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Design of a Trajectory Tracking Sliding Mode Controller Based on Non-Linear Reduced Order CNPK Model for the Nuclear Research Reactors

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Abstract: The aim of this study is to design a sliding mode controller to follow the reference power trajectory, overcome the external disturbances and eliminate the chattering phenomenon in nuclear reactors. This controller is designed based on a Reduced Order Classical Neutron Point Kinetic (ROCNPK) model. This model is presented based on the measurable variables such as: the reactor power and the coolant temperature. The stability analysis of the close-loop system is performed using lyapunov method. Also, the chattering phenomenon in the control law is eliminated by using narrow-band saturation function. The proposed Reduced Order Sliding Mode Controller (ROSMC) is simulated using matlab/simulink and its performance is evaluated in different operation conditions. The simulation results illustrate proposed controller follow the reference power trajectory accurately and is satisfactory in the presence of the external disturbances.

Key words: Nuclear reactor, reduced order classic neutron point kinetic, sliding mode, lyapunov stability, external disturbances, Tehran research reactor

INTRODUCTION

The purpose of the power control is to follow the reference power trajectory and to overcome the uncertainties and the external disturbance to prevent the accidents in nuclear reactors. The different control methods are proposed for the nuclear reactor power control by Dong (2011), Rojas *et al.* (2013), Xia *et al.* (2014), Na *et al.* (2006), Li and Zhao (2013) and Coban (2014). In 2011, a novel nonlinear state-feedback controller is presented to control the reactor power level and the asymptotic closed-loop stability and the states-observer convergence has been investigated (Dong, 2011). In 2013, an adaptive fuzzy controller for the TRIGA-type research reactor is proposed by Ramirez. This controller is based on a CNPK model which can follow the reference power profile and decreased the undesirable power fluctuation (Rojas *et al.*, 2013). A state-feedback controller is presented based on the LQR method. The core power distribution control has been performed by using this controller and its performance is investigated on both the linearized and the nonlinear models (Xia *et al.*, 2014). The Model Predictive Control (MPC) approach is designed during the load following (Na *et al.*, 2006). This controller is designed based on some constraints on the input and output variables and can be kept within acceptable limits. Another control method is proposed based on the combination of the Linear Quadratic Gaussian (LQG), the PID controller and the Improved Adaptive Genetic Algorithm (IAGA) (Li and Zhao, 2013). It should be notice that the non-linear model is replaced by the linear multi-model to describe the reactor core dynamic behavior. Another control method, for the control of the reactor power trajectory, is a multi-feedback layer neural network-particle swarm optimization which is presented by Na *et al.* (2006).

The first stage of controller design is to choose an appropriate model for the reactor dynamics. In the above mentioned control methods, the reactor power controller design has been performed based on the CNPK model (Rojas *et al.*, 2013; Xia *et al.*, 2014; Na *et al.*, 2006; Li and Zhao, 2013; Coban, 2014). The second stage include to select an appropriate control strategy for the reactor output power control which must be robust against the uncertainties and external disturbances. One of the robust control techniques is the Sliding Control (SMC) method.

The Sliding Mode Control (SMC) method is one of the robust control techniques. The SMC is a model based variable structure control system that was first proposed

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by Emelyanov and have the attainable advantages such as: the inherent robustness to the external disturbances and the inherent insensitivity to the system uncertainties (Emelyanov and Mamedov, 1995). The uncertainty can be related to the measurement of the actual power reactivity coefficients. Since, some of the parameters such as xenon concentration and delayed neutron precursors densities are not measureable, by Eom *et al.* (2015) a robust observer based feedback linearization controller is designed for a research reactor. The SMC is a powerful technique which can control both linear and non-linear systems. A SMC is designed for the spatial oscillation control of the Advanced Heavy Water Reactor (AHWR) (Munje *et al.*, 2013). A sliding mode control is designed using the sliding mode observer for the power control of the load following PWR which estimates unmeasurable parameters (Ansarifar and Akhavan, 2015).

In another research, a higher order sliding mode control is proposed to overcome disadvantage of chattering phenomenon of SMC by Ansarifar and Akhava (2015).

In this study, a ROCNPK model is used to describe the dynamic behavior of the Tehran Research Reactor (TRR). A SMC controller is presented based on the physically measurable feedbacks. The close loop system stability has been investigated by Lyapunov approach. The proposed controller can track the time-varying reference signal and guarantee system stability. A narrow-band saturation function is used instead of sign function to overcome the chattering phenomenon in the control law.

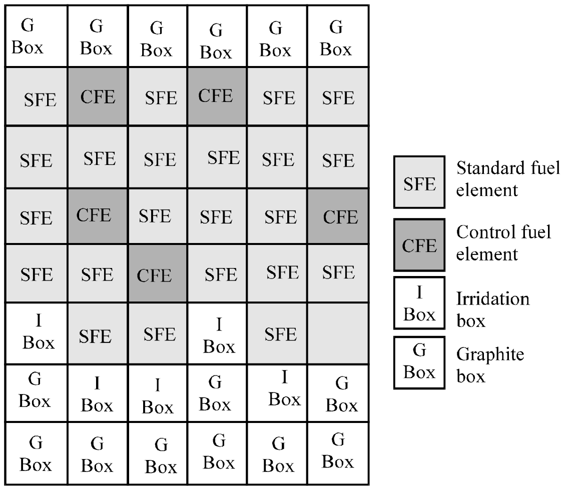
Structure of Tehran Research Reactor (TRR): The TRR is the pool type reactor and the light water is used as coolant, moderator and shielding. The reactor operates with solid fuel of U3O8AL with aluminum cladding. The reactor controls using the neutron-absorbing control rods. There are two different types of neutron-absorbing control rods, SSR and FRR that are used in the fork shape. The reactor control and its protection system are responsible for two important duty:

- Support of reactor against the improper operation and the possible malfunctions (protection system)
- Control of the neutrons production in some predetermined level (control system)

In the FOC, the reactor core operates with the 14 SFE (consists of 19 fuels plates) and 5 CFE (consists of 14 fuel plates) that is shown in Fig. 1. The general characteristics of TRR is listed in Table 1 (AAEOI, 2009).

Table 1: General characteristics of TRR

Parameters	Values
Initialthermal power	10-9 W
Thermal power	5 MW
Fuel	Low enriched 235UMTR type, AL clad
Number of plate PER fuel element	19 for SFE; 14 for CFE
Core dimensions (FOC)	40.5×38.54×89.7 cm
Moderator	Light water
Primary coolant flow	500 m^3/h
Primary Coolant inlet temperature	
full power (at 5 MW)	37.8°C
Cold and clean (at 10^{-9}W)	20°C
Primary Coolant outlet temperature	
full power (at 5 MW)	46°C
Cold and clean (at 10^{-9}W)	20°C
Control	Shim safety rods: Ag-In-Gd; Regulating rod:1 stainless steel



G Box	G Box	G Box	G Box	G Box	G Box
SFE	CFE	SFE	CFE	SFE	SFE
SFE	SFE	SFE	SFE	SFE	SFE
SFE	CFE	SFE	SFE	SFE	CFE
SFE	SFE	CFE	SFE	SFE	SFE
I Box	SFE	SFE	I Box	SFE	
G Box	I Box	I Box	G Box	I Box	G Box
G Box	G Box	G Box	G Box	G Box	G Box

SFE	Standard fuel element
CFE	Control fuel element
I Box	Irridation box
G Box	Graphite box

Fig. 1: First low enriched uranium operating core of the TRR

MATERIALS AND METHODS

Model description

Reactor dynamic model: The CNPK model with the fuel and coolant temperature feedbacks is used to design the controller. The nonlinear dynamic model which is normalized respect to the equilibrium condition is given as following Eq. 1 and 2 (Arab-Alibeik and Setayeshi, 2005). Where the system variables are explained in the nomenclature:

$$\frac{dn_r}{dt} = \frac{\rho(t)-\beta}{\Lambda}n_r + \lambda C_r \tag{1}$$

$$\frac{dC_r}{dt} = \frac{\beta}{\Lambda}n_r - \lambda C_r \tag{2}$$

When the reactor output power varies the fuel and coolant temperatures immediately are changed which the equations related to the variations of the reactor core parameters are represented by Eq. 3 and 4:

$$\frac{dT_f}{dt}=\frac{f_f P_o}{\mu_f}P_r-\frac{\mu}{\mu_f}T_f(t)+\frac{\mu}{2\mu_f}T_l(t)+\frac{\mu}{2\mu_f}T_e \tag{3}$$

$$\begin{aligned}\frac{dT_l}{dt}=\frac{(1-f_f)P_0}{\mu_c}P_r+\frac{\mu}{\mu_c}T_f(t)-\\ \frac{2M+\mu}{2\mu_c}T_l(t)+\frac{2M-\mu}{2\mu_c}T_e\end{aligned} \tag{4}$$

The total reactivity is obtained by control rod reactivity and the feedback due to fuel and coolant temperature which is demonstrated in Eq. 5:

$$\rho(t)=\rho_{ex}+\alpha_f\left(T_f(t)-T_{f0}\right)+\alpha_c\left(T_c(t)-T_{c0}\right) \tag{5}$$

The control rod reactivity variation (ρ_{ex}) is obtained from Eq. 6:

$$\frac{d\rho_{ex}}{dt}=G_r Z_r \text{ or } \rho_{ex}=G_r\int_0^t Z_r d\tau \tag{6}$$

where, the reactor power P(t) can be defined as follow:

$$P(t)=P_0 n_r=P_0 P_r=\gamma_f \Sigma_f \phi N V_f$$

Model order reduction: Some variables of reactor system is not measurable by detectors. Therefore, the CNPK model is reduced based on the measurable variables such as power and coolant temperature. The first order derivation of Eq. 1 is given by:

$$D^2P_r=\frac{D\rho(t)}{\Lambda}P_r+\frac{\rho(t)-\beta}{\Lambda}DP_r+\lambda DC_r \tag{7}$$

where, D = d/dt and $P_r = n_r$. By substituting the combination of Eq. 6 and first order derivation of Eq. 7-8 can be obtained as follow:

$$\begin{aligned}D^2P_r=\frac{1}{\Lambda}\left[G_r Z_r+\alpha_f DT_f+\alpha_c DT_c\right]P_r+\\ \frac{\rho(t)-\beta}{\Lambda}DP_r+\lambda DC_r\end{aligned} \tag{8}$$

Finally, by substituting Eq. 2-9 the overall system can be represented with single Eq. 9:

$$\begin{aligned}D^2P_r=-\frac{\beta}{\Lambda}DP_r+\begin{pmatrix}\frac{\lambda\beta}{\Lambda}+\frac{\mu\alpha_f T_e}{2\Lambda\mu_f}+\\ \frac{\alpha_c(2M-\mu)T_e}{4\Lambda\mu_c}\end{pmatrix}P_r+\begin{pmatrix}\frac{\alpha_f p_0 f_f}{\Lambda\mu_f}+\\ \frac{0.5\alpha_c(1-f_f)p_0}{2\Lambda\mu_c}\end{pmatrix}P_r^2+\\ \begin{pmatrix}\frac{\alpha_f\mu}{2\Lambda\mu_f}-\\ \frac{\alpha_c(2M+\mu)}{4\Lambda\mu_c}\end{pmatrix}P_r T_l+\begin{pmatrix}\frac{\alpha_c\mu}{2\Lambda\mu_C}-\\ \frac{\alpha_f\mu}{\Lambda\mu_f}\end{pmatrix}P_r T_f+\\ \left[\frac{\rho}{\Lambda}DP_r+\frac{G_r P_r}{\Lambda}Z_r\right]\end{aligned} \tag{9}$$

The system with Eq. 9 can be represented as Eq. 10 for control design process:

$$D^2P_r=f+bU \tag{10}$$

Where:

U = Control input (Z_r)

b = Input gain function

f = Nonlinear function of system variables which is not precisely known or physically measurable

This function can be estimated as $\hat{f}$ and the estimation error supposed to be limited with the known value of M:

$$f-\hat{f}=\Delta f,\ \left|\Delta f\right|\le M \tag{11}$$

where, Δf is the estimation error and includes the variables are not measurable physically by detectors by detectors such as: the relative Precursor Concentrations (C_r) and the fuel Temperature (T_f) and the non-modeled system dynamics. The reduced order system with the known variables is presented in Eq. 12:

$$D^2P_r=\hat{f}(DP_r,P_r,P_r^{\,2},T_l)+\Delta f(C_r,T_f)+bU \tag{12}$$

where, b is the function of reactor Power P_r but it has known limit range and can be estimated as a constant $\hat{b}$ where, $0<b_{min}\le b$, $b\le b_{max}$, b_{min} and b_{max} are the known lower and upper limits of the input gain function, respectively. And:

$$\hat{f}=\left[-A_1DP_r+A_2P_r+A_3P_r^2+A_4P_rT_l\right] \tag{13}$$

Where:

$$A_1=\frac{\beta}{\Lambda},A_2=\frac{\lambda\beta}{\Lambda}+\frac{\mu\alpha_f T_e}{2\Lambda\mu_f}+\frac{\alpha_c(2M-\mu)T_e}{4\Lambda\mu_c}$$

$$A_3=\frac{\alpha_f p_0 f_f}{\mu_f\Lambda}+\frac{\alpha_c(1-f_f)p_0}{4\mu_c\Lambda}$$

$$A_4 = \frac{\alpha_f \mu}{2\mu_f \Lambda} - \frac{\alpha_c(2M+\mu)}{4\mu_c \Lambda}$$

And:

$$\Delta f = \left(\frac{\alpha_c \mu}{2\Lambda \mu_C} - \frac{\alpha_f \mu}{\Lambda \mu_f} \right) P_r T_f + \frac{\rho}{\Lambda} DP_r - \lambda^2 C_r \tag{14}$$

And:

$$b = \frac{G_r P_r}{\Lambda}, U = Z_r$$

The obtained overall system of Eq. 12 is used for the proposed ROSMC design process in the following study.

Proposed ROSMC: The system with Eq. 1-6 may not exactly be able to describe the real system dynamics. Therefore, the model may have uncertainty as non-modeled dynamics which is not seen Eq. 1-6 and must be considered in the control design process. The SMC is robust control method which can overcome to the uncertainties and external disturbances like considered system of Arab-Alibeik and Setayeshi (2005). This controller is designed based on CNPK model. Generally, the design process of the IOSMC consists of two steps:

- Suggestion of sliding surface which guarantees the error to become zero
- Determination of an appropriate control law which tends the system toward this surface and guarantees the closed-loop system stability

The sliding surface S is defined as follows:

$$S = De + \lambda_1 e, \lambda_1 > 0 \tag{15}$$

$$e = P_{rd} - P_r \tag{16}$$

Where:

e = Tracking error
P_{rd} = The reference relative power
λ_1 = Positive control parameters which determine the error damping dynamic

Equation 15 all coefficients are considered to be constant and positive. Therefore, a proper lyapunov function can be suggested which guarantees the stability of linear Eq. 15. However, with the assumption of S = 0, the long-time response of Eq. 15 will be e = 0 means that the output reactor power error will be zero. The aim of the control law is to keep system on the presented sliding surface in Eq. 15. For the sliding surface being asymptotically stable, the candidate lyapunov function is considered as Eq. 17:

$$V(S) = \frac{1}{2} S^2, V(0) = 0, \text{for}\, S \neq 0 \tag{17}$$

If the derivation of lyapunov function is negative definite $(\dot{V}<0)$, then the sliding surface will tend toward zero after the finite time. Therefore $\dot{V}$ supposed to be as follows:

$$\dot{V} = \frac{1}{2} \frac{d(S^2)}{dt} \leq -\gamma |S|,\ \gamma > 0 \tag{18}$$

where, γ is control parameter and positive. Equation 18 can be rewritten as:

$$\text{sgn}(S)\dot{S} \leq -\gamma \text{ and } \text{sgn}(S) = \frac{S}{|S|} \tag{19}$$

Where:

$$\text{sgn}(S) = \begin{cases} 1 & S > 0 \\ \text{Undefined} & S = 0 \\ -1 & S < 0 \end{cases}$$

The derivation of the sliding surface is derived from Eq. 15 as follows:

$$\dot{S} = D^2 e + \lambda_1 De \tag{20}$$

and from Eq. 16 is given:

$$\dot{S} = D^2 P_{rd} - D^2 P_r + \lambda_1 De \tag{21}$$

By substituting Eq.12 in Eq. 21 it is given:

$$\dot{S} = D^2 P_{rd} - f - \Delta f - bU + \lambda_1 De + \hat{b}U - \hat{b}U \tag{22}$$

By substituting obtained Eq. 22 in Eq. 19 we have:

$$\text{sgn}(S)\left(D^2 P_{rd} - \hat{f} - \Delta f - bU + \lambda_1 De + \hat{b}U - \hat{b}U \right) \leq -\gamma \tag{23}$$

To achieve control purpose, the term $\hat{b}u$ should be set so that the inequality Eq. 23 becomes true for all time. Therefore, the control law can be obtained by some mathematical manipulation as follows:

$$U = Z_r = \frac{1}{\hat{b}} \left[D^2 P_{rd} - \hat{f} + \lambda_1 De + K\text{sgn}(S) \right] \tag{24}$$

where, K is the control coefficient and can be chosen as follow:

$$K = \beta\gamma + \beta M + (\beta - 1) \left| D^2 P_{rd} - \hat{f} + \lambda_1 De \right|$$

where, β is called design gain margin and $\beta=\sqrt{b_{min}/b_{max}}$. In Eq. 24, the sign function (sgn S)) in the control law may cause the chattering phenomenon in the control effort. To eliminate this effect, the saturation function can be used instead of sign function. However, the proposed ROSMC will be in the form of Eq. 25:

$$U = Z_r = \frac{1}{\hat{b}}\left[D^2P_{rd} - \hat{f} + \lambda_1 De + K\text{sat}(S)\right] \tag{25}$$

Where:

$$K = \beta\gamma + \beta M + (\beta - 1)\left|D^2P_{rd} - \hat{f} + \lambda_1 De\right|$$

And:

$$\text{Sat}(S) = \begin{cases} 1 & S > \varepsilon \\ \dfrac{S}{\varepsilon} & |S| \le \varepsilon, \varepsilon > 0 \\ -1 & S < -\varepsilon \end{cases}$$

RESULTS AND DISCUSSION

In this study, four simulation has performed on TRR using matlab/simulink software to evaluate of the ROSMC performance. The reactor core dynamics is modeled by Dong (2011), Rojas *et al.* (2013), Xia *et al.* (2014), Na *et al.* (2006), Li and Zhao, (2013) and Coban, (2014). The block diagram representation of the obtained ROSMC (25) is show in Fig. 2. As shown in this Fig. 2, controller inputs are relative output power (P_r), coolant Temperature (T_l). The control rod speed (Z_r) is as controller output. The controller purpose is to adjust the output power according to the reference power trajectory. Three different trajectories consist of full power, middle power and emergency operation are employed here to investigate the controller performance. In each condition, the reactor output relative power, the power tracking error and the control rod speed (control effort signal) are plotted and analyzed. As shown in Fig. 2, reliability assessment of controller performance can be done by inserting of external disturbance signal.

Full power operation: In this simulation, the power demand increase from 100-110% with 10%/min ramp increase of a desired power at 25 sec. Figure 3 demonstrates the performance of RIOSMC in this case. As seen in Fig. 3a, the controller properly follows the reference power without the significant overshoot or oscillation. The power tracking error is the difference between reference and actual relative power which is shown in Fig. 3b. It is obvious that the tracking error

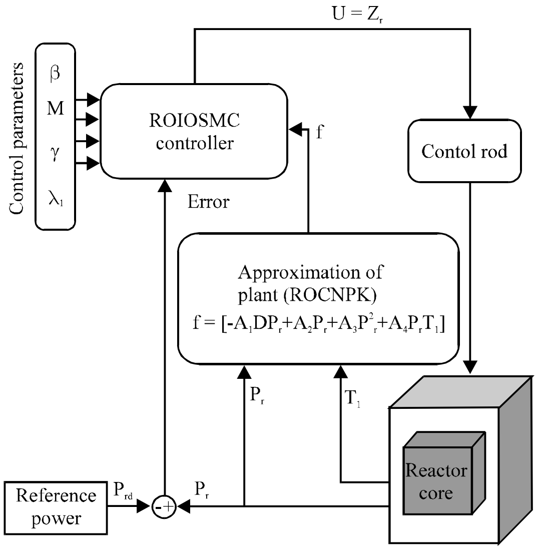


Fig. 2: Block diagram representation of proposed ROSMC

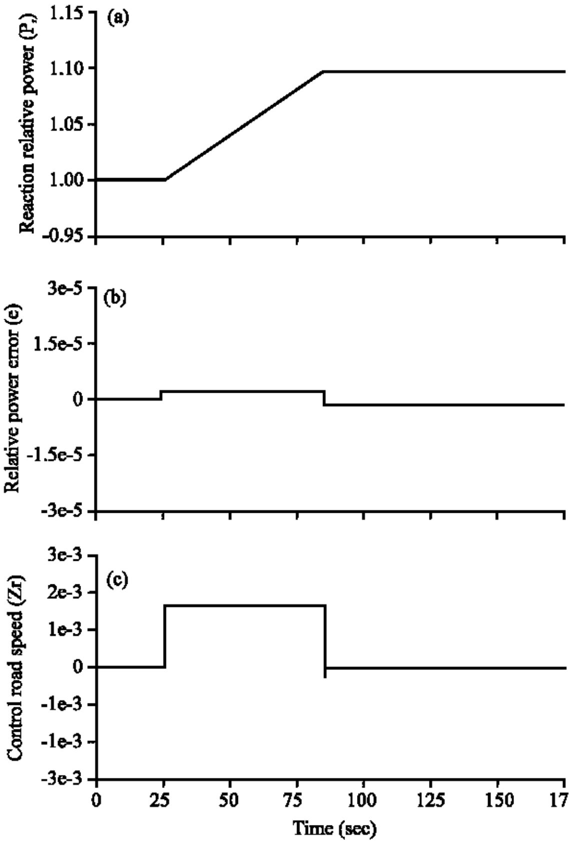


Fig. 3: Simulation results obtained in the full power operation with the 10%/min decrease rate (100-110%): a) The reactor output relative power; b) The power tracking error; c) The control rod speed

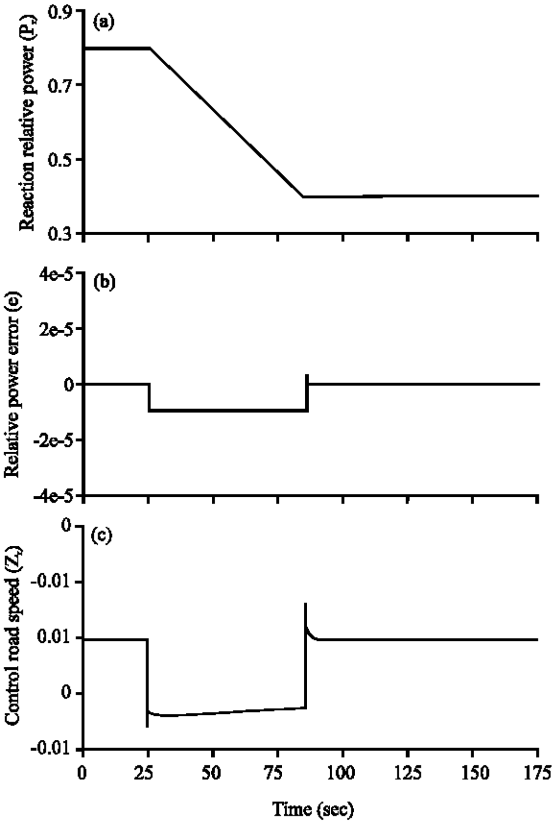


Fig. 4: Simulation results obtained in the middle power operation with the 40% /min decrease rate (80-40%): a) The reactor output relative power; b) The power tracking error; c) The control rod speed

signal of the proposed ROSMC is $>1\times10^{-3}$%. Moreover, the control rod speed (the control effort signal) is shown in Fig. 3c which is not exceeded from 2×10^{-3} and has no chattering.

Middle power operation: In this study, a change in power from 80-40% with 40%/min ramp decrease of a desired power is considered. The reference power tracking, the tracking error signal and the control rod speed are demonstrated in Fig. 4, respectively. It is obvious from Fig. 4a that the performance of ROSMC is quite acceptable in tracking of the reference power. The tracking error reached approximately to zero and the amplitude of control effort is not >0.01 as shown in Fig. 4b, c, respectively.

Emergency operation: To study this simulated case, the reference power was supposed 100%, then decrease to 10% by the ramp variation. After 60 sec the reference power returned to 100% by the ramp variation. Figure 5 shows the simulation results. The relative power properly tracked its reference power signal and the error signal reach to zero after finite time during/after the variations as shown in Fig. 5a and b they are shown that the controller follow the reference power very good. From Fig. 5c, similar to the previous cases, the control effort signal has no chattering and its amplitude was limited.

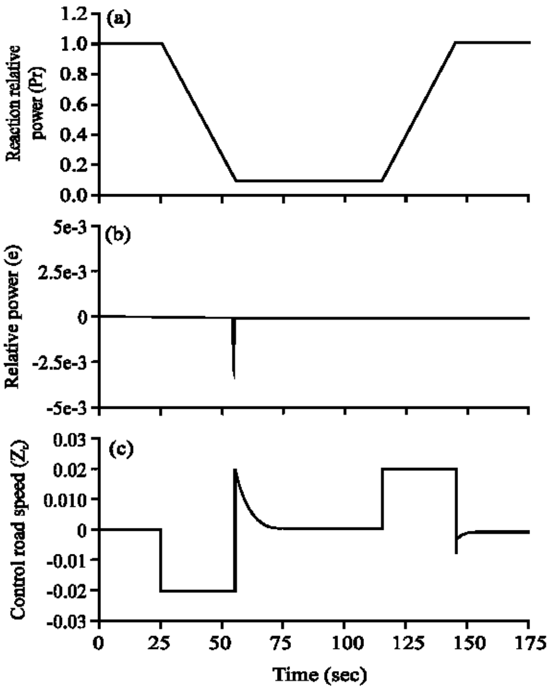


Fig. 5: Simulation results obtained in the emergency operation with the 90%/0.5min decrease and increase rate (100-10% and 10-100%): a) The reactor output relative power; b) The power tracking error and c) The control rod speed

Disturbance of reactivity insertion: In the 4th simulation the efficiency and effectiveness of the controller in confronting with a certain disturbance is investigated. It is assumed that the disturbance signal is inserted between the controller output and system (added to control effort) when the reactor is operated in 100% of its nominal power as shown in Fig. 6a. The supposed disturbance trajectory is shown in Fig. 7 which two disturbances values of 0.03 and -0.03 are inserted at 30 and 90's, respectively. The results consist the output relative power, error signal and control effort signal are shown in Fig. 8.

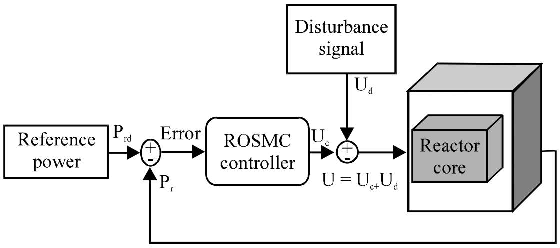


Fig. 6: Location of Inserted disturbance signal between the controller output and reactor

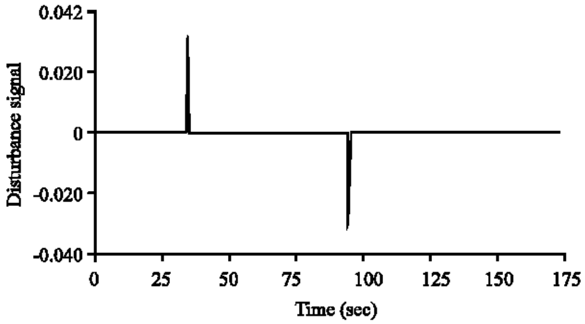


Fig. 7: Disturbance signal

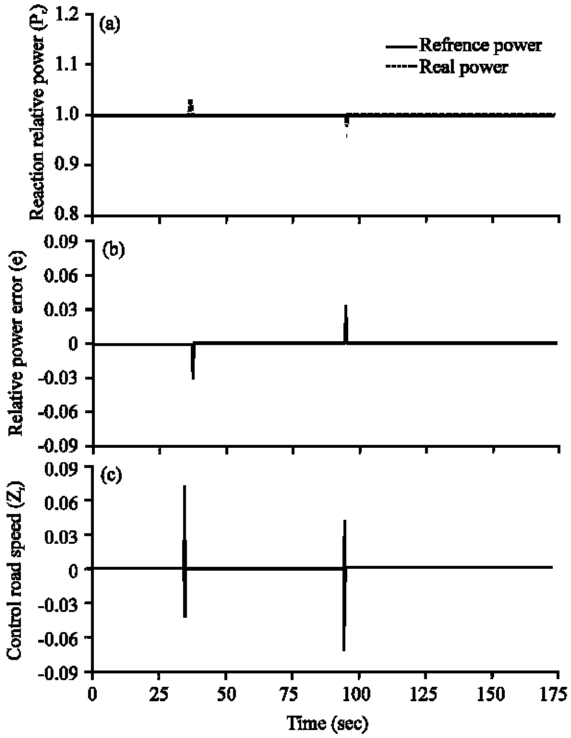


Fig. 8: Simulation results of the proposed controller in confronting with a disturbance signal: a) The reactor output relative power; b) the power tracking error and c) the control rod speed

CONCLUSION

In this study, a sliding mode controller based on reduced order CNPK model to control the reactor power in TRR is developed. The CNPK model is only based on the measurable variable of the system such as relative output power and coolant temperature which is considered as control inputs and the controller output is control rod speed. The stability of the closed loop system is investigated using lyapunov method. Finally, a control law based on output relative power and coolant temperature, tracking error and controller parameters (λ_1, β, γ, M) is presented. This controller is simulated using Matlab/Simulink.

Finally, the closed-loop system is tested in three different cases, the full power operation, the middle power operation and the emergency operation. The simulation results show that proposed ROSMC has an acceptable performance in the reference power trajectory tracking. Also, to investigate the controller robustness in the face of the external disturbance, a certain disturbance signal is inserted between controller and reactor system and results are discussed. This controller has high robustness in the presence of external disturbance and has very small error.

NOMENCLATURE

CFE = Control Fuel Elements
C = Core Averaged Precursor Density (atom/cm3)
C_0 = Initial Equilibrium (Steady-State) Density of Precursor (atom/cm^3)
C_r = Relative concentrations of delayed neutrons
FOC = First Operating Core
FRR = Fine Regulating Rod
f_f = Fraction of reactor power deposited in the fuel
G_r = Total reactivity worth of control rod
φ = Neutron Flux (n/cm^2.sec)
P_0 = Nominal power (Mw)
n_r = Neutron density relative to initial equilibrium density (n/n_0)
n = Neutron density (n/cm^3)
n_0 = Initial equilibrium neutron density (n/cm^3)
M = Mass flow rate multiplied by heat capacity of the coolant (MW/k)
N = Number of the fuel elements
SSR = Shim safety rod
SFE = Standard fuel elements
Z_r = Control input, control rod speed in units of fraction of core length per second
γI = Iodine yield
Σf = Macroscopic fission cross section

σ^x_a = Xenon microscopic absorption cross section (cm^2)
TRR = Tehran Research Reactor
T_e = Coolant inlet Temperature (°C)
T_f = Average fuel Temperature (°C)
Tf^0 = Initial equilibrium (steady-state) fuel average Temperature (°C)
TI = Coolant outlet Temperature (°C)
T_c = Average reactor coolant Temperature
Tc_0 = Initial equilibrium (steady-state) coolant average Temperature (°C)
V_f = Volume of the Fuel (cm^3)
αc = Coolant temperature reactivity coefficient (Δk/k/°C)
αf = Fuel temperature reactivity coefficient (Δk/k/°C)
β = Total delayed neutron fraction
Λ = Neutron generation time (sec)
λ = Decay constant for precursor decay
ρ = Total reactivity (Δk/k)
μ = Heat transfer coefficient between fuel and coolant (Mw/°C)
μ_f = Total heat capacity of the fuel (Mj/°C)
μ_c = Total heat capacity of the reactor coolant (Mj/°C)
ρ_{ex} = Reactivity due to the control rod movement

REFERENCES

AAEOI., 2009. Final safety analyses report for Tehran research reactor. Atomic Energy Organization of Iran, Tehran, Iran.

Ansarifar, G.R. and H.R. Akhavan, 2015. Sliding mode control design for a PWR nuclear reactor using sliding mode observer during load following operation. Ann. Nucl. Energy, 75: 611-619.

Ansarifar, G.R. and M. Rafiei, 2015. Higher order sliding mode controller design for a research nuclear reactor considering the effect of xenon concentration during load following operation. Ann. Nucl. Energy, 75: 728-735.

Arab-Alibeik, H. and S. Setayeshi, 2005. Adaptive control of a PWR core power using neural networks. Ann. Nucl. Energy, 32: 588-605.

Coban, R., 2014. Power level control of the TRIGA Mark-II research reactor using the multifeedback layer neural network and the particle swarm optimization. Ann. Nucl. Energy, 69: 260-266.

Dong, Z., 2011. Nonlinear state-feedback dissipation power level control for nuclear reactors. IEEE. Trans. Nucl. Sci., 58: 241-257.

Emelyanov, S.S. and I.G. Mamedov, 1995. Variable Structure Control Systems. Vol. 51, CRC Press, Moscow, Russia,.

Eom, M., D. Chwa and D. Baang, 2015. Robust disturbance observer-based feedback linearization control for a research reactor considering a power change rate constraint. IEEE. Trans. Nucl. Sci., 62: 1301-1312.

Li, G. and F. Zhao, 2013. Load following control and global stability analysis for PWR core based on multi-model, LQG, IAGA and flexibility idea. Prog. Nucl. Energy, 66: 80-89.

Munje, R.K., B.M. Patre, S.R. Shimjith and A.P. Tiwari, 2013. Sliding mode control for spatial stabilization of advanced heavy water reactor. IEEE. Trans. Nucl. Sci., 60: 3040-3050.

Na, M.G., I.J. Hwang and Y.J. Lee, 2006. Design of a fuzzy model predictive power controller for pressurized water reactors. IEEE. Trans. Nucl. Sci., 53: 1504-1514.

Rojas, R.E., J.S.B. Read and A.S.D.L. Rios, 2013. A stable adaptive fuzzy control scheme for tracking an optimal power profile in a research nuclear reactor. Ann. Nucl. Energy, 58: 238-245.

Xia, L., J. Jiang and J.C. Luxat, 2014. Power distribution control of CANDU reactors based on modal representation of reactor kinetics. Nucl. Eng. Des., 278: 323-332.