IJCSE International Journal of Computer Sciences and Engineering Open Access
Research Paper Volume-4, Special Issue-6, Aug 2016 E-ISSN: 2347-2693

Conventional Power System Stabilizer Design

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Available online at: www.ijcseonline.org

Received: Jun/26/2016 Revised: July/08/2016 Accepted: July/26/2016 Published: Aug/12/2016

Abstract—Power System Stabilizer (PSS) is used to add damping to generator's oscillations. It is achieved by modulating the generator's excitation so as to produce adequate of electrical torque in phase with the rotor speed deviations. In this paper a power system stabilizer has been designed based upon lead-lag compensator and a washout time constant. The effectiveness of the power system stabilizer designed through this method is demonstrated by simulation of a sample power system for various loading conditions using MATLAB.

Keywords- Low frequency oscillations, Power system stabilizer, Power system stability, Lead-Lag compensator.

I. INTRODUCTION

The electrical power generation is a complex system with highly non-linear dynamics. Its stability mainly depends on the loading conditions of the power system and its topology. In many cases, instability and eventual loss of synchronism are initiated by some spurious disturbance in the system resulting in oscillatory behavior that, if not damped, may eventually build up. This is very much a function of the operating condition of the power system. Un-damped oscillation, even if at low frequencies, are undesirable because they limit power transfer on transmission line and in some cases, induce stress in the mechanical shaft.

The electromechanical oscillations are of two types:

1. Local mode, typically in the 1 to 3 Hz range between a remotely located power station and the rest of the system.
2. Inter mode oscillation in the range of less than 1 Hz.

Two kinds of analysis are possible:
1. A single-machine infinite bus system case that investigates only local oscillations.
2. A multi machine linearized analysis that computes the Eigen value.

In this paper a power system stabilizer is designed that stabilizes a machine with respect to the local mode of oscillation [1] [2].

Low frequency oscillations are a common problem in large power systems. The low frequency oscillations are observed in power system in the interconnected large scale power system with weak tie- line due to insufficient damping provided for the system [3].

In different loading condition and in any type of abnormal condition like three phase fault in a transmission line, increase the mechanical input, these oscillations will grow and deteriorate the performance of the system and lead to system instability. It is also observed that the change in loading condition make the machine parameters vary leading to instability of the system.

Power System Stabilizer (PSS) is a device that improves the damping of the generator electromechanical oscillations. In this idea an electrical torque is produced in the generator proportional to speed deviation.
Generally the inputs of PSS are shaft speed of generator, terminal bus frequency, electrical or accelerating power. It consists of gain block, lead-lag block and a high pass filter which is called as a washout block in power system. so that the stabilizer should maintain the stability of the system even though the change occur in complex manner. So the PSS should be designed in such a way that it can withstand the change in machine parameters, loading and operating conditions etc.

II. POWER SYSTEM MODEL

In this paper, the simplified model of a single machine infinite bus (SMIB) system is used which is shown in Fig.1 where a generator is connected to an infinite bus through a transmission line.[4]

A. Single machine infinite bus system

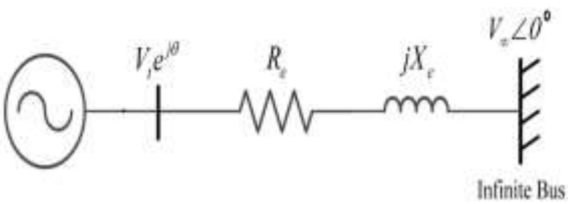

Fig.1 Single machine connected to an infinite bus

A single machine connected to an infinite bus is chosen to analyze the local mode of oscillation in the 1 to 3 Hz range. A flux decay model [1] of the machine is linearized with E_{fd} as an input, and the model so obtained is put in the block diagram form shown in fig.2

The single machine connected to an infinite bus through an external reactance X_e and resistance Re is the widely used configuration with a flux decay model neglecting stator resistance. No local load is assumed at the generator bus. The flux decay model of the machine (1-3), with the E_{fd} being treated as an input. The equations are given bellow [5].

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

$$\frac{d\omega}{dt} = \frac{T_M}{M} - \frac{E'_q I_q}{M} - \frac{(X_q - X_d)}{M} I_d I_q - \frac{(\omega - \omega_s)}{M}$$
(2)

$$\frac{dE'_q}{dt} = -\frac{E'_q}{T'_{do}} - \frac{(X_d - X'_d)}{T_{do}} I_d + \frac{E_{fd}}{T'_{do}}$$
(3)

The stator algebraic equations are given by E_{qn} (4 & 5)

$$V \sin(\delta - \theta) + R_s - I_d - X_q I_q = 0$$
(4)

$$E'_q - V \cos(\delta - \theta) - R_s I_q - X'_d I_d = 0$$
(5)

We use V_t to denote the magnitude of the generator terminal voltage. The algebraic equations are

$$X_q I_q - V_t \sin(\delta - \theta) = 0$$
(6)

$$E'_q - V_t \cos(\delta - \theta) - X'_d I_d = 0$$
(7)

The power system generally consists of synchronous machines, associated with excitation system, interconnecting transmission network and load etc. The dynamics of the synchronous machine rotor circuits and excitation systems are represented by differential equations, whereas the synchronous machine stator circuits and the network part of the power system are represented by algebraic equations. The power system thus in general can be describe by a set of differential-algebraic equations of the following form:

The differential-algebraic nonlinear model of a single machine connected to an infinite bus is given by

$$\dot{x} = f(x, y, u)$$
(8)

$$0 = g(x, y)$$
(9)

Where x is the state vector, y is the vector of algebraic variables, and g consists of the stator algebraic and the network equations [4].

Linearization of eqn. (8) and (9) leads to

$$\Delta \dot{x} = A\Delta x + B\Delta y + E\Delta u$$
(10)

$$0 = C\Delta x + D\Delta y$$
(11)

If D is invertible,

$$\Delta y = -D^{-1} C \Delta x$$
(12)

Therefore

$$\Delta \dot{x} = (A - BD^{-1} C)\Delta x + E\Delta u = A_{sys}\Delta x - E\Delta_u$$
(13)

A, B, C, D, and E are appropriate jacobians of eqn.(8) and (9) evaluated at the operating point.

B. Flux-decay Model

To the single machine infinite bus system of fig.2 ,we add a fast exciter whose state space equation is [1][6][7]

$$T_A \dot{E}_{fd} = -E_{fd} + K_A(V_{ref} - V_t)$$
(14)

The linearized form of this

$$T_A \Delta \dot{E}_{fd} = -\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta V)_t$$
(16)

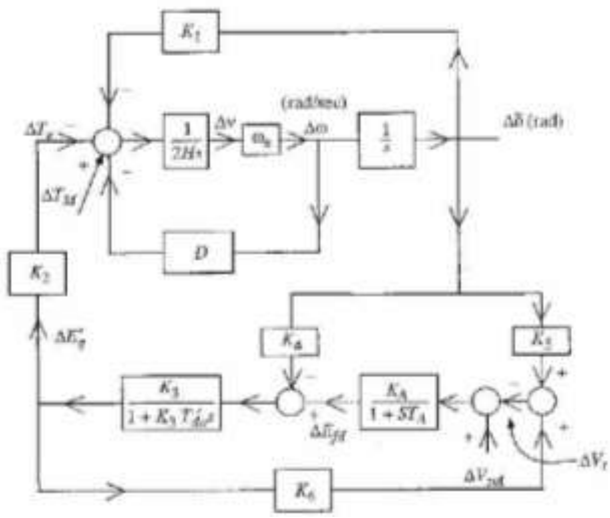

Fig.2 Block diagram of the incremental flux-decay model with fast exciter

There are two ways to explain the damping phenomena:

1. State-space analysis.
2. Frequency-domain analysis.

In state-space analysis the oveall state-space model becomes as shown here.

$$\begin{bmatrix}\Delta\dot{E}'_q\\ \Delta\dot{\delta}\\ \Delta\dot{v}\\ \Delta\dot{E}_{fd}\end{bmatrix} = -\begin{vmatrix}\frac{-1}{K_{3T'do}} & \frac{-K_4}{T'_{do}} & 0 & \frac{1}{T'_{do}}\\ 0 & 0 & \omega_s & 0\\ \frac{-K_2}{2H} & \frac{-K_1}{2H} & \frac{D_{\omega s}}{2H} & 0\\ \frac{-K_{AK_6}}{T_A} & \frac{-K_{AK_5}}{T_A} & 0 & \frac{-1}{T_A}\end{vmatrix}\begin{vmatrix}\Delta E'_q\\ \Delta\delta\\ \Delta v\\ \Delta E_{fd}\end{vmatrix} + \begin{vmatrix}0\\ 0\\ 0\\ \frac{K_A}{T_A}\end{vmatrix}\Delta V_{ref}$$

II. POWER SYSTEM STABILIZER DESIGN

A. Speed Input PSS

Stabilizing signals derived from machine speed, terminal frequency, or power are processed through a device called the power system stabilizer (PSS) with a transfer function G(s) and its output is connected to the input of the exciter. Fig.3 shows the PSS with speed input and the signal path from Δv to torque angle loop [1] [8] [9] [10].

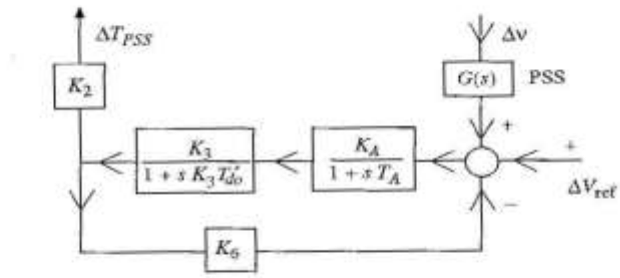

Fig.3 Speed input PSS

In frequency domain approach from fig ,the contribution of the torque-angle loop is (assuming ΔV_{ref}=0 and Δδ=0)

$$\frac{\Delta T_{pss}}{\Delta_v} = \frac{G(s)K_2K_AK_3}{K_AK_3K_6+(1+sK_3T'_{do})(1+sT_A)}$$
(17)

$$= \frac{G(s)\,K_2K_A}{\left(\frac{1}{K_3}+K_AK_6\right)+s\left(\frac{T_A}{K_3}+T'_{do}\right)+s^2T'_{do}T_A}$$
(18)

= G(s)GEP(s)
(19)

B. Conventional power system stabilizer(cpss)

This figure representing the conventional power system stabilizer.

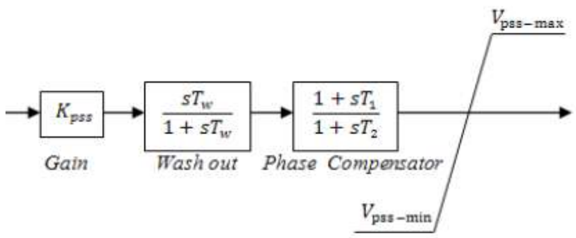

Fig. 4 Block diagram of conventional power system stabilizer.

This block diagram of the CPSS has three blocks:

a) Phase compensation block

It provides the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical torque. Normally, the frequency range of interest is 0.1 to 3.0 Hz and the phase-lead network should provide compensation over this entire frequency range. Generally some under compensation is desirable so that the PSS, in addition to significantly increasing the damping torque, results in a slight increase of the synchronizing torque.

b) Washout block

The washout circuit is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. It provides high pass filter with time constant Tw which is enough to perform this task.

c) Gain block

Gain block which ascertain the generated damping introduced by the PSS.

The time constants T_1,T_2 should be set to provide damping over the range of frequencies at which the oscillations are likely to occur. Over this range they should compensate for the phase lag introduced by the machine.

Typical values of the parameters are:

K_{pss} is in the range of 0.001 to 50

T1 is the lead time constants, 0.2 to 1.5 sec.

T2 is the lag time constants, 0.02 to 0.15sec.

T_w is set at 10 sec.

The basic function of a PSS is to extend the angular stability of a power system. This is done by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. This damping is provided by
an electric torque applied to typically occur in the frequency range of 0.2 to 3.0 Hz, and insufficient. In practical damping of these oscillations may limit ability to transmit power system, the various modes (of oscillation) can be grouped into three broad categories.

III. DESIGN PROCEDURE USING THE FREQUENCY DOMAIN METHOD

The conventional design procedure [1] has been followed here.

Let

$$\frac{\Delta T_{pss}}{\Delta v} = GEP(s)G(s)$$
(20)

Where GEP(s) is given by

$$GEP(s) = \frac{K_2 K_A K_3}{K_A K_3 K_6 + (1+sT'_{do}K_3)(1+sT_A)}$$
(21)

STEP 1.

Neglecting the damping due to all other sources, find the un-damped natural frequency in ω_n rad/sec of the torque-angle loop from

$$\frac{2H}{\omega_s}s^2 + K_1 = 0, \quad i.e\ s_{1,2} = \pm\omega_n$$
(22)

Where

$$\omega_n = \sqrt{\frac{K_1\omega_s}{2H}} (23)$$

STEP 2.

Find the phase lag of GEP(s) at s=j ω_n

STEP 3.

Adjust the phase lag of G(s) in eq-1, in such that

$$< G(s)|_{s=\omega_n} + < GEP(s)|_{s=\omega_n} = 0$$
(24)

Let

$$G(s) = K_{pss}\left(\frac{1+sT_1}{1+sT_2}\right)^k$$
(25)

Neglecting the washout filter whose net phase contribution is approximately zero. k=1 or 2 withT1 > T2. Thus, if k=1:

$$< 1 + j\omega_n T_1 = < 1 + j\omega_n T_2 - < GEP(j\omega_n)$$
(26)

Knowing ω_n and <GEP ($j\omega_n$), we can select T1. T2 can be chosen as some value between 0.02 to0.15 sec.

STEP 4.

To compute Kpss, we can use root locus method to compute K*pss, i.e. the gain at which the system becomes unstable using the locus, and then have Kpss=1/3 K*pss. An alternative procedure that avoids having to use the root locus is to design for a damping ratio ζ due to PSS alone. In a second order system whose characteristics equation is

$$\frac{2H}{\omega_s}s^2 + Ds + K_1 = 0$$
(27)

The damping ratio is

$$\zeta = \frac{\frac{1}{2}D}{\sqrt{MK_1}}$$
(28)

Where M=2H/ω_s

The characteristic roots of eq^n are

$$s_{1,2} = -\frac{-\frac{D}{M} \pm \sqrt{(\frac{D}{M})^2 - \frac{4K_1}{M}}}{2}$$
(29)

$$= -\frac{D}{2M} \pm j\sqrt{\frac{K_1}{M} - (\frac{D}{2M})^2}\ if\ (\frac{D}{M})^2 < \frac{4K_1}{M}$$
(30)

$$= -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$
(31)

We note that

$$\omega_n = \sqrt{\frac{K_1}{M}}$$
(32)

So we can write

$$\zeta = \frac{D}{2M\omega_n} = \frac{D}{2M}\sqrt{\frac{M}{K_1}} = \frac{D}{2\sqrt{K_1 M}}$$
(33)

Verify that

$$\omega_n{}^2\zeta^2 = K_{pss}|GEP(s)|_{s=j\omega_n}||G_1(s)|_{s=j\omega_n}$$
(34)

To revert to step 4,since the phase lead of G(s) cancle phase lag due to GEP(s) at the oscillation frequency ,the contribution of the PSS through GEP(s) is a pure damping torque with a damping coefficient D_{pss}. Thus again ignoring the phase contribution of the washout filter,

$$D_{PSS} = K_{PSS}|GEP(s)|_{s=j\omega_n}||G_1(s)|_{s=j\omega_n}$$
(35)

Therefore the characteristic equation is

$$s^2 + \frac{D_{pss}}{M}s + \frac{K_1}{M} = 0$$
(36)

$$i.e., s^2 + 2\,\zeta\omega_n s + \omega_n{}^2 = 0$$
(37)

As a result

$$D_{PSS} = 2\zeta\omega_n M = K_{PSS}|GEP(j\omega_n)||G_1(j\omega_n)$$
(38)

Thus we can find K_{pss}, knowing ω_n and the desired ζ. A reasonable choice of ζ is between 0.1 and 0.3

STEP 5.

The PSS should be activated only when low frequency oscillation develop and should be automatically terminated when the system oscillation ceases. It should not interfere with the regular function of the excitation system during steady state operation of the system frequency. The washout stage has the transfer function.

$$G_W(s) = \frac{sT_W}{1+sT_W}$$

(39)

IV. SIMULATION RESULTS

To investigate the effectiveness of the proposed PSS the response of the power system shown in fig.1 is simulated with and without the PSS installed at different loading conditions of the system. The details of the loading conditions are given in Appendix. The simulation results are shown in Fig.3 to Fig.7.
The PSS was designed for the nominal loading condition. The PSS parameters obtained are given in Table-1

TABLE-I
PSS PARAMETERS

Kpss	T_1	T_2
0.0018	0.3618	0.0200

A disturbance was created by raising the mechanical input to the generator by 10% for a period of 0.1 sec.

Following system conditions are considered:

i) Rotor speed as the input with nominal load:

a)When there is no PSS and system having nominal load.

b)System with nominal load condition and the PSS installed.

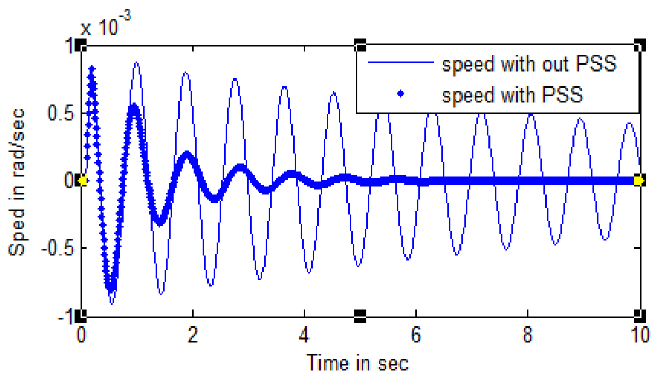

Fig.3 Response with and without PSS with speed input with at nomonal load.

ii)Rotor speed as the input at off nominal load:

a)When there is no PSS and system having nominal load.

b)System with off nominal load condition and the PSS installed.

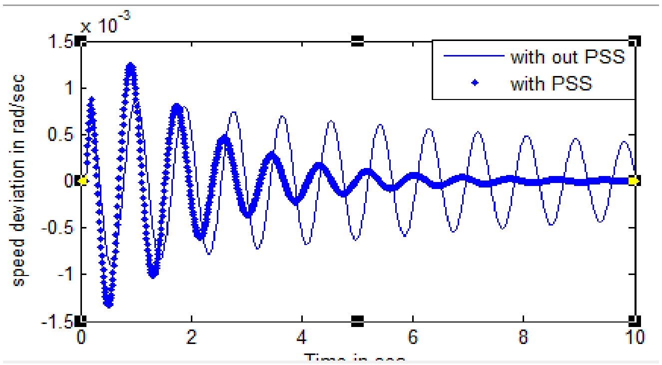

Fig.4 Response with and without PSS as a speed input with off nomonal load.

iii) Power angle as the input with nominal load:

a) When there is no PSS and system having nominal load.

b) System with nominal load condition and the PSS installed.

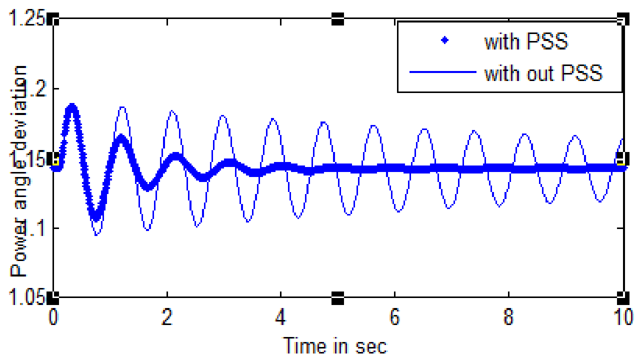

Fig.5 Response with and without PSS with power angle as the input.

iv) Bode Plot Representation.
a) Bode plot of the plant without PSS.
b) Bode plot of the plant with PSS.

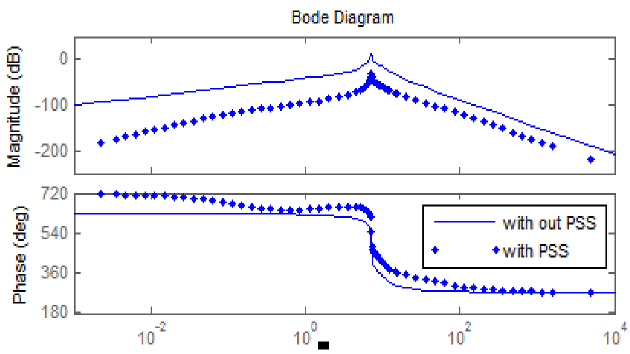

Fig 6.Bode plot with and without PSS.

v) Singular Value Plot.

a)Singular value of the plant

b)singular value of the plant with PSS.

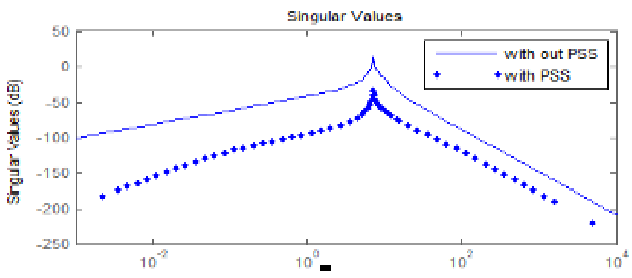

Fig.7 Singular Value Plot

V. APPENDIX

The nominal parameters and the operating conditions of the system are presented below:

X_d= 2.5p.u X'_d= 0.39 p.u

X_q= 2.1p.u X_d''= 0.39p.u

X_q''= 2.1 p.u X_q'= 2.1 p.u

X_1= 0.16p.u R_a= 0.003 p.u

T'_{d0}= 9.6s

ω= 377 rad/s KD= 0

K_A= 400 T_A= 0.2s

K_E= 1p.u T_E= 0

Nominal Load P= 0.5436 Q= -0.0285

Off Nominal load P=0.59796 Q= -0.03135

VI. CONCLUSION

In this paper a Power System Stabilizer has been designed based on lead lag compensator and a wash out time constant. Conventional design procedure was applied. The effective of the proposed PSS has been demonstrated by simulation with an SMIB system at nominal and off-nominal load. From the response shown it is obvious that the PSS designed in this work is capable of damping rotor oscillation of low frequency at different condition of the system. Bode plot and singular value plot also substantiate this fact.

ACKNOWLEDGMENT

I express my deep gratitude and respect for my supervisor Dr. Subrata Paul, Professor, Electrical Engineering Department, Jadavpur University, Kolkata, India for his keen interest, valuable guidance and strong motivation during the course of my work.

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