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Original Research

LFO Damping Enhancement in Multimachine Network Using African Vulture Optimization Algorithm

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Abstract

The prolonged presence of low-frequency oscillation (LFO) in power system networks (PSN) poses a significant threat to their stability. Hence, engineers and researchers have continuously developed effective strategies to mitigate the issue and enhance the stability of the PSN. This article proposes a new approach using the African Vultures Optimization Algorithm (AVOA) to design robust Power System Stabilizers (PSS) and enhance the LFO damping in multi-machine networks. The damping ratio-based objective function minimizes the oscillations and increases the system damping. Conventional power system stabilizer (CPSS) is adopted as its parameters are tuned with the help of the African Vulture optimization algorithm to achieve a proper damping ratio over a wide range. Using a pair of multi-machine networks likely to experience three-phase faults, we examine the execution of the process. The results obtained by the simulations are compared with the three reputable optimization algorithms called particle swarm optimization (PSO), backtracking search algorithm (BSA), and dragonfly algorithm (DA), and AVOA-tuned PSS outperforms in terms of minimum damping ratio for tested PSN (Network-1 and Network-2). The AVOA provides a percentage improvement of 76%, 50%, 22%, and 25% compared to CPSS, PSO, BSA, and DA, respectively, for Network-1 and 85%, 83%, and 10% for PSO, BSA, and DA, respectively for Network-2. Therefore, the proposed AVOA optimization technique surpasses other methods to enhance the tested networks' minimum damping ratio.

Keywords

Damping ratio; multi-machine network; AVOA; LFO damping; PSS

1. Introduction

There is much interest in power system stability due to the development of massively interconnected power networks. That means transmission and distribution systems are all linked together to impact electricity supply, including power stations at a national level, as the electricity demand is increasing daily. The PSN is a complex and vast network constructed by humans. Various types of disturbances over time subject it to conditions that can lead to low-frequency oscillations known as electromechanical oscillations (EMO) [1, 2]. These oscillations can cause instability in the PSN [3]. When managing correspondent power systems, the load receives significant power transfer. This causes the power system to operate near its momentary and dynamic stability limits, which can lead to the introduction of low-frequency electromechanical oscillations (0.1-3 Hz) in the system [4, 5]. These oscillations can harm the stability of the PSN [6]. This increased the effort to transfer the electric power over massive geographical and electrical distances. If it is not damped out soon, these LFOs can build dramatically over time, resulting in cause system failures [7, 8]. Maintaining stability after being subjected to equivalent oscillations has been one of the most important outfits in the power industry since its early beginnings. In addition to the regular minor disturbances, integrating renewable energy sources into the generation and distribution systems creates a continuous mismatch between the load and the generation [9]. This mismatch can lead to low-frequency oscillations in the PSN. These oscillations occur due to the constant variation in the amount of power generated by renewable sources, which can negatively affect the system's stability.

Many power plants widely apply automatic voltage controllers (AVR) for voltage regulation. However, the AVR could not leave the low-frequency oscillation for extended times as it could not produce the "fine adjustments" demanded to rule oscillation in the speed [10]. That is why the volume of power conducted on the system was confined. The PSS was integrated into synchronic generators to permit fine-tuning power fluctuations, also understood as low-frequency oscillations. PSS is used with the synchronous generator's excitation mechanism to offer an additional control signal that improves system damping [8, 11-13]. Integrating renewable energy sources can introduce LFOs into the PSN [14]. Although the PSN is very nonlinear, conventional methods are designed and controlled in a region where they reflect linear behavior. In minor disturbances, the operating points remain close to the region. That is why conventional PSSs are designed using a linear model. However, when nonlinearities grow significantly and linear models cannot maintain stability, significant changes in the operating point are due to substantial disturbances. For this reason, it is essential to consider the effect of the nonlinearities. This article [15] proposes a modified AVR and PSS architecture to increase the damping of these systems.

Intelligent control, variable structure control, optimum control, and adaptive control are only a few of the current control theory-based PSS models developed recently [16-18]. Despite current control techniques, power system utilities still prefer the traditional lead-leg PSS structure because of its simplicity [19]. One may sequentially create PSS using conventional methods and address one electromechanical mode at a time [20]. Selecting the correct parameter values can vastly improve the performance of PSS. However, the stabilizer with one electromechanical mood could make other moods unstable. Sequential approaches are abandoned as a reaction [21]. This research [22] recommends a gradient-based approach, which also may underperform if they become trapped in a local optimum.

Meta-heuristic optimization approaches have exploded in popularity during the previous two decades. The backtracking search algorithm [23], particle swarm optimization [24], whale optimization algorithm [25], genetic algorithms [26, 27], cultural algorithms [28], artificial bee colony [29], political optimization algorithm [30], arithmetic optimizer algorithm [31], slime mould algorithm [32], red deer algorithm [33], fuzzy gravitational search algorithm [34], social engineering optimizer [35], and design problems for multi-machine PSS have widely used other algorithms based on these methods. R. Devarapalli *et al.* [36] proposed amended Grey Wolf Optimizer (GWO) algorithms for optimizing traditional PSS, but there is no experimental evidence to support them, and they did not use renewable energy. Another study by Abd-Elazim *et al.* [37] presented an SVC based on the bacteria foraging optimization algorithm for dampening power system oscillations. Although this study considered numerous loading factors, it tested only a small network and did not consider renewable energy sources. Researchers also explored other meta-heuristic algorithms to optimize the parameters of the PSS [38-40].

In 2021, Abdollahzadeh *et al.* [41] introduced AVOA, a novel nature-inspired metaheuristic algorithm, and several actual engineering applications have utilized it. At first, 36 standard benchmark functions are examined to measure AVOA's performance. When it comes to handling complicated technical challenges with both small and large dimensions, AVOA gives better results. A comparative analysis demonstrates the suggested algorithm's superiority over several other algorithms. A range of design and optimization problems, among other things, have been effectively solved using this particular optimization technique. The suggested algorithm's distinguishing factor and strength in balancing frequency and diversity is that it has a lower computational complexity and is more adaptable than previous metaheuristic algorithms. However, AVOA has not yet been applied to improve PSS parameters in the MMPS networks.

This paper aims to design a robust PSS and enhance the LFO damping for MMPS networks as an optimization problem. The AVOA method identifies the optimal PSS parameter values. The following methodology investigates two multimachine networks, comparing the performance of AVOA-tuned PSS with CPSS, BSA, PSO, and DA-tuned PSS.

The article is divided into six sections. In the next section, Section 2 contains the power system modeling, while Section 3 has a detailed review of the proposed optimization problem. Section 4 describes the African vulture optimization algorithm. Section 5 discusses the simulation results and evaluation of the proposed method. The conclusion is incorporated in Section 6 and provides the direction for future work.

2. Materials and Methods

2.1 Synchronous Generator

Synchronous generator modelling is crucial for power system analyses. As a generator, it determines the electric properties of the power system, particularly for system security, and the ability to tolerate rapid disruptions such as faults, switching, and load variations. A fourth-order equation model can represent a PSN with *n* number of generators [8, 15, 16]. These equations mathematically describe each i^{th} generator on that network:

$$\dot{\delta_l} = \omega_b(\omega_i - 1) \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M}(P_{mi} - P_{ei} - P_{Di}) \tag{2}$$

$$\dot{e}_q = \frac{1}{T_{do}}\left[E_{fdi} - e_{qi} - (x_{di} - x'_{di})i_{di}\right] \tag{3}$$

$$\dot{E}_{fdl} = \frac{1}{T_{Ei}}\left[K_{Ei}(v_{tri} - v_{ti} + u_{PSSi}) - E_{fdi}\right] \tag{4}$$

The rotor angle can be enumerated by equation 1 where δ refers to the rotor angle, ω represents the angular frequency, and i is for i^{th} generator. In the 2nd equation, M stands for system inertia coefficient, P_m is the input mechanical power, P_e is the output electrical power, andP_D represents the damping coefficient. The internal voltage of the generator can be determined by equation 3, $\dot{e}_q$ stands for the internal voltage of the generator, T'_{do} which represents the time constant of the open circuit field, E_{fd} which represents the field excitation, x'_d which is the transient reactance of the direct axes and i_d is the current of the direct axes. Field voltage can be enumerated by equation 4, where $\dot{E}_{fdl}$ refers to the field voltage, T_E stands for the time constant for the excitation system, K_E represents the gain in the excitation system, v_{tr} and v_t represents the reference and terminal voltages, respectively, u_{PSS} which is the control input. With some approximation, these nonlinear differential equations from (1) through (4) may be linearized [16].

2.2 Conventional PSS

The original designs are transformed individually into their corresponding generalized chains (kinematic chains). In the following steps, the generalized chain will involve various types of members (edges) and joints (vertices, or said kinematic pairs) for all possible assembly (Figure 1).

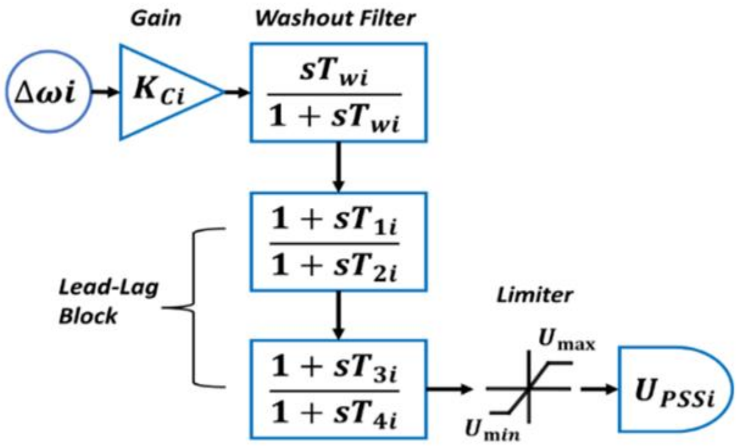

Figure 1 Conventional lead-lag PSS structure.

It comprises an amplifier or gain block (K_{Ci}) that is utilized to produce the required positive damping. While the limiter block controls the size of the control signal, the washout/rest block is attached to turn off PSS in steady-state operation with time constant T_w. Two lead-leg phase compensators with time constants T_1, T_2, T_3, and T_4 connect between the washout filter and limiter block. When low-frequency oscillation occurs, the phase lead of CPSS tries to compensate for the overall lag of the excitation system.

The CPSS can be shapely as:

$$U_{PSSi} = K_{Ci} \frac{sT_{wi}}{(1+sT_{wi})} \left[\frac{(1+sT_{1i})}{(1+sT_{2i})} \frac{(1+sT_{3i})}{(1+sT_{4i})} \right] \Delta\omega_i \tag{5}$$

where U_{PSSi} is the output signal, and $\Delta\omega_i$ utilized as the PSS input signal.

3. Proposed Optimization Problem

The challenging part is tuning the PSS parameters to increase the system damping ratio. The objective function is chosen to be the minimum damping ratio of the generator. Maximizing the objective function *(J)* is the goal of the optimization problem.

$$J = \max \{\zeta_i, i = 1,2,3, \dots, n\} \tag{6}$$

Here, ζ_i is the i^{th} machine's minimum damping ratio, and *n* is the number of machines.

Maximization of *J*

$$K_{ci}^{min} \le K_{ci} \le K_{ci}^{max}$$

$$T_{1i}^{min} \le T_{1i} \le T_{1i}^{max}$$

$$T_{3i}^{min} \le T_{3i} \le T_{3i}^{max}$$

Where, K_c, T_1 and T_3 represent the previously explained PSS parameters. The lower and upper bounds for the gain of the conventional PSS K_{ci} are set at 0 to 50. Further, these bounds are 0 to 1 for the time constants for conventional PSS T_{1i} and T_{3i}.

4. African Vulture Optimization Algorithm for Power System Stability Enhancement

Abdollahzadeh introduced the AVOA in [41]. It is based on the lifestyle, food search, and competition for food by various vultures in the African continent. A pseudo-code of the proposed algorithm is given below:

1. Start the algorithm.
2. Collect and read the system data, i.e., Line data, bus data, and generator constants.
3. Initialize the control parameters of the algorithm, i.e., population size, maximum number of iterations, and boundary conditions.
4. Run the load flow analysis for the system using Newton Raphson's method with system uncertainties and set the initial condition.
5. Generate the initial population of the solution randomly within the search space.
6. Initialize the population matrix for the search agents and check for the inequality constraints.
7. Update the population matrix for an individual search agent in case of boundary violation.
8. Update the positions of vulture groups with the best-achieved values.
9. Evaluate objective function and identify the best solution.
10. Update the solution following updating the equation.
11. Select the better solutions to take part in the next iteration.
12. Go to steps 5-9 until any termination criterion is met.
13. END.

It is necessary to collect system data and control parameters to initiate the power system stability process. Following the initialization of system parameters, apply AVOA and the damping coefficients. Then, it searches for the best convergence by adjusting the parameter value. Upon achieving optimized convergence, implement damping enhancement and test the system stability.

5. Simulation Results and Discussion

A MATLAB-based simulation of the linear model of an IEEE-39 bus ten-machine system and a two-area four-machine system is used to test the efficiency of the AVOA in MMPS networks. The AVOA-optimized PSS simulation results are compared with the other PSS, based on PSO, BSA, DA, and conventional PSS or without conventional PSS. All the parameter values are the same. For each generator, the problem dimension is 5, the size of the population is 100, and the maximum iteration is 1000. In the reset block, T_w is set to 10 s. This paper optimizes K_{ci}, T_{1i}, and T_{3i} using AVOA. The limit for $K_{ci}$is set as [0.0 to 50.0], while the limits for T_{1i}, T_{2i}, T_{3i}, and T_{4i} are set as [0.01 to 1.00]. This technique successfully enhanced the damping of low-frequency oscillations (LFO) in the multimachine network. The performance of the proposed method responded more quickly under small or large disturbances and made the system stable early. Moreover, this technique gave a larger minimum damping ratio than other reputed techniques. The proposed AVOA algorithm improves the stable capability of the system with fast convergence.

5.1 Network 1: Two-Area Four-Machine Network

Figure 2 represents the test network-1 (two-area four-machine). Ref. [8] provides more information about the network data. It consists of eleven buses and two regions linked by a weakened link between buses 7 and 9. At buses 7 and 9, two loads are applied to the system. Two shunt capacitors are additionally equipped at buses 7 and 9. The main frequency of the system is 60 Hz. A weak connection in this system links two comparable regions. Each section has two generators with a 20 kV and a 900 MVA rating. For a particular base case [8], the AVOA technique is employed to optimize three parameters: K_{ci}, T_{1i}, and T_{3i}. T_{2i} and T_{4i} are both set to 0.0500. Different optimization techniques are applied to test this MMPS network, and the resulting damping ratios are provided in [24]. Table 1 displays the optimized parameter values.

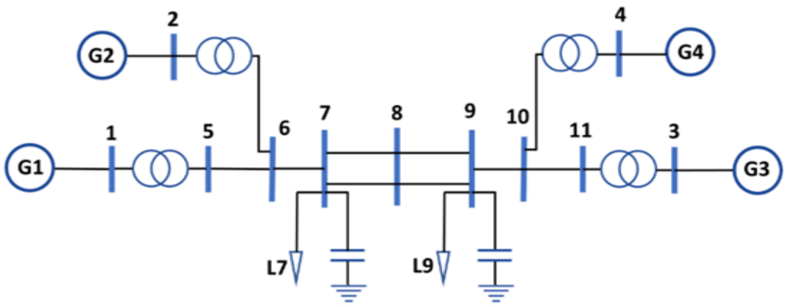

Figure 2 Two-area four-machine network.

Table 1 Optimized parameter value of AVOA in network-1.

Generator No.	AVOA-tuned PSS		
	K_c	T_1	T_3
G_1	17.6167	0.0766	0.0133
G_2	39.3891	0.0553	0.1030
G_3	30.9652	0.0622	0.2017
G_4	9.7077	0.0195	0.1723

Figure 3 illustrates the objective function concerning the iteration numbers for the AVOA-tuned PSS. AVOA provides a minimum damping ratio (MDR) of 0.6454. Bus 7 is subjected to a 3-φ fault for 0.1 s, beginning at 0.5 s. The whole process was simulated for 5 seconds. Figure 4 demonstrates angular frequency variations for four machines, where the oscillations are dampened using the conventional PSS. It shows that CPSS cannot stabilize the system within 5 seconds. Figure 5 illustrates the angular frequency was damped within 3 s for the AVOA-tuned PSS.

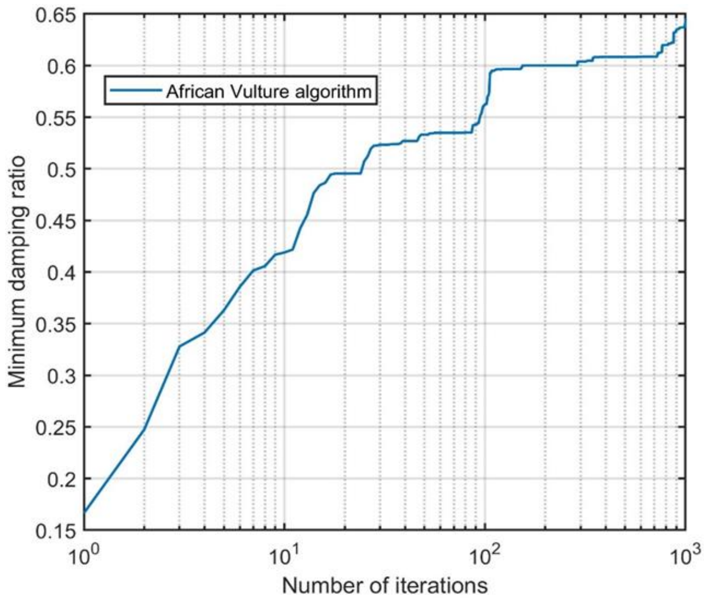

Figure 3 Objective function of AVOA.

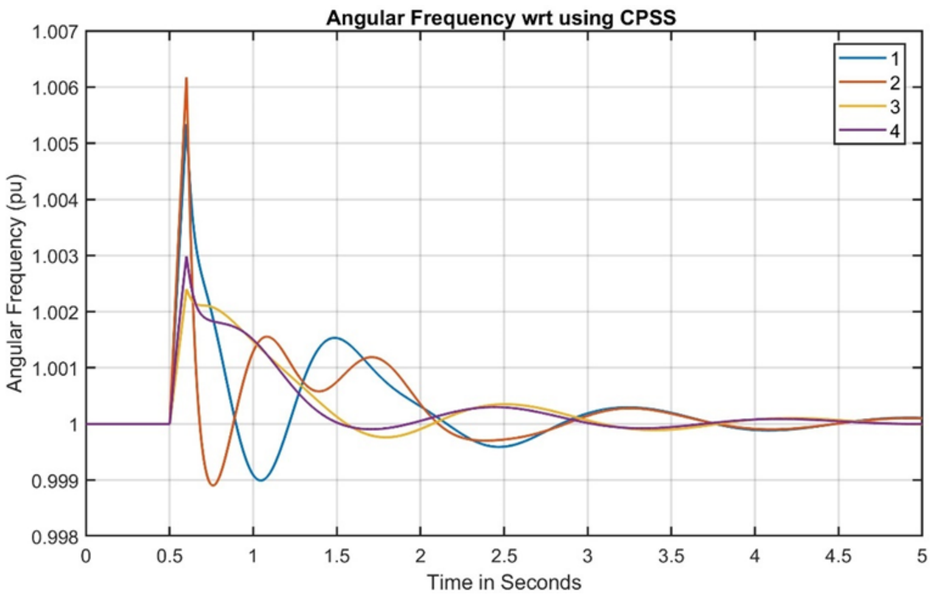

Figure 4 Angular frequency for four generators.

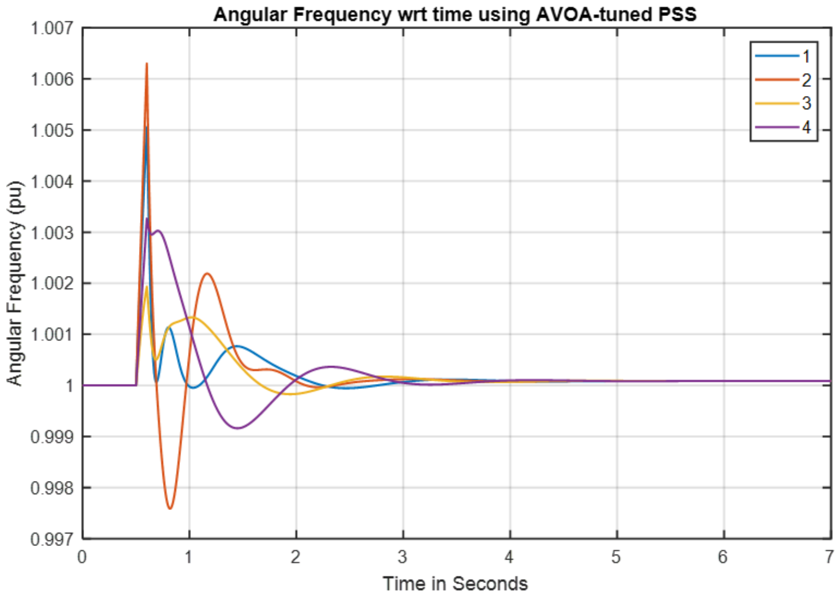

Figure 5 Angular frequency for four generators with AVOA-tuned PSS.

Figure 6 shows the variations in G_3 rotor angle for the same fault, demonstrating that the AVOA-based PSS can stabilize oscillations much faster than CPSS. Control signal G_3, shown in Figure 7, also indicates stable performance. The AVOA technique has a substantially shorter settling time than CPSS. Other generators show similar performance.

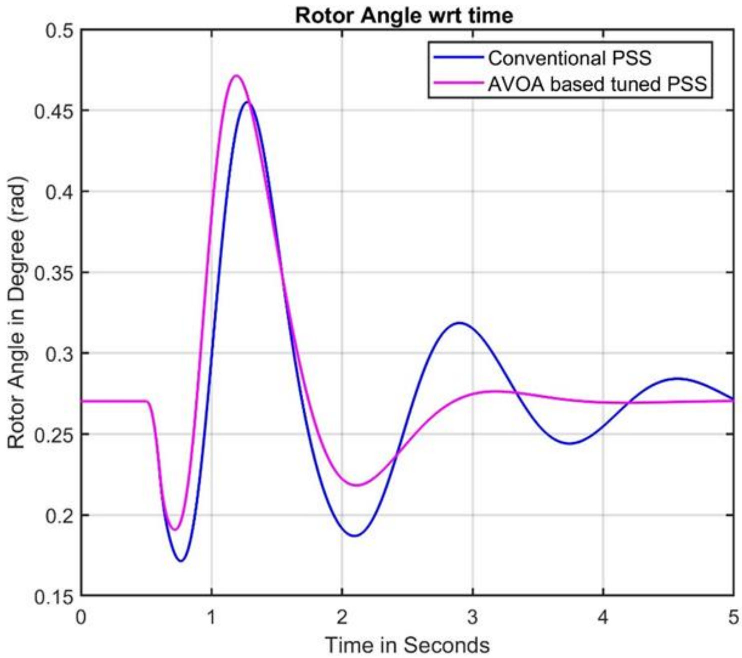

Figure 6 Rotor angle of G_3.

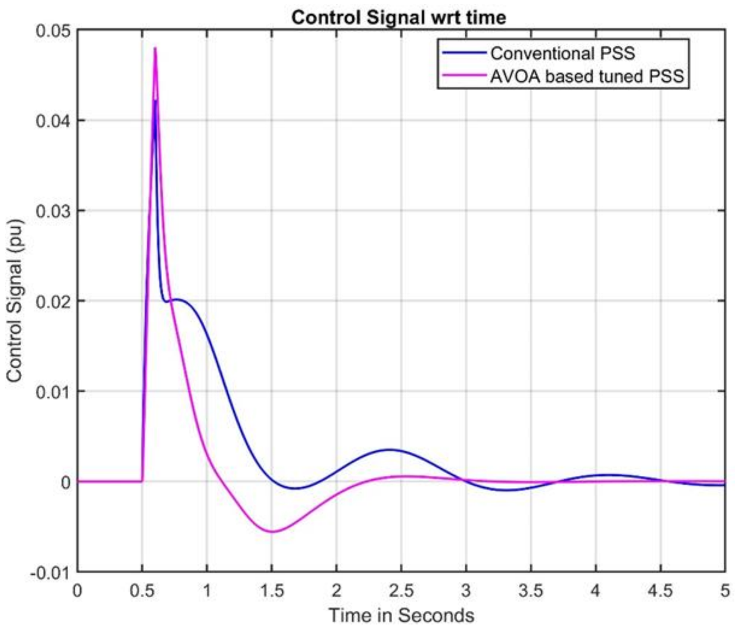

Figure 7 Control signal of G_3.

5.2 Network 2: IEEE 39-Bus Network

The IEEE 39-bus system is the New England Power System [15]. The system comprises 36 transmission lines, 39 buses, 10 generators, 19 loads, and 12 tap-changing transformers. Generator 1 represents the aggregation of a large number of generators. Figure 8 shows the single-line diagram of the IEEE 39-bus system. Table 2 illustrates the optimized parameters for AVOA-tuned techniques. Figure 9 depicts the objective function for the AVOA algorithm technique concerning the number of generations.

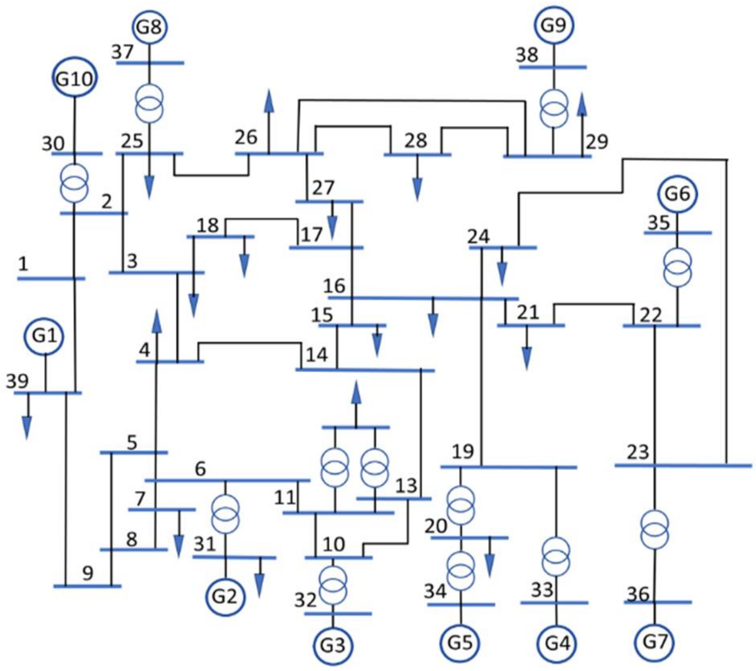

Figure 8 IEEE 39-bus network.

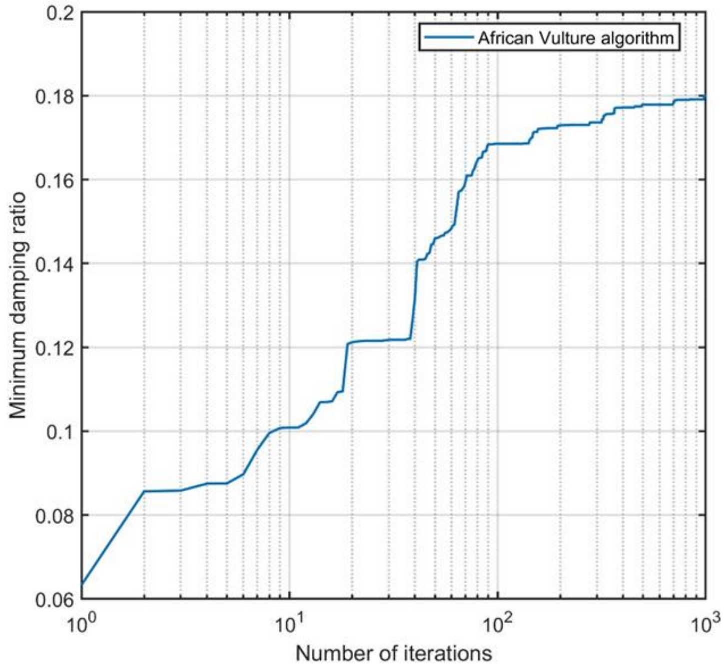

Figure 9 Objective function of AVOA.

Table 2 Optimized parameter value of AVOA in network-2.

Generator No.	AVOA-tuned PSS		
	K_c	T_1	T_3
G_1	0	0	0
G_2	21.3666	0.8338	0.7994
G_3	49.8013	0.7247	0.3499
G_4	47.5655	0.9104	0.6092
G_5	7.4048	0.3242	0.6963
G_6	17.9248	0.1922	0.5317
G_7	4.0426	0.8070	0.1041
G_8	31.1698	0.9548	0.9794
G_9	47.8398	0.1914	0.1889
G_{10}	49.2408	0.9491	0.8038

AVOA provides an MDR of 0.1802. Bus 29 is exposed to a three-phase fault that starts at 0.5 s, lasts for 0.1 s, and ends at 0.6 s. The fault is simulated for 5 s. Figure 10 illustrates the angular frequency for ten generators using AVOA-tuned PSS for time; this technique can stabilize the angular frequency within 2.5 s, faster than conventional PSS. Figure 11 displays the control signal for G_5 illustrating stable performance. The AVOA technique has a substantially shorter settling time than CPSS. Other generators offer similar performance. This design suggests that the AVOA-based PSS design is more compatible and robust.

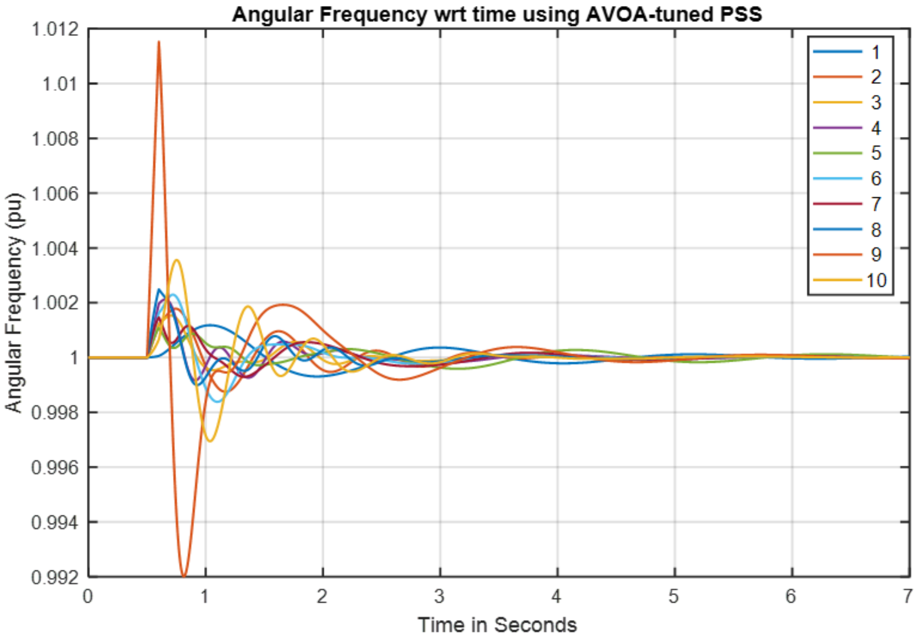

Figure 10 Angular frequency of ten generators with AVOA-tuned PSS.

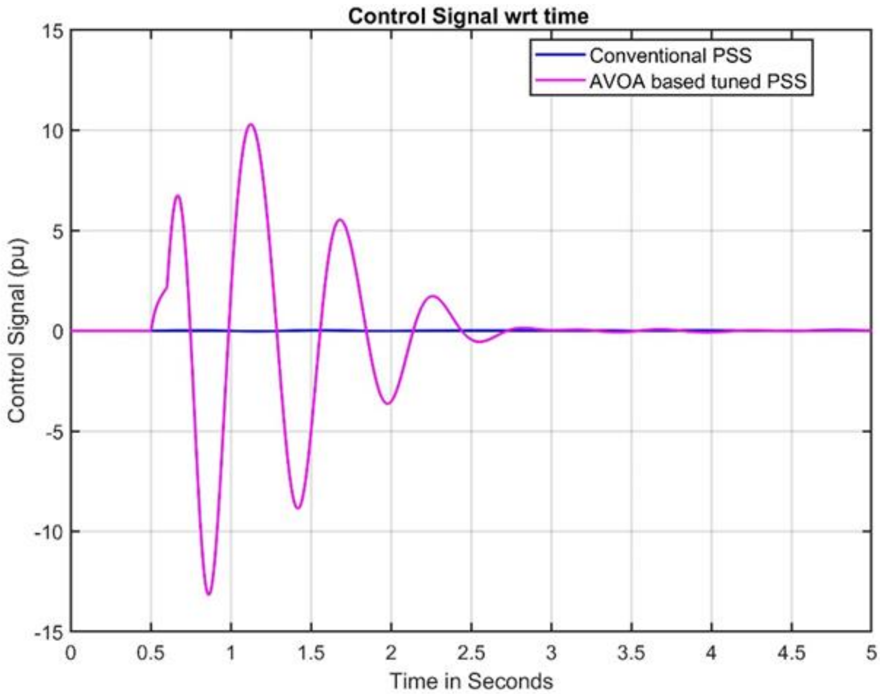

Figure 11 Control signal of G_5.

5.3 Comparative Study

The comparative study over different optimization algorithms like conventional PSS, BSA, PSO, and DA-tuned PSS with AVOA-tuned PSS is based on a better minimum damping ratio. AVOA gives a larger minimum damping ratio than the other approached optimization algorithm for the two-area four-machine network and IEEE 39-bus network. Figure 12 illustrates the comparison among the results obtained using different optimization algorithms for the tested networks. It compares MDR among conventional PSS, BSA, PSO, DA, and AVOA-tuned PSS. It shows AVOA-tuned PSS provides 4.1 times, 2 times, 1.3 times, and 1.4 times larger minimum damping ratio than conventional PSS, PSO, BSA, and DA-tuned PSS, respectively. For the second network, the AVOA-based technique provides 6.2 times, 5.8 times, and 1.2 times larger minimum damping ratio compared to PSO, BSA, and DA-optimized methods for the same system configuration.

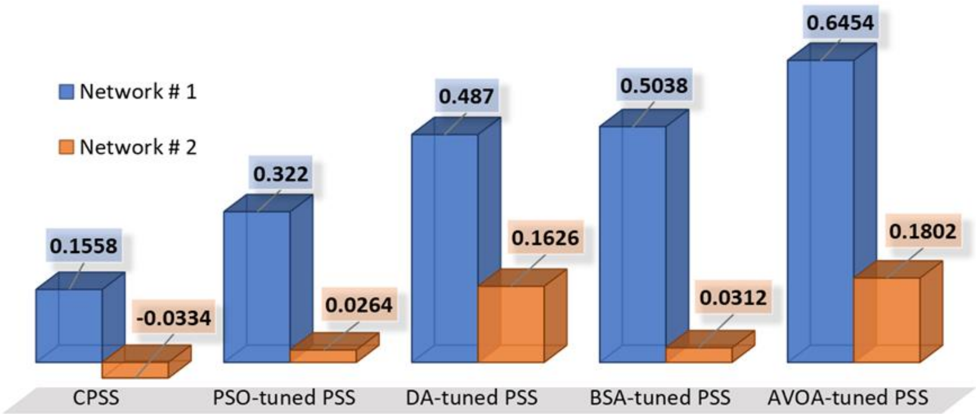

Figure 12 MDR comparisons for different optimization techniques for the tested networks.

6. Conclusions

Various disturbances continuously produce LFOs, thereby reducing the stability of the PSN. Synchronous generators and PSSs are combined to increase system stability. The African Vultures Optimization Algorithm, a novel optimization algorithm, is proposed in this paper as a new PSS design technique for the multimachine power system network. Two models of multimachine power systems with various system configurations are used to evaluate the recommended methodology. The technique's robustness in both situations is shown by its convergence occurring regardless of the initial assumption. Time-domain simulations of the rotor angle, angular frequency, and control signal demonstrate that the system can stabilize significantly more quickly with AVOA-tuned PSS than conventional PSS.

Additionally, investigating the damping ratio of two MMPS networks for the same system design demonstrates that the AVOA-based method offers a superior damping ratio than the PSO, BSA, and DA-optimized methodologies. AVOA-tuned PSS provides a higher minimum damping ratio than conventional PSS, PSO, BSA, and DA-tuned PSS for network-1 (two-area four-machine network) and network-2 (IEEE 39-bus network). The AVOA-based approach needs the fewest evaluations of objective functions to reach convergence. Time-domain simulations demonstrate that the recommended PSS designs considerably increase system stability after 3-φ fault introduction. The PSS uses pre-defined values rather than real-time optimization. Future research may explore the effectiveness of incorporating FACTS devices and renewable energy sources into the AVOA-based PSS design technique.

Additionally, further investigation into the algorithm's robustness in various system configurations and its ability to handle different disturbances can be explored. Furthermore, developing real-time optimization techniques for PSS designs can also be considered to improve the system's stability. Overall, continued research into PSS design techniques can lead to the development of more effective and efficient methods for enhancing the stability of the power system networks.

Nomenclature

$K_1 - K_6$	Fourth-order model constants
T'_{do}	Time constant of the open circuit field
T_1, T_2, T_3, T_4	Time constants for CPSS
K_C	Gain of the CPSS
T_E	Time constant for the excitation system
K_E	gain in the excitation system
T_w	Constant washout block time
v_{tr}, v_t	Reference and terminal voltages
v_q, v_d	Voltages of the quadrature and direct axes
i_q, i_d	Currents of the quadrature and direct axes
x'_q, x'_d	Transient reactance of the quadrature and direct axes
x_q, x_d	reactance of the quadrature and direct axes
ω_0	Base angular frequency
M	System inertia coefficient
∇E_{fd}	Field excitation
e'_q	Internal voltage of the generator
δ, ω	Rotor angle, Angular frequency
P_D	Damping Coefficient
u_{PSS}	Control input
P_e, P_m	Output electrical power and input mechanical power

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Author Contributions

Mohammad Forhad: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing—original draft preparation; **Mehedi Hasan Shakil:** Methodology, Resources, data curation, Software, Validation, Writing—original draft preparation; **Md. Rashidul Islam:** Methodology, Resources, Data curation, Investigation, Validation, Supervision, Writing—review and editing; **Muhammed Y. Worku:** Conceptualization, Resources, Formal analysis, Validation, Project administration, Writing—review and editing; **Md Shafiullah:** Conceptualization, Methodology, Resources, Data curation, Software, Supervision, Writing—review and editing.

Competing Interests

The authors have declared that no competing interests exist.

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