

ADVANCED HEFFRON-PHILLIPS MODEL FOR DAMPING OSCILLATIONS BASED ON WALRUS AND ENHANCED SNAKE OPTIMIZATION ALGORITHMS

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Abstract

A reliable, safe, and secure operation of power systems is essential for all-round development. Low-Frequency Oscillations (LFO) hamper the smooth operation of the system. This manuscript develops an Advanced Heffron-Phillips Model (AHPM) for damping oscillations based on a higher-order Synchronous Machine (SM) Model 1.1. The effectiveness of AHPM is compared for the system without any controller and with Power System Stabilizer (PSS) based on Walrus and Enhanced Snake Optimization Algorithms (ESOA) for three loading conditions. The best damping results are obtained with AHPM, including PSS based on ESOA. The damping ratios (98.60%, 94.50%, and 78.90%) for the three loading conditions obtained with ESOA are higher than with the Walrus algorithm. The settling time, undershoot, and overshoot are also less with ESOA. The simulation is performed with MATLAB R2020. The challenges associated with integrating renewable energy sources into the grid can be met by this AHPM due to better mathematical modelling. By using AHPM with PSS based on ESOA, a robust, secure, and reliable power system is created. Based on four novel strategies, the ESOA tuned the parameters of PSS and produced excellent damping results due to improved performance in terms of speed, accuracy, convergence, and optimization. The simulation can be carried out on multimachine power systems to demonstrate the effectiveness of optimization algorithms. The multi-objective function can be designed for improving stability.

Keywords: Algorithms; Controller; Damping; Eigenvalues; Oscillations; Parameters; Power System; Robust; Stability

Introduction

The need to interconnect various power networks that are spread geographically arises from the ever-growing demand for electrical energy. This is also necessary for the secure, reliable, and safe operation of the power system. However, as generation is adjusted in response to ongoing changes in load demand, generator rotor oscillations result. If these

oscillations continue to occur, they intensify and bring the system to an end. Power System LFOs, which range in frequency from 0.1 Hz to a few Hz, are oscillations of active power transmitted along specific transmission corridors in a power system (Mujeer *et al.*, 2023). The power transfer capacity of the system is also affected due to these LFO. There

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is a change in the electromagnetic torque (T_e) of a SM due to a disturbance, which can be resolved into two components: the synchronizing torque (T_s) and the damping torque (T_d). Automatic voltage regulators with high gain and fast action provided the (T_s), but there is no guarantee for providing adequate (T_d). Hence, PSS is added to the system for providing the required damping torque. The PSS acts through the excitation system to enhance the stability of the system (Nocoń and Paszek, 2023).

Various algorithms are implemented for the design and tuning of PSS like, Improved Atom Search (Izci, 2021), Modified Arithmetic Optimization Algorithm (Izci, 2022), Tunicate Swarm Neural Network (Aribowo *et al.*, 2021), Statistical T-Test (Thu and Lin, 2021), Time Delay Approach (Sahu *et al.*, 2022a), Improved Harris Hawk (Chaib *et al.*, 2021), Improved Particle Swarm (Latif *et al.*, 2022), Dingo (Aribowo *et al.*, 2023a), a hybrid of Particle Swarm and Mean-Variance algorithm (Singh *et al.*, 2024), Sliding Mode Control (Canabal *et al.*, 2023), and Sea Horse (Aribowo, 2023b). A novel hybrid Whale Optimization algorithm the Nelder Mead approach (Sahu *et al.*, 2022b) has been used for coordinated PSS and Flexible Alternating Current Transmission System (FACTS) device. The Delay-Dependent Controller (Sun *et al.*, 2021) is used for damping oscillations. A type-2 Fuzzy Lead-Lag-Structured is implemented with FACTS device and PSS for improving stability (Khampariya *et al.*, 2022). Many alternative techniques available for PSS design include feedback linearization, H-infinity control, mathematical programming, eigenvalue assignment, modern control theory, gradient procedures, self-tuning regulators, and pole positioning and shifting (Panda *et al.*, 2013). However, these approaches have a number of drawbacks, including high computation requirements, lengthy computer processing times, delayed convergence, a propensity to become stuck in local minima, and the achievement of unacceptable outcomes (Izdebski *et al.*, 2022). Damping characteristics of wind-thermal power systems have been analysed (Zheng and Ma, 2024).

A novel rotational invariant technique has been discussed for estimating the LFO modes (Samal and Khadanga, 2023). The PSS has been designed with a hybrid of genetic and bacterial algorithms (Zadehbagheri *et al.*, 2023). A number of studies treated loads as impedances. The block diagram of the generalized model is comparable to that of Heffron-Phillips and can be used to extend dynamic investigations of networks with impedance loads to networks with voltage- and frequency-dependent loads (Hasan *et al.*, 2021).

To improve the dependability of the renewable energy system, it is necessary to reduce the voltage stability and power quality problems that arise from their variable nature (Abdulkader *et al.*, 2023). In a distribution system, the FACTS device with storage energy is a potent tool for managing the flow of both active and reactive power (Khidrani *et al.*, 2024). The problems related to transmission networks, like loss reduction and voltage stability related to transmission networks, have been discussed (Kanagasabai, 2024). The various power quality issues and problems related to renewables are mitigated (Nagaraju and Bethi, 2024). These studies deal with a range of power-related issues, including transmission loss, harmonics, power quality, managing active and reactive power (Arumugam and Kumar, 2023), voltage regulation (Albanna *et al.*, 2024), power generation cost (Tran *et al.*, 2023), optimal power flow, and energy metering manipulation (Gopalakrishnan, 2024). However, there are fewer conversations about LFO-related problems. LFO impedes the power system's ability to operate smoothly. If these oscillations persist, they will intensify and bring the power system to collapse (Padiyar, 1996). Therefore, it is necessary to address the LFO issues in the power system.

Despite the promising results with these algorithms, according to the No Free Lunch Theory, there is always a chance for improvement, and no algorithm can solve all the engineering tasks. This theory motivated me to take on the challenge of mitigating the problems of LFO in this work. The parameters of PSS are tuned by two optimization algorithms called the Walrus Optimization Algorithm (WaOA) and Enhanced Snake Optimization Algorithm (ESOA), and the results are compared. The eigenvalue analysis and damping ratios are calculated for the system with no controller and with PSS based on WaOA and ESOA. With an excellent settling time, this PSS based on ESOA greatly decreased the oscillations' amplitude when compared to WaOA and lessened the system response's overshoot. This ESOA incorporates an improvement to the Snake Optimization algorithm to produce a robust algorithm that can produce PSS parameters with confidence. To increase power system stability and improve the damping of electromechanical oscillations in power systems, ESOA is implemented for tuning the PSS parameters. The simulation work is carried out for three loading conditions with the two algorithms.

Figure 1 shows the Vos viewer map for the keywords PSS and stability. VOS viewer is a powerful and useful tool for the identification of topics, journals, and trends in a field. Figure 1 shows the various terms associated with PSS and stability,

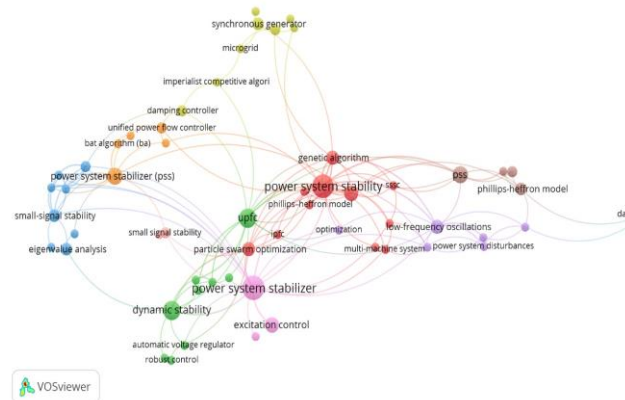


Figure 1. Vos viewer map

like small signal stability, excitation control, eigenvalue analysis, etc. It shows that the Heffron-Phillips model is extensively used for stability improvement of the system.

The PSS is required to be coordinated with the FACTS device for stability (Alwan, 2023). It is very essential to tune the parameters of the coordinated device properly. Improper coordination brings instability to the system. The CPSS are based on fixed operating points, so when the operating conditions change, the CPSS sometimes fails to bring stability to the system (Nader *et al.*, 2023). A power system's robustness refers to its capacity to continue operating and endure disruptions. Put another way, it's the system's ability to carry on functioning even in the face of changing external circumstances. A combination of optimization algorithms (differential evolution) and optimal control theory has been implemented for damping oscillations (Jokarzadeh *et al.*, 2019). The different cases considered are the system with PSS, the system with TCSC, and the system with coordinated PSS and TCSC. The parameters of the feedback controller are determined using control theory. Employment of a single strategy for bringing the best damping results will reduce the system's complexity. The old Heffron-Phillips model is based on SM model 1.0 (a 3rd order model) and has 6 K-constants. In the present work, the Heffron-Phillips model, based on a higher-order and detailed SM model 1.1 (a 4th-order model) with 10 K-constants for representing the system dynamics, is implemented. Here the dynamics of both the d-axis and q-axis internal voltages are taken into consideration. In this model, the exciter dynamics can be easily included. This Heffron-Phillips model is called the Advanced Heffron-Phillips Model (AHPM) in this paper. This model considers the damper winding on the q-axis and the generator main field winding.

As energy generation from Renewable Energy Sources (RES) such as wind farms, solar, and photovoltaic installations increases, the power system's inertia constant and stored kinetic energy decrease, posing greater stability challenges. Due to the increased number of photovoltaics installed, there are inter-area modes of oscillation in the system. There are problems with unforeseen and unpredictable environmental conditions with renewables. These obstacles and problems with grid integration with RES can be addressed by this AHM. The system is now safe, secure, and reliable with this model. With the improvement in mathematical modelling, and implementation of advanced optimization algorithms, the new model is capable of controlling the local and inter-area modes of oscillations in the system.

The primary aim is to develop a damping controller with SM Model 1.1 that will stabilize the system in an efficient manner. The robustness of this AHPM has been checked for three loading conditions. The model based on ESOA provided stability in all three scenarios with higher damping ratios and less settling time. There is no need to integrate the FACTS device with this AHPM. The parameters are tuned with an optimization strategy only. The LFO limits the system's capability for power transfer. Optimizing the generator's electrical output power, which is dependent upon the rotor angle, can enhance the damping of the system. Power can be delivered by the current power system in a safe and dependable manner using AHPM by damping LFO. The provision of inexpensive and clean energy to everybody is one of the 17 Sustainable Development Goals, which this model helps to achieve. This shows that this is cost-effective, economically viable, and a robust model.

The major contributions of the manuscript are:

- Improved mathematical model of the system with fewer assumptions.
- Mathematical modelling with SM model 1.1.
- Development of an Advanced Heffron Phillips model for stability improvement.
- Development of 10 K-constants for analysing stability.
- Increasing the damping torque contribution with the new model.
- Implementation of WaOA and ESOA.
- Capability of AHPM to meet the challenges of grid integration with renewables.
- Eigenvalue, time domain simulation, and damping ratio analysis of the system.
- Checking the model with three loading conditions.

The organization of the paper is Section 1 deals with the introduction. In Section 2, the proposed methodology is discussed. Section 3 deals with different optimization algorithms. Section 4 is about results and discussion. Section 5 summarizes the results. Section 6 is the list of references.

Proposed Methodology

For the development of the AHPM, various equations governing the system dynamics are involved. These are the equations for deviation in rotor angle and speed, the deviation in internal voltage along the q-axis, the deviation in internal voltage along the d-axis, and the deviation in field voltage. The K-constants fluctuate along with the SM's operating conditions, which also affects the location of the poles in the left half of the plane and the sensitivity of the oscillation modes (Gandhi and Joshi, 2011). Following the application of the Taylor series method to the SM model 1.1 equations, the linearized equations obtained are: Figure 2 shows the AHPM.

$$\Delta \dot{\delta} = \omega_b \Delta \omega_m \quad (1)$$

$$\Delta \dot{\omega}_m = -\frac{D}{2H} \Delta \omega_m + \frac{1}{2H} \Delta T_m - \frac{K_1}{2H} \Delta \delta - \frac{K_2}{2H} \Delta E'_q - \frac{K_3}{2H} \Delta E'_d \quad (2)$$

$$\Delta \dot{E}'_q = \frac{1}{T_{d0}} (\Delta E_{fd} - K_5 \Delta \delta - \frac{\Delta E'_d}{K_4}) \quad (3)$$

$$\Delta \dot{E}'_d = \frac{1}{T_{q0}} (K_7 \Delta \delta - \frac{\Delta E'_q}{K_6}) \quad (4)$$

$$\Delta \dot{E}_{fd} = -\frac{K_A K_8}{T_A} \Delta \delta - \frac{K_A K_9}{T_A} \Delta E'_q - \frac{K_A K_{10}}{T_A} \Delta E'_d + \frac{K_A}{T_A} \Delta V_{ref} - \frac{1}{T_A} \Delta E_{fd} \quad (5)$$

The equations (1) and (2) represent the dynamics of a synchronous generator, where (δ) is the rotor angle of the generator, ($\Delta \omega$) is the speed deviation, and H is the machine inertia constant. For considering the flux linkages, two equations (3) and (4) are shown. The equation (5) shows the dynamics of the exciter. (T'_{d0}) stands for d-axis open circuit Time Constant, (T'_{q0}) stands for q-axis open circuit Time Constant.

The detailed expansion of these 10 K-constants (Gandhi and Joshi, 2014a):

$$K_1 = \frac{\partial T_e}{\partial \delta} = -[E'_{d0} + ((x'_d - x'_q) i_{q0})] \frac{E_{d0} E_b \sin \delta_0}{x_e + x'_d} + [(x'_d - x'_q) i_{d0} + E'_{q0}] \frac{E_b \cos \delta_0}{x_e + x'_d} \quad (6)$$

$$K_2 = \frac{\partial T_e}{\partial E'_q} = -[E'_{d0} + ((x'_d - x'_q) i_{q0})] \frac{1}{x_e + x'_d} + E'_{q0} \frac{1}{x_e + x'_q} + i_{q0} \quad (7)$$

$$K_3 = \frac{\partial T_e}{\partial E'_d} = [i_{d0} + ((x'_d - x'_q) i_{d0})] \frac{1}{x_e + x'_q} \quad (8)$$

$$K_4 = \frac{\partial E'_q}{\partial E_q} = \frac{x_e + x'_d}{(x_e + x'_d) + (x_d - x'_d)} \quad (9)$$

$$K_5 = \frac{\partial E'_q}{\partial \delta} = (x_d - x'_d) \frac{E_b \sin \delta_0}{x_e + x'_d} \quad (10)$$

$$K_6 = \frac{\partial E'_d}{\partial E_d} = \frac{x_e + x'_q}{(x_e + x'_q) + (x_q - x'_q)} \quad (11)$$

$$K_7 = \frac{\partial E'_d}{\partial \delta} = -(x_q - x'_q) \frac{E_b \cos \delta_0}{x_e + x'_q} \quad (12)$$

$$K_8 = \frac{\partial E_{fd}}{\partial \delta} = \frac{V_{d0}}{V_{t0}} \left(-E_b \cos \delta_0 + \frac{x_e E_b \cos \delta_0}{x_e + x'_d} \right) \quad (13)$$

$$K_9 = \frac{\partial E_{fd}}{\partial E'_q} = \frac{V_{q0} x_e}{V_{t0}} \frac{1}{x_e + x'_d} \quad (14)$$

$$K_{10} = \frac{\partial E_{fd}}{\partial E'_d} = \frac{V_{d0} x_e}{V_{t0}} \frac{1}{x_e + x'_q} \quad (15)$$

The values of K-constants are based on machine parameters and loading conditions. The stability of the system has been analysed with the conventional Heffron-Phillips model based on 6 K-constants.

There is no dampening on the q-axis in this model. Figure 2 shows the AHPM. In this AHPM model there are 10 K constants due to the inclusion of damper winding on the q-axis. The 4th-order model of SM has been considered. The operating point is obtained from power flow analysis. The subscript (0) shows the initial conditions. The initial conditions are calculated from the set of initial conditions equation and are used in the determination of the values of K-constants. (x_e) is the reactance of the line, and (x_d) and (x_q) are the d-axis and q-axis synchronous reactance, respectively. (K_A) and (T_A) are the Gain and Time Constant of the exciter. The details and meaning of all machine parameters are provided in Padiyar, 1996; Gandhi and Joshi, 2014b).

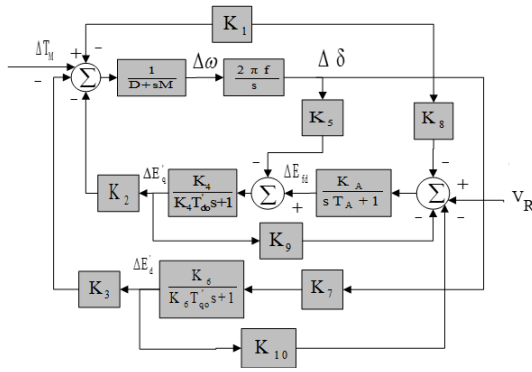


Figure 2. The AHPM

State Space Representation of the AHPM

There are 5 state variables, which are the deviation in rotor angle, rotor speed, internal voltage along the d and q axes, and field voltage (Gandhi and Joshi, 2014b). The state space representation is given below:

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega}_m \\ \Delta \dot{E}_q' \\ \Delta \dot{E}_d' \\ \Delta \dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{2H} & -\frac{D}{2H} & -\frac{K_2}{2H} & -\frac{K_3}{2H} & 0 \\ -\frac{K_5}{T_{d0}} & 0 & -\frac{1}{T_{d0}K_4} & 0 & \frac{1}{T_{d0}} \\ \frac{K_7}{T_{q0}} & 0 & 0 & -\frac{1}{T_{q0}K_6} & 0 \\ -\frac{K_A K_8}{T_A} & 0 & -\frac{K_A K_9}{T_A} & -\frac{K_A K_{10}}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega_m \\ \Delta E_q' \\ \Delta E_d' \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} V_R$$

Optimization Algorithms

The different algorithms used for tuning the PSS parameters are:

The Walrus Optimization Algorithm(WaOA)

The WaOA is a bio-inspired metaheuristic algorithm that emulates walrus behaviors in the wild

and is used in this manuscript to optimize PSS's parameters. WaOA's design is largely inspired by the processes of feeding, migrating, evading, and combating predators. The three phases of the WaOA implementation process exploration, migration, and exploitation are mathematically modelled. To assess WaOA performance in optimization applications, 68 Standard Benchmark Functions Unimodal, Fixed-Dimensional Multi-Modal, High-Dimensional Multi-Modal, Congress on Evolutionary Computing (CEC) 2015, and CEC 2017 Test Suite are used. Four statistical indicators are used to report optimization results: mean, median, best, and standard deviation. Furthermore, the average criteria are used to determine the rank of each algorithm (Trojovský and Dehghani, 2023). Figures 3 and 4 show the walrus and snake in nature.



Figure 3. Walrus in nature

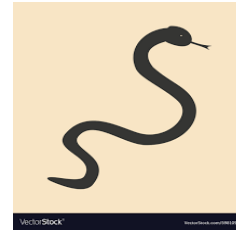


Figure 4. The Snake in nature

The WaOA Pseudo Code

Figure 5 shows the pseudocode of WaOA.

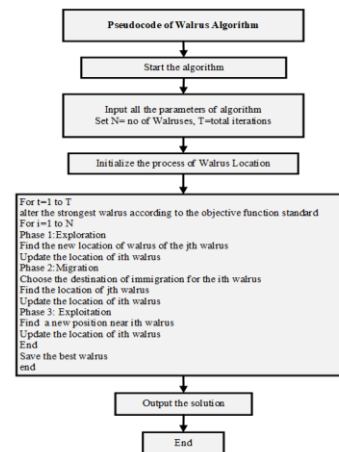


Figure 5. The Flowchart WaOA

The Enhanced Snake Optimization Algorithm(ESOA)

The Snake Optimization Algorithm (SOA) is a newly developed, continuous, naturally inspired method that emulates the mating and fighting habits of snakes. Fighting and mating modes are included in SOA. The former happens when it's cold outside. In contrast, the latter involves the snakes fighting until one of the sexes wins and the female mates with the strongest male. The exploration stage is initiated to look for food if none is found. On the other hand, this is an instance of exploitation if the snakes consume the food (Hashim and Hussien, 2022).

The ESOA has some new features, which are (Yao *et al.*, 2023):

A. Mechanism for Novel Updating

The amount of food consumed by the Snake Optimizer determines whether the phase of algorithm(exploration or exploitation). The values of c_1 , c_2 , and c_3 in the equations are set to fixed constants, which prevents the algorithm from wandering randomly during the exploration phase. As a result, perturbation factors are added to the original values for getting the values of c_1 , c_2 , and c_3 .

B. Convex Lens Imaging supports the Mirror Imaging

The Lens Imaging Learning approach, a type of Opposition-Based Learning, derives from Convex Lens Imaging in the Law of Optics. The approach refracts the object on one side of the convex lens to the other side of the convex lens in order to achieve more optimal solutions.

C. Sine-Cosine Composite Perturbation Factors

The compound perturbation of cosine and sine is used in the paper's proposed new perturbation factors. By adding perturbation factors, the algorithm can break free from the local range and become more adept at pursuing optimality while avoiding local optimum.

D. Cauchy Mutation and Tent Chaos

In the most recent iteration, Cauchy mutation strategies and Tent Chaos are introduced to enhance the algorithm's ability to break out of the local optimum and prevent it from doing so, thereby accelerating the rate of convergence.

E. Checking with Standard and CEC Benchmark Functions

The ESOA has been checked with standard and 10 CEC 2019 Benchmark Functions. The functions are Storn's Chebyshev Polynomial Fitting Problem, Inverse Hilbert Matrix, Lennard-Jones Minimum Energy Cluster, Rastrigin's Function Griewangk's Function, Weierstrass Function, Modified Schwefel's Function, Expanded Schaffer's F6 Function, Happy Cat Function and Ackley Function. The SOA flowchart is displayed in Figure 6. (Hashim and Hussien, 2022).

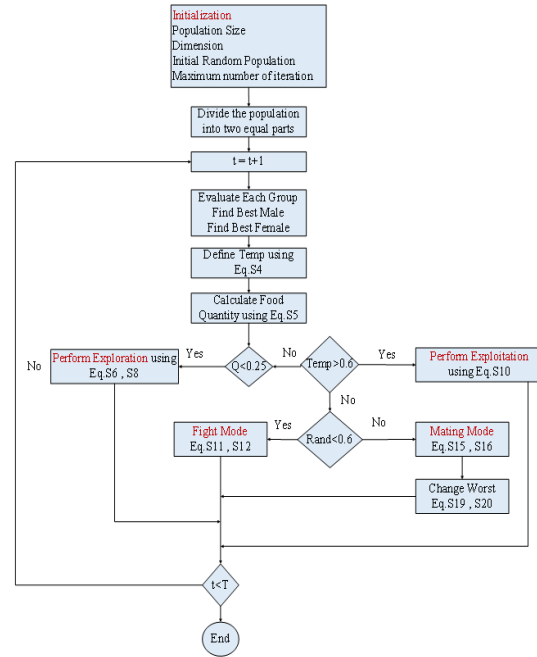


Figure 6. The SOA Flowchart

Proposed AHPM with PSS

Figure 7 shows the AHPM with PSS. Table 1 shows the parameters of algorithms and PSS. The Population_size (N) is 25 and the Maximum_Number_of_Iterations (Max_iter) is 50 to provide a fair comparison with two algorithms (WaOA and ESOA). The dimension (10) is chosen for this problem as it is a low-dimension problem. The number of variables for PSS is 5, which are the gain and four-time constants. The upper and lower bounds (limits) for PSS parameter tuning are set to 1.00 and 0.01. These bounds are so selected to provide appropriate phase compensation between input and output signals. The limiter limits the PSS output to hitting the upper and lower limits. The washout time constant of PSS (T_W) is 10

seconds. This value is so selected as to allow only LFO and block the steady state bias. The simulation is run for 10 seconds for plotting the deviation in the values of parameters.

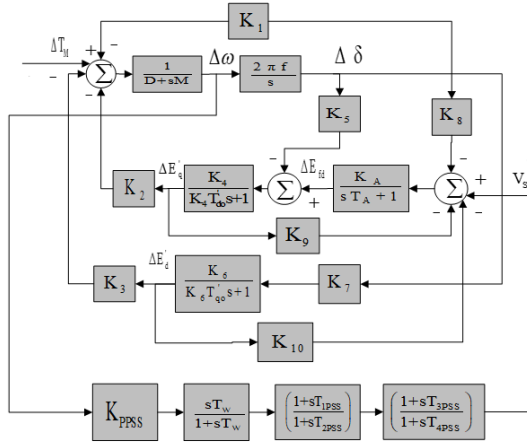


Figure 7. The AHPM with PSS

Parameters for PSS, WaOA, and ESOA

Figures 8 and 9 show the flowchart for PSS with WaOA and ESOA. Table 1 shows the parameters for PSS and algorithms.

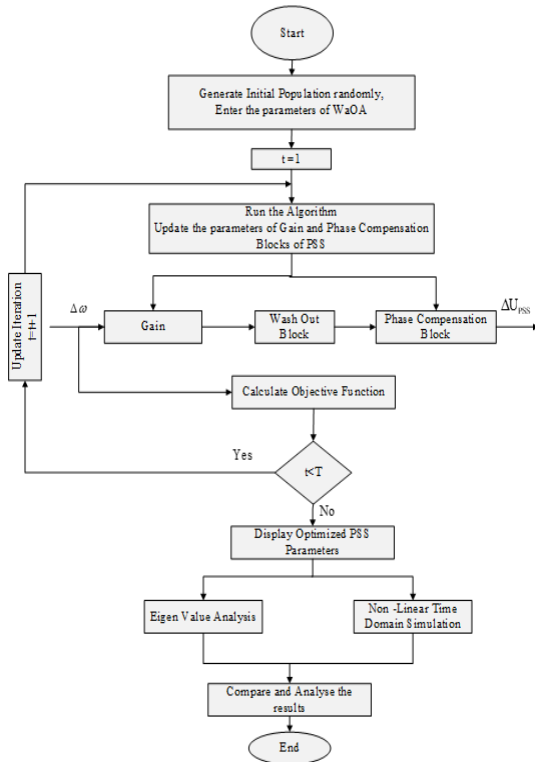


Figure 8. The flowchart with WaOA

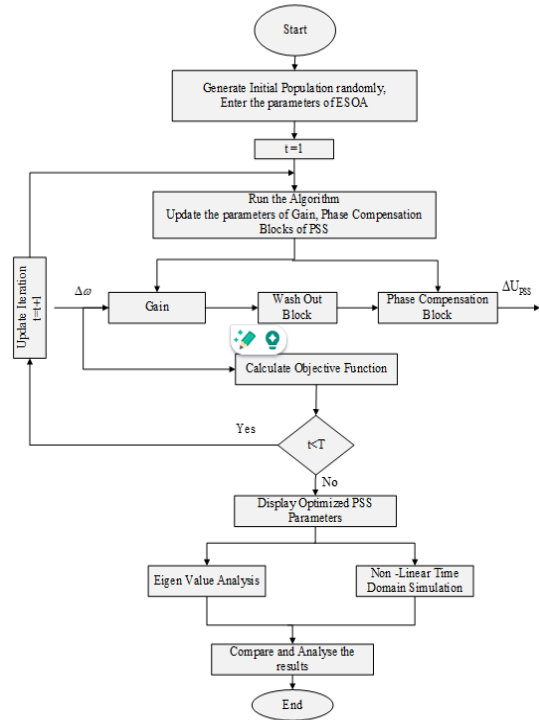


Figure 9. The flowchart with ESOA

Table 1. Parameters

Parameter	Value
N	25
Max_iter	50
Dimension of the problem (Dim)	10
PSS variables	5
The upper bound of PSS	1.00 Seconds
The lower bound of PSS	0.01 Seconds
Time for simulation	11 Seconds
Washout Time constant of PSS	15 Seconds

Results and Discussion

Objective Function(OF)

The algorithms minimize the OF to determine the best gain constant and the PSS time constant. The primary goal is to use PSS to dampen the system's LFO. The generator rotor speed deviation reflects these oscillations. The Integral Time Absolute Error (ITAE) performance index is used in this study. The OF = $\int_0^{t_{sim}} t |\Delta\omega(t)| dt$ where, t_{sim} is the simulation time. Figure 10 shows the overall process flowchart.

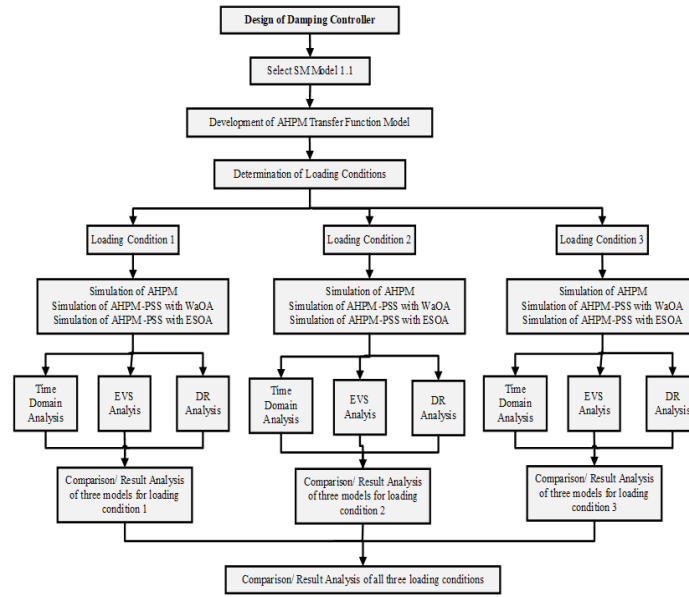


Figure 10. The overall process flowchart

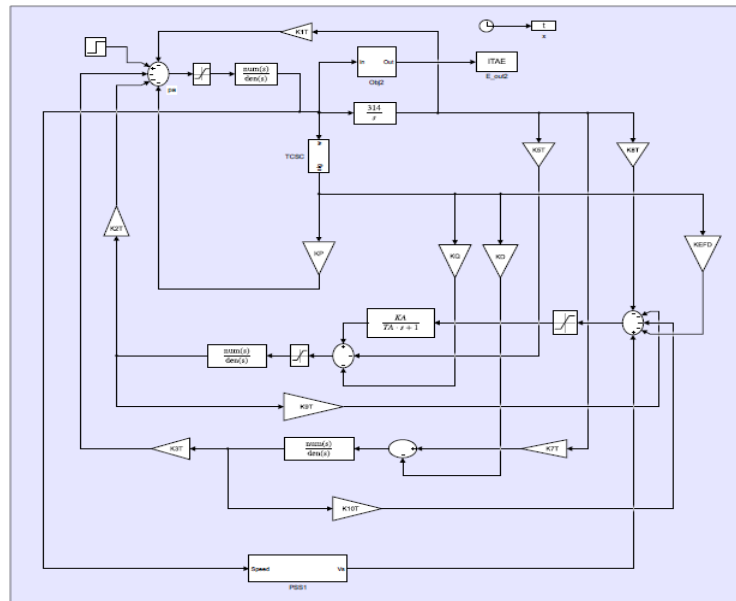


Figure 11 MATLAB Simulation Model

WaOA and ESOA are the two approaches for evaluating the performance of AHPM. By contrasting ESOA with WaOA by performing eigenvalue analysis, MATLAB simulation, and damping ratio analysis, the superiority of the proposed ESOA in designing PSS is assessed. The response of the system with AHPM based on WaOA and ESOA is analysed for three loading conditions for a disturbance. Figure 11 shows the MATLAB simulation model. The three loading conditions are:

- Case 1: $P = 0.60$ and $Q = 0.0224$
- Case 2: $P = 0.75$ and $Q = 0.10$
- Case 3: $P = 1.20$ and $Q = 0.20$

When evaluating the OF, a 10% step increase in input mechanical power at time $t = 1.0$ second, is considered. The oscillations should stop quickly for the best dampening effects. The data needed, including machine parameters and transmission line values, is outlined in Gandhi and Joshi (2014b).

Gain and Time constants

Table 2 and Table 3 show the gain and time constants (in seconds) with WaOA and ESOA.

Table 2. The Gain and Time Constants with WaOA

S. No		AHPM based on WaOA		
		Case 1	Case 2	Case 3
1	KPSS	3.9285	10.000	10.000
2	T1PSS	0.7857	1.0000	1.0000
3	T2PSS	0.1506	0.7752	0.7752
4	T3PSS	0.2738	1.0000	1.0000
5	T4PSS	0.1782	0.7954	0.7944

Table 3. The Gain and Time Constants with ESOA

S. No		AHPM based on ESOA		
		Case 1	Case 2	Case 3
1	KPSS	8.1630	10.000	5.0000
2	T1PSS	0.8428	1.0000	1.0000
3	T2PSS	0.8535	0.5805	0.5805
4	T3PSS	0.4737	1.0000	1.0000
5	T4PSS	0.3942	0.5804	0.5804

Case 1: Response of the System

Figures 12 through 17 below show the variation of different parameters with different models. These models are:

- Model 1: AHPM with no PSS or No Controller(NC)
- Model 2: AHPM with PSS based on WaOA (PSSWOA)
- Model 3: AHPM with PSS based on ESOA (PSSESO)

The NC (No Controller) open-loop framework is very unstable. When using PSS based on WaOA, there is reduced variation in the system parameters. The PSSESO model has the least amount of variation. Based on ESOA, PSS has the least overshoot and settling time. This shows how much the suggested AHPM based on ESOA can accomplish to enhance the damping profile of the system. This outstanding ESOA is used to create a robust controller, which is illustrated by comparing the response curves. The AHPM with ESOA can function well in a variety of operational environments. The system's stability, dampening profile, and power transmission capability are all enhanced by the AHPM.

The Data Statistics tool of MATLAB is used for finding the values of undershoot and overshoot

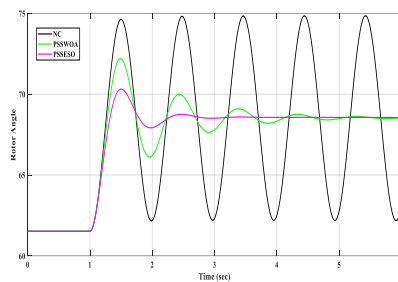


Figure 12. Rotor Angle

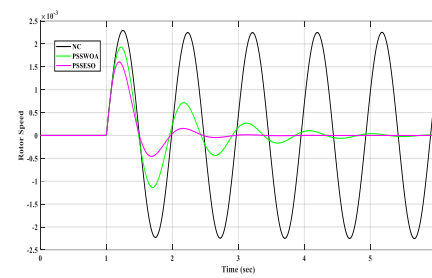


Figure 13. Rotor Speed

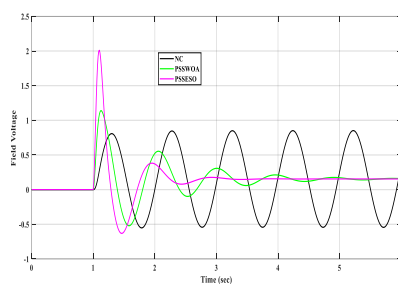


Figure 14. Field Voltage

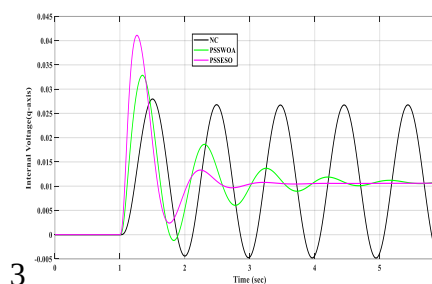


Figure 15. Internal Voltage(q-axis)

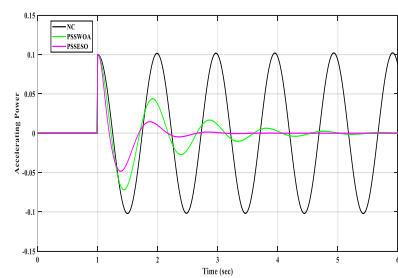


Figure 16. Accelerating Power

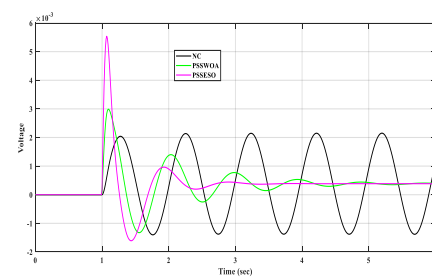


Figure 17. Terminal Voltage

for all the parameters. The undershoot and overshoot are the Minimum and Maximum values (decimal numbers) of the parameters on the Y-axis of the graph.

Tables 4, 5, and 6 show that these values are least in the ESOA model.

Case 1: Analysis of System EigenValues (EVS) and Damping Ratio (DR)

The EVS are determined for the three models. The system matrix (A) is determined by implementing the characteristic equation $\det(\lambda I - A) = 0$. The EVS are given by $\lambda_i = \sigma_i \pm j\omega_i$, the damping ratio is $\xi_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$ and the frequency of

oscillations $f_i = \frac{\omega_i}{2\pi}$. The system's damping is shown by the real part of EVS, and the oscillation frequency is shown by the imaginary part of complex EVS.

Table 7 shows the EVS and DR with model 1 (NC) and model 2 (AHPM with PSS based on WaOA). The model 1 shows two negative DRs each (-1.94e-04) corresponding to EVS

(0.0012 ± 6.4000i). The EVS is not lying to the negative half of the s-plane. All these things show an unstable system. In the AHPM system with PSS based on WaOA, all the EVS are negative and lying to the left half of the s-plane, indicating stability improvement behaviour. The different DR in the NC model are 59.90%, corresponding to EVS(-20.3000 ± 27.2000i). In the WaOA model, the different DRs are 55.80%, 63.70%, and 85.90%, corresponding to EVS (-16.2000 ± 24.2000i, -6.2400 ± 7.5600i, -4.0600 ± 2.4200i). The DRs 63.70% and 85.90% are higher DRs in this model. The highest DR obtained with WaOA for this loading condition is 85.90%. The system shows stability improvement with WaOA.

Table 8 shows the EVS with NC and AHPM with PSS based on ESOA. The different DR in the ESOA-based model are 51.10%, 78.50%, and 98.60%, corresponding to EVS (-14.4000 ± 24.2000i, -5.97 ± 4.72i, -2.5700 ± 0.4380i). Some DR with ESOA is higher than the DR in the WaOA model. The damping results are the best with the ESOA model. The oscillations settled fast here, and overshoot is also the least in the response plot.

Table 4. The Undershoot and Overshoot values for Rotor Angle and Speed

S.No	Rotor Angle			Rotor Speed	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	0.0000	0.2326	-0.002253	0.002294
2	AHPM with PSS -WaOA	0.0000	0.1864	-0.001137	0.001931
3	AHPM with PSS-ESOA	0.0000	0.1535	-0.0004558	0.001606

Table 5. The Undershoot and Overshoot values for Internal and Field Voltage

S.No	Rotor Angle			Rotor Speed	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.004826	0.0297	-0.5520	0.8516
2	AHPM with PSS -WaOA	-0.001195	0.03285	-0.5211	1.1400
3	AHPM with PSS-ESOA	0.0000	0.04109	-0.6312	2.0110

Table 6. The undershoot and overshoot values for Accelerating Power and Terminal Voltage

S.No	Rotor Angle			Rotor Speed	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.1022	0.1022	-0.001402	0.002151
2	AHPM with PSS -WaOA	-0.07194	0.1000	-0.001326	0.002987
3	AHPM with PSS-ESOA	-0.04839	0.1000	-0.001609	0.005538

Table 7. EVS and DR with NC and WaOA

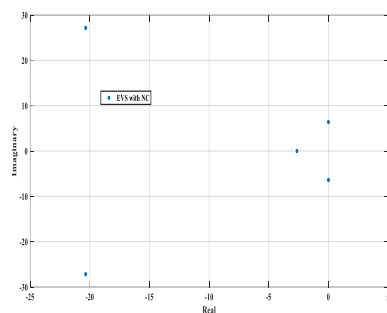
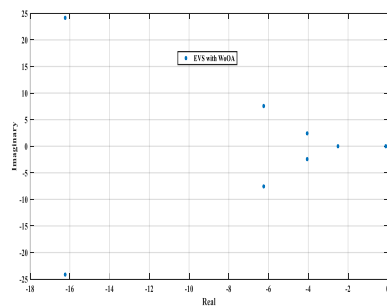
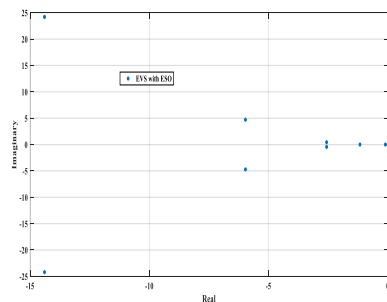
S. No	No Controller(NC)		AHPM with PSS based on WaOA	
	EVS	DR(%)	EVS	DR(%)
1	-20.3000 + 27.2000i	59.90	-16.2000 + 24.2000i	55.80
2	-20.3000 - 27.2000i	59.90	-16.2000 - 24.2000i	55.80
3	0.0012 + 6.4000i	-1.94e-02	-6.2400 + 7.5600i	63.70
4	0.0012 - 6.4000i	-1.94e-02	-6.2400 - 7.5600i	63.70
5	-2.64		-4.0600 + 2.4200i	85.90
6			-4.0600 - 2.4200i	85.90
7			-0.1020	
8			-2.51	

Table 8. EVS and DR(%) with model 1 (NC) and model 3(based on ESOA)

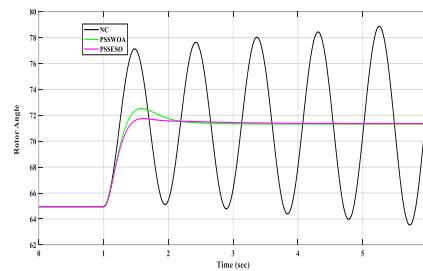
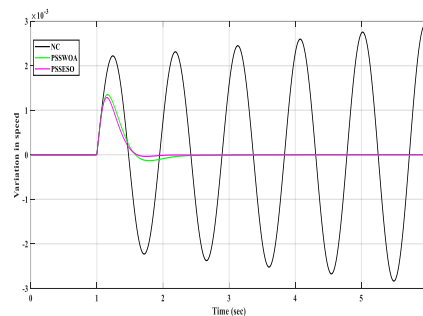
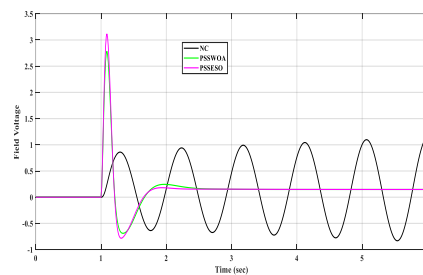
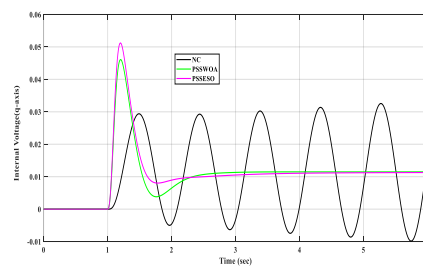
S. No	No Controller(NC)		AHPM with PSS based on ESOA	
	EVS	DR(%)	EVS	DR(%)
1	$-20.3000 + 27.2000i$	59.90	$-14.4000 + 24.2000i$	51.10
2	$-20.3000 - 27.2000i$	59.90	$-14.4000 - 24.2000i$	51.10
3	$0.0012 + 6.4000i$	$-1.94e-02$	$-5.97 + 4.72i$	78.50
4	$0.0012 - 6.4000i$	$-1.94e-02$	$-5.97 - 4.72i$	78.50
5	-2.64		$-2.5700 + 0.4380i$	98.60
6			$-2.5700 - 0.4380i$	98.60
7			-1.02	
8			-1.17	

Case 1: Plot of EVS

Figures 18 to 20 show the location of EVS in the s-plane.

**Figure 18. EVS NC****Figure 19. EVS with WaOA****Figure 20. EVS with ESOA****Case 2: Response of the System**

The response for the same contingency is shown in Figures 21 through 26 for the second operating condition. The oscillation results are best with ESOA. By using ESOA-based PSS, the various parameters, such as overshoot and settling time, are improved.

**Figure 21. Rotor Angle****Figure 22. Rotor Speed****Figure 23. Field Voltage****Figure 24. Internal Voltage**

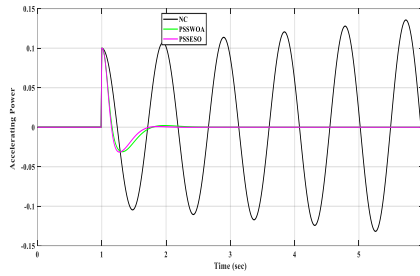


Figure 25. Accelerating Power

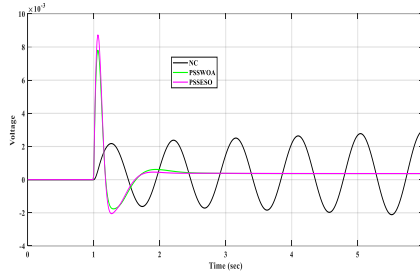


Figure 26. Terminal Voltage

Tables 9, 10, and 11 show that these values are lowest in the ESOA model.

The ESOA model produces the best results due to its unique features mentioned in Section 3.3. One of the most important things when designing

algorithms is to create the methodology with the least amount of complexity possible. One major criterion to consider when selecting an algorithm is to select the one with the lowest time complexity among the algorithms available for solving the given problem. The ESOA applies the Big O concept. Even with the addition of multiple strategies, the ESO algorithm's complexity remains unchanged.

Case 2: System EVS and DR Analysis

According to the EVS analysis, when a PSS based on ESOA is present, the EVS are more negative, which makes the system much more stable and the poles in the s-domain far from the origin. When comparing the ESOA-based PSS to the WaOA-based PSS, the damping factor has also improved. The results of the non-linear simulation demonstrate that ESOA-based PSS rapidly damps out oscillations in rotor angle and speed deviation.

Table 12 shows the NC system is highly unstable. There is negative DR corresponding to EVS ($0.0623 \pm 6.6500i$). The different DR in the WaOA model is 54.30% and 70.50%, corresponding to EVS ($14.8000 \pm 23.0000i$, $-5.5500 \pm 5.5800i$). The DR of 70.50% is highest in the WaOA model. The stability results are improved with the WaOA model.

Table 9. Undershoot and Overshoot values for Rotor Angle and Speed

S.No	Model	Rotor Angle		Rotor Speed	
		Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.02481	0.2429	-0.002837	0.002921
2	AHPM with PSS -WaOA	0.0000	0.1323	-0.0001329	0.001351
3	AHPM with PSS-ESOA	0.0000	0.1187	-3.66e-05	0.001286

Table 10. Undershoot and Overshoot values for Internal and Field voltages

S.No	Model	Internal Voltage		Field Voltage	
		Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.009839	0.03256	-0.8316	1.1530
2	AHPM with PSS -WaOA	0.0000	0.04611	-0.6890	2.7840
3	AHPM with PSS-ESOA	0.0000	0.05123	-0.7831	3.1150

Table 11. Undershoot and Overshoot values for Accelerating Power and Terminal Voltage

S.No	Model	Accelerating Power		Terminal Voltage	
		Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.1318	0.1357	-0.002112	0.002922
2	AHPM with PSS -WaOA	-0.03101	0.1000	-0.00176	0.007807
3	AHPM with PSS-ESOA	-0.0314	0.1000	-0.002048	0.008723

Table 12. EVS and DR with NC and AHPM with WaOA

S. No	No Controller(NC)		AHPM with PSS based on WaOA	
	EVS	DR(%)	EVS	DR(%)
1	-20.4000 + 26.1000i	61.60	-14.8000 + 23.0000i	54.30
2	-20.4000 - 26.1000i	61.60	-14.8000 - 23.0000i	54.30
3	0.0623 + 6.6500i	-9.36e-01	-5.5500 + 5.5800i	70.50
4	0.0623 - 6.6500i	-9.36e-01	-5.5500 - 5.5800i	70.50
5	-2.68		-1.01	
6			-2.08	
7			-1.84	
8			-1.18	

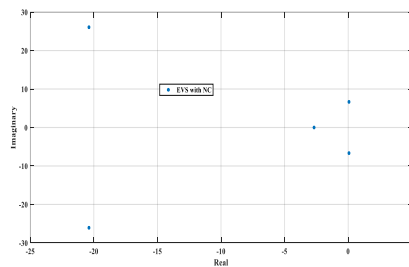
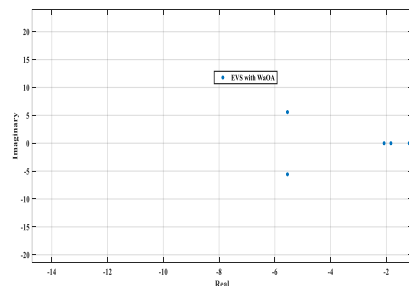
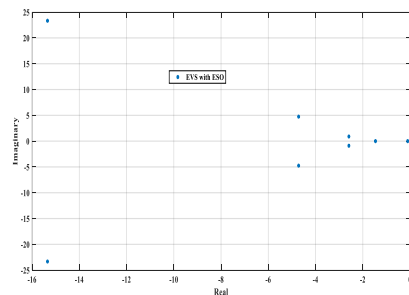
Table 13. EVS and DR with NC and AHPM with ESOA

S. No	No Controller(NC)		AHPM with PSS based on ESOA	
	EVS	DR(%)	EVS	DR(%)
1	$-20.4000 + 26.1000i$	61.60	$-15.3000 + 23.3000i$	55.00
2	$-20.4000 - 26.1000i$	61.60	$-15.3000 - 23.3000i$	55.00
3	$0.0623 + 6.6500i$	$-9.36e-01$	$-4.7200 + 4.7500i$	70.50
4	$0.0623 - 6.6500i$	$-9.36e-01$	$-4.7200 - 4.7500i$	70.50
5	-2.68		$-2.5900 + 0.8970i$	94.50
6			$-2.5900 - 0.8970i$	94.50
7			-1.01	
8			-1.46	

Table 13 shows the EVS and DR with the NC and ESOA models. The different DR with ESOA is 55%, 70.50%, and 94.50% corresponding to EVS ($-15.3000 \pm 23.3000i$, $-4.7200 \pm 4.7500i$, $-2.5900 \pm 0.8970i$), respectively. The highest DR with ESOA is 94.50%. The damping results are the best with the ESOA model.

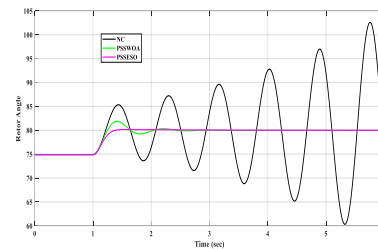
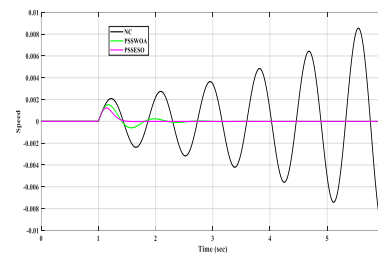
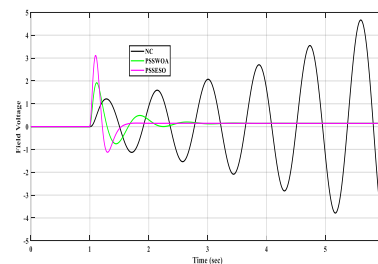
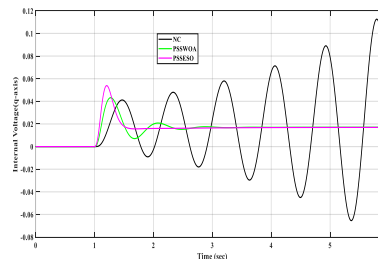
Case 2: Plot of EVS

Figures 27 to 29 show the location of EVS in s-plane.

**Figure 27. EVS NC****Figure 28. EVS WaOA****Figure 29 EVS ESOA**

Case:3 Response of the System

Figures 30 to 35 show the plot for the third loading condition. The best results are obtained with the ESOA model. The oscillations are settled fast in the ESOA model.

**Figure 30. Rotor Angle****Figure 31. Rotor Speed****Figure 32. Field Voltage****Figure 33. Internal Voltage(q-axis)**

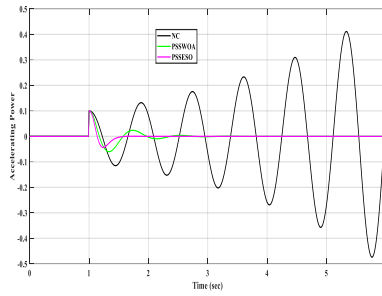


Figure 34. Accelerating Power

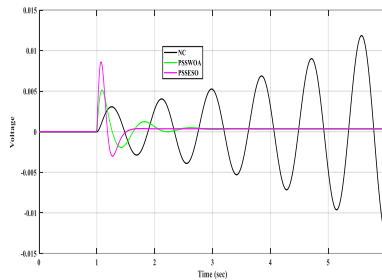


Figure 35. Terminal Voltage

Tables 14, 15, and 16 show that these values are lowest in the ESOA model.

Case 3: System EVS and DR Analysis

Table 17 shows the EVS and DR with the NC and WaOA models. The NC system is unstable. There is negative DR corresponding to EVS ($0.3280 \pm 7.2700i$). The damping results are improved in the WaOA model. The different DRs in the WaOA model are 58.20%, 78.50% corresponding to EVS ($-12.2000 \pm 17.1000i$, $-8.0900 \pm 6.3800i$). The highest DR with WaOA model is 78.50% for this condition.

Table 18 shows the EVS with NC and ESOA models. The damping results are best with the ESOA model for this loading condition also. The DR with ESOA is 58% and 78.90% corresponding to EVS ($-12.2000 \pm 17.1000i$, $-8.1300 \pm 6.3300i$), respectively. The highest DR is 78.90% with ESOA for this loading condition.

Table 14. Undershoot and Overshoot values for Rotor Angle and Speed

S.No	Rotor Angle			Rotor Speed	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.2546	0.4831	-0.009851	0.008544
2	AHPM with PSS -WaOA	0.0000	0.1216	-0.000589	0.001531
3	AHPM with PSS-ESOA	0.0000	0.09167	-1.03e-05	0.001237

Table 15. Undershoot and Overshoot values for Internal and Field voltage

S.No	Internal Voltage			Field Voltage	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.06546	0.1127	-4.9300	4.6670
2	AHPM with PSS -WaOA	0.0000	0.0432	-0.7521	1.9180
3	AHPM with PSS-ESOA	0.0000	0.05387	-1.1240	3.1160

Table 16. Undershoot and Overshoot values for Accelerating Power and Terminal Voltage

S.No	Accelerating Power			Terminal Voltage	
	Model	Undershoot	Overshoot	Undershoot	Overshoot
1	AHPM without any PSS	-0.4740	0.4112	-0.01288	0.11850
2	AHPM with PSS -WaOA	-0.0601	0.1000	-0.00193	0.005127
3	AHPM with PSS-ESOA	-0.0434	0.1000	-0.003019	0.0003416

Table 17. EVS and DR with NC and AHPM with WaOA

S. No	No Controller(NC)		AHPM with PSS based on WaOA	
	EVS	DR(%)	EVS	DR(%)
1	-20.6000 +22.1000i	68.10	-12.2000 +17.1000i	58.20
2	-20.6000 -22.1000i	68.10	-12.2000 -17.1000i	58.20
3	0.3280 + 7.2700i	-4.51	-8.0900 + 6.3800i	78.50
4	0.3280 - 7.2700i	-4.51	-8.0900 - 6.3800i	78.50
5	-2.79		-2.53	
6			-1.01	
7			-1.40	
8			-1.12	

Table 18. EVS and DR with NC and AHPM with ESOA

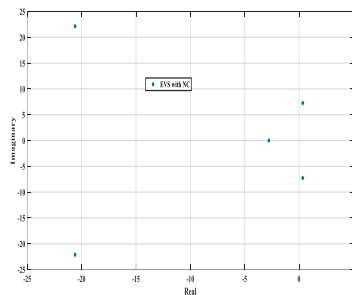
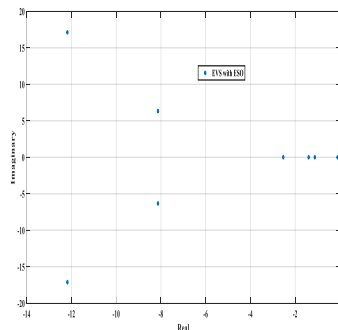
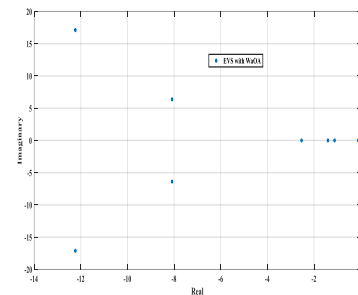
S. No	No Controller(NC)		AHPM with PSS based on ESOA	
	EVS	DR(%)	EVS	DR(%)
1	-20.6000 + 22.1000i	68.10	-12.2000 + 17.1000i	58.00
2	-20.6000 - 22.1000i	68.10	-12.2000 - 17.1000i	58.00
3	0.3280 + 7.2700i	-4.51	-8.1300 + 6.3300i	78.90
4	0.3280 - 7.2700i	-4.51	-8.1300 - 6.3300i	78.90
5	-2.79		-2.53	
6			-1.01	
7			-1.40	
8			-1.12	

Table 19. EVS with maximum DR

No.	Model	DR(%)	EVS
Loading Condition 1			
1	NC	59.90	-20.3000 ± 27.2000i
2	PSS based on WaOA	85.90	-4.0600 ± 2.4200i
3	PSS based on ESOA	98.60	-2.5700 ± 0.4380
Loading Condition 2			
4	NC	61.60	-20.4000 ± 26.1000i
5	PSS based on WaOA	70.50	-5.5500 ± 5.5800i
6	PSS based on ESOA	94.50	-2.5900 ± 0.8970i
Loading Condition 3			
7	NC	68.10	-20.6000 ± 22.1000i
8	PSS based on WaOA	78.50	-8.0900 ± 6.3800i
9	PSS based on ESOA	78.90	-8.1300 ± 6.3300i

Case 3: Plot of EVS

Figures 36, 37, and 38 show the location of EVS. The EVS are shifted to the left half with WaOA and ESOA. Table 19 shows the EVS with maximum DR for three conditions.

**Figure 36. EVS NC****Figure 37. EVS WaOA****Figure 38. EVS ESOA**

The results in brief are:

- In the classical model, the field flux decay is ignored. With fewer assumptions and carelessness, this AHPM is a realistic model.
- It is determined that the two-axis model, or SM Model 1.1, is a better fit for stability analysis.
- The model 1 is highly unstable.
- The EVS location are improved with PSS based on WaOA and ESOA models.
- The location of EVS is best with ESOA algorithm.
- The undershoot, overshoot, and settling time are least with ESOA.
- The damping torque contribution is highest with ESOA.

The damping results agree with the studies of Izci (2021) and Izci (2022) regarding the gain and time constants of PSS. The highest DR is 54.36%, and the settling time is around 3 seconds (Izci, 2022). The highest DR is 53.45% in Izci (2021) and 65.21% in Ekinici (2021). In this manuscript, the settling time with model 3 is less than 2 seconds. The DRs for three loading conditions are (98.60%, 94.50%, and 78.90%), respectively, with ESOA-based PSS. The PSS and TCSC have been coordinated for stability improvement using neural networks (Gandhi and Joshi, 2014). There is no need to integrate the FACTS device in this model. This shows that this is an economical and cost-effective model. The combination of twin technologies, the optimization algorithm, and linear quadratic regulator methodology has been applied for improvement in stability (Jokarzadeh *et al.*, 2019). However, in the present work, only an optimization algorithm is implemented for bringing the best results. It has been concluded in Kalyani *et al.* (2011) and Morab *et al.* (2015) that SM model 1.1 is a better model for transient stability analysis. The parameters of Walrus and Snake optimization algorithms have been taken from (Hashim and Hussien, 2022; Trojovský and Dehghani, 2023; Yao *et al.*, 2023). The AHPM with PSS is efficient in working in different operating conditions. Robustness refers to the capacity to endure disruptions and maintain operation amid shifting external circumstances (Makwana and Gandhi, 2018; Behzadpoor *et al.*, 2022). The results of the three loading conditions show that the AHPM is a robust and efficient model.

The ESOA produces better damping results. The effectiveness of ESO and 13 algorithms has been investigated on two sets of scenarios and four problems for engineering design optimization. The ESO algorithm significantly improves the model's performance and problem-solving ability. Issues arise from the fixed values of certain algorithm parameters, inadequate population diversity, imbalance between exploitation and exploration in the search space, and limited potential for significant spatial leaps in population updates. All these problems have been addressed in ESOA. Hence, ESOA has been implemented in this research work.

Conclusions and Future Scope

The behaviour of a power system's stability is examined with AHPM and PSS based on two algorithms. For stability, the EVS must be on the left side of the s-plane. For the electromechanical oscillations, the desired EVS needs to be dampened as fast as possible. The EV analysis is carried out

taking various loading conditions into account to confirm that the suggested ESOA-based controller raises the system's linear model stability. Time domain simulation results show the improvement in stability with PSS based on WaOA and ESOA. The DRs are highest with the ESOA model for all three loading conditions, which are 98.60%, 94.50%, and 78.90%, respectively. The best damping results are obtained with the ESOA model for all three loading conditions.

Applying AHPM and PSS that have been optimized by the suggested ESOA results in the LFO being damped with a high positive DR, a quick settling time, and fewer oscillations. It is seen that by offering noticeably more damping to all oscillation modes, the proposed AHPM-based PSS performs better under a range of operating conditions. The reason is improved mathematical modelling of the system with a 4th-order SM model 1.1 taking the dynamics of internal voltage along both the d and q axes. The ESOA worked effectively, which has been evaluated and validated with CEC 2019. A robust power system has been developed with ESOA-based AHPM. The problems with RES's penetration into the grid can be handled by this AHPM with PSS. The ESOA tuned the system successfully, and a stable power system is developed against all the operating conditions.

The proposed damping controller may be designed with the help of storage technologies like Superconducting Magnetic Energy Storage (SMES) and Capacitor Energy Storage (CES) systems. There is a rapid response with SMES and large storage with CES. A combination of SMES and CES can also be developed. But this combination involves huge costs. Hence, there is a need for affordable technology. Other storage technology, like battery energy storage, can be used in research work. The other higher-order models of SM may be used for mathematical modelling of the system, and the results can be analysed with the old models. The state space modelling can be done with higher-order models. Multimachine systems and multi-objective functions can be analysed.

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