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A Generalized Pss Architecture For BalancingTransient And Small Signal Response

Mr. S. Deepak kumar[1], Mr. M. Thavachelvam[2] , Ms. S. Kamatchi[3],

[1,2,3]Department of Electrical and Electronics Engineering Dhanalakshmi Srinivasan College of Engineering and Technology.

ABSTRACT

Power system stabilizers are added to the excitation systems to enhance the damping during low frequency oscillations. Due to high gain of AVR, terminal voltage of the system stays within control and it improves steady state stability limit, though it amplifies the negative damping into the system. Power system stabilizers paired with high initial response automatic voltage regulators have served as an effective means of meeting system stability requirements. They are designed to nullify the adverse effect of the high gain, fast responding (low time constant) AVR thereby improving small-signal and transient stability. Driven primarily by increase in power electronically- coupled generation and load, the dynamics of large- scale power systems are rapidly changing. Electric grids are losing inertia and traditional sources of voltage support and oscillation damping. The system load is becoming stiffer with respect to changes in voltage. Here we propose a PSS architecture that can be viewed as a generalization of the standard Δω-type stabilizer. The ability of the stabilizer to improve the damping of electromechanical modes is decoupled from its role in shaping the system response to transient disturbances. The control strategy utilizes a real- time estimate of the center-of-inertia speed derived from wide-area measurements. This approach creates a flexible set of trade-offs between transient and small-signal stability, making synchronous generators better able to adapt to changes in system dynamics. The phenomena of interest are examined using a two-area test case and simulations are done on MATLAB platform. The simultaneous focusing on both transient and small signal stability shows the effectiveness of the proposed control strategy.

Keywords: PSS, AVR, Stability, MATLAB, Δω-type stabilizer.

1. INTRODUCTION

The ability of the synchronous generator in an interconnected power system to remain in synchronism after being subjected to disturbances. It depends on the ability of the machine to maintain equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability of this kind occurs in the form of swings of the generator rotor which leads to loss of synchronism.

Rotor angle stability can be divided into two subcategories:

1. Small-signal rotor angle stability is defined as the ability of the power system to maintain synchronism under small disturbances.
2. Large-disturbance rotor angle stability (transient stability) describes the ability of the power system to maintain synchronism after being subjected to a severe disturbance.

The change in electromagnetic torque of a synchronous machine following a disturbance can be broken down into two components as:

1. Synchronizing torque: in-phase with rotor angle deviation.
2. Damping torque: in-phase with speed deviations.

$\Delta Te = Ks.\, \Delta\delta + Kd.\, \Delta\omega$

Small-signal stability problems occur in a form of increasing rotor oscillations due to insufficient damping torque. In contrast, in transient stability, instability comes in a form of aperiodic angle separation occurs due to insufficient synchronizing torque. Under normal operating conditions both components are positive K_s, K_d, therefore, a change in rotor's speed or angular position produces electrical torque that acts on the rotor to restore equilibrium. Note that in the phase-domain speed deviation $\Delta\omega$leads angle deviation $\Delta\delta$by 90 degrees.
Where,
$K_s*\Delta\delta$=component of torque change in phase with rotor angle=Synchronizing torque (Lack of this resultsin aperiodic drift in rotor angle-Non oscillatory instability)
$K_d*\Delta\omega$= component of torque change in phase with speed deviation=Damping torque (Lack of this results rotor oscillations of increasing value-Oscillatory instability)
System stability depends on both components of torque for each of synchronous machine.

The power control system is designed to achieve two goals. The first is to control the generator output voltage, and the second is to increase the damping ratio to generator so as to increase the stability margin of the closed-loop system and to prevent the disturbance of the utility grid from oscillation in thegenerator. The overall feedback system consists of plant, the Automatic Voltage Regulator (AVR), and the Power System Stabilizer.

BASIC COMPONENTS OF PSS

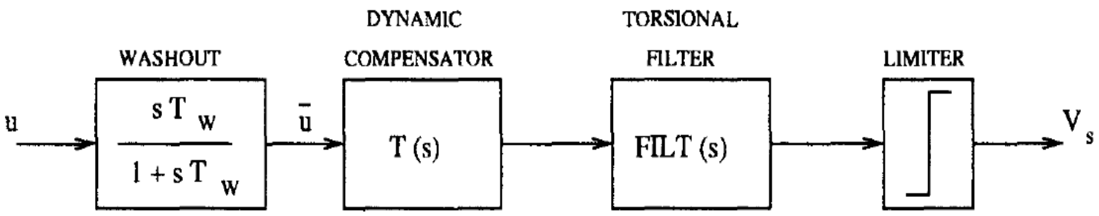

Fig.1.1 Basic block diagram of PSS

1. Washout block

The washout block is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS is expected to respond only to transient variations in theinput signal (say rotor speed) and not to the dc offsets in the signal. This is achieved by subtracting from it the low frequency components of the signal obtained by passing the signal through a low pass filter. Fig.1.1 shows the basic blocks of PSS containing washout block, compensator, torsional filter and limiter.

2.Dynamic Compensator

The dynamic compensator used in industry is made up of two lead-lag stages and has thefollowing transfer function

$$T(s) = \frac{K_s(1 + sT_1)(1 + sT_3)}{(1 + sT_2)(1 + sT_4)}$$

where Ks is the gain of PSS and the time constants, T_1 to $T_4$are chosen to provide a phase lead for the input signal in the range of frequencies that are of interest (0.1 to 2 Hz).

3.Torsional filter

Torsional filter, out the high frequency oscillations of the system which are caused due to thetorsionalinteractions of the alternator.

EXISTING METHODS

This structure uses the rotational speed measured from the shaft as an input signal to the stabilizer. Fig1.1 shows the conventional Δω-type stabilizer. The main concern of Delta-Omega stabilizer is that the shaft run-out may distort the input signal. Moreover, using sensed rotor speed as an input may affect the stability of torsional modes in thermal units. Torsional filters should be used to solve this problem. The stabilizer gain should be selected as the value that leads to maximum damping. The torsional filter may limit this value.

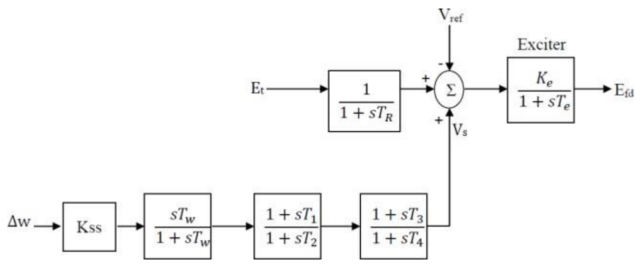

Fig. 1.2 Conventional Δω-type stabilizer

PROPOSED SYSTEM

In this section, power system stabilizer architecture is presented that can be viewed as a generalization of the standard Δω-type stabilizer. This control strategy stems from a time-varying linearization of the equations of motion for a synchronous machine. It utilizes a real-time estimate ofthe center-of-inertia speed derived from a set of wide-area measurements. The proposed strategy improves the damping of both local and inter-area modes of oscillation. The ability of the stabilizer to improve damping is decoupled from its role in shaping the system response to transient disturbances. Consequently, the interaction between the power system stabilizer and automatic voltage regulator can be fine tuned based on voltage requirements. This approach creates a flexible set of trade-offs between transient and small-signal response, making synchronous generators better able to adapt to changes in system dynamics. Here we briefly restate some key concepts and definitions from the theory of continuous-time linear time varying systems. In the control strategy derivation, these concepts will be applied to the nonlinear form of the swing equation.

NON-EQUILIBRIUM SPEED TRAJECTORY

In this, we will examine the implications of treating ωcoi(t) as a real-time estimate of the center-of-inertia speed

$$\overline{\omega}(t) \approx \frac{\sum_{i\in\mathcal{I}} H_i \omega_i(t)}{\sum_{i\in\mathcal{I}} H_i}$$

The right-hand side of above equation corresponds to the classical center-of-inertia definition.

ωcoi(t) for real-time control applications is straight forward way of estimating above equationwould be a weighted average of frequency measurements if rotor speed measurements are seldom available through wide area measurement systems is,

$$\overline{\omega}(t) = \frac{1}{f_0} \sum_{k\in\mathcal{K}} \alpha_k f_k(t)$$

where k is the sensor index, and f0 the nominal system frequency.

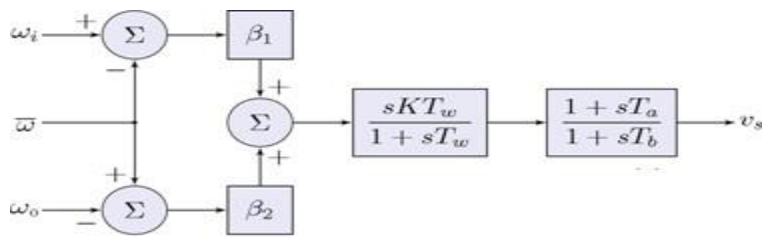

Fig. 1.3 Generalized Δω-type PSS block diagram.

Splitting the linear time-invariant (LTI) control error Δω,

$$\Delta\nu(t) \triangleq \beta_1\left[\omega_i(t) - \overline{\omega}(t)\right] + \beta_2\left[\overline{\omega}(t) - \omega_0\right]$$

β_1 and β_2 are independent tuning parameters restricted to the unit interval. Fig. 2.5 shows the block diagram corresponding to this control strategy where v_s is the output of the PSS. If necessary, more than one lead-lag compensation stage may be employed.

Table 2.1 Effect of control parameters on PSS tuning

Parameter Values	Tuning Description
$\beta_1 > \beta_2$	Targets inter-area and local modes
$\beta_1 < \beta_2$	Targets the frequency regulation mode
$\beta_1 = \beta_2 \neq 0$	Standard Δω-type PSS
$\beta_1 = \beta_2 = 0$	No PSS control

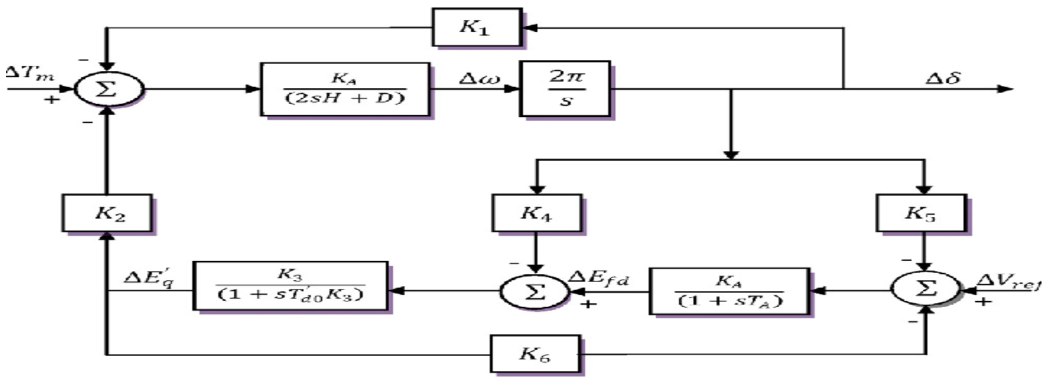

Fig 1.4 Heffron-Phillips Model

SIMULATION OUTPUTS

TWO AREA SYSTEM MODEL SPECIFICATIONS

Here a multi machine power system is considered as case study. The following data and model has been taken from Kundur's book. Fig 3.3 shows the two-area Kundur's system line diagram. The system consists of a weak tie which connects two similar areas. Each area have two coupled units, each having a rating of900 MVA and 20 kV. The generator parameters in per unit on the rated MVA and kV are as follows:

$X_d = 1.8 \qquad X_q = 1.7 \qquad X_l = 0.2 \qquad X'_d = 0.3 \qquad X'_q = 0.55$

$X''_d = 0.25 \quad X''_q = 0.25 \quad R_a = 0.0025 T'_{d0} = 8.0s \qquad T'_{q0} = 0.4s$

$T''_{d0} = 0.03s \; T''_{q0} = 0.05s \; A_{sat} = 0.015 \; B_{sat} = 9.6 \qquad \Psi_{T1} = 0.9$

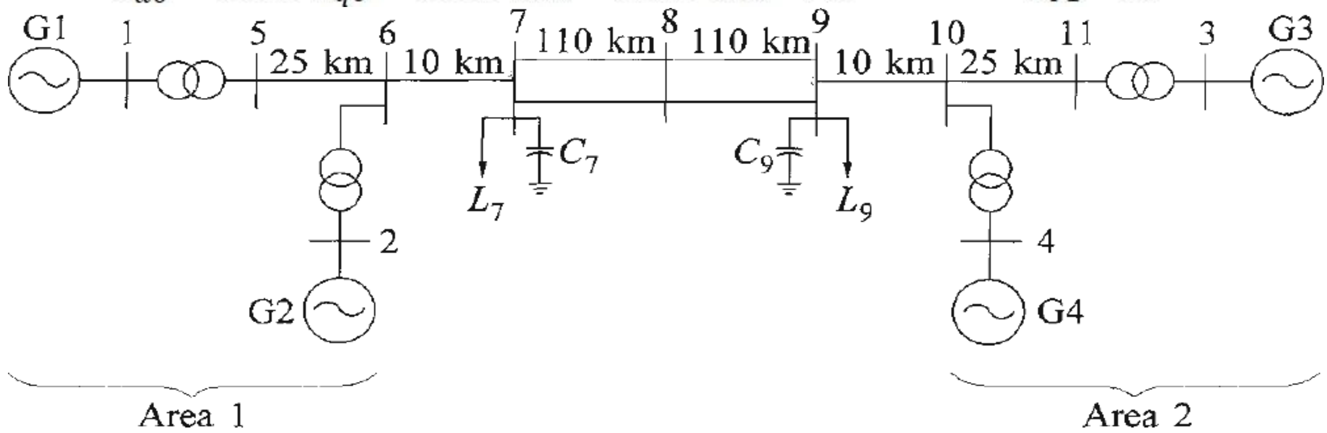

Fig 1.5 Two-area system line diagram

Each step-up transformer has an impedance of 0+j0.15 per unit on 900 MVA and 20/230 kV, and has an off-nominal ratio of 1.0. The transmission system nominal voltage is 230 kV. The line lengths are identified in Fig.3.3. The parameters of the line in per unit on 100 MVA, 230kV base are R= 0.0001 pu/km, X= 0.001 pu/km, B_c= 0.00175 pu/km. Thyristor exciter with high transient gain K_e=200, T_r=0.01, T_w=10.

The State variables are

[Δω12 Δω13 Δω14 Δδ12 Δδ13Δδ14ΔEq1′ ΔE_{fd1} ΔEq2′ ΔE_{fd2} ΔEq3′ ΔE_{fd3} ΔEq4′ΔE_{fd4}]

EIGEN VALUE ANALYSIS

EIGEN VALUE ANALYSIS WITHOUT PSS

First I will do eigen-value analysis in PSAT MATLAB toolbox for without PSS(AVR only) it is shown in the table 1.2.

Table 1.2 Eigenvalues, Frequency of oscillation & damping Ratio of the System without PSS

Eigen values	Frequency(Hz)	Damping ratio	Comments
-0.15078±6.47257i	1.0301	0.0233	Local mode in area 1
-0.14835±6.29085i	1.0012	0.0236	Local mode in area 2
-0.02994±3.34651i	0.53261	0.00895	Inter area mode
-1000	0	-	-
-10.3237	0	-	-
-9.5047	0	-	-

-0.3538 ±0.3072i	0.04889	0.7551	Frequency reg mode

From the eigen values in Table 1.2, it is seen that the system has very low damping at the verge of instability due to high gain AVR(K_e=200).So we can attach PSS to increase damping for small and large signal disturbances.

EIGEN VALUE ANALYSISWITH GENERALIZED Δω PSS

By varying the PSS parameters β1,β2we can alter the inter area, local and frequency regulation mode as per the table 1.1.

EIGEN VALUE ANALYSISWITH GENERALIZED Δω PSS(β1>β2)

By increase β1, the inter area mode moves to left half of S-plane and decrease slightly in frequency also local mode to left half of S-plane and decrease slightly in frequency. Exciter mode moves to right but remains comfortably in left half of complex plane. Alsoβ1 variations not affect any frequency regulation mode. Fix β2=0 and vary β1 from 0 to 1(0.33,0.667,1) with K_{PSS}=18.
The following inference obtained from the eigen-values table 1.3 and table 1.4,

- As β1 increases, the inter area mode moves to left and decrease slightly in frequency.
- As β1 increases, the local mode move to left and increase slightly in frequency.
- Exciter mode moves to right but remains comfortably in left half of S-plane.
- So, For all intents and purposes, the frequency regulation mode is unaffected by changes inβ1.
- Hence, β1 dictates the extent to which the PSS damps inter-area and local modes of oscillation.

I. **β1=0.33, β2=0(β1>β2)**

The eigen values for β1=0.33, β2=0 shown in the table 4.3.

Table 1.3 Eigenvalues, Frequency of oscillation & damping Ratio of the System with Generalized Δω PSS (β1>β2)(β1=0.33, β2=0)

Eigen values	Frequency(Hz)	Damping ratio	Comments
-1.309±7.7263i	1.2297	0.16657	Local mode in area 1
-1.286±7.3821i	1.175	0.1715	Local mode in area 2
-0.722±3.425i	0.556	0.2035	Inter area mode
-1000	0	-	-

-0.6786	0	-	-
-0.25458±0.2517i	0.0400	0.7112	Frequency regulation mode

II. **β1=0.667, β2=0(β1>β2)**

The eigen values for β1=0.667, β2=0 shown in the table 1.4.

Table 1.4 Eigen values, Frequency of oscillation & damping Ratio of the System with Generalized ΔωPSS (β1>β2)(β1=0.667, β2=0)

Eigen values	Frequency(Hz)	Damping ratio	Comments
-2.5749±7.7399i	1.23184	0.3156	Local mode in area 1
-2.468±7.39981i	1.1777	0.31638	Local mode in area 2
-1.3789±3.390i	0.5395	0.3769	Inter area mode
-1000	0	-	-
-0.9867	0	-	-
-0.25458±0.2517i	0.0400	0.7112	Frequency regulation mode
-0.25111±0.279i	0.0444	0.6689	Frequency regulation mode

EIGEN VALUE ANALYSISWITH GENERALIZED Δω PSS(β1<β2)

By increase β2, the frequency regulation mode moves to left half of S-plane. High frequency exciter mode affected to both β1 andβ2 variable moves upward. Also, frequency regulation mode plays an important role in shaping in system response to transient disturbance. Also β2 variation not affects any inter-area and local modes of oscillation. Fix β1=0 and vary β2 from 0 to 1(0.33, 0.667) with K_{PSS}=18.

The following inference obtained from the eigen-values table 4.5,

- As β2 increases, frequency regulation mode moves to left and increase slightly in frequency.
- In contrast, the inter-area and local modes are relatively unaffected by changes in β2.
- Hence, β2 dictates the extent to which the PSS damps frequency regulation mode of oscillation.
- The control mode exhibits some sensitivity to both β1 and β2.I.

β1=0, β2=0.667(β1<β2)

The eigen values for β1=0, β2=0.667 shown in the table 1.5.

Table 1.5 Eigen values, Frequency of oscillation & damping Ratio of the Systemwith Generalized Δω PSS **(β1<β2)(β1=0, β2=0.667)**

Eigen values	Frequency (Hz)	Damping ratio	Comments
-1.32579±7.72354i	1.22924	0.16918	Local mode in area 1
-1.24569±7.38597i	1.1755	0.16631	Local mode in area 2

-1.16333±0.3199i	0.05091	0.96421	Frequency regulation mode
-0 .72651±3.499i	0.55688	0.20329	Inter area mode
-1000	0	-	-
-0.49596	0	-	-
-1.3241±0.3157i	0.05024	0.9727	Frequency regulation mode

EIGEN VALUE ANALYSIS WITH STANDARD Δω PSS

The eigen values for β1=β2=0.33,K_{PSS}=6shown in the table 1.6.

Table 1.6 Eigen values, Frequency of oscillation & damping Ratio of the System with standardΔω PSS(β1=β2)(β1=0.33, β2=0.33)

Eigen values	Frequency(Hz)	Damping ratio	Comments
-1.30528±7.72654i	1.2297	0.1665	Local mode in area 1
-1.28543±7.38297i	1.175	0.171	Local mode in area 2
-0.72638±3.4951i	0.556	0.2031	Inter area mode
-1000	0	-	-
-0.48566	0	-	-
-0.34418±0.29507i	0.046 96	0.7591	Frequency regulation mode
-0.35316±0.2979i	0.04741	0.7643	Frequency regulation mode

The only drawback with Standard Δω PSS is it does not provide separate target of inter-area mode, local mode and frequency regulation mode. This is nullify by using Generalized Δω PSS, it targets separately inter-area mode, local mode and frequency regulation mode as given in table 1.2.

MATLAB SIMULATION RESULTS

For analysis of multi machine power system take two area kundur test case simulations aredone in MATLAB platform. Taking into the interactions between the four machines the MATLABSimulation diagram can be modeled and simulated with AVR, Steam governor, generalized Δω PSS Shown in Fig 1.6, 1.7, 1.8.

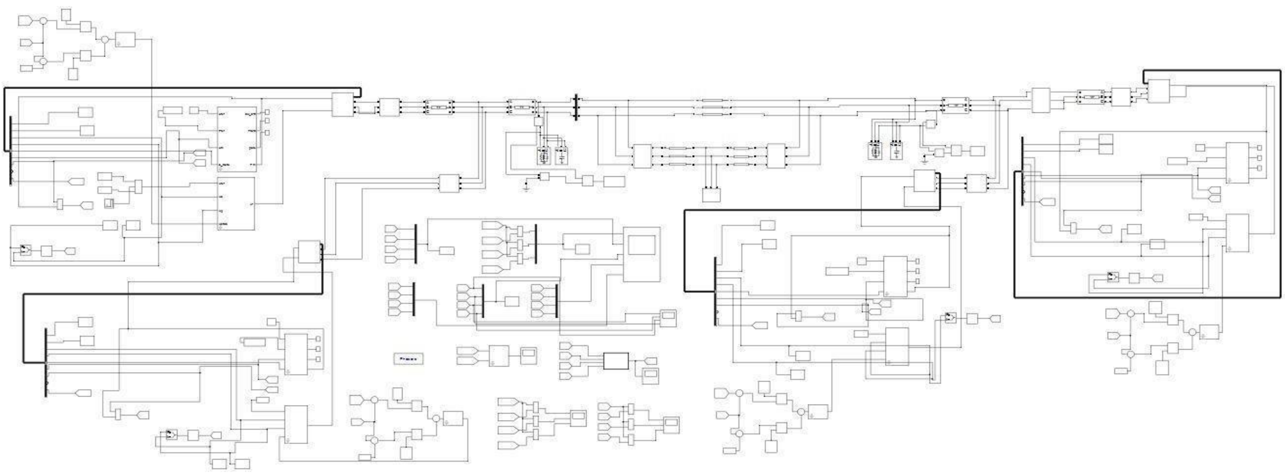

Fig. 1.6 MATLAB Simulation Diagram for 4 Machine 11 Bus System

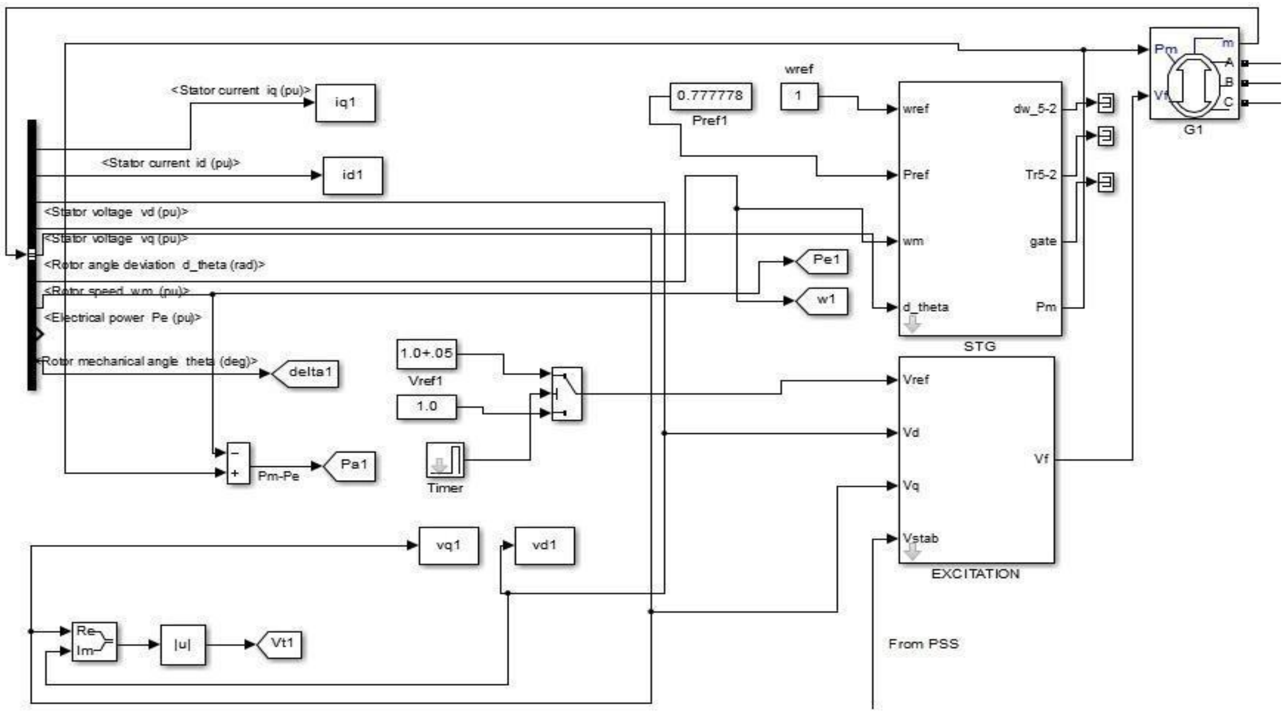

Fig. 1.7 Components used for each generator

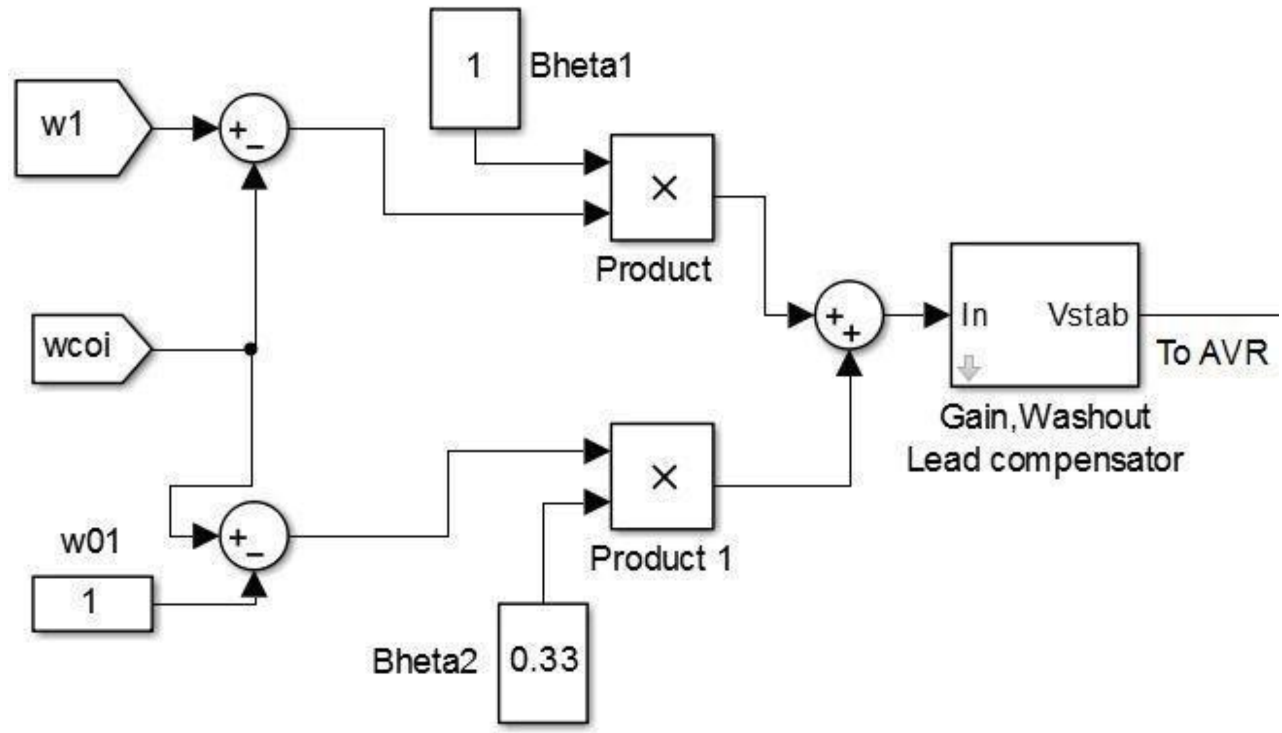

Fig 1.8 Generalized Δω PSS as simu link model

Effect of 3-phase fault on middle of one of the double circuit line

Effect of large signal disturbance is analyzed by applying 3-phase fault on one of the doublecircuit line at 0.5s and this line is isolated by using circuit breakers at 0.55s.

Effect of 3-phase fault on middle of one of the double circuit line without PSS

Fig 1.9 shows the responses effect of 3-phase fault on middle of one of the double circuitline without PSS.

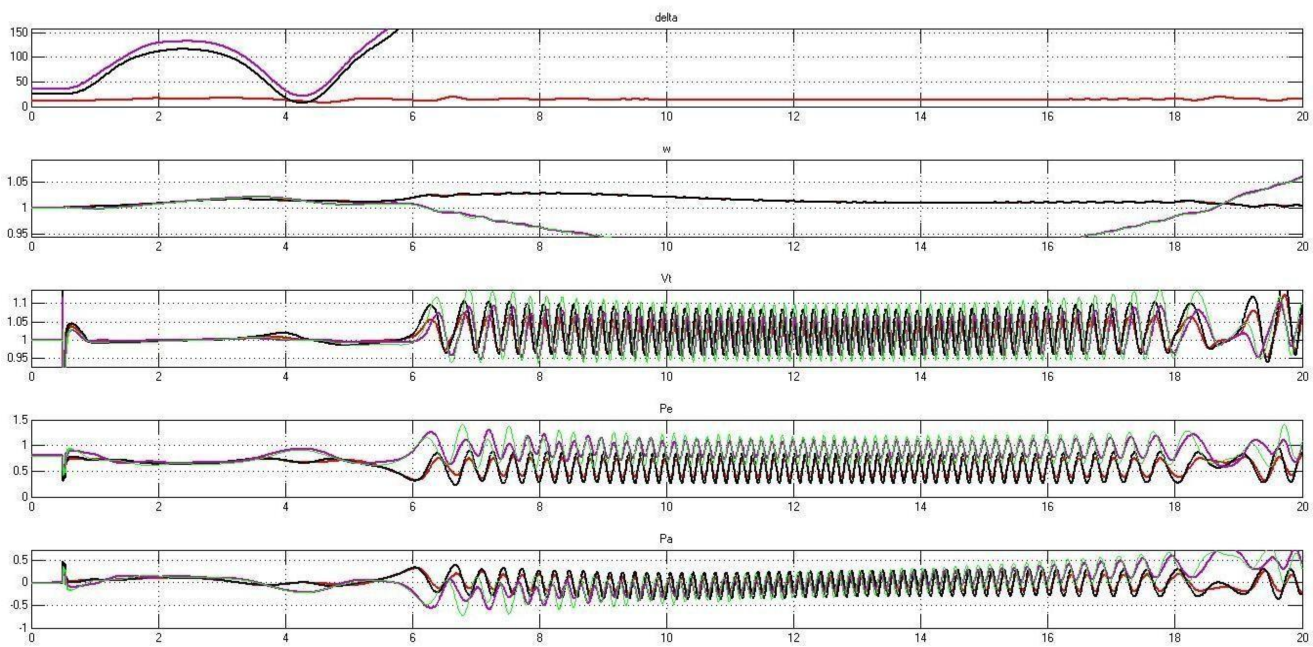

Fig 1.9 Effect of 3phase fault on middle of one of the double circuit line without PSS

Due to large signal disturbance the system goes to unstable it is seen by the relative delta Vs timegraph. So we can attach PSS to increase damping for large signal disturbances.

Effect of 3-phase fault on middle of one of the double circuit line with Generalized Δω PSS

I. Fix β2=0.33 and vary β1 from 0 to 1(0.33, 0.667, 1) with K_{PSS}=18.

The following inference obtained from the responses for relative delta, relative speed,terminal voltage shown in Fig. 4.5, Fig. 4.6 and Fig. 4.7,

- β1 dictates the extent to which the PSS damps inter-area and local modes of oscillation.
- As β1 vary, large signal trajectories of terminal voltage and its post disturbance value are unchanged.
- β1 only alters the small signal characteristics of field current.
- Frequency of the system is unaltered by varying β1.
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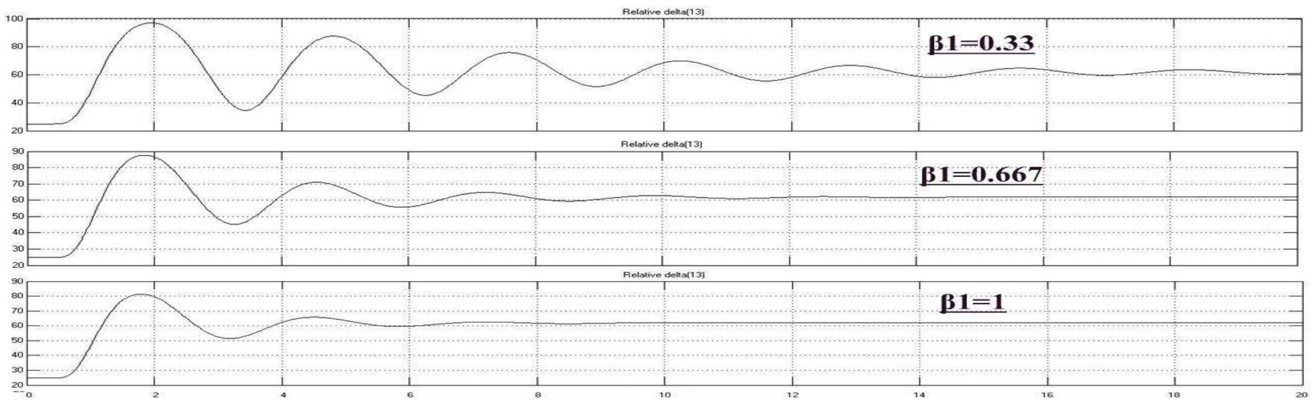

Fig.1.10 Relative delta for β2=0.33 and vary β1 from 0 to 1

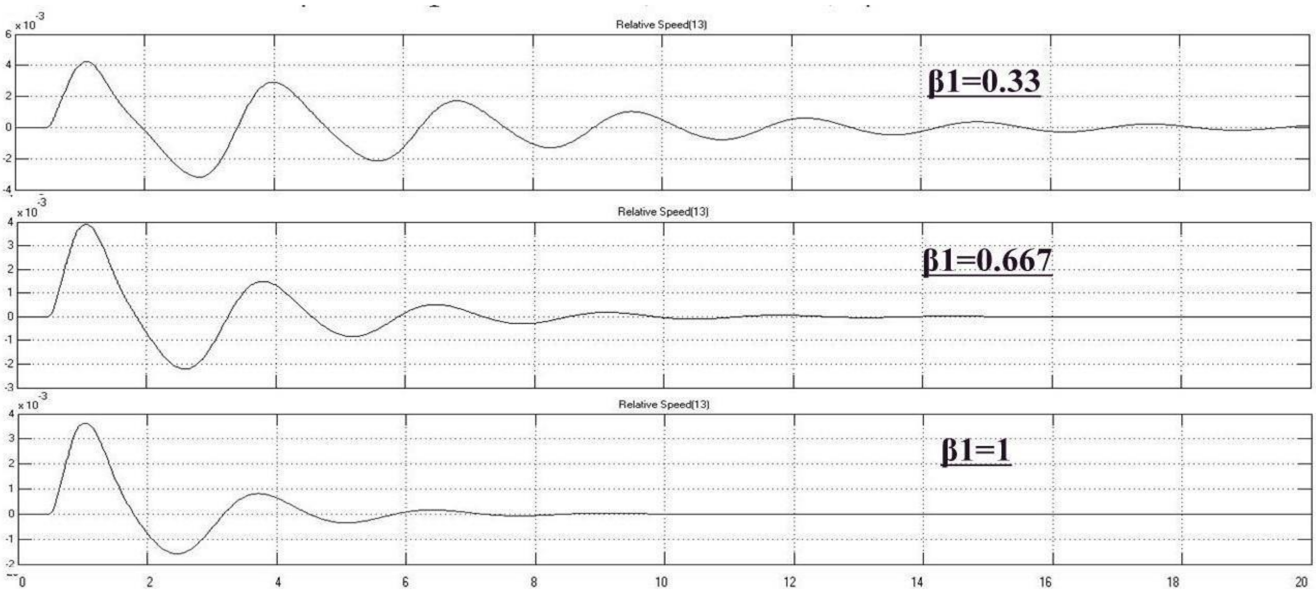

Fig.1.11 Relative Speed for β2=0.33 and vary β1 from 0 to 1

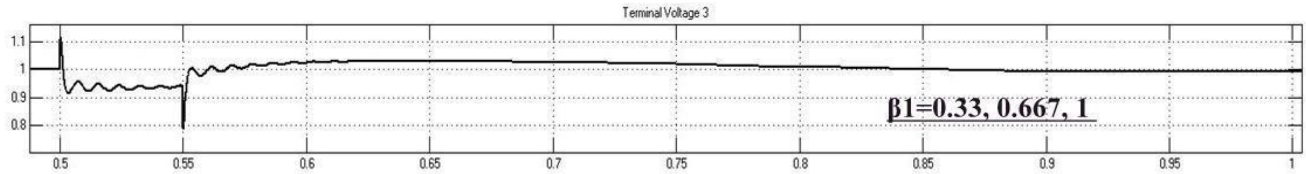

Fig.1.12 Terminal voltage for β2=0.33 and vary β1 from 0 to 1

II. Fix β1=0.33 and vary β2 from 0 to 1(0, 0.33, 0.667) with K_{PSS}=18.

This shows the system frequency, which readily shows the behavior of the frequency regulation mode.

The frequency improves significantly as β2 increases from 0 to 0.33 and modestly as it goes from 0.33 to 0.667

- Effectively, β2 determines the level of overshoot in the system response.
- On β2 increase, terminal voltage following fault becomes incrementally more depressed because of field current supplied by exciter decrease. This can be attributed to the fact that β2 increases, it amplifies the steady state component of control error Δω.
- Thus, there is a trade-off between improving the frequency and degrading the voltage response.

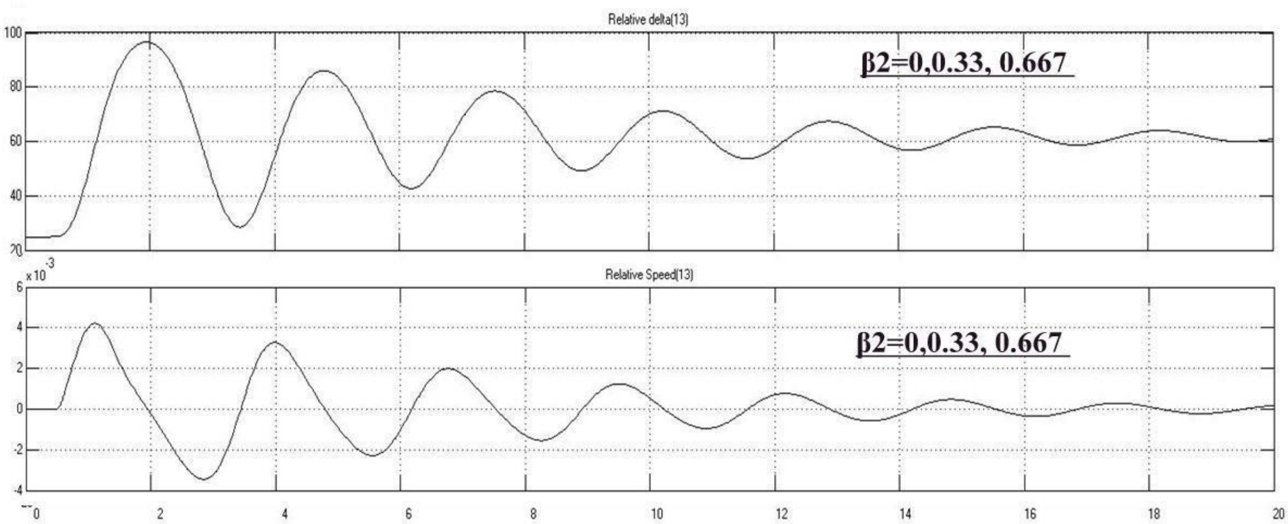

Fig. 4.8 Relative delta and relative speed forβ1=0.33 and vary β2 from 0 to 1

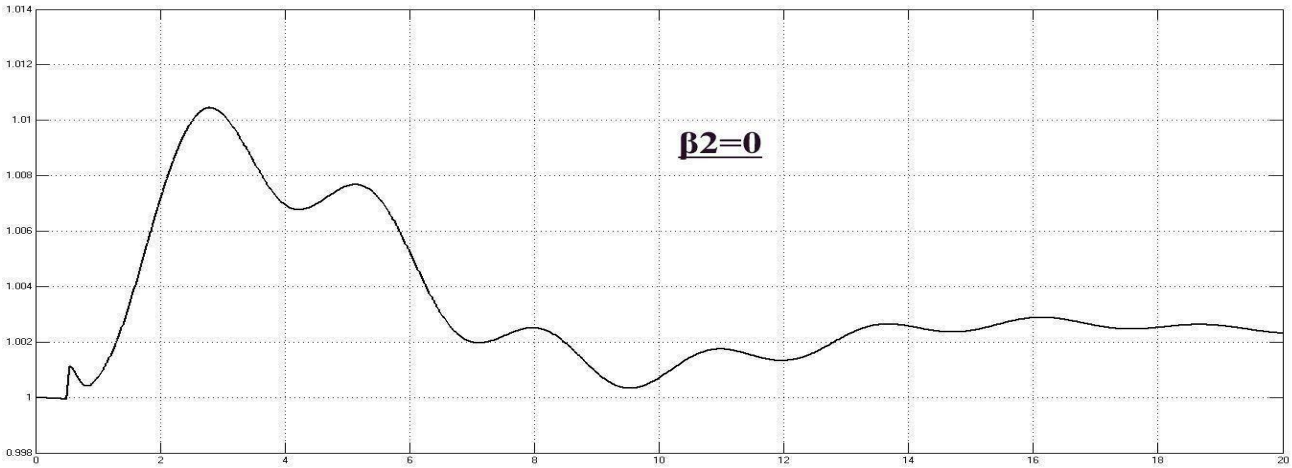

Fig. 4.9 System Frequency for β1=0.33 andβ2=0

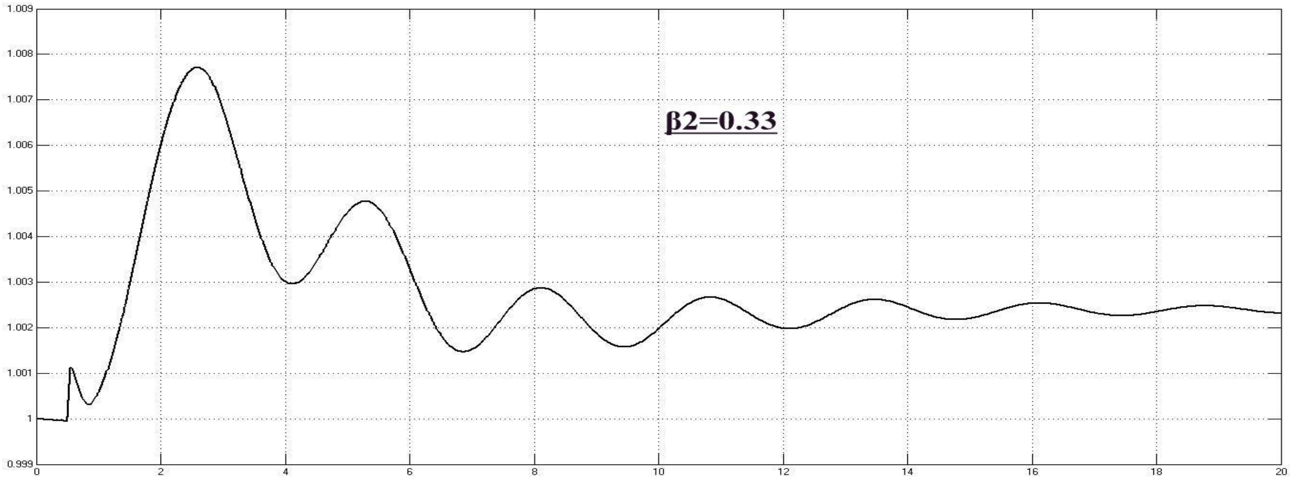

Fig.4.10 System Frequency for β1=0.33 and β2=0.33

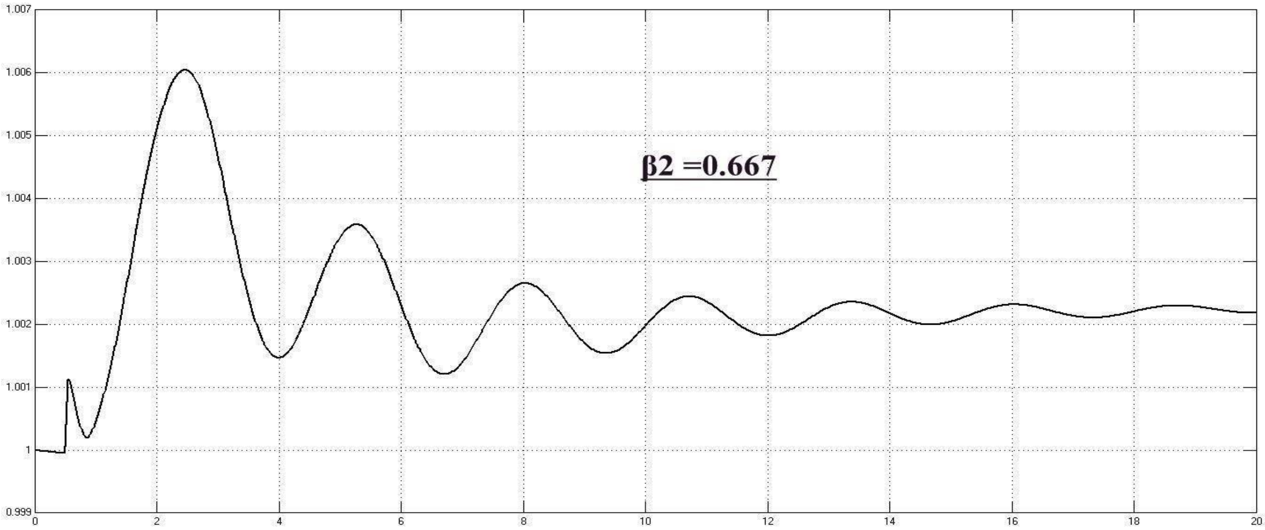

Fig.4.11 System Frequency for β1=0.33 and β2=0.667

Effect of 5% change in reference voltage in AVR of G1

Effect of small signal disturbance is analyzed by applying5%(1.05pu) change in referencevoltage in AVR of Generator 1 at 0.5s and again to 1pu at 0.7s.

Effect of 5% change in reference voltage in AVR of G1 without PSS

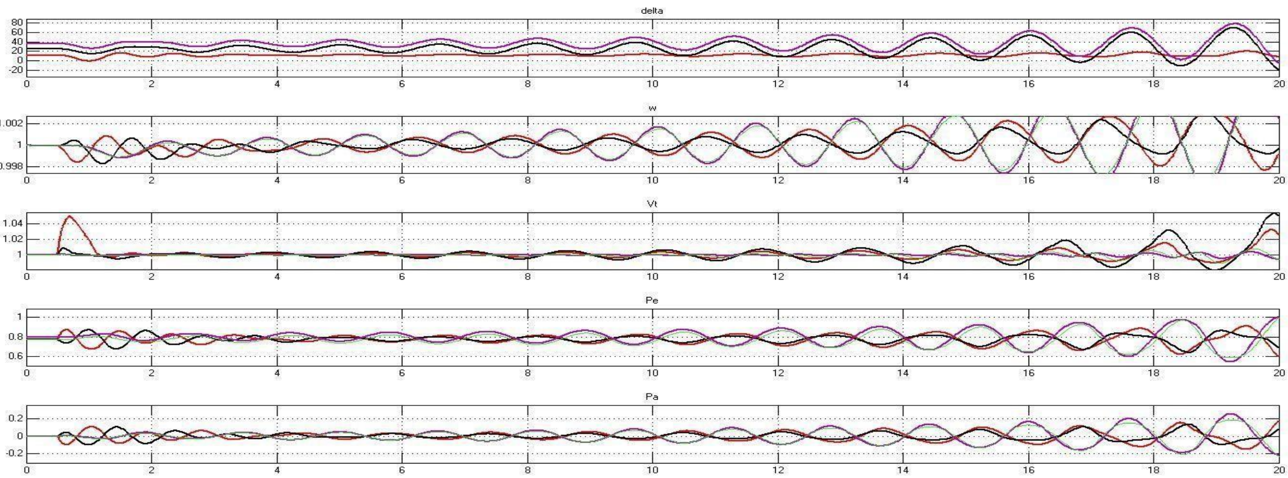

Fig 4.12 shows the responses effect of 5% change in reference voltage in AVR of G1without PSS

Due to small signal disturbance the system goes to unstable it is seen by the Speed, delta Vs time graph.So we can attach PSS to increase damping for small signal disturbances.

Effect of 5% change in reference voltage in AVR of G1 with Generalized Δω PSS

I. **Fix β2=0.33 and vary β1 from 0 to 1(0.33, 0.667, 1) with K_{PSS}=18.**

The following inference obtained from the responses for relative delta, relative speed, terminal voltage shown in Fig. 4.13, Fig. 4.14 and Fig. 4.15,

- β1 only alters the small signal characteristics of field current.
- But, large signal trajectories of terminal voltage are unchanged.
- Hence,β1 dictates the extent to which the PSS damps inter-area and local modes of oscillation.

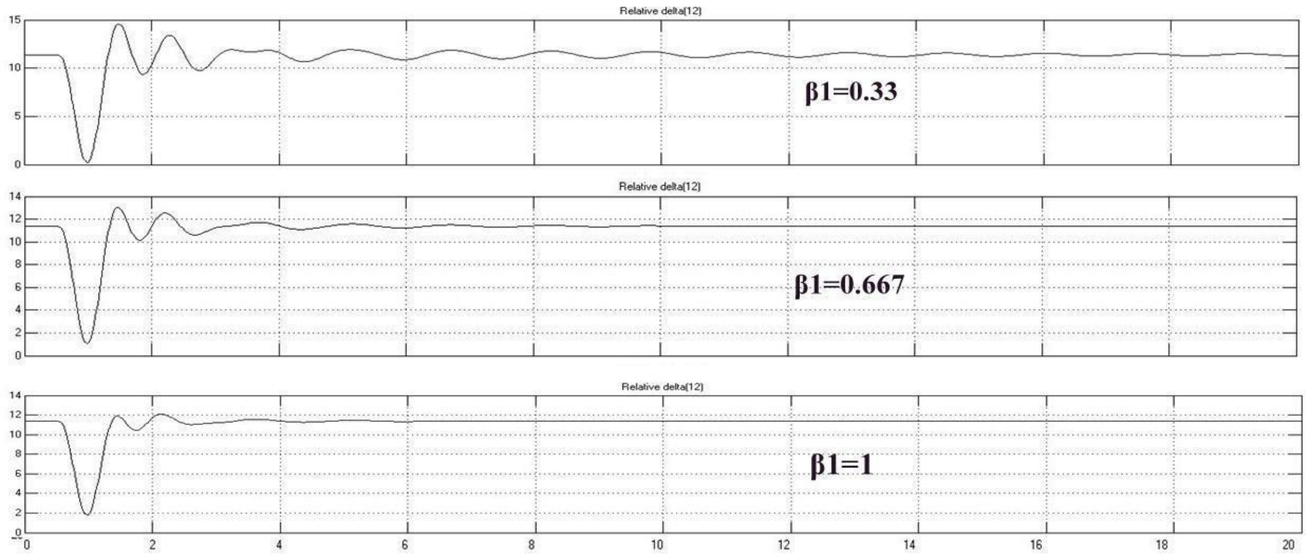

Fig. 4.13 Relative delta for β2=0.33 and vary β1 from 0 to 1

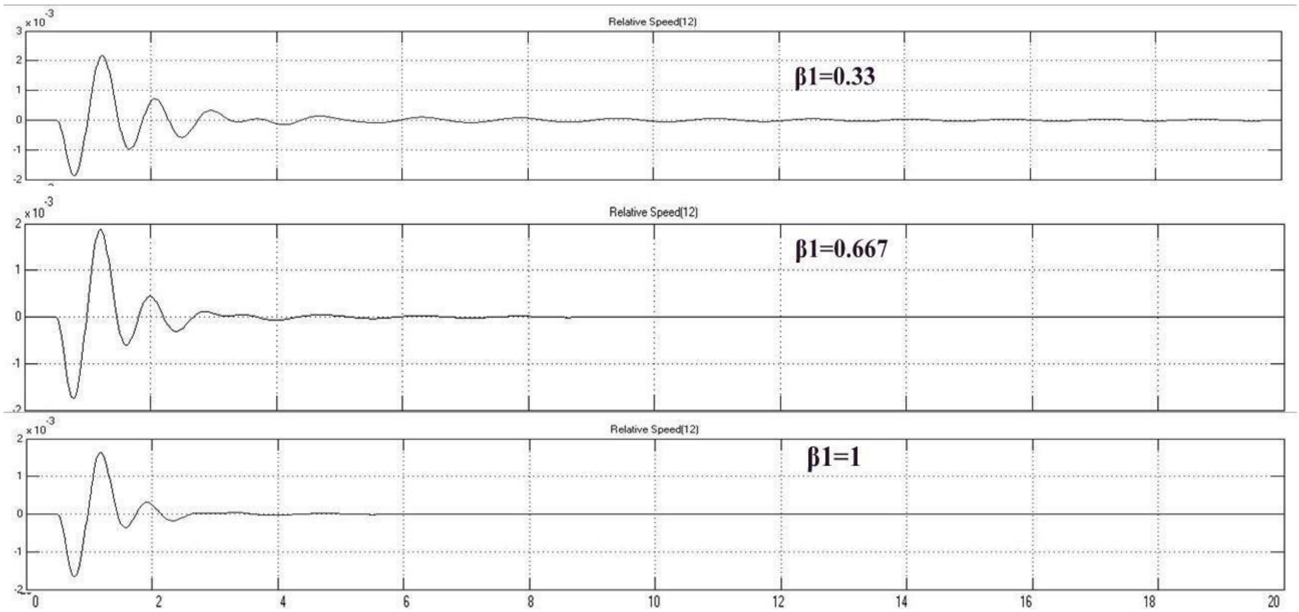

Fig. 4.14 Relative Speed for β2=0.33 and vary β1 from 0 to 1

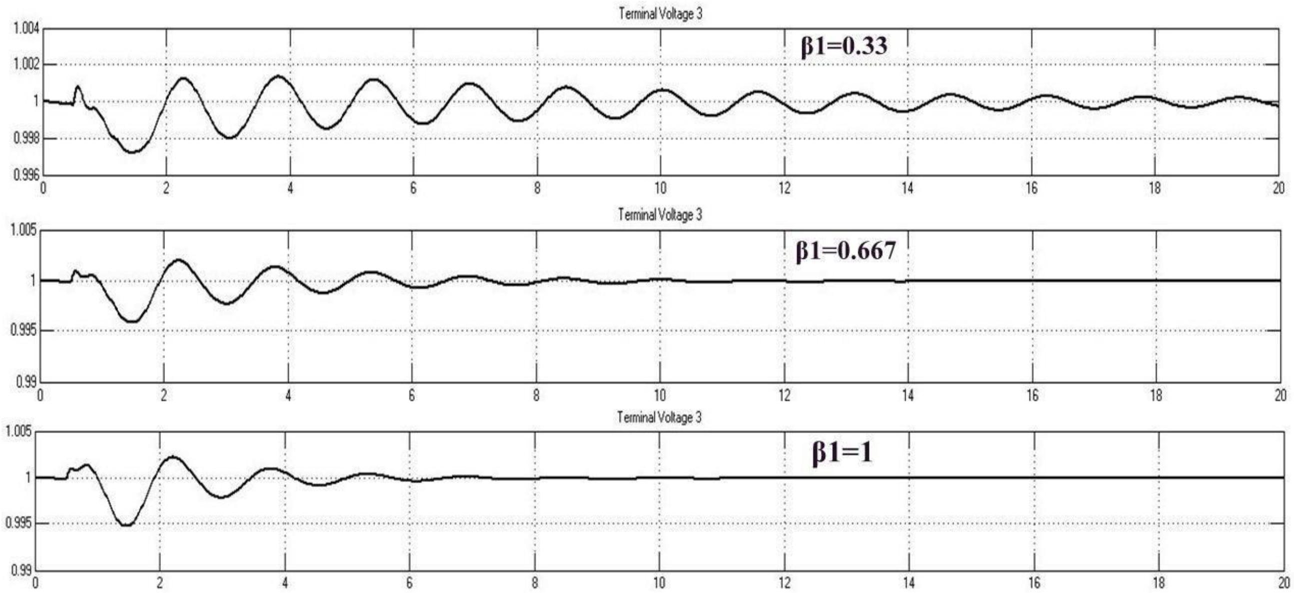

Fig. 4.15 Terminal voltage of G3 for β2=0.33 and vary β1 from 0 to 1

Thus, the control strategy generalized Δω PSS makes it possible to fine-tune the interaction between the PSS and AVR without affecting the damping of inter-area and local modes, andvice versa.

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