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Linearized Modeling of Single Machine Infinite Bus Power System and Controllers for Small Signal Stability Investigation and Enhancement

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***Abstract*—Small signal stability investigation is vital as the system outage due small signal perturbation being unknown to the system operators. The small signal disturbance may be initiating event for large system outage. The Single Machine Infinite Bus (SMIB) power system helps in tuning the controllers at one machine without considering the effect of other machines in the power system. The effect of disturbance seen by the machine being 100%, whereas in interconnected power system the effect gets distributed among different machines. Therefore, the controller tuning with SMIB remains valid for miltimachine power system as well. In this paper a comparison of PID, PSS, TCDB controllers is presented through small signal stability of power system comprising of one machine connected to infinite bus and modeled through six K-constants. The power system components such as synchronous machine, exciter, power system stabilizer, PID, TCDB are also modeled after linearization of governing equations.**

***Index Terms*—Heffron-Phillips, ISE, PID, PSS, TCDB, SMIB, Small signal stability, TGR,**

I. Introduction

Small-signal stability investigations usually involve the analysis of the linearized system governing equations that define the power system dynamics. Whereas, transient stability of the power system deals with system analysis, following a severe disturbance, such as a single or multi-phase short-circuit or a generator loss. Under these conditions, the linearized power system model does not remain valid. A third term, dynamic stability, has been widely used in the literature as a class of rotor angle stability. The stability criterion with respect to synchronous machine equilibrium has been presented. The mathematical model presented for small scale stability state is a set of linear time invariant differential equations [1]. P.M. Anderson and A.A. Fouad, had mentioned , the stability under the condition of small load changes has been called steady state stability[2]. The concepts of synchronous machine stability as affected by excitation control and the phenomenon of stability of synchronous machines under small perturbations in the case of single machine connected to an infinite bus through external reactance has been presented by F.P.demello and C. Concordia. The analysis also develops insights into effects of thyristor-type excitation systems and establishes understanding of the stabilizing requirements for such systems [3]. These stabilizing requirements include the voltage regulator gain parameters as well as the transfer function characteristics for a machine speed derived signal superposed on the voltage regulator reference for providing damping machine oscillations [4]. Trends in design of power system components have resulted in lower stability and led to increased reliance on the use of excitation control to improve stability [2]. IEEE Committee Report (1981), the working group of IEEE on computer modeling of excitation systems, in their report has discussed excitation system models suitable for use in large scale stability studies [5]. Michael J. Basler Richard C. Schaefer discusses power system instability and the importance of fast fault clearing performance to aid in reliable production of power [6]. In the past decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention. Extensive research has been conducted in such fields as effect of PSS on power system stability, PSS input signals, PSS optimum locations, and PSS tuning techniques. The k-constant model developed by Phillips and Heffron, is used to explain the small signal stability, high impedance transmission lines, line loading, and high gain, fast acting excitation systems. The paper discusses the various types of power system instability. It will cover the effects of system impedance and excitation on stability. Synchronizing torque and damping torque is discussed and a justification is made for the need for supplemental stabilization [1,4, 7]. Kundur et al. presented a detailed analytical work to determine the parameters of phase- lead PSSs so as to enhance the steady-state as well as transient stability of both local and inter-area modes. These parameters included the signal washout, stabilizer gain, and the stabilizer output limits. They concluded that by proper tuning, the fixed-parameter PSS can satisfy the requirements for a wide range of system conditions and hence the need of adaptive PSS is of little incentive [7]. Larsen and Swann [8-10] deeply discussed, in a three-part paper, the general concepts associated with PSSs. Yuan Yih Hsu and Kan Lee Liou in their paper, “Design of PID power system stabilizers for synchronous generators” proposed a self -tuning proportional integral derivative (PID) power system stabilizer in order to improve the dynamic performance of a synchronous machine under a wide range of operating conditions [11]. M. L. Kothari.,A. Sharma, R. Segal, J. Nanda and Ashish Kumar Batrawa, presented the phase compensation technique for designing the optimum PSS [12]. M. Ataei, R. Hooshmand and M. Parastegari , gave a new method for determining the coefficients of a self tuning PSS with lead – lag controller based on pole assignment and pole shifting techniques[13]. Wen Tan, Jizhen Liu, Tongwen

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Chen, Horacio J. Marquez discussed criteria based on disturbance rejection and system robustness to assess the performance of PID controllers. A simple robustness measure is defined and the integral gains of the PID controllers are shown to be a good measure for disturbance rejection. An analysis of some well-known PID tuning formulas reveals that the robustness measure should lie between 3 and 5 to have a good compromise between performance and robustness[14]. Kiam Heong Ang, Gregory Chong, and Yun Li gave an overview on modern PID technology including PID software packages, commercial PID hardware modules and patented PID tuning rules[15].

In this paper a comparison of PID, PSS, TCDB controllers is presented through small signal stability of power system comprising of one machine connected to infinite bus and modeled through six K-constants. The power system components such as synchronous machine, exciter, power system stabilizer, PID, TCDB are also modeled after linearization of governing equations.

II. System Modeling

A. Synchronous Machine Modeling [1,2,16-23,26]

The synchronous machines are probably the most important components of a power system while carrying out power system stability studies, as synchronous generators form the principal source of electric energy, as a synchronous motor are used to drive large loads, as a synchronous condenser are used for reactive power compensation. An approximate synchronous machine model may be derived eliminating stator, network, and damper winding fast dynamics. This model is classified as one- axis machine model. One axis machine model of the synchronous generator [26] is given by the differential equations (1) to (3) and is shown in block diagram form in Figure 1.

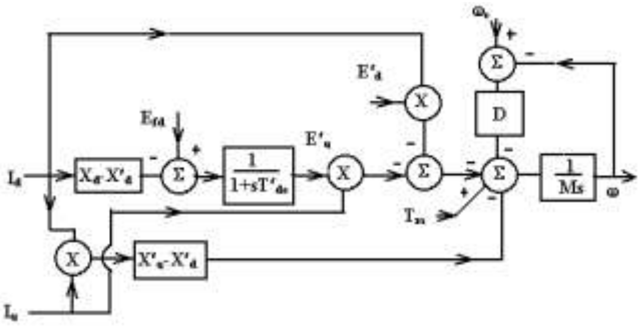

Figure 1 One-Axis Block Diagram of Synchronous Machine

$$\frac{d\delta}{dt}=\omega-\omega_s, \quad (1)$$

$$\frac{2H}{\omega_s}\frac{d\delta}{dt}=T_M-E_q^{'}I_q-E_d^{'}I_d-(X_q^{'}-X_d^{'})I_dI_q-D(\omega-\omega_o), \quad (2)$$

$$T_{do}^{'}\frac{dE_q^{'}}{dt}=-E_q^{'}-(X_d-X_d^{'})I_d+E_{fd}. \quad (3)$$

The Phasor diagram of the synchronous machine is shown in the Figure 2. The e.m.f., the voltage, and the current equations can be written with the help of the this phasor diagram [1, 2, 21].

The above dynamic model includes a friction and windage torque term as a function of machine speed. This term is called damping torque. In the literature the damping torque term is included in machine dynamics as

$$T_D=D(\omega-\omega_s), \quad (4)$$

B. Excitation System and its Modeling [1-3,5,17,19,27]

The excitation system of electric machine should be able to supply the direct current to its field winding and be able to keep its terminal voltage constant at a desired level with the help of an automatic voltage regulator for all operating conditions from no load to rated load. Different kinds of exciters are in existence from manual operated to solid-state type. Excitation system contains normally the rectifiers, error detectors, amplifier, stabilizer, pilot and main exciter. The excitation systems are of five types depending upon the hardware and control methodology [2]. The time delays in the static system are negligible and the excitation system can be represented by small time constant T_A, and with a gain K_A as given below in Fig. 2.

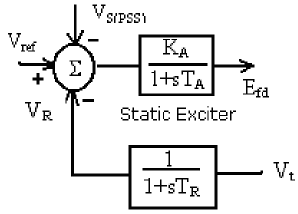

Figure 2 Block Diagram of Static Exciter

$$T_A\frac{dE_{fd}}{dt}=\left[-E_{fd}-K_A(V_{ref}-V_R)\right], \quad (5)$$

$$T_R\frac{dV_R}{dt}=V_t-V_R. \quad (6)$$

In the above differential equations E_{fd} is the e.m.f. due to d-axis flux, V_{ref} is the steady state magnitude of the terminal voltage V_t , V_R is output voltage obtained after the first-order smoothing filter time having a time constant of T_R. Usually T_R is very small and is often approximated as zero[2].

C. Power System Stabilizer Modeling [1,2,4,7-10,25-32]

The power system stabilizer (PSS) is a stabilizing device used to damp-out the low frequency oscillations of the synchronous generators. The design of power system stabilizer is based on the single-machine-infinite-bus system model of the synchronous generator. Its parameters are tuned to suppress the modes, both local and inter-area modes of oscillations [26]. Usually, the PSS consists of a phase compensation block, a signal washout block, and a gain block as shown in Figure 3. The phase lag-lead compensation block provides the appropriate phase characteristic to compensate for the phase lag between the exciter input and the generator electrical (air- gap) torque. In practice, two or more first-order blocks may be used to achieve the desired phase compensation [1,2,26].

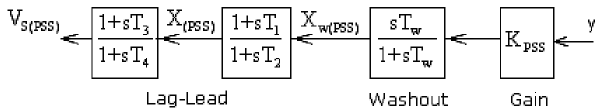

Figure 3 Block Diagram of Power System Stabilizer

The signal washout block serves as a high- pass filter, with the time constant T_W high enough to allow signals associated with oscillations in input signal to pass unchanged. In the absence of washout block, steady changes in speed would modify the terminal voltage. It allows the PSS to respond only to changes in speed. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1 to 20 seconds. The stabilizer gain K_{PSS} determines the amount of damping introduced by the PSS. The gain of the PSS should be set at a value corresponding to optimum damping.

The time constants T_1, T_2, T_3, T_4 should be set to provide damping over the range of frequencies such as from 0.1 to 2.0 Hz at which oscillations are likely to occur during steady-state operation of power system. Over this range they should compensate for the phase lag introduced by the machine and as well as the regulator. The typically the value of lead time constant T_1 and T_3 between vary in the range 0.2 to 1.5 seconds, lag time constants T_2 and T_4 ranges between 0.02 to 0.15 seconds, and gain K_{PSS} between 0.1 to 50 [26].

The mathematical representation of the power system stabilizer shown in Figure 3 is given below

$$\frac{dX_{w(PSS)}}{dt}=K_{PSS}\dot{y}-\frac{1}{T_w}X_{w(PSS)}, \quad (7)$$

$$\frac{dX_{(PSS)}}{dt}=\frac{T_1}{T_2}\dot{X}_{w(PSS)}+\frac{1}{T_2}X_{w(PSS)}-\frac{1}{T_2}X_{(PSS)}, \quad (8)$$

$$\frac{dV_{S(PSS)}}{dt}=\frac{T_3}{T_4}\dot{X}_{(PSS)}+\frac{1}{T_4}X_{(PSS)}-\frac{1}{T_4}V_{S(PSS)}. \quad (9)$$

Several different quantities, including electrical power, shaft speed, and frequency deviation have been successfully used as the input to power system stabilizer. Use of synchronous machine terminal frequency rather than shaft speed as the input signal to the stabilizer has the advantages of reduced susceptibility to electrical noise and permits the stabilizing to be derived with all static components [26].

D. *Thyristor Controlled Dynamic Brake [33-36]*

The small deviation in braking power provided by the TCDB and the corresponding torque are given by the following equation

$$\Delta T_{TCDB}=K_{12}\Delta\alpha_{(TCDB)}, \quad (10)$$

where, $$K_{12}=\left[\frac{2V_{do}}{\omega_o R}\right]\frac{3\sqrt{3}}{\pi}\sqrt{2}\left[V_{to}\cos\left(\alpha_{TCDBo}\right)\right]. \quad (11)$$

E. *Modeling of Single Machine Infinite Bus System*

To study the stability of power system, the system can be reduced to either to a two-machine equivalent system or single machine connected to an infinite bus through equivalent transfer impedance. In the single machine infinite bus system the entire electric power system connected to the machine under investigation can be modeled as Thevenin's equivalent [18,19,21, 26].

The machine behaviour can be investigated by solving differential and algebraic equations. The quantities, which are not affected by the disturbance, can be written as constants. The SMIB system dynamic equations can be represented as Heffron-Phillips model.

F. *Heffron-Phillips Model [1,4,7]*

Heffron-Phillips representation of SMIB system for small signal analysis is given by the linearized differential equation (1) to (5) and the linearized algebraic equation (.6) and (7). The dynamic characteristics of the SMIB system may be expressed in terms of six constants K_1 to K_6 [17-19, 22-23]. The corresponding mathematical relations among the different variables and constants expressed through the linearized differential equations are given below:

$$\frac{d\Delta\delta}{dt}=\Delta\omega, \quad (12)$$

$$\frac{d\Delta\omega}{dt}=\left(\frac{\omega_o}{2H}\right)\left[\Delta T_m-\left(\Delta T_e+\Delta T_{TCDB}\right)-D\Delta\omega\right] \quad (13)$$

$$\frac{d\Delta E_q'}{dt}=\left(\frac{1}{T_{do}'}\right)\left[-\frac{1}{K_3}\Delta E_q'+\Delta E_{fd}-K_4\Delta\delta\right], \quad (14)$$

$$\frac{d\Delta E_{fd}}{dt}=\left(\frac{1}{T_A}\right)\left[-\Delta E_{fd}+K_A\left(\Delta V_{REF}-\Delta V_R+\Delta V_{S(PSS)}\right)\right], \quad (15)$$

$$\frac{d\Delta V_R}{dt}=\left(\frac{1}{T_R}\right)\left[\Delta V_t-\Delta V_R\right]. \quad (16)$$

The related algebraic equations are given below

$$\Delta T_e=K_1\Delta\delta+K_2\Delta E_q', \quad (17)$$

$$\Delta V_t=K_5\Delta\delta+K_6\Delta E_q'. \quad (18)$$

The units of various constants are: H is the inertia constant in MW-s/MVA, T_{do}' is the d-axis open circuit time constant of the machine field winding, T_A is the time constant and K_A the amplifier gain in the exciter and voltage regulator circuit, T_R is the total time constant of machine terminal voltage transducer and measuring circuit. Where in the above linear differential and algebraic equation, $\Delta\delta$, $\Delta\omega$, $\Delta E_q'$, ΔE_{fd}, ΔV_R, ΔV_t and ΔV_{REF} are the small signal deviations in rotor angle expressed in electrical radians, angular rotor speed expressed in rad/sec, q-axis component of internal e.m.f. behind transient reactance, exciter output voltage, transducer output voltage, machine terminal voltage and reference voltage respectively. All the variables are in per unit if otherwise not defined. ΔT_m is the small deviation in mechanical torque input in per unit and ΔT_e is the small deviation in electrical torque in per unit.

G. *Power System Stabilizer [1, 2, 19, 26]*

The improvement of small signal stability of power system may be achieved through the power system stabilizers. The input signal to the PSS may be rotor speed, rotor angle, accelerating power, or a combination of these signals. The output signal of PSS is used as a supplementary stabilizing signal. Any stabilizing signal must produce a torque component in phase with $\Delta\omega$ so that positive damping may be produced [19]. The most common power system stabilizer block diagram is shown in Figure 3. The block diagram comprises of stabilizer gain, signal washout, and twin lag-lead blocks. The linearized differential equations of PSS are

$$\frac{d\Delta X_{w(PSS)}}{dt}=K_{PSS}\Delta\dot{\omega}-\frac{1}{T_w}\Delta X_{w(PSS)}, \quad (19)$$

$$\frac{d\Delta X_{(PSS)}}{dt}=\frac{T_1}{T_2}\Delta\dot{X}_{w(PSS)}+\frac{1}{T_2}\Delta X_{w(PSS)}-\frac{1}{T_2}\Delta X_{(PSS)}, \quad (20)$$

$$\frac{d\Delta V_{S(PSS)}}{dt}=\frac{T_3}{T_4}\Delta\dot{X}_{(PSS)}+\frac{1}{T_4}\Delta X_{(PSS)}-\frac{1}{T_4}\Delta V_{S(PSS)}. \quad (21)$$

Where variables, $\Delta X_{w(PSS)}$ represent the output of washout filter, $\Delta X_{(PSS)}$ represent output of first lag-lead network, ΔV_S is the output signal of PSS block. T_W is the

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washout time constant, and T_1, T_3, are lead-time constants, and T_2, T_4 are the lag time constants of lag-lead networks.

H. Block Diagram of SMIB System With Controllers

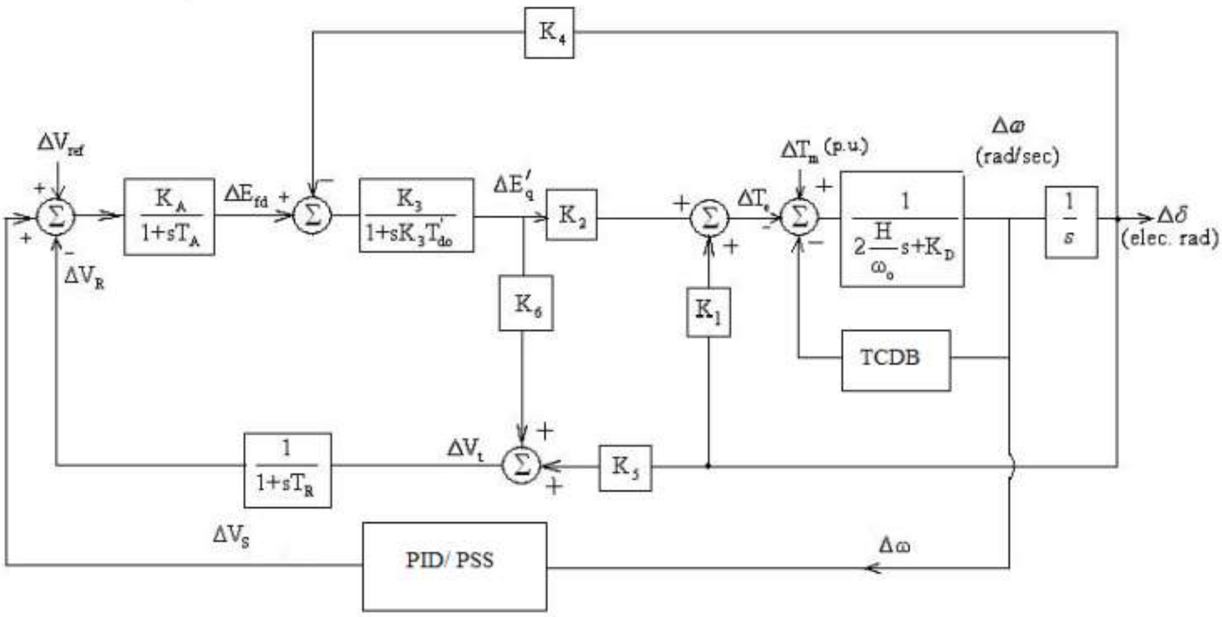

Fig. 4 Block Diagram of SMIB System with Controllers

The linearized state-space equations Heffron- Phillips model of SMIB system with controllers is shown in Fig. 4.

III. System Data

SMIB Test system data for the small signal stability investigation is taken from the reference [4, 29, 35]. The generator and external network data is given in Table I and Table II.

Table I Data for the SMIB System [2]

Inertia Constant, H	2.37KW-s/KVA
Generator Rating,	160 MVA
Rated Voltage	15 KV, Y-Connected
Excitation Voltage	375 KV
Stator Current, I_G	6158.4 A
Field Current	926 A
Power factor	0.85
X_d	1.7
X_d'	0.245
X_q	1.64
Xq'	0.38
R_S	0.001096
T_{do}'	5.9

Table II SMIB System External Network Parameters [2]

Re	0.02
Xe	0.4

All resistances and reactances are in per unit to the machine rated MVA and voltage, and the time constants are in seconds, unless otherwise stated.

The initial conditions of SMIB Test system are tabulated in Table III. All other quantities are in per unit unless otherwise stated.

Table III SMIB System Initial Conditions [2,26]

Parameter	Magnitude	Parameter	Magnitude
I_G	1.176∠-31.78°	I_d	1.112
E_q	2.665∠66.99°	I_q	0.385
V_d	0.641	E_q'	1.0484
V_q	0.776	V_{ref}	1.0533
V_∞	0.828	T_M	1.0012
V_t	1.0∠27.89°	δ_o	66.99°
E_{fd}	2.6658		

Where, I_G is the generator stator current, I_d and Iq are its d-axis and q-axis components.

The static exciter and transient gain reduction parameters are given in Table IV. The gain K_A is in per unit and all time constants are in seconds.

Table IV Parameters Of Static Exciter and TGR For SMIB System [18, 26]

Parameter	Magnitude
K_A	50
T_A	0.01
T_C	1
T_B	10

where, T_C and T_B are the time constants of transient gain reduction .

Few parameters of PSS are given Table V and those not mentioned in value are to be determined during tuning of controller parameters.

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Table V PSS Parameters For SMIB System [18, 24, 26]

Parameter	Magnitude
Lead Time constant, T_1	0.5
Lag Time constant, T_2	0.05
Lead Time constant, T_3	0.5
Lag Time constant, T_4	0.05
Wash out Time Constant, T_w	10

The Heffron-Phillips constants in per unit for representation of SMIB system and for Modified form of Heffron-Phillips model of SMIB Test system are given in Table VI.

Table VI Heffron-Phillips SMIB System Constants

K_1	1.0749	K_2	1.2576
K_3	0.3072	K_4	1.7124
K_5	-0.3988	K_6	0.4657

IV. Test Disturbance For System Performance Evaluation

Typical disturbance for small signal stability investigations corresponds to a network disturbance, such as small variation in load. The SMIB system is subjected to unit angular impulse disturbance representing the system acceleration at the start of simulation.

V. System Response and Analysis

The test system has been modeled through Matlab programming. The controller has been tuned for minimum Integral of Squared Error (ISE) in generator load angle. The response of the system, for impulse disturbance, applied at start of the simulation, has been obtained and presented through graphical results given in Fig. 5 to Fig. 16. The system performance indicators settling time and ISE, are also given Table. VII, for more comprehensive understanding. The results indicate that in the presence of tuned PID only, the settling time of 10.002 remains same as system without any controller, whereas, ISE reduces from 0.7338 to 0.3903. In the presence of tuned PSS, settling time reduces to 2.895 and ISE to 0.1480 indicating substantial improvement. In the presence of tuned TCDB the settling time reduces to 1.395 and ISE to 0.2504. Next various combinations of PID, PSS, and TCDB have been investigated and the results are presented through Fig. 8 to Fig. 16. The settling time with tuned combination of PID and PSS reduces to 3.58 and ISE to 0.3081. In this combination of controllers settling time and ISE has been reduced as compared to PID controller alone. Further combination of PID and TCDB has been investigated resulting in settling time of 3.621 and ISE of 0.224, indicating an improvement over PID controller acting alone. Combination of PSS and TCDB renders settling of 2.782 and ISE of 0.1425 magnitude, resulting in further improvement. Finally combination of all the controllers has been applied and the settling time 3.544 and ISE 0.2818 have been observed.

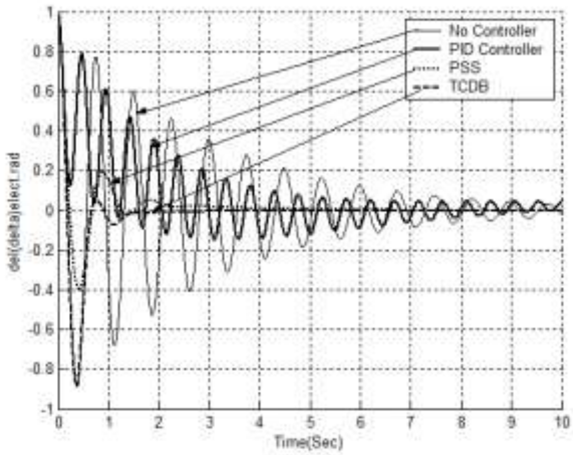

Fig. 5 Variation of Generator Load Angle in the Presence of individual Controller.

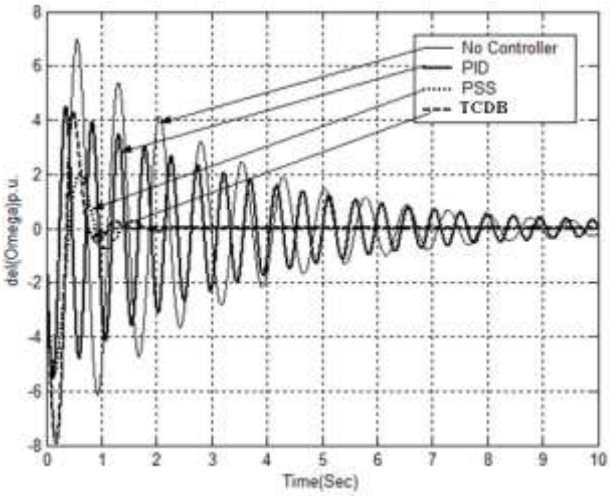

Fig. 6 Variation of Generator Angular Frequency in the Presence of individual Controller.

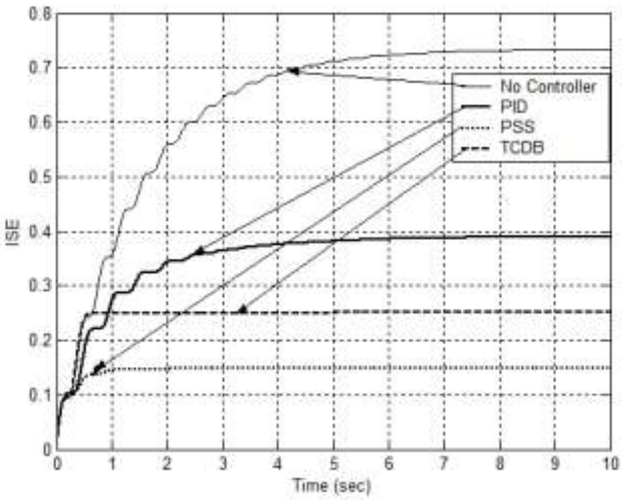

Fig. 7 Variation of Integral Square Error in load angle the Presence of individual Controller.

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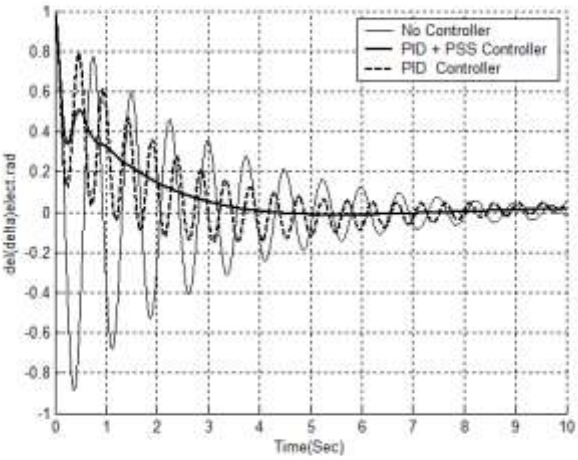

Fig. 8 Variation of Generator Load Angle in the Presence of PID and Combination of PID & PSS Controllers.

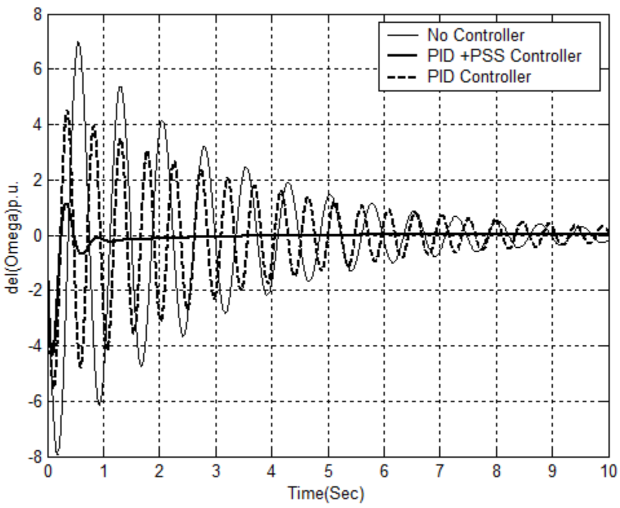

Fig. 9 Variation of Generator Angular Frequency in the Presence of PID and Combination of PID & PSS Controllers.

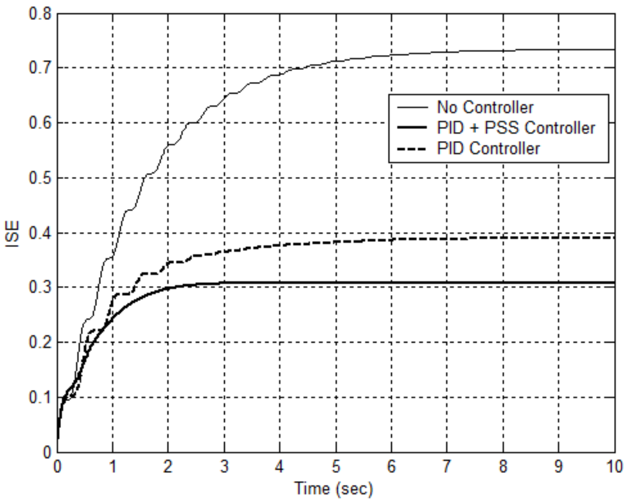

Fig. 10 Variation of Integral Square Error in load angle the Presence of PID and Combination of PID-PSS Controllers.

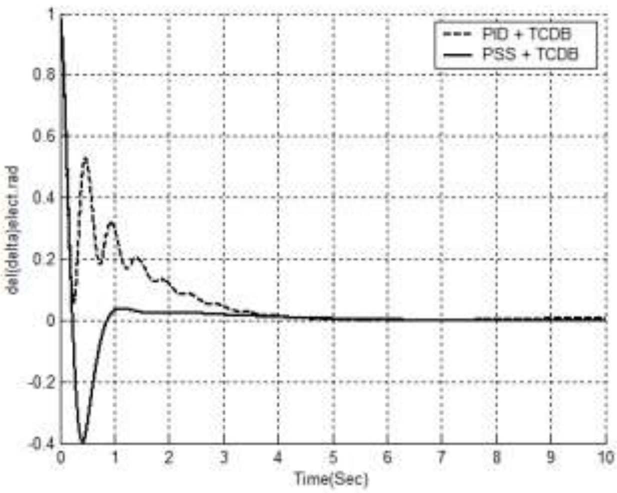

Fig. 11 Variation of Generator Load Angle in the Presence of combinations of PID & TCDB, and PSS & TCDB Controllers.

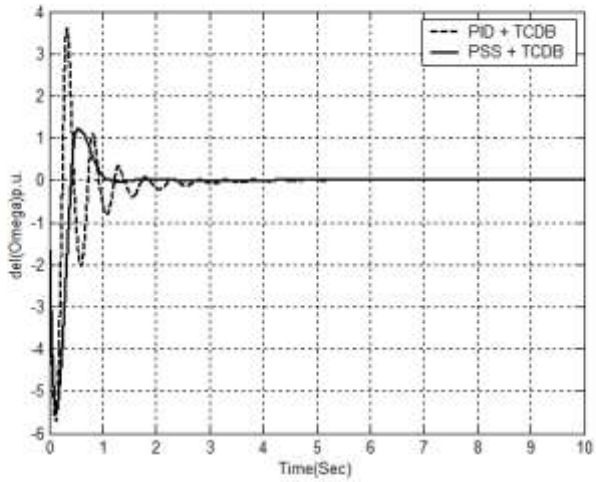

Fig. 12 Variation of Generator Angular Frequency in the Presence of combinations of PID & TCDB, and PSS & TCDB Controllers.

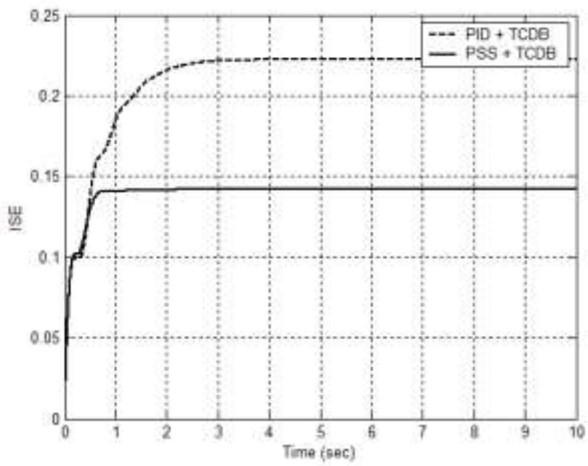

Fig. 13 Variation of Integral Square Error in load angle the Presence of combinations of PID-TCDB, and PSS-TCDB Controllers.

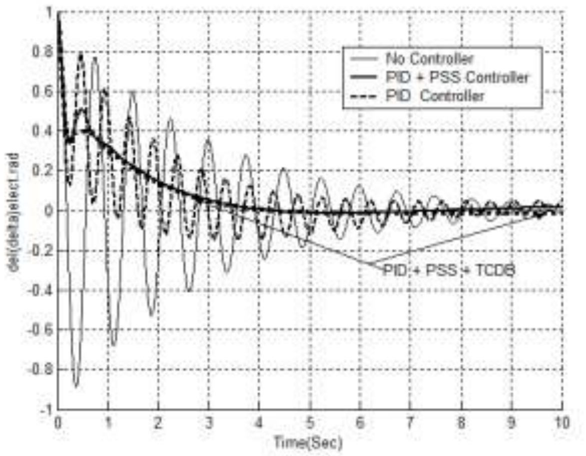

Fig. 14 Variation of Generator Load Angle in the Presence of combinations of PID, PID-PSS, PID-PSS-TCDB Controller.

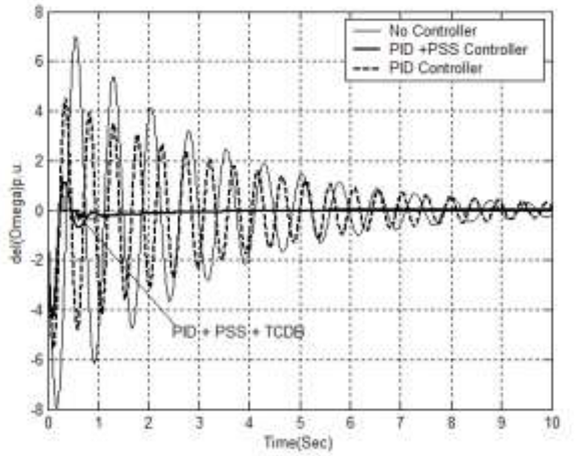

Fig. 15 Variation of Generator Angular Frequency in the Presence combinations of PID, PID-PSS, PID-PSS-TCDB Controller.

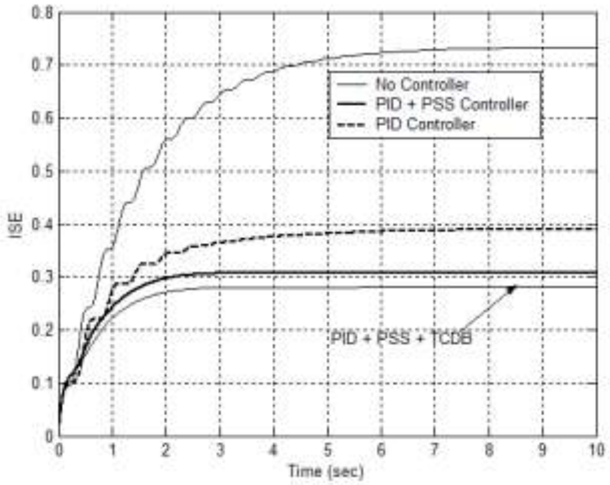

Fig. 16 Variation of Integral Square Error in load angle the Presence of combinations of PID, PID-PSS, PID-PSS-TCDB Controller

Table VII Comparative System Performance

Controller	ISE	Settling Time
None	0.7338	> 10.0
PID	0.3903	>10.0
PSS	0.1480	2.895
TCDB	0.2504	1.395
PID-PSS	0.3081	3.58
PID-TCDB	0.224	3.621
PSS-TCDB	0.1425	2.782
PID-PSS-TCDB	0.2818	3.544

VI. CONCLUSIONS

From the results obtained for different possible combinations of the controllers considered, it can be concluded the PID controller in combination with other controller is effective in the improvement of settling time and ISE. The minimum settling time of 1.395 has been observed for TCDB. The minimum ISE of 0.1425 has been rendered by PSS-TCDB controller. The TCDB acts only in the acceleration period results in more ISE as compared to PSS with acts in acceleration and retardation period.

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