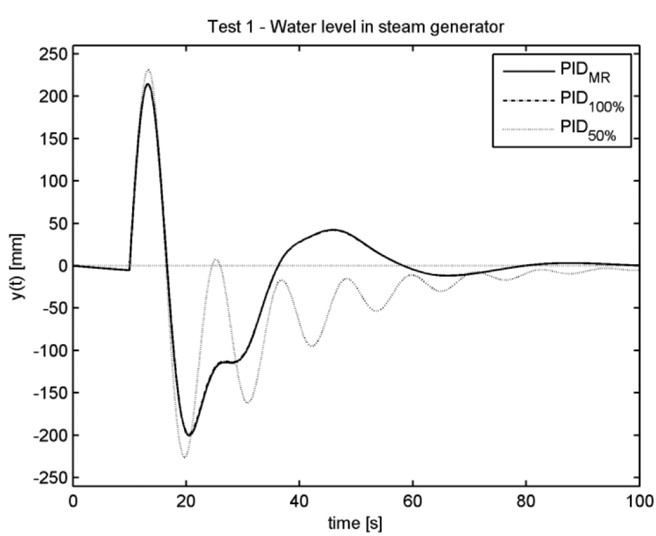

Fig. 8. Water level in the steam generator – positive step change of thermal power.

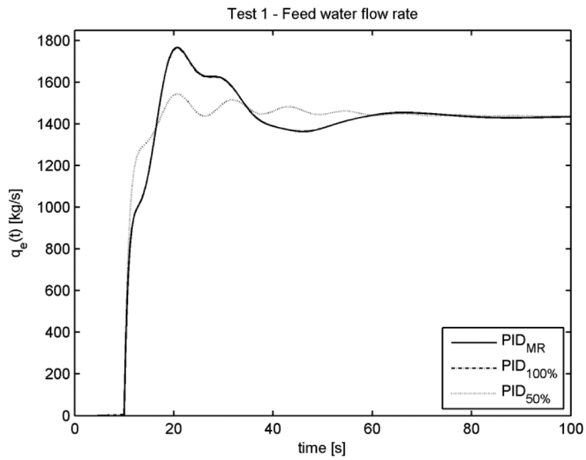

Fig. 9. Flow rate of feed water into steam generator – positive step change of thermal power.

The first test showed that the PID 100% controller tuned for the 100% of the thermal power output operated identically to the multi-region controller PID MR. At this point, the multi-region controller generates control signal by solely using the PID 100% controller – this action is justified. The control system with PID 50% controller set up for 50% thermal power output has slower response and an oscillatory nature compared to the PID MR and PID 100%.

4.2. Negative step change of thermal power from 100% to 5%

Results of negative step tests are presented in Fig. 10 and Fig. 11.

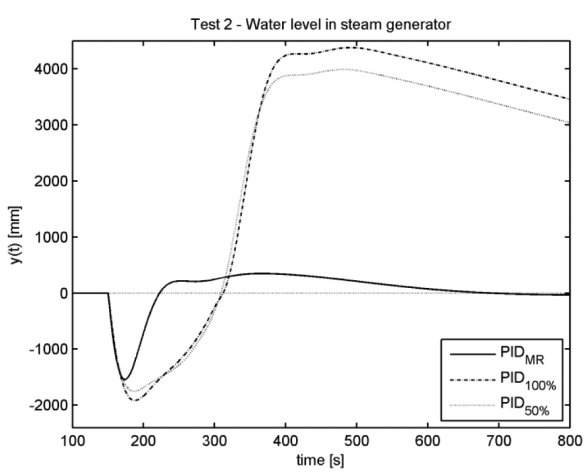

Fig. 10. Water level in the steam generator – negative step change of thermal power.

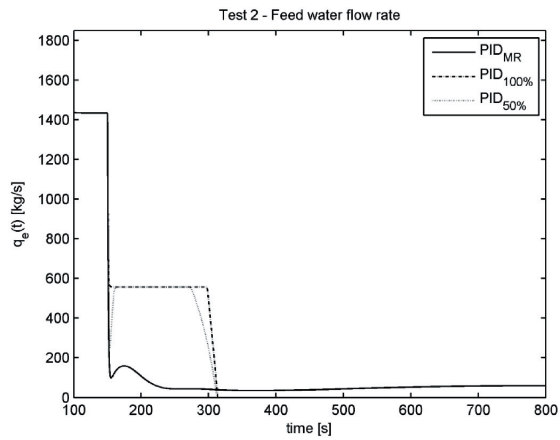

Fig. 11. Flow rate of feed water into steam generator – negative step change of thermal power.

The second test proved that the multi-region controller presents better control quality than its traditional counterpart. PID controllers set up for 100% and 50% thermal power output are incapable to maintain the reference water level in the steam generator. The multi-region controller PID MR through Takagi-Sugeno fuzzy logic softly switches between local PID controllers depending on the operating condition. In this way appropriate continuous control signal is always derived. The water level in steam generator is stabilized to a satisfactory level at low power outputs and consequently equals the reference water level.

4.3. Thermal power change – positive and negative slopes of power curve

Results concerning power change at rising and falling slopes of power level reference signal are presented in Fig. 12, 13 and Fig 14.

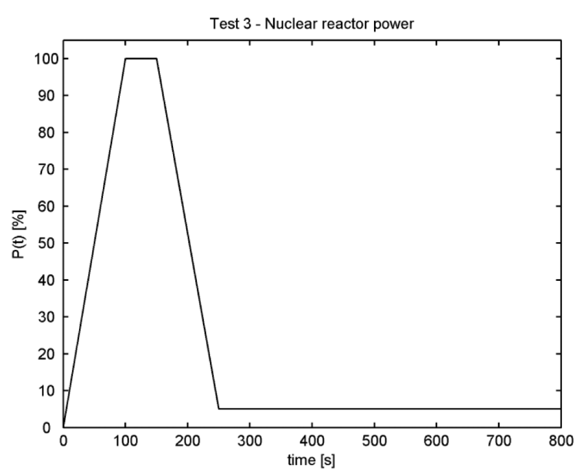

Fig. 12. Thermal power change – positive and negative slope of power curve.

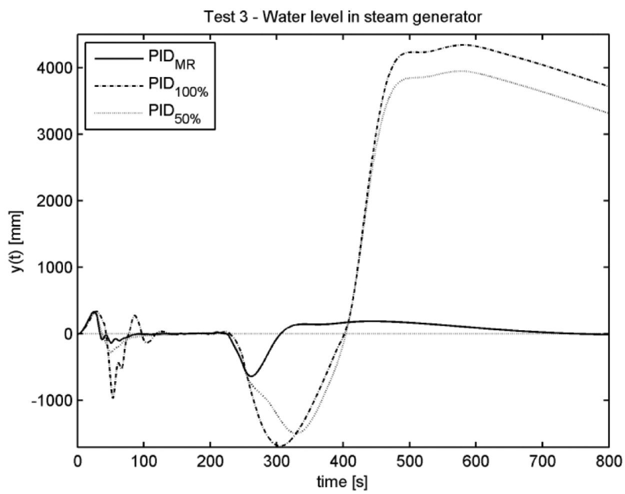

Fig. 13. Water level in steam generator – positive and negative slope of power curve.

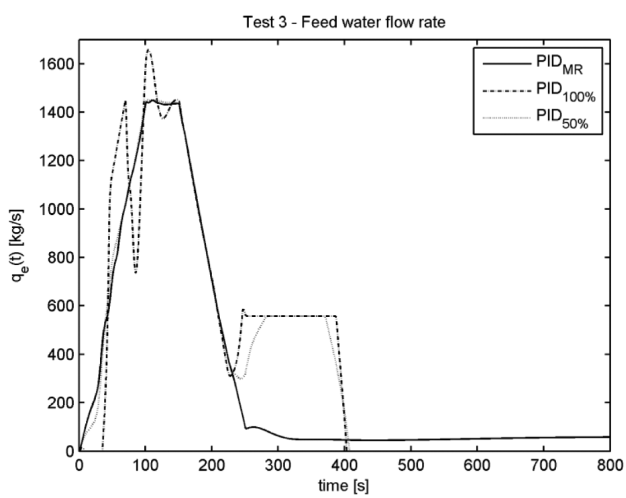

Fig. 14. Flow rate of feed water into steam generator – positive and negative slope of power curve.

The third test proved once more that the multi-region controller is better than its traditional counterpart. The test was devised to show controller performance at slowly changing thermal power output as well as to verify whether fuzzy logic based PID controller switching operates correctly. The multi-region controller showed satisfactory control performance during power changes and at low thermal power outputs. Traditional PID controllers provides inferior control performance in both scenarios. At low power outputs, the traditional PID controllers fails to guarantee good control performance as portrayed already in test no 2 and confirmed by the third test.

Based on waveform characteristics of control signal (feed water fed into the steam generator as in Fig. 11 and Fig. 14) obtained in second and third test, the multi-region controller again dominates over its traditional counterpart. Control signal generated by the multi-region controller does not change abruptly as opposed to the traditional controller. It is a welcomed effect for secondary loop elements e.g. feed water pumps and feed water piping systems. During abrupt flow rate changes those elements are exposed to substantial loads and may potentially sustain damage over short periods of operation.

5. Summary

The multi-region controller designed for controlling feed water flow rate into the steam generator has many advantages. It is capable of stabilising water level in the steam generator at the reference level across a wide operating range of thermal power outputs whilst maintaining satisfactory control performance as opposed to traditional PID controllers set up for a specific design point (100% and 50% reactor power).

The multi-region controller generates better characteristics of the control variable in contrast to a typical controllers. The generated control signal is free of abrupt flow rate changes expanding expected lifetime of secondary loop system elements.

The operating principle, structure and synthesis of the multi-region fuzzy logic controller designed for control of feed water in the steam generator in order to stabilise water level at pre-determined reference level was presented in this paper. Based on simulation tests, the multi-region controller proved to generate better control signal (feed water flow rate) than the traditional controllers and to obtain overall better control system performance. Traditional PID controllers or manual control commonly used in nuclear power stations today may be replaced by a simple to implement multi-region fuzzy logic controller presented in this paper.

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