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Original Article

Designing a Novel Sliding Mode Controller Applying a Hybrid Integration of PSO-GWO-ABC Algorithms for Interconnected Power Systems in Load-Frequency Control Strategy

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Abstract *- This work focuses on a Load-Frequency Control (LFC) problem of two-area interconnected multi-source power systems. It is a new kind of network, consisting of numerous sophisticated inter-weavings: generation rate constraints, temporal delay, and Superconducting Magnetic Energy Storage (SMES), as well as Unified Power Flow Controller (UPFC), which can be used to more accurately reflect the operating states in real life. To enhance the network frequency stability, a new type of Sliding Mode Controller (SMC) is developed, in which the parameters of the sliding surface are optimized from a hybrid PSO-GWO-ABC algorithm. The developed approach leverages the benefits of PSO, GWO, and ABC to optimally yield the explicit solution and thus improve control performance. By primary indicators like frequency difference of two zones, power oscillations on interconnecting lines, overshoot, and stabilization time, the performance of the controller is inspected under step response and random load perturbations. MATLAB/Simulink package was used to simulate the proposed PSO-GWO-ABC-SMC controller, showing enhanced quickness and stability with reduced oscillation and stabilization times relative to other optimization solutions. These findings show the effectiveness of the newly proposed LFC methodology in increasing frequency stability in the interconnected power grid.*

Keywords *- LFC, UPFC, SMES, PSO, GWO, ABC, Novel SMC.*

1. Introduction

Load Frequency Control (LFC) is still considered an important problem in modern power system operation. It is becoming more important as grids grow ever more interconnected, renewable energy becomes integrated into the grid in greater quantities, and load variations become less predictable. It showed that the LFC problem is now not a common frequency system control issue anymore in modern power systems, but an intricate one with various kinds of power sources, physical constraints, energy storage devices, and communication problems engaged simultaneously [1-2].

In recent years, a large number of control methodologies integrated with optimization techniques have been developed for solving the LFC problem with higher performance. Meta-algorithmic approaches for tuning controller parameters of thermal, hydroelectric, and multi-source coupled systems are extensively used, such as Particle Swarm Optimization (PSO), Gray Wolf Optimization (GWO), Artificial Bee Swarm Algorithm (ABC), etc., that enhance frequency deviation, dampen oscillations, and short settling time [3-7]. Also, several works have focused on more recent system configurations like multi-region systems comprising virtual sources, renewable sources, and energy storage systems [8-10] underlining the positive impact of service-providers elements in the system eigenvalues. Sliding Mode Controllers (SMC) are an alternative and increasingly studied option over classical controllers, due to their excellent performance regarding disturbance rejection, parameter uncertainty, and system nonlinearity. The use of better sliding mode, improved sliding observer, or modified sliding surface structures has been shown in several recent works for application to multi-zone power systems, and superior dynamic response quality and increased system noise immunity are reported [11-15]. Besides, the performance of an SMC is strongly affected by the selection of a sliding surface with the necessary parameters. If these parameters are not good enough, not only the frequency deviations but also the tie-line power flow fluctuations will be greatly increased. This phenomenon is particularly considered in a real power network with uncertainties and nonlinearities.

The LFCs have to face another major challenge due to the coexistence of constraints and non-idealities, which encompasses GRC limits, time delays that happen in measurement - signal carrying - control processing, as well as inter-area power coordination via the link lines. New results indicate that time delays and dynamic constraints can lead to a serious degradation of control performance, manifested in higher coefficients of oscillation and longer settling duration [16-18]. At the same time, devices such as Superconducting Magnetic Energy Storage systems (SMES) and Unified Power Flow Controllers (UPFCs) can provide rapid power support under transitional conditions and flexible adjustment of transmission power, thereby opening up the possibility of improving frequency stability quality if properly coordinated with appropriate control. Based on the aforementioned, this paper presents a novel work of designing a sliding mode controller for a two-zone interconnected power system with multiple power sources[including GRC effects and time delay characteristics], implemented through Superconducting Magnetic Energy Storage (SMES) and Unified Power Flow Controller (UPFC), in which the parameters are tuned optimally through the PSO-GWO-ABC hybrid algorithm. This method benefits parameter optimization efficiency by taking advantage of the fast convergence ability of PSO, the exploration-exploitation balance ability of GWO, and the ability to avoid local extrema of ABC. Using characteristic metrics such as frequency deviation in the two zones, power oscillation on the link line overshoot, and settling time, this proposed controller is evaluated under the influence of step load and random load conditions.

While still several publications on load frequency control exist, to the best of our knowledge, most of these works rely on employing only one single PSO, GWO, or ABC algorithm at a time or at most two combined algorithms, and as a common approach for simplification in modeling the system, we refer to as few practical factor like GRC, communication delay SMES or UPFC has been neglected. Moreover, the majority of the published studies are limited to ladder load tests and thus, do not cover in detail controller behavior during continuously varying disturbances. We encountered a research gap in creating LFC strategies based on both a more realistic linked system model and a more effective hybrid optimization framework. In order to overcome this gap, the current research proposes a brand new sliding mode controller to tune by means of a couple of fully built-in powers: PSO-GWO-ABC for a two-zone multi-source connected energy system. The hybrid control methodology applies a novel three-level search metaheuristic optimization to improve the tuning quality. Furthermore, such a control method enhances published reports by using an effective evaluation framework that executes from the bottom to the top of the algorithm. This kind of controller is highly suitable for designing a control system with nonlinear constraints and auxiliary support elements working under practical operations. Thus, the uniqueness of this work is primarily in the simultaneous utilization of PSO, GWO, and ABC to tune the SMC parameter with a thorough validation for controller performance in an actual LFC scenario.

2. Mathematical Model of Interconnected Power Systems

The configuration diagram of the connection-type power system used in this paper is shown in Figure 1. It consists of thermal, hydro, and gas turbine sources; also takes into account their linkage with Superconducting Magnetic Energy Storage (SMES), Unified Power Flow Controller (UPFC), (Governing Resonant Controllers (GRC), and time delays for incorporation to better describe the actual operation, not only within the framework of traditional generation mode. In this configuration, SMES, being a fast energy storage device, can exchange power and at the same time compensates for instantaneous power exchange between generator and load, which aids in mitigating frequency deviations and enhancing transient response. On the interconnection line, UPFC is integrated to flexibly change the transmission power between two areas, which effectively improves inter-regional power coordination and conditions tie-line active power oscillation suppression and system frequency stability maintenance. GRC also indicates the maximum rate of change in power output of the generator unit, as a theoretical physical limitation for frequency control. GRC inhibits the instantaneous change of mechanical power from generating units to control signals and limits the replenishment ability in particular, since GRC is mostly reflected at high system frequencies and urgently needs compensation, which is called control capability. This results in more frequent deviations and longer recovery time of the system.

But the most prominent and detrimental factor that comes into play against quality control is time delay. This component exists within the measurement, signal transmission, control processing, and actuator response phases, where instantaneous effects of control signals being sent to generating units or support equipment are prevented. The time delay is aggravated in the case of GRC, because not only does the system need a considerable amount of time in communicating signals to each other and processing them, but it also limits the generating source's power response speed. As a result, the correction power becomes slower than the change in load, causing oscillation amplitudes to become larger with overshoot and stabilization time longer, potentially resulting in decreased dynamic stability amplitude. The nature of the interaction is even more intricate since oscillations in one zone can transfer across to the other through tie-line power, thus reinforcing the interaction considerably and making the control problem much harder; however, this complicates a two-region linked investigation system. From the above analysis, it can be concluded that while SMES and UPFC are capable of assisting. In this context, an LFC controller has to be built to ensure several outstanding performances, such as fast and robust response to the appearance of uncertainty. Hence, considering such advantages, the SMC sliding mode controller is chosen for this study based on robustness and noise immunity properties, and to select the optimal parameters of the controller, hybrid PSO-GWO-ABC optimization algorithms are used.

This can lead to better frequency regulation, lower frequency deviation, and power line oscillation, while at the same time improving the dynamics of a two-area multi-source power system with SMES, UPFC, in conjunction with GRC, along with time delay.

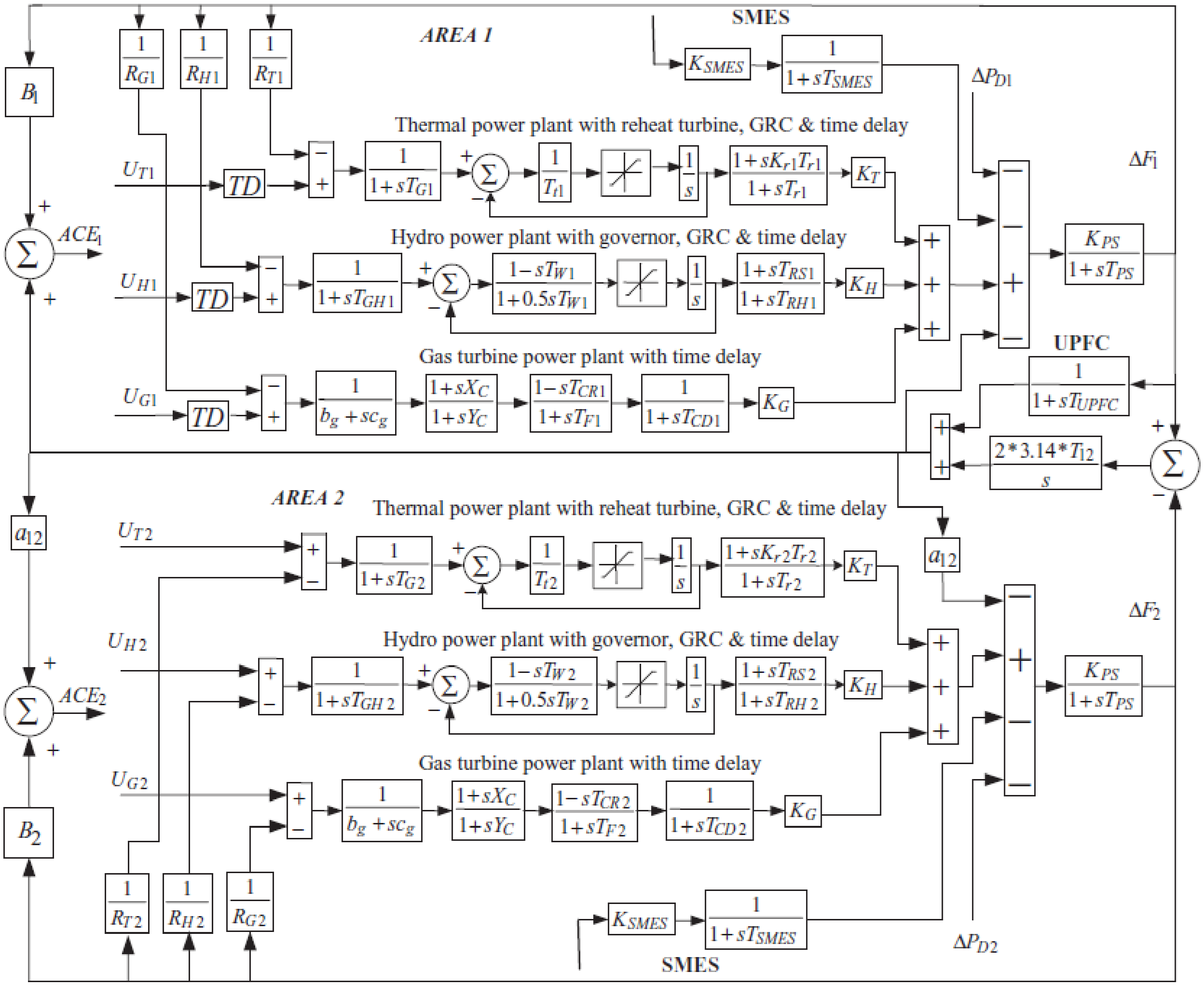


Fig. 1 An interconnected power system model considering GRC, SMES, UPFC, and time delay

3. Design of an Effective LFC Controller

3.1. Sliding Mode Controller Design with Hysteresis Compensation

In the current study, an effective LFC strategy applying sliding mode control is proposed. Such a control method integrates a hysteresis compensation loop in order to enhance the control quality of the interconnected electric power grid. Currently, the problem of delay elimination may not be the major goal in the LFC strategy. Importantly, the objective is to dampen the unwanted impact on the system that might be created by the communication latency. In this perspective, such a control method can reduce the system's transients as well as maintain the stable boundary. The control error for this kind of LFC controller is chosen as $e(t) = ACE(t)$. Thus, the compensation error can be constructed using a special mechanism defined as the first-order prediction.

$$\hat{e}(t) = e(t) + \tau \dot{e}_f(t) \qquad (1)$$

Where $\dot{e}_f(t)$ is denoted as the derivative of the error e(t) after filtering through the following filter:

$$\dot{e}_f(s) = \frac{Ns}{s+N} e(s) \qquad (2)$$

This predictive component helps reduce phase shift caused by delay time τ when τ is in the small-to-medium range (usually 0.1-0.5 s), thereby improving the ability to suppress frequency oscillations and link power in a delay environment. The sliding surface is built in case of using the error, $\hat{e}(t)$ as shown below:

$$s(t) = \dot{\hat{e}}(t) + \lambda\hat{e}(t) \tag{3}$$

Here, the control law is newly designed to obtain a fast convergence to the system trajectory to the sliding manifold. It is also necessary to minimize the negative phenomenon of chattering and ensure the improvement of the real operation. Equation (4) describes this control law:

$$u(t) = -Ksat\left(\frac{s(t)}{\phi}\right) \tag{4}$$

where,

- ✓ K denotes the degree of robustness, which is used to reduce the effect of noise and model uncertainty characteristics.
- ✓ ϕ is a factor that handles the boundary layer thickness. This operation is to improve the balance between control signal smoothness and tracking error.

To achieve a good objective of keeping the control structure compact and optimally suited, the three key parameters (λ, K, ϕ) are considered the decision variables and are fine-tuned using the PSO-GWO-ABC hybrid optimization algorithm based on the ITAE objective function, taking into account frequency deviation, linked power oscillations, and control work. Theoretically, it is reasonable to select the following Lyapunov candidate:

$$V = \frac{1}{2}s^2 \tag{5}$$

In terms of stability, based on the Lyapunov function $V = \frac{1}{2}s^2$, the time derivative of Vcan be deduced in the form $V = s\dot{s}$. When considering a system with a blocked communication delay $\tau \in [0, \tau_{max}[]]$, the dynamics of the sliding variable can be expressed as a function that simultaneously depends on $s(t)$ and $s(t-\tau)$. By appropriately selecting control coefficients and using a saturation function with boundary layers, we can establish a decay inequality for V, $\dot{V} \le -\eta|s(t)| + \gamma|s(t-\tau)|$, $\eta > 0$, $\gamma \ge 0$. Under sufficient conditions, $\eta > \gamma$it follows that $V$is defined in the Razumikhin, thereby ensuring that s(t) converges to the vicinity of the origin and the system trajectory approaches a sliding manifold. Consequently, the control error ACE is reduced and approaches 0, ensuring the asymptotic stability of the closed-loop system within the defined operating range. Therefore, the proposed method should be presented as a delay-compensated/delay-mitigated sliding mode control strategy emphasizing the ability to maintain the stability and robustness of the LFC problem under the simultaneous effects of communication delay and load variation.

3.2. Optimizing Controller Parameters using the PSO-GWO-ABC Hybrid Algorithm

When designing an SMC controller, it is important to select a key set of parameters that strongly affect the control quality. This study presents an effective method to solve the tuning problem of key parameters for a controller. This solution uses a metaheuristic-based optimization mechanism executed in MATLAB. A set of parameters needs to be optimized λ, K and ϕ. The factor $\lambda$is to control the convergence speed of the sliding surface, while the second one, K, is to determine the robustness against noise and model uncertainty. The last one, phi, regarding the boundary layer thickness, is used to eliminate the chattering phenomenon and smooth the control signal. Here, it is reasonable to choose the searching domains to ensure the stable and feasible characteristics as follows:

$$\lambda \in [0.2,5], K \in [0.1,5], \phi \in [0.001,0.1].$$

The major aim of the LFC in an electric power grid is to eliminate the fluctuation of both frequency and tie-line power flow. In this study, the Integral Time Absolute Error (ITAE) criterion, one of the most efficient control criteria, is selected for dealing with the objective of the LFC issue.

$$\begin{aligned} J(x) &= \int_0^T t\left(|\Delta f_1(t)| + |\Delta f_2(t)| + \alpha\,|\Delta Ptie(t)|\right)dt \\ &+ \beta\int_0^T u^2(t)dt \end{aligned} \tag{6}$$

In (6), α and β are denoted as two weight factors, while T is the simulation time. In this work, these factors are chosen as follows:

α = 1; β = 0.05 and $T \in$ [50s; 100s].

According to the working principle of the proposed optimization mechanism, at each objective function evaluation, the updating parameters mentioned above are assigned to the Simulink model. Then, the simulation for the LFC problem will be executed, providing the output parameters to calculate the fitness function (6).

A working flow of the proposed hybrid PSO-GWO-ABC algorithm is orderly executed as PSO → GWO → ABC. This flow ensures the convergence reliability of the algorithm, thereby enhancing the control quality of the system. The PSO is to rapidly discover a global area according to the searching mechanism of food for the swarms, like birds or fish. The GWO is utilized to keep directional mining around the best region with major parameters α, β, and δ. Finally, the ABC algorithm utilizes employed/onlooker bees to locally search the neighborhood, thereby obtaining superior solution quality. The flow chart of the proposed hybrid optimization with a detailed working principle is plotted in Figure 2.

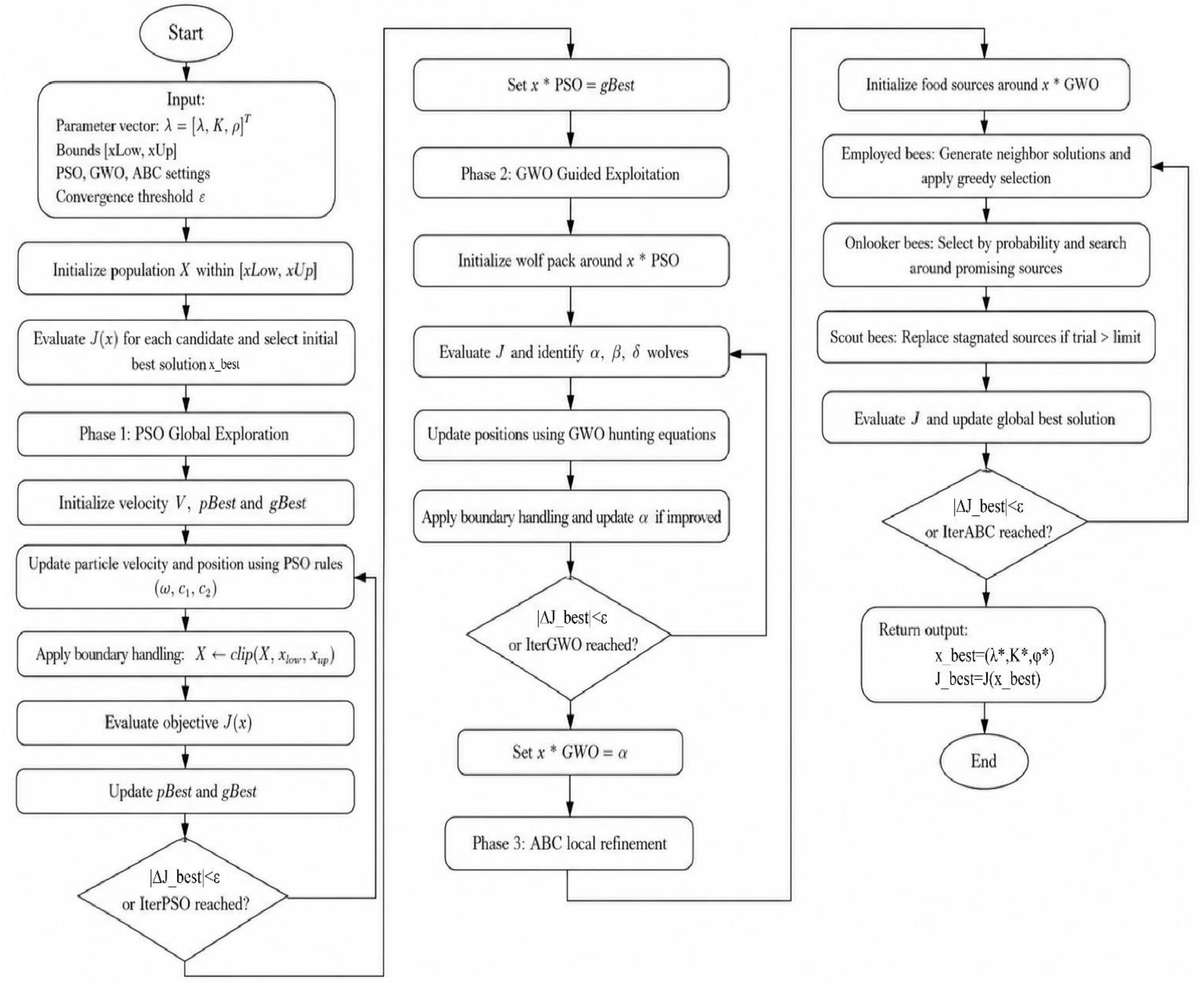


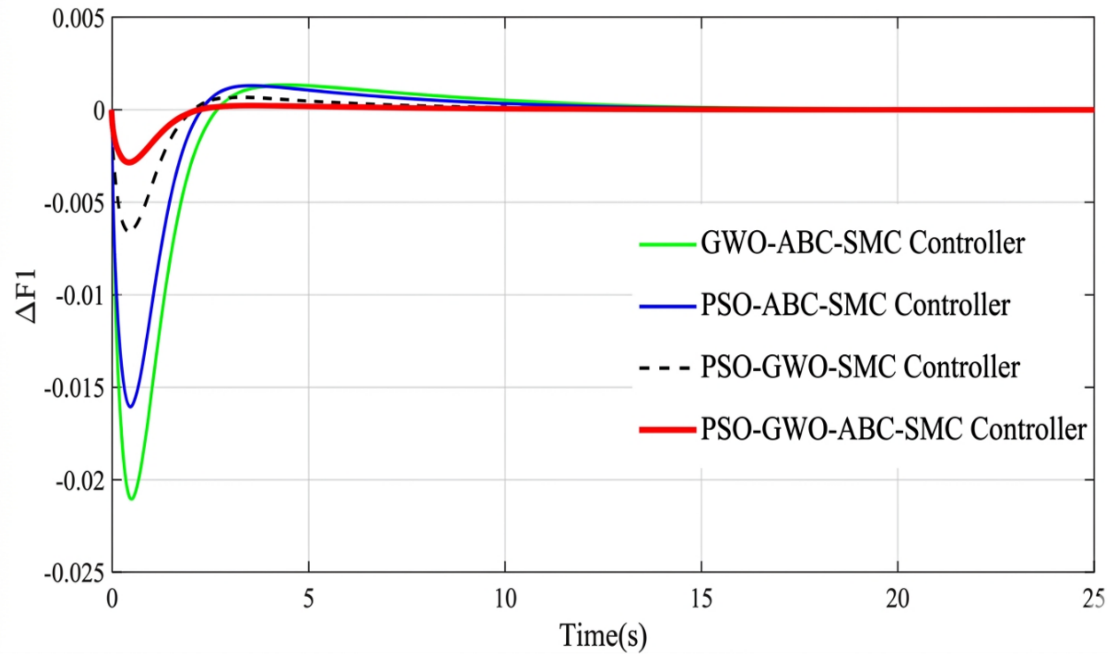
Fig. 2 A flowchart of the PSO-GWO-ABC algorithm for optimizing SMC parameters

4. Simulation Results

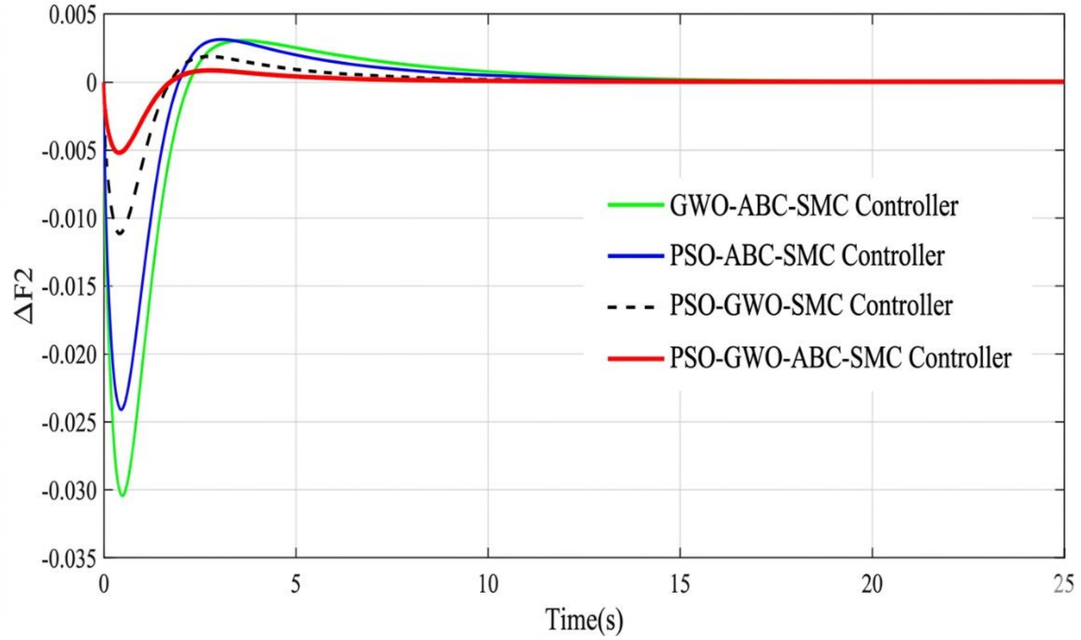
Because delay time can represent the impact of measurement, signal transmission, and actuator response in actual operating conditions on system performance indicators under real circumstances, it is common to simulate with a delay of 2s. After building the system model and getting an optimal controller, we will continue carrying out simulations and analyzing the results based on the simulation frequency stabilization effectiveness for the characteristic load disturbance. Two disturbance cases are considered in the present study; one is a step load, and the other is a random load. When performance metrics like overshoot, stabilization time, and amplitude of oscillation are used to measure the transient behavior of a system, a step load scenario is applied. It also ensures that the controller is able to maintain control quality even with a continuously varying load, which is closer to actual operational conditions. Time delay of 2s in the system increases the rigor of the control problem, so the performance evaluation of optimization algorithms is clearer in case a delay appears in the system. These test scenarios are used to compare the optimization methods in terms of areas' frequency response and changes in line power.

Case 1: All load changes are assumed to be types of step at the right beginning: $\Delta P_{d1} = 0.03$ *pu*; $\Delta P_{d1} = 0.04$ *pu*.

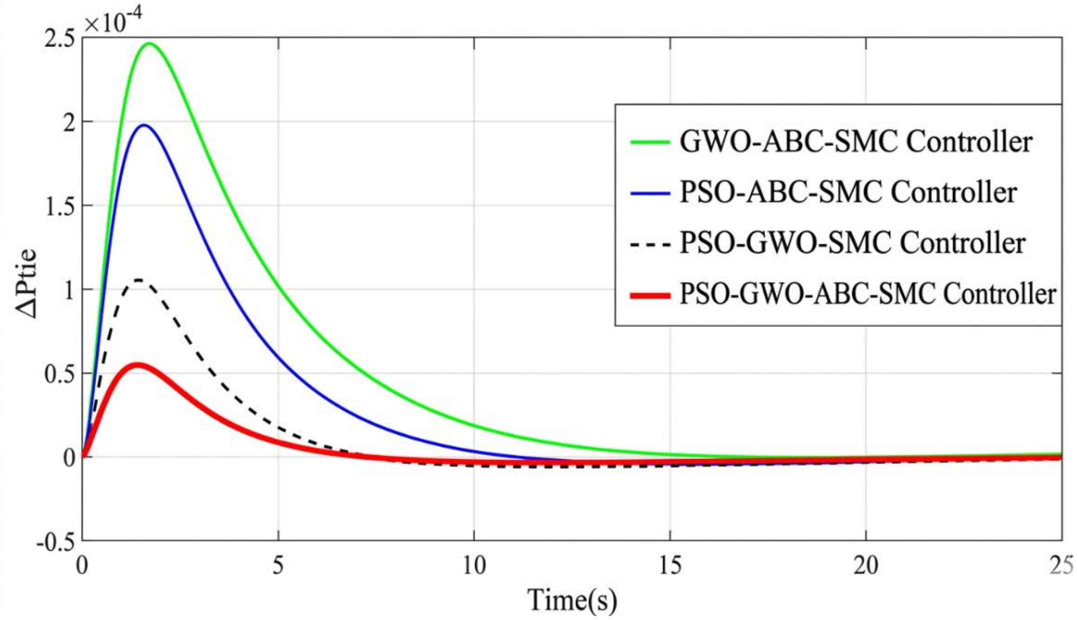
In order to better benchmark the effectiveness of the proposed PSO-GWO-ABC-based method for tuning the sliding surface parameters of the SMC controller, key dynamic performance metrics are listed in Table 1. The PSO-GWO-ABC-SMC controller offers the best dynamic response quality among other optimization approaches investigated in this study, according to simulation performance. The proposed method with the best dynamic performance is chosen among the compared algorithms. It generated the smallest frequency deviation in both control regions, ΔF1 and ΔF2, with the lowest overshoot and shortest stabilization time. Link line power feedback was also improved, having the lowest peak amplitude and much faster oscillation damping. The results show that the hybrid PSO-GWO-ABC method outperforms, in terms of the parameter optimization of the sliding surface for the SMC controller frequency stability, with a significant reduction in inter-regional power oscillations when compared to both GWO-ABC and PSO-ABC methods.



(a)



(b)

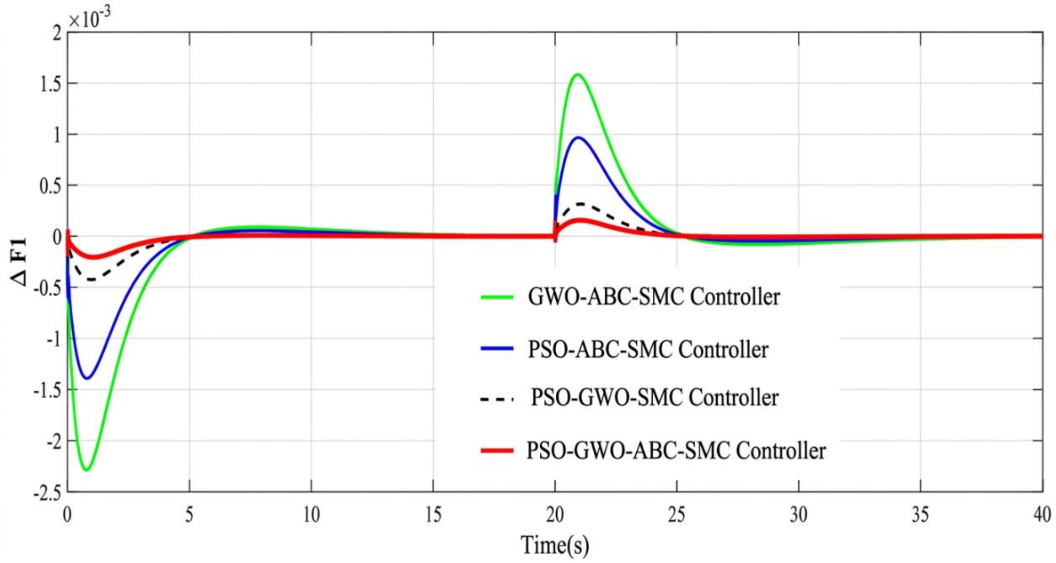


(c)

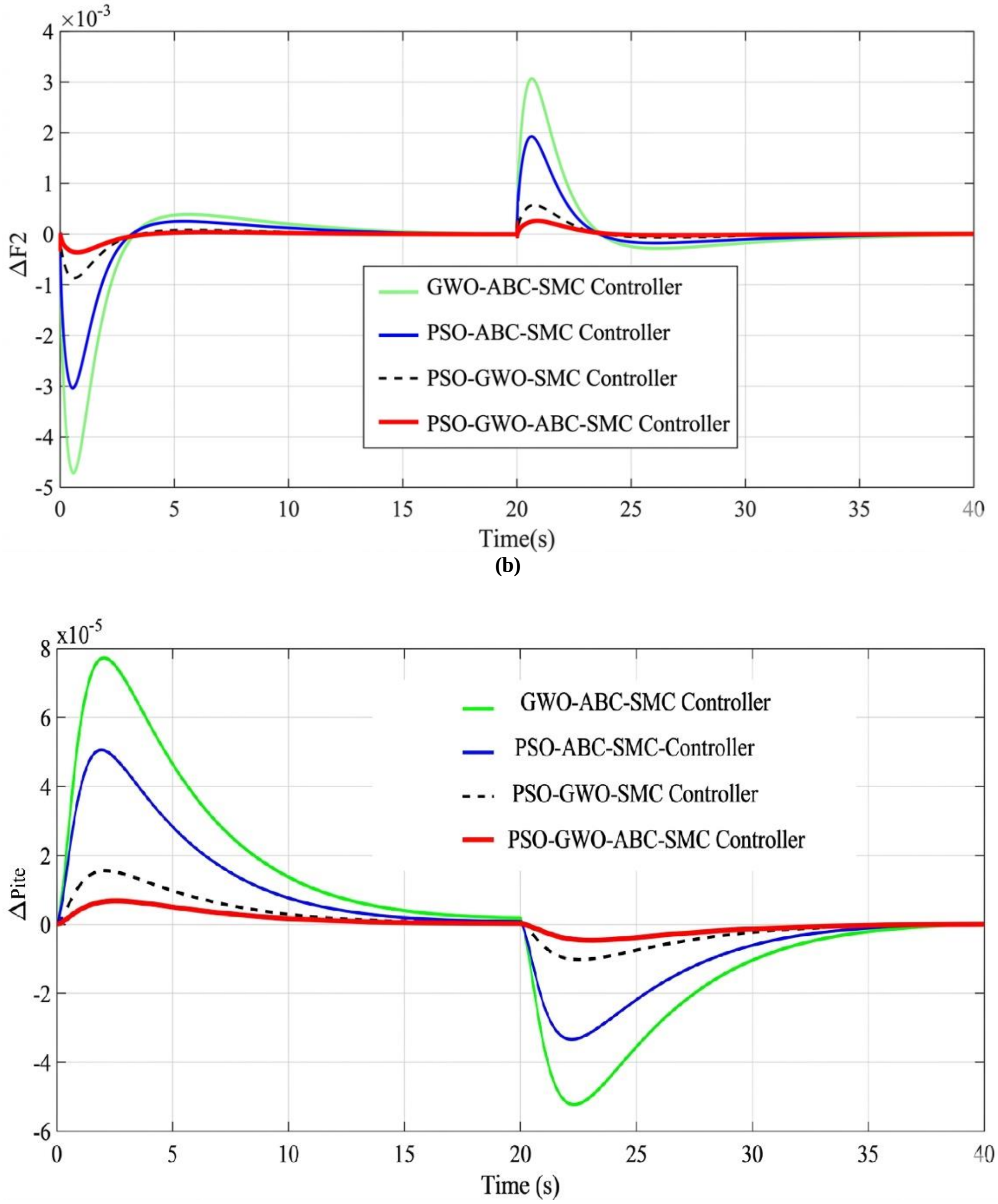
Fig. 3 System dynamic responses under step-load disturbance: (a) ΔF1, (b) ΔF2, and (c) ΔPtie

Table 1. Comparison of different optimization methods

Methods of optimization	ΔF1 (Undershoot)	ΔF1: (Overshoot)	ΔF1: Settling time (s)	ΔF2: (Undershoot)	ΔF2: (Overshoot)	ΔF2: Settling time (s)	ΔPtie: Peak value	ΔPtie: Settling time (s)
GWO-ABC-SMC	-0.022	0.0012	10-12	-0.180	0.0045	10-12	2.45	17-18
PSO-ABC-SMC	-0.015	0.0010	8-10	-0.150	0.0040	8-10	2.00	14-16
PSO-GWO-SMC	-0.008	0.0008	6-8	-0.115	0.0035	6-8	1.10	10-12
PSO-GWO-ABC-SMC	-0.003	0.0005	4-5	-0.075	0.0025	4-5	0.55	7-8



(a)



(b)

(c)

Fig. 4 System dynamic responses under step-load disturbances for two areas: (a) ΔF1, (b) ΔF2, and (c) Δptie

The controller is then further tested under random load disturbances to assess its robustness and performance under continuously changing loads, as is common in real-world power system operation.

Case 2: All load changes are assumed to be types of step $\Delta P_{d1} = 0.03\ pu$; $\Delta P_{d2} = 0.05\ pu$. The simulation results in this perspective are shown in Figure 4.

From the results of the three responses, ΔF1, ΔF2, and ΔPtie, the effectiveness of the PSO-GWO-ABC-SMC controller is much higher than other optimization approaches. Both the frequency deviation signals confirm that the response curve of the proposed method always has a minimum oscillation amplitude value, at both instances when the dip occurs for the first time and after disturbance acting again on the system, also overshoot comparatively less than controllers tuned with GWO-ABC, PSO-ABC, and PSO-GWO. In addition, the PSO-GWO-ABC-SMC answer exhibits considerably improved damping qualities by reaching steady-state values quickly with less settling time and no significant residual oscillations. Similar trends can also be observed in link power response ΔPtie, where the proposed method has the smallest peak value and the highest oscillation decay rate, followed by larger and lasting oscillations of the remaining methods, GWO-ABC-SMC especially. The outcome thereby confirms that the slip surface parameters extracted through PSO-GWO-ABC are a better fit for the system of interest, while at once enhancing frequency stability in both areas and restricting power oscillations on the line. That is to say, the advantages of the accelerated convergence characteristic by PSO, exploration-exploitation balance capacity attributed to GWO, and local extremum avoidance capability demonstrated in ABC have promoted the proposed algorithm, improving the sliding surface parameters more efficiently, which ultimately achieved a significant improvement of dynamic response quality and verified the superiority of the PSO-GWO-ABC-SMC controller.

5. Conclusion and Recommendations for Future Research

Time delay, GRC, SMES, and UPFC are included in this work for a better approach with realistic operational conditions in actual practical applications to formulate the proposed sliding mode controller for interlinked power systems. By means of the hybrid PSO-GWO-ABC algorithm, this optimization processor sufficiently makes use of the advantages of the three component algorithms and effectively improves the quality of optimization. PSO-GWO-ABC-SMC controller demonstrates superior transient characteristics compared to the rest for stepped and random load cases. In particular, it decreases frequency deviation in the 2 control regions, dampens line power oscillation, and reduces overshoot and stabilization time. The ensuing results demonstrate that the proposed controller is capable of maintaining frequency stability in interconnected power systems involving various non-linear characteristics and different real-world operating constraints. Future work will address multi-zone power systems with diverse renewable energy sources and storage devices to reflect a modern grid realistically. More focus should also be on adaptive SMC schemes, higher-order SMC algorithms, and their experimental validation, which can highlight the applicability of the proposed control methods.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

[1] Mrinal Ranjan, and Ravi Shankar, “A Literature Survey on Load Frequency Control Considering Renewable Energy Integration in Power System: Recent Trends and Future Prospects,” *Journal of Energy Storage*, vol. 45, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Désiré D. Rasolomampionona et al., “A Comprehensive Review of Load Frequency Control Technologies,” *Energies*, vol. 17, no. 12, pp. 1-74, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Ozay Can et al., “A Novel Grey Wolf Optimizer Based Load Frequency Controller for Renewable Energy Sources Integrated Thermal Power Systems,” *Electric Power Components and Systems*, vol. 49, no. 15, pp. 1248-1259, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Neelamsetti Kirn Kumar et al., “Fuzzy Logic-Based Load Frequency Control in an Island Hybrid Power System Model Using Artificial Bee Colony Optimization,” *Energies*, vol. 15, no. 6, pp. 1-20, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[5] Ahmed Fathy, Ahmed Kassem, and Zaki A. Zaki, “A Robust Artificial Bee Colony-Based Load Frequency Control for Hydro-Thermal Interconnected Power System,” *Sustainability*, vol. 14, no. 20, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Sina Gouran-Orimi, and Ali Ghasemi-Marzbali, “Load Frequency Control of Multi-Area Multi-Source System with Nonlinear Structures Using Modified Grasshopper Optimization Algorithm,” *Applied Soft Computing*, vol. 137, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Amit Sharma, and Navdeep Singh, “Load Frequency Control of Connected Multi-Area Multi-Source Power Systems Using Energy Storage and Lyrebird Optimization Algorithm Tuned PID Controller,” *Journal of Energy Storage*, vol. 100, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Saeed Tavakoli, Abbas-Ali Zamani, and Ali Khajehoddin, “Efficient Load Frequency Control in Multi-Source Interconnected Power Systems Using an Innovative Intelligent Control Framework,” *Energy Reports*, vol. 11, pp. 2805-2817, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[9] Zeyi Wang et al., “Load Frequency Control of Multiarea Power Systems with Virtual Power Plants,” *Energies*, vol. 17, no. 15, pp. 1-10, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Yunrui Lan, and Mahesh S. Illindala, “Robust Distributed Load Frequency Control for Multi-Area Power Systems with Photovoltaic and Battery Energy Storage System,” *Energies*, vol. 17, no. 22, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] Van Van Huynh et al., “Advanced Sliding Mode Observer Design for Load Frequency Control of Multiarea Multisource Power Systems,” *International Transactions on Electrical Energy Systems*, vol. 2022, pp. 1-21, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Javad Ansari, Mohamadreza Homayounzade, and Ali Reza Abbasi, “Load Frequency Control in Power Systems by a Robust Backstepping Sliding Mode Controller Design,” *Energy Reports*, vol. 10, pp. 1287-1298, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Kun Xu, Yugang Niu, and Yekai Yang, "Load Frequency Control for Wind-Integrated Multi-Area Power Systems: An Area-Based Event-Triggered Sliding Mode Scheme," *Journal of the Franklin Institute*, vol. 359, no. 17, pp. 9451-9472, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Yang Ran et al., "H∞ Load Frequency Control of Multi-Area Power Systems with Multi-Time-Varying Delays against Deception Attacks via a Sliding Mode Control Strategy," *Journal of the Franklin Institute*, vol. 361, no. 18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[15] Anh-Tuan Tran et al., "Enhanced Sliding Mode Controller Design via Meta-Heuristic Algorithm for Load Frequency Control in Multi-Area Power Systems," *IET Generation, Transmission & Distribution*, vol. 18, no. 3, pp. 460-478, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[16] Chongxin Huang et al., "DMPC-Based Load Frequency Control of Multi-Area Power Systems with Heterogeneous Energy Storage System Considering SoC Consensus," *Energy*, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Peter Anuoluwapo Gbadega, and Yanxia Sun, "Multi-Area Load Frequency Regulation of a Stochastic Renewable Energy-Based Power System with SMES Using Enhanced-WOA-Tuned PID Controller," *Heliyon*, vol. 9, no. 9, pp. 1-21, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[18] Muhammad Inshal Shahzad et al., "Advanced Frequency Stabilization Framework for Multi-Area Renewable Energy Grids with EV Aggregator Support: A Multi-Stage Control Perspective," *Sustainable Computing: Informatics and Systems*, vol. 46, 2025. [CrossRef] [Google Scholar] [Publisher Link]

Appendix: Simulation parameters

B1 = B2 = 0.4312 p.u. MW/Hz; RT1 = RT2 = RH1 = RH2= RG1 = RG2 = 2.4 Hz/p.u.; TG = 0.06 s; Tt1 = Tt2= 0.3 s; Kr1 = Kr2 = 0.3; Tr1 = Tr2 = 10.2 s; KP1 = KP2 = 68.9655 Hz/p.u. MW;

TP1 = TP2 = 11.49 s; T12=0.0433; a12=−1; TW1 = TW2 = 1.1 s;

TRS1 = TRS2 = 4.9 s; TRH1 = TRH2 = 28.749 s; TGH1 = TGH2 = 0.2 s;

XC = 0.6 s; YC=1.1 s; Cg = 1; bg = 0.049 s;

TF = 0.239 s; TCR1 = TCR2 = 0.01 s.