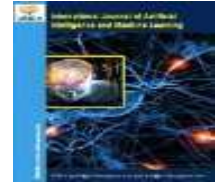




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LOAD FREQUENCY CONTROL OF SINGLE AREA MULTI-SOURCE POWER SYSTEM USING ATOM SEARCH OPTIMIZED HIGHER ORDER SLIDING MODE CONTROLLER

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Abstract

In this paper, a robust load-frequency control (LFC) scheme of a single-area multi-source power system is proposed. To create a realistic multi-source power grid scenario, the power system is augmented with reheated thermal, hydro and gas power generating units. Due to the diverse dynamics and non-linearities of these generating units (such as reheater delays and non-minimum-phase water-acceleration features), standard linear controllers are insufficient to maintain frequency stability during load changes. To address this, a Higher-Order Sliding Mode Controller (HOSMC) using the Second Order Sliding Surface is proposed. The sliding surface coefficients and controller gains are tuned using the Atom Search Optimization (ASO) algorithm, which simulates Lennard-Jones potential forces and covalent bonds in molecular dynamics. Integral Time-weighted Absolute Error (ITAE) is used as the objective function. The performance of the proposed ASO-HOSMC scheme is validated through comprehensive simulation and compared with classical Sliding Mode Controllers (SMC), an ASO-tuned FOPID controller, a DE-optimized PI controller, and an optimal controller. The simulation results show that the proposed controller reduces the frequency deviations and the settling times dramatically and eliminates the steady state error. Robustness and sensitivity analyses demonstrate that the proposed controller maintains high-frequency stability under parameter variations ($\pm 25\%$ and $\pm 50\%$ changes in system parameters).

Keywords— Load Frequency Control, Single Area Power System, Multi-Source Power System, Higher-Order Sliding Mode Control, Atom Search Optimization.

I. INTRODUCTION

Large-scale power systems consist of many coupled control areas with various generating units, e.g., thermal, hydro, gas and nuclear power plants. Since system frequency directly reflects the balance between generation and demand, any sudden change in load or generation can produce frequency deviations from the nominal operating value [1]. Large or persistent frequency deviations can adversely affect system stability, equipment operation, and supply reliability, thereby increasing the vulnerability of connected loads [2-4]. The LFC problem becomes more challenging in modern multi-source generation systems, where thermal, hydro, and gas units exhibit substantially different dynamic characteristics [5-9]. Thermal generating units generally have relatively slow responses because of steam expansion and reheater dynamics, whereas hydro units exhibit water-inertia effects and non-minimum-phase characteristics that can produce an initial power reduction following a gate-opening command. Gas turbines, in contrast, provide a rapid response but are subject to stringent temperature and valve constraints [10-13].

Proportional-integral-derivative (PID) controllers remain widely used in industrial LFC applications

because of their simple structure and ease of implementation. However, their performance can deteriorate under nonlinear operating conditions and significant variations in parameters. Consequently, advanced control structures, including fuzzy PID, cascade PID, and fractional-order PID (FOPID) controllers, have been investigated to enhance LFC performance. Kumar and Sikander developed a fuzzy PID cascade controller for LFC [14], while fuzzy FOPID parameter identification was investigated in [15]. A hybrid fuzzy-logic and optimization-based strategy was also proposed for LFC applications [15].

Among the robust nonlinear control techniques, Sliding Mode Control (SMC) has attracted considerable attention due to its inherent robustness to match uncertainties and external disturbances. However, the classical SMC design uses a discontinuous signum function that can generate high frequency oscillations of the control signal, known as chattering. In LFC applications, excessive chattering may lead to undesirable actuator activity and adversely affect components such as governor valves. Higher-Order Sliding Mode Control (HOSMC) mitigates this limitation by shifting the discontinuous control action to higher-order derivatives, thereby achieving improved control smoothness while retaining the robustness of sliding-mode control [16]. The performance of such controllers, however, strongly depends on the appropriate selection of their control parameters. Metaheuristic optimization techniques have therefore become attractive for automated controller tuning.

In this paper, the Atom Search Optimization (ASO) algorithm is proposed to optimize the parameters of Second Order Sliding Surface Based Sliding Mode Control for load-frequency control of single area multi-source power system. The ASO algorithm models molecular dynamics with Lennard-Jones and covalent bond forces. The paper has the following contributions:

- (i) A Second Order Sliding Surface-Based Sliding Mode Control is designed for
- (ii) The Atom Search Optimization (ASO) algorithm is applied for tuning the sliding surface coefficients and controller gains considering a centralized objective function of Integral of Time-weighted Absolute Error (ITAE).
- (iii) The proposed ASO-HOSMC is compared with ASO-tuned FOPID and classical SMC under nominal conditions, parameter variations ($\pm 25\%$ and $\pm 50\%$) and random load.

The remainder of this paper is organized as follows. Section II presents the system configuration and mathematical modeling of the considered power system. Section III describes the design of the higher-order sliding surface-based controller. Section IV presents the Atom Search Optimization (ASO) algorithm and its application to optimize the controller parameters. Section V presents and discusses simulation results, including comparative and robustness analyses. Finally, Section VI concludes the paper and highlights the main findings and possible directions for future work.

II. SYSTEM CONFIGURATION AND MATHEMATICAL MODELING

The power system shown in Fig. 1 is a single-area power system with multiple generating sources. The system includes a reheated thermal plant, a hydro plant, and a gas plant. Power generation is allocated among the units based on participation factors:

Reheated Thermal Power Plant Model

The thermal power plant consists of a speed governor, a reheated steam turbine, and a reheater, as shown in Fig. 1. The transfer functions of the governor, reheater, and turbine are given by

$$G_{SG}(s) = \frac{1}{T_{SG}s}$$

$$G_R(s) = K_R \frac{T_{RS} + 1}{T_{RS} + 1}$$

$$G_T(s) = \frac{1}{T_Ts + 1}$$

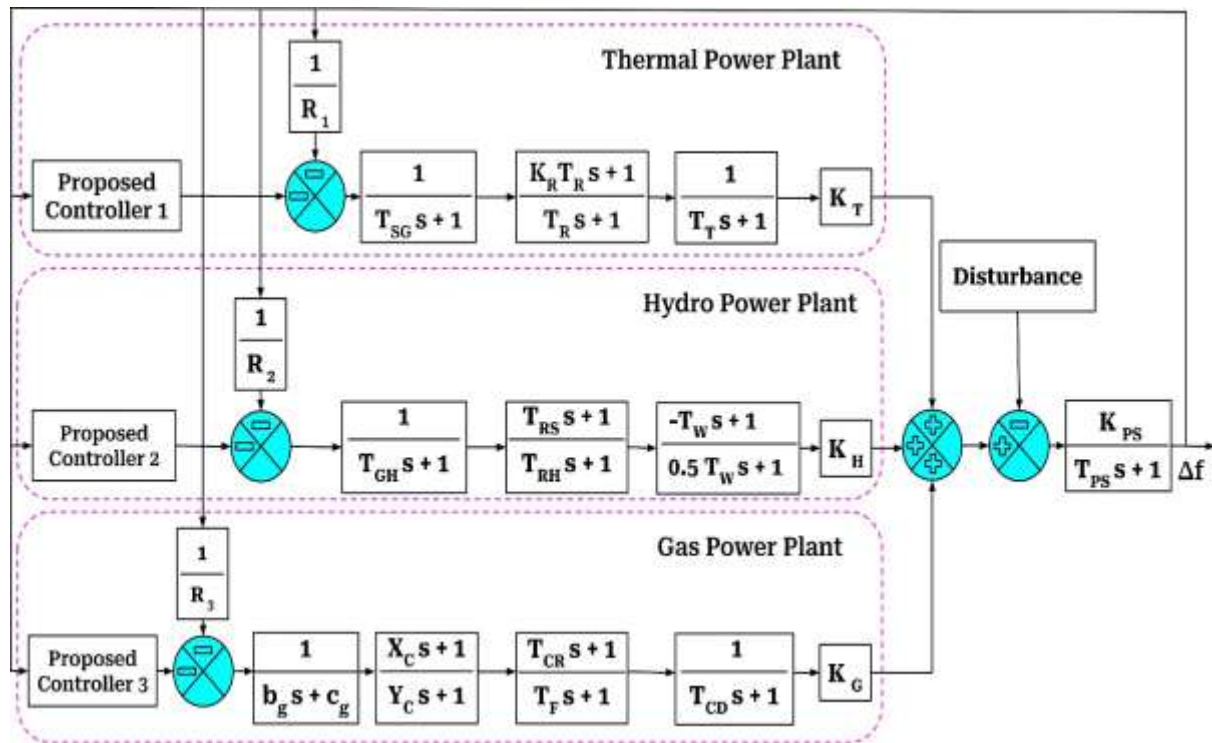


Figure 1. Multi-source single area power system

The governor receives the control input and frequency feedback via the speed-regulation characteristic. The input to the thermal power plant is therefore expressed as The governor receives the control input and frequency feedback via the speed-regulation characteristic. The input to the thermal power plant is therefore expressed as

$$u_{th} = K_T u - \frac{1}{R_1} \Delta f$$

where K_T is the participation factor of the thermal power plant, R_1 is the speed regulation coefficient, u is the control signal, and Δf is the frequency deviation.

The corresponding thermal power output deviation is denoted by ΔP_{th} .

Hydro Power Plant Model

The hydro power plant consists of a speed governor, a transient droop compensator, and a hydraulic penstock. The transfer function of the hydro governor is given by

$$G_{GH}(s) = \frac{1}{T_{GH}s}$$

The transient droop compensator is represented by

$$G_{RH}(s) = \frac{T_{RH}s + 1}{T_{RH}s + 1}$$

The hydraulic penstock dynamics are represented by

$$G_W(s) = \frac{1 - T_W s}{1 + 0.5 T_W s}$$

The hydropower plant also includes the hydropower gain K_H . The input to the hydro power plant is given by

$$u_{hy} = K_H u - \frac{1}{R_2} \Delta f$$

where K_H is the hydro participation factor and R_2 is the speed regulation coefficient of the hydro power plant. The corresponding hydro power output deviation is denoted by ΔP_{hy} .

Gas Power Plant Model

The gas power plant consists of a governor, a valve positioner with lead-lag characteristics, a fuel system, and a combustor discharge lag. The governor is represented by

$$G_{Gg}(s) = \frac{1}{b_g s + c_g}$$

where b_g and c_g are the gas turbine governor parameters. The lead-lag valve positioner is represented by

$$G_C(s) = \frac{X_C s + 1}{Y_C s + 1}$$

The combustor dynamics are given by

$$G_{CR}(s) = \frac{1}{T_{CR} s + 1}$$

The combustor discharge dynamics are represented by

$$G_{CD}(s) = \frac{1}{T_F s + 1}$$

$$G_{CD}(s) = \frac{1}{s + 1}$$

The gas power plant gain is denoted by K_G . The input to the gas power plant is expressed as

$$u_{gas} = K_G u - \frac{1}{R_3} \Delta f$$

where K_G is the gas power plant participation factor and R_3 is its speed regulation coefficient. The resulting gas power output deviation is denoted by ΔP_{gas} .

Single-Area Power System Dynamics

The frequency dynamics of the single-area power system are represented by the equivalent power-system transfer function

$$G_{PS}(s) = \frac{K_{PS}}{T_{PS} s + 1}$$

where K_{PS} and T_{PS} are the power-system gain and time constant, respectively. The total generated power deviation is given by

$$\Delta P_g = \Delta P_{th} + \Delta P_{hy} + \Delta P_{gas}$$

The frequency deviation of the system is denoted by Δf . Considering the load disturbance ΔP_d , the frequency deviation can be represented by

$$\Delta f(s) = \frac{K_{PS}}{T_{PS} s + 1} [\Delta P_g(s) - \Delta P_d(s)]$$

The control input to the three generating units is distributed according to their respective participation factors. Thus,

$$u_{th} = K_T u - \frac{1}{R_1} \Delta f$$

$$u_{hy} = K_H u - \frac{1}{R_2} \Delta f$$

$$u_{gas} = K_G u - \frac{1}{R_3} \Delta f$$

The participation factors satisfy

$$\boxed{K_T + K_H + K_G = 1}$$

III. HIGHER-ORDER SLIDING MODE CONTROLLER DESIGN

The sliding surface for the proposed Higher-Order Sliding Mode Controller (HOSMC) is defined as

$$s(t) = ACE(t) + \lambda \int_0^t ACE(\tau) d\tau$$

where $\lambda > 0$ is the sliding-surface design parameter. The time derivative of the sliding variable is $\dot{s}(t) = ACE(t) + \lambda ACE(t)$.

The objective of the HOSMC is to drive both the sliding variable and its derivative to zero in finite time, i.e., $s(t) \rightarrow 0$, $\dot{s}(t) \rightarrow 0$.

The proposed control law is given by

$$u(t) = -k_1 |s(t)|^{1/2} \text{sgn}(s(t)) + v(t)$$

with

$$\dot{v}(t) = -k_2 \text{sgn}(s(t))$$

where $k_1 > 0$ and $k_2 > 0$ are the HOSMC gains.

The control signal generated by the proposed controller is applied to the thermal, hydro, and gas power plants through their corresponding participation factors K_T , K_H , and K_G . The integral action embedded provides a continuous control signal, thereby reducing the chattering associated with conventional first-order sliding-mode control.

A. Stability Analysis using Lyapunov Method

To guarantee finite-time convergence, the stability of the Super-Twisting algorithm is verified using the Lyapunov function candidate. Define the state vector $\xi = [\xi_1, \xi_2]^T = [|s|^{0.5} \text{sign}(s), v]^T$. We can rewrite the sliding surface dynamics as:

$$\dot{\xi}_1 = \frac{1}{2|\xi_1|} (-k_1 \xi_1 + \xi_2 + \phi(t))$$

$$\dot{\xi}_2 = -k_2 \text{sign}(\xi_1)$$

where $\phi(t)$ is the bounded perturbation representing parameter uncertainties and disturbances, satisfying

$$|\phi(t)| \leq \delta_c |\xi_1|$$

Define a quadratic Lyapunov function:

$$V(\xi) = \xi^T P \xi$$

where P is a symmetric positive-definite matrix:

$$P = \begin{bmatrix} k_2 + 2k_1^2 & -k_1 \\ -k_1 & 1 \end{bmatrix}$$

The derivative of V along the trajectory of the system is:

$$\dot{V} = -\frac{1}{|\xi_1|} \xi^T Q \xi$$

where Q is positive-definite, provided that the gains satisfy:

$$k_1 > 2\delta_c$$

$$k_2 > \frac{5\delta_c k_1 + 4\delta_c^2}{2(k_1 - 2\delta_c)}$$

Since

$$\dot{V} \leq -\gamma_c V^{0.5}$$

for some positive constant γ_c , the system states are guaranteed to converge to the sliding manifold $s = 0$ in finite time.

ATOM SEARCH OPTIMIZATION (ASO) ALGORITHM

Atom Search Optimization (ASO) is a population-based metaheuristic optimizer inspired by molecular dynamics [17–18]. The search is guided by Lennard–Jones potential forces and covalent bond forces.

Mathematical Model of ASO

Let N be the number of atoms, and D be the dimension of the search space. The position of the i -th atom is represented as

$$x_i = [x_i^1, x_i^2, \dots, x_i^D]$$

The fitness value of each atom represents its energy. At each iteration t , the mass $m_i(t)$ of the i -th atom is calculated based on its fitness:

$$M_i(t) = \exp\left(-\frac{Fit_i(t) - Fit_{best}(t)}{Fit_{worst}(t) - Fit_{best}(t)}\right)$$

$$m_i(t) = \frac{M_i(t)}{\sum_{j=1}^N M_j(t)}$$

The Lennard-Jones potential force acting on atom i from atom j is:

$$F_{ij}^d(t) = \eta(t) \left[2 \left(\frac{\sigma_{ij}(t)}{r_{ij}(t)} \right)^{13} - \left(\frac{\sigma_{ij}(t)}{r_{ij}(t)} \right)^7 \right] \frac{r_{ij}^d(t)}{r_{ij}(t)}$$

where $r_{ij}(t)$ is the Euclidean distance and $\sigma_{ij}(t)$ is the equilibrium distance.

The interaction force on atom i in dimension d is a weighted sum of forces from the K_{best} atoms:

$$F_i^d(t) = \sum_{j \in K_{best}} rand_j F_{ij}^d(t)$$

where K_{best} decreases linearly.

The covalent bond force (constraint force) due to the best atom is:

$$G_i^d(t) = \lambda_a(t) (x_{best}^d(t) - x_i^d(t))$$

where $\lambda_a(t)$ is the Lagrangian multiplier.

The acceleration of atom i is:

$$a_i^d(t) = \frac{F_i^d(t) + G_i^d(t)}{m_i(t)}$$

The velocity and position updates are:

$$v_i^d(t+1) = rand_i^d v_i^d(t) + a_i^d(t)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1)$$

objective Function Definition

To achieve high frequency stability, the Integral of Time-weighted Absolute Error (ITAE) is chosen as the objective function:

T_{sim}

$$J = \int_0^{T_{sim}} t \cdot |\Delta f(t)| dt$$

ASO is executed to search for the optimal parameters $[\lambda, k_1, k_2]$ that minimize J .

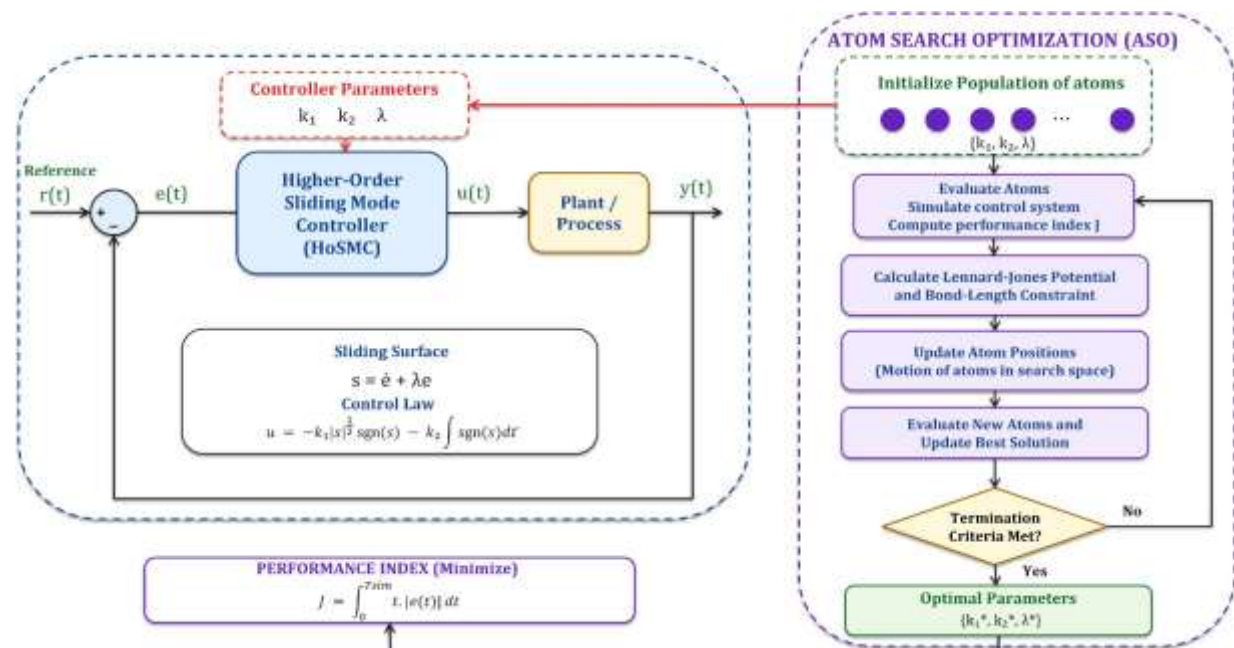


Figure 2. Schematic representation of the proposed ASO-tuned HOSMC

SIMULATION RESULTS AND DISCUSSIONS

The proposed ASO-HOSMC is implemented on a single-area multi-source power system. The simulation results are compared with those of an ASO-optimized FOPID controller, a classical SMC, a DE-optimized PI

controller, and an optimal controller.

Case 1: Nominal System

A 1% step load disturbance (SLD) is applied to the power system at $t = 1.0$ s. The dynamic response of frequency deviation (Δf) is plotted in Fig. 3.

TABLE I. TIME-DOMAIN RESPONSE PARAMETERS FOR THE NOMINAL SYSTEM

Parameter	Proposed HOSMC	MC	FOPID	DE [19]	Optimal [20]
Settling Time, t_s (s)	2.25	6	3.5	5.4	15.76
Peak Undershoot	-0.0041055	0.009850	-0.017182	-0.064018	-0.062675
Peak Time, t_p (s)	1.1136	2807	1.5494	2.773	2.714

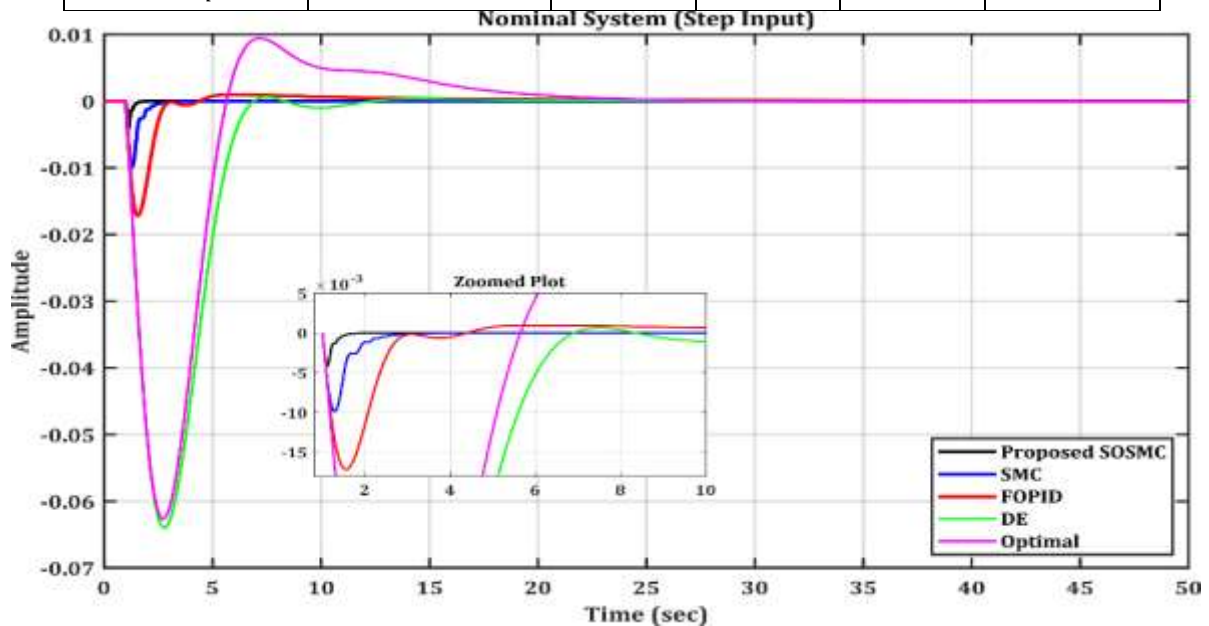


Figure 3. Dynamic response under nominal step load change

As shown in Fig. 3 and Table 1, the proposed controller achieves fast frequency restoration. The proposed controller achieves the lowest undershoot and settling time. The time domain parameters and statistical comparison are summarized in Table I and II.

TABLE II. ERROR INDICES FOR THE NOMINAL SYSTEM

Controller	IAE	ISE	ITAE	SE
Proposed HOSMC	0.00092005	2.2603×10^{-6}	0.0014132	5718×10^{-6}
SMC	0.005379	3.2705×10^{-5}	0.0087228	3625×10^{-5}
FOPID	0.029442	0.00022504	0.21511	0.0042595
DE [19]	0.19563	0.0090128	0.7106	0.27269
Optimal [20]	0.23108	0.0083348	1.2281	0.26317

Case 2: Robustness and Parameter Variation

To evaluate the robustness of the controllers, a sensitivity analysis is conducted. All system parameters are varied by +25% and +50% simultaneously. The dynamic response under these variations is shown in Fig. 4 and 5. The proposed ASO-HOSMC response remains virtually identical to the nominal case, demonstrating insensitiveness to system parameters. The statistical comparison is summarized in Table III and IV.

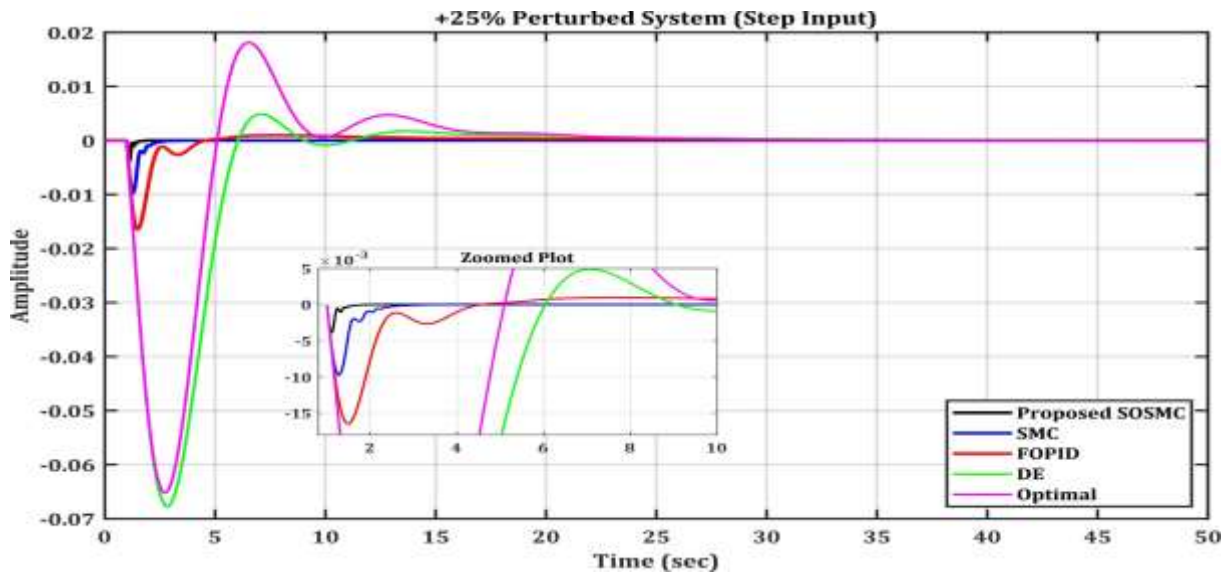


Figure 4. Frequency deviation under +25% variation in system parameters

TABLE III. ERROR PERFORMANCE INDICES FOR THE +25% PERTURBED SYSTEM

Controller	IAE	ISE	ITAE	ITSE
Proposed HOSMC	0.00076822	1.7347×10^{-6}	0.001483	1.9469×10^{-6}
SMC	0.0048026	2.9332×10^{-5}	0.0074868	3.8424×10^{-5}
FOPID	0.028731	0.00018021	0.22529	0.00035287
DE [19]	0.21945	0.0098744	1.048	0.030103
Optimal [20]	0.23692	0.0087985	1.2754	0.02817

TABLE IV. ERROR PERFORMANCE INDICES FOR THE +50% PERTURBED SYSTEM

Controller	IAE	ISE	ITAE	ITSE
Proposed HOSMC	0.00070279	1.5191×10^{-6}	0.001484	1.7024×10^{-6}
SMC	0.0044606	2.6258×10^{-5}	0.0070012	3.4064×10^{-5}
FOPID	0.027732	0.00015273	0.23305	0.00031758
DE [19]	0.23758	0.010237	1.3054	0.031541
Optimal [19]	0.266	0.0095061	1.5647	0.033611

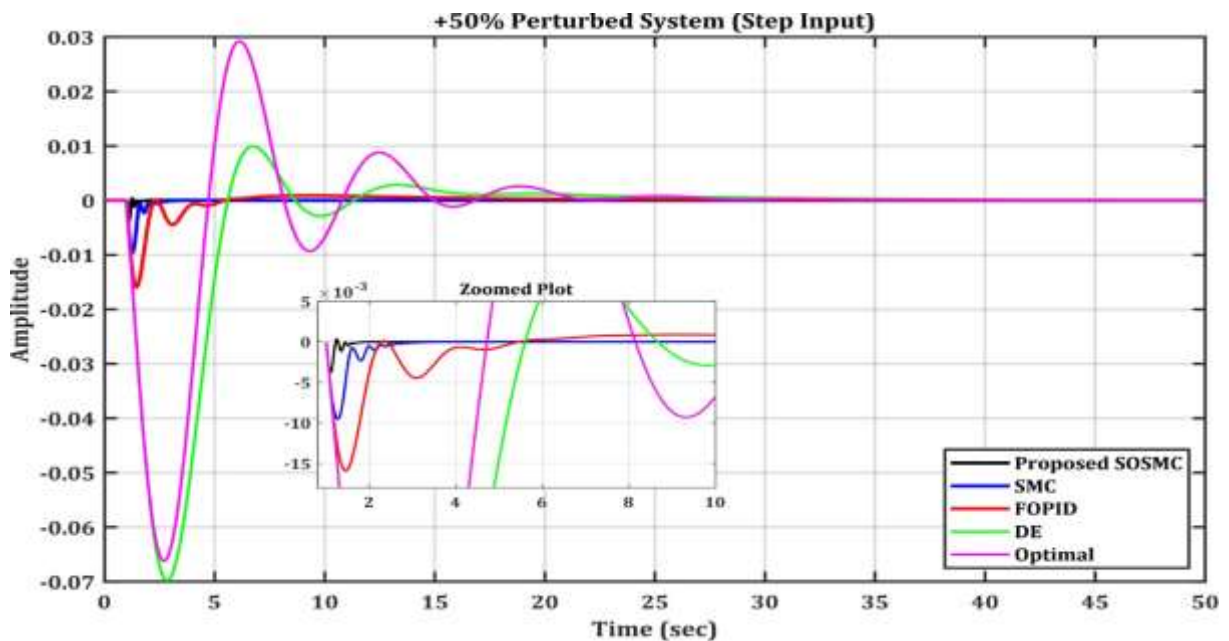


Figure 5. Frequency deviation under +50% variation in system parameters

Case 4: Response under Random Load Disturbances

The proposed controller is tested under a random load-disturbance profile, and the resulting frequency deviation is plotted in Fig. 6. The ASO-HOSMC successfully dampens the random variations, keeping the frequency within limits, whereas the controller exhibits much larger deviations.

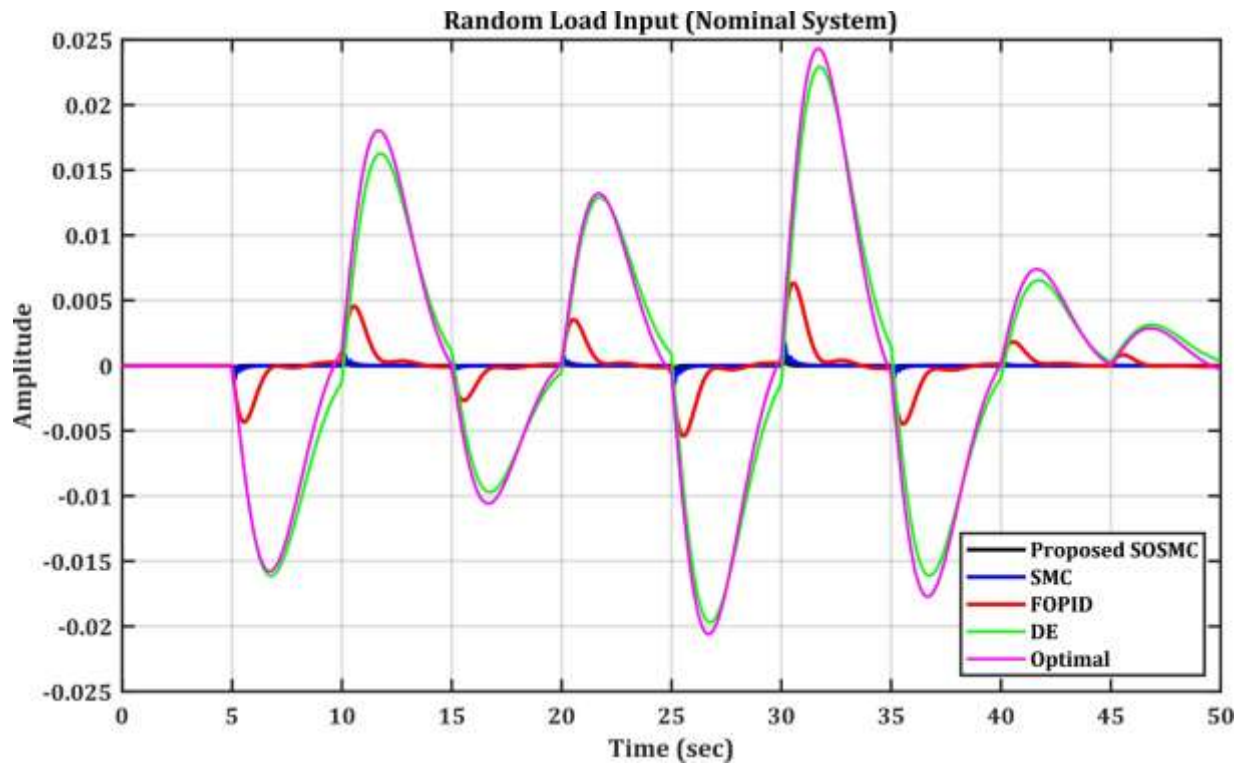


Figure 6. Dynamic performance under random load variation profile

CONCLUSIONS

In this study, a Higher-Order Sliding Mode Controller (HOSMC) based on a second order sliding surface is developed and implemented for load-frequency control (LFC) of a single-area, multi-source power system. The system incorporates reheated thermal, hydro, and gas power plants to represent a realistic multi-source generation environment. The controller gains are optimally tuned using the Atom Search Optimization (ASO) algorithm. Simulation results demonstrate that the proposed ASO-HOSMC approach provides improved robustness against step load disturbances, parameter variations, and random load changes. In addition, the higher-order sliding mode formulation effectively suppresses the chattering associated with conventional sliding mode control, thereby improving the practicality of the proposed controller for real-world power system applications.

IV. DISCLOSURES AND ETHICAL STATEMENTS

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Author Contributions: System Description; Simulation and Result Analysis, R.K and J.K; Draft Preparation, R.K.G and S.S; Writing Review and Editing, L.K, K.S.R and P.D; Supervision, R.K, P.D; All authors reviewed the manuscript

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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