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Robust nonlinear control for nuclear reactors using sliding mode observer to estimate the xenon concentration

G. R. Ansarifar[1] · H. R. Akhavan[1]

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Abstract This paper presents findings on the sliding mode controller for a nuclear reactor. One of the important operations in nuclear power plants is load following. In this paper, a sliding mode control system, which is a robust nonlinear controller, is designed to control the pressurized-water reactor power. The reactor core is simulated based on the point kinetics equations and six delayed neutron groups. Considering neutron absorber poisons and regarding the limitations of the xenon concentration measurement, a sliding mode observer is designed to estimate its value, and finally, a sliding mode control based on the sliding mode observer is presented to control the core power of reactor. The stability analysis is given by means Lyapunov approach; thus, the control system is guaranteed to be stable within a large range. The employed method is easy to implement in practical applications, and moreover, the sliding mode control exhibits the desired dynamic properties during the entire output-tracking process independent of perturbations. Simulation results are presented to demonstrate the effectiveness of the proposed observer-based controller in terms of performance, robustness and stability.

Keywords Pressurized-water reactor · Robust nonlinear controller · Sliding mode observer · Point kinetics equations · Xenon concentration · Lyapunov approach

✉ G. R. Ansarifar
ghr.ansarifar@ast.ui.ac.ir

[1] Department of Nuclear Engineering, Faculty of Advanced Sciences and Technologies, University of Isfahan, Isfahan 81746-73441, Iran

1 Introduction

For a nuclear power plant, controlling and improving its availability and load following capability is an important issue [1]. Reactor power control has been used in base-load operating conditions traditionally. But with the increasing share of nuclear power plants (NPPs) in electricity generation, it seems that the load-follow operation of nuclear reactors will be inevitable in the future. It is hard to get satisfying performance with the classic control strategy to control the reactor power [2]. In order to establish good operation performance of NPPs, many investigations have been proposed for reactor core control. Edwards et al. [3] demonstrated improved robustness characteristics of state feedback assisted classical control (SFAC) to cope with changes in reactor parameters over that of conventional state feedback control (CSFC). Park and Cho introduced a model-based feedback linearization controller with adaptive PI gains [1]. They also designed a model-based two-stage controller [4]. These control systems mostly were designed based on an approximate linear core model and hold true in limited range; the performance would lapse if the range is gone beyond.

Various controllers including neural network method, fuzzy logic method [5, 6], emotional learning-based intelligent controller [7] and robust optimal control systems have been used for controlling the reactor's power [2]. Boroushaki et al. [8] proposed an intelligent nuclear reactor core controller for load following operations, using recurrent neural networks and fuzzy systems. An improved temperature control of a PWR reactor using an LQG/LTR-based controller was designed by Arab-Alibeik and Setayeshi [9]. They also proposed adaptive control of a PWR core power using neural networks [10].

A nuclear reactor is a nonlinear and complex system whose parameters vary with the power level. In spite of many advanced control methods proposed for controlling the reactor core power, it seems that a simple and high-performance control system is still needed. On the other hand, a successful strategy to control the uncertain nonlinear systems is sliding mode control. The sliding mode controller is an attractive robust control algorithm because of its inherent insensitivity and robustness to plant uncertainties and external disturbances [11]. In this paper, a sliding mode control system is designed to control PWR power based on the point kinetics equations with six groups of the delayed neutrons considering neutron absorber poison [12]. Since the measurement of the xenon concentration is practically difficult and it should be measured to design the controller, a sliding mode observer which has the robust characteristics facing the external disturbances and parameters' uncertainties is proposed based on reactor power measurement to estimate the xenon concentration.

Finally, a sliding mode control (SMC) system based on the sliding mode observer is presented to control the reactor core power. The computer simulations demonstrate effectiveness of the proposed control system in diverse operating conditions. The results show that the sliding mode observer follows the actual system variables accurately and is satisfactory in the presence of the parameter uncertainties and disturbances.

2 Nuclear reactor core model

To simulate the nuclear reactor core, point kinetics equations with six groups of the delayed neutrons are used [12]. The model assumes the feedbacks from lumped fuel and coolant temperatures. The effect of xenon concentration is also included. The normalized model, with respect to an equilibrium condition, based on point kinetics equations with six delayed neutrons groups are as follows:

$$\begin{cases} \dfrac{dn_r}{dt} = \dfrac{\rho - \beta}{l} n_r + \sum_{i=1}^{6} \dfrac{\beta_i}{l} c_{ri} \\ \dfrac{dc_{ri}}{dt} = \lambda_i n_r - \lambda_i c_{ri} \quad i = 1, \ldots, 6 \end{cases}, \tag{1}$$

where n_r is neutron density relative to initial equilibrium density and c_{ri} is ith group precursor relative density normalized with the initial equilibrium density. The reactor power is displayed as follows:

$$P(t) = P_0 n_r(t), \tag{2}$$

where P_0 is the nominal power (MW). Based on lumped fuel model, the thermal-hydraulics model of the reactor core is represented as follows [12]:

$$\begin{cases} \mathrm{dT_f}/\mathrm{d}t = \dfrac{f_f p_0}{\mu_f} n_r - \dfrac{\Omega}{\mu_f} \mathrm{T_f} + \dfrac{\Omega}{\mu_f} \mathrm{T_c} \\ \mathrm{dT_c}/\mathrm{d}t = \dfrac{(1 - f_f) P_0}{\mu_c} n_r + \dfrac{\Omega}{\mu_c} \mathrm{T_f} - \left(\dfrac{2M + \Omega}{2\mu_c} \right) (2\mathrm{T_c} - 290) + \left(\dfrac{2M - \Omega}{2\mu_c} \right) 290 \end{cases} \tag{3}$$

Changes in xenon concentration can be expressed as [13]:

$$\begin{cases} \dfrac{dx}{dt} = \gamma_x \Sigma_f \phi + \lambda_I I - \sigma_x x \phi - \lambda_x x \\ \dfrac{dI}{dt} = \gamma_I \Sigma_f \phi - \lambda_I I \end{cases} \tag{4}$$

Finally, the reactivity input and feedback to the point kinetics model can be written as:

$$\begin{aligned} \rho &= \rho_r + \alpha_f (T_f - T_{f_0}) + \alpha_c (T_c - T_{c_0}) - \sigma_x (x - x_0)/\Sigma_f \\ &= \rho_r + \rho_T + \rho_x, \end{aligned} \tag{5}$$

$$\frac{d\rho_r}{dt} = G_r Z_r. \tag{6}$$

All the parameters are described in Table 1.

3 Preliminary

In this section, a brief description of the relevant theory and control design algorithms used in the development of the PWR power controller is given.

3.1 Sliding mode control

Sliding mode control is a variable structure control system. For the class of systems which can be applied, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. The sliding mode controller is an attractive robust control

Table 1 Nomenclature

Parameters	Signs
Fraction of delayed fission neutrons	β
Effective precursor radioactive decay constant(1/s), chosen to match the three group reactor transfer function to a six delayed neutron group reactor transfer	λ_i
Effective prompt neutron lifetime (s)	l
Core reactivity	ρ
Reactivity change due to the control rod	ρ_r
Feedback reactivity change due to temperature changes	ρ_T
Feedback reactivity change due to xenon concentration variation,	P_x
Control rod speed (fraction of core length per second)	Z_r
Total reactivity of the rod	G_r
Macroscopic fission cross-section (1/cm)	Σ_f
Heat transfer coefficient between fuel and coolant (MW/°C)	Ω
Mass flow rate times heat capacity of the water (MW/°C)	M
Neutron flux (n/cm^2 s)	Φ
Fraction of reactor power deposited in the fuel	f_f
Total thermal capacity of the fuel and structural material (MW s/°C)	μ_f
Total heat capacity of the reactor coolant (MW s/°C)	μ_c
Xenon decay constant (1/s)	λ_x
Iodine decay constant (1/s)	λ_i
Xenon yield	γ_x
Iodine yield	γ_i
Microscopic absorption cross-section of xenon (cm^2)	σ_x
Averaged reactor fuel temperature, coolant temperature (°C)	T_c, T_f

algorithm because of its inherent insensitivity and robustness to plant uncertainties and external disturbances [11].

Consider a general nonlinear system

$$\begin{cases} \dot{x}(t) = f(x) + g(x)u \\ y = h(x) \end{cases}, \tag{7}$$

where f, g and h are sufficiently smooth functions. Let $e(t) = y_d - y$ be the tracking error. Furthermore, a stable switching surface $s(t)$ in the state space $R^{(r)}$ can be defined by the scalar equation $s(t) = 0$, where

$$s(t) = \left(\frac{d}{dt} + m\right)^{r-1} e(t), \tag{8}$$

where r is a relative degree and m is a strictly positive constant which defines the bandwidth of the error dynamics.

Remark 1 The relative degree r for Eq. (7) is the integer for which the following equations hold [14]:

$$\begin{cases} L_g L_f^k h(x) = 0, \quad k < r - 1 \\ L_g L_f^{r-1} h(x) \neq 0 \end{cases}, \tag{9}$$

where $L_p h(x) = [\partial h(x)/\partial(x] \cdot p$ for $p = f,\ g$ is the Lie derivative of the function $h(x)$ [14].

From Eq. (8), the tracking problem amounts to remaining on the switching surface $s(t)$ for the rest of time. The sliding mode control design is to choose the control input and satisfy the following attractive equation:

$$\frac{1}{2}\frac{d}{dt} s^T s \leq -\eta |s|, \tag{10}$$

where η is a strictly positive constant which determines the desired reaching time to the sliding surface. The attractive Eq. (10) is also called sliding condition which implies that the distance to the sliding surface decreases along all system trajectories. Furthermore, the sliding condition makes the sliding surface an invariant set; that is, once a system trajectory reaches the surface, it remains on it for the rest of time. In addition, for any initial condition, the sliding surface is reached within a finite time.

In order to achieve the sliding mode, the control rule needs to be discontinuous along the switching surface $s(t)$. Since switching is not spontaneous and the S value is not exact, the variable structure control application is not completed and chattering occurs in the vicinity of the sliding surface, and it is possible to excite the dynamic high frequencies. Therefore, it should be reduced and deleted, so to apply the variable structure controller well [14]. Here, in order to reduce chattering, boundary layer around sliding surface strategy will be used [15].

In sliding mode control, tanh(s) is used instead of sign(s):

$$\dot{s} = -\eta \tanh\left(\frac{s}{\varphi}\right), \tag{11}$$

where φ is the width of the boundary layer.

3.2 Sliding mode observer

The actual state $x(t)$ may not be measurable, so we need to design an observer and use the observed state for feedback. Based on the work done by Lyon-Berger, applying the state observer indicated that not only is it usable in observing and controlling the system, but also in detecting the faults in dynamic system. This is due to the fact that the entire observer designs are based on the mathematical model of the system. The disturbances, dynamic system uncertainties and nonlinear factors cause a big challenge in practical applications. Therefore, designing the robust observer with good function is considered and several observers are developed. The sliding mode observer is considered to be robust compared to the conventional observers. The sliding mode observer is based on sliding mode principle. Similar to sliding mode control design, the sliding mode observer design procedure consists of performing the following two steps:

1. Design the manifold $s(y, t)$ such that the estimation error trajectories restricted to $s(y, t)$ has the desired stable dynamics.
2. The observer gain is determined to drive the estimation error trajectories to $s(y, t)$ and maintain it on the set, once intercepted, for all subsequent time.

In other words, sliding mode observer works by minimizing the error between plant model and the observer model using a switching function. The observer gain is adjusted by the error such that the plant output matches with observer output and error surface moves toward minimum [16].

Because of simplicity, a nonlinear system has been considered which is described as follows:

$$\begin{cases} \dot{x} = f(x, u, t) \\ y = g(x, u, t) \end{cases}, \tag{12}$$

Sliding mode observer (SMO) is defined for nonlinear system as follows [17]:

$$\begin{cases} \dot{\hat{x}} = f(\hat{x}, u, t) + k(y - \hat{y}) + \psi \text{sign}(y - \hat{y}) \\ \hat{y} = g(\hat{x}, u, t) \end{cases}, \tag{13}$$

where $\hat{x}$ and $\hat{y}$ are estimated state and estimated output of the system (13) with SMO, respectively.

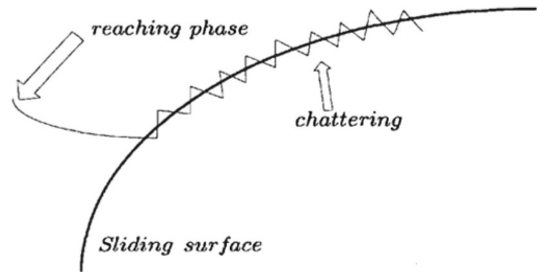

Fig. 1 The schemes of chattering phenomenon

An ideal sliding mode does not exist in practice since it would imply that the control commutes at an infinite frequency. In the presence of switching imperfections, such as switching time delays and small time constants in the actuators, the discontinuity in the feedback control produces a particular dynamic behavior in the vicinity of surface, which is commonly referred as chattering (Fig. 1).

In order to reduce chattering, boundary layer around sliding surface strategy with saturation functions such as tanh(s) instead of sign function is used. Indeed, tanh(s) is a continuous and smooth approximation in boundary layer as shown in the Fig. 2.

This avoids from the high-frequency oscillations and reduces chattering phenomena. In this case, as control designing, the tanh(s/φ) is used instead of switching function in order to prevent the chattering phenomenon in sliding mode observer design where $s = y - \hat{y}$ and φ is the width of the boundary layer [15].

4 Sliding mode observer design to estimate the xenon concentration

Since the xenon concentration in reality cannot be measured in nuclear reactors, an observer is needed to estimate the immeasurable values. In this section, a sliding mode observer which has the robust characteristics facing the external disturbances and parameters' uncertainties is proposed for the reactor power measurement.

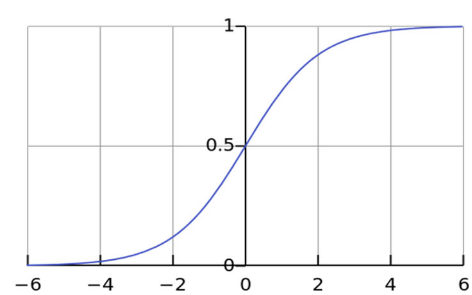

Fig. 2 Behavior of tanh function

According to Eq. (13), the reactor core power, as an output and immeasurable value, can be estimated as:

$$\dot{\hat{n}}_r = \frac{\hat{\rho} - \beta}{l}\hat{n}_r + \sum_{i=1}^{6}\frac{\beta_i}{l}c_{ri} + k_1(n_r - \hat{n}_r) + \psi_1 \tanh\left(\frac{n_r - \hat{n}_r}{\varphi}\right), \tag{14}$$

where

$$\begin{aligned}\widehat{\rho} &= \rho_r + \alpha_f(T_f - T_{f_0}) + \alpha_c(T_c - T_{c_0}) - \sigma_x(\widehat{x} - x_0)/\Sigma_f \\ &= \rho_r + \rho_T + \rho_{\widehat{x}},\end{aligned} \tag{15}$$

$\widehat{x}$ is the estimated xenon concentration.

The equation related to the changes of the estimated xenon concentration is as follows:

$$\begin{cases}\dot{\hat{x}} = \gamma_x \Sigma_f \phi + \lambda_I \hat{I} - \sigma_x \widehat{x}\phi - \lambda_x \hat{x} + k_2(n_r - \hat{n}_r) + \psi_2 \tanh\left(\frac{n_r - \hat{n}_r}{\varphi}\right) \\ \dot{\hat{I}} = \gamma_I \Sigma_f \phi - \lambda_I \hat{I} + k_3(n_r - \hat{n}_r) + \psi_3 \tanh\left(\frac{n_r - \hat{n}_r}{\varphi}\right)\end{cases}. \tag{16}$$

In order to prove that the sliding mode observer can provide convergent state observation, Lyapunov synthesis can be used [18]. Using the estimation error of states, consider the Lyapunov-like function:

$$V = \frac{1}{2}\left(e_{n_r}^2 + e_x^2 + e_I^2\right), \tag{17}$$

where

$$\begin{cases} e_{n_r} = \hat{n}_r - n_r \\ e_x = \hat{x} - x \\ e_I = \hat{I} - I \end{cases}. \tag{18}$$

Considering the Eq. (17), its derivative is identified as follows:

$$\dot{V} = e_{n_r}\dot{e}_{n_r} + e_x \dot{e}_x + e_I \dot{e}_I. \tag{19}$$

Now, by calculating $\dot{e}_{n_r}, \dot{e}_x \& \dot{e}_I$ using the previous equations with choosing appropriate observer gains and substituting them into Eq. (19), we have:

$$\dot{V} = -k_1 e_{n_r}^2 - \psi_1 e_{n_r} \tanh\left(\frac{e_{n_r}}{\varphi}\right) - \sigma_x e_x^2 \phi - \lambda_x e_x^2 - \lambda_I e_I^2, \tag{20}$$

which shows the negative definiteness of $\dot{V}$ and confirms that the sliding mode observer ensures the bounded states and can provide the convergence of observed states to the their actual values.

5 SMC design based on the observer to control the PWR power

According to point kinetics equations and considering control rod speed z_r as the control input, relative degree of the reactor system is 2, and therefore, at the first step of the sliding mode controller design, the desirable sliding surface is represented as follows:

$$S(t) = me(t) + \dot{e}(t). \tag{21}$$

where $e(t)$ is tracking error of the desired relative power as:

$$e(t) = n_r - n_{rd}. \tag{22}$$

The sliding surface is reached in a finite time $t_r = |S(0)|/\eta$ and the system's trajectory stays on the manifold thereafter where $S(0)$ is an initial value of a sliding surface and $\eta > 0$. Using the sliding surface and estimated values from observer, control input is designed to satisfy the attractive Eq. (10) using Eq. (11) as follows:

According to the desirable sliding surface, Eq. (21), and considering control rod speed z_r as the control input, to derive the sliding mode controller using Eq. (11), should be satisfied. Therefore, we achieve the first-time derivative of sliding surface as follows:

$$\dot{s} = m\dot{e} + \ddot{e}, \quad e = n_r - n_{rd} \Rightarrow \dot{s} = m\dot{e} + \ddot{n}_r - \ddot{n}_{rd}. \tag{23}$$

According to the point kinetics equations and using Eqs. (11), (23) can be written as:

$$-\eta \tanh\left(\frac{s}{\varphi}\right) = m\dot{e} + \left(\frac{\rho - \beta}{l}\right)\dot{n}_r + \frac{\dot{\rho}}{l}n_r + \sum_{i=1}^{6}\frac{\beta_i}{l}\dot{c}_{ri}. \tag{24}$$

Now, using the Eqs. (5) and (6) and estimated value $\widehat{x}$ from observer, control input can be obtained as:

$$\begin{aligned} z_r = \frac{l}{n_r G_r}&\left[\ddot{n}_{rd} - m\dot{e} - \eta \tanh\left(\frac{S}{\varphi}\right) - \frac{\hat{\rho} - \beta}{l}\dot{n}_r - \frac{1}{l}\sum_{i=1}^{6}\beta_i \dot{c}_{ri}\right] \\ &- \frac{1}{G_r}\left[\alpha_f \frac{dT_f}{dt} + \alpha_c \frac{dT_c}{dt} - \sigma_x \hat{x}/\Sigma_f\right]. \end{aligned} \tag{25}$$

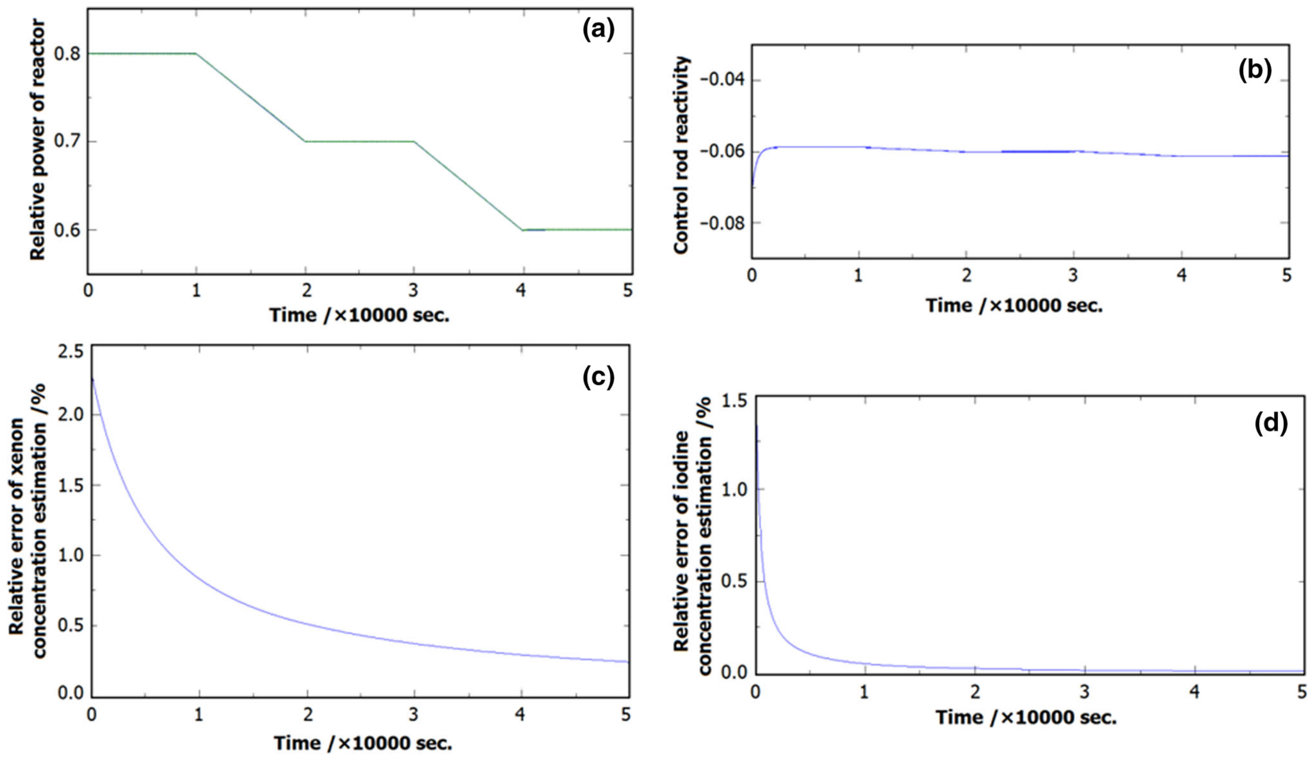

Fig. 3 Performance of the SMC system for power level demands changing from 80 to 70 to 60 % at a rate of 3.6 %/h, **a** relative power of reactor, **b** control rod reactivity and relative error of xenon (**c**) and iodine (**d**) concentration estimation

5.1 Stability analysis of the designed SMC system

In this section, stability of the designed sliding mode control system based on the sliding mode observer is analyzed using the Lyapunov synthesis. Consider the Lyapunov-like function:

$$V = \frac{1}{2} s^2(t), \tag{26}$$

where $s(t)$ is the desirable sliding surface. Using Eq. (25), derivative of the Lyapunov-like function of Eq. (26) is identified as follows:

$$\dot{V} = s\left[\left(\frac{\rho - \hat{\rho}}{l}\right)\dot{n}_{\mathrm{r}} + \frac{n_{\mathrm{r}}}{l}\left(\frac{\sigma_{\mathrm{x}}\dot{e}_{\mathrm{x}}}{\Sigma_{\mathrm{f}}}\right) - \eta \tanh\left(\frac{s}{\varphi}\right)\right]. \tag{27}$$

According to Eq. (20) and stability of sliding mode observer, the convergence of states estimation error to zero can be satisfied and hence $\dot{e}_{\mathrm{x}} \to 0, \hat{\rho} \to \rho$. Therefore, from Eq. (27) we can have:

$$\dot{V} = -\eta s \tanh\left(\frac{s}{\varphi}\right) \le 0. \tag{28}$$

Equation (28) implies that the Lyapunov function is bounded; hence, s is bounded. However, the convergence of s to zero cannot be established. To show the convergence of s, we can use Barbalat's lemma [19]. Toward this end, consider:

$$\ddot{V} = \eta^2 \tanh\left(\frac{s}{\varphi}\right)\left[\tanh\left(\frac{s}{\varphi}\right) + \frac{s}{\varphi}\left(1 + \tanh^2\left(\frac{s}{\varphi}\right)\right)\right]. \tag{29}$$

It can be seen that $\ddot{V}$ is bounded since s and $\tanh(s/\varphi)$ are bounded. Since V is bounded $\dot{V}$ is bounded and $\ddot{V}$ is also bounded, we can infer from the Barbalat's lemma that $\dot{V} \to 0$ as $t \to \infty$ and hence $s \to 0$. This proves that the control law of Eq. (25) with observed states satisfies the existence condition of the sliding mode in the system on the sliding surface of Eq. (21) and ensures the perfect tracking of the desired reactor power.

Based on the applicable inputs in nuclear power plants, designed sliding mode control system is applied to the reactor and results are indicated in the next section.

6 Results and discussion

In this section, a set of simulations is performed on the reactor model described in Sect. 2, to evaluate the performance and robustness of the proposed control structure. Two different transients have been used to evaluate the

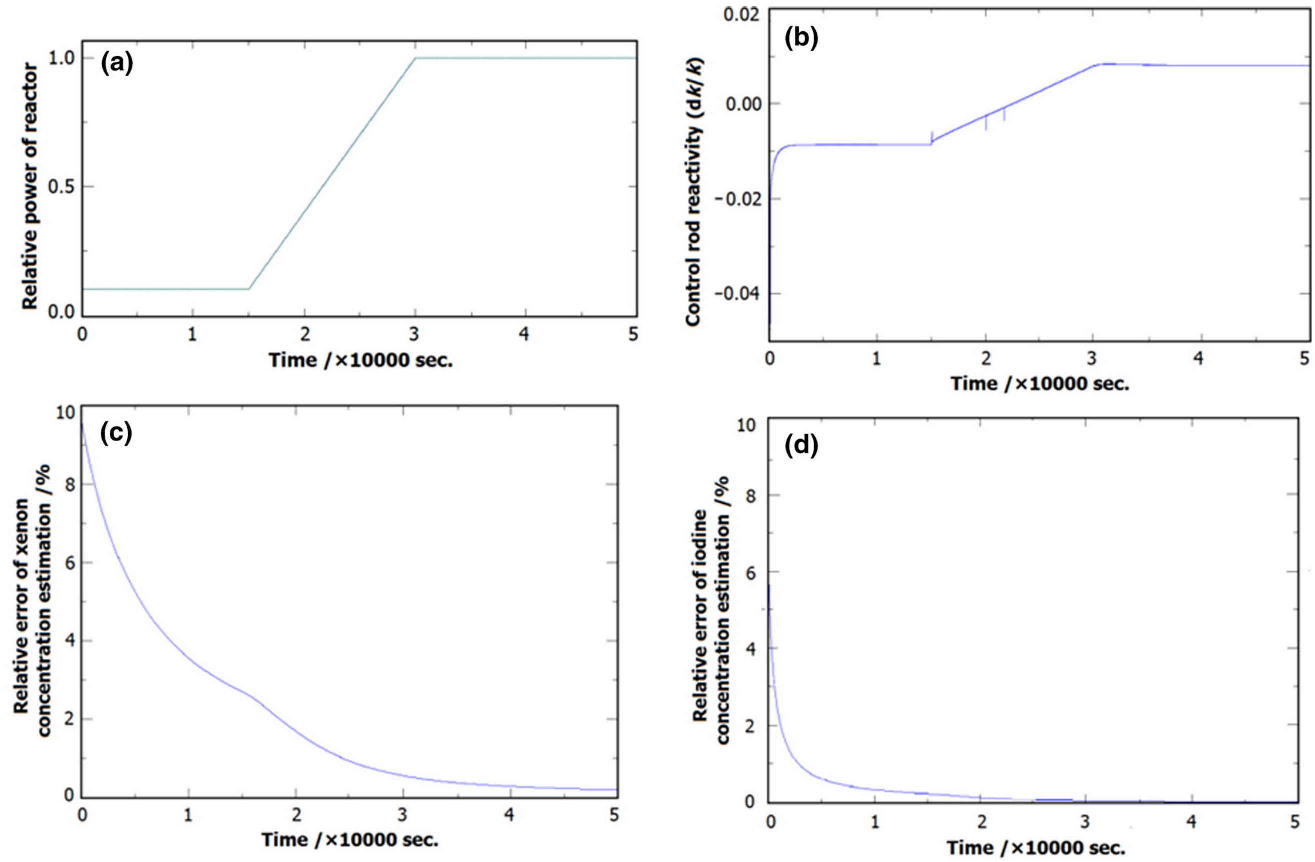

Fig. 4 Performance of the SMC system for power level demands from 10 to 100 %, **a** relative power of reactor, **b** control rod reactivity and relative error of xenon (**c**) and iodine (**d**) concentration estimation

performance of the controller. In all of these cases, the objective is to follow the reference power in reactor.

Figure 3a, b shows performance of the SMC system for demand of power level changing from 80 to 70 to 60 % with the rate of 3.6 %/h. The desired power is reached quickly, with no overshoot and oscillation. Figure 3c, d, based on Eq. (30), shows the relative estimation error of Xe and I concentrations, respectively (Fig. 4).

$$\begin{cases} \mathrm{REE} = \dfrac{\hat{x} - x}{x} \\ \mathrm{REE} = \dfrac{\hat{I} - I}{I} \end{cases} \tag{30}$$

Figure 5 illustrates the SMC system behavior under the parameters' uncertainties and external disturbance. All system parameters are perturbed by ±20 % from their nominal values. The results show that the robustness and stability have indeed been achieved. Also, it is observed that the sliding mode observer is satisfactory in the presence of the parameters' uncertainties and disturbance.

A comparison of the SMC and the conventional PID controller with optimal gains is depicted in Fig. 6. Faster response and better tracking of the desired power can be observed for the SMC.

7 Conclusion

In this paper, a sliding mode control system based on the sliding mode observer has been presented for core power control of the pressurized-water reactor to improve the load following capability. The reactor core was simulated based on the point kinetics equations and six delayed neutron groups. In order to deal with shortcomings arising from system states unavailability, a sliding mode observer has been developed to estimate the xenon concentration which is difficult to measure in practice. Stability of the designed sliding mode control system based on the sliding mode observer has been analyzed using the Lyapunov synthesis; thus, the control system was guaranteed to be stable within a large range. The main advantage of the SMC technique is its inherent insensitivity and robustness to plant uncertainties and external disturbances. This approach provides a high-performance controller on the system. Besides,

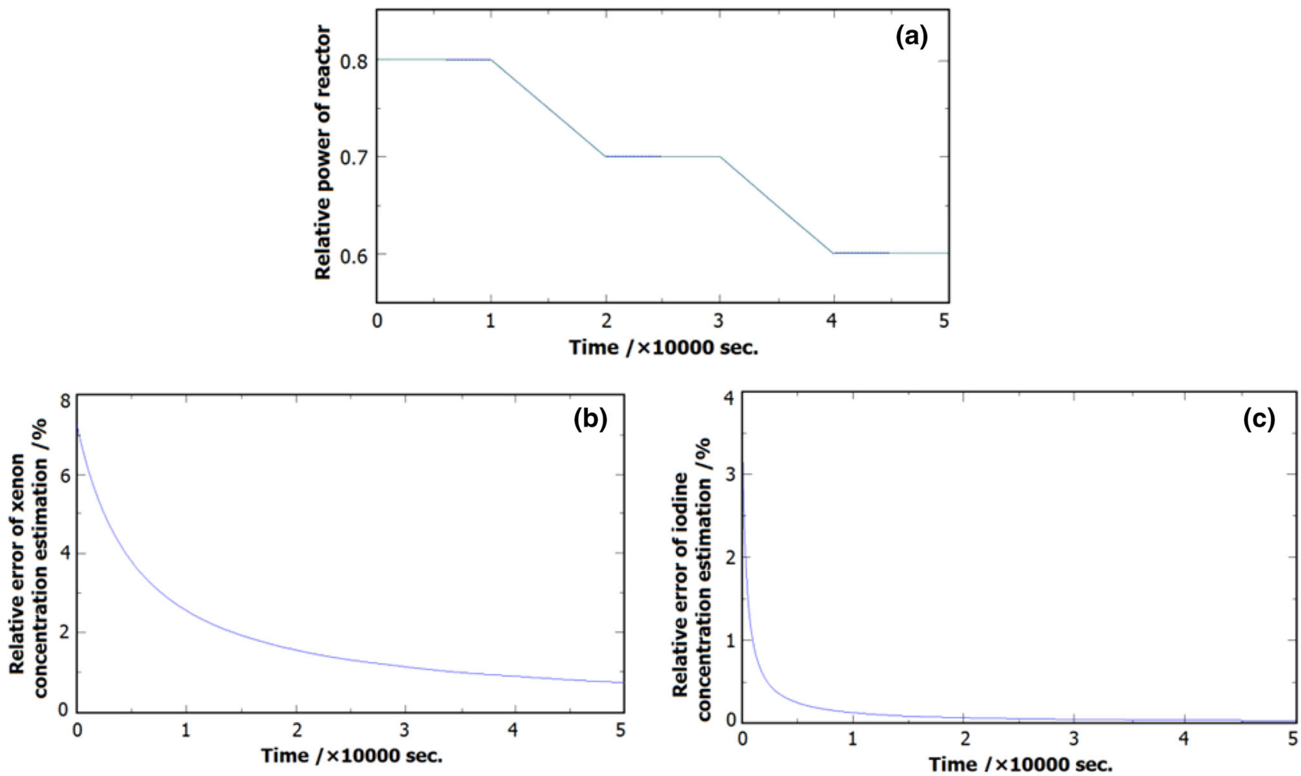

Fig. 5 The SMC system behavior under parameter with uncertainties and external disturbance. **a** relative power of reactor and relative error of xenon (**b**) and iodine (**c**) concentration estimation

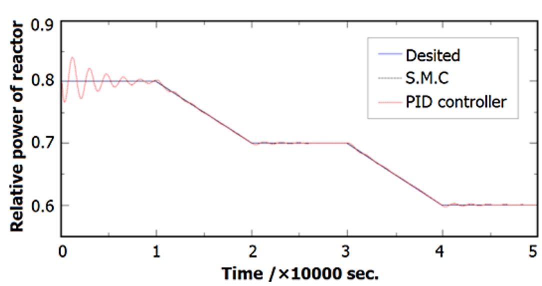

Fig. 6 Comparison of the proposed controller and conventional PID controller

simplicity of the controller structure and design procedure as well as satisfactory tracking performance and robust stability are remarkable as compared with the previous designs.

Simulation results demonstrated that clear asymptotic output tracking was insensitive to the external disturbance and parameters' uncertainties. Besides, it was observed that the sliding mode observer was satisfactory in the presence of the parameters' uncertainties and disturbance. The comparison between SMC and the conventional PID controller showed a significant improvement in the desired core power tracking for SMC system.

Further, to extend the results to MIMO system, it should be defined at least two sliding surfaces containing suitable tracking errors and considering at least two control inputs such as control rods speeds, Z_{r1} and Z_{r2}, as the control inputs. Similar to the SISO system, control inputs are chosen to satisfy the attractive Eq. (10) using Eq. (11). Also, as control designing, SMO can be extended to MIMO system.

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