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Design of Fixed Parameter Decentralized Power System Stabilizers for Multi Machine Power Systems

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Abstract: **-- This paper proposes a technique to design fixed parameter decentralized Power System Stabilizers (PSSs) for interconnected power systems. To tune the parameters of a PSS, local information available at each machine in the multi-machine environment is used. Frequency Response estimation called GEP(s) between AVR input and resultant torque is also used, with the knowledge of equivalent external reactance incorporated at generating unit of step-up transformer and infinite bus voltage or their estimated values at each machine. Conventional design techniques like P-Vr frequency response approach and method of residues are based on complete system information. In the proposed method, information available at high voltage bus of step-up transformer is used to set up a modified Heffron – Phillip's model, thus to decide the structure of PSS compensator and tune its parameters at each machine in a multi-machine environment by the signals available at Generating Station. The efficacy of the proposed stabilizer to damp out inter area and local modes of oscillations effectively over a wide range of operating conditions is evaluated by a wide area system. Simulation studies compare the proposed stabilizer with conventional design.**

***Keywords*—Power System Stabilizer, Small Signal Stability, Power System Dynamic stability**

I. INTRODUCTION

Insufficient natural damping in the system is one of the major problems in power system operation. Small – signal oscillatory instability is the result of it. Thus to counter Small – signal oscillatory instability, Auxiliary controllers called power system stabilizers (PSS) are used that provide additional damping to the synchronous generator rotor oscillations by modulation of generator excitation[1][2].Fixed gain stabilizers if tuned properly work well. These are tuned by computer simulation modeling or by field tests requiring knowledge of system parameters external to the generating station. But, these parameters change during normal operation of power system[2]. They can't be readily available all times. Even in classical Single Machine Infinite Bus model, estimates of equivalent line impedance and voltage at external bus are required. PSS design require rotor angle δ measured with respect to external bus[2]. Reduced order models connected to the generator are needed to directly measure these parameters, even if we measure, if the available information for the system is inaccurate, PSS designed in a conventional way result in poor performance.

Thus a need to design Coordinated PSS design that is based on damping torque approach used for wide range of operating conditions arise[4]. P-Vr characteristics obtained by disabling the shaft dynamics in all the machines is obtained in this method. System dynamics of $i^{th.}$ machine in a multi-machine system is linear zed by taking secondary bus voltage of step-up transformer but, this cannot be sutiable for very large power systems[3][4] Analysis from[5] showed that GEPTF computed for SMIB is adequate for multimachine environment. By a thorough analysis[5] of frequency responses of generator electrical torques, shown that, frequncy responses between AVR input and resultant electrical torque at the rotor shaft has two components. One depends on Assocated generator and admittance matrix and the other depends only on Associated generator. Diagonal dominancy property of admittance matrix make first component less affected by the generators external parameters. Thus required dynamic information for PSS design concentrated only on generating plant. Thus as per the tuning guidelines, the PSS tuning for a full load for speed and power input signals have a maximum phase lag. Even if the dynamics of external generators are ignored the stabilized designed provides maximum phase lead around the local mode of oscillations. The desinged PSS will have sufficient lead around the local mode of oscillations and at inter area modes that are largely influenced by the dynamics of external geenrators. This

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designed PSS will damp both loal mode and inter area modes of oscillation.

The proposed method of design of PSS is based on Conventional design, but opposed to a conventional stabilizer design, system dynamics are linear zed by taking the secondary bus voltage of step-up transformer of high voltage bus as reference. Infinite bus is taken reference in conventional methods[1][2]. Local plant information is taken by incorporation of external reactance originating from generating unit step-up transformer. This adds phase lead to the phase response of P-Vr Transfer Function. Thus this model parameters are independent of external system information. Thus this model can be used for any machine in the multi –machine environment. PSS's are designed independently for each machine and All PSS design parameters are calculated from local measurements. Local measurements are the Voltage and Power measurements at high voltage bus. By this method, we don't require the values of Equivalent external impedance, bus voltage and rotor angle.

The performance of proposed stabilizer is investigated by 16 machine 68 bus wide area test system[8]. The performance evaluated under various operating conditions and comparison with the Conventional designed PSS[1][2][3], and better damping characteristics under heavy and nominal loading conditions are shown.

II. POWER SYSTEM MODELING

A dynamic modeling of power system is needed for small- signal stability analysis. It includes, synchronous generator, excitation system, avr, transmission lines, etc.

The model shown is used to obtain the linear zed dynamic model of heffron- Phillips or k-constant model. The dynamic equations of ieee model 1.0 for a synchronous generator equipped with static exciter is given as:

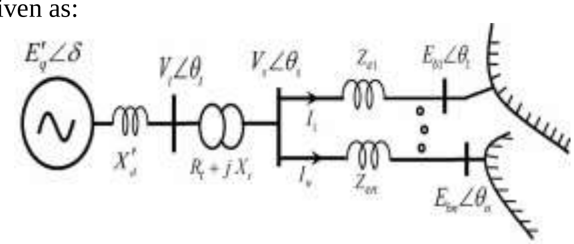

Fig 1: single machine in a connected network.

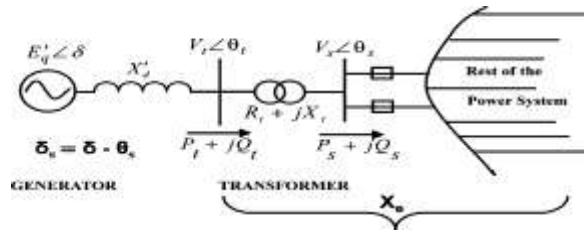

Fig 2: Single Machine In A Connected Network Representation Of Various Parameters.

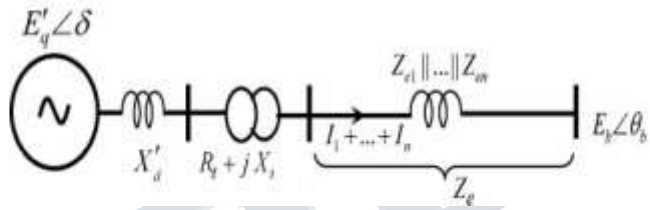

Fig 3: Proposed Equivalent Representation Of Single Machine.

The models shown in the above fig.1 and fig.2 are the single machine in a connected network representation with various parameters. These are used to obtain the linearized dynamic model i.e. Heffron –philip's or k- constant model[7]. This model is used to model the synchronous generator with a high gain, low time constant static exciter. The dynamic equations governing the system are:

$$\dot{\partial} = \omega_B S_m \text{ .... (1)}$$

$$\dot{S}_m = \frac{1}{2H}\{T_{mech} - T_{elec} - DS_m\} \text{ .... (2)}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}\{-E'_q + (X_d - X'_d)i_d + E_{fd}\} \text{ ...... (3)}$$

$$\dot{E}_{fd} = \frac{1}{T_e}\{-E_{fd} + K_e(V_{ref} + V_{pss} - V_t)\} \text{ ...... (4)}$$

$$T_{elec} = E'_q i_q + (X'_d - X'_q) i_d i_q \text{ ....(5)}$$

***Algebraic Equations Of The Stator Are Given As*:**

$$V_q = E'_q + (X'_d i_d - R_a i_q) \text{ .... (6)}$$

$$V_d = = X'_q i_q - R_a i_d \text{ .... (7)}$$

The Variables Above Are Taken Form [3][7].The Rotor Angle With Respect To The High Voltage Bus Of transformer $v_s\angle\Theta_s$. The rotor angle is denoted as: $\partial_s = \partial - \Theta_s$.

The equivalent phasor diagram as in fig 4 for a single machine in a connected network
From the phasor diagram,

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$$\delta_s = \tan^{-1}\frac{P_s(X_t+X_q)-Q_s(R_a+R_t)}{P_s(R_a+R_t)+Q_s(X_t+X_q)+V_S^2} \quad \text{............(8)}$$

$$E'_q = \frac{X_t+X'_d}{X_t}\sqrt{\left\{V_t^2-\left(\frac{X_q}{(X_t+X_q)}V_s\sin\delta_s\right)^2\right\}} - \frac{X'_d}{X_t}V_s\cos\delta_s \quad \text{........... (9)}$$

The values of v_s, P_s and q_s can be evaluated from the secondary bus of the step-up transformer [3]
Currents i_d and i_q are given as:

$$i_d = BE'_q - YV_s\cos(\delta_s + \angle Y) \quad \text{............ (10)}$$

$$i_q = GE'_q - YV_s\sin(\delta_s + \angle Y) \quad \text{............... (11)}$$

HERE $\angle Y = \frac{\pi}{2} - \tan^{-1}(BG^{-1})$ WITH $Y = |Y_{eq}|$
AND

$$Y_{eq} = \{(R_a + R_t) + j(X_t + X_q)^{-1}\} = G + jB$$

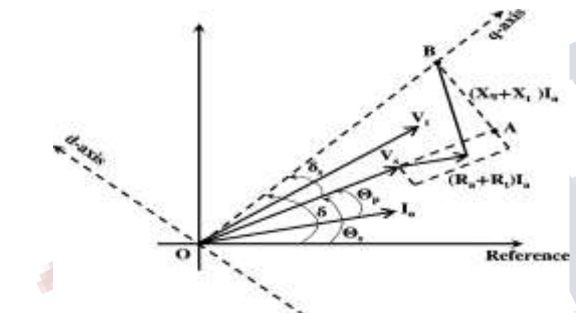

Fig 4: phasor diagram of single machine system.

Locally obtainable data for the i[th] transmission line originating from the secondary bus of step-up transformer are evaluated to obtain e_{bi} and $\boldsymbol{\alpha}_i$ is given form the equivalent single machine transmission phasor diagram as

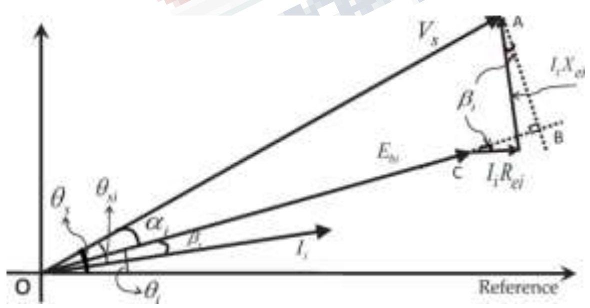

Fig 5: Phasor Diagram of Equivalent System in Fig 3

From The Phasor Diagram, E_{BI} AND $\mathbf{A}_I$ IS GIVEN as:

$$\alpha_i = \tan^{-1}\frac{P_{si}X_{ei}-Q_{si}R_{ei}}{V_S^2-P_sR_{ei}-Q_sX_{ei}} \quad \text{................(12)}$$

$$E_{bi} = V_s\cos\alpha_i - I_i(R_{ei}\cos\beta_i + X_{ei}\sin\beta_i) \quad \text{(13)}$$

HERE, $P_{si} = V_sI_i\cos\theta_{si}$, $Q_{si} = V_sI_i\sin\theta_{si}$ AND $\beta_i = \theta_{si} - \alpha_i$

$\boldsymbol{\Theta}_{SI}$ Is the power factor angle at the high voltage bus W.R.T? I_I

III. PROPOSED APPROACH - LINEARIZATION

Proposed Approach

Standard model of heffron philips model of smib can be obtained by [7] by linearization of system equations around an operating condition. The developments of model with necessary modifications are discussed in [6]. By conversion of machine quantities in parks reference frame to synchronously rotating kron's reference frame, machine network interface is achieved.

The authoritative linearized model of smib system formally known as heffron philips model of k-constant was introduced in [7].modifications to heffron philips model is proposed in [4] for large interconnected power systems. Thus we investigate by replacing stiff bus voltage phasor of smib system with a non-stiff bus voltage phasor of step-up transformer, to establish a linearized model of a single machine in a multi-machine environment using local information[3][4].

Considering two lossless transmission lines, of reactance X_{e1} and X_{e2} with $R_e = 0$ and terminal voltage $E_{b1}\angle\theta_1$ and $E_{b2}\angle\theta_2$ stator currents i_q and i_d can be expressed as:

$$i_q = \frac{X_e\left\{\frac{E_{b1}}{X_{e1}}\sin(\delta_s+\alpha_1)+\frac{E_{b2}}{X_{e2}}\sin(\delta_s+\alpha_2)\right\}}{X_q+X_t+X_e} \quad (14)$$

$$i_d = \frac{X_e\left\{\frac{E_{b1}}{X_{e1}}\cos(\delta_s+\alpha_1)+\frac{E_{b2}}{X_{e2}}\cos(\delta_s+\alpha_2)\right\}-E'_q}{X'_d+X_t+X_e} \quad (15)$$

HERE $X_e = X_{e1}X_{e2}(X_{e2} + X_{e1})^{-1}$

The above algebraic equations can be re written as:

$$i_q = (X_q + X_t + X_e)^{-1}E_b\sin(\partial - \theta_b) \quad (16)$$

$$i_d = (X'_d + X_t + X_e)^{-1}E_b\cos(\partial - \theta_b) - E'_q \quad (17)$$

The Equivalent Single Machine Infinite Bus System Taken In The Above Discussion Is

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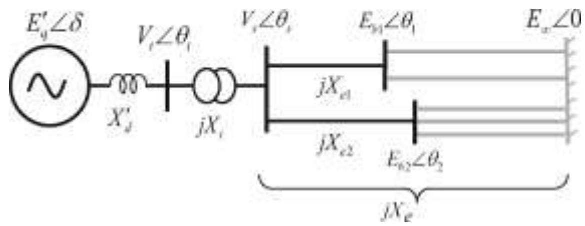

Fig 6: Single Machine Infinite Bus System.

The Stator Currents Representing Smib System with a Single Equivalent Bus of Voltage Phasor $E_b\angle\theta_b$ and reactance X_e are expressed as:

$$\boldsymbol{E_b = X_e\sqrt{\sum_{j=1}^{n}\sum_{i=1}^{n}\frac{E_{bj}}{X_{ej}}\frac{E_{bi}}{X_{ei}}\cos(\alpha_i - \alpha_j)}} \quad \textbf{(18)}$$

$$\boldsymbol{X_e = \left[\sum_{i=1}^{n}\frac{1}{X_{ei}}\right]^{-1}} \quad \textbf{(19)}$$

$$\boldsymbol{\partial_b = \partial - \theta_b = \tan^{-1}\left(\frac{\sum_{i=1}^{n} E_{b1}X_{e1}{}^{-1}\sin(\partial_s + \alpha_i}{\sum_{i=1}^{n} E_{b1}X_{e1}{}^{-1}\cos(\partial_s + \alpha_i}\right)} \quad \textbf{(20)}$$

If ‘n’ lossless transmission lines are emanated from secondary bus of step-up transformer to the external network as in fig 1, its voltage magnitude equivalent E_b and reactance X_e are obtained. From local quantification of power and voltage measurements at the secondary bus of step-up transformer for E_b[3][4].

To yield a relatively robust plant model additional dynamic information is needed, in comparison **TO ∂_s, $\theta_s - \theta_b$ AND X_e**

Linearization

Linearization of SMIB is taken from [7][9] by application
of Kirchhoff’s Voltage law between the generator terminal and infinite bus of a rotating Kron’s reference frame The following linearization equations are given for SMIB

$$V_Q + j\,V_D = \left(V_q + jV_d\right)e^{j8}$$
$$= \left(i_q + ji_d\right)(R_e + jX_e)e^{j8} + E_b\angle 0$$

(21)

Here D and Q refer to the d axis and q axis respectively in Kron’s reference frame. Similarly‘d’ and ‘q’ refers to d and q axis in Park’s reference frame.

Here infinite bus $E_\propto\angle 0$ is replaced with a non-stiff bus $V_s\angle\theta_s$ for the design of PSS and a non linear voltage regulator for interconnected power systems.

The modification to design PSS independent of external system parameters is

$$(V_q + jV_d) = (i_q + ji_d)(R_t + jX_t) + V_s\angle\theta_s e^{j8} \quad (22)$$

To make modified PSS perform independent of external parameters we replace ∂ by$\partial_s - \theta_s$. The modified equation is given as:

$$(V_q + jV_d) = (i_q + ji_d)(R_t + jX_t) + V_s\angle{-\partial_s} \quad (23)$$

By simplification, the modified stator algebraic equations referred to the transformer bus, the voltage in a multi-machine environment for any machine are given as:

$$V_q = R_t i_q - X_t i_d + V_s\cos(\partial_s) \ (24)$$

$$V_d = R_t i_d - X_t i_q + V_s\ \sin(\partial_s) \quad (25)$$

Thus the linearized model of a single machine in a connected network is formulated as shown in fig.7

The system mechanical equations, electrical equations i.e. V_q and V_d are linearized to obtain the following constants.

$$G_1 = \frac{V_{S0}E_{qo}\cos\delta_{S0}}{X_q + X_t} + \frac{X_q - X'_d}{X'_d + X_t}V_{S0}\sin\delta_{S0}$$

$$G_2 = \frac{X_q + X_t}{X'_d + X_t}i_{q0}$$

$$G_3 = \frac{X'_d + X_t}{X_d + X_t}$$

$$G_4 = \frac{X_d - X'_d}{X'_d + X_t}V_{S0}\sin\delta_{S0}$$

$$G_5 = \frac{V_{d0}E_q\cos\delta_{S0}}{(X_q + X_t)V_{t0}} - \frac{X'_d V_{q0}}{(X'_d + X_t)V_{t0}}V_{S0}\sin\delta_{S0}$$

$$G_6 = \frac{X_t}{X'_d + X_t}\frac{V_{q0}}{V_{t0}} \quad (26)$$

$$\mathrm{G_{V1}} = \frac{\mathrm{E_{qo}\sin\delta_{S0}}}{\mathrm{(X_q + X_t)}} - \frac{\mathrm{(X_q - X'_d)i_{q0}\cos\delta_{S0}}}{\mathrm{(X'_d + X_t)}}$$

$$\mathrm{G_{V2}} = -\frac{\mathrm{(X_d - X'_d)\cos\delta_{S0}}}{\mathrm{(X'_d + X_t)}}$$

$$\mathrm{G_{V3}} = \frac{\mathrm{X_q V_{d0}\sin\delta_{S0}}}{\mathrm{(X_q + X_t)V_{t0}}} - \frac{\mathrm{X'_d V_{q0}\cos\delta_{S0}}}{\mathrm{(X'_d + X_t)V_{t0}}} \quad (27)$$

Here $E_{q0} = E'_{q0} - (X_q - X'_d)i_{d0}$

The above definition constants form G_1 to G_6 be Heffron Philips model constants only, but they are independent of equivalent reactanceX_e, rotor angle δ and voltage of the systemV_b [8].

The proposed model also introduces three additional constants G_{V1}, G_{V2} and G_{V3}. .[3][4]

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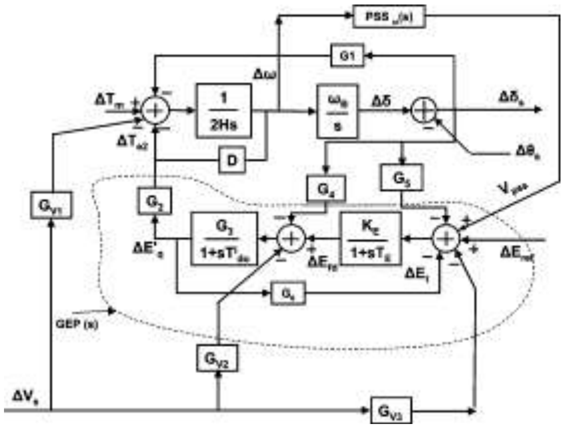

Fig. 7 Linearized model of a single machine in a connected--network

The constants are introduced at Torque, field voltage and terminal voltage junction points. This model represents a strong system with the external reactance X_e equal to transformer reactance X_t.

The GEP form of this model will give maximum phase lag, on system with full loading condition. The above G constants can be obtained in real time by load flow information at the transformer and at generator terminals.

In the proposed PSS technique design, system parameters can be easily modified to accommodate major structural changes from time to time by local measurements.

IV. DESIGN & TUNING OF POWER SYSTEM STABILIZER (PSS)

PSS action is effective by the transfer function block GEP(S), from the fig .7, between electric torque output and reference voltage input with variation in the machine speed assumed constant.

$$\mathbf{GEP(s)} = \frac{G_2 G_3 EXC(s)}{(1+sT'_{d0}G_3)+G_6 G_3 EXC(s)} \qquad \mathbf{(28)}$$

Here EXC(S) is the transfer function of the excitation system for every machine in a multi-machine system. The linear zed state equations for each generator is of the form

$$\dot{x} = Ax + B_1 \Delta Vref + B_2 \Delta\theta_s + B_3 \Delta V_s$$

Here $x = [\Delta\partial_b; \Delta S_m; \Delta E'_q; \Delta E_{fd}]$

A compensator with complex zeros is advisable to use if the GEP(S) contain resonant peak. In the absence of resonant peak, compensator with a simple pole zero configuration is used.

The form of compensator required for resonant response of GEP(S) is:

$$\mathbf{H(S)} = K_{pss}\frac{sT_w}{1+sT_w}\frac{(s^2\frac{1}{\omega_n^2}+\frac{2\zeta}{\omega_n}s+1)}{(1+sT_1)(1+sT_2)} \qquad \mathbf{(29)}$$

The form of compensator required for non-resonant response of GEP(S) is:

$$\mathbf{H(s)} = K_{pss}\frac{sT_w}{1+sT_w}\left(\frac{(1+sT_1)}{(1+sT_2)}\right)^m \qquad \mathbf{(30)}$$

Here, m is the number of lead – lag stages.

To establish a greatest phase lag as the Tuning condition for the designed stabilizer, Gain of the PSS is set to one-third of the instability gain. Limiting gain of stabilizers with speed or power input signals occur with a strong transmission system. Thus it is set to establish a strongest credible system to give highest stabilizer loop gain. To establish the maximum damping of rotor oscillations as in (2)(4)(G), it is needed to establish the weakest power system conditions and associated loading

Adequacy of PSS gain settings will be determined under these conditions. Thus tuning guide lines are summarized for tow forms of GEP(s) for a resonant peak and a non resonant peak. These principles are taken from [10]. The tuning guide lines for dual input stabilizer are discussed in [3][4][11].

For local mode of oscillations in the range of 0.8 to 2.0 Hz wash out time i.e. T_w of 1s is sufficient. For other low frequency inter area modes T_w of 10s is desirable. Lower the frequency, significant the phase lead. For inter area mode damping and robustness, we need completer system data, but by this design, considerable improvement in the phase lag from uncompensated GEP(s) to that of compensated GEP(s) around the frequency range of inter area modes i.e. form 0.2 Hz to 0.6 Hz, damping component of these modes are significantly increased by PSS tuning.

V. SIMULATION – OBSERVATION – COMPARISION

For the illustration of the proposed technique and compare with conventional methods, A 16 machine, 68 bus test system is considered as in [8]. All the data relating to the 16 machine 68 bus test system is in correspondence to [8]. The exciter is replaced with a static exciter with time constants of 0.05 and a high gain of 200. System loads are varied from 35% to 250% of the nominal loading conditions as from [8]. For nominal loading conditions, similar to SMIB case in model [3] phase plot of GEP(s) is obtained. On comparison, lesser phase lead compensation is selected for Generators.

The 16 machine 68 bus system taken for simulation studies is shown in Fig. 8

PSS design by proposed technique is more adequate for PSS design than conventional design techniques [1].To demonstrate robust performance of proposed PSS over wide range of operating conditions, different operating scenarios are taken in [13], and we take them all similarly. The overall performance of P-Vr PSS designed on conventional basis is highly oscillator for several operating conditions as compared to proposed PSS. From the following test results it is shown that the system exhibit superior damping performance with proposed method as compared with P-Vr PSS.

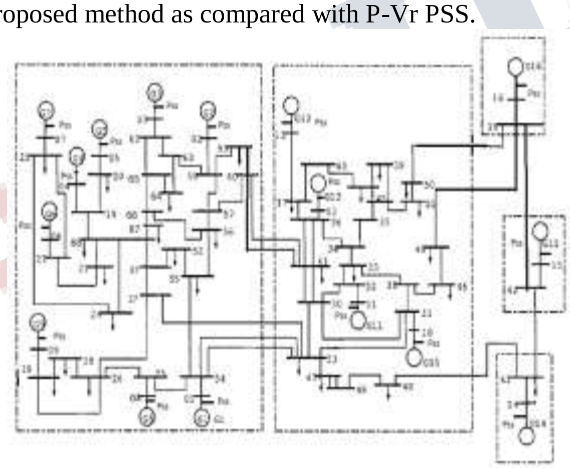

Fig .8: 16 generator 68- bus test system, with all PSS

For the above 16 Generator 68 bus test system, the total data and system parameters are taken from [8]. The sample Voltage and Power Generation for each machine range close to 1 pu for Voltage and take a Maximum of 40 pu for Power generation for a machine.

From total data taken from [8], we compare the simulink results of a 16 machine 68 bus system, with conventional method of design on various parameters that determine the robust performance of a stabilizer designed on the proposed method. The results we compare are Oscillation damping capability of a stabilizer during the occurrence of a fault under System Heavy load, light loading conditions that include change in voltage and mechanical torque.

The Phase and Magnitude characteristics of both the designs are compared, to show the design accuracy and robust performance.

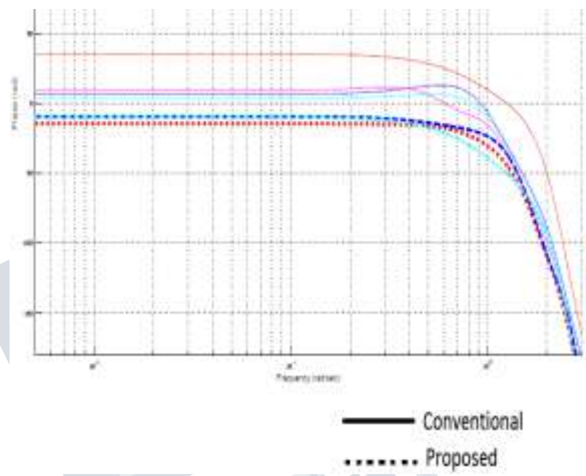

Fig 9. GEP P-Vr Characteristics Phase Response

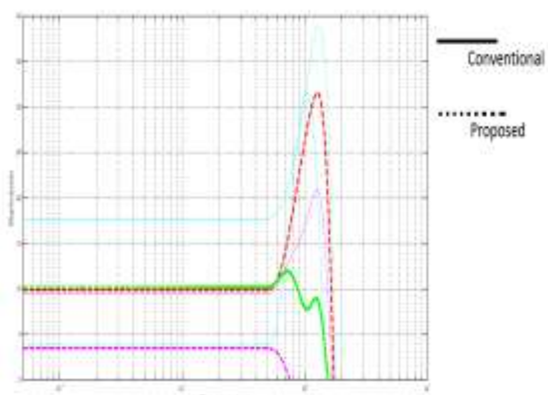

Fig.10 GEP P-Vr Characteristics Magnitude Response

The magnitude and Phase Responses characteristics for all possible cases are obtained and is compared with conventional and our proposed methods in Fig.9, Fig.10.The responses are much closer and nearly match with conventional methods Thus GEP(s) Closely match with P-Vr TF.

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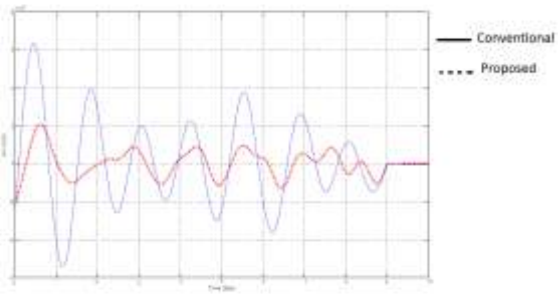

Fig. 11 Oscillation Damping- System Heavy Load, Responses for a 3 – Φ Fault for 10 ms

To demonstrate robust performance over wide range of operating conditions, System responses over heavy loading condition was compared, and we see that system exhibit superior damping performance for 10 ms 3 – Φ fault, the result is demonstrated in Fig. 11

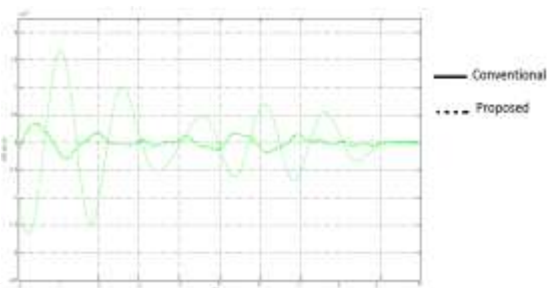

Fig.12: Oscillation Damping Light loading, 30% Step change in Tm, Mechanical Torque Disturbance

Fig 13: Oscillation Damping-Heavy loading, 3-∅ fault 100ms

Simulation results of 3-∅ fault of 100ms followed by tripping of lines in a system, are shown in Fig 12, Fig 13 and we see that clearing times with the proposed PSS for nominal and Heavy Loading Conditions show the efficacy of the proposed stabilizer.

From the above simulation results, PSS designed by proposed method has shown better performance under variable conditions as compared to Conventional methods.

VI. CONCLUSION

The PSS design method proposed in this paper is based on the conventional design techniques but, the system dynamics are linearized by equivalent bus as reference, instead of Infinite bus as in conventional design. This method advances the methods followed in for design of PSS parameters by proposing a synthesized equivalent bus by using local measurements available at power station. The need to calculate or compute the values of equivalent external impedances, bus voltage and rotor angles at external bus is eliminated. The designed PSS based on proposed principle has shown better performance than stabilizers designed by complete system data in a multi-machine environment. The designed PSS and data applied for 16 machine 68 bus test system shown comparable better performance.

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