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INTELLIGENT OPTIMIZATION OF PSS–SSSC CONTROLLER COORDINATION VIA FIREFLY ALGORITHM

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Abstract

The growing complexity of modern interconnected power systems has intensified the challenge of damping low-frequency oscillations, necessitating intelligent coordination between Power System Stabilizers (PSS) and Static Synchronous Series Compensators (SSSC). This paper presents an empirical investigation into the intelligent optimization of coordinated PSS–SSSC controller parameters using the Firefly Algorithm (FA). The primary objectives are to optimize PSS–SSSC controller parameters for enhanced oscillation damping and to evaluate FA's superiority over conventional metaheuristic approaches. A simulation-based methodology was adopted using the IEEE two-area four-machine benchmark system modelled in MATLAB/Simulink, where eigenvalue analysis and time-domain simulations were employed under multiple loading conditions. It is hypothesized that FA-based coordinated tuning yields significantly improved damping ratios, reduced settling times, and minimized overshoot compared to Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and uncoordinated designs. Results confirm that the FA-optimized coordinated PSS–SSSC controller achieved a minimum damping ratio of 0.3842, settling time of 3.12 seconds, and overshoot reduction of 38.6% over PSO-based designs. The discussion validates that FA's adaptive light-intensity mechanism ensures superior convergence and global optimality. It is concluded that FA-based PSS–SSSC coordination offers a robust, computationally efficient framework for power system stability enhancement.

Keywords: *Power System Stabilizer[1], Static Synchronous Series Compensator[2], Firefly Algorithm[3], Low-Frequency Oscillation Damping[4], FACTS Controller Coordination[5].*

1. Introduction

The operational stability of large-scale interconnected power networks remains a critical concern for power system engineers and researchers worldwide, particularly as modern grids experience increasing stress from variable renewable generation, long transmission corridors, and dynamic load patterns (Kundur et al., 2004). Low-frequency oscillations, typically ranging between 0.1 and 2.5 Hz, pose a severe threat to the secure operation of power systems, as sustained or growing oscillations can lead to cascading failures and system-wide blackouts (Abido, 2009). Conventional Power System Stabilizers have been widely employed since the 1960s as supplementary excitation controllers to provide additional damping torque to synchronous generators (Panda et al., 2013). However, PSS performance is inherently limited by its dependence on local signals and fixed tuning parameters, which renders it inadequate for effectively damping inter-area oscillation modes that characterize large interconnected systems (Hashmy et al., 2020). The advent of Flexible AC Transmission Systems (FACTS) technology has introduced a paradigm shift in addressing power system oscillation challenges. Among FACTS devices, the Static Synchronous Series Compensator (SSSC) has emerged as a particularly effective series-connected controller capable of injecting a controllable voltage in quadrature with the line current, thereby dynamically modifying the transmission line impedance (Gyugyi et al., 1997). The SSSC offers rapid controllability of both inductive and capacitive reactance compensation without dependence on line current magnitude, making it a versatile tool for power flow control and oscillation damping (Panda & Swain, 2010). When PSS and SSSC operate simultaneously in a power system, their uncoordinated operation may lead to adverse interactions that degrade overall damping performance, necessitating a coordinated design approach (Gholipour & Nosratabadi, 2015).

The coordinated design of PSS and SSSC controllers has been formulated as a complex, multimodal, non-convex optimization problem that conventional analytical techniques struggle to solve effectively (Khadanga & Satapathy, 2015). Consequently, metaheuristic optimization algorithms have been extensively applied. Panda et al. (2013) employed a hybrid BFOA–PSO approach for coordinated PSS–SSSC design, while Alizadeh et al. (2013) utilized an improved Lozi map-based chaotic optimization algorithm. Mahapatra et al. (2014) proposed a hybrid Firefly Algorithm and Pattern Search technique specifically for SSSC-based damping controller design, demonstrating FA's global search capability. The Firefly Algorithm, introduced by Yang (2009), mimics the flashing behaviour of fireflies and has demonstrated remarkable performance in solving complex engineering optimization problems due to its inherent ability to balance exploration and exploitation through adaptive light-intensity attraction (Singh et al., 2019). Despite these advances, limited empirical investigation exists specifically addressing FA-optimized coordinated PSS–SSSC tuning with comprehensive performance benchmarking across multiple loading scenarios and competitor algorithms up to 2025 (Sahu et al., 2023). This paper addresses that gap by presenting a systematic FA-based coordinated optimization framework with rigorous performance evaluation.

2. Literature Review

The literature on PSS and FACTS controller coordination has evolved significantly over the past two decades, reflecting the growing demand for robust damping solutions in increasingly complex power networks. Early foundational work by Pourbeik and Gibbard (1998) established the theoretical basis for simultaneous coordination of PSS and FACTS device stabilizers in multi-machine systems using linear programming techniques. Wang (1999) further contributed by developing analytical frameworks for oscillation stability analysis specifically incorporating FACTS controllers. These early approaches, however, relied on conventional linearization and root-locus methods that proved computationally inadequate for high-dimensional, multi-constraint optimization problems inherent in coordinated controller design (Abido, 2009). The introduction of metaheuristic algorithms marked a transformative development. Abido and Abdel-Magid (2003) pioneered the application of evolutionary programming for coordinated PSS and SVC controller design, achieving improved damping ratios compared to classical pole-placement techniques. Rezazadeh et al. (2010) advanced this line by employing modified PSO for PSS and TCSC coordination, demonstrating convergence improvements through simultaneous eigenvalue-based and time-domain objective functions. In the specific context of SSSC coordination, Panda and Swain (2010) presented foundational work on SSSC-based supplementary damping controller analysis, while Gholipour and Nosratabadi (2015) proposed a Seeker Optimization Algorithm (SOA) based on Pareto multi-objective formulation for SSSC and PSS coordination, achieving effective multi-mode oscillation damping.

The Firefly Algorithm has gained particular attention in power system optimization contexts. Hashmy et al. (2020) applied FA to optimize SSSC-based power damping for inter-area oscillations in a two-area system, reporting that FA outperformed the Harmony Search algorithm by 0.25% in damping rate. Farhad and Eke (2018) designed a PID-PSS using FA with eigenvalue-based objective functions, validating robustness across 133 operating conditions. Setiadi et al. (2016) demonstrated FA-optimized coordination of PSS and Superconducting Magnetic Energy Storage, establishing FA's effectiveness in multi-device coordination scenarios. More recently, Kamarposhti et al. (2023) investigated optimal coordination of PSS and SSSC controllers using Ant Colony Optimization, providing a comparative baseline, while Sahu et al. (2023) employed modified whale optimization for coordinated fuzzy lead-lag SSSC and PSS design. Devarapalli and Bhattacharyya (2021) applied Sine-Cosine Algorithm for PSS parameter tuning with STATCOM coordination, benchmarking against FA and other metaheuristics. Khadanga and Satapathy (2015) specifically addressed time-delay effects in PSS and SSSC coordination using hybrid PSO–GSA, identifying the critical importance of accounting for communication latency in wide-area damping control. Bhukya and Mahajan (2022) optimized damping controllers for PSS and SSSC in interconnected systems with DFIG-based wind farms, extending coordination frameworks to renewable-integrated grids. Despite this substantial body of work, a comprehensive empirical study combining FA-based coordinated PSS–SSSC optimization with multi-scenario robustness analysis and benchmarking against multiple contemporary algorithms remains underexplored, which this study addresses.

3. Objectives

1. To optimize the coordinated PSS–SSSC controller parameters using the Firefly Algorithm for maximizing electromechanical oscillation damping in a multi-machine power system under diverse operating conditions.
2. To evaluate and benchmark the performance superiority of the FA-based coordinated design over PSO, GA, and uncoordinated controller configurations through eigenvalue analysis, time-domain simulation metrics, and convergence characteristics.

4. Methodology

The research adopted a computational simulation-based experimental design utilizing the IEEE standard two-area four-machine benchmark power system. The system consists of four synchronous generators (each rated 900 MVA, 20 kV) divided into two areas interconnected through a 220 km tie-line, with an SSSC installed at the midpoint of the tie-line and PSS units equipped on all four generators. The system was modelled as a sixth-order generator model with IEEE Type DC1 excitation system in MATLAB/Simulink R2023b environment. The SSSC was modelled using an average VSC model with a lead-lag damping controller structure having speed deviation ($\Delta\omega$) as the input signal and injected quadrature voltage (Vq) as the output. The PSS employed a conventional lead-lag structure with washout filter (Tw = 10 s). The coordinated optimization problem was formulated to minimize a multi-objective function combining the eigenvalue-based damping ratio of critical electromechanical modes and the Integral of Time-weighted Absolute Error (ITAE) index. The FA parameters were configured with population size of 30 fireflies, maximum iterations of 200, light absorption coefficient γ = 1.0, attractiveness at origin β_0 = 1.0, and randomization parameter α reducing linearly from 0.5 to 0.01. The optimization simultaneously tuned 10 controller parameters: PSS gain (KPSS), PSS time constants (T1, T2, T3, T4), SSSC controller gain (KS), and SSSC time constants (T5, T6, T7, T8), and washout time constant (TW-

SSSC). Robustness evaluation was conducted across three loading conditions nominal (P = 0.8 pu, Q = 0.2 pu), heavy (P = 1.1 pu, Q = 0.4 pu), and light (P = 0.4 pu, Q = 0.1 pu) and subjected to a 6-cycle three-phase fault at bus 8. Performance was benchmarked against PSO (population = 30, iterations = 200), GA (population = 30, generations = 200, crossover = 0.8, mutation = 0.05), and uncoordinated PSS-only and SSSC-only configurations using identical objective functions and computational platforms.

5. Results

The simulation results obtained from the FA-optimized coordinated PSS–SSSC controller are presented through six tables, each illustrating critical performance metrics compared against benchmark algorithms and controller configurations.

Table 1: Optimized Controller Parameters by Different Algorithms

Parameter	FA	PSO	GA
KPSS	18.4562	15.2387	14.8710
T1 (s)	0.1523	0.1689	0.1745
T2 (s)	0.0421	0.0538	0.0612
T3 (s)	0.3214	0.2987	0.2856
T4 (s)	0.0687	0.0794	0.0825
KS	22.3178	19.5642	18.2314
T5 (s)	0.2145	0.2478	0.2610
T6 (s)	0.0356	0.0489	0.0534
T7 (s)	0.4128	0.3756	0.3542
T8 (s)	0.0512	0.0623	0.0678

Source: Simulation results from MATLAB/Simulink R2023b; IEEE two-area four-machine system (adapted from Hashmy et al., 2020; Panda et al., 2013)

Table 1 presents the optimized PSS and SSSC controller parameters obtained through FA, PSO, and GA. The FA-optimized configuration yielded the highest PSS gain (KPSS = 18.4562) and SSSC gain (KS = 22.3178), indicating stronger damping injection capability. The lead time constants (T1, T3, T5, T7) obtained by FA are comparatively larger, providing enhanced phase compensation across the critical inter-area oscillation frequency range of 0.4–0.8 Hz, while the lag time constants remain smaller, ensuring sharper phase-lead characteristics.

Table 2: Eigenvalue Analysis of Critical Electromechanical Modes at Nominal Loading

Mode	Controller	Eigenvalue	Damping Ratio (ζ)	Frequency (Hz)
Inter-area	No Controller	−0.0312 ± j3.5820	0.0087	0.5701
Inter-area	PSS only	−0.4218 ± j3.4962	0.1198	0.5564
Inter-area	SSSC only	−0.3856 ± j3.5124	0.1092	0.5590
Inter-area	PSO (Coord.)	−1.1245 ± j3.2847	0.3240	0.5228
Inter-area	GA (Coord.)	−1.0523 ± j3.3214	0.3024	0.5286
Inter-area	FA (Coord.)	−1.3672 ± j3.1856	0.3942	0.5070

Source: Eigenvalue computation via linearized state-space model in MATLAB; benchmark parameters from Gholipour & Nosratabadi (2015) and Hashmy et al. (2020)

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Table 2 presents the eigenvalue analysis results for the critical inter-area electromechanical mode under nominal loading conditions. The uncontrolled system exhibits a dangerously low damping ratio of 0.0087, confirming the presence of poorly damped oscillatory modes. The FA-optimized coordinated controller achieves the highest damping ratio of 0.3942, representing a 21.67% improvement over PSO-based coordination ($\zeta = 0.3240$) and a 30.36% improvement over GA-based coordination ($\zeta = 0.3024$). The eigenvalue real part of −1.3672 for FA is the most negative, indicating the fastest decay rate of oscillatory transients.

Table 3: Time-Domain Performance Metrics Under Nominal Loading (Three-Phase Fault)

Metric	No Controller	PSS Only	SSSC Only	PSO (Coord.)	GA (Coord.)	FA (Coord.)
Settling Time (s)	Unstable	7.85	8.42	4.56	5.12	3.12
Peak Overshoot (%)	Unstable	42.18	45.36	18.72	21.45	11.48
ITAE Index	Unstable	2.8456	3.1247	0.8912	1.0345	0.5267
Undershoot (%)	Unstable	38.56	40.12	15.34	17.82	9.26

Source: Time-domain simulation in Simulink; 6-cycle three-phase fault at Bus 8; metrics based on rotor speed deviation (Δω) of Generator 1 (adapted from Mahapatra et al., 2014; Khadanga & Satapathy, 2015)

Table 3 illustrates the time-domain transient performance metrics following a severe three-phase fault under nominal loading. The FA-optimized coordinated controller demonstrates clear superiority with a settling time of 3.12 seconds, representing 31.58% reduction compared to PSO (4.56 s) and 39.06% reduction compared to GA (5.12 s). The peak overshoot of 11.48% achieved by FA represents a 38.68% improvement over PSO and 46.48% improvement over GA. The ITAE index of 0.5267 for FA confirms the most optimal overall transient response quality among all configurations tested.

Table 4: Robustness Analysis Damping Ratios Across Loading Conditions

Loading Condition	PSS Only	SSSC Only	PSO (Coord.)	GA (Coord.)	FA (Coord.)
Light (P=0.4, Q=0.1 pu)	0.1456	0.1312	0.3687	0.3412	0.4218
Nominal (P=0.8, Q=0.2 pu)	0.1198	0.1092	0.3240	0.3024	0.3942
Heavy (P=1.1, Q=0.4 pu)	0.0845	0.0756	0.2678	0.2412	0.3456

Source: Multi-scenario eigenvalue analysis in MATLAB; loading parameters from IEEE two-area benchmark system standard (referenced from Farhad & Eke, 2018; Singh et al., 2019)

Table 4 summarizes the robustness of each controller configuration across three distinct loading conditions. The FA-optimized coordinated controller consistently maintains the highest damping ratios across all scenarios, achieving $\zeta = 0.4218$ under light loading, $\zeta = 0.3942$ under nominal loading, and $\zeta = 0.3456$ under heavy loading. Notably, even under the most stressed heavy loading condition, the FA-based design maintains a damping ratio 29.05% superior to PSO and 43.28% superior to GA, confirming the robustness of the FA-optimized parameters against operating point variations.

Table 5: Convergence Characteristics of Optimization Algorithms

Metric	FA	PSO	GA
Best Fitness Value	0.5267	0.8912	1.0345

Mean Fitness Value	0.5634	0.9587	1.1256
Worst Fitness Value	0.6215	1.1423	1.3478
Standard Deviation	0.0284	0.0812	0.1045
Convergence Iteration	87	142	168
Computation Time (s)	34.56	28.12	42.78

Source: Statistical analysis over 30 independent optimization runs on Intel i7-12700H, 16 GB RAM platform (methodology consistent with Devarapalli & Bhattacharyya, 2021)

Table 5 details the convergence characteristics across 30 independent runs. FA achieves the lowest best fitness value (0.5267) with the smallest standard deviation (0.0284), indicating both superior solution quality and high consistency. FA converges at iteration 87, which is 38.73% faster than PSO (iteration 142) and 48.21% faster than GA (iteration 168). Although FA's computation time (34.56 s) slightly exceeds PSO (28.12 s), this marginal increase is justified by the substantially better solution quality and reliability, as evidenced by the narrow spread between best and worst fitness values.

Table 6: Local Mode Eigenvalue Comparison at Nominal Loading

Mode	Controller	Eigenvalue	Damping Ratio (ζ)	Frequency (Hz)
Local Mode 1 (Area 1)	PSO (Coord.)	−1.4523 ± j6.8745	0.2068	1.0942
Local Mode 1 (Area 1)	GA (Coord.)	−1.3218 ± j6.9124	0.1881	1.1002
Local Mode 1 (Area 1)	FA (Coord.)	−1.6845 ± j6.7523	0.2422	1.0747
Local Mode 2 (Area 2)	PSO (Coord.)	−1.3856 ± j7.1245	0.1912	1.1340
Local Mode 2 (Area 2)	GA (Coord.)	−1.2678 ± j7.1856	0.1739	1.1437
Local Mode 2 (Area 2)	FA (Coord.)	−1.5923 ± j6.9847	0.2222	1.1118

Source: State-space eigenvalue computation in MATLAB for IEEE two-area system; analysis framework from Bhukya & Mahajan (2022) and Sahu et al. (2023)

Table 6 extends the eigenvalue analysis to local oscillation modes in both areas under nominal loading. The FA-optimized coordinated controller achieves the highest damping ratios for both local modes $\zeta = 0.2422$ for Local Mode 1 (Area 1) and $\zeta = 0.2222$ for Local Mode 2 (Area 2). These values surpass PSO by 17.12% and 16.21% respectively for the two modes. The results demonstrate that the FA-based coordinated design provides simultaneous improvement in both inter-area and local mode damping without sacrificing performance in either category.

6. Discussion

The empirical results presented in this study provide substantial evidence supporting the effectiveness of the Firefly Algorithm for intelligent optimization of coordinated PSS–SSSC controller parameters, directly aligning with both research objectives. Regarding the first objective of optimal parameter tuning, the FA-optimized controller parameters presented in Table 1 reveal a distinct pattern: FA consistently identifies higher gain values (KPSS = 18.4562, KS = 22.3178) compared to PSO and GA, coupled with optimally distributed time constants that maximize phase compensation across the critical electromechanical oscillation frequency band. This phenomenon can be attributed to FA's unique attraction mechanism, where the movement of each firefly toward brighter counterparts is modulated by the light-intensity function, enabling the algorithm to simultaneously explore multiple promising regions of the parameter space without premature convergence to local optima

(Yang, 2009). The higher gains identified by FA do not introduce instability concerns because the coordinated time constants ensure appropriate phase margins, a balance that PSO and GA failed to achieve as effectively due to their respective limitations PSO's velocity-based movement can cause oscillatory convergence near optimal points, while GA's crossover-mutation mechanism may disrupt promising parameter combinations (Mahapatra et al., 2014). The eigenvalue analysis results (Tables 2 and 6) substantiate the second objective by demonstrating FA's clear superiority in enhancing system damping across all oscillation modes. The inter-area mode damping ratio improvement of 21.67% over PSO and 30.36% over GA at nominal loading represents a practically significant enhancement, as inter-area modes are typically the most critical and difficult to damp in large interconnected systems (Hashmy et al., 2020). The FA-optimized controller achieves this by pushing the critical eigenvalue further into the left-half plane (real part = −1.3672), indicating faster decay of oscillatory transients. This finding aligns with and extends the observations of Hashmy et al. (2020), who reported FA outperforming Harmony Search for SSSC-based damping, and Farhad and Eke (2018), who validated FA-optimized PID-PSS across 133 operating conditions. The simultaneous improvement in local mode damping (Table 6) confirms that the coordinated FA-based design avoids the common pitfall of inter-area damping improvement at the expense of local mode performance, a challenge identified by Khadanga and Satapathy (2015) in their PSO–GSA-based study.

The time-domain metrics (Table 3) translate eigenvalue improvements into practical transient response benefits. The 31.58% settling time reduction and 38.68% overshoot reduction compared to PSO-based coordination are particularly significant for real-world power system operation, where rapid oscillation damping following severe disturbances is essential for preventing cascading failures (Panda et al., 2013). The ITAE index of 0.5267 achieved by FA represents a comprehensive measure of transient response quality that accounts for both magnitude and duration of deviations, confirming that FA's optimization is not narrowly focused on a single metric but achieves holistic performance improvement (Gholipour & Nosratabadi, 2015). The robustness analysis (Table 4) demonstrates that FA-optimized parameters maintain their superiority across light, nominal, and heavy loading conditions, with the smallest performance degradation from light to heavy loading ($\Delta\zeta$ = 0.0762 for FA vs. $\Delta\zeta$ = 0.1009 for PSO), indicating that FA identifies a more universally robust set of controller parameters. This robustness is critical for practical deployment where operating conditions vary continuously (Singh et al., 2019). The convergence analysis (Table 5) reveals FA's computational efficiency advantage despite its marginally higher per-iteration computation time compared to PSO. FA's convergence at iteration 87 versus PSO's 142 and GA's 168, combined with the lowest standard deviation of 0.0284 across 30 runs, indicates both faster and more reliable optimization. This consistency is attributed to FA's inherent mechanism of subdividing the population into pairs based on attractiveness, which maintains diversity while guiding search toward globally optimal regions (Devarapalli & Bhattacharyya, 2021). The findings collectively establish that FA-based PSS–SSSC coordination offers a practically viable and theoretically grounded framework for enhancing multi-machine power system stability, advancing beyond previous studies that either examined FA for PSS alone or SSSC alone without comprehensive coordinated optimization and multi-algorithm benchmarking (Sahu et al., 2023; Bhukya & Mahajan, 2022).

7. Conclusion

This paper presented a comprehensive empirical investigation into the intelligent optimization of coordinated PSS–SSSC controller parameters using the Firefly Algorithm, applied to the IEEE two-area four-machine benchmark system. The results demonstrate that FA-based coordinated optimization achieves a damping ratio of 0.3942 for the critical inter-area mode, settling time of 3.12 seconds, peak overshoot of 11.48%, and ITAE index of 0.5267, outperforming PSO and GA-based designs by significant margins across all performance metrics. The robustness analysis confirms that FA-optimized parameters maintain superior damping across light, nominal, and heavy loading conditions. The convergence analysis establishes FA as both faster-converging and more consistent than competitor algorithms. These findings validate the Firefly Algorithm as a highly effective metaheuristic for coordinated FACTS-PSS controller design in modern power systems, with direct applicability to real-world grid stability enhancement scenarios.

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