

Article

# Small signal stability analysis of typical power system and its improvement using power system stabilizer

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Received: 29 July 2024; Accepted: 23 February 2026; Published: 04 May 2026

**Abstract:** The modern power network is composed of a huge number of transmission lines and generators. The synchronous generator modelling and its stability analysis are crucial in a power system network. The single machine is analyzed with Phillips Heffron or K1 to K6 model, usually all constants are positive in the general case. In a few cases, the constants K4 and K5 are negative; for high values of external system reactance and high generator outputs, K5 becomes negative. With a negative K5 value automatic voltage regulator action introduces a positive synchronizing torque and negative damping torque. The classical system usually has a positive K4 value; as long as it is positive, it introduces positive damping torque. In some special situations, it can become negative; hence, this article aims to show that typical power systems lead to negative K4 values and their effects on system small-signal stability. The two typical power systems lead to negative K4 values being realized and modeled for stability study in this article, and the improvement of small signal stability is achieved with the design and implementation of a PID controller and power system stabilizer. Finally, comparison is performed without any controller, with a PID controller, and with power system stabilizers on small signal stability; the results prove the effectiveness of the PSS on SSS improvement.

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## 1. Introduction

The interconnected power system comprises a huge number of network components like generators, transformers and transmission lines. Power system stability plays a key role in power system performance and in preventing outages or power interruptions. The power system stability has been classified into

**How to cite this article:** Ambati, Giriprasad; Devi, G. Anjali; Sudhakar, T.; Yarlagadda, Venu; Duvvuru, Raja Reddy; Babu, B. Ganesh; Reddy, Ch. Rami. Small signal stability analysis of typical power system and its improvement using power system stabilizer. *Transactions on Energy Systems and Engineering Applications*, 7(1): 726, 2026. DOI:10.32397/tesea.vol7.n1.726

steady state, transient and dynamic stability and it is due to a lack of positive damping torque or a lack of synchronizing torque [1]. It is possible to notice LFOs in power systems as a result of a variety of disruptions. These LFOs will continue to develop and eventually bring the system to its knees if they are not managed. Additionally, the capability of the system to transfer power is impacted as a result of LFO. A disturbance causes a change in the electromagnetic torque of an SM, which can be broken down into two components: the synchronizing torque and the damping torque. This change can be rectified after the disturbance has occurred [2]. There is no assurance that the requisite damping torque will be delivered by automatic voltage regulators with high gain and rapid action; yet, the synchronization torque was provided by these regulators [3]. Consequently, PSS is incorporated into the system to supply a suitable amount of damping torque. The traditional PSS was developed with the intention of functioning in a state of constant operation. As a result, the performance of the Conventional Power System Stabilizer (CPSS) was discovered to be inadequate when the operating conditions were altered [4]. In light of this, a number of different optimization strategies have been utilized in order to fine-tune the parameters of the stabilizer. The PID controller is a controller that has been utilized in a variety of industrial applications due to its efficiency in power systems [5,6]. When it comes to dampening the local modes of oscillations, the PSS is an efficient tool. The power system is characterized by a number of different oscillation modes, including the local, interarea, control, and torsional modes, among others [7]. The FACTS device known as TCSC is integrated with PSS in order to accomplish the task of controlling oscillations in both the local and inter-area modes [8,9]. A comparison is made between the various simulation models. Using a novel meta-heuristic SOA [10,11], the parameters of the PSS, PID, and CPT models are modified to achieve optimal performance [12,13]. A knowledge-based system has recently offered a new algorithm that has the primary benefits of exploration and exploitation [14,15]. Over the course of the last few decades, researchers have been conducting research on renewable power-generating systems. These systems primarily include wind, biomass, solar, and micro hydro systems [16]. When there is a rise in the output of energy from renewable sources such as wind farms, solar, and photovoltaic installations, there is a decrease in the inertia constant of the power system as well as the stored kinetic energy. This results in an increase in the difficulties associated with maintaining stability [17,18]. Inter-area modes of oscillation are becoming more prevalent in the system as a result of the growing number of photovoltaics that have been deployed. In the case of renewable energy sources, there are issues that arise from environmental conditions that are unexpected and unpredictable [19]. This NGHPM is able to overcome these difficulties and problems associated with the integration of renewable energy sources into the grid. With the implementation of this approach, the system is now safe, secure, and reliable. The design and tweaking of the parameters of PSS have been accomplished through the utilization of a number of different algorithms, such as MAOA, MASO, TSA, and STT [20–23]. This is accomplished through the utilization of a time delay technique [24] and a unique HWOA-NMA [25] for synchronized PSS and FACTS devices. In order to dampen oscillations, the delay-dependent DOFC technology is utilized [26]. Additionally, SSSC and PSS are utilized in the implementation of Type-2 Fuzzy Lead-Lag-Structured to enhance stability [27]. The results that these algorithms produced were encouraging. However, according to the Free Lunch Theory, there is always the possibility of improvement, and there is no algorithm that can solve all of the technical jobs involved [28,29].

The inherent damping of the generator is not sufficient to enhance dynamic stability due to load perturbations or outages. The synchronous machine is analyzed with Phillips Heffron or K1 to K6 model, usually, all constants are positive in the general case. In a few cases, the constants K5 and K4 are negative, for high values of external system reactance and high generator outputs the K5 becomes negative. With a negative K5 value Automatic Voltage Regulator (AVR) action introduces a positive synchronizing torque and negative damping torque. The classical system usually has a positive K4 value; as long as it is positive,

it introduces positive damping torque [30, 31]. The two typical cases of power systems have been modelled with K1 to K6 constants and these typical results have been considered in negative values of K5 and K4. In some special situations, it will become negative; hence, this article deals with the modelling of a typical power system. The typical power systems may arise in two distinct types. One type of situation arises when a hydraulic generator i.e., a projected or salient pole type generator without damper bars, is operating at a lightly loaded condition connected to a line of relatively high resistance to reactance ratio to a large system with plenty of generating resources [32]. The second situation arises when a single machine is connected to a large local load and it is supplied partly by the generator and partly by the large remote system [33]. Under these situations, the torques produced by the induced currents in the field due to armature reaction have components out of phase with the angular frequency and produce negative damping [34, 35].

This article focused on the realization that typical power systems lead to negative K4 values and their effects on system small signal stability (SSS). The small signal stability of a typical power system is modelled and a transfer function model with appropriate values of constants from K1 to K6. The MATLAB Simulink models of the said system were developed without any controller, with a PID Controller and with a PSS. The simulation is carried out and the results have been presented and analyzed in three cases. In the case of one without any controller, the swing curves have been plotted and analyzed for stability in terms of oscillations and steady-state settling time. Case two with PID controller and case three with PSS have been simulated and analyzed for the SSS of a typical power system in terms of oscillations and steady-state settling time. In the last part of the article, a comparison is made for all three cases, and a conclusion is made as on the merit of the result.

The main author's contributions in this research are as follows,

- Phillips Heffron or K1 to K6 model has been developed for a typical hydro power system and steam power systems with negative K4 and K5 constants.
- Designed and developed PID controller for improving the small signal stability of the said systems.
- To improve the dynamic stability of the typical system, the power system stabilizers.
- A comparative assessment has been made between PID controllers and power system stabilizers on the improvement of small signal stability.
- Time domain simulations are performed using negative damping torque with negative K4 and K5 constants and achieved positive damping torque.

The remaining paper is organized into the following sections. The second section discusses the system description; the third section presents small-signal stability with power system stabilizers; the results with the PID controller are discussed in section four; and, lastly, the conclusions are presented in section five.

## 2. System description

This section describes the typical power systems one and two, along with the mathematical modelling of the typical power system.

### 2.1. Typical power system - I

The Synchronous machine is modelled with K1 to K6 model or the Phillips Heffron Model, in which each part of the synchronous machine is modelled with its differential equation and its transfer functions. All these blocks are interconnected to obtain the complete model of a single machine with appropriate constant values of K1 to K6.

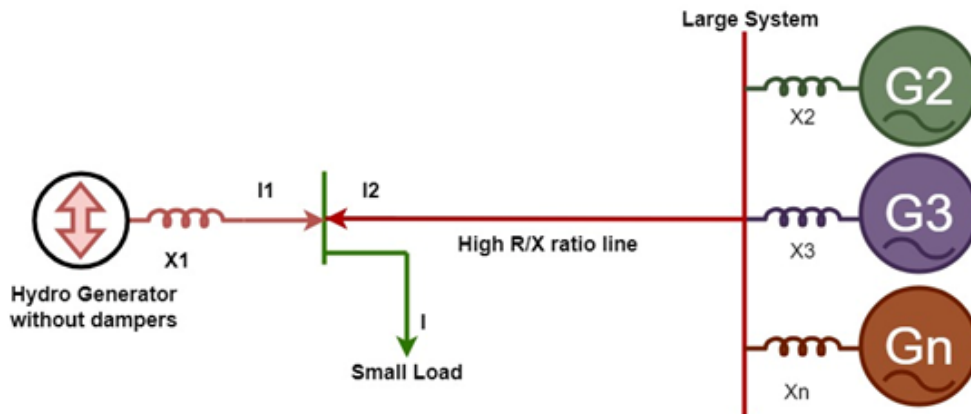


Figure 1. Typical power system one leading to - K4 value.

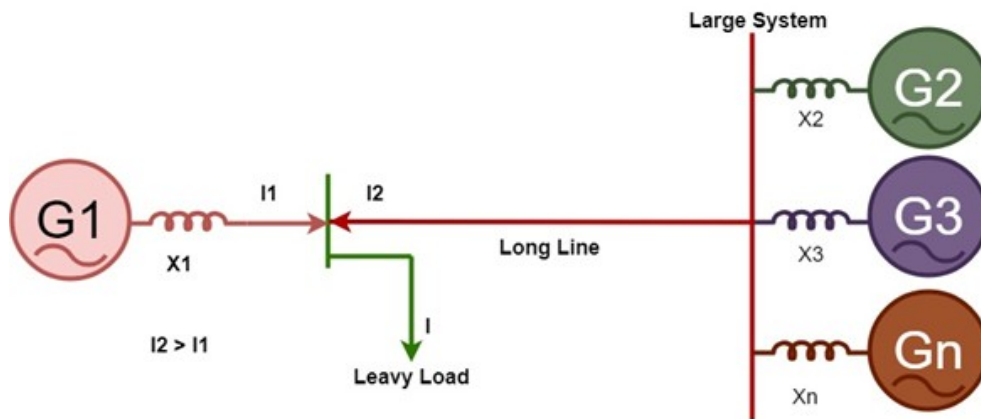


Figure 2. Typical power system two leading to - K4 value.

The same method is now extended to obtain the complete model of a typical power system. Figure 1 illustrates the typical Power System one leading to a negative K4 Value, which comprises a hydro power generator i.e., a projected pole or salient pole machine, which has a dumbbell-shaped rotor without damper winding. The hydro generator without damper windings having a direct axis reactance of  $X1$  is connected to a small load at bus 1 and is connected to a transmission line of high resistance to reactance ratio, as shown in Figure 2. The line is connected to a large system comprising many generators with plenty of generating resources at bus 2. The small load located at bus1 is fed partially by the hydro generator and partially by the large system.

### 2.2. Typical Power system - II

The typical power system two is illustrated by Figure 2, which consists of a single machine connected to bus 1 to which a large load is connected and a long transmission line is connected. The line is fed by a large system comprising many of the generators with plenty of generating resources. The generator is feeding the load with a small amount of current  $I1$  and the large system is supplying a load current of  $I2$ . Usually  $I2 > I1$  and leads to negative damping torque due to a negative K4 value.

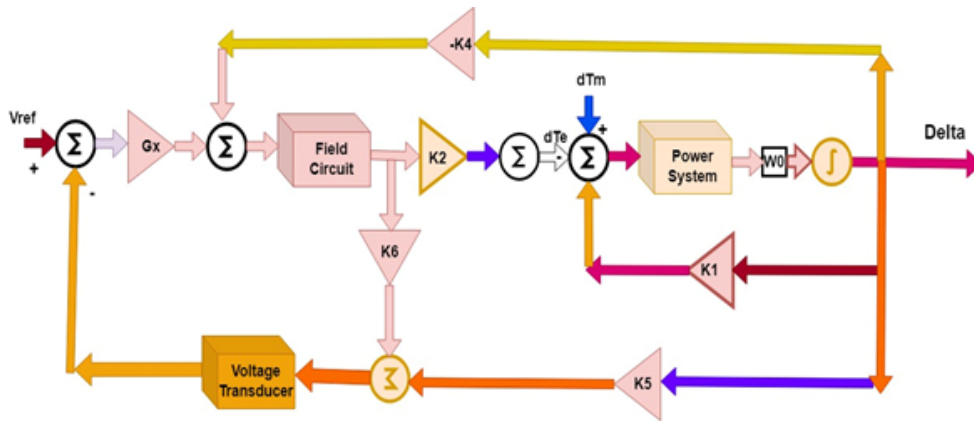


Figure 3. Typical power systems one and two model without any controller.

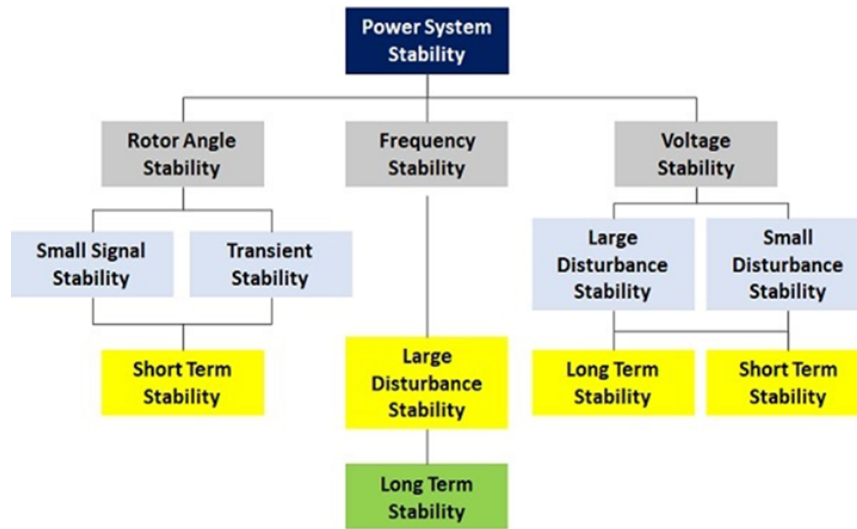
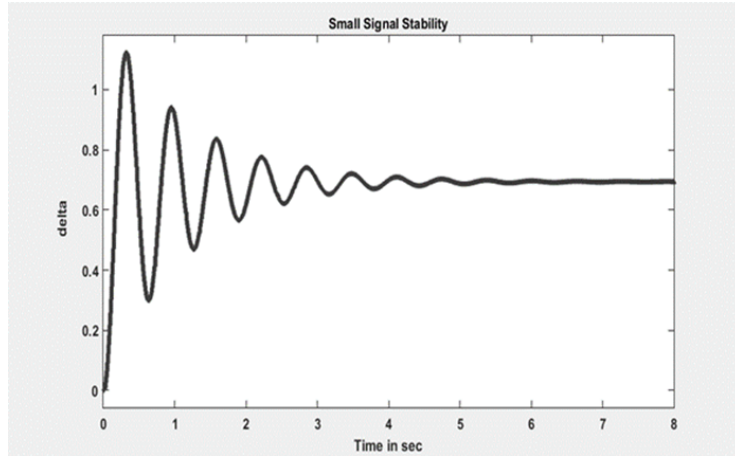


Figure 4. Power system stability stratification.

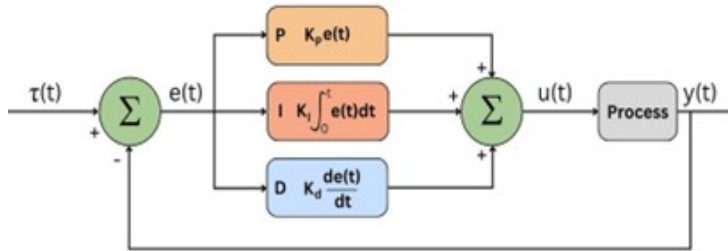
2.3. Mathematical modelling

The mathematical modelling of typical power systems has been obtained starting with a single machine system with the following set of equations listed below from Equations (1) to (23), and for the systems described earlier i.e., typical power system 1 and typical power system 2, the K5 value of the system is negative due to high values of external system reactance and high generator outputs. The Equations (18) to (21) describes the expressions for K4 associated terms which is crucial for our typical power systems 1 and 2, K4 is expressed in terms of total reactance and resistances of the transmission system to which machine and loads are connected, in both the typical systems the resistance term is greater than the inductance term as it expressed by the term.  $(X_{Tq} \sin \delta_0 - R_T \cos \delta_0)$  Since in typical systems, the resistance term is greater than the inductance term. In system one, it is so because the line which is connected to the large system has having high R/X ratio and in system 2 it is due to armature reaction having the components out of phase with the angular frequency. Figure 3 describes the typical Power Systems one and two transfer function model with negative K5 and K4 values without any controller for the said systems.

The power injected by the incoming generator is illustrated in Equation (1), expressed in terms of voltages and reactance and load angle. Equation (2) describes the power injected by the incoming generator



**Figure 5.** Swing curve illustrating dynamic stability.



**Figure 6.** Schematic of PID Controller.

to the power system, Equation (2) gives the expression for the total reactance, Equation (3) gives the simplified expression of power injection, Equation (4) describes about excitation system, Equation (5) describes the electrical torque and TE is excitation system time constant. Equations from (6) to (9) describe the voltage expressions. Equations (10) and (11) give the expressions of direct axis and quadrature axis current expressions, Equations from (12) to (14) describe the torque equations, Equation (15) describes the synchronizing torque coefficient and Equation (16) describes the state space model of rotor dynamics of synchronous machine. Equation (17) represents the field circuit dynamics and T3 is its time constant. Equations (18) to (25) describe the modelling of the typical power systems one and two as mentioned earlier, and K4 will become negative, which introduces the negative damping; therefore, overall, the small signal stability of the typical power systems deteriorates to some extent, and it can be minimized by the use of a power system stabilizer and subsequently presented in this article. The first part of the result analysis focused on the system behaviour without any controller, the second part with the PID Controller and lastly, the PSS and its companion with two earlier cases.

$$P_e = \frac{|\tilde{E}| |\tilde{V}|}{X_t} \sin \delta + \frac{|V|^2}{2} \left( \frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta, \tag{1}$$

$$X(t) = x'_d + x_e = x'_d, \tag{2}$$

$$P_e = \frac{|E'| |V|}{X_t} \sin \delta = P_{\max} \sin \delta, \tag{3}$$

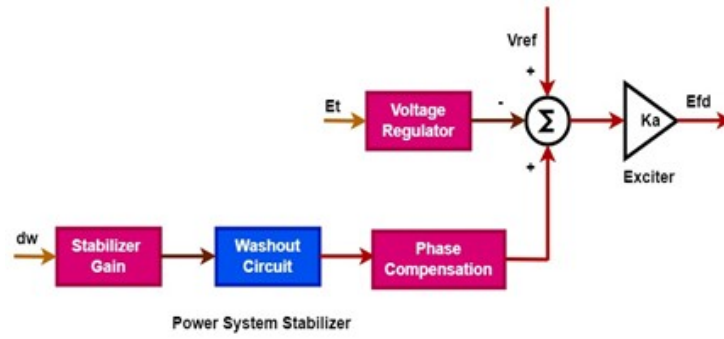


Figure 7. Schematic of PSS.

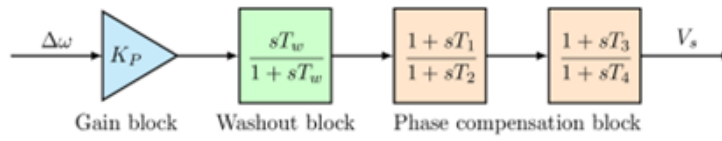


Figure 8. Transfer function model of power system stabilizer.

$$E_{fd} = \frac{K_E}{1 + sT_E} (V_{ref} - V_t), \quad (4)$$

$$T_e = E'_q i_q - (x_q - x'_d) i_d i_q, \quad (5)$$

$$E'_q + x'_d i_d = v_q, \quad (6)$$

$$-x_q i_q = v_d, \quad (7)$$

$$V_q = -x_e i_d + R_e i_q + v_{qL}, \quad (8)$$

$$V_d = R_e i_d + x_e i_q + v_{dL}, \quad (9)$$

$$\Delta i_q = Y_q \Delta E'_q, \quad (10)$$

$$\Delta i_d = Y_d \Delta E'_q, \quad (11)$$

$$\Delta T_e = K_2 \Delta E'_q, \quad (12)$$

$$\Delta T_e = K_1 \Delta \delta + K_2 \Delta E'_q, \quad (13)$$

$$\Delta T_e = \frac{\partial T_e}{\partial \delta} \Delta \delta = \frac{E'_E B}{X_T} \cos(\delta_0) \Delta \delta, \quad (14)$$

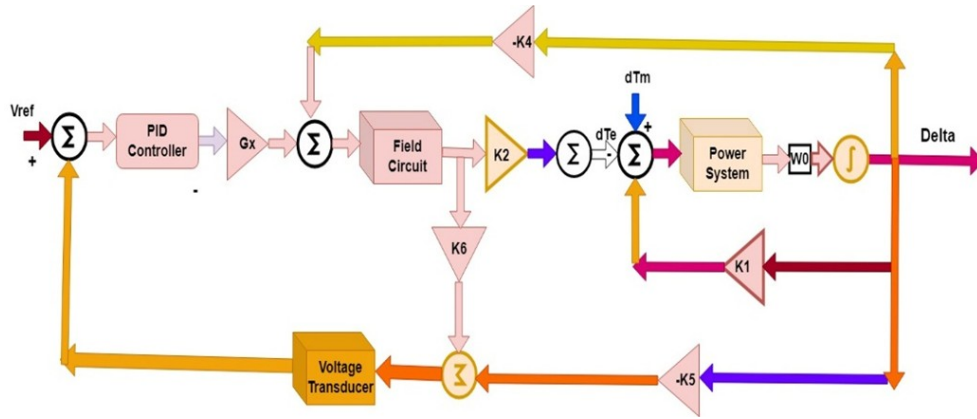


Figure 9. Typical power systems one and two model with PID controller.

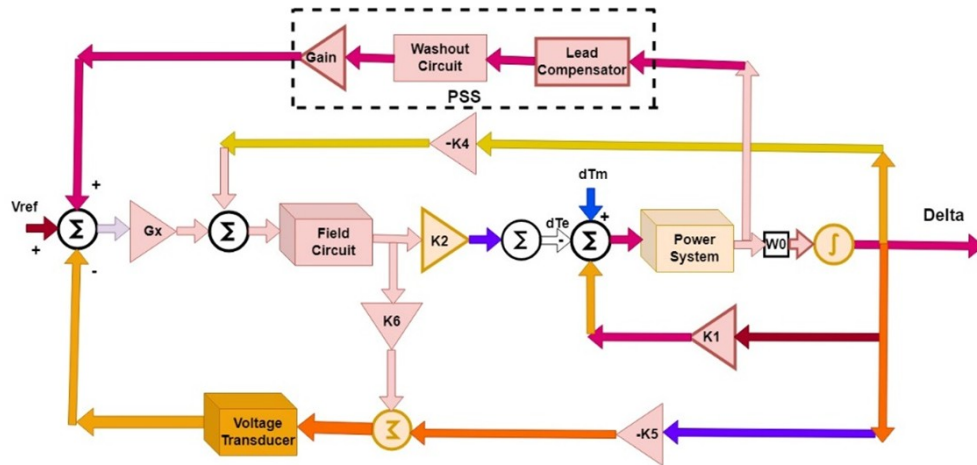


Figure 10. Typical power systems one and two model with PSS.

$$K_S = \frac{EE_B}{X_T} \cos \delta_0, \tag{15}$$

$$\frac{d}{dt} \begin{bmatrix} \Delta\omega \\ \Delta\delta \end{bmatrix} = \begin{bmatrix} -\frac{K_D}{2H} & -\frac{K_S}{2H} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} \\ 0 \end{bmatrix} \Delta T_m, \tag{16}$$

$$\Delta\psi_{fd} = \frac{K_3}{1 + sT_3} [\Delta E_{fd} - K_4\Delta\delta], \tag{17}$$

$$K_4 = \frac{E_B}{D} (X_d - X'_d)(X_{Tq} \sin \delta_0 - R_T \cos \delta_0), \tag{18}$$

$$X_{Tq} = X_E + X_q, \tag{19}$$

$$R_T = R_E + R_a, \tag{20}$$

$$(X_E + X_q) \sin \delta_0 - (R_E + R_a) \cos \delta_0, \tag{21}$$



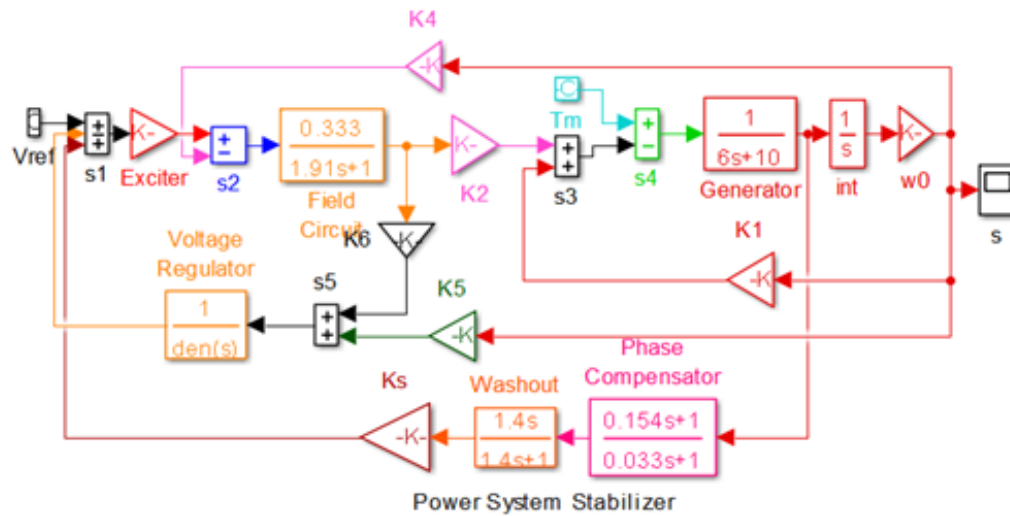


Figure 13. Simulink model with PSS.

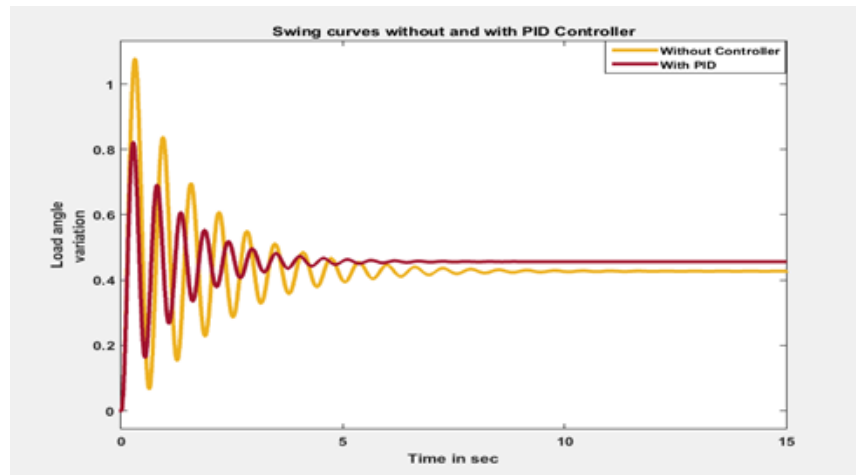


Figure 14. System swing curves without and with PID controller.

### 3. Small signal stability

The classification of the power system stability has been illustrated by Figure 4, and one of the important stability issues for the security of the power system is SSS due to a lack of damping torque and Figure 5 shows the swing curve to illustrate SSS of K1 to K6 models.

#### 3.1. PID controller

The Proportional Integral and Derivative (PID) controller is used to improve the system dynamic and steady state response and small signal stability of the said systems as shown in Figure 6. The PID introduces two zeros and one pole at the origin; the zeros may improve the dynamic performance and the pole at the origin improves the steady state performance of the system. The PID is designed and implemented using the hit-and-trial method and used in simulation for improving its SSS as described by the case study and result analysis section. The mathematical modelling of the PID controller is described by the following Equations from (26) to (28), Equation (28) describes its pole at the origin and zeros at -a and -b locations in the s-plane.

$$G_{\text{PID}} = K_p + sK_d + \frac{K_i}{s}, \quad (26)$$

$$G_{\text{PID}} = \frac{s^2K_d + sK_p + K_i}{s}, \quad (27)$$

$$G_{\text{PID}} = \frac{(s+a)(s+b)}{s}, \quad (28)$$

### 3.2. Power system stabilizer (PSS) model

PSS is tuned for providing the positive damping torque, which mitigates the rotor swings subjected to load perturbations of the oscillation frequency range 1 to 2 Hz. The structure of the PSS comprises three blocks, one is a phase lead block to compensate for the phase lag between the exciter input and the electrical torque of the generator. The design of phase compensation may provide slightly undercompensation, which provides positive damping torque and a slight increase in synchronizing torque. The second block is a washout block that serves as a high-pass filter, which allows the PSS to respond only to speed changes. The time  $T_w$  of the washout block is typically about 1 to 20 sec only. The third block of PSS is the stabilizer gain of  $K_s$ , which determines the amount of damping torque for improving small signal stability. Fig. 7 illustrates the schematic diagram of PSS and Fig. 8 depicts the transfer function model of PSS, as each block has already been described.

## 4. Result analysis

The modelling of the typical power system with negative  $K_5$  and negative  $K_4$  values has been presented in the Table. 1 and it also shows the data considered for the case study and simulation. The Simulink models of the power system model have been developed for the case study and result analysis. Fig. 9 illustrates a typical power system one and two model with a PID controller, and Fig. 10 depicts the typical power systems one and two model with PSS. Fig. 11 shows its Simulink model without any controller and Fig. 12 shows. Simulink model with PID controller and Fig. 13 shows the Simulink model with PSS. The PID controller is designed with  $K_P$  value of 200,  $K_i$  value is of 100 and  $K_d$  value is of 1 and the PSS is designed with  $K_S$  is of 153.5,  $T_w$  is of 1.4 sec,  $T_1$  is of 0.154 sec and  $T_2$  is of 0.033 sec.

The simulation is carried out without any controller and with PID Controller and with PSS and the results and comparison are also made with swing curves and angular frequency deviations and the results of settling time for both load angle deviation and also for angular frequency deviations. The bar charts for settling time of load angle as well as settling time for angular frequency have been plotted and result analysis has been performed and conclusions have been made based on the result analysis in the subsequent section of this article. The simulation of the system has been performed and the results are presented in the following section as Figure 14 illustrates the system swing curves without and with PID Controller, Figure 15 presents the system angular frequency responses without and with PID controller, Figure 16 depicts the system swing curves without and with PSS, Fig. 17 shows the system angular frequency responses without and with PSS, Figure 18 depicts the comparison of system swing curves for different cases and Figure 19 presents the comparison of system angular frequency responses for different cases.

The comparison of the case study and results has been illustrated in Figure 20 and Figure 21, which encapsulates the comparison of the settling time of angular frequency deviation and load angle deviations for three different cases. The settling time of the system with PSS is the least in both cases and shows a significant improvement in the SSS of the system. Both the controllers have improved the performance of the system, especially SSS, but the impact of the PSS is more predominant.

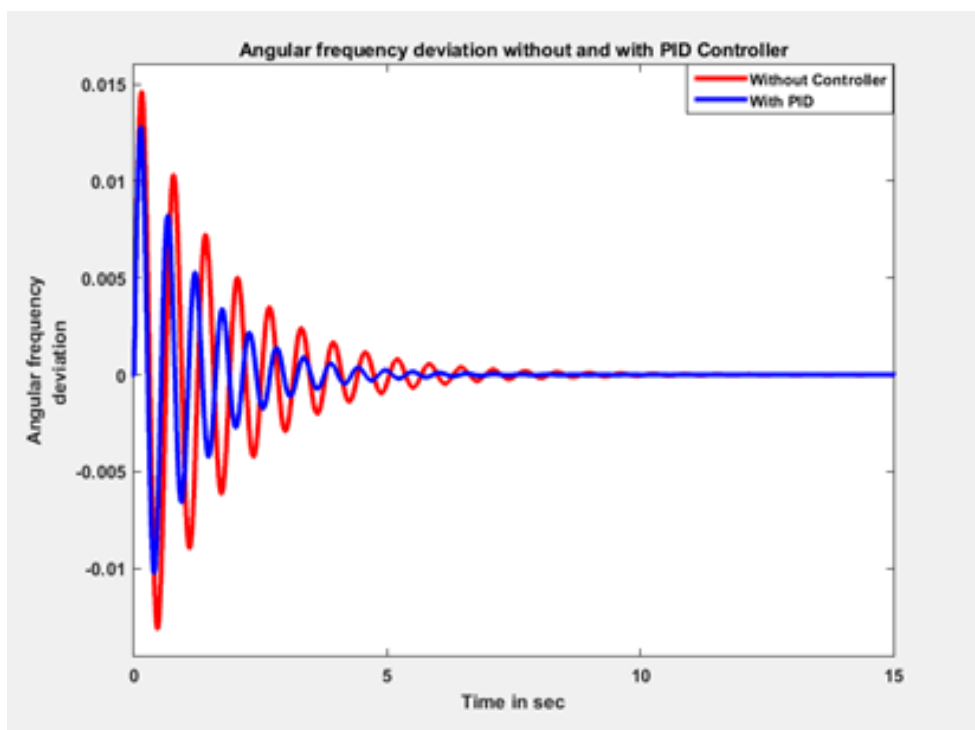


Figure 15. System angular frequency responses without and with PID controller.

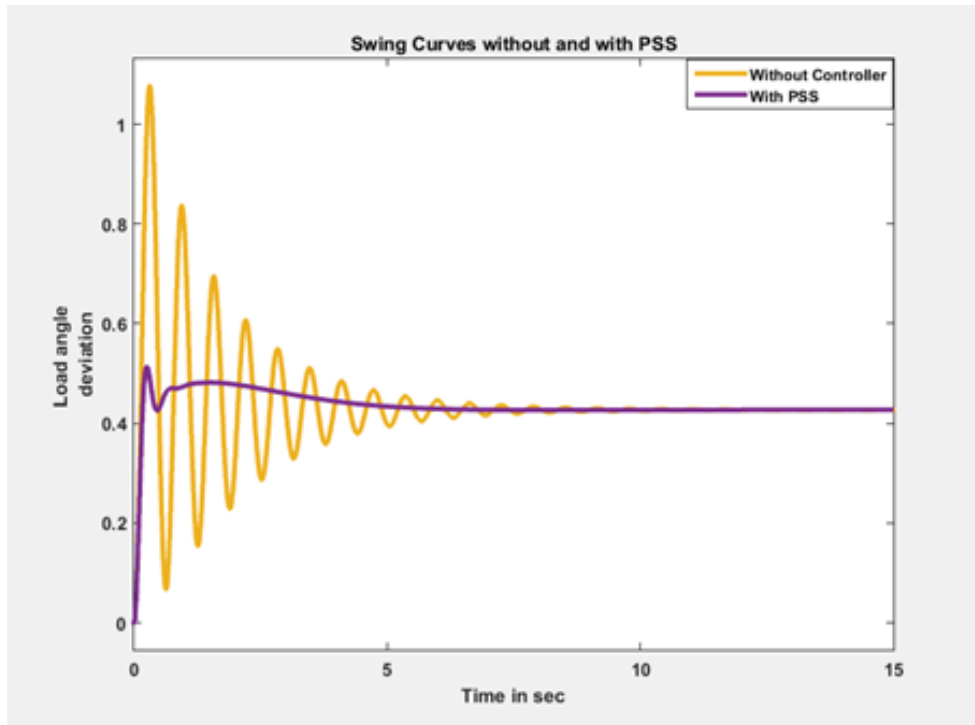


Figure 16. System swing curves without and with PSS.

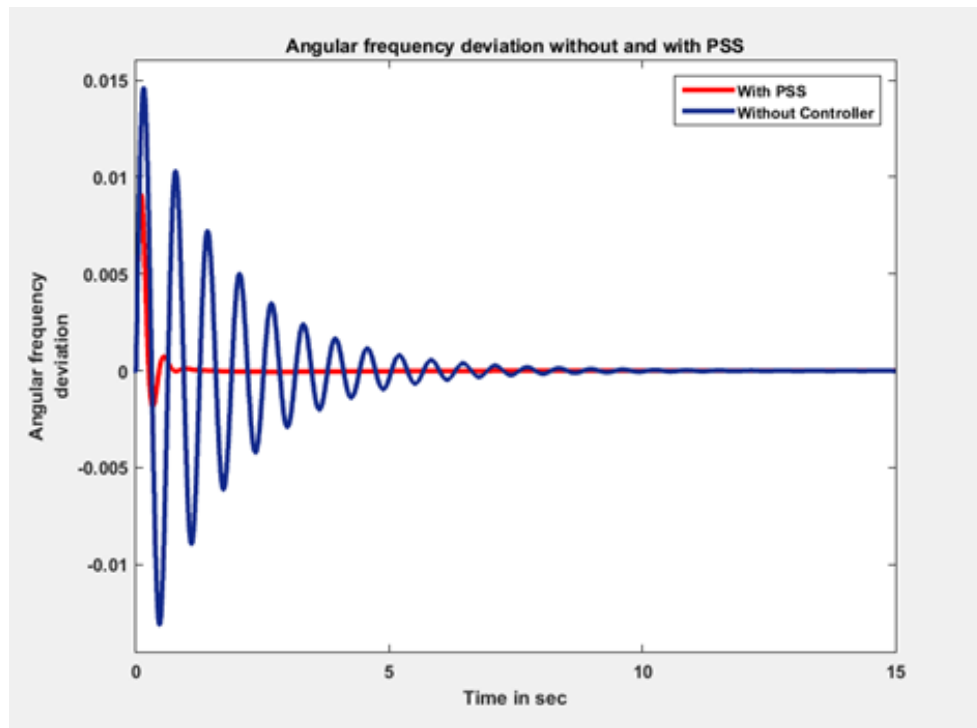


Figure 17. System angular frequency responses without and with PSS.

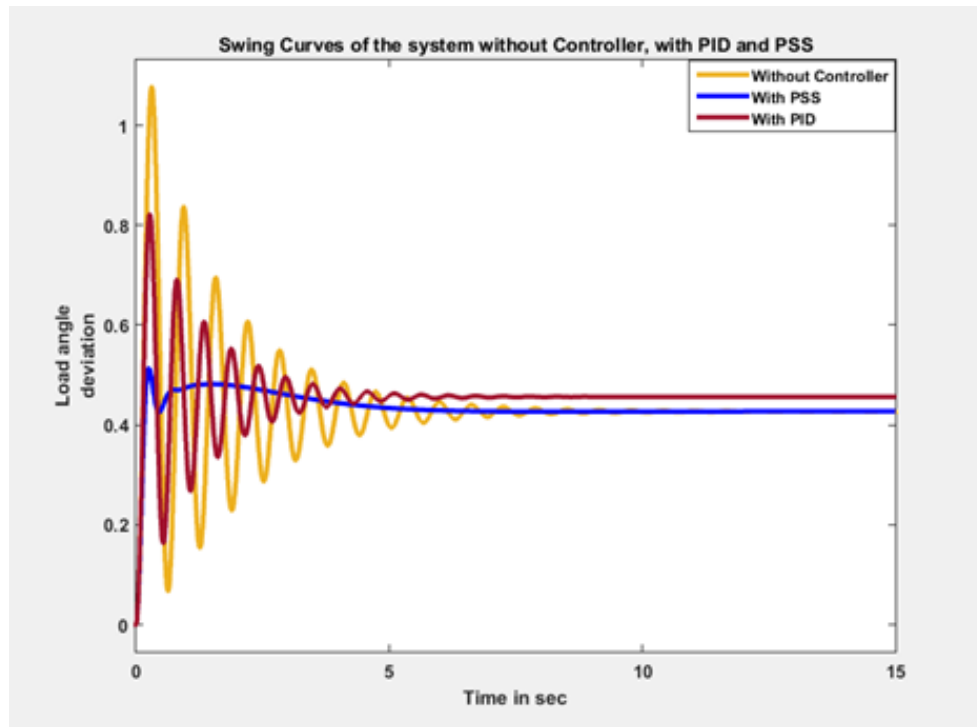
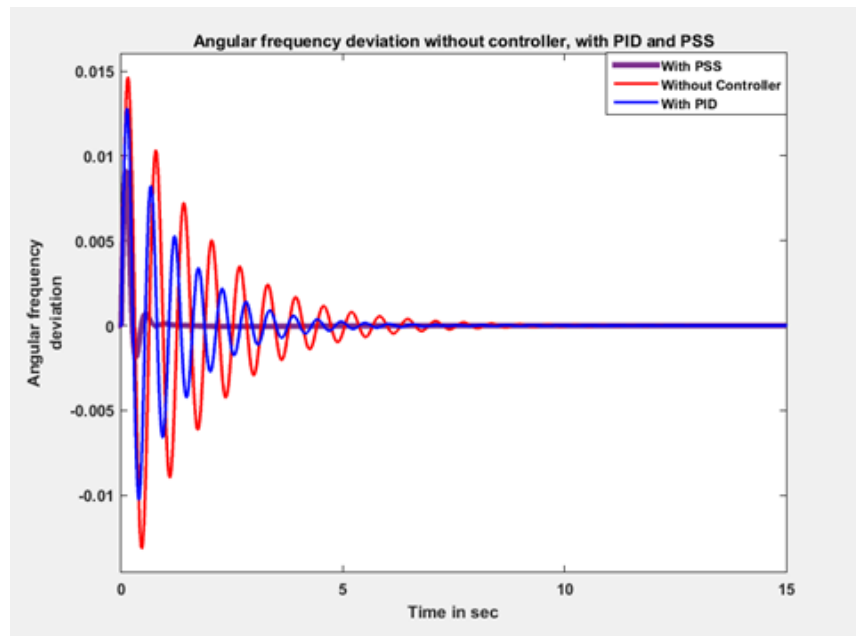
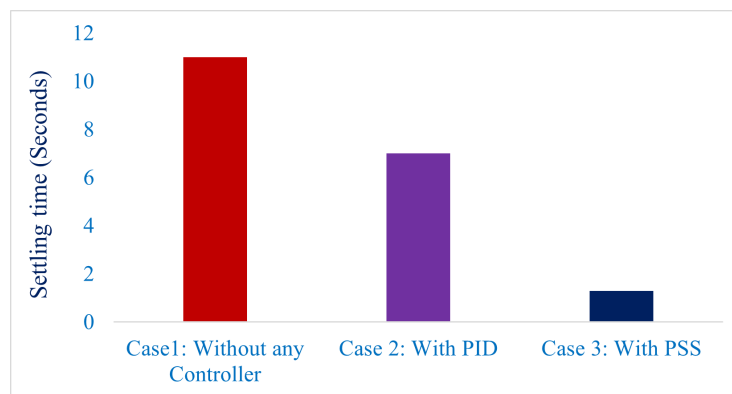


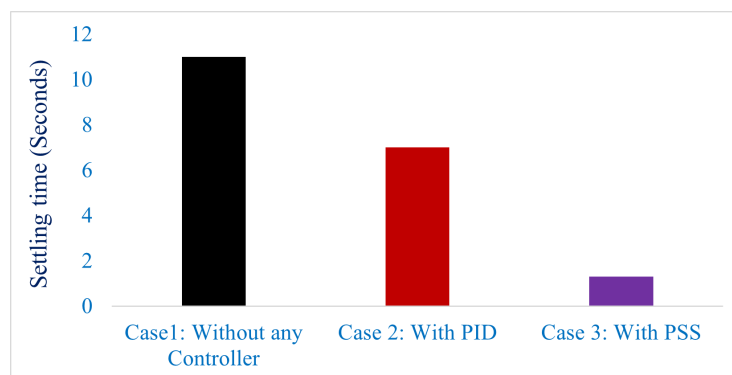
Figure 18. Comparison of system swing curves for different cases.



**Figure 19.** Comparison of system angular frequency responses for different cases.



**Figure 20.** Deviation in angular frequency settling time.



**Figure 21.** Deviation in load angle settling time.

**Table 1.** Power system parameters

S. No	Parameter	Value	Description
1	$K_1$	1.6	Power system model constant
2	$K_2$	1.5	Power system model constant
3	$K_3$	0.34	Power system model constant
4	$K_4$	-1.8	Power system model constant
5	$K_5$	-0.12	Power system model constant
6	$K_6$	0.3	Power system model constant
7	$K_D$	10	Damping torque coefficient
8	$T_M = 2H$	6	Mechanical starting time
9	$T_3$	1.9	Field circuit time constant
10	$T_R$	0.02	Voltage regulator time constant
11	$K_A$	200	Exciter power amplifier gain

## 5. Conclusions

The modern power network is composed of a huge number of transmission lines and generators. The Synchronous generator modelling and its stability analysis is crucial in a power system network. The single machine is analyzed with Phillips Heffron or K1 to K6 model, usually all constants are positive in the general case. In a few cases, the constants K5 and K4 are negative, for high values of external system reactance and high generator outputs the K5 becomes negative. With a negative K5 value Automatic Voltage Regulator (AVR) action introduces a positive synchronizing torque and a negative damping torque. The system is developed for the typical power system 1 and 2 without any controller and with the design and implementation of PID controller and PSS and the simulation is carried out without any controller and with PID Controller and with PSS and presented the results and also comparison is also made with swing curves and angular frequency deviations and obtain the results of settling time for both load angle deviation and also for angular frequency deviations. The bar charts for settling time of load angle as well as settling time for angular frequency have been presented and result analysis has been performed and conclusions have been made based on the result analysis in the subsequent section of this article. Comparison results have been presented with bar charts of the settling time of swing curves and angular frequency deviations. The settling time of the system with PSS is the least in both cases and shows a significant improvement in the SSS of the system. Both the controllers have improved the performance of the system, especially SSS but the impact of the PSS is more predominant.

**Funding:** This research received no external funding.

**Author contributions:** "Conceptualization, GA, GAD, TS, VY; Methodology, RRD, CRR, GA; Software, GAD, TS; Validation, RRD, CRR, GAD, BG; Formal Analysis, TS, GA, RRD; Investigation, RRD; Resources, GA, CRR; Data Curation, RRD, VY; Writing – Original Draft Preparation, VY; Writing – Review & Editing, CRR; Visualization, BG, CRR; Supervision, CRR; Project Administration, GA, BG; Funding Acquisition, CRR".

**Disclosure statement:** The authors declare no conflict of interest.

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