Designing of Power System Stabilizer and It Effects on Power System

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***Abstract*— The small signal instability is one of the major problems in power system operation caused by insufficient natural damping in the system. High values of external system reactance and high generator output with high response exciter can introduce negative damping even though synchronizing torque is increased and leads to system instability. The most cost-effective way of countering this instability is to use auxiliary controllers called power system stabilizers. It acts through the excitation system and enhances the dynamic stability by providing additional damping electrical torque. In the present work, to study local mode of power oscillation, Eigen values analysis and time domain analysis were carried out on a test system. To suppress the power oscillations the parameters of power system stabilizer were determined using a conventional design and simulation results shows its effectiveness.**

Keyterms-Single Machine Infinite Bus, Power System Stabilizer, Small Signal Stability, Damping oscillations, Eigen Values.

I INTRODUCTION

Power system stability is the ability of an electrical power system, for given operating conditions, to regain its state of operating equilibrium after being subjected to a physical disturbance, with the system variables bounded, so that the entire system remains intact and the service remains uninterrupted. The rotor angle stability is 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.

II PROBLEM FORMULATION

The objective of the present work is to design a power system stabilizer to increase system stability by damping the local oscillations. For a single machine infinite bus power system, the linearized equations are

$$\frac{d\delta}{dt} = \omega_B(\Delta S_m) \quad (1)$$

$$\frac{2Hd(\Delta S_m)}{dt} = -D\Delta S_m + T_m - T_e \quad (2)$$

where,

$$T_e = E_q' i_q - (x_q - x_d')i_d x_d' \quad (3)$$

Equations (1)-(3) along with other system states like exciter can be solved to determine the stability of the system..

III SMALL SIGNAL ANALYSIS OF SMIB

Fig.1 shows a single line diagram of a single machine system. For simplicity it is assumed that the synchronous machine is represented by a classical model. Further it is assumed that damper windings both in the d and q axes and armature resistance are neglected. The linearized model of the single machine infinite bus system is given in Fig 2

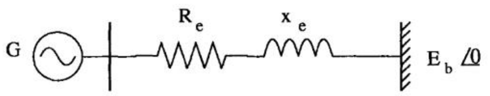

Fig.1. Single line diagram of SMIB

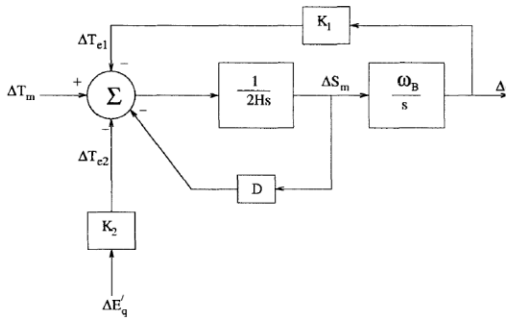

Fig.2. SMIB with classical model of synchronous generator

The state space model can be developed from equations (1), (2) and (3) by taking Laplace transforms,

$$\Delta\delta = \left(\frac{\omega_B}{s}\right)\Delta S_m \quad (4)$$

$$\Delta S_m = \left(\frac{1}{2H}\right)(\Delta T_m - \Delta T_e - D\Delta S_m) \quad (5)$$

$$\Delta T_e = K_1\Delta\delta + K_2\Delta E_q' \quad (6)$$

Equation (4) and (5) can be written in matrix form as

$$\dot{x} = Ax + Bu$$

$$\begin{pmatrix} \Delta\dot{S}_m \\ \Delta\dot{\delta} \end{pmatrix} = \begin{pmatrix} -D/2H & K_1/2H \\ \omega_B & 0 \end{pmatrix}\begin{pmatrix} \Delta S_m \\ \Delta\delta \end{pmatrix} \quad (7)$$

It may be observed here that the elements of state matrix A depend on D, H and the initial operating conditions.

The characteristic equation is given by,

$$Hs^2 + Ds + K_1\omega_B \quad (8)$$

For stability, both damping co-efficient (D) and K_1 should be positive. If D is negligible, the roots of the characteristic equations are

$$s_1, s_2 = \pm\sqrt{(K_1\omega_B/_{2H})} = \pm j\omega_n \quad (9)$$

The stability of the system for different cases has been analyzed by Eigen value analysis and time domain analysis. The Eigen values have conjugate pairs. If they have zero real parts the system here is marginally stable with sustained oscillations. If contain negative real parts the oscillations will be damped and system become stable and if contain positive real parts so the oscillation grows. The eigen value analysis are carried out for the above state matrix and the results are tabulated in the Table I and Table I. The results shows the characteristic of the system based on the damping co-efficient D for the different loading conditions. The eigen value analysis is validated by using the time domain analysis.

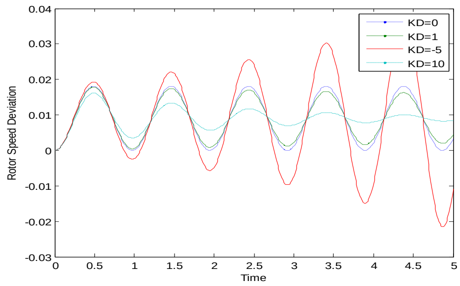

Fig.3. Rotor Angle Deviation classical model high loading (Pg=1pu)

From Fig.3 it is clear that the system becomes unstable for the negative damping co-efficient. The damping of power oscillation increases with damping co-efficient D.

IV Small Signal Analysis Of SMIB With Field Circuit

To study the effect of field winding flux linkage on system stability, the flux decay model of generator is considered. Fig 4 shows the linearized model of the SMIB system with the field flux variation.

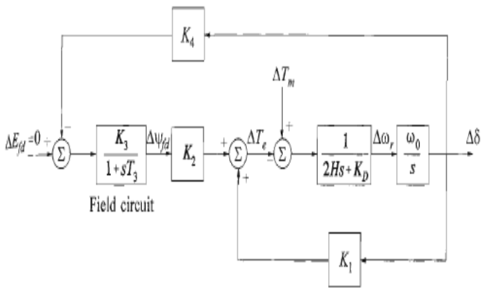

Fig.4. Block diagram of SMIB with effect of field flux

TABLE I

Effect Of Damping Co-efficient For Classical Model (Low Loading)

D	0	1	10	-5
Eigen Values	±9.2128i	-.05±9.2181i	-.5 ±9.2047i	.25 ±9.2148i
Damping ratio	0	0.2698	0.7335	-0.3668
Frequency(rad/sec)	9.22	9.22	9.22	9.22

TABLE II

Effect Of Damping Co-efficient For Classical Model (High Loading)

D	0	1	10	-5
Eigen Values	± 7.4772i	-.05±7.4771i	-.5 ± 7.4605i	. 25 ± 7.4731i
Damping ratio	0	.3331	.9053	-.4520
Frequency(rad/sec)	7.48	7.48	7.48	7.48

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The field winding dynamics can be expressed as

$$T'_{d0}\left({dE'_q}/{dt}\right) = E_{fd} - E'_q + (x_q - x'_d)i_d \quad (10)$$

By taking Laplace transform of equation (10)

$$(1 + sT'_{d0}K_3)\Delta E'_q = K_3\Delta E_{fd} - K_3K_4\Delta\delta \quad (11)$$

$$\Delta\dot{E}'_q = {\Delta E_{fd}}/{T'_{d0}} - {K_4\Delta\delta}/{T'_{d0}} - {K_3\Delta E'_q}/{T'_{d0}} \quad (12)$$

The dynamical behavior of the SMIB system in a compact form can be given as,

$$\begin{pmatrix}\Delta\dot{S}_m \\ \Delta\dot{\delta} \\ \Delta\dot{E}'_q\end{pmatrix} = \begin{pmatrix} -D/2H & -K1/2H & -K2/2H \\ \omega_B & 0 & 0 \\ 0 & -K4/T'_{d0} & -1/K3T'_{d0}\end{pmatrix}\begin{pmatrix}\Delta\omega \\ \Delta\delta \\ \Delta E'_q\end{pmatrix} \quad (13)$$

The eigen value analysis and time domain analysis is carried using expression (13) for different operating conditions.

The resulting eigen values are tabulated in the Table III and Table IV. The results obtained for the various damping coefficients illustrates that negative real part of eigen values indicates the stable condition of the system. The system is partially damped due to the effect of field flux variation in both lo loading and high loading conditions. Fig. 5 shows the local oscillations are damped by flux decay model. The effect of field flux variation reduces the synchronizing torque and increase the damping torque component at the rotor oscillation frequency.

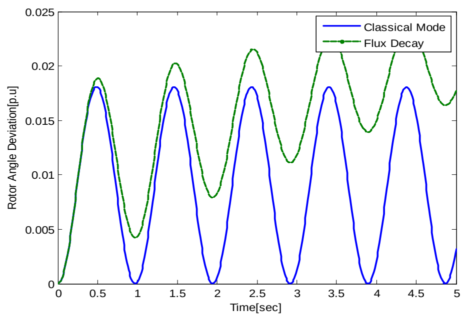

Fig.5. Comparison of rotor deviation between classical model and flux decay model high loading (Pg=1pu)

V Small Signal Analysis Of SMIB With Excitation System

The main objective of the excitation system is to control the field current of the synchronous machine. The SMIB with excitation control is shown in Fig. 6. The field current is controlled so as to regulate the terminal voltage. Commonly used functions are the field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-Hertz regulator and protection, and under excitation limiter. These are normally distinct circuits and their output signals may be applied to the excitation system at various locations as a summing input or a gated input. The static exciter IEEE TYPE ST1 is considered. The perturbation in the terminal voltage V_t can be expressed as

$$\Delta V_t = -\left({V_{do}}/{V_{to}}\right)\Delta V_d + \left({V_{qo}}/{V_{to}}\right)\Delta V_q \quad (14)$$

TABLE III
Effect Of Damping Co-efficient For Flux Decay Model (Low Loading)

D	0		1		10	
Eigen Values	-.226	-0.1185 ± 5.9314i	-.2258	-.1686 ±5.9322i	-.2244	-.6193 ± 5.9204
Damping ratio	1	.2707	1	.3844	1	.3826
Frequency(rad/sec)	.8314	5.93	.8314	5.93	.824	5.95

TABLE IV
Effect Of Damping Co-efficient For Flux Decay Model (High loading)

D	0		1		10	
Eigen Values	-.1225	-.1703±6.45i	-.1224	-.2203±6.4529i	-.1215	-.6708±6.4456i
Damping ratio	1	.3573	1	.4615	1	.3826
Frequency (rad/sec)	.4488	6.45	.4488	6.46	.4451	6.48

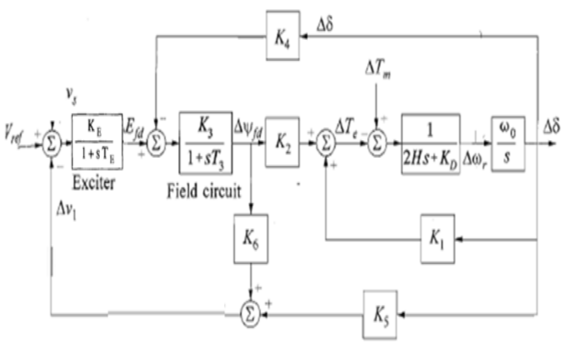

Fig 6 The Block diagram of SMIB with exciter control

By linearizing the expression(14),

$$\Delta V_t = K_5\Delta\delta + K_5\Delta E_q^{'} \qquad (15)$$

The system equation can be derived as

$$\Delta\dot{E}_{fd} = {}^{\Delta E_{fd}}/_{T_E} + {}^{K_E}/_{T_E}\,(\Delta V_{ref} - K_5\Delta\delta - K_6 \qquad (16)$$

$$\begin{pmatrix}\Delta\dot{S}_m\\ \Delta\delta^{\cdot}\\ \Delta\dot{E}_q^{'}\\ \Delta\dot{X}_1\end{pmatrix} = \begin{pmatrix} {}^{-D}/_{2H} & {}^{-K1}/_{2H} & {}^{-K2}/_{2H} & 0\\ \omega_B & 0 & 0 & 0\\ 0 & {}^{-K4}/_{T_{d0}^{'}} & {}^{-1}/_{K3T_{d0}^{'}} & {}^{-KA}/_{T_{d0}^{'}}\\ 0 & {}^{K5}/_{T_R} & {}^{K6}/_{T_R} & {}^{-1}/_{T_R}\end{pmatrix}\begin{pmatrix}\Delta S_m\\ \Delta\delta\\ \Delta E_q^{'}\\ \Delta X_1\end{pmatrix} \qquad (17)$$

The result for the system with exciter is tabulated in Table V and Table V. They infers that under low loading condition with exciter control the system is stable and the system becomes unstable hen the system is highly loaded. The positive real values of eigen values represent the unstable condition of the system due to heavy loading.

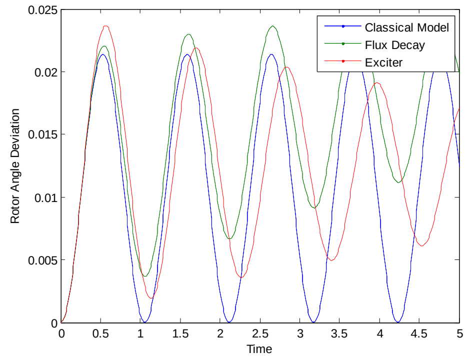

Fig.7. Comparison of Rotor angle deviation for Classical model vs Flux Decay model vs Exciter low loading (Pg=.5pu)

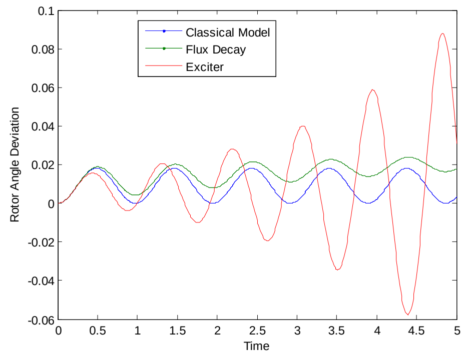

Fig.8. Comparison of Rotor angle deviation for Classical model vs Flux Decay model vs Exciter high loading (Pg=1pu)

TABLE V

EFFECT OF DAMPING CO-EFFICIENT WITH EXCITATION CONTROL (LOW LOADING)

D	0		10	
Eigen Values	-2.41±3.39i	-1.1919 ±5.98i	-2.41 ± 3.39i	-1.38±5.990i
Damping ratio	2.13	0.7308	2.13	.8458
Frequency(rad/sec)	4.16	5.99	4.16	6.0

TABLE VI

EFFECT OF DAMPING CO-EFFICIENT WITH EXCITATION CONTROL (HIGH LOADING)

D	0		10	
Eigen Values	-2.88 ±3.77i	.5518 ±6.18i	-2.88 ±3.78i	1.3412± 6.18i
Damping ratio	2.2330	-.3275	2.2294	-0.2165
Frequency (rad/sec)	4.75	6.18	4.75	6.18

Fig.7 depicts that the system is stable when the system is lightly loaded and Fig 8 depicts that system becomes unstable under the heavy loaded condition. The system becomes unstable due to negative damping produced by exciter at high loading condition.

VI Designing Of Power System Stabilizer

A cost efficient and satisfactory solution to the problem of oscillatory instability is to provide damping for generator rotor oscillations. This is conveniently done by providing power system stabilizers (PSS) as shown in Fig 10 which are supplementary controllers in the excitation systems. The signal V_s in is the output from PSS which has input signal derived from rotor velocity, frequency, electrical power or a combination of these variables. The power system stabilizer provides stabilizing signals to the voltage regulator to damp out oscillations in the power system. It consists of a washout circuit, dynamic compensator, torsional filter and limiter. The major objective of providing PSS is to increase the power transfer in the network, which would otherwise be limited by oscillatory instability. The PSS must also function properly when the system is subjected to large disturbances. The washout circuit 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 the input signal (say rotor speed) and not to the dc offsets in the signal. The washout circuit acts essentially as a high pass filter and it must pass all frequencies that are of interest.

$$T(s) = (K_s(1 + sT_1)(1 + sT_3)) /((1 + sT_2)(1 + sT_4)) \quad (18)$$

where,

K_s 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 3.0 Hz). With static exciters, only one lead-lag stage may be adequate.

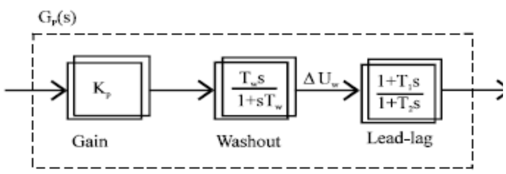

Fig.9. Block diagram of PSS

In general, the dynamic compensator can be chosen with the following transfer function

$$T(s) = K_s N(s) / D(s) \quad (19)$$

The zeros of D(s) should lie in the left half plane. They can be complex or real. Some of the zeros of N(s) can lie in the right half plane making it a non-minimum phase. For design purposes, the PSS transfer function is approximated to T(s), the transfer function of the dynamic compensator. The effect of the washout circuit and torsional filter may be neglected in the design but must be considered in evaluating performance of PSS under various operating conditions. There are two design criteria. The time constants, T_1 to T_4 in (18) are to be chosen from the requirements of the phase compensation to achieve damping torque. The gain of PSS is to be chosen to provide adequate damping of all critical modes under various operating conditions.

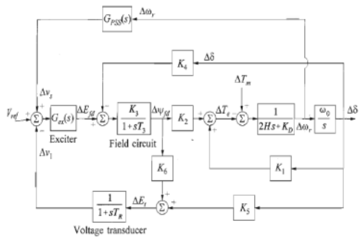

Fig.10. Block diagram of system with PSS

The eigen value analysis and time domain analysis are performed for the test system with low loading and high loading conditions. The result for the eigen value analysis for the system with power system stabilizer for the high loading and low loading conditions are tabulated in Table VII and Table VIII. The Table VII infers that the stability of the system is improved with the power system stabilizer and in Table VIII the system was unstable without the PSS under high loading condition due to effectiveness of the PSS the system becomes stable represented by negative real part of eigen values.

TABLE VII
EIGEN VALUE ANALYSIS WITH PSS AND WITHOUT PSS ON LOW LOADING CONDITION

	With PSS				Without PSS			
Eigen Values	-7.00±15.66i	-2.174±4.89i	-.5326	-39.13	-2.41±3.39i	-.1919±5.98i	---	---

TABLE VIII
EIGEN VALUE ANALYSIS WITH PSS AND WITHOUT PSS ON HIGH LOADING CONDITION

	With PSS				Without PSS			
Eigen values	-5.39±13.67i	-3.44±6.56i	-.5294	-39.82	-2.88±3.77i	.5518 ±6.18i	---	---

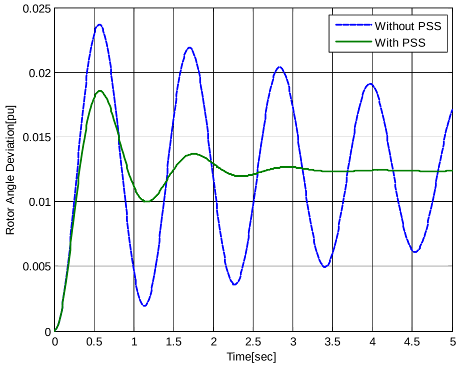

Fig.11. Effect of PSS on low loading condition

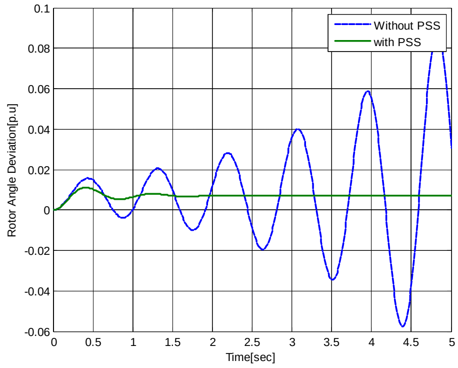

Fig.12. Effect of PSS on high loading condition

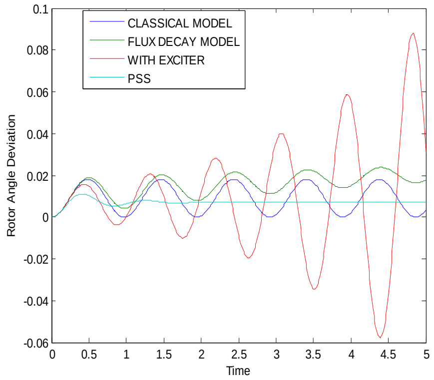

Fig.13. Effect of PSS on stabilization

In Fig.11, the system remains in stable condition and due to the effect of PSS, the system comes to stable condition much earlier than the system with excitation control. Fig.12 depicts that the system is unstable under heavily loaded condition without PSS and the system becomes stable when the PSS is added to the system. It does that by providing supplementary perturbation signals in a feedback path to the alternator excitation system. Fig 13 shows the effectiveness of power system stabilizer on the system stability in damping the oscillations. Thus a power system stabilizer improves the small signal power system stability by damping out the low frequency oscillations in the power system.

VII CONCLUSION

In this paper, a comprehensive study on low frequency oscillations in a single machine infinite system is presented. Small signal analysis is carried out on the simple system to find the mode of oscillations. The simulation results shows that an electromechanical mode with low damping ratio and the introduction of exciter push the critical mode towards the imaginary axis by adding negative damping on it. Adding PSS on the machine with exciter is pulling the critical Eigen value by adding more damping. The time domain analysis also conducted to validate the small signal analysis and it shows the effectiveness of PSS on system stability.

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APPENDIX

Generator:

$T'_{d0} = 6.0s$; $X_d = 1.6$ pu; $X_q = 1.55$ pu; $X'_d = 0.32$ pu; H = 5; D = 0;

Transmission:

$X_e = 0.4$ pu

Excitation system:

$K_E = 200$; $T_E = 0.05s$

Operating condition:

(a)$P_g = .5$pu; $V_t = 1.0$pu; $E_b = 1.0$pu; $f_B = 60$Hz

(b) $P_g = 1$pu; $V_t = 1.0$pu; $E_b = 1.0$pu; $f_B = 60$Hz

Parameters of PSS:

$T_w = 2s$; $T_1 = 0.078s$; $T_2 = 0.026s$; $K_S = 10$