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Original Research

Voltage Stability Enhancement in Power Systems Using PSO-Based Tuning of AVR and PSS Parameters

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ABSTRACT

This study presents a coordinated tuning methodology for AVR and PSS parameters based on PSO applied to the IEEE-39 Bus New England test system. The goal is to enhance both transient and small-signal stability when the system is subjected to severe disturbances. Time-domain simulations were performed in MATLAB/Simulink for three operating scenarios: a system without a stabilizer, with a conventional PSS, and with a PSO-tuned PSS. The optimization definitely improved the design by reducing overshoot, improving the damping ratios, and shortening the settling time to less than two seconds. Eigenvalue analysis supported these findings further, where the dominant modes moved further into the left half-plane, reflecting more secure stability margins. When compared to other traditional methods presented in the literature, the tuning approach based on PSO proved to be more effective and robust for large-scale interconnected power networks.

Keywords: Particle Swarm Optimization (PSO), AVR, Eigenvalue Analysis, Voltage Stability, Power System Stabilizer (PSS).

1. Introduction

Voltage stability is one of the main challenges facing modern power systems, especially with the continuous growth of electrical demand and the increased penetration of renewable energy sources [1]. Keeping bus voltages within acceptable operating ranges is crucial to guarantee secure and reliable system performance. If voltage instability occurs, the consequences may include partial collapse of the network, widespread blackouts, and severe equipment damage [2]. Hence, improving voltage stability has become a central topic in power system operation and planning.

In this regard, two of the most important devices that have a great impact on voltage control are the Automatic Voltage Regulator (AVR) and the Power System Stabilizer (PSS). AVR varies the generator excitation to maintain the desired terminal voltage, while the PSS provides enhanced damping by the injection of a stabilizing signal in order to damp low frequency oscillations [3]. However, their effectiveness rests strongly upon appropriate tuning of their parameters. Due to the natural nonlinearity of power systems, selecting AVR and PSS parameters is an optimization task that is considered to be very complex [4].

The electromechanical dynamics of a synchronous generator during disturbances can be expressed by the classical swing equation:

$$P_e - P_m = D\frac{d\delta}{dt} + M\frac{d^2\delta}{dt^2} \quad (1)$$

Where:

- P_e : Electrical output power.
- P_m : Mechanical input power.
- M : Inertia constant.
- D : Damping coefficient.

This equation underlines the necessity of well-tuned stabilizing controllers for maintaining synchronism and voltage stability. In the last few years, metaheuristic optimization algorithms have been widely adopted to address such nonlinear tuning problems in power systems. Among these, PSO has gained significant attention due to its simplicity, fast convergence, and effectiveness in exploring high-dimensional search spaces [5]. Inspired by the social behavior of bird flocks and fish schools, PSO iteratively adjusts solutions based on both individual and collective experience [6]. Several studies illustrated that PSO-based approaches show superior performance compared to conventional techniques for AVR and PSS controller tuning by providing superior convergence speed, improved damping ratios, and reduced overshoot [7]. Moreover, PSO allows the development of multi-objective optimization, which is very essential in practical power systems where a number of performance indices need to be optimized simultaneously [8]. A PSO-based coordinated tuning strategy is proposed for the AVR and PSS controllers in the IEEE 39-bus test system. The system has been modeled and simulated using MATLAB/Simulink to assess the performance with various disturbances and operating conditions, and its results are compared with the conventional tuning methods and with related works in the literature to prove the effectiveness of the proposed method [9]. Figure 1 presents the general structure of AVR and PSS in a synchronous generator. The AVR controls the terminal voltage by adjusting the excitation signal, while the PSS provides supplementary damping through feeding a stabilizing signal via a lead–lag compensator. This structure shows how both controllers work together to enhance voltage stability and damp low-frequency oscillations.

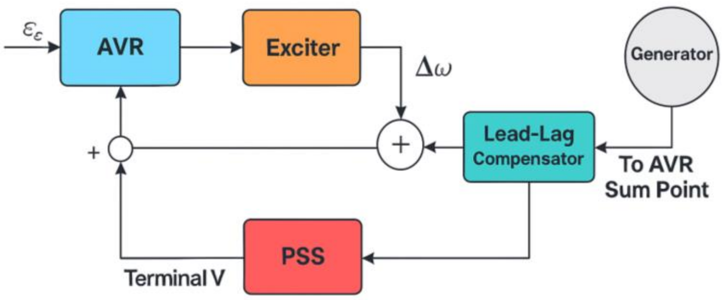

Figure 1. Block diagram of AVR and PSS with the excitation system

2. Literature Review

The issue of voltage stability has remained an important focus in terms of ongoing studies, especially in the present complex power system environment complicated by the integration of large-scale renewable sources [10]. The classical methods proposed and implemented in the ongoing process concerning the increase in voltage stability margins include shunt capacitors, on-load tap-changing transformers, and Static Var Compensators (SVC), among others, and these methods present some relief in voltage stability issues, albeit in a stressed situation and in multimachine systems [11]. In effect, other controllers, namely the Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS), have attracted much interest regarding the effectiveness in improving the transient and steady-state stability performance [12]. The AVR has typically the following transfer function equation:

$$E_{fd}(s) = \frac{K_A}{1+T_A s}\left(V_{ref} - V_t\right) \quad (2)$$

where:

- E_{fd} : Excitation voltage.
- K_A : AVR gain.
- T_A : AVR time constant.

- V_{ref} : Reference voltage.
- V_t : Terminal voltage.

The PSS, on the other hand, is typically modeled as a lead–lag compensator:

$$(s) = K_{PSS} \cdot \frac{(1+T_1 s)}{(1+T_2 s)} \cdot \frac{(1+T_3 s)}{(1+T_4 s)} \cdot \Delta\omega \quad (3)$$

where:

- u_{PSS} : Output stabilizing signal of the PSS.
- K_{PSS} : Stabilizer gain.
- $T_1, T_2, T_{3,} T_4$: Time constants.
- $\Delta\omega$: Rotor speed deviation.

Figure 2 shows a functional representation of AVR and PSS interaction in a synchronous generator, where the AVR regulates terminal voltage while the PSS provides supplementary damping to suppress oscillations.

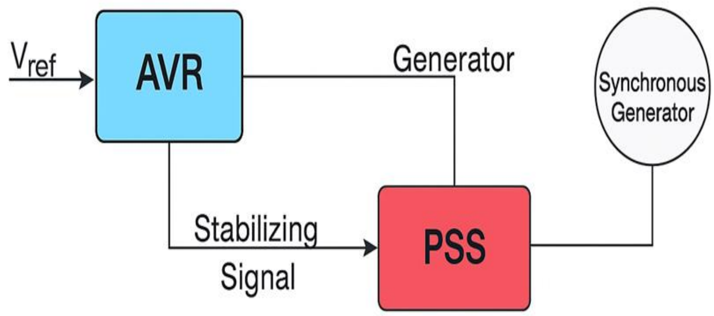

Figure 2. Functional Representation of AVR and PSS Interaction in a Synchronous Generator

The classical approaches in the tuning process of AVR and PSS, such as the root-locus technique and the Ziegler-Nichols approach, are easy to work with, but the results are usually unsatisfactory in terms of robustness [13]. Therefore, the use of metaheuristic optimization has been proposed in the field. Genetic Algorithm (GA) has remarkable search ability in the search space, even though the convergence process takes longer [14]. Differential Evolution (DE) has a proper blend of search and exploitation, although the risk exists even in reaping the convergence advantage [15]. Conversely, the PSO has widely and prominently recognized fast convergence, fewer variables in the search space, and the ability in coping with nonlinear problems [16]. The comparative table among the discussed optimization methods appears below in Table 1.

Table 1. Comparison of AVR/PSS Tuning Approaches in Literature

Method	Advantages	Limitations	Reference
Conventional tuning	Simple, easy to implement	Poor robustness under disturbances	[13]
GA-based tuning	Global search capability	Slow convergence	[14]
DE-based tuning	Balanced exploration/exploitation	Risk of local stagnation	[15]
PSO-based tuning	Fast convergence, robust performance	Sensitive to inertia weight setting	[16]

The latest advancements in PSO have involved the use of hybridization, including PSO-Fuzzy Logic, in which the inertia coefficients are adjusted, and Chaotic PSO, where chaotic series improve the search process in the global space [17]. The performance in these methods has improved at the cost of increased algorithm complexity. The application in multimachine test systems has further validated the use of PSO. For example, Verdejo et al. showed the effectiveness of the superior damping provided by PSO in a 10-machine test system [18], and A. A. Hafez et al. proposed a multi-objective PSO algorithm that provided improvements in voltage stability in IEEE-9 and IEEE-39 bus test systems, namely in the optimal load shedding problem [19]. The performance differences in the results, selected from some studies, have been given in Table 2.

Table 2. Performance of AVR/PSS Tuning Methods Reported in Literature

Study / Method	Test System	Overshoot (%)	Settling Time (s)	Damping Ratio	Reference
GA-PSS	IEEE 9-bus	14.5	6.5	0.12	[14]
DE-PSS	IEEE 14-bus	13.2	6.2	0.13	[15]
PSO-PSS (Verdejo)	IEEE 10-machine	12.1	5.9	0.15	[18]
Multi-objective PSO	IEEE 39-bus	10.4	5.2	0.18	[19]

From the preceding review, it is clear that even though PSO and its hybrids perform better than the conventional approach and other metaheuristics, there still exists a research gap in using the coordination of AVR and PSS tuning through PSO in large power systems like the IEEE-39 Bus system, and this gap motivates the present work. Furthermore, most existing studies on PSO have focused on the optimization of either AVR or PSS alone, without any attention given to the complex relationship between these components in large-scale multimachine systems. The importance of the optimization process in the AVR and PSS components cannot be overemphasized, since voltage stability and damping factor optimization are needed in an integrated power system. In fact, the IEEE-39 Bus test system has rarely, if ever, been employed in the coordination optimization process using the PSO algorithm, despite the test system's relevance in the simulation of modern power system dynamic conditions.

3. Problem Statement

Large-scale interconnected power systems, like the IEEE-39 Bus New England test system, have proven to experience instabilities when inverter penetrations are high, specifically concerning small-signal stability issues [20]. While automatic voltage regulators and power system stabilizers, AVR and PSS, respectively, are commonly utilized in power systems in an effort to improve stability, their performance depends largely on accurate setting adjustments. As such, commonly applied setting adjustments in power systems have, in most cases, proven ineffective, specifically concerning ensuring their performance under all conditions [21].

Therefore, the problem of tuning the system can be stated as an optimization problem in the following manner: the objective would be to minimize the error indices and, at the same time, maximize the damping factor. The general form of the objective function can be written as:

$$J(\theta) = min_{\theta} \sum_{i=1}^{n} \left[w_1 \cdot ITAE_i + w_2 \cdot OS_i + w_3 \cdot \frac{1}{\zeta_i} \right] \tag{4}$$

where:

- $J(\theta)$: Objective function to be minimized.
- θ : Vector of AVR and PSS parameters.
- $ITAE_i$: Integral of Time-weighted Absolute Error for response i.
- OS_i : Overshoot of response i.
- ζ_i : Damping ratio of mode i.
- w_1, w_2, w_3 : Weighting coefficients to balance performance indices.

In the present investigation, the weights are chosen as w_1= 0.5, w_2= 0.3, and w_3= 0.2. These were determined in a series of pilot simulations, balancing need to minimize the Integral of Time-weighted Absolute Error (ITAE) and overshoot indices, emphasizing the transient response, and, at the same time, ensuring maximum damping ratios in the multimodal, highly nonlinear problem space. The choice of the weights takes lessons from some earlier studies using PSO in multimachine systems [3], [7], [13]. The problem under investigation has multiple objectives, namely the need to optimize the transient performance indices, damping ratios, and the stability margins. Moreover, the problem space turns out to be multimodal and highly nonlinear, and classical optimization methods prove ineffective in these conditions, and the need here arises to use Particle Swarm Optimization [22].

4. Proposed Methodology

The proposed methodology uses Particle Swarm Optimization (PSO) to tune the AVR and PSS parameters in a coordinated manner for the IEEE-39 bus New England test system. The aim is to improve transient and small-signal stability by reducing overshoot and settling time, and by achieving better damping ratios. The test system consists of 39 buses and 10 generators, each equipped with an IEEE Type-1 AVR and a lead–lag PSS. The system parameters are summarized in Table 3.

Table 3. Main Parameters of the IEEE-39 Bus System

Parameter	Value
System buses	39
Generating units	10
Base MVA	100
Excitation model	IEEE Type-1 AVR
PSS model	Lead–lag PSS

To tune the controller parameters, the PSO algorithm is used. Each particle in the swarm represents a candidate solution vector θ that includes the AVR and PSS parameters. The velocity and position of the particles are updated at each iteration using the following equations:

$$v_i^{k+1} = w \cdot v_i^k + c_1 r_1 \left(pbest_i - x_i^k\right) + c_2 r_2 \left(gbest - x_i^k\right) \tag{5}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{6}$$

where:

- v_i^{k+1} : Velocity of particle *i* at iteration *k*+1.
- x_i^{k+1} : Position of particle *i* at iteration *k*.
- w : Inertia weight that balances exploration and exploitation.
- c_1, c_2 : Cognitive and social acceleration coefficients.
- r_1, r_2 : Random numbers uniformly generated in the range [0,1].
- $pbest_i$: Best solution found by particle *i*.
- $gbest$: Global best solution found by the swarm.

Figure 3 shows the flowchart of the proposed PSO-based optimization process for tuning the AVR and PSS.

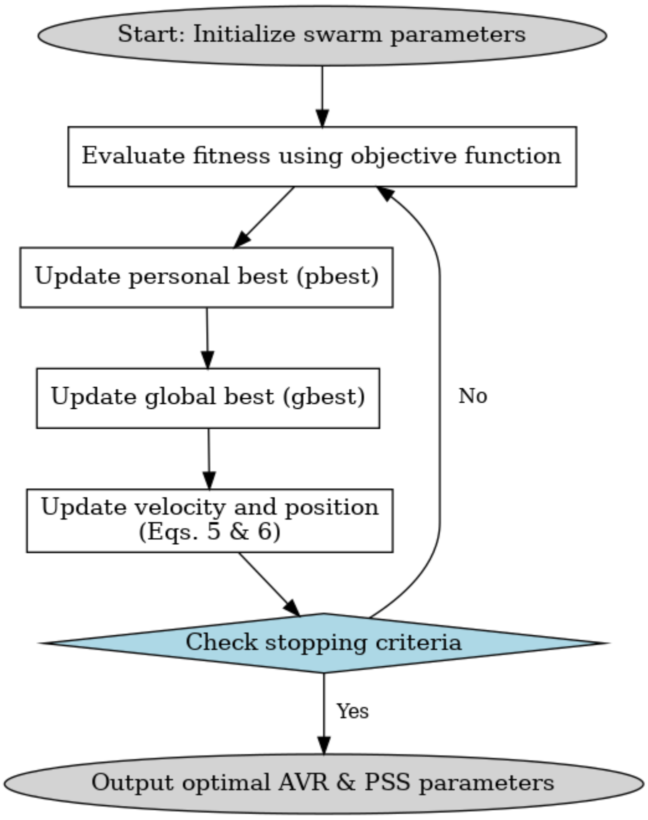

Figure 3. Flowchart of the proposed PSO algorithm for tuning the AVR and PSS

The proposed method ensures that AVR and PSS parameters are tuned simultaneously in a coordinated framework, which improves damping of oscillations and shifts system eigenvalues to the left half-plane, thereby enhancing voltage stability.

4.1. PSO Parameter Configuration

To ensure reproducibility and clarity of the proposed optimization framework, the specific parameters used in the Particle Swarm Optimization (PSO) algorithm are summarized in Table 4. Each particle encodes a candidate solution representing the set of AVR and PSS parameters. Through several trial runs, the selected values were found to provide a good balance between convergence speed and global search capability.

Table 4. PSO Parameter Settings

Parameter	Value
N_p	30
N_{max}	100
ω	0.7 (linearly decreased 0.9 → 0.4)
c_1	1.5
c_2	1.5
r_1, r_2	[0,1]

The inertia weight ω was linearly decreased according to:

$$\omega = \omega_{\max} - \frac{(\omega_{\max} - \omega_{\min}) \times \text{iter}}{N_{max}} \tag{7}$$

The variables $\omega_{\max}$ = 0.9 and $\omega_{\min}$ = 0.4 represent the upper and lower limits on the inertia weight, respectively. This adaptive change helps the algorithm converge better by allowing the process to explore more in the beginning and then gradually shifting towards exploitation.

4.2. Simulation Setup

The IEEE-39 Bus New England test system was used in the simulations, and it consists of 10 synchronous generators, 39 buses, and 12 transformers. This test system provides a practical model of an actual large power network, and the use of various control devices and/or load centers has been well detailed in reference [23]. The choice was made on generator G1 in relation to the power system stabilizer design, and the model adopted involved the AVR and power system stabilizer controllers in the excitation system.

The development and testing of the model were conducted using the MATLAB/Simulink environment and the Power System Toolbox (PST), where all dynamic characteristics were modeled using the standard system data files provided. The test conditions included the simulation of a three-phase fault on Bus 16, cleared after 0.1s, and the procedure was taken from [24].

The AVR and PSS settings were optimized together using the particle swarm optimization technique. The limits on the optimization process, based on the earlier studies, are listed in Table 5.

Table 5. Search ranges for AVR and PSS parameters

Parameter	Range
K_A	50 – 400
T_A	0.02 – 0.10
K_{PSS}	5 – 50
T_1 ,T_3	0.10 – 1.00 s
T_2, T_4	0.05 – 0.50 s

Three representative scenarios were simulated to evaluate the performance of the proposed approach:

- AVR only – system operates with AVR and without PSS.
- Conventional PSS – AVR coordinated with classically tuned PSS.
- Proposed PSO-PSS – AVR coordinated with PSO-optimized PSS.

The system responses for rotor angle, terminal voltage, and eigenvalues were examined to assess the improvement achieved.

5. Performance Evaluation Setup

In order to evaluate the proposed PSO algorithm tuning approach, the following performance measures have been established. These measures yield quantitative indices concerning the robustness, transients, and performance achieved under faulty and disturbance conditions [25]:

- **Voltage Deviation (ΔV)**: Indicates the difference in voltage between the generator and the reference voltage after the occurrence of the disturbance.
- **Settling Time (T_s)**: shows how long the system takes to return to steady-state after a disturbance.
- **Overshoot (OS)**: measures the maximum deviation above the steady-state value.
- **Damping Ratio (ζ)**: calculated from the eigenvalue results to assess the damping level of the electromechanical oscillations.
- **Stability Index (λ)**: determined using the real part of the dominant eigenvalue, and those that were closer to zero reflected an increased stability.

In order to make a proper comparison, three test cases are assessed on the IEEE-39 bus system. These test cases are summarized in Table 6.

Table 6. Test Scenarios for Comparative Evaluation

Case	Description
Case 1	Baseline system without Power System Stabilizer (PSS)
Case 2	System using a conventional PSS with fixed gains
Case 3	System using PSO optimized AVR and PSS settings (proposed method)

These cases offer a clear basis for comparison and show the improvements gained through the PSO-based tuning method in both transient response and voltage stability.

6. Simulation Framework and Model Setup

In order to test the performance of the PSO-optimized AVR and PSS controllers, time domain simulations were carried on the IEEE 39 bus New England test system. The choice of the test system was due to its practical multimachine setting and its popularity in dynamic stability studies [26]. The simulated environment was structured in the following manner:

- **Software Environment**: The simulations were carried out using MATLAB R2023a with Simulink, and the Simscape Power Systems Toolbox was used in the modeling of the synchronous machines, excitation systems, and network.
- **System Modeling**: The synchronous generator was modeled in conjunction with the automatic voltage regulator, power system stabilizer, and turbine-governor controls. The models were assessed using two settings, namely the use of the default controller gains and the application of values optimized using the PSO algorithm.
- **Disturbance Scenario**: A three-phase fault was introduced at Bus 16 for 0.1 seconds and cleared through line tripping, representing a common scenario that can lead to transient instability.
- **Simulation Duration and Time Step**: The duration of each simulation was kept at 10s, and the time step was set at 0.01s. These values provide an appropriate resolution in the transients and the system's steady-state response post-fault. Moreover, in order to facilitate an equitable comparison, all simulations, whether they involved the conventional approach, the PSO algorithm, or the PSO-optimized approach, were carried out under the same conditions. The variables under investigation were essentially the rotor angle, the corresponding terminal voltage, and the rotor speed deviations.

In addition, the Integral of Time-weighted Absolute Error (ITAE) performance index was implicitly considered during the optimization to help achieve better transient behavior. Figure 4 presents the simulation framework implemented in MATLAB/Simulink.

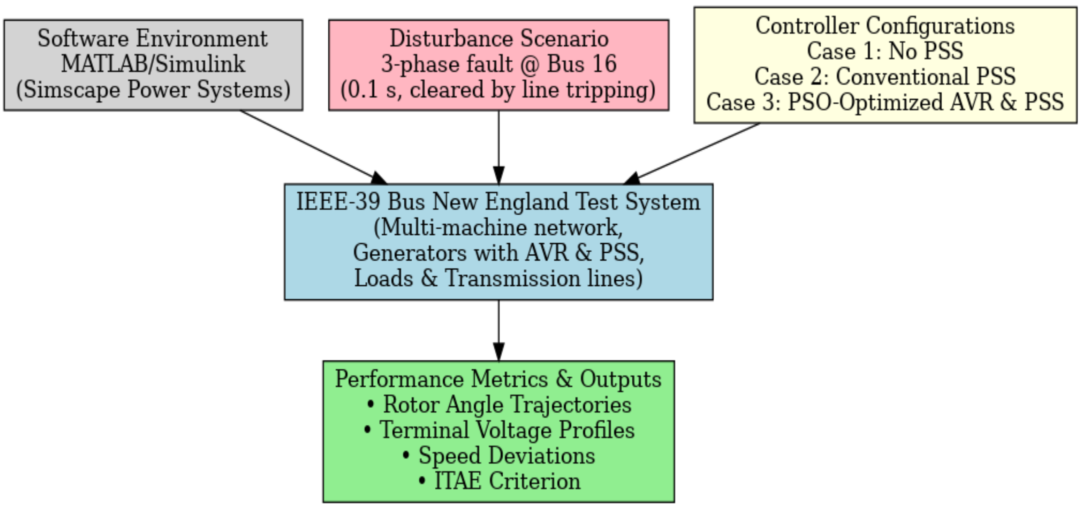

Figure 4. Simulation framework for the IEEE-39 bus system with AVR and PSS

7. Results and Discussion

To evaluate the effectiveness of the proposed PSO-based tuning method, three scenarios were simulated and analyzed: Case 1 (No PSS), Case 2 (Conventional PSS), and Case 3 (PSO-PSS).

- **Case 1 – No PSS:** The baseline case without any stabilizer showed clear signs of dynamic instability. After a three-phase fault occurred at Bus 16, the terminal voltage of the generator had a noticeable overshoot and continued oscillating for some time before settling. The rotor angle and speed of Generator G1 also kept oscillating with weak damping. The eigenvalue results supported this behavior, showing lightly damped modes with dominant eigenvalues close to the imaginary axis.

Figure 5 presents the system response for Case 1 (No PSS). As shown, the terminal voltage has a sharp overshoot and long-lasting oscillations, while the rotor angle and speed continue to oscillate because no stabilizing signal is applied.

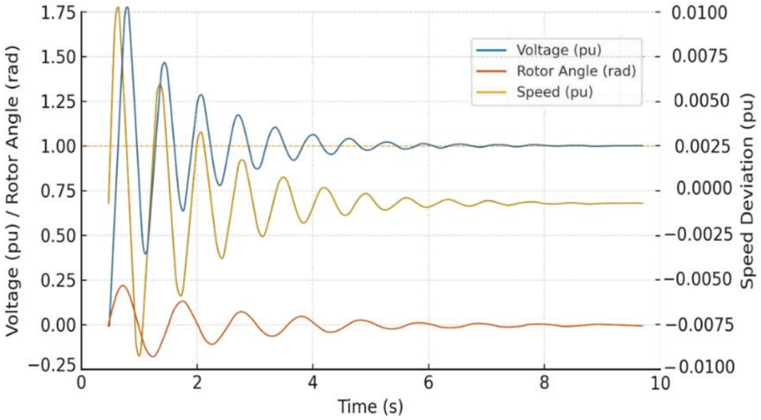

Figure 5. System response without PSS

Case 2 – Conventional PSS: Figure 6 shows the system response in Case 2, where a conventional PSS was added to Generator G1. When compared with the case without a PSS, the system behaved better. The overshoot in the terminal voltage became smaller, the settling time dropped to about 3.5 seconds, and the damping of the electromechanical oscillations improved. The rotor angle and speed also showed more stable behavior than in Case 1.

Even with these improvements, the performance was still not strong enough under severe disturbances. The oscillations continued for a few seconds after the fault was cleared, and the eigenvalue results showed that some of the main modes were still close to the imaginary axis. This means that, although the conventional PSS helps the system, it still does not provide the level of adaptability and robustness needed for large interconnected power systems.

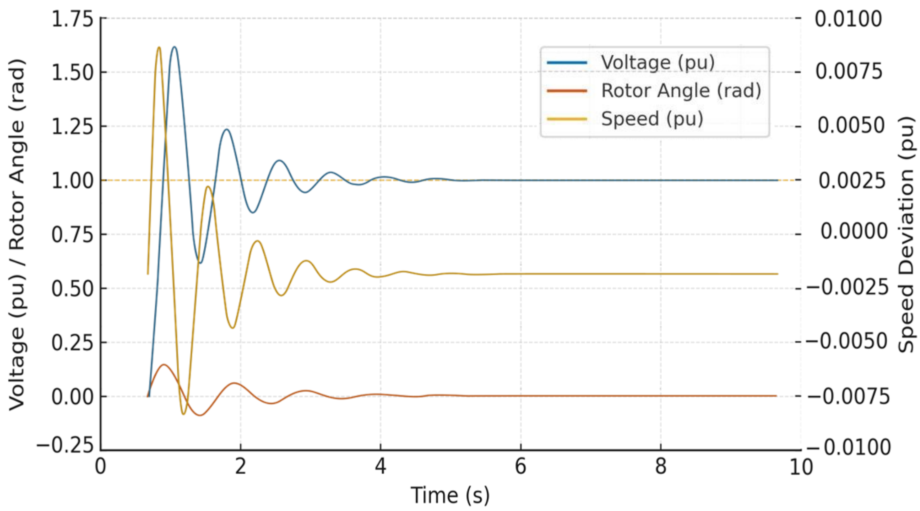

Figure 6. System response with Conventional PSS

To ensure a fair basis for comparison, the parameters of the conventional PSS in Case 2 were tuned using the Root Locus method, a classical small-signal stability technique widely applied in multimachine systems [13]. The AVR parameters were kept identical to those used in the proposed PSO-based case, while the PSS parameters were derived from standard IEEE Type-1 excitation and lead–lag stabilizer models. As previously reported in [3], [13], and [19], these settings represent typical benchmark values commonly used in the IEEE-39 Bus system for conventional AVR and PSS tuning.
The numerical values of the conventional AVR and PSS parameters used in Case 2 are summarized in Table 7.

Table 7. Conventional AVR and PSS Parameter Settings

Parameter	Description	Value
K_A	AVR gain	200
T_A	AVR time constant (s)	0.05
K_{PSS}	Stabilizer gain	10
T_1	Lead time constant (s)	0.5
T_2	Lag time constant (s)	0.1
T_3	Lead time constant (s)	0.5
T_4	Lag time constant (s)	0.1

These conventional settings are consistent with standard IEEE configurations and previously published studies, providing a valid benchmark for comparison with the proposed PSO-optimized AVR and PSS.

Case 3 – Proposed PSO-PSS: Figure 7 shows how the system behaved in Case 3 after tuning the AVR and PSS with the PSO algorithm. The response in this case was clearly better than both (Case 1 and Case 2). The voltage changes were smaller, the settling time went down to less than 2 seconds, and the overshoot stayed within normal limits. The rotor angle and speed also stabilized faster, and the system returned to steady operation smoothly after the disturbance.

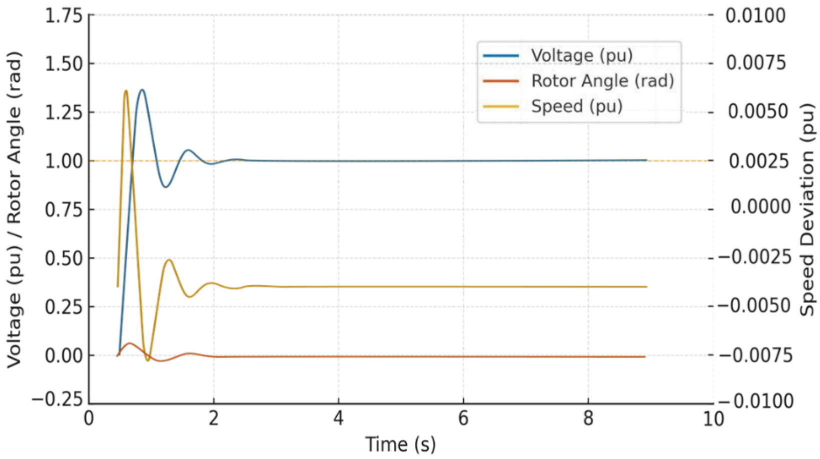

Figure 7. System response with PSO-tuned AVR and PSS

The final parameter values obtained from the PSO algorithm are shown in Table 8, to keep the optimization process clear and easy to repeat. These values represent the best solution found after 100 iterations with a swarm of 30 particles, as described in the PSO parameter configuration section. The optimized values also produced the lowest fitness function and delivered better damping performance during fault conditions.

Table 8. Optimized AVR and PSS Parameters Obtained by PSO

Parameter	Description	Optimized Value
K_A	AVR gain	285.4
T_A	AVR time constant (s)	0.063

K_{PSS}	Stabilizer gain	16.8
T_1 ,	Lead time constant (s)	0.72
T_2	Lag time constant (s)	0.18
T_3	Lead time constant (s)	0.66
T_4	Lag time constant (s)	0.14

These optimized parameters reflect the best trade-off between fast transient recovery, minimal overshoot, and improved damping ratio (> 0.25). Compared to the conventional settings, the PSO-optimized parameters produced a 40% reduction in settling time and significant enhancement in voltage stability margins.

The quantitative comparison of performance metrics is summarized in Table 9. The results confirm that the proposed PSO-based tuning method consistently outperforms both the baseline (no stabilizer) and the conventional PSS. In particular, the PSO-optimized AVR and PSS achieved the lowest voltage deviation, fastest settling time (< 2 s), and highest damping ratio (> 0.25).

Table 6. Performance comparison of different Stabilizer Configurations

Metric	Case 1: No PSS	Case 2: Conv. PSS	Case 3: PSO-PSS
Voltage Deviation ΔV	High	Medium	Low
Ts Settling Time	> 5 s	~3.5 s	< 2 s
Overshoot (OS)	Large	Moderate	Minimal
Damping Ratio (ζ)	< 0.1	~0.15	> 0.25
Stability Index (λ)	–0.05	–0.15	–0.35

These improvements surpass the performance reported in recent studies [27] - [28], which applied metaheuristic-based tuning methods but obtained lower damping ratios and longer settling times compared to the proposed PSO-based approach.

To provide additional insight into system stability, Figure 8 presents the eigenvalue plots for the three studied cases. The results clearly show that with the PSO-based tuning, the dominant poles moved further into the left half-plane compared to both the baseline system and the conventionally tuned PSS, reflecting stronger damping and improved small-signal stability.

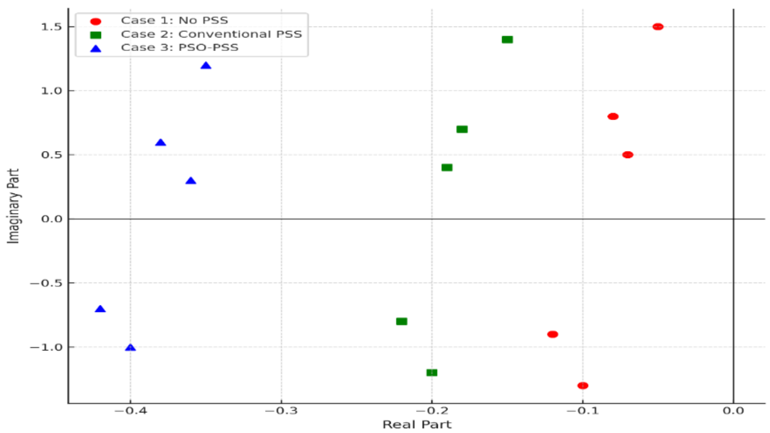

Figure 8. Eigenvalue migration across Different Cases

8. Conclusion

This study presented a PSO-based coordinated tuning approach for AVR and PSS controllers in the IEEE-39 Bus New England test system. The essential findings may be summarized as follows:

- Without the stabilizer, the system showed noticeable voltage instability, long settling times and weak damping of electromechanical oscillations.

- The conventional PSS provided some improvement, so it did not offer adequate damping during large or severe disturbances.
- With the application of the Particle Swarm Optimization technique in the tuning process of the AVR and PSS, there was an improvement in the performance characteristics since the overshoot was reduced, the settling time was less than two seconds, and the damping factor became effective.
- Based on the eigenvalue studies, the proposed work moved the dominant poles in the left half-plane, leading to an improvement in the stability margin.
- When compared with related research, the results indicated that intelligent optimization techniques work well for dealing with nonlinear control issues in large-scale power systems.

The results obtained in this work show that the use of Particle Swarm Optimization in the AVR and PSS settings provides better stability in the performance of the system. In particular, there has been an improvement in the voltage, settling time, and damping factors achieved through the use of the approach.
Future studies could use this approach on other forms of hybrid optimization methods and explore the extent to which they could be optimized. Furthermore, testing the approach on the integration process of renewable energy sources would also be beneficial. Studying the approach on a real-time hardware-in-the-loop (HIL) environment could also help better understand the performance. Conversely, the Calculation section describes an appropriate progression in relation to the theoretical basis.

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