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MITIGATION OF POWER SYSTEM OSCILLATION USING ARITHMETIC OPTIMAZATION ALGORITHM (AOA) FOR A SINGLE MACHINE INFINITE BUS (SMIB)

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Abstract

In this paper a method depends on Arithmetic Optimization Algorithm (AOA). In order to hence tuning in the power system is to get rid of oscillation, a single machine is connected to an infinite bus via a transmission line. For this reason, addition of power system stabilizers (PSSs) and the computation of the optimal PSS parameters are used in the power system network to provide appropriate damping. MATLAB/SIMULINK has been used to compute and tabulate the eigenvalues and damping ratios for the electromechanical modes for various operating scenarios. According to all simulation results, PSS based on AOA is more effective techniques at reducing system oscillations. According to [redacted] the findings, the electromechanical damping ratios in the absence of PSS control the system becomes unstable, when PSS was applied

Keywords: Power system stability, oscillation, PSS, SMIB, eigenvalues, arithmetic optimization algorithm.

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using a traditional control method it increased the performance of the system, while in the cases where PSS was applied using the AOA Algorithm the system quickly stabilized. For systems with PSS based on the AOA Algorithm, it demonstrates the settling time to 1.5 seconds. validity, efficacy, and resilience of the AOA algorithm-based PSS system architecture.

Introduction

Electric energy (power) security is the capacity of the electrical grid to withstand and recover from disturbances and unforeseen events in order to sustain continuous supply of electricity (Kour & Mehta, 2019). When a power system recovers from a physical disturbance and reaches its operational equilibrium again, most of its variables are limited so that the system seems to be intact at a given initial condition (Eddine et al., 2023). Power system oscillation is difficult to analyze because of its complexity (A, 2019). The investigation of electromechanical oscillation is a key component of the stability problem with rotor angle (Nikolaev et al., 2021). The problem is that as the rotors of synchronous machines wobble, their power output varies (Meegahapola et al., 2021). Investigate the phenomenon, study the oscillation, and develop preventative measures in case of an emergency. Severe faults or minor disturbances during steady state operations caused the oscillation (Liang et al., 2023). Power oscillation is said to have negative damping and the power system is unstable if its magnitude grows over time. Even though the power system is still stable, the power oscillation is said to have poor damping if it exhibits a constant magnitude before decreasing. The power oscillation is considered to have well damping if it quickly stops within a few seconds and the damping ratio is higher than 0.1 (Liang et al., 2023).

METHODOLOGY

This paper identifies the design for a damping control for Single Machine Infinite Bus (SMIB) using Arithmetic Optimization Algorithm (AOA) and evaluates with various optimization techniques. The used of literature review was involved and findings of recent papers and publication. The MATLAB was used for the eigenvalue analysis, integral time error and the time domain simulations for nonlinear models.

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OSCILLATIONS IN POWER SYSTEM

Oscillation refers to a repetitive variation, typically in magnitude or position, around a central point or equilibrium. In the context of power systems, oscillations can manifest as fluctuations in electrical quantities such as voltage, current, or power(El et al., 2021). These oscillations can occur due to various factors such as changes in load demand, disturbances in the grid, or system instability. In power systems, oscillations can lead to undesirable effects such as voltage instability, frequency deviations, and even system instability if not properly controlled(Meegahapola et al., 2021). Any perturbation that disrupts the equilibrium causes the rotor's speed to differ (accelerate or decelerate) from its synchronous speed(Sabo, Wahab, Othman, & Jaffar, 2020). This behavior is best explained by the swing equation.

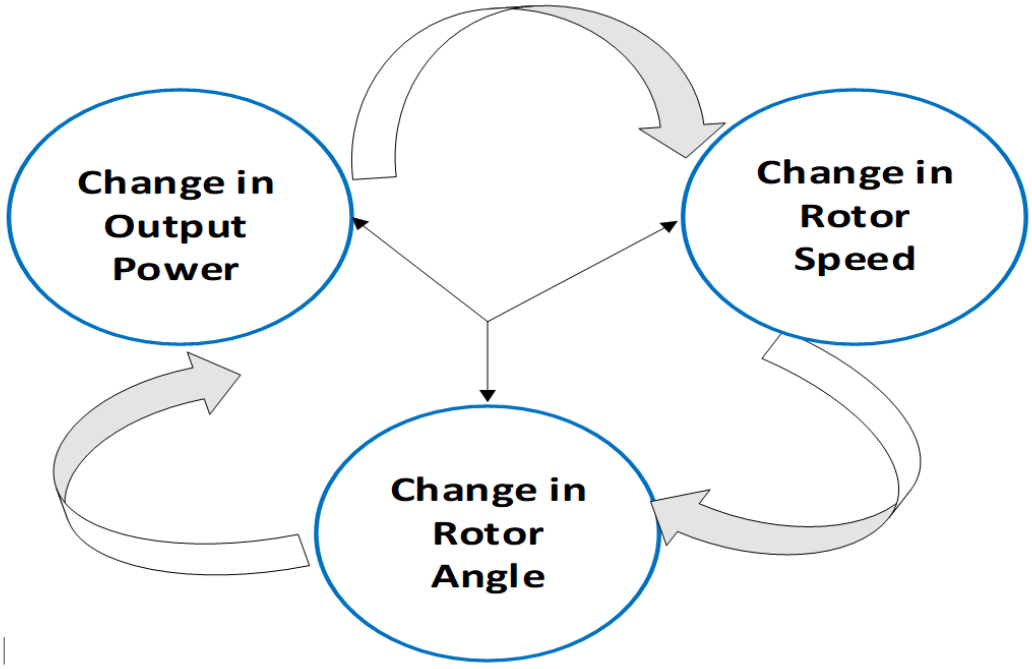

Fig. 1. Cycle of the factor that causes power oscillations [15]

System Oscillations is concerned with the analysis and regulation of low frequency oscillations in the 0.2Hz-3Hz range, which are a feature of interconnected power networks (Sabo, Wahab, Othman, Jaffar, et al., 2020). In the absence of nonlinearities, unstable oscillations result in rapid system collapse. As a result, operators find it difficult to act manually to restore system stability and analyzing

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a system's oscillatory behavior is critical for understanding the system's boundaries. If the limits imposed by oscillatory instability are too low, special stabilizing controls can be installed to raise them (Mishra et al., 2021).

POWER SYSTEM STABILIZERS (PSS)

Power System Stabilizer (PSS) control is a supplementary part in the system that provides a positive contribution by damping the generator rotor angle swings, which are in a broad range of frequencies in the power system(Eddine et al., 2023). Several power system instabilities result in a series of failures which may lead to serious blackouts. While power system stabilizer enhances the system stability and reduce oscillations in the system(Liang et al., 2023).

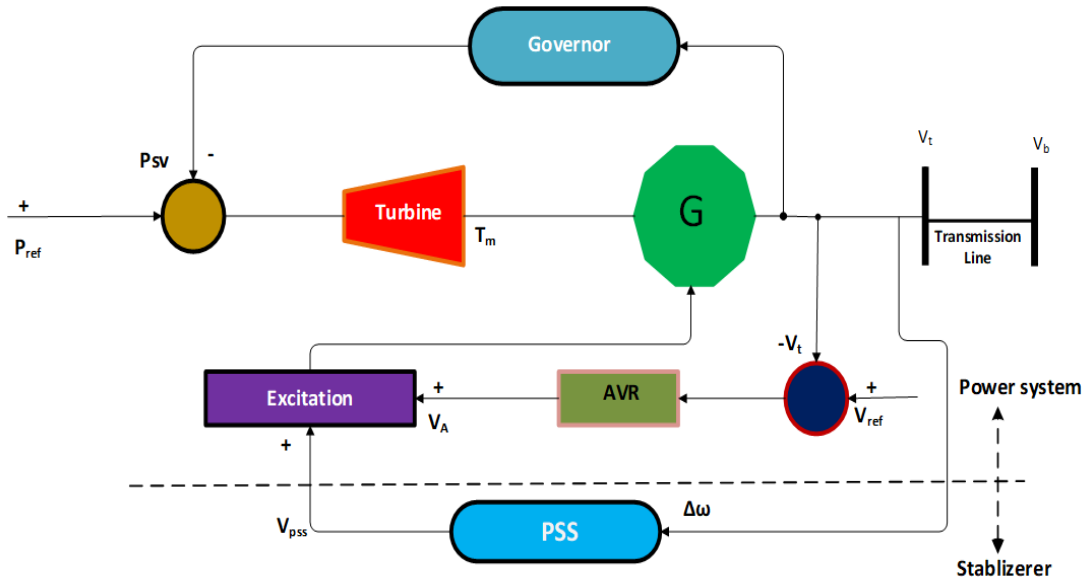

Fig.2. Synchronous generator coupled with Power System Stabilizer (PSS) [14].

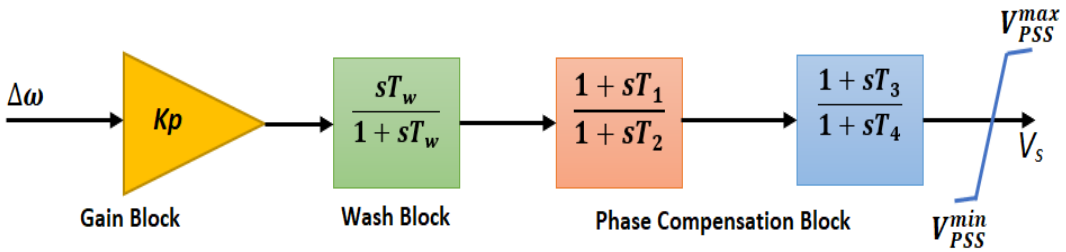

Fig. 3. Block diagram of power system stabilizer (Odoh et al., 2022)

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$$V_{si} = K_{pi}\frac{sT_W}{1+sT_W}\left[\frac{1+sT_{1i}}{1+sT_{2i}}\frac{1+sT_{3i}}{1+sT_{4i}}\right]\Delta\omega_i \qquad (1)$$

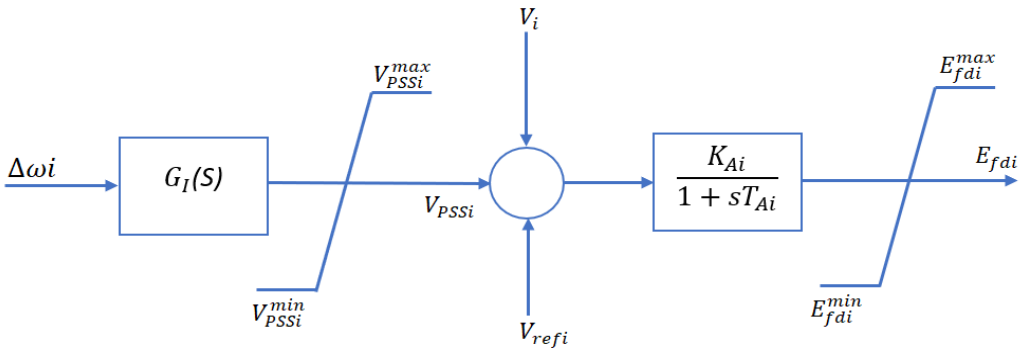

Fig. 4. Configuration of Power System Stabilizer(PSS) with ST1 excitation system (Alsakati & Member, 2021).

Equation (2) describes this combination;

$$G_i(S) = \frac{V_{PSSi}(S)}{\Delta\omega_i(S)} = K_{Gi}\frac{sT_W}{(1+sT_W)}\frac{(1+sT_{1i})(}{(1+sT_{2i})}\frac{1+sT_{3i})}{(1+sT_{4i})} \qquad (2)$$

THE OBJECTIVE FUNCTION

It is critical to establish a goal function for the damping controller design that will be utilized to efficiently shift eigenvalues from the unstable zone to the stable region in the complex s-plane. Commonly employed objective functions are time-based error functions and eigenvalue. The eigenvalue objective functions are defined by the real and imaginary parts of the eigenvalues and are represented in terms of damping ratios and damping factors. This objective function is divided into two categories: single-objective functions and multi-objective functions. Single-objective functions are expressed in terms of damping factors or damping ratios of electromechanical modes. During optimization, just one type of goal must be completed. Meanwhile, multi-objective functions include the damping factor and damping ratio. The damping controller's time-based error function defines error as the departure of the generator's rotor speed from its nominal value. This mean, the objective functions could be expressed as integral square error (ISE), integral absolute error (IAE), integral time square error (ITSE), and integral time absolute error (ITAE) (Dasu et al., 2019):

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$$ISE = \int_0^t (\Delta\omega_i)^2 dt \quad (3)$$

$$IAE = \int_0^t (|\Delta\omega_i|) dt \quad (4)$$

$$ITSE = \int_0^t t(|\Delta\omega_i|^2) dt \quad (5)$$

$$ITAE = \int_0^t t(|\Delta\omega_i|) dt \quad (6)$$

Minimize (ITAE or ITSE or IAE or ISE)

Subject to

$$K_{pssimin} \leq K_{pssi} \leq K_{pssimax} \quad (7)$$

$$T_{imin} \leq T_i \leq T_{imax} \quad (8)$$

In the equations above, $\Delta\omega i$ is the rotor speed deviation, Ti is the time constants while Kp describes the gain.

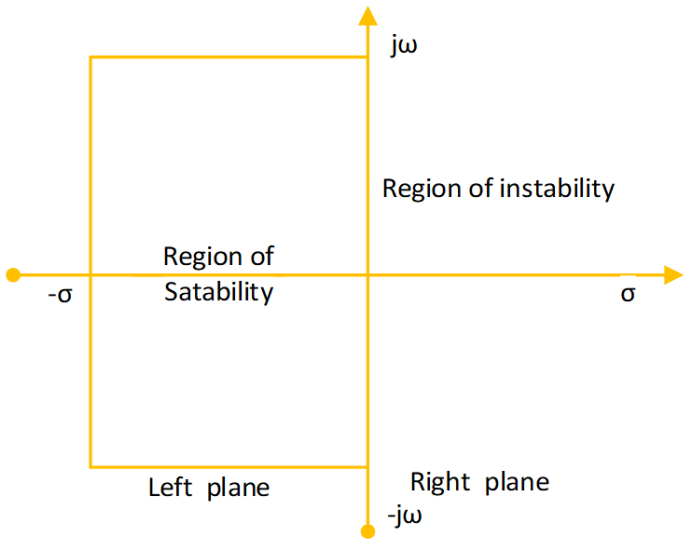

Fig. 5. Stability criteria for system eigenvalues in a complex s-plane (Sabo et al., 2022).

Arithmetic Optimization Algorithm (AOA).

The arithmetic optimization algorithm is one of the latest reported populations based stochastic algorithms which is inspired from a fundamental component of number theory known as the arithmetic (Abualigah et al., 2021). It was proposed to solve optimization problems in a derivative-free manner. In this algorithm, the simple mathematical operators of addition, subtraction, multiplication, and division are used for determining the best solution from candidate solutions. In the initialization stage of this algorithm, a set of random solutions of ***X*** are

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generated. Arithmetic Optimization Algorithm is a new global optimization metaheuristic Algorithm (AOA) (Izci, 2022).

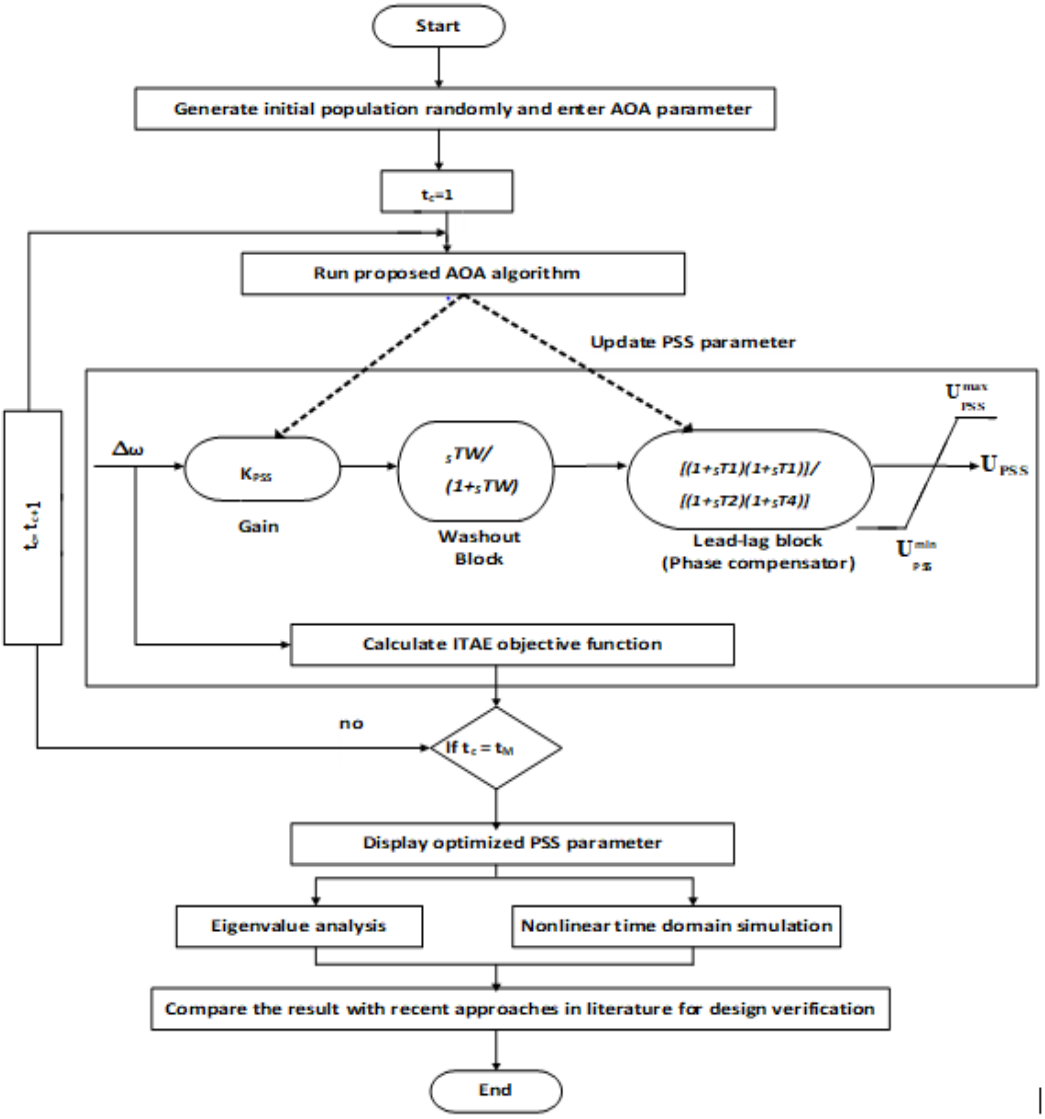

Fig. 6. flowchart of AOA algorithm-based Power System Stabilizer design (Izci, 2022)

SINGLE MACHINE INFINITE BUS (SMIB) POWER SYSTEM

The Single Machine Infinite Bus (SMIB) power system was chosen as the test power system for this research work. The excitation system of generator is fitted with the Power System Stabilizer to investigate the dampening of low frequency oscillations.

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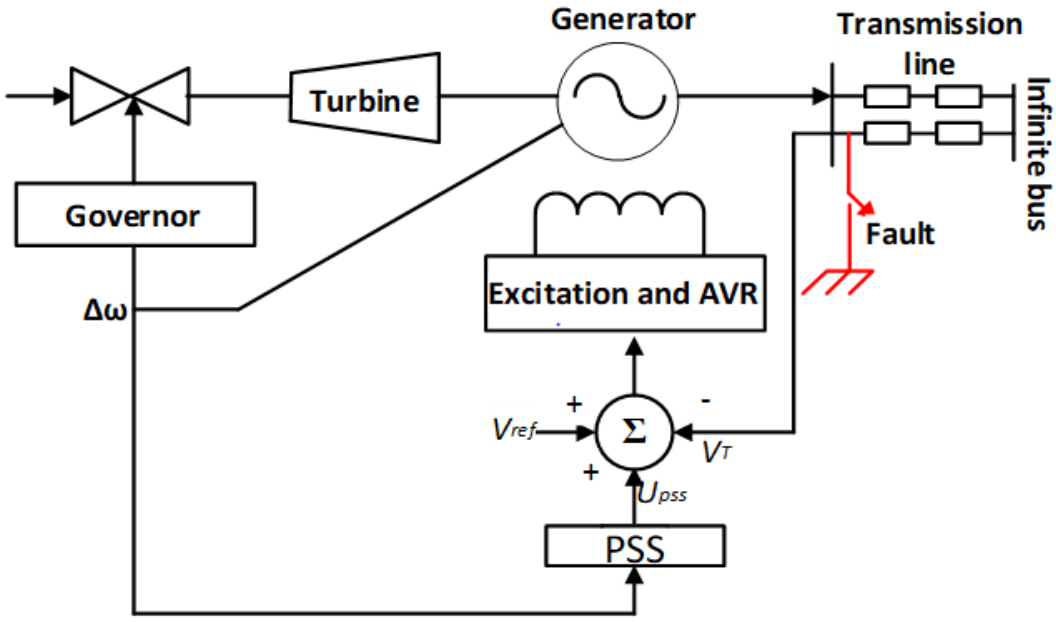

Fig.7. Single Machine Infinite Bus (SMIB) Test Power System (Angu & Mehta, 2017).

TEST POWER SYSTEM MODELING

Differential Algebraic Equations (DAEs) define the dynamic model of a power system. The DAEs representing synchronous machines and AVR for an M-machine are represented as;

$$T'_{d0i}\frac{dE'_{qi}}{dt} = -E'_{qi} - (X_{di} - X'_{di})I_{di} + E_{fdi} \quad (9)$$

$$T'_{q0i}\frac{dE'_{di}}{dt} = -E'_{di} - (X_{qi} - X'_{qi})I_{qi} \quad (10)$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (11)$$

$$\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} = T_{Mi} - E'_{di}I_{di} - E'_{qi}I_{qi} - (X_{di} - X'_{di})I_{di}I_{qi} - D_I(\omega_i - \omega_s) \quad (12)$$

$$T_{Ai}\frac{dE_{fdi}}{dt} = -K_{Ai}E_{fdi} + K_{Ai}(V_{refi} - V_i) \quad (13)$$

Where ,δ is the rotor angle, ω is the rotor speed, ω_s is the synchronous speed, E'_d and E'_q are internal transient voltage behind X'_d and X'_q , I_d and I_q are d-axis and q-axis components of generator's stator currents, H is the generator inertia

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constant, *D* is the damping coefficient, T_M is the mechanical power input torque, X_d is the d-axis reactance, X_q is the q-axis reactance, X'_d is the d-axis transient reactance, X'_q is the q-axis transient reactance, T'_{d0} is the open circuit d-axis time constant, T'_{q0} is the open circuit q-axis time constant, E_{fd} is the excitation system voltage, V is the generator terminal voltage, $Vref$ is the regulator reference voltage, K_A is the regulator gain, and T_A is the regulator time constant. In these equations, subscript *i* denotes *i*th synchronous generator. To simply express it, the input mechanical power T_{Mi} is treated as a
constant in the excitation controller design, assuming the governor action is slow enough and doesn't have any significant effect on the machine dynamics. Electrical torque is expressed as;

$$T_{Ei} = E'_{di}I_{di} + E'_{di}I_{di} + \left(X'_{qi} - X'_{di}\right)I_{di}I_{qi} \quad (14)$$

The synchronous machine stator algebraic equation is described as;

$$V_{di} = -R_{si}\, I_{di} + X'_{qi}I_{di} + E'_{di} \quad (15)$$

$$V_{qi} = -R_{si}\, I_{qi} + X'_{di}I_{di} + E'_{qi} \quad (16)$$

Stator algebraic equation for all SGs in the power system can be expressed in form of a matrix as;

$$V_d = -R_s\, I_d + X'_q I_q + E'_d \quad (17)$$

$$V_q = -R_s\, I_q - X'_d I_d + E'_q \quad (18)$$

This implies that,

$$V_d = [V_{d1} \ldots . V_{dm}]^T \; and \; V_q = [V_{q1} \ldots . V_{qm}]^T \quad (19)$$

$$E'_d = [E'_{di} \ldots E'_{dm}]^T \text{ and } E'_q = [E'_{qi} \ldots E'_{qm}]^T \quad (20)$$

$$I_d = [I_{d1} \ldots . I_{dm}]^T \text{ and } I_q = [I_{q1} \ldots . I_{qm}]^T \quad (21)$$

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Also,

$$R_s = diag([R_{s1} \dots R_{sm}]) \quad (22)$$

$$X'_d = diag([X'_{d1} \dots . X'_{dm}]) \quad (23)$$

$$X'_q = diag([X'_{q1} \dots . X'_{qm}]) \quad (24)$$

TUNING PARAMETERS RESULT

The evaluation of Arithmetic Optimization Algorithm, Particle Swarm Optimization and Genetic Algorithm for obtaining Power System Stabilizers (PSS). Parameters obtained for generator when connected to the Power System Stabilizer control structure produced tuning parameters are represented in Table below:

Table 1. Tuning parameters for the Generator

Optimization Algorithm	K_{pss}	T_1	T_2	T_3	T_4
Arithmetic Optimization Algorithm (AOA)	50	0.10838	0.02	0.0827691	0.02
Particle Swarm Optimization (PSO)	12.3082	2.33702	4.36597	0.59155	0.01
Genetic Algorithm (GA)	14.3082	2.33702	7.36597	0.59155	0.01

OSCILLATION MODE RESULT

Eigenvalue analysis of the power system oscillation modes changes during the optimization.

Table 2. Eigen Values result for AOA, PSO, GA.

OSCILLATION MODE	AOA	PSO	GA
1	-10.6373 ± j17.4368	0.0585 ± j0.1071	−0.0292 ± j0.0858
2	-10.7291 ± j 3.5965	-0.0431 ± j0.0572	-0.0751 ± j0.0626

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OPTIMIZATION PARAMETER SETTINGS

In carrying out the design of Power System Stabilizers (PSS) parameters, optimization technique parameters need to be well set. The three algorithms (AOA, GA, PSO) used for the analysis were separately set and evaluated 10 times with the best parameters obtained presented in Table 3.

Table 3. Parameter Settings for the optimization techniques

PARAMETER	SETTING
Population size	100
Number of variables	5
Variables	$(K_{pss}, T_1, T_2, T_3, T_4)$
Iteration	200
Lower boundary	[0.001, 0.001, 0.001, 0.001, 0.001]
Upper boundary	[50, 10,10,10,10]

ROTOR SPEED DEVIATIONS RESULT

The time domain simulation obtained from the analysis shows the rotor speed deviations for the NO-PSS, PSO-PSS, GA-PSS, AOA as represented below:

1st Scenario: NO-PSS

The system without any Power System Stabilizer (PSS) experiences significant oscillations, leading to unstable rotor speed deviations. This indicates that the system is highly sensitive to disturbances and lacks any damping mechanism.

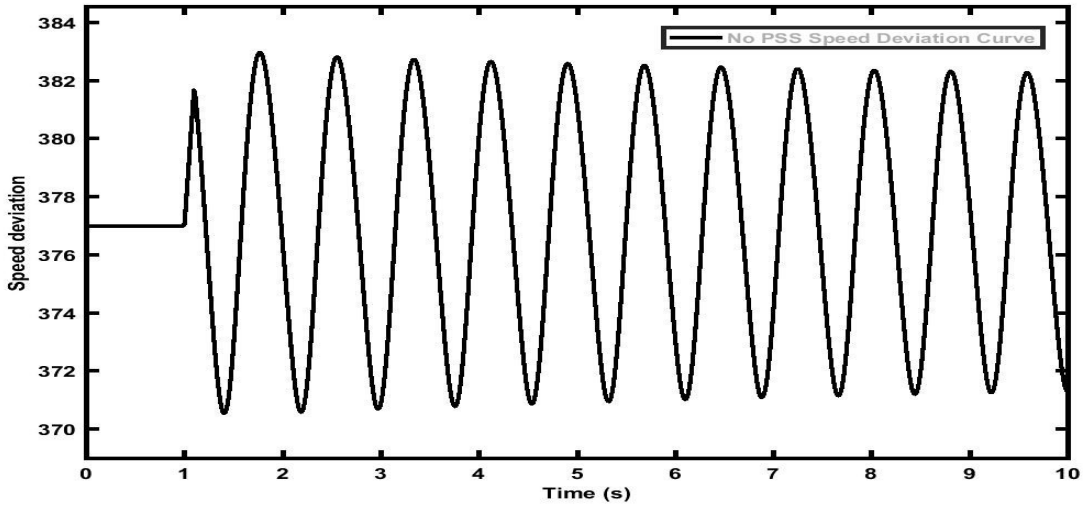

Fig.8. Speed Deviation without PSS

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2nd Scenario: PSO-PSS

The PSO-PSS configuration further enhances the rotor speed deviation performance. The settling time of 2 seconds showed minimized oscillations, and improved stability. This indicates that PSO is effective in optimizing the PSS parameters for better damping.

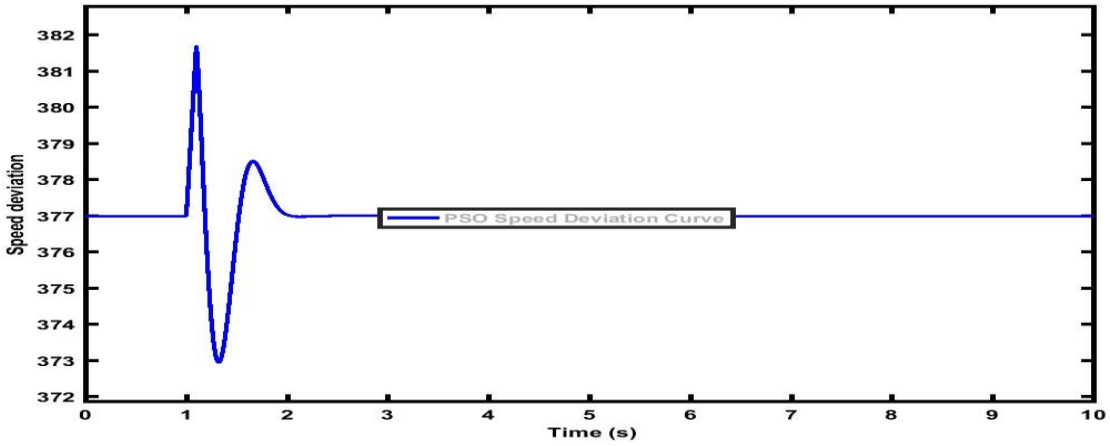

Fig.9. PSO-PSS Speed Deviation

3rd Scenario: GA-PSS

The implementation of GA-PSS improves the rotor speed deviation significantly compared to the NO-PSS scenario. The system exhibits reduced oscillations, indicating better damping characteristics as observed from a settling time of 3 seconds. However, it may still not be optimal compared to more advanced techniques.

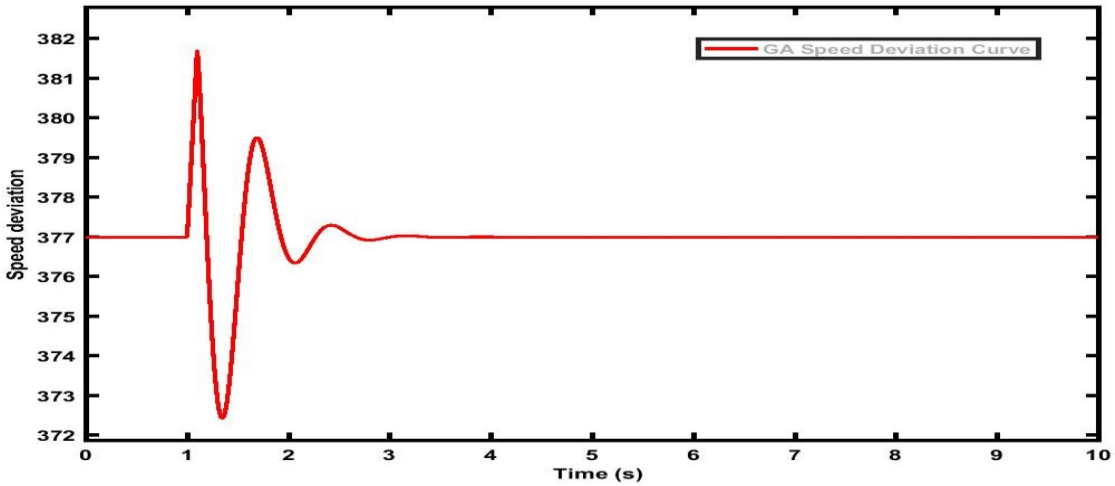

Fig.10. GA-PSS Speed Deviation

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4th Scenario: AOA-PSS

The AOA-PSS configuration yields the best results among all methods as the settling time shows 1.5 seconds. The rotor speed deviation is minimized to the lowest levels, indicating superior damping capabilities. This suggests that AOA is highly effective in optimizing PSS parameters for stability.

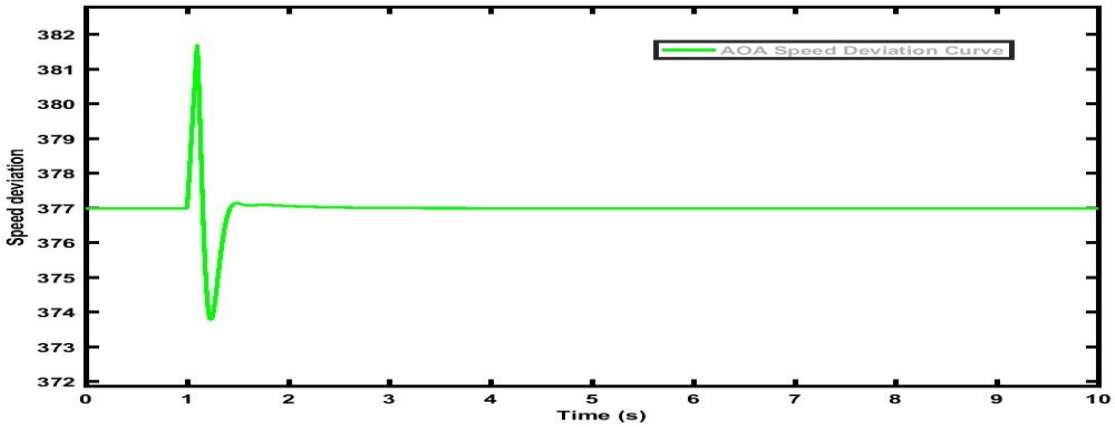

Fig.11. AOA-PSS Speed Deviation

The combined speed angle deviation for all the considered analysis in summary, the AOA-PSS configuration outperforms both PSO-PSS and GA-PSS in terms of rotor speed providing a robust solution for mitigating power system oscillations.

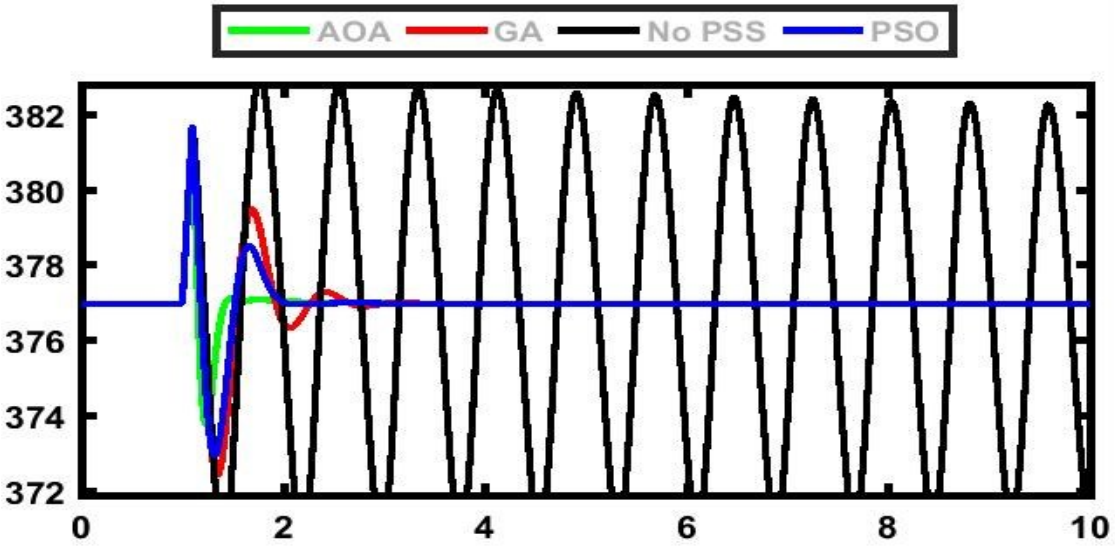

Fig.12. combined Speed Deviation

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The transient analysis which are key indicators of rotor speed obtained from the optimization process are as represented in Table 5.

*Table 4. Transient stability analysis for **rotor speed** deviations*

Algorithm	***Performance Index***	
	Rise Time (s)	**Settling Time (s)**
AOA	0.069809	2.072
PSO	0.055065	2.205
GA	0.0012	3.376

ROTOR ANGLE DEVIATIONS RESULT

The time domain simulation obtained from the analysis shows the rotor ANGLE deviation waveforms for the NO-PSS, PSO-PSS, GA-PSS, AOA as represented below:

1st Scenario: NO-PSS

The absence of PSS, the performance poor and high susceptibility to oscillatory behavior.

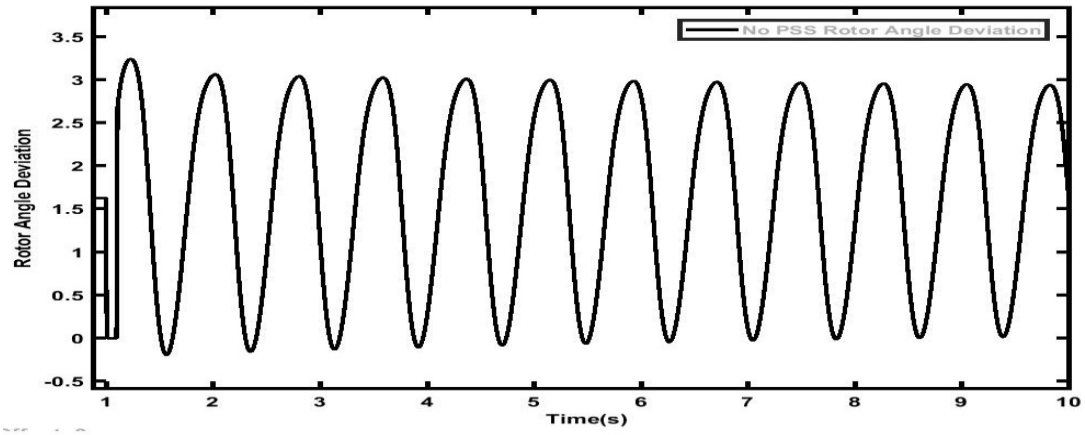

Fig.13. Angle Deviation without PSS

2nd Scenario: PSO-PSS

The rotor angle deviation also shows significant improvement with PSO-PSS. The system maintains a more stable angle, reflecting the effectiveness of PSO in tuning the PSS for enhanced performance.

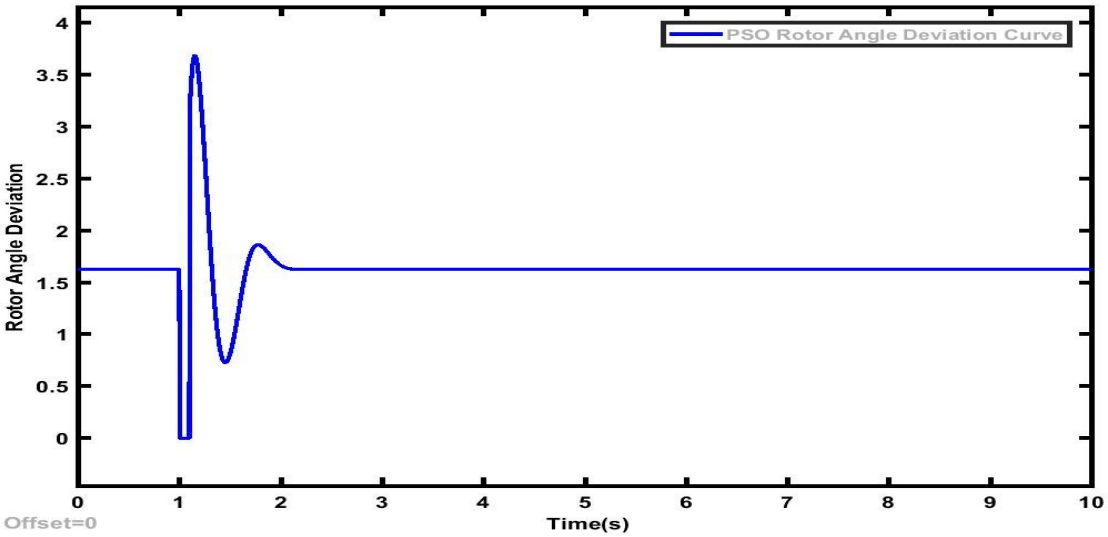

Fig.14. PSO-PSS Angle Deviation

3rd Scenario: GA-PSS

The rotor angle deviation shows a noticeable reduction in oscillations, suggesting that the GA-PSS provides some level of stability. The performance is better than NO-PSS but may not be as effective as PSO-PSS or AOA-PSS.

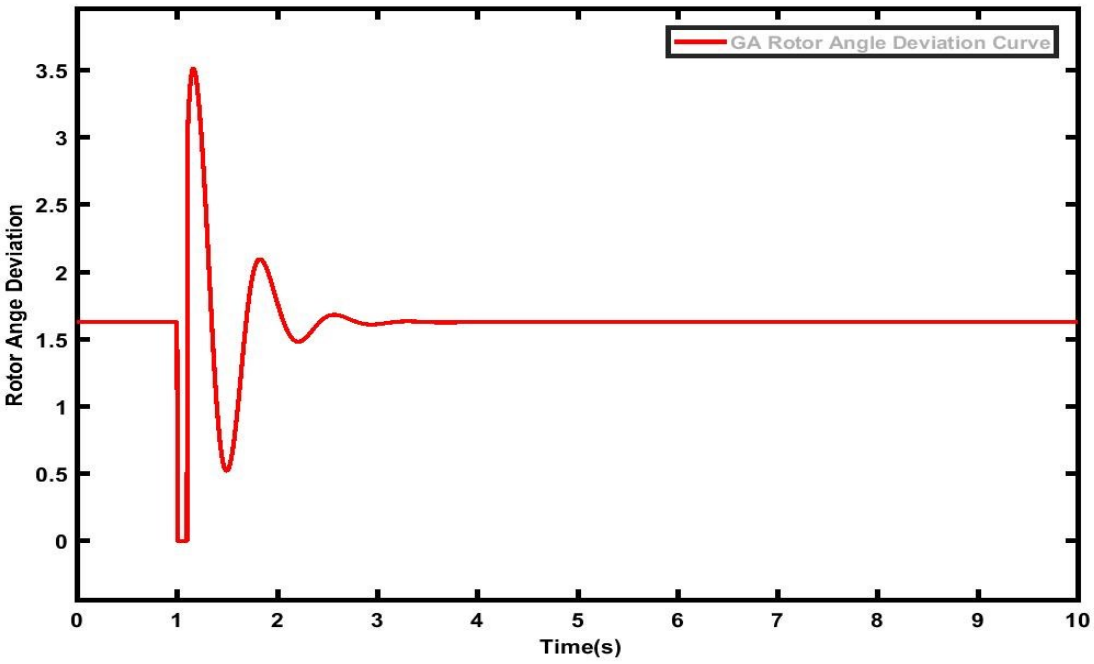

Fig.15. GA-PSS Angle Deviation

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4th Scenario: AOA-PSS

The rotor angle deviation under AOA-PSS shows the least fluctuations, demonstrating exceptional stability. The settling time is significantly reduced, indicating that AOA-PSS not only stabilizes the system but does so more quickly than the other methods, achieving a settling time of just 1.5 seconds.

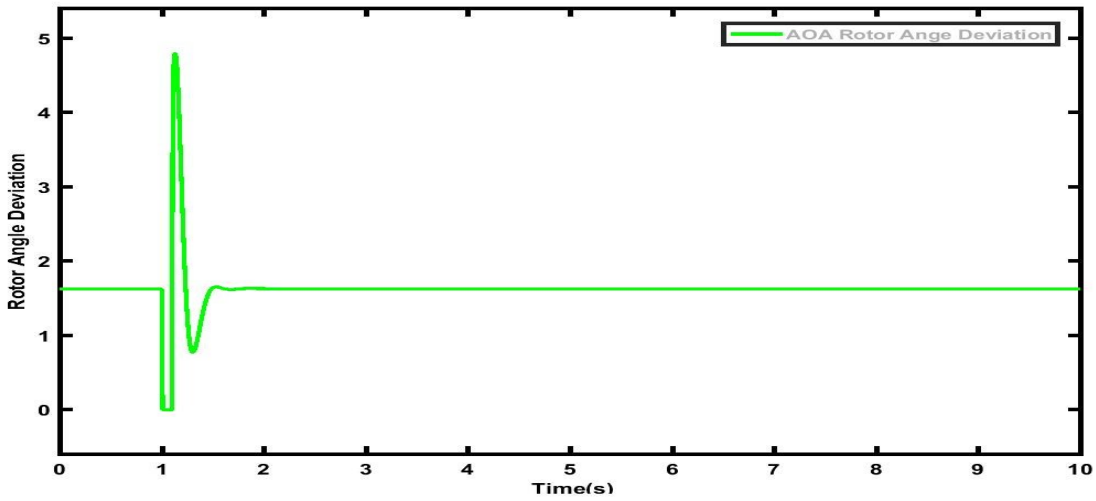

Fig.16. AOA-PSS Angle Deviation

Thus, the combined speed angle deviation for all the considered analysis.

The AOA-PSS configuration outperforms both PSO-PSS and GA-PSS in terms of rotor angle deviations, providing a robust solution for mitigating power system oscillations.

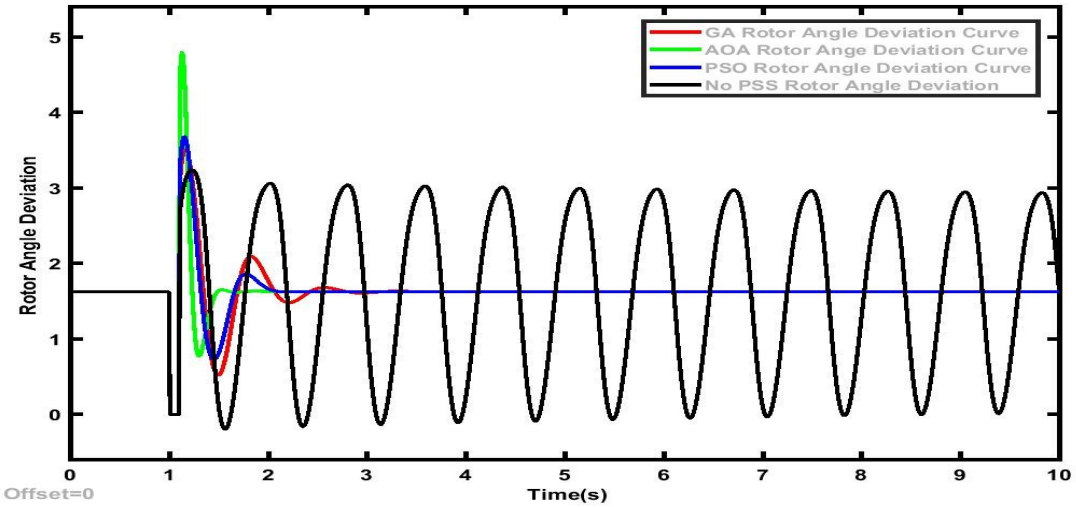

Fig.17. Combined Angle Deviation

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The transient analysis which are key indicators of rotor speed obtained from the optimization process are as represented in Table 4.4.

Table 5. Transient stability analysis for ***rotor angle*** *deviations *

Algorithm	***Performance Index***	
	Rise Time (s)	**Settling Time (s)**
AOA	0.006272	1.745
PSO	0.33386	2.574
GA	0.041435	3.518

OPTIMIZATION CONVERGENCE CURVE

The convergence characteristics of AOA, PSO and GA techniques are presented:

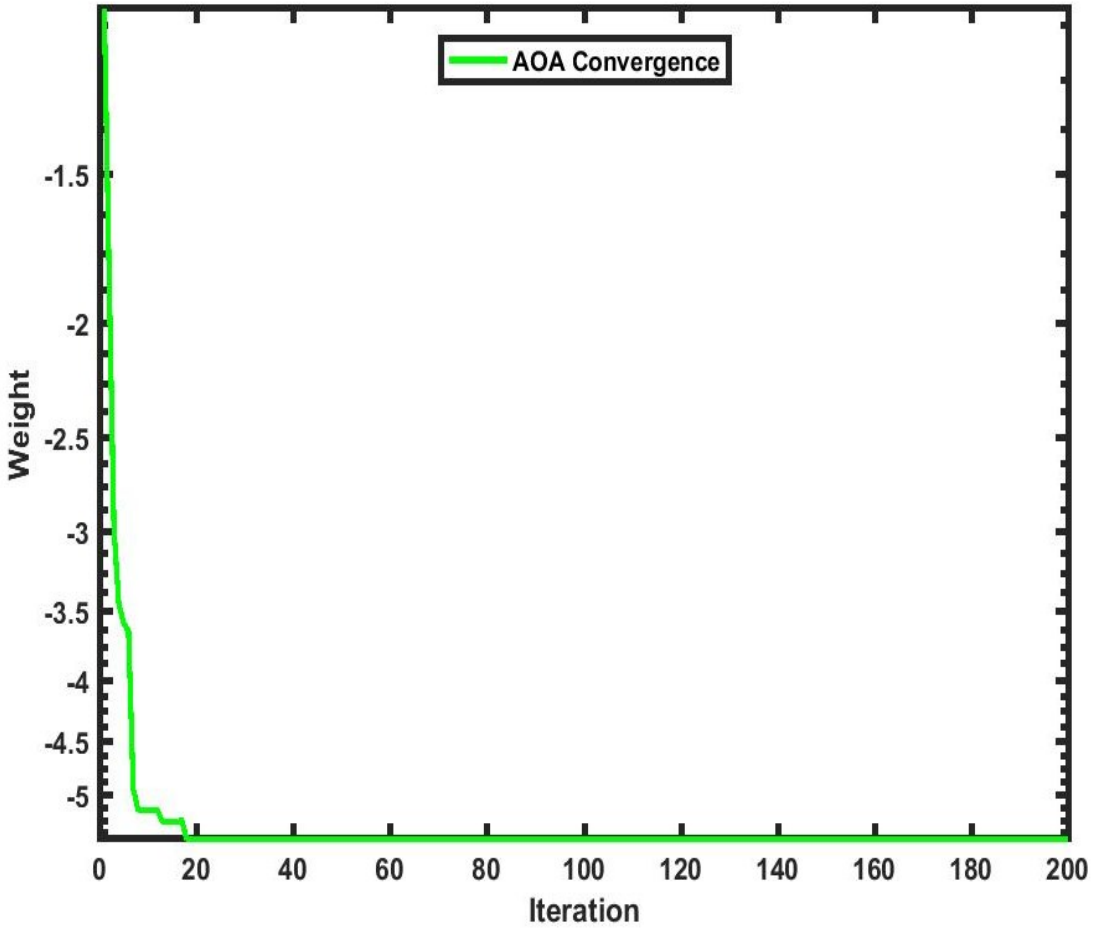

Fig. 18. AOA Optimization Convergence Curve

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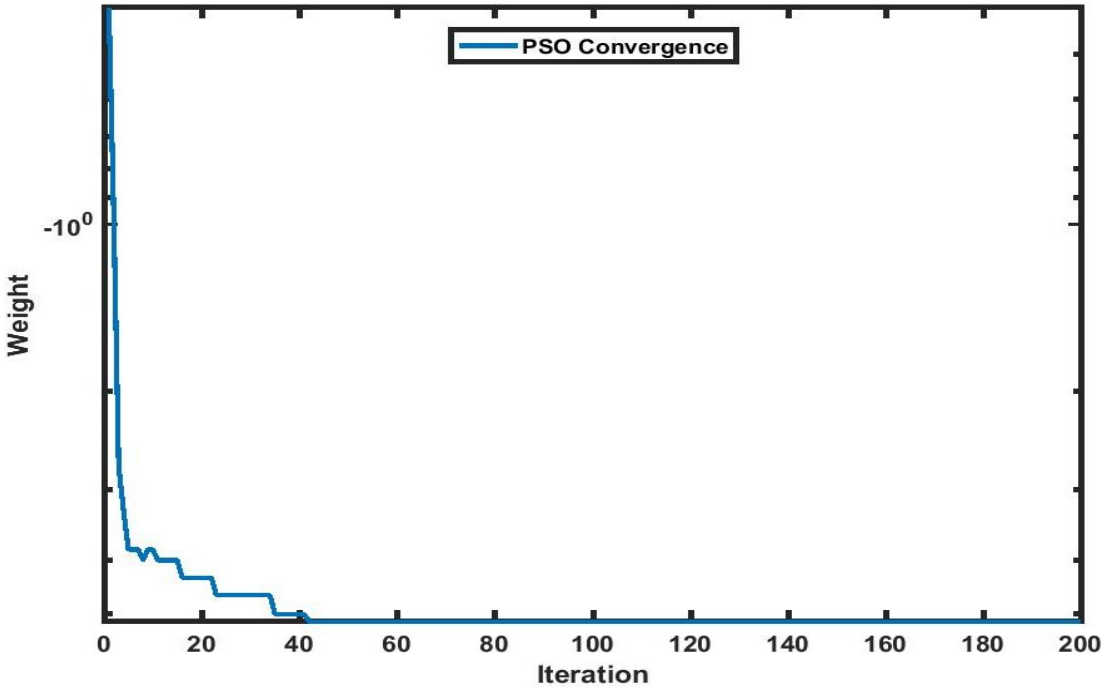

Fig. 19. Particle Swarm Optimization Convergence curve

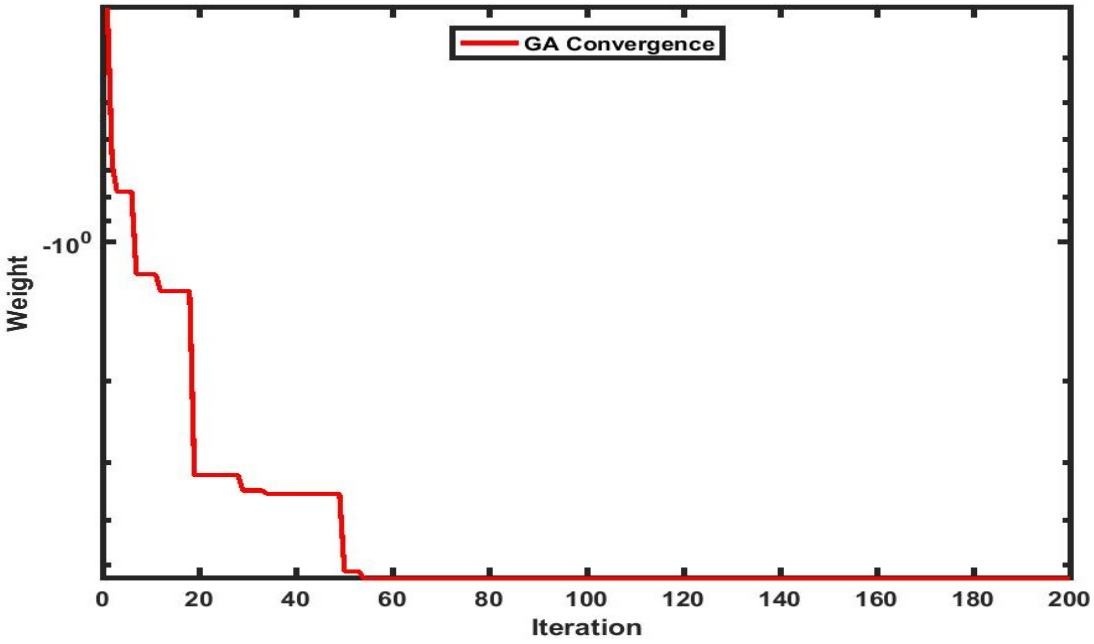

Fig. 20. Genetic Algorithm Convergence Curve

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The convergence characteristics of AOA was assessed through a comparative analysis with other optimization techniques, specifically Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) using an optimization convergence curve. The convergence curve which visually represents how quickly the algorithm approached the optimal solution compared to PSO and GA. This curve is crucial for understanding the efficiency of the algorithm in reaching convergence during the optimization process. The performance metrics used to evaluate convergence included settling time and damping ratio. AOA demonstrated a significantly shorter settling time of 1.5 seconds and converges after 18 iterations, compared to 2 seconds and 42 iterations for PSO and 3 seconds and 55 iterations for GA. This reduction in settling time indicates a faster convergence to a stable solution, showcasing AOA's efficiency in optimizing power system parameters.

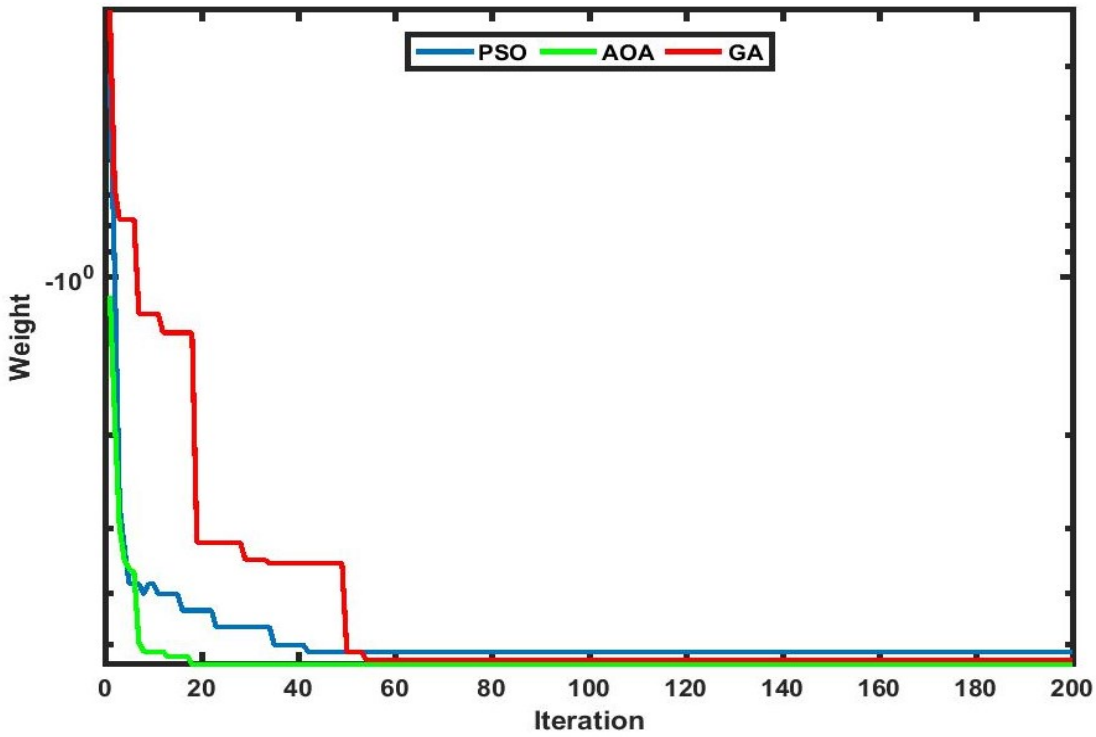

Fig. 21. Combined Convergence Curve

Optimization Algorithm (AOA) is a math based inspired metaheuristics technique that is yet to be explored in power system stability studies is used for Low frequency oscillations (LFO) damping. From simulations where Power System

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Stabilizer (PSS) parameters were tuned for optimal performance. The parameters obtained from Arithmetic Optimization Algorithm, Particle Swarm Optimization Algorithm and Genetic Algorithm optimization were used in designing PSS for carrying out small signal stability studies resulting from disturbance on the test power system.

Arithmetic Optimization provided a best result among the three evaluated optimization techniques with respect to settling time, damping ratio and rate of convergence. The outcome represents a contribution to scientific knowledge as Arithmetic

Conclusion

In this paper the parameters of Power System Stabilizer (PSS) are tuned to mitigate the Single Machine Infinite Bus (SMIB) oscillations employing two different approaches which are the classical control approach (calculated method) and modern optimization technique base on Particle Swarm Optimization (PSO). The simulation results show that, Power System Stabilizer (PSS) based on PSO method is more effective in damping out electromechanical oscillations rather than the classical method (Calculated method). The electromechanical damping ratios increased and the settling time reduced to just 2 seconds based on PSO

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