Original Article

New design of variable structure control based on lightning search algorithm for nuclear reactor power system considering load-following operation

M. Elsisi [a], [*], H. Abdelfattah [b]

[a] Electrical Engineering Department, Faculty of Engineering in Shoubra, Benha University, Egypt
[b] Electrical Engineering Department, Faculty of Industrial Education, Suez University, Egypt

A B S T R A C T

Reactor control is a standout amongst the most vital issues in the nuclear power plant. In this paper, the optimal design of variable structure controller (VSC) based on the lightning search algorithm (LSA) is proposed for a nuclear reactor power system. The LSA is a new optimization algorithm. It is used to find the optimal parameters of the VSC instead of the trial and error method or experts of the designer. The proposed algorithm is used for the tuning of the feedback gains and the sliding equation gains of the VSC to prove a good performance. Furthermore, the parameters of the VSC are tuned by the genetic algorithm (GA). Simulation tests are carried out to verify the performance and robustness of the proposed LSA-based VSC compared with GA-based VSC. The results prove the high performance and the superiority of VSC based on LSA compared with VSC based on GA.

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1. Introduction

The nuclear power plant is a thermal power station that generates electrical power by using the output heat from nuclear reactions. This operation is carried out within the reactor. This output heat is used to operate a steam turbine which rotates a generator to make electricity. The generated electricity by nuclear power plants is called nuclear power [1]. Reactor control is a main control problem in nuclear power stations. The implementation of a proper controller for the reactor core can improve the security and the performance of the nuclear power plant. Over the decades, most of the researches devoted their work to improve the performance of reactor cores. The classical control procedure is not enough to get a good performance from the nuclear reactor [2]. In [3], a robust control approach is introduced to overcome the changes of reactor parameters instead of the conventional state feedback control. The parameters of the controller are found by the trial and error method. In [4], a model-based feedback linearization controller with an adaptive proportional integral (PI) controller is introduced. They additionally planned a model-based two-arrange controller in [5]. These control methods generally were composed in view of an estimated direct model and remain constant in constrained range. As of late, different controllers including neural network strategy, a fuzzy logic technique [6—9], and robust control methods have been utilized for controlling nuclear reactors control [10,11]. A nuclear reactor controller utilizing the neural network and the fuzzy logic are introduced in [12]. In [13], adaptive control of a nuclear reactor power utilizing neural systems is illustrated. Model predictive control technique has been utilized for the reactor power control in [14,15]. However, these techniques are difficult to actualize and have high computational volume. Since nuclear reactor parameters vary with the power level, it requires a robust control method. The variable structure controller (VSC) based on the sliding mode is an effective robust control method to overcome system uncertainties and outer disturbances [16,17]. In this paper, a VSC is proposed to control a nuclear reactor. The variable structure controller needs a proper tuning of the sliding equation gains and the feedback gains to give a good performance. This paper proposes a new optimization technique named lightning search algorithm (LSA) for the optimal design of the VSC parameters. In addition, the VSC parameters are optimized by the genetic algorithm (GA) as a standard optimization technique in different applications [23]. The results emphases the high performance and the superiority of VSC based on LSA compared with VSC based on GA.

The contributions of the paper are represented in the following points.

* Corresponding author.
   E-mail addresses: elsisimahmoud22@yahoo.com (M. Elsisi), hanyaboayta@gmail.com (H. Abdelfattah).

- This paper introduces an improved VSC based on the sliding mode and the LSA for nuclear reactor control.
- The LSA is utilized as a new optimization technique to get the optimal parameters of the VSC instead of the trial and error or the designer's expertise methods.
- A comparison between the suggested VSC based on the LSA and the VSC based on GA is carried out. The comparison emphasizes the superiority of the suggested VSC based on the ICA.

The rest of this paper is sorted out as follows: Section 2 gives a short portrayal and numerical plan of the nuclear reactor. In Section 3, the idea of variable structure control is discussed. In sections 4 and 5, the concept of LSA and GA are illustrated. The nuclear reactor model is presented in Section 6. Section 7 demonstrates the results of the test system. In the final, the conclusions of the research are in Section 8.

2. Dyadic bilinear system

The continuous nuclear reactor system is a bilinear model, where the control input (reactivity) acts with additive and multiplication simultaneously. The significance of the issue is underscored by the presence of a few bilinear models of real control forms in [18]. Extraordinary classes of bilinear models are the dyadic bilinear model which fits the model of the nuclear reactor kinetics. A control scheme and the purported division controller of dyadic models were proposed in [19] and they are adjusted to consider the constraints on the neutron level and the size of reactivity. The bilinear system under consideration is defined as follows,

$$\dot{x} = \boldsymbol{A}x + \sum_{i=1}^{m}(\boldsymbol{B_i}x + \boldsymbol{b_{io}})u_i \tag{1}$$

$$\boldsymbol{B_i}x + \boldsymbol{b_{i0}} = \boldsymbol{b_{i0}}\left(\boldsymbol{c_i^T}x + 1\right) \tag{2}$$

where $x \in R^n$, $\boldsymbol{u} = [u_1 \ u_2....u_m]^T \in R^m$, and $\boldsymbol{A}$, $\boldsymbol{B_i}$, $\boldsymbol{b_{io}}$ for $\boldsymbol{i} = 1, 2, ...m$ are real constant matrices of appropriate dimensions. The control signal 'u' acts with additive and multiplication simultaneously. The bilinear system in (1) is called dyadic of order d, $d \in \{1, 2, ..., m\}$[19].

By considering a single input dyadic system,

$$\begin{cases} \dot{x} = \boldsymbol{A}x + (\boldsymbol{B}x + \boldsymbol{b})u, & x \in R^n, u \in R \\ \boldsymbol{B}x + \boldsymbol{b} = \boldsymbol{b}\left(\boldsymbol{c^T}x + 1\right) \end{cases} \tag{3}$$

Let

$$\boldsymbol{d}(x) = \boldsymbol{c^T}x + 1 \tag{4}$$

Let v be a new control, where

$$v = \boldsymbol{d}(x)\, u \tag{5}$$

For a single input bilinear dyadic system, the new system becomes,

$$\dot{x} = \boldsymbol{A}x(t) + \boldsymbol{b}v(t) \tag{6}$$

where $x \in R^n$, $v \in R$ and symmetric constraint state and control sets. In this paper, the problem of designing a state feedback VSC controller is defined as follows,

$$v(t) = \boldsymbol{\psi}x(t) \tag{7}$$

Such that, the closed-loop system is represented as,

$$\dot{x} = \boldsymbol{A_C}\, x(t) \tag{8}$$

where

$$\boldsymbol{A_C} = \boldsymbol{A} + \boldsymbol{b}\psi \tag{9}$$

3. Variable structure control concept

Variable-structure control has a vital property called sliding mode in which the execution of the system is uncaring to changes of the plant parameters through wide ranges. This property was first researched by Emelianov [20], who found that a sliding mode may exist in a VSC. The transient response can be enhanced by methods for a sliding mode. For the multivariable linear VSC, reasonable decision of the control law can yield a sliding mode, at the same time, on a few exchanging hyper-planes. The choice of exchanging hyper-planes is a crucial significance while considering the practical execution of the VSC controller. The fundamental ideas of sliding mode and switching hyper-plane are represented in [21]. The major prerequisite of this theory is to locate the important and adequate conditions for the presence of a sliding mode on a composed sliding hyper-plane. Different prerequisites incorporate the stability and invariance regime of the sliding mode that assurance hitting the sliding hyper-plane from any location in the state space. Moreover, the sliding mode is the case under which the system states are ensured to move towards and achieve a sliding surface. There are different strategies for characterizing this condition [20]. The Lyapunov function can ensure this purpose of stability and it is characterized as follows:

$$V = \frac{1}{2}\, \sigma^2 \tag{10}$$

$$\dot{V} = \dot{\sigma}\, \sigma < 0 \tag{11}$$

where σ is switching hyper-planes and defined as follows,

$$\sigma = \sum_{i=1}^{N} \boldsymbol{c_i}x_i \ i = 1, 2, ..., N \tag{12}$$

where x_i is the ith state variable of the system, N is the dimension of x. Writing (12) in a more compact form as,

$$\sigma = \boldsymbol{c^T}x \tag{13}$$

where $\boldsymbol{c} = [c_1, c_2, ..., c_N]^T$ is the switching vector, $\boldsymbol{x} = [x_1, x_2, ..., x_N]^T$ is the state vector of the system. The VSC control law for the system of (7) is defined by

$$v = \psi^T x = \sum_{i=1}^{N} \psi_i x_i \ ; \quad i = 1, 2, ...N \tag{14}$$

where, the feedback gains are defined as

$$\psi_i = \begin{cases} \alpha_i \ , & if \ X_i\, \sigma > 0 \\ -\alpha_i \ , & if \ X_i\, \sigma < 0 \end{cases} \quad i = 1, 2, ...N \tag{15}$$

The important and adequate conditions for the presence of a

sliding mode on the hyper-planes $\sigma = 0$ are defined by [16].

For proving the robustness of the VSC against the system parameters uncertainty and the disturbance.

Let the design of VSC for zeroing the output $y = x_1$ of the following phase canonic form system,

$$\dot{x}_i = x_{i+1}, \; i = 1, \dots \dots, N-1 \tag{16}$$

$$\dot{x}_N = -\sum_{i=1}^{N} a_i x_i + f(t) + u \tag{17}$$
where.

u A control signal
$f(t)$ A disturbance
a_i constants or time-varying parameters

$f(t)$ and a_i may be unknown. Assume that the control signal 'u' as a function of the system state vector 'x' undergoes discontinuities on some plane $\sigma = 0$, where σ is defined in (12) and $c_i = const$, $c_N = 1$. If the trajectories are direct towards the plane, aσ = 0sliding mode is achieved in this plane. The following pair of inequalities can ensure the existing sliding mode [16].

$$\lim_{\sigma \to 0^+} \frac{d\sigma}{dt} < 0 \text{ and } \lim_{\sigma \to 0^-} \frac{d\sigma}{dt} > 0 \tag{18}$$

The invariances of the sliding mode with respect to the system parameters 'a_i' and the disturbance '$f(t)$' can be proved by solving the equation $\sigma = 0$for the state variable x_N and substitution into (16) result the following equation from the sliding mode which depending on the parameters c_i.

$$\dot{x}_i = x_{i+1}, \; i = 1, \dots \dots, N-2 \tag{19}$$

$$\dot{x}_{N-1} = -\sum_{i=1}^{N-1} c_i x_i \tag{20}$$

The real problem in the design of a VSC controller is the choice of the switching vector '**c**' and the feedback gains 'α_i' [16]. In the present work, a new intelligent technique named LSA is proposed for the tuning of the VSC switching gains and feedback gains. This is proficient by formulating the VSC gains selection as an optimization issue. Then, the LSA is utilized in the optimization procedure. The proposed technique gives an ideal and orderly method for gains determination of the VSC.

4. Lightning search algorithm overview

Lightning search Algorithm is a heuristic optimization algorithm developed in [22]. It depends on the characteristic wonder of lightning and the foundation of step leader reproduction by utilizing the idea of quick particles known as projectiles. Three projectile composes are produced to represent the progress projectiles that make the initial step leader population, the space projectiles that endeavor to end up the leader, and the lead projectile that represents the projectile discharged from best-situated step leader. As opposed to that of the partners of the LSA, the real investigation highlight of the proposed algorithm is demonstrated by using the exponential random conduct of space projectile and the simultaneous arrangement of two leader tips at fork focuses utilizing restriction hypothesis. Lightning search Algorithm component worked in three stages; projectile and step leader engendering, projectile properties, and projectile displaying and development. The LSA is concluded in the following steps.

Step 1 The execution start by defining the LSA parameters, for example, number of iterations T, size of population N, the dimension of the problem D.
Step 2 The initial populations for problem parameters are delivered.
Step 3 After the initial population is assessed, the oversee and position are updated as follows,

$$P^s_{i\_new} = P^s_i \pm \exp rand(\mu_i) \tag{21}$$

$$P^L_{new} = P^L + normrand(\mu_L, \sigma_L) \tag{22}$$

where $P^s_{i\_new}$ is the new space projectile, $P^s_i$is the old space projectile, and P^L_{new} is the new lead Projectile. $\mu_i$for a particular space projectile P^s_i is taken as the separation between the lead projectile P^L and the space projectileP^s_i. μ_L for the lead projectile P^L is taken as P^L, and the scale parameter $\sigma_L$exponentially decreases as it progresses toward the Earth or as it finds the best solution.

Step 4 In the wake of updating the positions, the procedure proceeds to the next iteration. This updating continuous until the point that the maximum iteration is reached, as clarified in the flowchart of LSA to tune the VSC for the nuclear power system in Fig. 1.

5. Genetic algorithm

The genetic algorithm is inspired by the Darwinian Theory of evolution. In this algorithm, the space of solutions is represented with a population of individuals. The new solution is created by changing some of the strings of the present generation. This operation is called Crossover. The Crossover is carried at each generation. Furthermore, there is another operation called Mutation. This operation is carried by altering some of the strings randomly. The GA is explained with more details in [26–28]. Fig. 2 summarizes the steps of the GA to tune the VSC for the nuclear power system.

6. Nuclear reactor model

The simplified neutron kinetics equations which described by Reisch in [24,25] with zero output power are given by:

$$\begin{cases} \dfrac{dN}{dt} = \dfrac{\delta k - \beta}{l} N + \sum_{i=1}^{6} \lambda_i C_i \\[2mm] \dfrac{dC_i}{dt} = \dfrac{\beta_i}{l} N - \lambda_i C_i \\[2mm] \dfrac{dT_F}{dt} = \dfrac{C_{NF}}{\tau_f} N - \dfrac{1}{\tau_f} T_F \\[2mm] \dfrac{dT_M}{dt} = \dfrac{C_{NM}}{\tau_m} N - \dfrac{1}{\tau_m} T_M \\[2mm] P_a(t) = p_0 N(t) \end{cases} \tag{23}$$

The control objective is the stabilization of (23) subject to neutron and reactivity constraints with VSC control. With equilibrium N_e chosen, the precursor level$C_e, T_{Fe}, T_{Me}$and $\delta k_e$from (23):

$$C_{ie} = \frac{\beta_i}{l\lambda_i} N_e, \; T_{Fe} = C_{NF} N_e, \; T_{Me} = C_{NM} N_e, \; \delta k_e = 0, \; \sum_{i=1}^{6} \beta_i = \beta$$

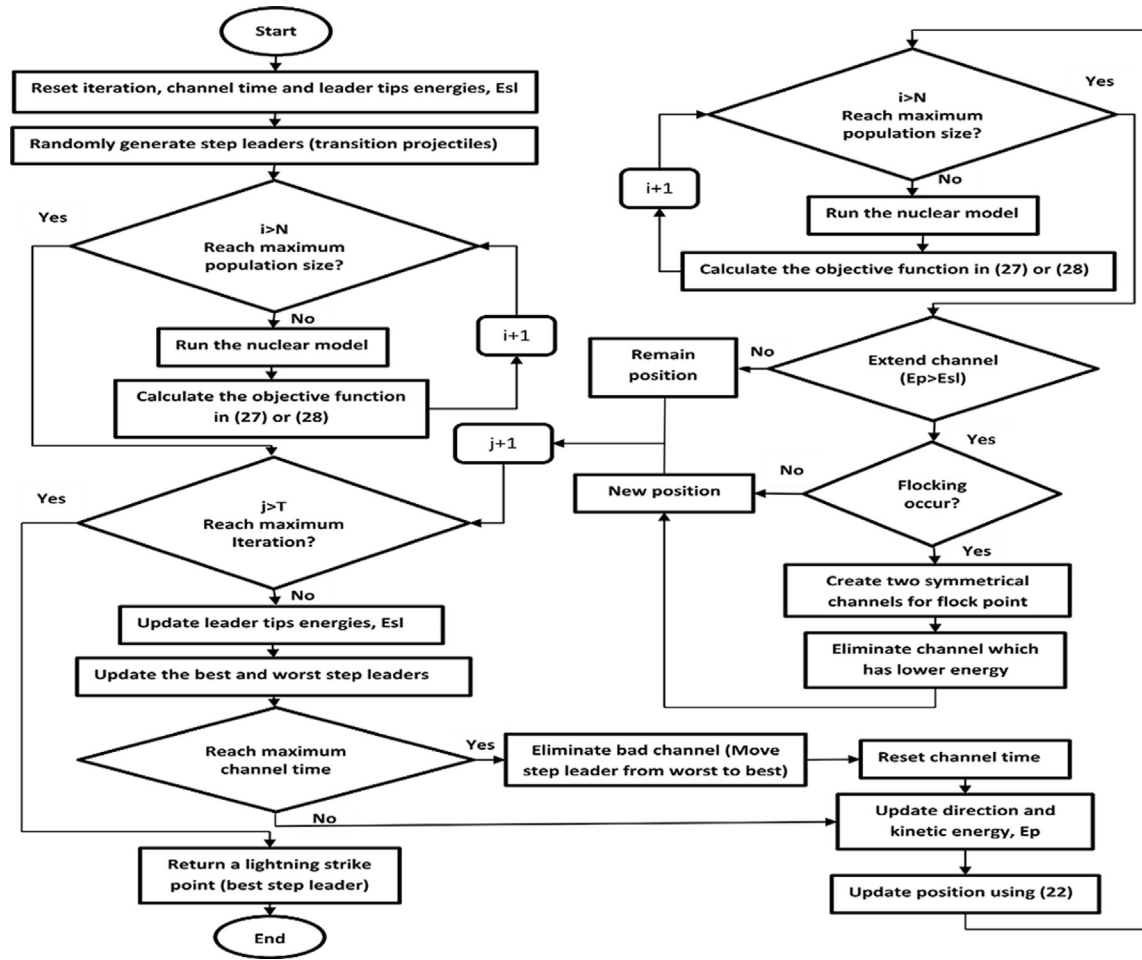The neutron data are listed in the Appendix.

Fig. 1. Flowchart of the LSA to tune the VSC for the nuclear power system.

The new state-space variables are chosen:

$$\begin{cases} x_1 = \dfrac{N - N_e}{N_e} \\ x_i = \dfrac{C_i - C_{ie}}{C_{ie}} \;, \quad i = 2, \ldots\ldots 7 \\ x_8 = \dfrac{T_F - T_{Fe}}{T_{Fe}} \\ x_9 = \dfrac{T_M - T_{Me}}{T_{Me}} \end{cases} \tag{24}$$

$$u = \delta k / \beta \tag{25}$$

Physically δk should be less than β. Hence $-\infty < \delta k < \beta$ and $-\infty < u < 1$.

Initial values of fuel and moderator temperature are:

$$T_{Fe}(0) = C_{NF}, T_{Me}(0) = C_{NM}.$$

By substitution in (23), the new state space becomes a single input bilinear dyadic system

$$\dot{x} = \mathbf{A}x + \mathbf{b}d(x)u \tag{26}$$

where $\mathbf{b} = [\beta\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$, $d(x) = \frac{x_1 + 1}{l}$.
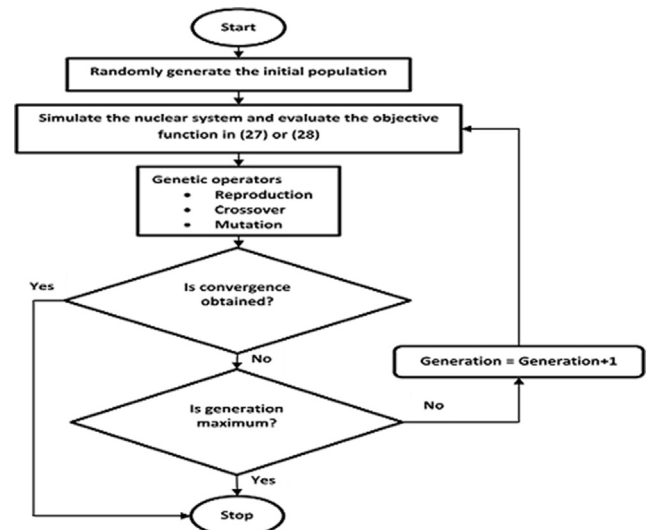
Fig. 2. Flowchart of GA to tune the VSC for the nuclear power system.

Table 1
Tuning parameters of VSC based on LSA and GA.

| State variable	LSA				GA			
	sliding gain (c)		feedback gain (α)		sliding gain (c)		feedback gain (α)	
	IAE	ISE	IAE	ISE	IAE	ISE	IAE	ISE
Neutron flux (x_1)	183.212	685.227	805.602	953.626	18.478	0.002	12.834	19.633
1^{st}delayed neutron (x_2)	139.438	770.009	613.97	497.936	20.618	19.61	12.352	18.575
2^{nd}delayed neutron (x_3)	296.045	737.769	920.764	316.166	3.907	5.418	12.683	15.031
3rd delayed neutron (x_4)	918.043	287.058	378.614	512.499	6.16	10.54	12.747	17.282
4th delayed neutron (x_5)	491.838	428.128	862.623	294.554	20.195	19.342	14.584	19.63
5th delayed neutron (x_6)	51.657	475.861	809.438	628.582	13.811	18.841	14.755	18.978
6th delayed neutron (x_7)	95.889	502.54	981.42	879.443	4.514	0.449	15.336	18.509
Fuel temperature (x_8)	682.247	816.731	362.492	624.137	5.807	7.596	11.881	19.103
Moderator temperature(x_9)	821.116	244.128	733.811	624.137	21.082	9.8	16.931	16.687
IAE	2.6507				8.1231			
ISE	0.0206				0.0360			
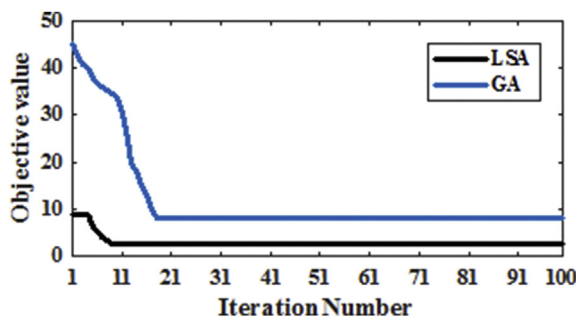
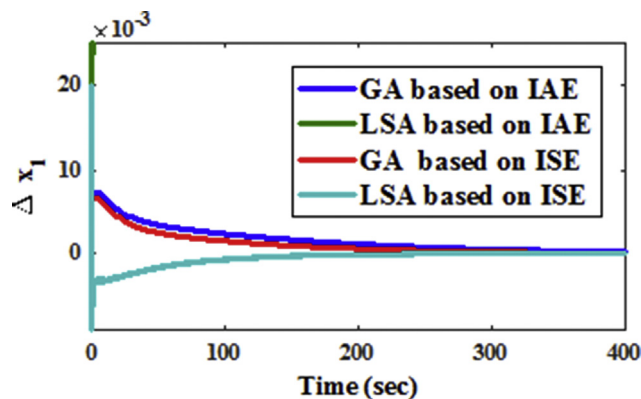Fig. 3. The convergence profile of LSA and GA for IAE.

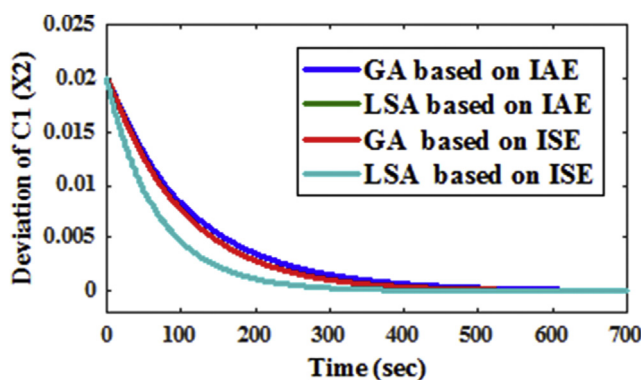Fig. 4. Deviation of the neutron level with two techniques.

Fig. 5. Deviation of the first delayed neutron with two techniques.

$$A = \begin{bmatrix} \frac{-\beta}{l} & \frac{\beta_1}{l} & \frac{\beta_2}{l} & \frac{\beta_3}{l} & \frac{\beta_4}{l} & \frac{\beta_5}{l} & \frac{\beta_6}{l} & 0 & 0 \\ \lambda_1 & -\lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_2 & 0 & -\lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_3 & 0 & 0 & -\lambda_3 & 0 & 0 & 0 & 0 & 0 \\ \lambda_4 & 0 & 0 & 0 & -\lambda_4 & 0 & 0 & 0 & 0 \\ \lambda_5 & 0 & 0 & 0 & 0 & -\lambda_5 & 0 & 0 & 0 \\ \lambda_6 & 0 & 0 & 0 & 0 & 0 & -\lambda_6 & 0 & 0 \\ \frac{1}{\tau_f} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{\tau_f} & 0 \\ \frac{1}{\tau_m} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{\tau_m} \end{bmatrix}$$

7. Results and discussion

The proposed VSC control technique can be applied to the system in (26) with neutron level state 'x_1' and control input 'u'constraints in order to fulfill the needed safety specifications.

Let $v = \left(\frac{x_1+1}{l}\right)u$, symmetric constraint state and control sets are $-0.5 \leq x_1 \leq 0.5, -16*10^{-3} \leq \delta k \leq 5*10^{-3}$, Thus $-2.4 \leq u \leq 0.8$ gives $-7.8 \leq v \leq 7.8$.
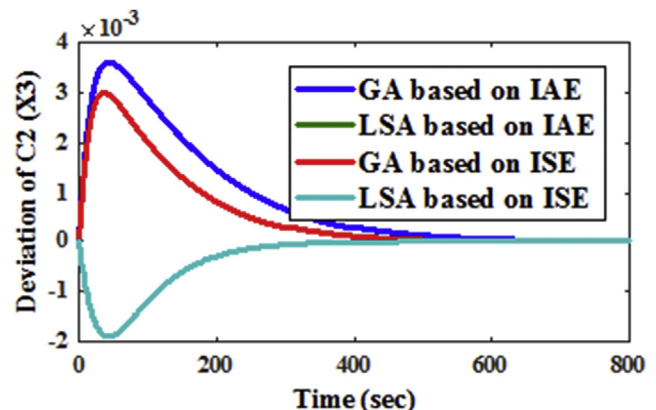

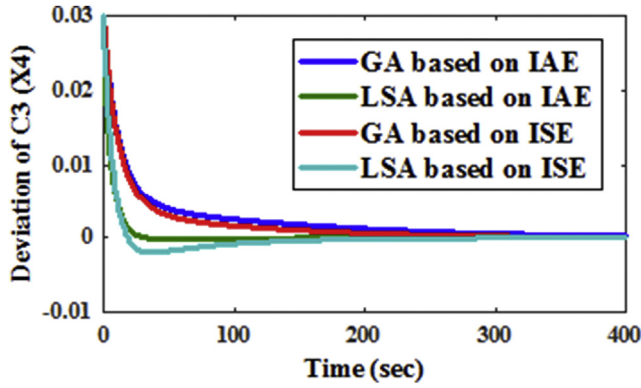Fig. 6. Deviation of the second delayed neutron with two techniques.

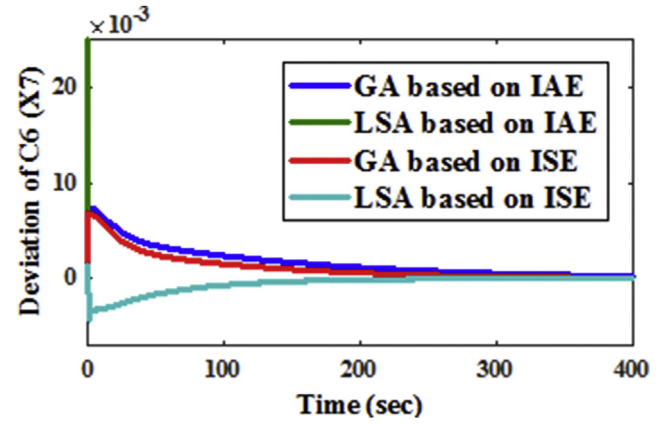**Fig. 7.** Deviation of the third delayed neutron with two techniques.

Fig. 8. Deviation of the fourth delayed neutron with two techniques.

Fig. 9. Deviation of the fifth delayed neutron with two techniques.

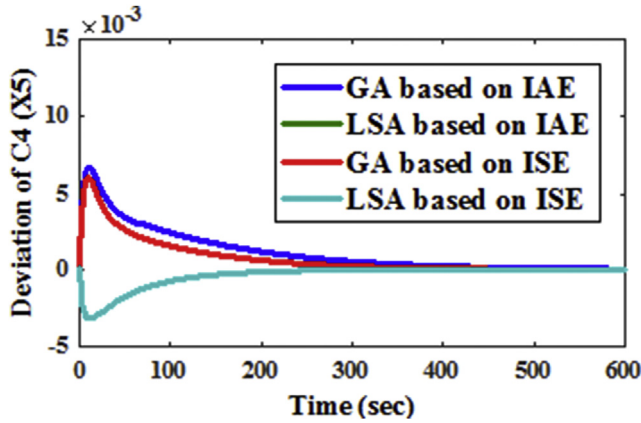**Fig. 10.** Deviation of the sixth delayed neutron C6 with two techniques.

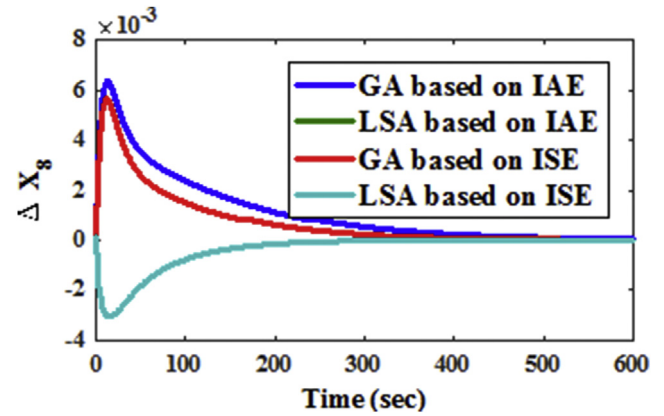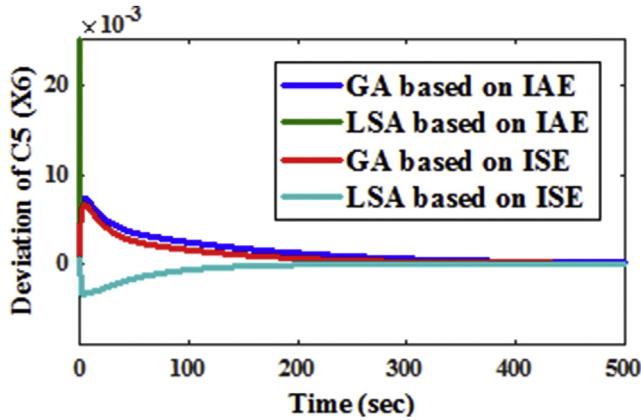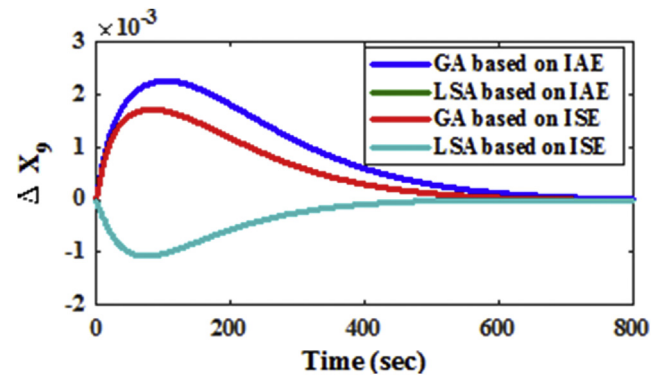**Fig. 11.** Deviation of the fuel temperature with two techniques.

Fig. 12. Deviation of the moderator temperature with two techniques.

The LSA and GA are devoted to find the optimal parameters of the VSC controller in order to minimize the integral absolute error (IAE) performance index which defined as follows,

$$IAE = \int_0^{T_s} \left(\sum_{i=1}^{9} |x_i| \right).dt \qquad (27)$$

where T_s is the simulation time.

Another performance index named integral square error (ISE) is chosen to prove the results of the proposed technique and it is defined as follows,

$$ISE = \int_0^{T_s} \left(\sum_{i=1}^{9} x_i^2 \right).dt \qquad (28)$$

The reactor core system is simulated for initial state variables values as follows:

$$x(0) = \begin{bmatrix} 0.02 & 0.02 & 0 & 0.03 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Table 2
The maximum overshoot and settling time values of all state curves based on LSA and GA in case of IAE.

State variable	LSA		GA	
	Settling time (sec)	Maximum overshoot	Settling time (sec)	Maximum overshoot
Neutron flux (x_1)	199.3	0.02493	449.3	0
1st delayed neutron (x_2)	483	0	664.4	0
2nd delayed neutron (x_3)	528	0.001706	800	0.003605
3th delayed neutron (x_4)	192.9	0	574.1	0
4th delayed neutron (x_5)	287.4	0.01063	680.5	0.006734
5th delayed neutron (x_6)	254.5	0.0253	513.4	0.007322
6th delayed neutron (x_7)	271.5	0.01444	578.5	0.007447
Fuel temperature (x_8)	471.8	0.007937	671.9	0.006332
Moderator temperature(x_9)	813.1	0.0006212	941,9	0.002258
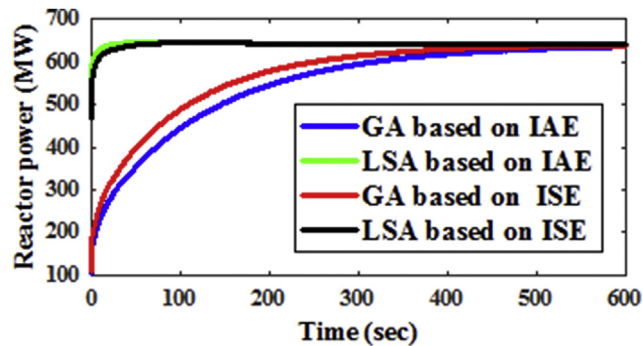
Fig. 13. The performance of the system with different methods in the case of load following operation.

The optimal values of the sliding equation gains and the feedback gains of the VSC controller corresponding to each state variable and the performance indices are listed in Table 1. The convergence profile of LSA and GA for IAE is shown in Fig. 3.

Table 1 clear that the value of IAE and ISE in the case of the LSA-based VSC controller has the minimum performance index value. Fig. 3 shows that, the LSA converges the cost function with low iterations number and cost value compared with the GA. Furthermore, the LSA takes 1.5 min and the GA takes 2 min for each iteration according to the Simulink model of the nuclear system and the used computer with the following details, Processor: Intel(R) Core(TM) i5-2450 M CPU@ 2.50 GHz, Installed memory (RAM): 4.00 GB.

The following figures demonstrate the dynamic responses of deviation state variables with time, where it is clear that all states decay with time and tend to zero for the two techniques. Fig. 4 shows the main neutron flux deviation response with LSA and GA optimization techniques. It is clear that the undershoot of the system response due to the LSA-based VSC in case of ISE has the
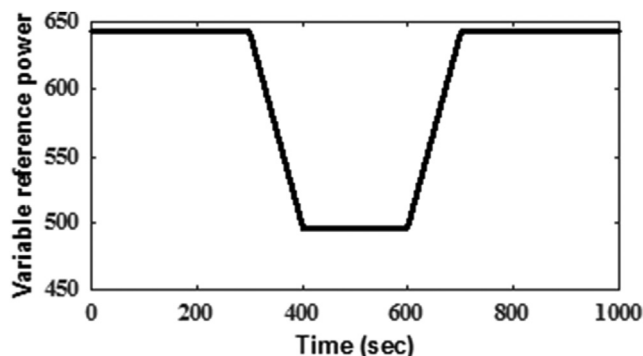
highest value compared with the other curves. This indicates that the ISE is not suitable to be used as a performance index. In contrast, the system response due to the LSA-based VSC in case of IAE has the best performance (small settling time and minimum overshoot) compared with the other curves. It concluded that the IAE better than the ISE to be used as a performance index for the tuning of VSC based on LSA.

Figs. 5–10 demonstrate the deviation of six delayed neutrons responses with two techniques. Fig. 5 shows that the LSA-based VSC has the best damping characteristics compared with GA-based VSC in case of IAE and ISE.

Fig. 6 shows that the LSA-based VSC in case of ISE has larger undershoot than the other techniques. But the response of the system due to LSA-based VSC has the short settling time compared with GA-based VSC in case of IAE and ISE. Furthermore, the performance of the LSA-based VSC in case of IAE is the best compared with other responses.

Fig. 7 shows that the LSA-based VSC has the best damping characteristics compared with GA-based VSC in case of IAE. But the performance of the LSA-based VSC in case of ISE large undershoot compared with other methods.

Fig. 8 shows that the LSA-based VSC has the short settling time compared with the GA-based VSC in case of IAE and ISE.

Figs. 9 and 10 like Fig. 8 shows that the LSA-based VSC has the short settling time compared with the GA-based VSC in case of IAE and ISE.

Figs. 11 and 12 show the fuel and moderator deviations. As cleared from these Figs, the LSA curves have a faster response than GA curves.

These figures represent robust stability of feedback controller (VSC) with the nuclear reactor system using the proposed LSA. The

Fig. 14. Practical input of load power.
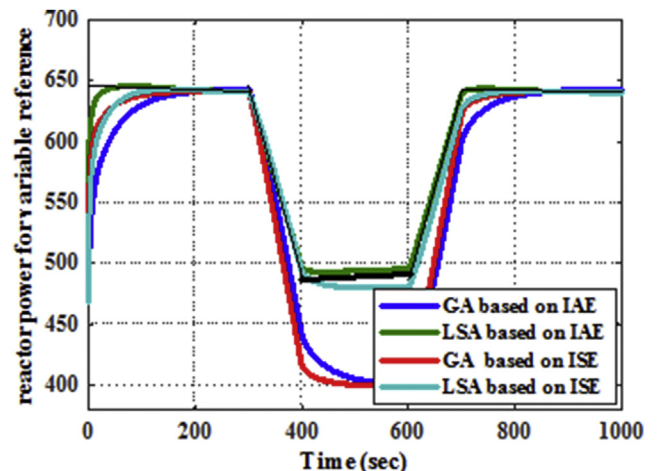
Fig. 15. The performance of the system with different methods in the case of load change.

maximum overshoot and settling time values of all state curves with the LSA and GA in case of IAE are listed in Table 2. It is concluded that form the above figures and Table 2, The VSC controller based on LSA in case of IAE have high performance compared with VSC controller based on GA.

A 640 MW step input of load power is carried out to investigate the capability of the LSA during load-following operation and the result of the different methods is shown in Fig. 13. It is clear that the proposed controller based on LSA in case of IAE has the best performance.

For further test, another practical input of load power is carried out as shown in Fig. 14 to ensure the performance of the proposed controller. Fig. 15 shows that the proposed method still has the best performance compared with the GA.

The previous results confirm that.

- The VSC based on LSA is able to reduce the states deviations compared with the GA-based VSC.
- The LSA-based VSC has the minimum performance index value compared with the GA-based VSC.
- The LSA-based VSC has better damping characteristic than the GA-based VSC.
- The VSC is robust to the system parameter variations compared with the GA-based VSC.

8. Conclusions

A new optimization algorithm named LSA is used for the tuning of sliding equation gains and the feedback gains of the VSC controller is introduced in this paper. This tuning problem is solved by formulating the VSC parameters as an optimization issue. The proposed technique gives an optimal and efficient method for the VSC gains selections compared with the GA. The utilization of the proposed VSC controller based on LSA to the nuclear reactor control issue improves the system performance rather than the GA-based VSC.

Appendix

The delayed neutron data are listed in Table 3 as follows.

Table 3
Delayed Neutron Data

Group	β_i	λ_i
1	0.000215	0.0124
2	0.001424	0.0305
3	0.001274	0.111
4	0.002568	0.301
5	0.000748	1.14
6	0.000273	3.01

Neutron mean lifetime 'l' = 0.001; Sum of the delayed neutron fractions 'β' = 0.006502; C_{NF} = 0.001; C_{NM} = 0.0005; τ_f = 5 s; Thermal time constant of the moderator 'τ_m' = 0.01 s; Initial power 'p_0' = 20 MW.

The default parameters of LSA and GA are selected for a fair comparison with Population size = 100; Number of iteration = 100; 30 runs for each algorithm are carried out. The GA in the Matlab toolbox is used and the LSA which uploaded by its main authors in the mathwork site "https://www.mathworks.com/matlabcentral/fileexchange/54181-lightning-search-algorithm-lsa" is used.

The simulation is carried out by a computer has the following details, Processor: Intel(R) Core(TM) i5-2450 M CPU@ 2.50 GHz; Installed memory (RAM): 4.00 GB.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.08.003.

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