Parameters Design of Power System Stabilizer for Damping Local Mode of Oscillations

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Abstract

The increasing complexity of interconnected power systems due to economy and population development sometimes leads systems to poor dynamic behaviors like power oscillations. These oscillations can cause risks of partial system collapses. Hence, PSSs are used to generate supplementary control signals for the excitation system to damp the low-frequency oscillations. In this paper, the design of PSS for single machine connected to an infinite bus through external line reactance (SMIB) using rotor velocity deviation is proposed. The nonlinear model of a machine is linearized at different operating points. The effectiveness of the proposed method in damping local mode of oscillations, over a wide range of loading conditions and system configurations, is confirmed through phase compensation analysis and simulation results.

Keywords: low-frequency oscllations, automatic voltage regulator, power system stabilizer.

1. Introduction

The stability of synchronous machines has received a great attention. Among several aspects of stability of synchronous machine operation, an important one is the mode of small perturbation stability referred to as steady state or dynamic stability [1].

The automatic voltage regulators (AVR) are suitable for the regulation of generated voltage through excitation control. But extensive use of AVR has detrimental effect on the dynamic stability of the power system as oscillations of low frequencies (typically in the range of 0.1 to 3 Hz) exist in the power system for a long period and sometimes affect the power transfer capabilities of the system. These oscillations are called electro-mechanical oscillations including local modes and inter-area modes [2].

The PSS were developed to damp these oscillations by modulation of excitation system and by this supplement stability to the system [3]. The basic operation of PSS is to apply a signal to the excitation system that creates damping torque that is in phase with the rotor oscillations.

In order to provide effective damping and ensure the stability of the system, PSS must be carefully designed. The tuning process is a topic of big interest for researchers and PSS manufacturers. Several methods are available in the literature to tune the PSS. Those methods could be classified in linear and non-linear approach, as described in [4].

However, two important aspects regarding the tuning and performance of PSS for damping low frequency oscillation should be considered: the good performance of the PSS at operating point for which it is tuned and a phase compensation over a wider frequency range, which may be difficult to achieve. Hence, this paper proposes a design method of a robust PSS using rotor velocity deviation based on the theoretical and phase compensation analysis.

This paper is organized as following. In Section 2, the basic of PSS is presented. Section 3 contains the modeling of single machine system. In section 4, a PSS tuning method is presented. Simulation results of the PSS performance for damping local oscillations in a SMIB model will be carried out. Conclusions and future work are stated in Section 5.

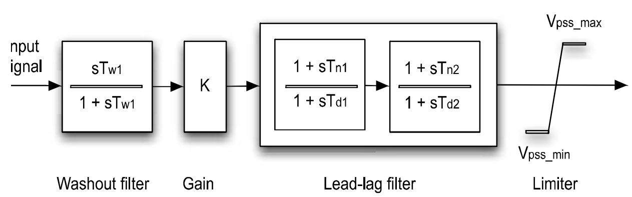

Fig. 1. Conventional structure of PSS.

2. Power system stabilizer

The PSS adds an electric torque that counteracts the mechanical dynamics to provide damping. The idea of power stabilization is that the voltage control system should take the control decision based on the voltage error only if there are no rotor speed

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deviations. But, if oscillations in the rotor speed appear, the voltage control system must produce a control signal based on the voltage error and an additional signal from the PSS. Obviously, the PSS is a feedback controller for generator.

The electric torque component should be in phase with the deviations of the generator rotor speed to constitute a damping torque component. To achieve this, the PSS must compensate the phase difference between the excitation system input and the electric torque. Fig. 1 shows a block diagram of a conventional PSS with a single input that is commonly used [5]. T_{w1} is the washout filter time constant, T_{n1}, T_{n2} are the leading time constants, T_{d1}, T_{d2} are the lag time constants and K is the PSS gain.

In the model, a ***Washout*** (a high pass filter) is used to define the frequency from which the PSS begins to operate. The measured signal is passed through this filter to prevent the PSS to act when slow changes occur (operating point changes). Without it, steady changes in speed would modify the terminal voltage. Therefore, 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.

The ***Gain*** determines the level of damping provided with the PSS. Ideally, the gain should be set at a value corresponding to maximum damping.

The PSS is also constituted by a phase compensation algorithm using ***Lead-Lag filter*** to supress the phase difference between the excitation system input and the resulting electrical torque. Normally, the frequency range of interest is 1 to 3Hz, and the phase lead network should provide compensation over this entire frequency range.

Finally, the ***Limiter*** block is used to keep the PSS output voltage within a range of values that it can be added to the voltage error in the AVR.

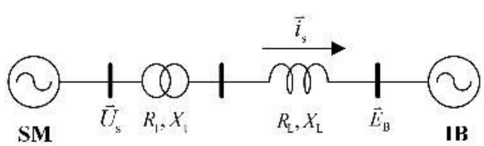

Fig. 2. Diagram of the SMIB system.

The input signals to the PSS have been identified as deviations in the rotor speed (Δω), the frequency (Δf), the electrical power and the accelerating power. Since the main action of the PSS is to control rotor oscillations, the input signal of rotor speed deviation is chosen. If other input signal is used with this structure, additional phase shift could be required from the stabilizer.

3. Single machine infinite bus modeling

The SMIB is a theoretical system that consists of a synchronous generator, a turbine, an excitation system, and a transmission line connected to an infinite bus. The SMIB is usually used for investigating the electromechanical interaction between a single generator and the power system. It is assumed that the modeled generator has three stator windings, one field winding connected to a source of direct current in the rotor, and three damper assumed to have a current flowing in closed circuits. Equations of synchronous generator in *qd0* reference frame are presented as follows [6]:

Stator voltage:

$$\begin{aligned} v_q &= -r_s i_q - x_d^{'} i_d + E_q^{'} \\ v_d &= -r_s i_d - x_q^{'} i_q + E_d^{'} \\ E_q &= E_q^{'} + (x_q - x_d^{'}) i_d \end{aligned} \quad (1)$$

Rotor voltage:

$$\begin{aligned} T_{d0}^{'} \frac{dE_q^{'}}{dt} + E_q^{'} &= E_f - (x_d - x_d^{'}) i_d \\ E_d^{'} &= (x_q - x_q^{'}) i_q \end{aligned} \quad (2)$$

Electromagnetic torque:

$$T_{em} = -\left\{ E_q^{'} i_q + E_d^{'} i_d + (x_q^{'} - x_d^{'}) i_d i_q \right\} = -E_q i_q \quad (3)$$

Rotor equation:

$$2H \frac{d\left\{(\omega_r - \omega_e)/\omega_b\right\}}{dt} = T_{em} + T_{mech} - T_{damp} \quad (4)$$

where E_q' and E_d' are the voltages behind the transient inductance in the q and d-axis, r_s is stator winding resistance, T'_{d0} is the transient time constant, H is inertia constant, w_r is rotor speed, w_e is synchronous speed, w_b is the based electrical angular frequency, T_{em} is electromagnetic torque, T_{mech} is the externally applied mechanical torque, T_{damp} is the friction torque.

All quantities are presented in per unit except for the time that is second, and balanced conditions are assumed that zero sequence component is not included. The excitation system for the generator is modeled according to [5].

Linearize the differential equations (1) - (4) and the exciter equation; we have a linearized state-space model of the SMIB system as:

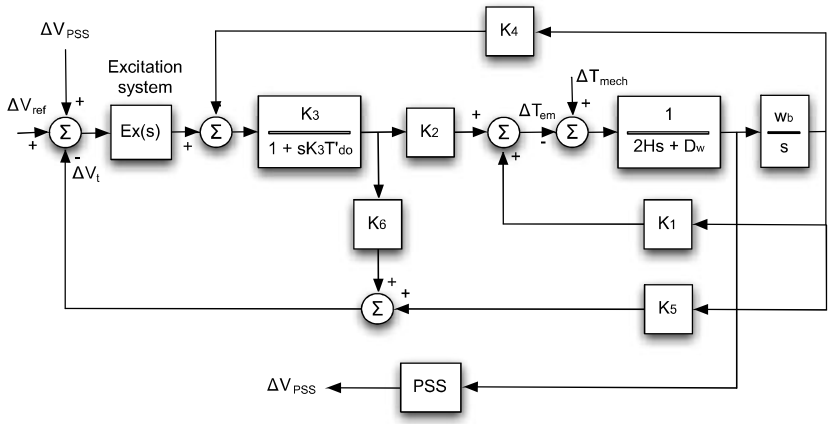

Fig. 3. Linearized model of SMIB with PSS.

$$\Delta P_{em} = K_1 \Delta\delta + K_2 \Delta E_q^{'}$$

$$T_{do}^{'} \frac{d\Delta E_q^{'}}{dt} + \frac{\Delta E_q^{'}}{K_3} = \Delta E_f - K_4 \Delta\delta$$

$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E_q^{'} \qquad (5)$$

$$\frac{d\Delta \frac{w_r}{w_b}}{dt} = \frac{1}{2H}\left\{\Delta P_{mech} + \Delta P_{em} - D_w \Delta \frac{w_r}{w_b}\right\}$$

where:

$$K_1 = \frac{E_{q0}V_i}{D_z}\left\{r_e \sin\delta_0 + (x_e + x_d^{'})\cos\delta_0\right\}$$

$$+\frac{i_{q0}(x_q - x_d^{'})V_i}{D_z}\left\{(x_e + x_q)\sin\delta_0 - r_e\cos\delta_0\right\}$$

$$K_2 = \frac{E_{q0}r_e}{D_z} + \frac{i_{q0}}{D_z}\left\{1 + (x_q - x_d^{'})(x_e + x_q)\right\}$$

$$K_3 = \left\{1 + (x_d - x_d^{'})(x_e + x_q)D_z^{-1}\right\}^{-1}$$

$$K_4 = V_i(x_d - x_d^{'})D_z^{-1}\left\{(x_e + x_q)\sin\delta_0 - r_e\cos\delta_0\right\}$$

$$K_5 = V_i \frac{v_{d0}}{V_t}\frac{x_q}{D_z}\left\{r_e\ \sin\delta_0 + (x_e + x_d^{'})\cos\delta_0\right\} +$$

$$+V_i \frac{v_{q0}}{V_t}\frac{x_d^{'}}{D_z}\left\{r_e\ \cos\delta_0 - (x_e + x_q)\sin\delta_0\right\}$$

$$K_6 = \frac{v_{q0}}{V_t}\left\{1 - \frac{x_d^{'}(x_e + x_q)}{D_z}\right\} + \frac{v_{d0}}{V_t}\frac{x_q r_e}{D_z}$$

Fig. 3 shows a block diagram of equations (5) with the machine speed, and rotor angle as the state variables. The linearized model will be used for PSS tuning while the complete one will allow to test the results reached from the PSS tuning process to damp power oscillations in the power system.

4. PSS tuning methodology

The PSS tuning objective is to provide the best damping for the local osscilation mode at specific frequencies. However, tuning conditions and performance requirements in this paper are considered as:

- The compensated system should get the maximum damping in the range from 0.2Hz to 3Hz. This is more important than perfect phase compensation;

- Some phase lag at lowest frequencies (from 0.2Hz to 0.5Hz) is needed since phase lead at those frequencies will cause the PSS to deteriorate the synchronizing torque component.

The methodology for tuning the PSS parameters is explained as below:

4.1. Phase compensation

As mentioned in Section 2, phase compensation algorithm is used to adjust the parameters of lead-lag filter. The phase lag depends on the operating point and the system parameters. Usually, the desired phase can be determined from phase plots of transfer function **G(s)** and **PSS(s)**.

Using the beginning condition that the torque component ΔP_{em} produced by PSS modulation is out of phase with $\Delta(w_r - w_e)/w_b$, we get:

$$\Delta P_{em} = -G(s)PSS(s)\Delta\frac{\omega_r - \omega_e}{\omega_b} = -D_{Pss}\Delta\frac{\omega_r - \omega_e}{\omega_b} \qquad (6)$$

where ΔP_{em} is the perturbation component of the electromagnetic power, **G(s)** is the transfer function of the generator and excitation system to the modulation signal, **PSS(s)** is transfer function of PSS and D_{Pss} is a positive coefficient.

Assuming that the speed deviation is small, the approximation of **G(s)** can be realized by ignoring contribution through K_4 and K_5 to **G(s)**:

$$G(s) \approx K_2 \frac{E(s)\dfrac{K_3}{1+sK_3T_{do}^{'}}}{1+K_6E(s)\dfrac{K_3}{1+sK_3T_{do}^{'}}} \quad (7)$$

The transfer function **E(s)** of the excitation system is [5]:

$$E(s) = \frac{\Delta E_f}{\Delta V_t} = \frac{\dfrac{K_A}{1+sT_A}\dfrac{1}{1+sT_e}}{1+\dfrac{K_A}{1+sT_A}\dfrac{1}{1+sT_e}\dfrac{sK_f}{1+sT_f}} \quad (8)$$

When the phase shift at the oscillation frequency that the PSS provide to the system is known, the parameters of the cascade lead-lag filters in the PSS shown in Fig. 1 can be tuned. It should be noted that the phase compensation per filter must ensure acceptable phase margin and noise sensitivity at high frequencies.

4.2. Gain tuning

The next step is to set the PSS gain K. It is known that the amount of damping depends on the gain of PSS transfer function at that frequency. Ideally, the gain should be set at a value corresponding to maximum damping. However, the chosen gain is related to the instability gain.

In order to get the instability gain of the system, the root locus plot of the system is used. This plot is a frequency response diagram that indicates how the poles and zeros of the open loop system are modified when the gain K takes different values. As the open loop gain takes different values, the roots or eigenvalues of the transfer function from ΔV_{ref} to ΔV_{PSS} change. For a certain value of gain, the closed loop system, with positive feedback in the case of the PSS, will be critically or marginally stable, which means that the real part of a pair of eigenvalues is zero. It is a common practice to set the PSS gain smaller than the gain where instability starts. The instability gain must be determined at the same system operating condition mentioned in the previous step for lead-lag filter tuning.

4.3. Time constant T_{w1}

Time constant T_{w1} depends on the oscillatory frequency. Hence, the lower the oscillatory frequency, the higher T_{w1} must be. In other words, it should be big enough to pass the stabilizing signals at the frequencies of interest but not so big that causes terminal voltage changes as a result of PSS action when the operation point change. T_{w1} can be set in the range from 1s to 10s as it is reported by many manufacturers.

5. Simulation results

The model of SMIB with PSS is built in MATLAB/SIMULINK. The parameters for the generator, automatic voltage regulator (AVR), excitation system, turbine, and governor are given in [6].

Using the equation (7), transfer function **G(s)** can be calculated easily.

$$G(s) = \frac{16.49s + 16.49}{0.005s^4 + 0.22s^3 + 10.15s^2 + 9.81s + 3.63} \quad (9)$$

Fig. 4 shows the Bode plots of **G(s)**. It can be seen from the phase plot of **G(s)** that it has two poles near 6 Hz. The desired phase characteristics of the PSS should be lagging below 37.7 rad/sec and leading above that angular frequency. Therefore, we choose T_{n1} and T_{n2} equal to 1/37.7 = 0.0265. T_{d1} of the lead-lag filter is 0.00265 and T_{d2} of the lag-lead filter is 0.265.

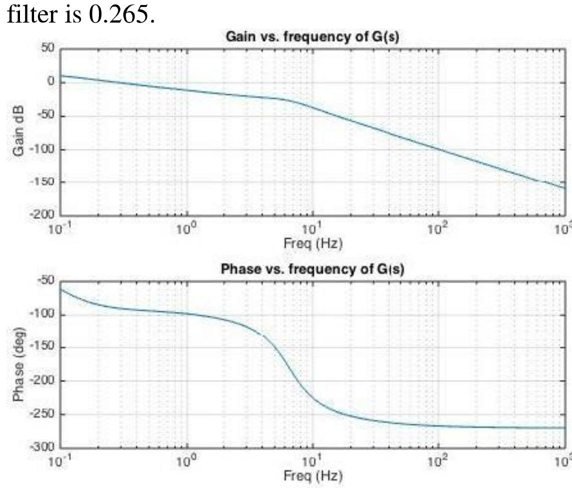

Fig. 4. Bode diagram of **G(s)**

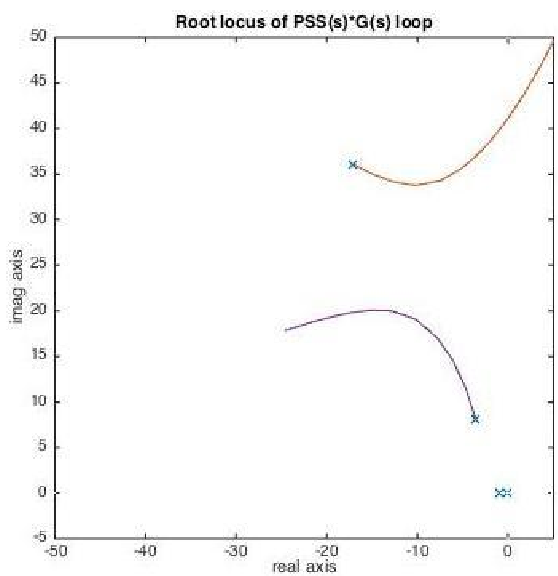

Fig. 5. Root locus of **PSS(s)G(s)** open loop.

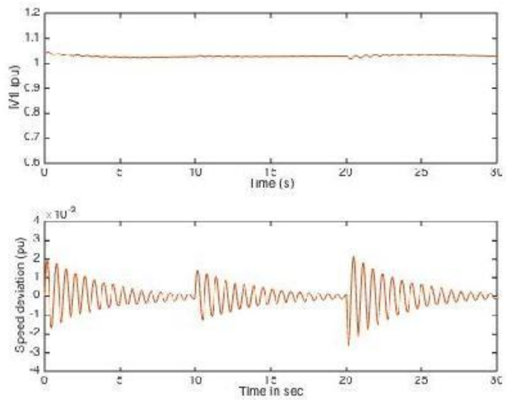

Fig. 6. System responses to 0.1pu step changes in the mechanical torque (without PSS).

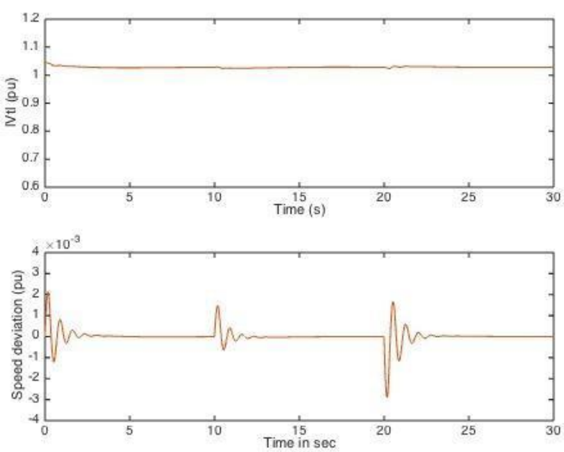

Fig. 7. System responses to 0.1pu step changes in the mechanical torque (with PSS).

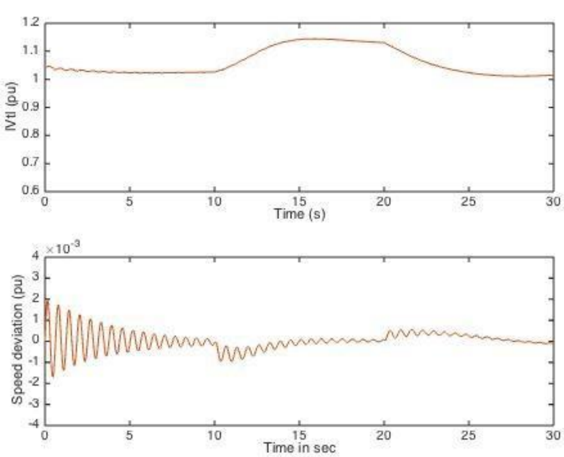

Fig. 8. System responses to 0.1pu step changes in the reference of terminal voltage (without PSS).

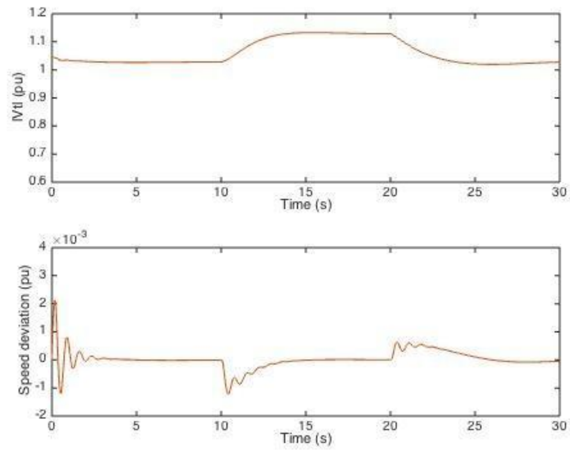

Fig. 9. System responses to 0.1pu step changes in the reference of terminal voltage (with PSS).

About T_{w1}, a sufficiently large T_{w1} is chosen not to disturb the phase compensation of the lead-lag and lag-lead filters. In this work, a value of 1s will be assumed as it is as a common value to be used with this parameter.

Fig. 5 shows the root-locus of the open-loop transfer function of **PSS(s)G(s)** over a range of K from 10 to 200. The instability gain is 122. Hence, K is chosen as 120.

To evaluate the performance of the designed parameters, the system response of SMIB is compared with the cases where there is no PSS and with a PSS in the system. These disturbances are: step changes in the mechanical torque and in the terminal voltage reference.

Fig. 6 and 7 show the simulation results with small step changes in torque perturbation of 0.1pu and -0.1pu about the chosen operating point at 10s and 20s respectively. The PSS provides good damping for the speed deviation.

Fig. 8 and 9 compare results with small step changes in the terminal voltage reference of 0.1pu during 10s to 20s. Again, the PSS gives good damping for the speed deviation. Moreover, the termial voltage response in Fig. 9 is obviously bettern than one in Fig. 8.

The PSS's parameters obtained using the linearized model of the system works well to damp out the oscillation created by the disturbance in the system. In the case of the step in the voltage reference, the terminal voltage response is infulenced by the output signal of the PSS.

6. Conclusions

In this paper, a PSS is designed using theory of phase compensation in the frequency domain based on speed deviation signals of synchronous generators. Therefore, the computations involved in the PSS tuning are minimal. The proposed method was evaluated on an SMIB. Simulation results for different kinds of disturbances demonstrate the effectiveness and robustness of the PSS under different operating conditions.

Power systems are highly nonlinear systems with configurations and parameters that change with time. To improve the performance of PSS, a PSS considering the nonlinear characteristics of the plant by adapting its parameters to the changes in the environment will be our next research.

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