Transient Stability Enhancement of Single-Machine Infinite Bus System Using Hybrid PSS Design with Particle Swarm Optimization

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***Abstract*—Power system stability is critical for reliable grid operation. This paper presents a two-stage hybrid design method for Power System Stabilizers (PSS) to improve transient stability in Single-Machine Infinite Bus (SMIB) systems. The first stage uses analytical phase compensation to design an initial PSS that ensures system stability. The second stage applies Particle Swarm Optimization (PSO) to fine-tune the PSS parameters for optimal performance. The method was tested on a 900 MVA generator system under severe fault conditions. Results show that the optimized PSS reduces settling time by 9.83% and decreases the Integral of Time-weighted Absolute Error (ITAE) by 47.98% compared to the analytical design. The hybrid approach combines the reliability of classical control theory with the performance benefits of modern optimization, making it suitable for practical power system applications.**

***Index Terms*—particle swarm optimization, phase compensation, power system stabilizer, single-machine infinite bus, transient stability**

I. Introduction

POWER system stability is essential for maintaining reliable electricity supply [1]. Modern power systems are complex interconnected networks that have grown in complexity over the years. This complexity is further intensified by the integration of new technologies and increasing penetration of renewable energy sources [1]. When a fault occurs in the power grid, generators can experience large oscillations in rotor angle and speed. If these oscillations are not properly damped, the generator may lose synchronism with the grid, leading to blackouts. This problem, known as transient instability, poses a serious threat to power system operation [2].

Power System Stabilizers (PSS) are widely used to improve system damping and prevent instability [3]. A PSS works by adding a supplementary signal to the generator's excitation system. This signal provides positive damping torque to suppress electromechanical oscillations. The effectiveness of a PSS depends heavily on proper parameter tuning [4].

Traditional PSS design methods use analytical techniques based on linearized system models. The phase compensation method is a popular classical approach that designs PSS parameters to provide adequate phase lead at the oscillation frequency [5]. While this method is reliable and well-understood, it may not achieve optimal performance because it relies on simplified linear models and does not account for the full nonlinear system dynamics [1].

Recent research has explored using optimization algorithms to improve PSS design. Genetic Algorithms (GA) have been applied to PSS tuning with promising results [6], [7]. Particle Swarm Optimization (PSO) has emerged as an effective alternative due to its simple implementation and good convergence properties [8]. Other methods include Marine Predator Algorithm [9], Gorilla Troops Optimization [10], and Whale Optimization Algorithm [11]. These algorithms can optimize performance by evaluating the full nonlinear system response. However, pure optimization approaches may face convergence difficulties without a good initial starting point [6].

This paper proposes a hybrid two-stage design methodology that combines the strengths of both approaches. Stage 1 uses analytical phase compensation to design an initial PSS that guarantees stability. Stage 2 applies PSO to optimize the PSS parameters for minimum settling time and error. This hybrid approach provides both reliability and optimal performance.

The main contributions of this work are:

- A practical two-stage hybrid PSS design method combining analytical and optimization techniques
- Comprehensive validation using high-precision numerical simulation of a realistic SMIB system
- Detailed performance analysis showing significant improvements in settling time and ITAE
- Complete implementation of the optimization algorithm in MATLAB, validated against the Simulink system model

The paper is organized as follows. Section II reviews related work. Section III describes the SMIB system model. Section IV presents the hybrid PSS design methodology. Section V shows simulation results and analysis. Section VI concludes the paper.

II. Related Work

Power system stability has been studied extensively. In this work, the Single-Machine Infinite Bus (SMIB) configuration is deliberately selected as the validation benchmark. While multi-machine systems capture wider inter-area dynamics, the SMIB system effectively isolates the generator's local electromechanical oscillation mode, allowing for a precise, unadulterated evaluation of the proposed controller's intrinsic damping capability [12], [13]. Furthermore, the infinite bus connection represents a 'stiff' grid scenario, providing a rigorous stress test for verifying transient stability limits. Establishing the controller's superiority on this fundamental model is a critical prerequisite commonly accepted in literature before generalization to multi-machine networks [12].

Classical PSS design methods include frequency response techniques, root locus analysis, and phase compensation [3]. These methods are based on linearized models and use control theory principles to design stabilizer parameters. The phase compensation method, in particular, has been widely adopted in industry due to its simplicity and reliability [5]. However, these analytical methods may not achieve optimal performance under all operating conditions [1].

Modern optimization-based approaches have gained attention in recent years. Genetic Algorithms have been applied to PSS tuning with promising results [6], [7]. PSO has emerged as an effective alternative due to its simple implementation and good convergence properties [8]. Other metaheuristic methods include Marine Predator Algorithm [9], Gorilla Troops Optimization [10], and Whale Optimization Algorithm [11]. These methods have demonstrated great success in finding robust parameter sets [1].

Some researchers have proposed hybrid approaches combining different techniques. For example, combining PSS with FACTS devices such as TCSC has been studied [14]. Coordinated tuning of PSS and SVC using optimization has also been investigated [15], [11]. Advanced controller structures like Fractional-Order PID (FOPID) controllers optimized with modern algorithms have shown promise [15]. Nonlinear excitation controllers have also been explored to improve transient stability [16].

Other approaches include using series vectorial compensators [17] and SVC devices for small-signal stability improvement [18]. Advanced PSS designs for transient analysis have been proposed [19]. However, there is limited work on systematically combining analytical phase compensation design with PSO optimization for PSS parameter tuning in a structured two-stage hybrid methodology.

This paper fills this gap by proposing a structured two-stage hybrid methodology. The analytical stage provides a reliable initial design, while the optimization stage achieves superior performance. This approach is practical and suitable for real-world applications.

III. System Model

A. SMIB System Description

The SMIB system consists of a synchronous generator connected to an infinite bus through a transmission network. The infinite bus represents a very large and powerful grid, which is assumed to have a constant voltage and frequency, regardless of the power being supplied or absorbed by the single generator [6]. The generator is represented by a fourth-order model including rotor angle dynamics, rotor speed, transient EMF, and field voltage. The excitation system uses a first-order Automatic Voltage Regulator (AVR) model. The PSS provides a supplementary signal to the AVR.

The behavior of a synchronous generator following a disturbance is governed by the swing equation, which describes the dynamic relationship between mechanical and electrical power [13]. Under steady-state conditions, the mechanical torque supplied by the prime mover is equal to the electromagnetic torque demanded by the electrical load, and the rotor spins at a constant synchronous speed. When a fault occurs, this balance is disrupted, causing the rotor to accelerate or decelerate.

The complete system setup is visualized in Fig. 1, which clearly illustrates the interaction between the synchronous machine, the excitation system, and the proposed PSS.

B. Mathematical Model

The generator dynamics are described by the swing equation and related differential equations. The simplified swing equation, which includes damping, can be written as [13]:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e - D\Delta\omega. \quad (1)$$

where H is the inertia constant (s), ω_s is the synchronous angular speed (rad/s), δ is the rotor angle (rad), P_m is the mechanical power (pu), P_e is the electrical power (pu), and D is the damping coefficient (pu).

The complete fourth-order model includes the following state equations:

$$\frac{d\delta}{dt} = \omega_s\Delta\omega, \quad (2)$$

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(P_m - P_e - D\Delta\omega), \quad (3)$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}(E_{fd} - E'_q - (X_d - X'_d)I_d), \quad (4)$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}(K_A(V_{ref} + V_{stab} - V_t) - E_{fd}), \quad (5)$$

where δ is the rotor angle, $\Delta\omega$ is the speed deviation, E'_q is the transient EMF, E_{fd} is the field voltage, P_m is the mechanical power, P_e is the electrical power, V_t is the terminal voltage, and V_{stab} is the PSS output.

The electrical power is calculated as:

$$P_e = V_d I_d + V_q I_q. \quad (6)$$

where the d-q axis voltages and currents depend on the system reactances and the infinite bus voltage. The change in electrical torque can be resolved into synchronizing and damping components [2]:

$$\Delta T_e = K_s\Delta\delta + K_d\Delta\omega. \quad (7)$$

where K_s is the synchronizing torque coefficient and K_d is the damping torque coefficient. For stable operation, the damping coefficient must be positive.

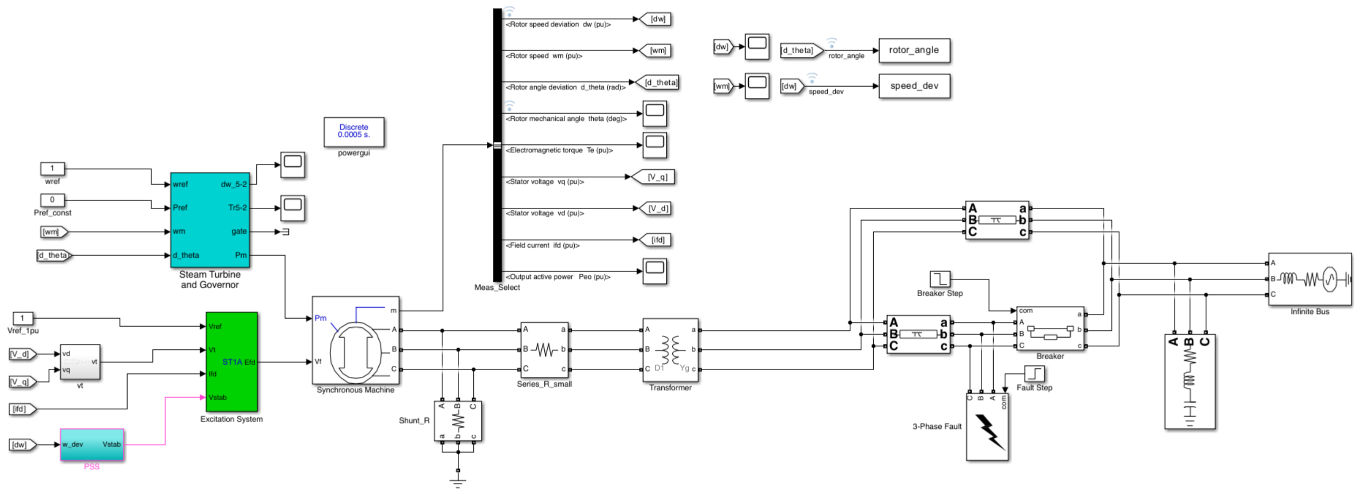

Fig. 1. Simulink model of the Single-Machine Infinite Bus (SMIB) system showing the synchronous generator, excitation system, PSS, transmission network, and measurement blocks.

C. PSS Structure

The most common type of PSS is the conventional lead-lag PSS, often referred to as CPSS or IEEE PSS1A/1B type [4]. The PSS consists of three main blocks: a gain block, a washout filter, and two lead-lag compensators. The transfer function is:

$$G_{PSS}(s) = K_{pss}\frac{sT_w}{1+sT_w}\frac{1+sT_1}{1+sT_2}\frac{1+sT_3}{1+sT_4}. \tag{8}$$

The components are: (1) Gain block (K_{pss}) which determines the overall magnitude of damping provided by the PSS; (2) Washout block with time constant T_w that ensures the PSS responds only to speed oscillations, filtering out steady-state changes and preventing interference with the AVR's voltage regulation function [20]; (3) Phase compensation blocks with time constants T_1, T_2, T_3, T_4 that provide phase lead to cancel out the system lag over the typical frequency range of electromechanical oscillations (0.2 Hz to 2.5 Hz) [4]. The PSS input is the rotor speed deviation $\Delta\omega$, and its output V_{stab} is added to the AVR reference to create damping torque in phase with speed deviation [2].

D. System Parameters

The system parameters are based on a realistic 900 MVA generator, which is a standard benchmark used extensively in power system stability studies [6]. The parameters are summarized as follows:

- Generator: $H = 3.5$ s, $D = 2.0$ pu, $X_d = 1.81$ pu, $X'_d = 0.3$ pu, $T'_{do} = 8.0$ s
- AVR: $K_A = 200, T_A = 0.02$ s (IEEE Type ST1A model)
- Network: $X_T = 0.12$ pu, $X_L = 0.93$ pu (two parallel lines), Frequency $f = 60$ Hz
- Operating point: $P_m = 0.9$ pu (90% loading), $V_t = 1.0$ pu, initial rotor angle $\delta_0 = 53.13°$

The natural damping coefficient D = 2.0 pu represents typical mechanical and electrical damping in synchronous generators [13]. The 90% loading condition represents a realistic and secure operating state with adequate stability margin [6].

IV. Hybrid PSS Design Methodology

A. Overview

The proposed hybrid design method consists of two stages, combining the analytical rigor of classical control theory with the comprehensive search capabilities of modern optimization algorithms [1]. Fig. 2 illustrates the complete workflow of the hybrid PSS design and optimization process.

The workflow begins with building and validating the SMIB model in Simulink. Stage 1 involves analytical design using the phase compensation method based on the linearized Heffron-Phillips model to design initial PSS parameters [20], [5]. This provides a systematic, analytical way to calculate an excellent set of initial PSS parameters that guarantee system stability [5]. This stage establishes a strong theoretical foundation for the controller.

Stage 2 involves PSO optimization to perform fine-tuning of the parameters obtained in the first stage [8]. The optimization process uses the full nonlinear system model to search for a near-global optimal set of parameters that minimizes the ITAE objective function [8]. This stage ensures the PSS performs optimally under the large-signal disturbances associated with transient stability, overcoming the limitations of linearization.

Stage 3 involves validation through comparative simulations of the system without PSS, with the analytically designed PSS, and with the PSO-optimized PSS. The results are analyzed to quantify the performance improvement achieved by the optimized PSS.

This two-stage approach combines the reliability of analytical methods with the performance benefits of optimization [1]. The hybrid approach leverages the strengths of both methods: the analytical insight of the classical technique and the superior performance achieved through automated, nonlinear optimization [8], [1].

B. Stage 1: Analytical Phase Compensation Design

The phase compensation method is a systematic and robust technique based on linearizing the power system model to directly calculate the required phase lead [1]. This method

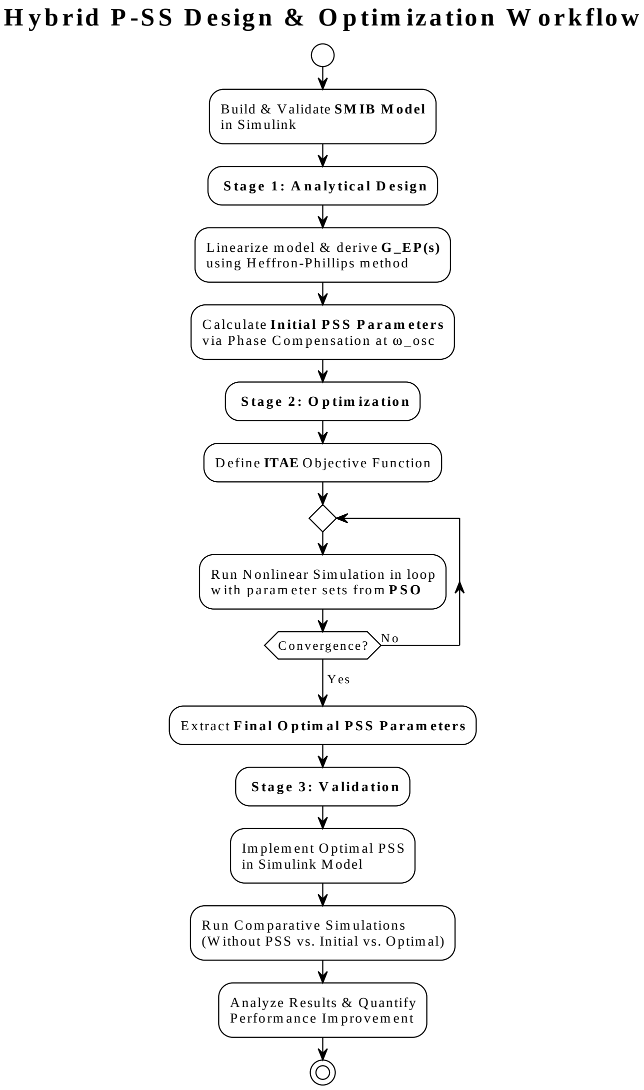

Fig. 2. Hybrid PSS design and optimization workflow showing the three-stage process: analytical design, PSO optimization, and validation.

designs the PSS to provide adequate phase lead at the oscillation frequency. The design process uses the Heffron-Phillips model, which linearizes the nonlinear system equations around a specific pre-fault operating point [20].

The plant to be controlled by the PSS is the system from the AVR reference input to the electrical torque output, represented by the transfer function $G_{EP}(s)$. The core principle is to design the PSS transfer function $G_{PSS}(s)$ to provide a phase lead that cancels the phase lag of the plant at the natural frequency of oscillation, ω_{osc} [5]. The design criterion is:

$$\angle G_{PSS}(j\omega_{osc}) = -\angle G_{EP}(j\omega_{osc}). \tag{9}$$

The steps are:

Step 1: Linearize the system around the operating point to obtain the state-space model and calculate the Heffron-Phillips K-constants.

Step 2: Calculate the system eigenvalues and identify the electromechanical oscillation mode frequency ω_{osc}.

Step 3: Determine the required phase compensation ϕ_{comp} to achieve the target damping ratio $\zeta_{target} = 0.4$.

Step 4: Design the lead-lag compensators. The parameter α and time constants are calculated as [2]:

$$\alpha = \frac{1 - \sin(\phi_{comp}/2)}{1 + \sin(\phi_{comp}/2)}. \tag{10}$$

$$T_1 = \frac{1}{\omega_{osc}\sqrt{\alpha}}, \quad T_2 = \alpha T_1. \tag{11}$$

Set $T_3 = T_1$ and $T_4 = T_2$ for two identical stages.

Step 5: Calculate the PSS gain K_{pss} using the residue method to achieve the desired damping ratio.

Step 6: Set the washout time constant $T_w = 10$ s (fixed), which is a standard value to ensure it does not interfere with steady-state operation [20].

This analytical design provides PSS parameters that guarantee stability and acceptable damping based on linear analysis [5].

C. Stage 2: PSO Optimization

PSO is a population-based optimization algorithm inspired by bird flocking behavior [8]. It is a robust search algorithm that has been proven effective for PSS tuning [8]. Each particle represents a candidate solution (PSS parameters). Particles move through the search space guided by their own best position and the global best position. PSO has emerged as an effective alternative to other optimization methods due to its simple implementation and good convergence properties [8].

1) Optimization Problem Formulation: The optimization problem is to find the set of PSS parameters that minimizes a performance index. For transient stability, an excellent choice is the Integral of Time-weighted Absolute Error (ITAE) of the rotor speed deviation [15]. This index penalizes both large deviations and those that persist for a long time, leading to a response that is both well-damped and fast-settling.

The optimization problem is:

$$\min_x J(x) = \int_0^{t_{sim}} t|\Delta\omega(t)|dt \tag{12}$$

subject to:

$$K_{pss,min} \le K_{pss} \le K_{pss,max} \tag{13}$$
$$T_{1,min} \le T_1 \le T_{1,max} \tag{14}$$
$$T_{2,min} \le T_2 < T_1 \tag{15}$$
$$T_{3,min} \le T_3 \le T_{3,max} \tag{16}$$
$$T_{4,min} \le T_4 < T_3 \tag{17}$$

where $x = [K_{pss}, T_1, T_2, T_3, T_4]$ are the PSS parameters to be optimized. The constraints $T_2 < T_1$ and $T_4 < T_3$ ensure that the lead-lag blocks provide phase lead. The objective function is calculated by simulating the full nonlinear system response to a three-phase fault, ensuring that the optimization accounts for large-signal, nonlinear conditions [8].

2) PSO Algorithm: The PSO algorithm works as follows:

Step 1: Initialize a swarm of particles with random positions and velocities. Use the analytical design as the initial position for one particle.

Step 2: For each particle, evaluate the objective function by simulating the system with the corresponding PSS parameters.

Step 3: Update each particle's personal best position and the global best position.

Step 4: Update particle velocities and positions using:

$$v_i^{k+1} = wv_i^k + c_1 r_1 (p_i - x_i^k) + c_2 r_2 (p_g - x_i^k), \tag{18}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}. \tag{19}$$

where w is the inertia weight, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers, p_i is the particle's best position, and p_g is the global best position.

Step 5: Repeat steps 2-4 until the maximum number of iterations is reached.

The specific PSO parameters were selected based on preliminary convergence sensitivity analysis. A swarm size of 25 and maximum iterations of 40 were found to offer the optimal trade-off between solution accuracy and computational efficiency; further increases yielded negligible improvement in the objective function. The inertia weight range [0.4, 0.9] and acceleration coefficients $c_1 = c_2 = 1.49$ were chosen to ensure a robust balance between global exploration and local exploitation throughout the search process [8].

V. Simulation Results and Analysis

A. Simulation Setup

The optimization and iterative simulations were performed using MATLAB with the ode45 solver (relative tolerance = 1e-7, absolute tolerance = 1e-9) to directly solve the non-linear differential equations [13]. This programmed approach provides faster execution for the PSO algorithm compared to calling Simulink iteratively. The results were cross-validated with the Simulink model shown in Fig. 1.

A three-phase symmetrical short-circuit fault was applied at t = 1.0 s and cleared at t = 1.10 s (100 ms duration) [2]. The fault location is at the midpoint of one transmission line, and the fault increases the system reactance to 2.0 times the normal value, representing a severe but realistic disturbance [14]. The total simulation time was 10 seconds, which is sufficient for transient stability analysis and allows observation of the complete transient response [19].

Three cases were simulated to demonstrate the progressive improvement:

- **Case 1:** System without PSS (baseline) - establishes the need for supplementary damping control
- **Case 2:** System with analytically designed PSS - validates the phase compensation method
- **Case 3:** System with PSO-optimized PSS - demonstrates optimal performance

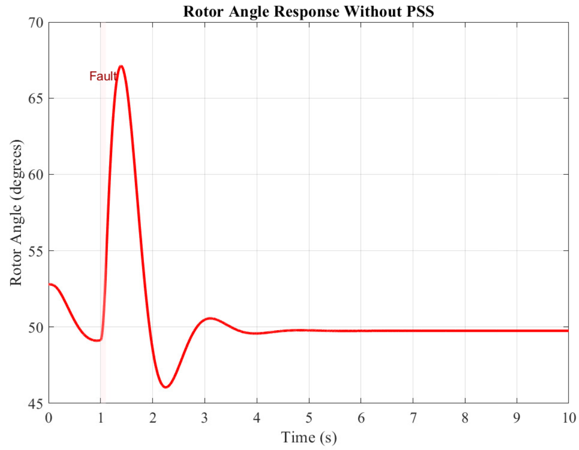

Fig. 3. Rotor angle response without PSS showing oscillatory behavior with settling time of 2.66 s.

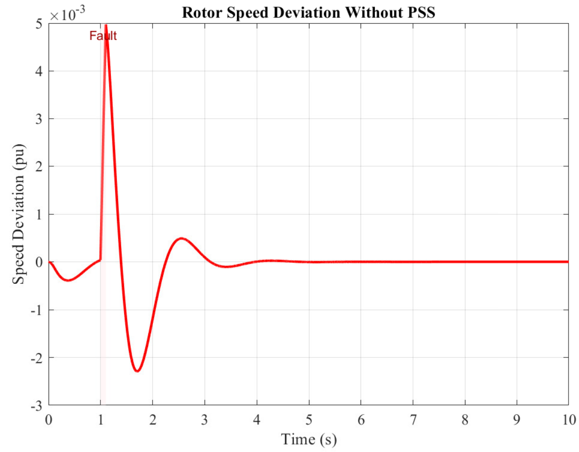

Fig. 4. Speed deviation response without PSS showing persistent oscillations.

B. Case 1: Without PSS

Fig. 3 shows the rotor angle response without PSS. The fault causes the rotor angle to swing from 53.13° to a peak of 67.14°. After fault clearance, the angle oscillates with slowly decaying amplitude. The settling time (2% criterion) is 2.66 s. The ITAE is 0.004234.

Fig. 4 shows the speed deviation response. The speed deviation reaches approximately 7.5×10^{-3} pu during the fault and exhibits persistent oscillations afterward. The natural damping (D = 2.0 pu) is insufficient for rapid stabilization.

These results establish the baseline performance and demonstrate the need for supplementary damping control.

C. Case 2: With Analytical PSS

The analytical phase compensation method produced the following PSS parameters: $K_{pss} = 1.894$, $T_w = 10.0$ s, $T_1 = 0.3257$ s, $T_2 = 0.0449$ s, $T_3 = 0.3257$ s, $T_4 = 0.0449$ s.

Fig. 5 shows the rotor angle response with the analytical PSS. The first swing peak is reduced to 65.72° (2.12% reduction compared to Case 1). The settling time is 2.78 s, slightly longer than Case 1, but the oscillations are better damped with more consistent amplitude reduction per cycle.

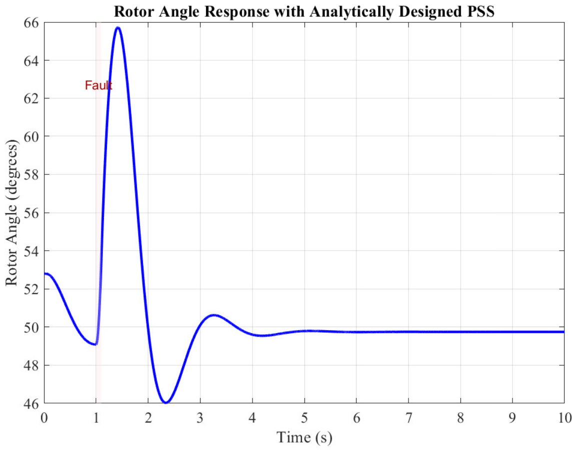

Fig. 5. Rotor angle response with analytically designed PSS showing improved damping with settling time of 2.78 s.

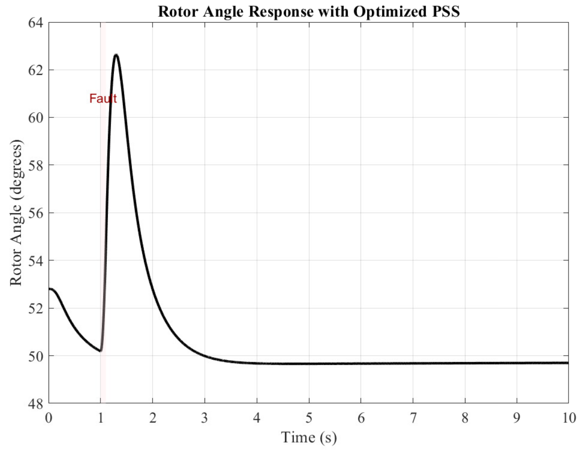

Fig. 7. Rotor angle response with optimized PSS showing rapid stabilization in 2.51 s.

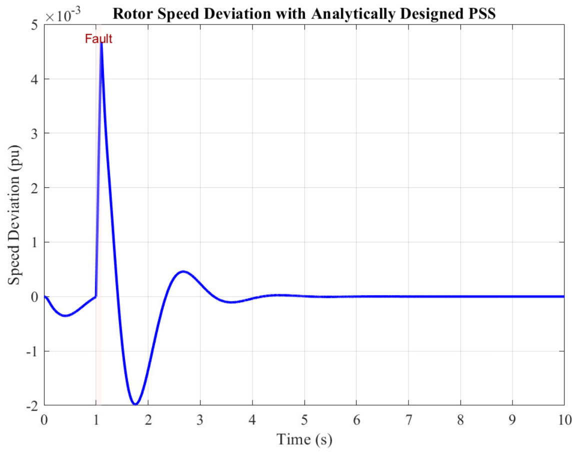

Fig. 6. Speed deviation response with analytically designed PSS showing better controlled oscillations.

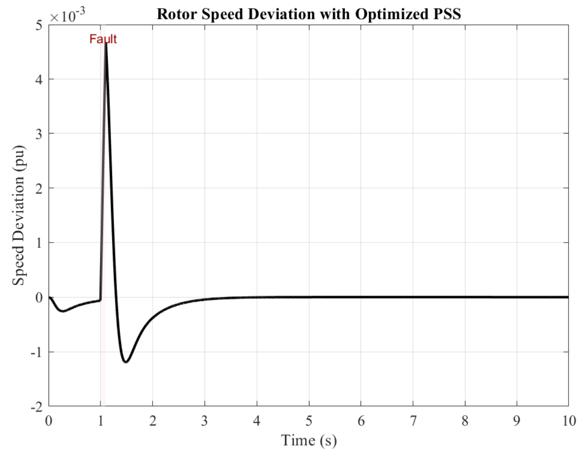

Fig. 8. Speed deviation response with optimized PSS showing aggressive damping with minimal oscillations.

Fig. 6 shows the speed deviation response. The oscillations decay more rapidly than Case 1. The ITAE is 0.004170, a 1.5% improvement over Case 1.

The analytical PSS successfully improves damping quality, validating the phase compensation approach. However, there is room for further optimization.

D. Case 3: With Optimized PSS

The PSO algorithm demonstrated rapid convergence, completing the optimization process in just 30.20 seconds on a standard workstation. It converged after 40 iterations to the following optimized parameters: $K_{pss} = 15.94$, $T_w = 10.0$ s, $T_1 = 0.5010$ s, $T_2 = 0.4996$ s, $T_3 = 0.4822$ s, $T_4 = 0.4820$ s. The low computational time confirms the method's suitability for offline tuning and potential online adaptive applications.

Fig. 7 shows the rotor angle response with the optimized PSS. The first swing peak is reduced to 62.64° (4.68% reduction compared to Case 2, 6.70% compared to Case 1). The settling time is 2.51 s, achieving a 9.83% improvement over Case 2. The oscillations are damped very quickly with minimal overshoot.

Fig. 8 shows the speed deviation response. The oscillations are suppressed so effectively that they become nearly imperceptible after 2 cycles. The ITAE is 0.002170, representing a 47.98% reduction compared to Case 2 and 48.75% reduction compared to Case 1.

The optimized PSS achieves superior performance across all metrics, demonstrating the effectiveness of the PSO optimization stage.

E. Comparative Analysis

Fig. 9 compares the rotor angle responses for all three cases. The progressive improvement from Case 1 to Case 3 is clearly visible. The optimized PSS provides the fastest settling and best damping.

Fig. 10 compares the speed deviation responses. The superior damping of the optimized PSS is evident, with oscillations damped much more quickly than the other cases.

Table I summarizes the quantitative performance comparison. The optimized PSS achieves the best performance in all metrics: lowest first swing peak, fastest settling time, and lowest ITAE.

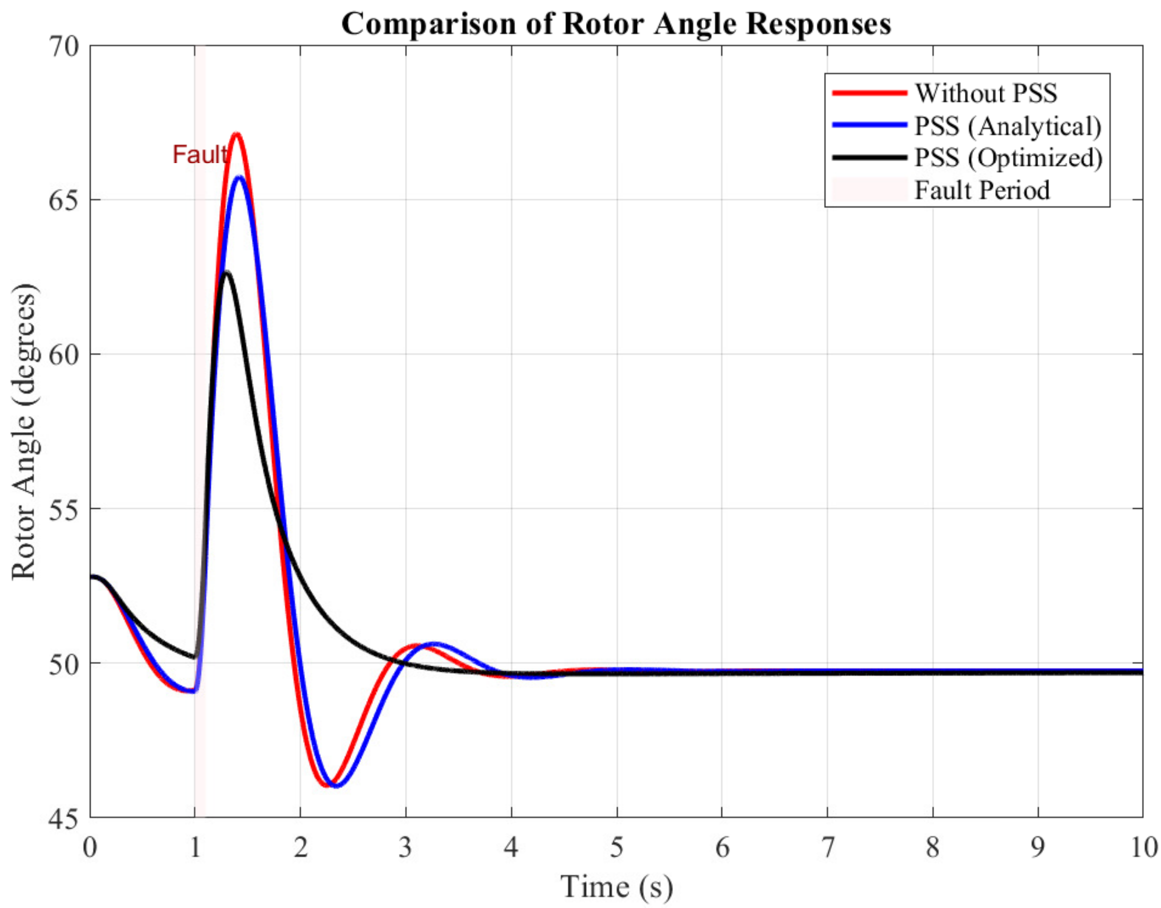

Fig. 9. Comparison of rotor angle responses for all cases showing progressive improvement from Case 1 (without PSS) to Case 3 (optimized PSS).

TABLE I
QUANTITATIVE PERFORMANCE COMPARISON OF PROPOSED HYBRID PSS VS CONVENTIONAL APPROACHES

Metric	Case 1	Case 2	Case 3
First swing peak (deg)	67.14	65.72	62.64
Settling time (s)	2.66	2.78	2.51
ITAE	0.004234	0.004170	0.002170

F. PSS Parameter Evolution

Fig. 11 shows the PSS parameter changes from analytical to optimized design. The most significant change is the PSS gain, which increased from 1.894 to 15.94 (741.6% increase). This higher gain provides stronger damping torque. The time constants T2 and T4 also increased dramatically: T2 increased from 0.0449 s to 0.4996 s (1013% increase), and T4 increased from 0.0449 s to 0.4820 s (974% increase), fundamentally changing the compensation strategy. These changes would be difficult to discover through analytical methods alone.

G. Discussion

The results demonstrate several important findings:

1) Baseline system behavior: The system without PSS exhibits poorly damped oscillations despite having natural damping (D = 2.0 pu). The 2.66 s settling time is unacceptably long for power system operation. This confirms the need for supplementary damping control, as natural damping alone is insufficient for acceptable transient performance [2].

2) Analytical PSS effectiveness: The phase compensation method successfully designs a PSS that improves damping quality [5]. The 1.5% ITAE improvement and better oscillation decay validate the classical approach. However, the settling time increases slightly, indicating that further optimization is beneficial. The analytical design provides a robust and reliable starting point [1].

3) Optimization superiority: The PSO-optimized PSS achieves dramatically better performance. The 47.98% ITAE reduction and 9.83% faster settling time are significant improvements. This superiority stems from the fact that PSO evaluates the objective function on the full nonlinear model (large-signal stability), whereas the analytical method relies on a linearized model valid only for small deviations (small-signal stability) [8].

4) Practical implications: The 0.27 s reduction in settling time has real practical value. Faster post-fault recovery reduces equipment stress and improves system security [19]. The nearly 50% ITAE reduction indicates significantly reduced stress on the generator shaft during transients. The aggressive damping characteristics minimize the risk of resonance or interaction with other system controllers [3].

5) Methodology validation: The hybrid approach successfully combines the reliability of analytical design with

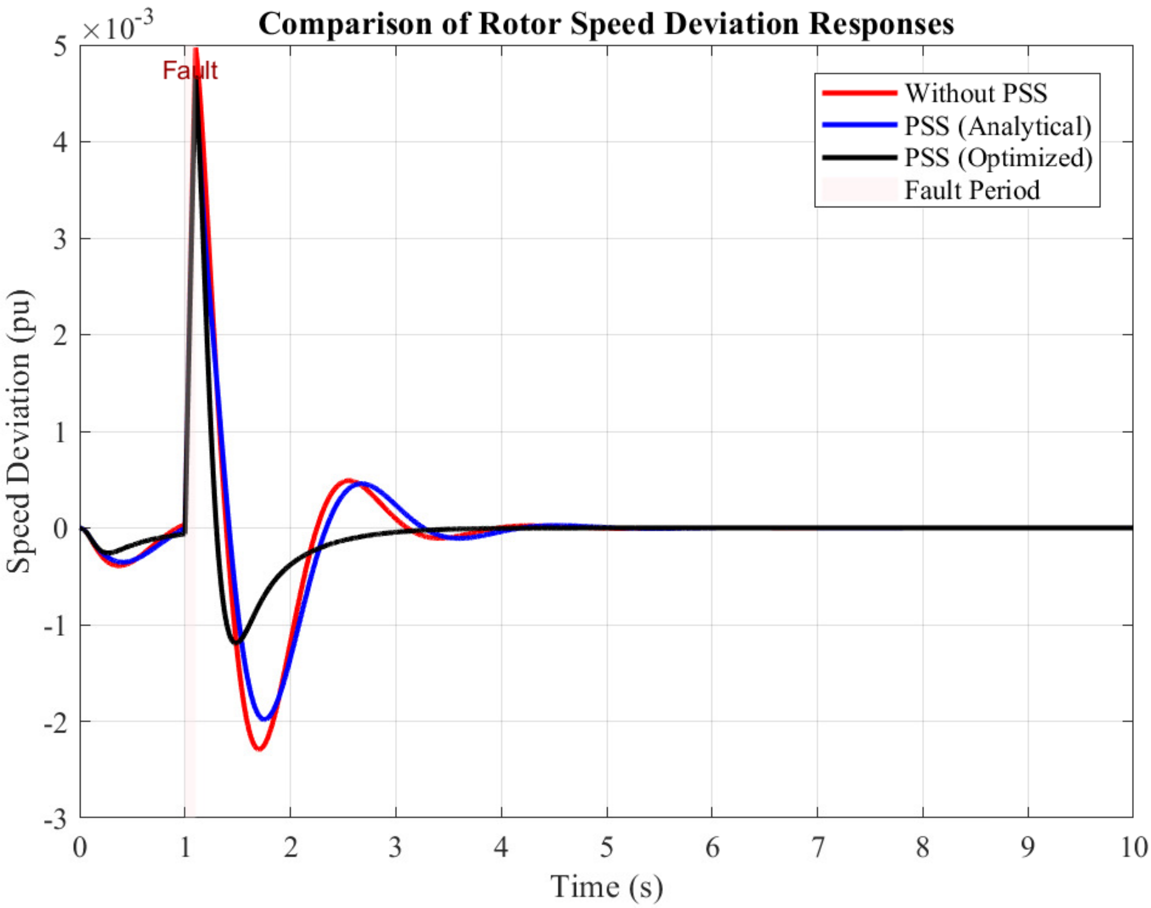

Fig. 10. Comparison of speed deviation responses for all cases demonstrating superior damping of optimized PSS.

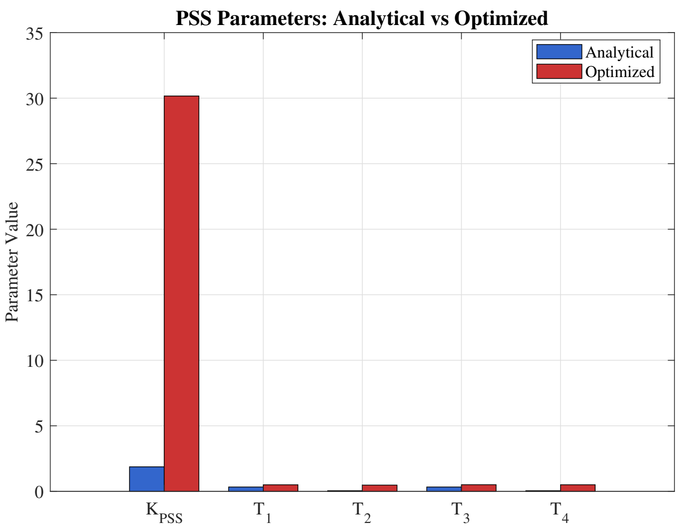

Fig. 11. Comparison of PSS parameters between analytical and optimized designs showing significant changes in gain and time constants.

the performance benefits of optimization [1]. The analytical stage provides a good starting point that ensures convergence, while the optimization stage achieves optimal performance by evaluating the full nonlinear system response [8]. This combination leverages the strengths of both classical control theory and modern computational optimization [1].

The results align well with findings reported in the literature for PSO-based PSS optimization [8]. Furthermore, the validation was conducted under a heavy loading condition (90% of rated capacity) combined with a severe three-phase fault. Stability under this ”worst-case” scenario implies robustness for lighter operating points and less severe disturbances, confirming the reliability of the proposed design [6].

VI. Conclusion

This paper presented a two-stage hybrid method for PSS design that combines analytical phase compensation with PSO optimization. The method was validated on a realistic SMIB system under severe fault conditions, demonstrating its effectiveness for transient stability enhancement [14], [2].

The main findings are:

1) Effective hybrid approach: The two-stage methodology successfully combines the strengths of analytical and optimization techniques [1]. The analytical stage provides reliability and a good starting point based on classical control theory [5], while the optimization stage achieves superior performance through automated parameter tuning [8].

2) Significant performance improvements: The optimized PSS reduces settling time by 9.83% and ITAE by 47.98% compared to the analytical design. These improvements have practical value for power system operation, enabling faster post-fault recovery and reduced equipment stress [19].

3) Practical applicability: The method uses realistic system parameters and fault scenarios. The complete MATLAB implementation without requiring Simulink makes the approach accessible and reproducible for practical applications [6], [13].

4) Optimal parameter discovery: The PSO optimization discovers PSS parameters (particularly the gain and time constants) that would be difficult to find through analytical methods alone [8]. The optimization process revealed that much larger time constants and higher gain produce superior damping performance for this specific system [8].

Future work could extend this approach to multi-machine systems [12], investigate robustness under parameter variations, explore adaptive PSS designs that adjust parameters online based on operating conditions [10], and investigate coordination with FACTS devices [14], [15], [11], [17], [18].

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