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Stability Analysis of SMIB Systems: Evaluating Small Signal Stability and the Impact of PSS and TCSC on Rotor Oscillations

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ABSTRACT

This study primarily focuses on analyzing the stability of the SMIB system when subjected to small signals. The small signal stability of a Single Machine Infinite Bus (SMIB) system is demonstrated by plotting the eigenvalue, which represents rotor oscillations, against the voltage regulator gain and machine loading. Furthermore, the integration of the pole placement technique and the utilization of TCSC in the production of PSS will enhance the reliability of the SMIB system's low-level signals. An analysis is conducted to compare the effects of PSS and TCSC on the oscillations of the rotor's speed and angle. In the final phase of the design process, careful thought was given to choosing a feedback control signal for the PSS. The duration required to respond to messages is a crucial determinant of their effectiveness.

Keywords: *SSS; SMIB; FACTs Devices; Power System Stabilizer (PSS).*

1.0 Introduction

To conduct a power systems analysis, it is essential to possess acute perception and meticulous thinking, given the escalating intricacy of the systems and the extensive interconnections among them. Even a minor disturbance has the potential to initiate oscillations, which, if left unchecked, can escalate to levels that pose a significant risk and cause extensive damage to the electrical system. It is crucial to design the system in a manner that allows for the identification and prevention of these oscillations, thereby avoiding any significant concerns. This is because it is imperative that the system be organized in a way that is practical.

Hence, it is imperative to investigate the system's behavior when referring to "small signal stability," which pertains to the power system's ability to maintain stability even in the presence of minor disturbances as mentioned earlier. This is one way in which the idea of stability in a constant state has been further developed. While there may be instances where the transient stability limits are exceeded, it is imperative that a power system always adheres to the constraints of small signal stability. This remains valid even in cases where the thresholds for transient stability are occasionally surpassed. Therefore, it is imperative to conduct research and enhance the stability of minuscule signals by employing ingeniously designed auxiliary controllers. The stabilization of low-frequency rotor oscillations is closely linked to the damping of these oscillations.

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The analysis of this phenomenon is conducted using the eigenvalue technique, which relies on a linearized dynamic model [1, 2]. Implementing Power System Stabilizers (PSS) is not only effective in achieving the objectives of reducing oscillation in the power system and improving system stability [3-7], but it is also economically advantageous in accomplishing these goals. To enhance the overall functionality of the system, numerous experiments were conducted using PSS [8-14] and TCSC controllers [15-22]. One way to enhance the stability of a power system is by utilizing the quick control capabilities of a TCSC to manage the system's status. This is one of the features that can be utilized. The study conducted by [22] examines the actions performed by TCSC controllers in situations where the signal oscillation is minimal.

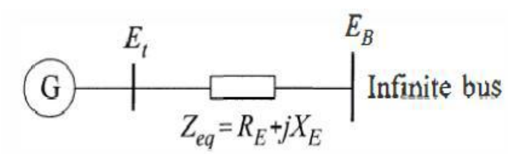
The primary emphasis of this research is on the stability of small signals. Firstly, it is necessary to consider the impact of adjusting the loading of the machine and the gain of the voltage regulator on the stability of the small signal detected by the SMIB. It is necessary to plot the eigenvalue associated with rotor oscillations in order to analyze this phenomenon. In addition, the design of the power system stabilizer for the SMIB power system incorporated a pole placement strategy and the application of TCSC to enhance the system's ability to respond to minor signals. The main motive behind this action was to ensure stability in the electricity grid. This page will compare the effects of PSS (Power System Stabilizer) and TCSC (Thyristor-Controlled Series Capacitor) on rotor oscillations and rotor speed. Furthermore, the choice of the PSS feedback signal was extensively investigated at every stage of the design process. Signals are evaluated based on the responses they provoke and the duration of those reactions.

The study comprises the following organizational components: Section II of this paper presents a model of the SMIB system, along with the proposed plans for the PSS (Power System Stabilizer) and TCSC (Thyristor-Controlled Series Capacitor). Lastly, in the final section, we will examine the results of the study conducted on each event individually. The fourth section of the essay examines the conclusion.

2.0 Model Formations

2.1 SMIB Platform [4]

Figure 1: Endless Bus System for One Machine



The infinite-bus receives its power from the synchronous generator via a transmission line. The equations for the machine are [7]:

$$\frac{d\omega}{dt} = \frac{(P_m - P_e)}{M} - \frac{K_d(\omega - \omega_o)}{M} \quad \dots (1)$$

$$\frac{d\delta}{dt} = \omega - \omega_o \quad \dots (2)$$

$$\frac{dI_d}{dt} = \frac{1}{T'_{do}} [\frac{1}{X'_{do}} E_{fd} \text{-} I_d \text{-} \left(\frac{x_d - X'_d}{X'_d}\right) i_d \quad \dots (3)$$

$$\frac{dE_{fd}}{dt} = \frac{-1}{T_R} E_{fd} + \frac{K_R}{T_R} (V_{ref} - V_t) \quad \dots (4)$$

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State space model is given by:

$$p\begin{bmatrix}\Delta\omega\\ \Delta\delta\\ \Delta I_d\\ \Delta E_{fd}\end{bmatrix}=\begin{bmatrix}a_{00} & a_{01} & a_{02} & a_{03}\\ a_{10} & a_{11} & a_{12} & a_{13}\\ a_{20} & a_{21} & a_{22} & a_{23}\\ a_{30} & a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\\ \Delta I_d\\ \Delta E_{fd}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ 0\\ b_4\end{bmatrix}\bar{u}$$

Where, $a_{00}=\frac{-K_D}{M}$, $a_{01}=\frac{-K_6}{M}$, $a_{02}=\frac{-K_5}{M}$, $a_{03}=0$; $a_{10}=1$, $a_{11}=0$, $a_{12}=0$, $a_{13}=0$; $a_{20}=0$, $a_{21}=\frac{-K_4}{T'_{do}}\left(\frac{x_d-x'_d}{x'_d}\right)$, $a_{22}=\frac{-1}{T'_{do}}\left(1+K_3\left(\frac{x_d-x'_d}{x'_d}\right)\right)$, $a_{23}=\frac{1}{T'_{do}x'_{do}}$; $a_{30}=0$, $a_{31}=\frac{-K_8K_R}{T_R}$, $a_{32}=\frac{-K_7K_R}{T_R}$, $a_{33}=\frac{-1}{T_R}$, $b_4=V_{ref}$

2.2 Design of PSS [15]

The PSS is commonly used in the power industry as a second-order, single-input dynamic compensator with the transfer function.

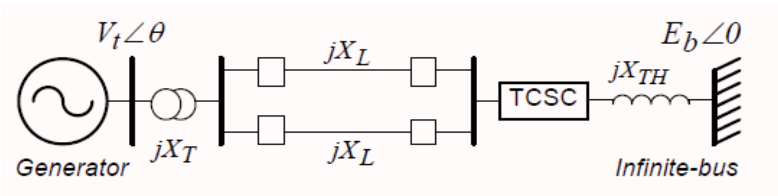
$$PSS(s)=\frac{\theta_o s^2+\theta_1 s+\theta_k}{s^2+\gamma_1 s+\gamma_k}$$

PSS is created via pole positioning method.

2.3 Design of TCSC[23]

The SMIB system integrated with TCSC is displayed in Fig 2 [8].

Figure 2: SMIB System with TCSC



Modifying the firing angle of the thyristor is necessary to change the reactance of the TCSC. This phenomenon can be defined as a sudden alteration in the reactance that is supplied to the power system [4]. Variations may occur due to changes in the firing angle or the conduction edge of the thyristor. The connection is stable. [9].

$$X_{TCSC}(\alpha)=X_C-\frac{X_C^2}{X_C-X_P}\frac{(\sigma+sin\sigma)}{\pi}+\frac{4X_C^2}{X_C-X_P}\frac{cos^2(\frac{\sigma}{2})}{(k^2-1)}\frac{[ktan\left(\frac{k\sigma}{2}\right)-\tan\left(\frac{\sigma}{2}\right)]}{\pi} \quad \dots (5)$$

3.0 Case Study

The appendix contains all the relevant material considered for the case study conducted on the single machine infinite bus system. The paper includes an appendix that conveniently provides this information. Tables 1 and 2 display the open-loop eigenvalues for the variable voltage regulator gain and the machine loads, respectively. Both tables are located below. Figures 3.1 and 3.2 depict the graphs of eigenvalues that correspond to rotor oscillations at various gain levels and machine loadings, respectively. The plots are exhibited for various loadings on the machine. These charts depict various magnitudes of gains across multiple scales.

Table 1: Impact of Altering the Voltage Regulation gain (Kr)

Voltage Regulation Gain (Kr)	Open Loop Eigen Values
20	0.0711 ± 6.3040i
30	0.1335 ± 6.3351i
40	0.1821 ± 6.3758i
50 (Base Case)	0.2168 ± 6.4198i
60	0.2406 ± 6.4639i
70	0.2551 ± 6.5051i
80	0.2627 ± 6.5433i

Figure 3: The Impact of Kr Variation on Rotor Oscillations

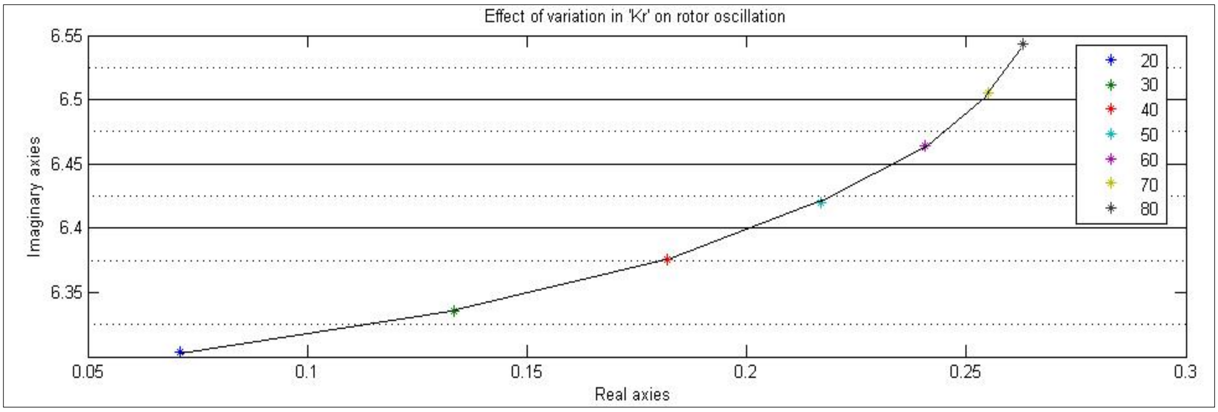


Figure 3 illustrates that as the gain of the voltage regulator increases, the real and imaginary components of the eigen values also rise in proportion to the rotor's increasing frequency of oscillation. This is demonstrated by the fact that when the gain of the voltage regulator increases, the rotor's frequency of oscillation also increases. This illustrates that the damping coefficient reduces as KR rises, and that an increase in KR also leads in an increase in the frequency of oscillations. Additionally, this demonstrates that an increase in KR also results in an increase in the amplitude of oscillations.

Table 2: Fluctuation in the Amount of Power Required

Power Consumption in p.u.	Open Loop Eigen Values
0.25	0.0018±7.3698i
0.50	0.0206±7.2457i
0.75	0.0668±6.9858i
1 (BASE CASE)	0.2167±6.4196i
1.1	0.5925±5.7098i

Figure 4 shows that when machine loading is increased, the real component of eigenvalues with respect to rotor oscillations increases and the imaginary component of the same values decreases. This causes the damping coefficient to drop, which in turn causes the frequency of rotor oscillations to drop, even as the machine's loading increases.

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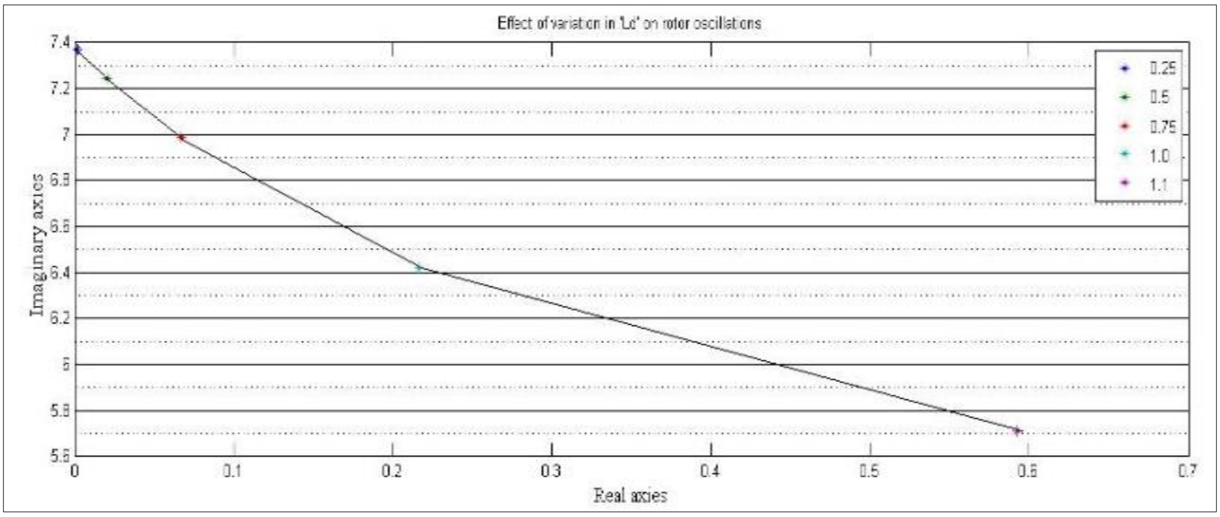
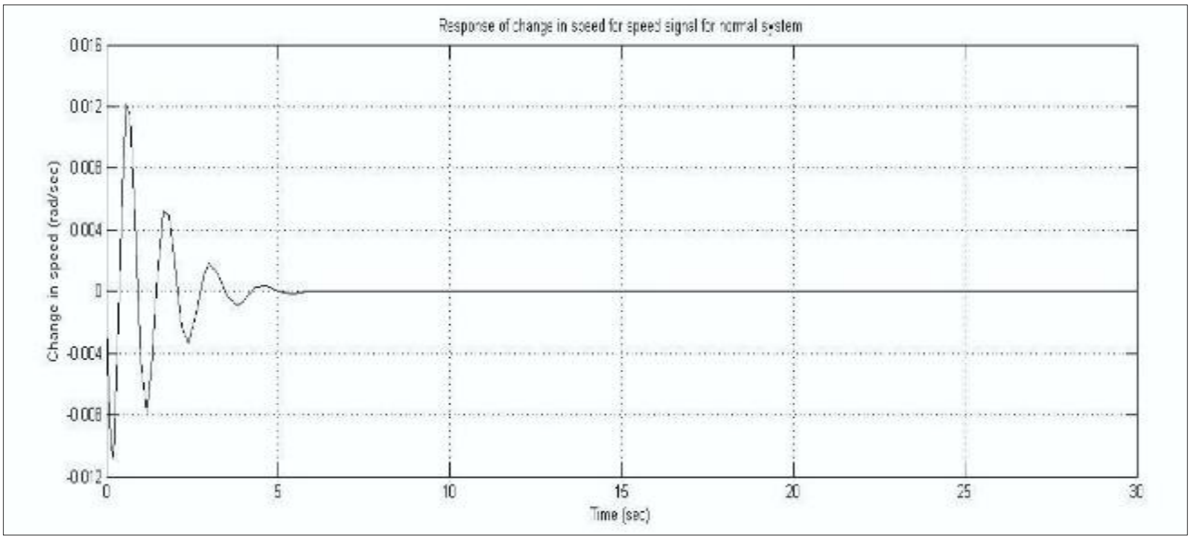
Figure 4: Rotor Oscillations as a Function of Load Variation



At every stage of development, the PSS was tailored to work with the system. The output feedback signal takes the rotor speed as its input. The closed-loop system's eigenvalue assignment was the design goal that was considered. Figures 5 and 6 show that the closed-loop system's and variables' temporal response, Δϋ and δ, is measured by making a step change in Vref. The figures clearly show this. After deploying the system, it becomes reliable due to the introduction of PSS.

Figure 5: Results Demonstration for the Change in Speed for the Normal System's Speed Signal



A change in rotor angular speed and Vref's temporal reaction is shown in Figures 7 and 8. The figures show a TCSC controller that controls this response. Using TCSC results in a more stable system operating environment, according to the research.

Figure 6: Ratio of Angular Position Change to Speed Signal in a Typical System

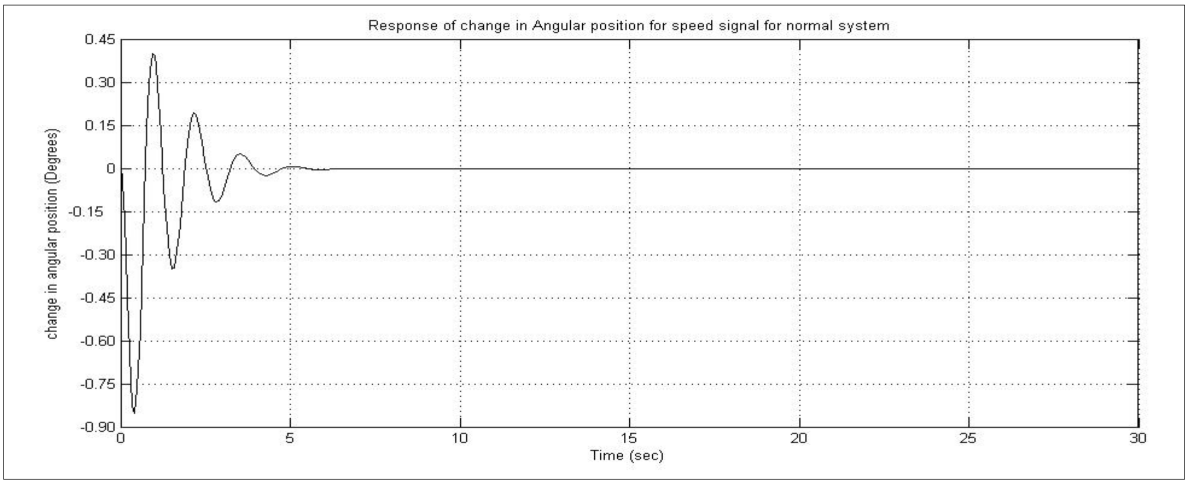


Figure 7: Response Time to a Variation in Rotor Speed (Δω)

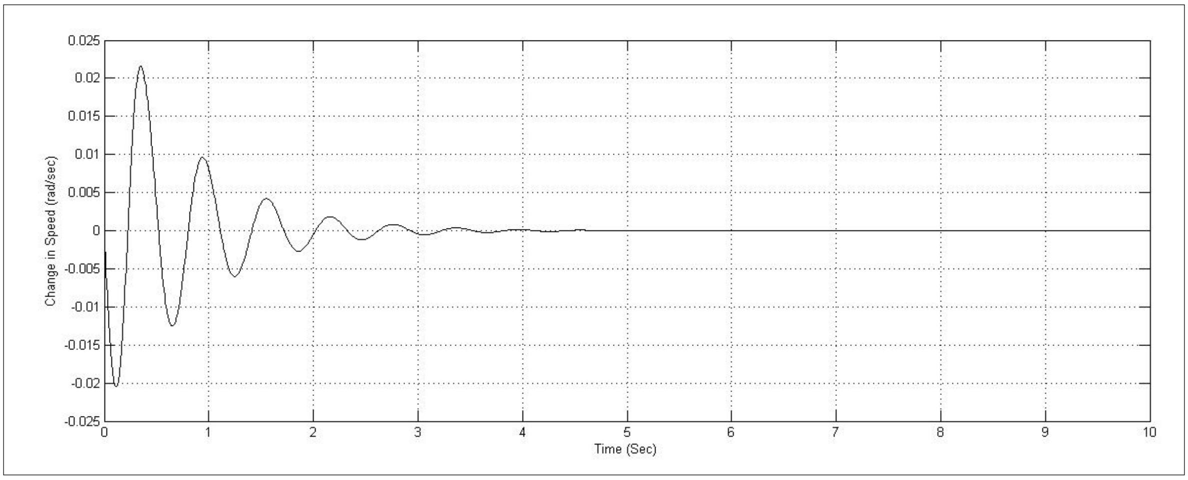
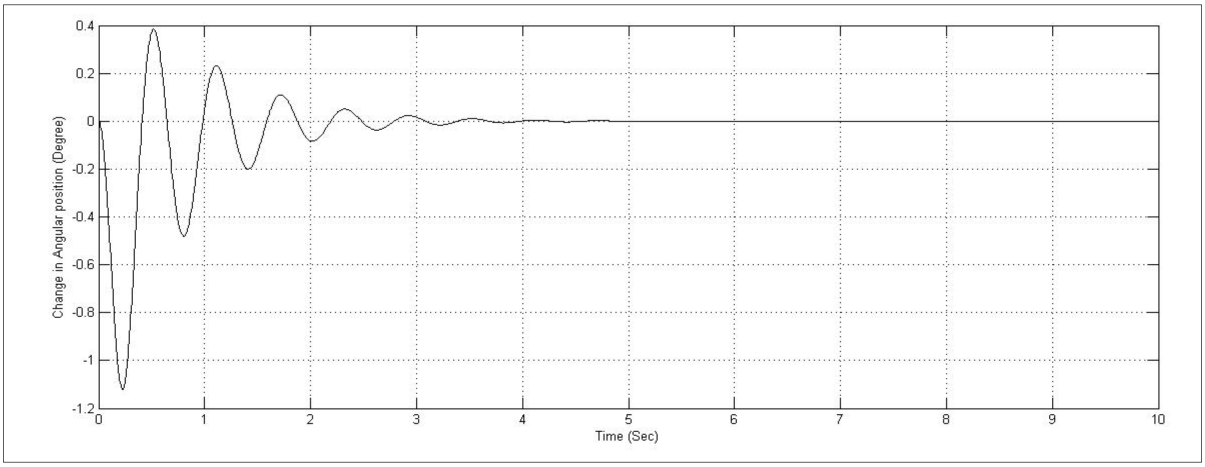


Figure 8: Rotor Angular Position Change Time Response (Δδ)



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By employing a pole assignment strategy and collecting one control signal at a time, PSS was designed to handle the three separate scenarios that were considered. In order to accommodate the data, this measure was implemented. To test the effectiveness of control signals across different system strengths, we have chosen five closed loop Eigen values. These spots can be located in -1 ±j7, -2.0, -6.0, -1.0. You can find more details about the closed-loop Eigen values for each of the discovered system strengths in the table that follows:

Table 3: Closed loop Eigen values for Strong System

Signal for Speed	Dynamic Signal for power	Signal's Frequency
-47.7119	-44.1457	-45.2311
-0.7767±J8.3808	-0.8664±J7.1693	-0.8421±J7.1887
-6.1223	-6.0056	-5.9327
-2.0045	-2.0004	-2.4523
-1.0071	-0.9998	-0.9901

Table 4: Closed Loop Eigen values for Normal system

Signal for Speed	Dynamic Signal for power	Signal's Frequency
-46.1068	-42.2823	-40.8524
-0.9223±J7.2714	-0.7224±J6.2779	-2.2438±J4.4477
-5.9735	-5.3846	-6.4836
-2.5436	-0.9994	-1.8478
-0.8492	-2.6873	-2.8455

Table 5: Closed Loop Eigen Values for Weak System

Signal for Speed	Dynamic Signal for power	Signal's Frequency
-45.0265	-44.8353	-40.8524
-0.9906±J6.2613	-0.6784±J5.5638	-2.2438±J4.4478
-0.7871	-0.4284	-1.8476
-3.7727	-3.3426	-2.8457
-5.6955	-5.7233	-6.4835

Figure 9: Speed Response for a Robust System

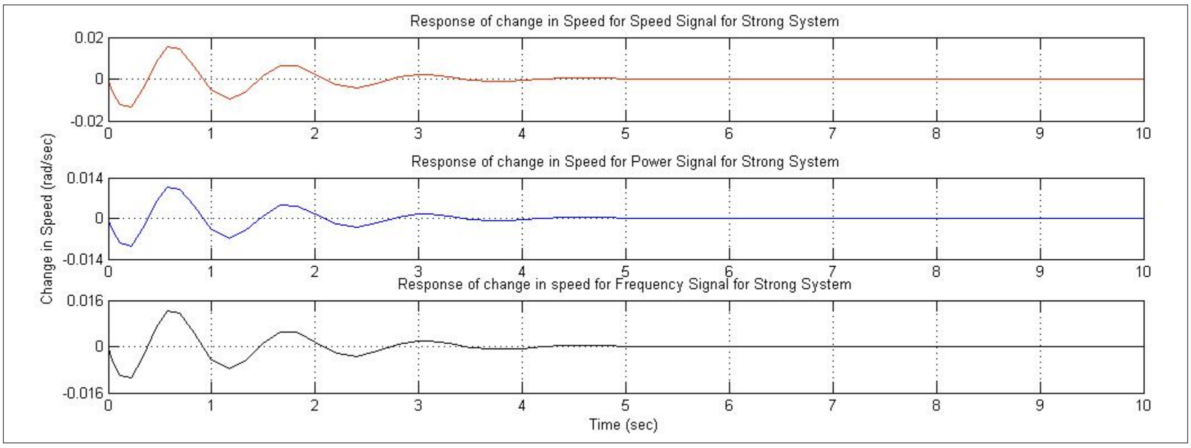


Figure 10: Strong System's Reaction to Angular Position Change

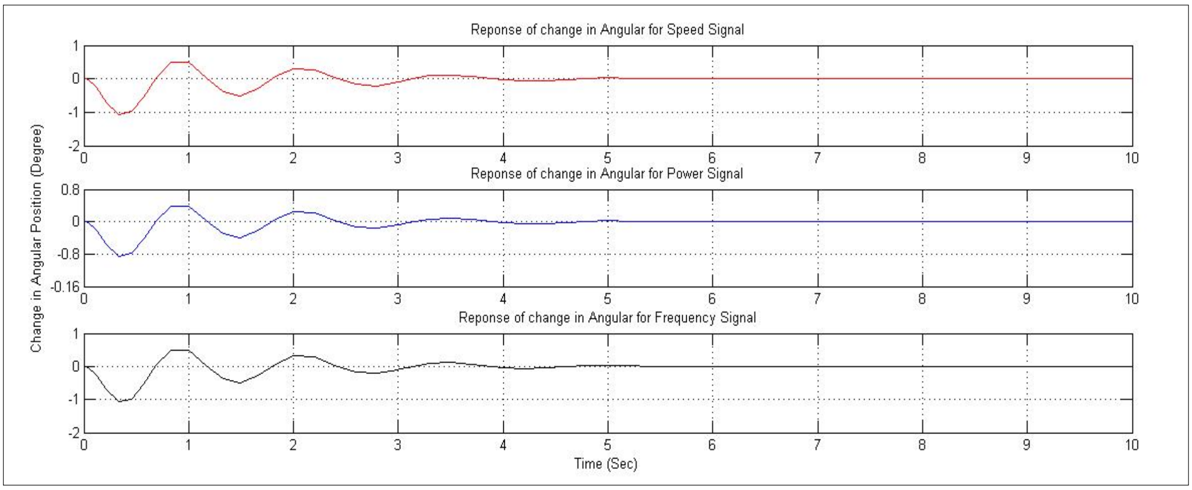


Figure 11: Normal System Speed Response to Change

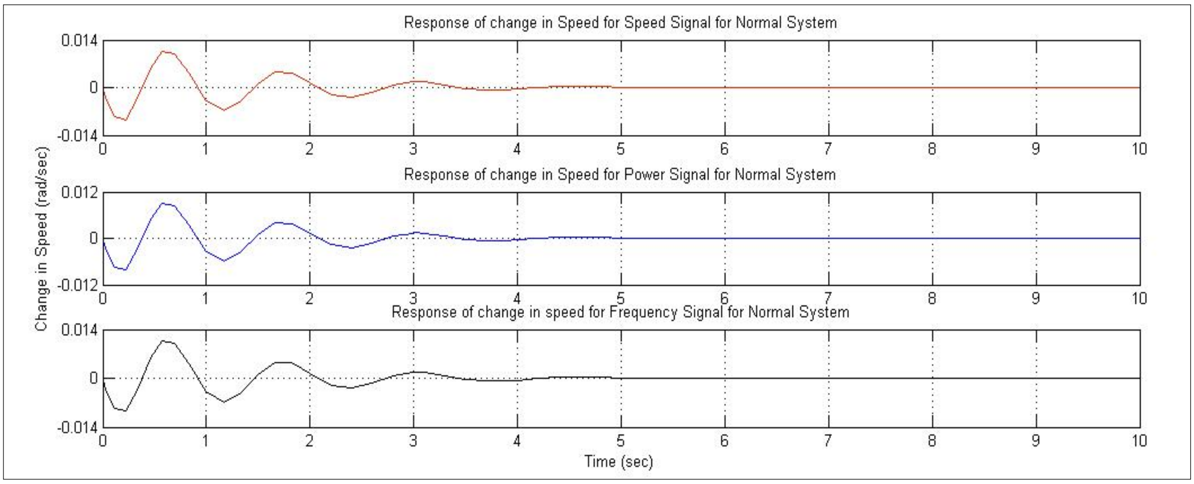
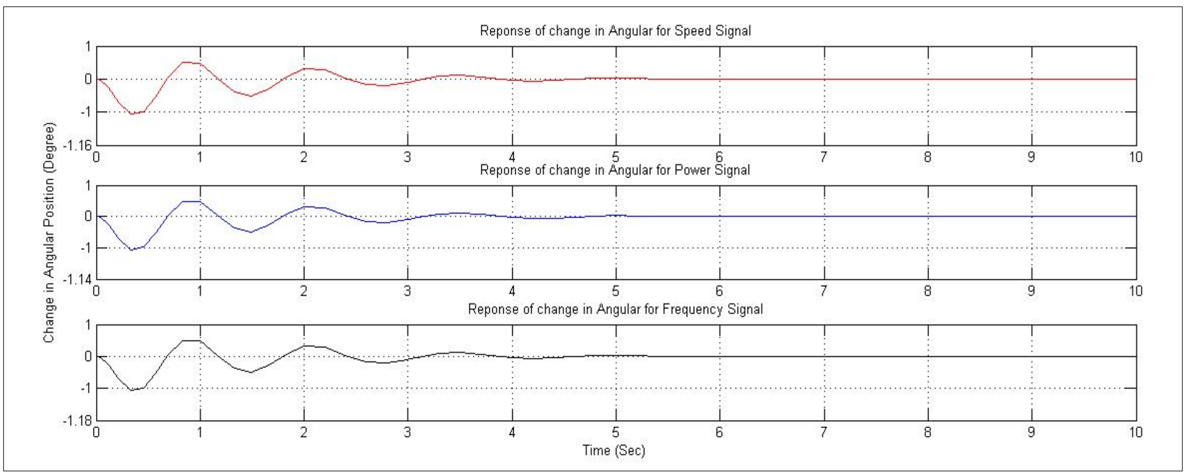


Figure 12: Reaction to Angular Displacement in the Normal System



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The design's goal of assigning five closed loop poles to each instance was met, and the sixth eigenvalue was located at a considerable distance from the origin, as shown in Tables 1, 2, and 3. In order to investigate the efficacy of various control signals, a time response analysis is performed on each individual case while considering a step change in the reference voltage. In order to find the most effective control signals, this analysis is done.

Figure 13: The Weak System's Reaction to a Change in Speed

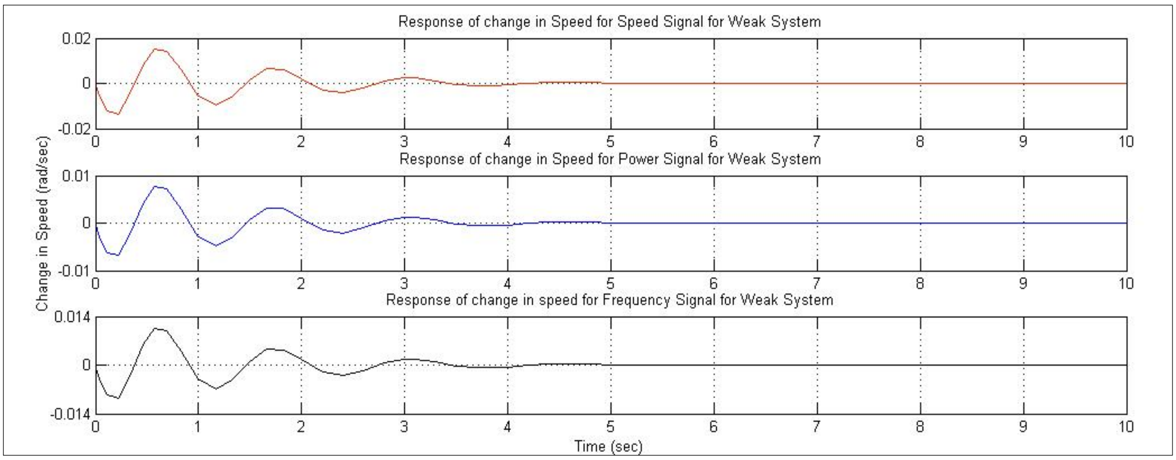
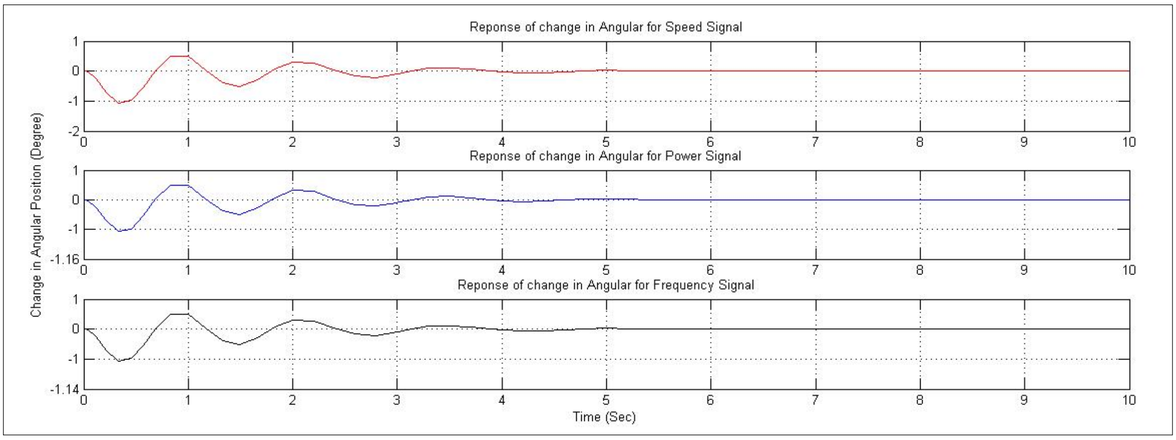


Figure 14: The Weak System's Reaction to Angular Position Changes



The power signal outperforms the speed and frequency signals in all operating scenarios, as shown by the temporal response of and for a step change in reference voltage. In comparison to the other two signals, this holds true. The signal's speed or frequency makes no difference; this remains true regardless. Efficiency is, without a doubt, the single most important consideration when designing robust systems.

4.0 Conclusion

It is possible to learn what happens when the voltage regulator gain and load demand are changed by using the outcomes of an eigenvalue analysis. As can be observed from the eigenvalue plots for rotor oscillations, the system's instability increases as both values are increased. It is possible to further enhance the SMIB system's tiny signal stability by utilizing PSS and TCSC. Prior to considering any other considerations, the PSS design prioritized finding the correct location for the eigenvalue. An analysis was performed in both the frequency domain and the temporal domain. Using TCSC is better than PSS when it comes to stabilizing the system, even though both strategies have that potential. The rotor's speed and angle responses over time can demonstrate this. The PSS's ability to process extremely tiny signals is enhanced by utilizing a range of feedback control signals. This is accomplished by making use of various feedback control signals. It is evident that the power signal outperforms the speed and frequency signals when comparing the rate of change of rotor speed and angle in response to a step change in reference voltage. This is what happens when you watch the rotor respond to a step change.

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