Kashf Journal of Multidisciplinary Research
Vol: 02 - Issue 06 (2025)
P-ISSN: 3007-1992 E-ISSN: 3007-200X
https://kjmr.com.pk

# DYNAMIC STABILITY ENHANCEMENT IN SMIB POWER SYSTEMS USING STATIC OUTPUT FEEDBACK OBSERVER DESIGN

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**Article Info**



**Abstract**

The power system is inherently a complex and nonlinear multi-input multi-output (MIMO) structure, highly susceptible to low-frequency oscillations due to dynamic disturbances and load variations. Traditional Power System Stabilizers (PSS), particularly those based on Proportional-Integral-Derivative (PID) control, often face challenges such as difficulty in parameter tuning, limited adaptability, and computational complexity. This paper presents a Static Output Feedback (SOF)-based observer design as a simplified yet robust alternative for damping electromechanical oscillations in a Single Machine Infinite Bus (SMIB) power system. By incorporating state observation techniques, the proposed SOF controller enables effective eigenvalue placement, improving system dynamic performance with reduced computational overhead. A comparative analysis is conducted between PID-based and SOF-based PSS through MATLAB/Simulink simulations. Results demonstrate that the SOF-based stabilizer offers faster settling time, enhanced damping characteristics, and superior stability under varying operating conditions. The proposed method proves to be a computationally efficient and practically viable solution for modern power system control applications.

**Keywords:**
*Power System (PS), Power System Stabilizers (PSSs), Proportional-Integral-Derivative (PID) Controller, Static-Output-Feedback (SOF) Controller.*

## Introduction

From a control engineering perspective, the power system is a highly nonlinear and large Multi-Input Multi-Output (MIMO) dynamic system comprising multiple variables, required protections, and distinct control loops to manage the complex dynamic responses and attributes [1]. Power system stabilizers (PSS) aim to mitigate the effects of frequency oscillations, enhancing performance and protecting the power system (PS) in critical and unfavorable states. Power stabilizer systems provide a safe mode of operation, preventing the electrical system from unsustainable situations.

The power system stabilizer (PSS), including the power facility, can connect directly to the generator. Typically, the control loop, which runs linearly, remains active and utilizes local measurements. Modern controller designs, including optimal control, robust control, elastic control, and fast control, have recently been developed to reduce power system damping oscillations. PID-based power system stabilizers (PSS) and lag-lead power system stabilizers are the most effective controllers for addressing unstable and oscillating damping scenarios. [2-10].

For conventional-based simple PSSs, the parameters are typically measured through repetitive readings, trial-and-error approaches, and experiments; however, they are not capable of achieving optimal performance across a variety of disturbances and operating conditions. In the practical world of power systems, even higher-order or complex power system stabilizers are often unsuitable. To solve this problem, another control theory was recently proposed, namely “the best (Optimal) control is not directly applicable to Power System Stabilizer (PSS) design problems based on Proportional Integral Derivative (PID)”. So, it was impossible to stabilize the nominal power system using the PID-based power system stabilizers [11]. Recently, another controller has been developed, which provided a suitable composition of PSS in a firm known as “PID controller”. Due to its simple functioning, this controller is widely used in big and complex industries. Calculating its parameters requires experience, trials, and repeated measurements, as well as error analysis techniques. However, tuning the gain of PID-based PSSs properly is quite effortful due to the power system's expansion, complexity, nonlinearity, and uncertainties.

Over the years, various mechanisms have been proposed to tune PID controllers and address these complex problems. Until 2002, a survey was given in reference [12,13]. This survey employed a frequency modification technique proposed by [14]. Additionally, some work has been done to find the analytical approach and tune the parameters [15,16]. Several other optimal and robust methods have also been introduced for designing PI and PID controllers [18, 22].

The PID stabilizers are used in controlling and operating power systems, just as they are in various industries. Because the complexity, operational procedures, and structural setup of power systems are increasing daily, PSS is based on classical PID. While higher-order controllers have been used to meet the design goals for multi-engine power systems, due to the control complexity, some unknown parameters have been designed, and physical constraints have been neglected.

For example, using a PID-based cloud system can achieve many of the dynamics of a cloud system [23-25]. For example, PI control, PID spatial distribution eigenvalue reference database [26-27], References [29, 30], and IEEE working groups have published summaries of generally accepted guidelines for generators in terms of PID-based power system stabilizers that maintain stability. Several logical techniques (Fuzzy) have been applied for PID-based PSSs [31,32,33]. A few methodologies were introduced in reference [34-36] to obtain the gain of PID controllers utilizing genetic algorithms and optimization particles for PSSs.

In this paper, SOF (Static Output Feedback) based PSSs (Power System Stabilizers) are introduced as an alternative to PID (Proportional Integral Derivative) based PSSs. The primary objective of this transmutation is to utilize SOF (Static Output Feedback) based power system control methodologies to stabilize power systems more effectively than PID-based power system controllers, and to calculate the fixed gains of the power system. Once the constant vector of SOF is fine, the SOF gain is in your hands, and no additional computation is required.

**Literature review:**

**The literature review and the key points are mentioned in the following table**

| Method | Algorithm | Advantages | Key Features | Implementation Complexity | Scalability | Use Cases |
|---|---|---|---|---|---|---|
| PID-based PSS | Proportional-Integral-Derivative (PID) | Widely used, easy tuning based on system response | Fixed-parameter tuning | Medium | Low | General industrial applications |
| SOF-based PSS | Static Output Feedback (SOF) | Simplifies control structure, enhances robustness against system non-linearities | Eigenvalue manipulation through feedback | Medium | Medium | Power system stability enhancement |
| Reactive Compensation Device | Reactive Compensation | Improves stability with online tap changers | Real-time voltage control | Low | Low | Microgrid voltage stabilization |
| Advanced SOF-based PSS | Advanced Static Output Feedback | Claims simplicity and effective results, better performance stability | Utilizes a static output feedback matrix | Medium | High | Enhanced power system dynamic responses |

**Generalized power system model**

The power system model or sample examined is based on a synchronous motor linear model connected to an infinite bus bar via a transmission line. The swing equation point of view is used to determine the relationship between various quantities, such as angle deviation, angular speed, electrical power, and torque. The regulated SMIB is displayed through the transmission line of the power plant in Figure 1 using a one-line key diagram. It comprises a voltage regulator and exciter, which are used to control the voltage at the terminals Vt. In contrast, the infinite bus bar voltage (V) is kept at predefined formal values. Parameters of SMIB are given in Appendix 1.

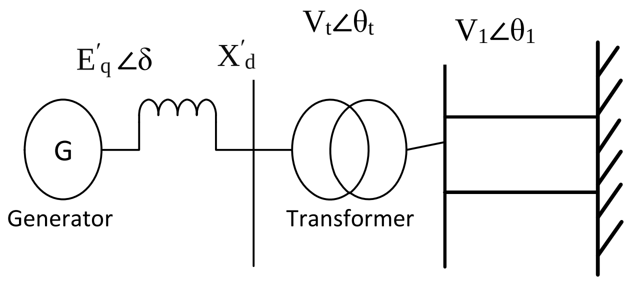


**Figure 1: SMIB System**

The synchronous machine linear model of a power system with an infinite bus is given in Figure [insert figure number]. The model is created and simulated using Simulink. The transfer function of the SMIB Power system sample is an open loop. That's why the state space representation of SMIB is

$$\begin{cases} \dot{y} = Ax + Bu \\ x = \mathbf{C}x \end{cases} \tag{1}$$

Where,

$$\mathbf{A} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & 0 & 0 \\ 0 & p_{32} & p_{33} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ b_1 \end{bmatrix} \tag{2}$$

$$\begin{cases} p_{11} = \frac{-K_D}{M}, p_{12} = \frac{-K_1}{M}, p_{13} = \frac{-K_2}{M} \\ p_{21} = \omega_o, \ p_{32} = \frac{-K_3 K_4}{\tau_3}, \ p_{33} = \frac{-1}{\tau_3} \end{cases} \tag{3}$$

$$b_1 = \frac{K_A}{\tau_3}, \tau_3 = K_3 \tau'_{d0}, \quad N = 2H \tag{4}$$

Here are the specified outputs and state variables:

$$X = [X_1 \ \ X_2 \ \ X_3 \ ]^T = [\ \Delta\omega_r \ \ \Delta\delta \ \ \Delta E' \ ]^T$$

$$u = \left[\Delta T_M \ \ \Delta E_{fd} \ \right]^T$$

The voltage and torque, which are also called electrical torque, are given as

$$\Delta T_E = K_1 X_2 + K_2 X_3 \tag{5}$$

$$\Delta V_t = K_5 X_2 + K_6 X_3 \tag{7}$$

where, Δ is minute change around an operating point, $T_E$, $T_M$, δ, $\omega_r$, $V_t$ and $E_{fd}$ are Mechanical torque, Electrical torque, angle of rotor, speed of the rotor, the voltage at the terminal, and the voltage at the field respectively.

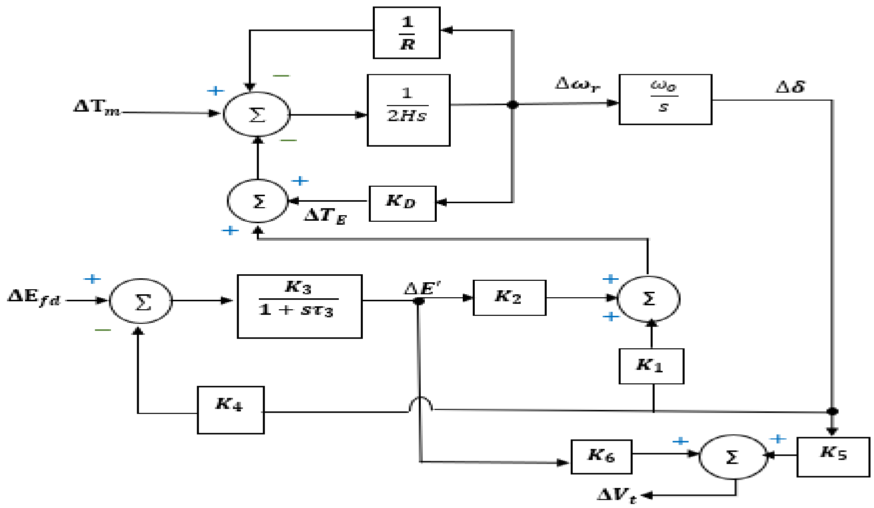


**Figure 2: The figure illustrates an infinite bus power system connected to a Synchronous machine.**

In this paper, an infinite bus power system is linked to a synchronous machine, which serves as a sample for implementing the proposed scheme. The PID-based PSS scheme was also implemented for the Synchronic machine connected to the infinite bus system. The results and performance of both schemes were compared.

**PID-based Power System Stabilizer**

As the name suggests, PID-based PSSs utilize the derivative and integration to operate the power system in a stable and optimal performance stage.

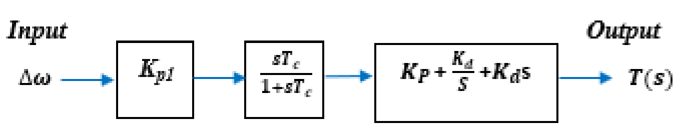


**Figure 3: PID-based PSS controller structure**

Figure 3 shows a block diagram representing the system interconnection in a cascaded configuration where the first block defines the proportional gain Kp1, the second block is for integration, and the third block represents the derivative. In this block diagram, every block accomplishes its dedicated work i.e. the proportional gain $K_{p1}$ palliates the low-frequency oscillation and controls the error up to some extent, the integration gain $K_i$ that is used to deal with steady-state error to reduce it, and the derivative portion $K_d$ is used for the transient to minimize the percent overshoot (%OS), so by the end, these will provide the stability to the system. $T_c$ means the time constant is present in the integration block, acting as a High-Pass Filter (HPF). The $T_c$ value is large enough to approach the input, allowing it to pass through without variation. The schematic diagram illustrates that the system's interconnection is in the form of a cascaded open-loop system. Therefore, for the transfer function T(s), the overall T(s) obtained by multiplying the gain of all blocks is given below.

The PID-based PSS structure T(s) (Transfer Function) is

$$T(s) = (K_{p1}) \left(\frac{sT_c}{1+sT_c}\right) \left( K_P + \frac{K_d}{s} + K_d s\right) \quad (9)$$

Where T(s) is the output.

The magnitude and phase properties are given by:

$$Mag(\omega) = K_{P1} \frac{T_c}{\sqrt{1+(T_c\,\omega)^2}} \sqrt{{K_P}^2 + \left(K_D\,\omega - \frac{K_1}{\omega}\right)^2} \quad (10)$$

$$\theta_p(\omega) = 180 + \tan^{-1} \frac{K_P - T_c(K_1 - K_D\,\omega^2)}{K_1 + (K_P\ T_c - K_D)\omega^2} \quad (11)$$

Here the $K_{P1}$ , $T_c$ ,$K_P$ , and $K_d$ Values for the above system are tuned using a genetic algorithm. The above calculation was performed for the PID-based PSS and implemented in the Simulink model. The results of PID-based PSS are shown in Figure 6.

**SOF-based PSS**

Using a state-of-the-art SOF-based PPS, the study enhances the stability of the SMIB power system. We design a feedback controller using the observer technique, based on a state observer. Feedback helps assign arbitrary values to the eigenvalues of the system, thereby allowing the design of system dynamics. The dynamical system states are those variables that, with a stationary output feedback loop, allow one to forecast future development and system management. One might use the idea of placing the closed-loop eigenvalues in desired positions to generate the Static Output Feedback control. Combining the dimensions of the inputs and outputs of a linear system with a model of the system's dynamics will help determine the position of closed-loop eigenvalues. In this work, we create and investigate the Single Machine Infinite Bus (SMIB) system, an equation-defined system characterized by a single machine and an infinite bus. Thanks for the given observations.

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(y - C\hat{x}) \quad (12)$$

Measured output includes the term L (y - C$\hat{x}$Which is subsequently sent back. The observer expects $C\hat{x} = y$ as the outcome. Finding the L matrix in a way that guarantees the eigenvalues of (A – LC) correspond to the fixed eigenvalues associated with the positioning issues is a challenge. L signifies

$$\mathbf{L} = \mathbf{W_0^{-1}\dot{W}_0} \begin{bmatrix} \mathbf{p_1 - a_1} \\ \mathbf{p_2 - a_2} \\ \vdots \\ \mathbf{p_n - a_n} \end{bmatrix} \quad (13)$$

where the matrix $W_o$ and $\widetilde{W_o}$ are given by

$$\mathbf{W_0} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \vdots \\ \mathbf{CA^{n-1}} \end{bmatrix}, \quad \mathbf{W_0^{-1}} = \begin{bmatrix} \mathbf{a_1} & \mathbf{1} & \mathbf{1} & \dots & \mathbf{0} \\ \mathbf{a_2} & \mathbf{1} & \mathbf{1} & \dots & \mathbf{0} \\ \mathbf{a_2} & \mathbf{a_2} & \mathbf{1} & \dots & \mathbf{0} \\ \vdots & & & & \\ \mathbf{a_{n-1}} & \mathbf{a_{n-2}} & \mathbf{a_{n-3}} & \dots & \mathbf{1} \end{bmatrix} \tag{14}$$

where

$\widetilde{W}_o$ = The Observability matrix for the system

$W_o$ = The Observability matrix for the controller

Under the closed-loop system characteristic poly, the error in the observer " $\tilde{x} = x - \hat{x}$Supervised by a differential equation.

$$F(x) = x^n + f_1x^{n-1} + \dots\dots + f_n \tag{15}$$

Using input and output to evaluate the system state, the dynamic system in Equation (12) is an evaluator of the system in Equation (1).

An observer is a dynamic process that generates output y from the input w. The estimate measures two different concepts of rate of change. The model $\hat{x}$ + Bu allows one to determine the rate of change by substituting "x" for the variable "y" in the equation. Equivalent to the difference between the estimated output, y, and its estimate, y, L (y - $\hat{y}$) is proportional to the error, e. The "L" matrix of gains in analysis measures the effect of error "e" and its distribution in many states. The controller combines all evaluations of the system's dynamic model. The reference control is one:

$$\mathbf{w} = -K\hat{x} + K_r r \tag{16}$$

$$\frac{d\hat{x}}{dt} = \mathbf{A}\hat{x} + \mathbf{B}_u + L(y - C\hat{x}) \tag{17}$$

Shows a closed loop system that has the following characteristics: polynomial

$$\mathbf{det}(sJ-M+NP)\ \ \det(sJ-M+QD) \tag{18}$$

For the systems under consideration, surface toxicity can have different roots. Figure 4 shows the SOF control. The characteristic polynomial in (18) is of the second order. While the other factor is det(sJ−M+QD) associated with the observer, the first factor is det(sJ−M+NP) associated with Static Output Feedback. Analyzing all the variables helps determine P, also known as profit return. The input y and the output y u form a dynamic system, which is the controller.

$$\frac{d\hat{x}}{dt} = (N - BK + LC)\hat{z} + Ly$$

$$W = -K\hat{x} + K_r r \tag{19}$$

The transfer function of the controller is

$$C(s)=K[sI-(A+BF+GC)]^{-1}G \tag{20}$$

The above controller, with the transfer function C(s), is used here to calculate Static Output Feedback.

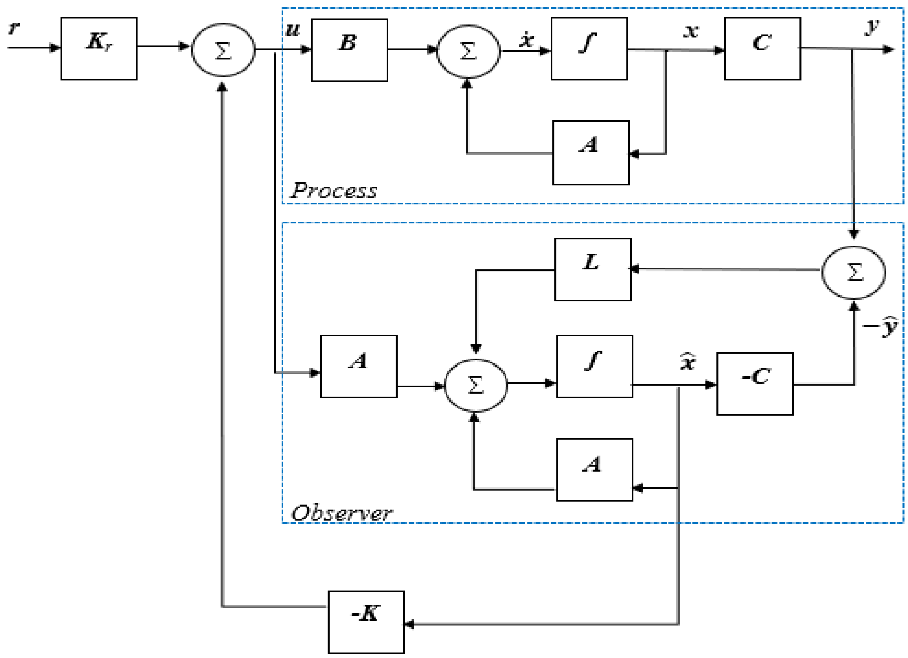


**Figure 4: Diagram of SOF controller-based observer**

The scheme, as mentioned above, was implemented in the Simulink model for the SMIB system. The results and performance obtained are shown in Figure 7.

**Simulation Results**

SOF-based PSS has been designed to enhance the damping characteristics of voltage deviations (ΔVt) in the normal state. The MATLAB/Simulink platform for the SMIB power system model evaluates SOF-based PSS accomplishment investigations. The simulations are conducted for both PID-based PSS and SOF-based PSS for SMIB power systems. The simulations without PSS are shown in Figure 5, the PID-based PSS in Figure 6, and the SOF-based PSS in Figure 7, respectively. Table 1 shows the different parameter values for PID-based PSS and SOF-based PSS. The error signal is in Figure 9.

The simulations for the SMIB power system are first implemented for the PID-based Power System Stabilizer (PSS). The system eigenvalues are provided in Table 2. The system response is viewed in Figure 6. The system exposes large damping oscillations, which are displayed in Figure 6. The achievement criteria, specifically the settling time (Ts) for speed deviation of SMIB, stabilized at 25 s. Some refinement is necessary for Figure 6 to minimize electromechanical oscillations, ensuring the system has a fast response with a more stable and lower steady-state error. The proposed methodology must be capable of reducing large oscillations under various circumstances, including different operating conditions, external disturbances, and parameter changes. The simulations for the SMIB power system are then implemented for SOF-based PSS. The system eigenvalues are provided in Table 2. Figure 7 shows the system response for SOF-based PSS. The system exposes small damping oscillations, which are displayed in Figure 7. The achievement criteria, specifically the settling time (Ts) for speed deviation of SMIB, stabilized at 15 seconds. To test the efficiency of the proposed SOF-based PSS and effectively monitor the reference control values under various operating conditions, the plant is subjected to variations in $\Delta T_m$ and $\Delta V_{ref}$. The results showed that the system performed better with greater stability, faster response, and lower overshoots. Therefore, the SOF-based control system concept offers efficient energy control, ensures rapid switching, and guarantees safety.

**Table 1:**

| P.S.S | Attributes |
|---|---|
| PID based on PSS | Ts=0.1159 s, $K_{p1}$=20.0, $K_p$=-0.6872, $K_1$=-7.9163, $K_D$=0.0687 |
| SOF-based P.S.S | Ks=10.0, Ts= 12 s, $K_{A}$= 50, $K_D$ =0, $\omega_O$= 314.20 rad/sec |

**Table 2: Eigenvalues for PID-based PSS and SOF-based PSS**

| PD built on PSS | SOF built on PSS |
|---|---|
| -2.7130±j10.8539<br>-7.8708±j3.6719<br>-3.7595±j6.3345<br>-1.3896 | **-8.12±j376.98**<br>**-6.9±j2.45**<br>**-1.26±j2.6**<br>**-1.26±j1.5** |

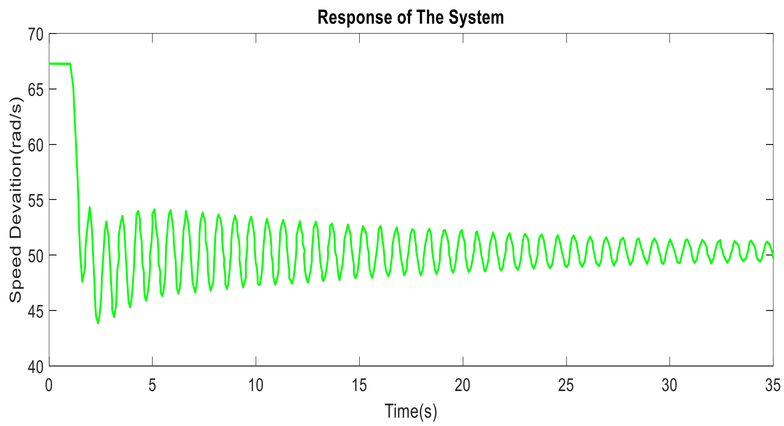


**Figure 5: SIMB System without PSS**

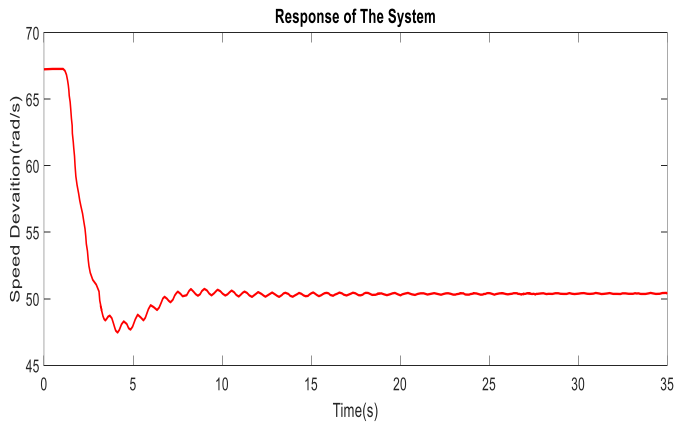


**Figure 6: SIMB System with PID-Based PSS**

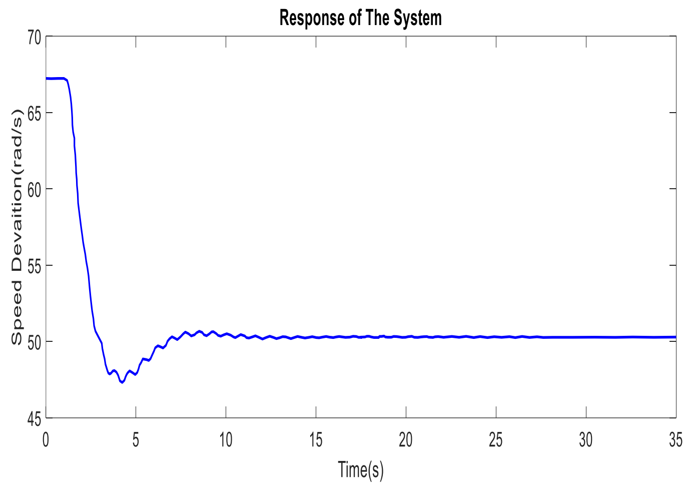


**Figure 7: SIMB System with SOF-Based PSS**

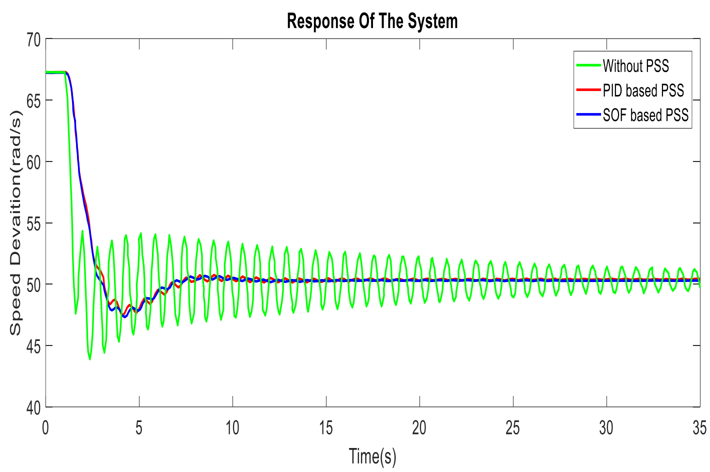


**Figure 8: Results**

Figure 8 shows the comparison of all results. SOF-based PSS shows a faster response for electromechanical oscillations with greater stability than PID-based PSS. Both reactions are compared without PSS. The error graph is shown in Figure 9. It was observed that the PID-based PSS has more errors than the SOF-based PSS.

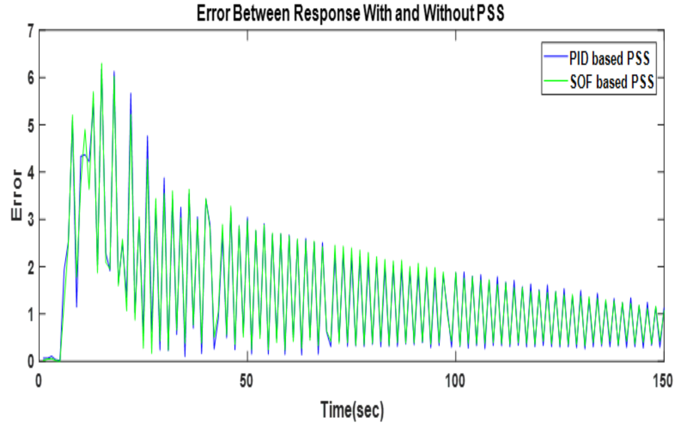


**Figure 9: Error**

**Conclusion:**

The purpose of this work is to reexamine in an all-inclusive manner the lit of PID (Proportional Integral Derivative) based PSS (Power System Stabilizers) and its comparison with the SOF-based PSS. The primary objective is to utilize the SMIB (Single Machine Infinite Bus) model and obtain positive results and solutions to mitigate low-frequency oscillations in the power system. Therefore, it's quite clear that using the SOF controller methodological analysis for designing the PSS to stabilize the power plant yields improved final results compared to those provided by a PID-based PSS. The proposed algorithmic program is computationally simple. No extra sensors are required for implementation, which is why it's the inexpensive and easiest proposed technique. This method also provides better performance for controlling the voltage by having the advanced potentiality of damping the small oscillation that is present in the power system The System states and disturbance states are simultaneously estimated by the observer for implementation of static output feedback and by utilizing the disturbance estimation can evaluate compensation of the uncertainties in parameters and the external fixed disturbances.

**Appendix 1: Power System Data**

| **Parameter** | **Value** |
|---|---|
| Line impedance, Re + j $X_e$ | 0.02 + j0.40 |
| D-axis reactance, $X_d$ | 1.7 |
| Q-axis reactance, $X_q$ | 1.64 |
| Armature resistance, r | 0.001096 |
| Infinite bus voltage, V | 1 |
| Inertia Constant, H | 2.37 |
| Rated speed, $\boldsymbol{\omega_o}$ | 314.1593 rad/sec |
| Field circuit time constant, | 8 s |
| Damping factor, $K_D$ | 0 |
| Regulator gain, $K_A$ | 50 |
| The exciter time constant, $\boldsymbol{\tau_E}$ | 0.5 |
| Exciter gain, $K_E$ | −0.05 |

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