Designing of Power System Stabilizer based on the Root Locus Method with Lead-Lag Controller and Comparing it with PI Controller in Multi-Machine Power System

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Abstract

This paper presents a method for designing a multi-machine power system stabilizer. The conventional design technique using a single machine infinite bus approximation involves a frequency response estimation called GEP(s). Frequency response is estimated between the input AVR and electrical output torque. The power system stabilizer is designed by frequency response and based on the root locus method to improve the damping of oscillatory modes. By using this method, we can adjust the structure of the PSS compensator and its parameters in the multi-machine system and it does not need to know the equivalent reactance of output and voltage of the infinite bus or the other estimations in every machine. In the proposed method, information available at the high voltage bus of the step-up transformer is used to set up a modified Heffron-Phillips model. Finally, this method is examined on three test systems. Simulation results indicate the performance and effectiveness of the proposed method.

Keywords: Four-leg Shunt Active Power Filter (4LSAPF); Enhanced Phase Locked Loop (EPLL); Self Tuning Filter (STF); Fuzzy Logic Control (FLC); Harmonics; Reactive power.

1. Introduction

When several generators are connected together, their interactions can cause disturbances in the performance of control systems. Therefore, proportional adjustment between generators in control systems is very useful [1, 2]. A generator swinging against the rest of the system causes local mode oscillations and, in interarea mode oscillations, groups of generators swinging against each other. These oscillations exist continuously in the system, but if the variation of load and generation rate causes the location of oscillating systems modes to change, moving them toward the right of the imaginary axis, then the system will be unstable [3, 4]. Therefore, it is necessary to increase the amount of damping of the oscillating modes [5, 6].

So, a control system called a power system stabilizer is used that add extra damping to the excitation system. Power system stabilizers are built to help damp these oscillations on the excitation system [7, 8]. This equipment provides additional damping to the system through lead compensation, which is caused between the input speed and output torque. Several methods have been used to design stabilizers [9, 10].

With the advent of power electronics and the production of equipment with high current and voltage, the usage of flexible alternating current transmission (FACTS) has become economically justified. Conventional PSS could not provide appropriate damping for interarea oscillations, so a combination of PSS and FACTS is used to provide optimal damping. In other words, the use of PSSs alone may not be effective in some cases in providing sufficient damping for power oscillations, specifically for long distance power transmis-
The concept of FACTS became feasible due to the application of high-power electronic devices for power flow, voltage control, and additionally enhancing the damping of power oscillations [13]. In the literature, several researchers propose the coordination of PSS with FACTS controllers to enhance the dynamic performance of the power system. In [14], the authors discussed a global tuning procedure for PSS and FACTS devices using a parameter-constrained nonlinear optimization algorithm. A robust coordinated design of a PSS and TCSC based stabilizer is thoroughly investigated in [15]. Generally, there are two kinds of power oscillation damping controllers in power systems, as shown in Fig. 1: PSS and FACTS controllers.

The main goal of most studies in recent years is the adjustment of a secondary control system for the excitation system in order to stabilize the oscillating modes. PSS is not usually installed in all generators, but is only installed in the generators that can cause the maximum amount of damping in the system and the oscillatory modes [16, 17]. The structure of PSS commonly includes a washout filter and a lead-lag block diagram. The PSS input signals can include terminal voltage, rotor speed deviation and electrical power [18, 19]. In previous studies, a linear combination of these signals is used as an input signal. The stabilizer is adjusted for lag compensation which is created between the generator, excitation system, and power system [20]. Typical stabilizers are divided into two categories: analog and digital. In this study, we discuss only analog PSS. Analog PSS parameters are adjusted by using linear and nonlinear methods. In previous studies, several methods were proposed based on linear methods in order to design PSS, including pole placement, pole shifting, optimal linear control, eigenvalues sensitivity analysis and characteristic method. In recent studies, the proposed methods are typically used for single-machine infinite-bus power systems.

This paper presents an approach to adjust the parameters of multi-machine power system stabilizers based on the root locus method and frequency response of the system. Adjustment of PSS parameters requires accuracy and good knowledge of the structure and dynamic model of the system. Therefore, accurate modeling of the power system has to be done before the desired design of PSS can be achieved.

2. Proposed Method

The flowchart of the proposed method is shown in Fig. 2. The transfer function which will be described below is obtained for all the system generators in which PSS will be installed. Finally, the parameters of the power system stabilizer are adjusted by using the root locus method and frequency response of the system. The PSS parameters are obtained for an operation point and operating conditions of the system. Therefore, several different scenarios of loading in the system are considered and parameters are adjusted for the worst loading conditions so that the system can respond to disturbances in the various operating conditions of the system.

3. Power System Model

Small-signal stability analysis requires dynamic modeling of the major components of the power system. These main components are: synchronous generator, excitation system, automatic voltage regulators and other components [21]. The model shown in Fig. 3 is used to obtain the linearized Heffron-Phillips or K-constant model. In order to analyze small signal stability, it is necessary to consider the effect of the excitation system, which indirectly controls the reactive power output of the generator [22]. The linearized dynamic equations of single machine infinite bus (SMIB) are as follows [23, 24]:

Figure 2: The flowchart of the proposed method

Figure 3: Single machine in a connected network
Figure 4: Linearized model of \( i^{th} \) synchronous machine

\[
\frac{d}{dt} \delta = 2 \pi f_o \delta
\]  

(1)

\[
\frac{d}{dt} \omega = \frac{1}{2H} (P_M - P_E - K_D \omega)
\]  

(2)

\[
\frac{d}{dt} E_F = \frac{1}{T_E} [E_F - E'_F + (X'_d - X_d) i_d]
\]  

(3)

\[
\frac{d}{dt} E'_q = \frac{1}{T'_d} [E_F - E'_q + (X'_d - X_d) i_d]
\]  

(4)

In Fig. 4, the constants of the linearized model depend on the machine parameters and operating conditions of the system [25, 26].

4. Power System Stabilizer (PSS) design

Due to the continual variation of dynamic system conditions, the operation point of the system and the load and generation levels change constantly, causing low-frequency oscillations in the system. Hence, PSS is designed and adjusted to add suitable damping to the system so that low-frequency oscillations do not cause small-signal instability. PSS is an additional control block that is added to improve system stability [27].

4.1. Design based on the general structure of the Power System Stabilizer

The main structure of the power system stabilizer is shown in Fig. 5. The transfer function \( G_E(s) \), shown in Fig. 6, was affected by assuming that variation of machine speed is zero. It is given by Shahgholian et al. [28]:

\[
G_E(s) = \frac{K_p K_E(s)}{(1 + sT_1)(1 + sT_2)}
\]  

(5)

where \( E(s) \) is the transfer function of the excitation system. According to (5), for every machine in the multi-machine system, \( G_E(s) \) can be calculated based on the power flow data in the transformer bus and initial condition of the generator. The compensator structure that is required for the resonant or non-resonant form of \( G_E(s) \) is given in (6) and (7).

\[
H(s) = K_{pss} \frac{sT_1}{1 + sT_1} \left( \frac{s^2 + \frac{2\zeta}{\omega_n} s + 1}{1 + sT_2} \right)
\]  

(6)

\[
H(s) = K_{pss} \frac{sT_1}{1 + sT_1} \left( \frac{1 + sT_1}{1 + sT_2} \right)
\]  

(7)

In (7), \( m \) is the number of lead-lag stages. After plotting the frequency response of the transfer function \( G_E(s) \) for every generator, if it is without resonance peak, we can use the procedure of Fig. 7.

4.1.1. Selection of stabilizer time constants

At first \( f_c \) and \( \beta \) are adjusted so that compensated phase of \( G_E(s) \) at the frequency of the local mode (7 rad/sec) is less than 50 degrees and intersection at 90 degrees occurs above 22 rad/sec (3.5 Hz). Phase margin of higher than 30° is suitable for compensated \( G_E(s) \). Here \( f_c \) is the central frequency of the compensator. The equations to obtain constants \( T_1 \) and \( T_2 \) are given in [29].

4.1.2. Plotting the root locus

Plot the root locus of the plant with compensator from A and matrices with slip speed as output. Now look for the departure of root locus branch at the modes near the imaginary axis. If it is not in the increasing damping direction adjust the zero of the compensator.

4.1.3. Gain Selection of compensator

The gain from the root locus plot is selected so that the damping ratio of rotor mode is maximized.
4.2. Power system stabilizer design for $G_p(s)$ with resonance peak

This condition occurs when the matrix has two pairs of complex eigenvalues with significant damping. In this case the proposed procedure in Fig. 8 is used to adjust the parameters of the power system stabilizer.

4.2.1. Restricting the complex pair of poles by zeros of compensator

The first step is to decide the complex pair of poles to be constrained by zeros. In order to determine the dominant pole of the system, a set of matrices is created as the transformer reactance is increased. The eigenvalues of this matrix are plotted. A pair of eigenvalues that are oriented toward the positive axis should be chosen as a pair that must be restricted by a zero pair.

4.2.2. Finding values of $\xi$ and $\omega_n$

This step is to find values of $\xi$ and $\omega_n$ of the second order transfer function; these values are significantly in accordance with the phase characteristic of $G_p(s)$. Now fix one of the poles say $T_1$ at 0.01 and adjust $T_2$ and $\omega_n$ of the numerator so that the compensated GEP has good phase margin (about 40 degrees).

4.2.3. Plotting the root locus and evaluation of branch deviation of root locus

After plotting the locus, the locus branch is checked to ensure it passes across the required complex pole. Otherwise, $T_2$ and $\omega_n$ are adjusted based on that. Moreover, the locus branch of the other complex poles must be far enough from the location of the complex zeros.

4.3. Using the PI controller for power system stabilizer design

In this study, the PI controller is used instead of the lead-lag controller in the power system stabilizer block. PI controller transfer function is indicated by $G_E(s)$ and is as per (9):

$$G_E(s) = K_p + K_i \frac{1}{s} = \frac{K_p s + K_i}{s}$$

By rewriting (8), the PI controller transfer function can be obtained as (9):

$$G_c(s) = K_p \frac{s + z_e}{s}, \quad K_i \leq K_p$$

Where $K_p$ is the static gain and $K_i/K_p$ indicate a stable zero that is close to the origin.

$$G_c(s) = \frac{s + z_e}{s}$$

The algorithm for designing this controller is given in the following section.

- Pole of PI controller is set at zero value and the value of zero is considered arbitrarily in a small amount close to the origin, for example $z_e=0.01$ or $z_e=0.1$.

- If necessary, the static loop gain $K_p$ is set at a value except one so that the desired value of steady error compensation is achieved.

Generally, PI controller design is an experimental procedure that is based on trial and error in order to achieve the desired phase margin.
If necessary, the static loop gain $K_P$ is considered 0.05.

Controller designs are evaluated by considering the high voltage bus of the step-up transformer as a slack bus and linearization state equations.

This system is the first case study that is used to evaluate the power system oscillations and stability analysis. Modal analysis is used to evaluate small-signal stability without PSS. Damping factors of eigenvalues are shown in Fig. 10. In this paper the minimum damping factor criterion is considered 0.05. As can be seen from Fig. 3, there is an unstable eigenvalue which indicates the instability of the system. In addition, two pairs of eigenvalues are less than 0.1; these eigenvalues are known as the critical eigenvalues. Table 5.1 shows these eigenvalues, the frequency, and their damping factors.

Eigenvalues, un-damped frequencies and the damping ratio of each generator are shown in Tables 5.1 and 5.1. Stability analysis is used to determine that this system has unstable eigenvalues. The frequency responses of generators are given in (11) to (13) and Fig. 11.

$$G_E(s) = \frac{152}{17.67 + 3.26s + 0.04905s^2}$$  \hspace{0.5cm} (11)

$$G_E(s) = \frac{193.43}{0.057s^2 + 1.1912s + 14.047}$$  \hspace{0.5cm} (12)

$$G_E(s) = \frac{221}{0.06s^2 + 1.2362s + 10.83}$$  \hspace{0.5cm} (13)

None of the frequency responses of the generators of three machines have resonance peak. In this case, generator 3 has the most steady-state stability due to its greatest gain. But from the point of time constant, all generators have poles that are close together in approximate terms; so the delays of the three generators are in approximately the same interval.

For the first generator, the phase margin is 22 degrees and the gain margin is infinite; so 30 degrees should be added by

<table>
<thead>
<tr>
<th>Eigenvalue</th>
<th>Frequency (Hz)</th>
<th>Damping Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>-0.000673   0</td>
<td>7.43</td>
</tr>
<tr>
<td>$G_2$</td>
<td>0.1207      11.1310</td>
<td></td>
</tr>
<tr>
<td>$G_3$</td>
<td>0.1141      14.8963</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Un-damped frequencies and damping ratio

5. Case Studies and Simulation Results

The proposed method was implemented in three systems: 3, 5, 10 machines and the results analyzed. First, small-signal stability analysis is done without PSS. Then, PSS is adjusted and small-signal stability is checked again to observe the adjustment effect. Finally, several different loading scenarios are evaluated in order to evaluate the effectiveness of PSS adjustment. Finally the results of the lead-lag controller are compared with the results of the PI controller.

5.1. Three-Generator Nine-Bus Power System

This system is the first case study that is used to evaluate power system oscillations and the implementation of the proposed method for stabilizer design. This system is taken from [30]. This is the most widely used test system for validating several control designs (Fig. 9). In this study the exciter is considered as a first order block diagram, with a gain and time constant of 200 and 0.05. Frequency response estimation and calculating the coefficients of the Heffron-Phillips model require data obtained with power flow. PST Toolbox of MATLAB is used for small signal stability analysis. Modal analysis is used to evaluate small-signal stability without PSS. Damping factors of eigenvalues are shown in Fig. 10. In this paper the minimum damping factor criterion is considered 0.05. As can be seen from Fig. 3, there is an unstable eigenvalue which indicates the instability of the system. In addition, two pairs of eigenvalues are less than 0.1; these eigenvalues are known as the critical eigenvalues. Table 5.1 shows these eigenvalues, the frequency, and their damping factors.

Eigenvalues, un-damped frequencies and the damping ratio of each generator are shown in Tables 5.1 and 5.1. Stability analysis is used to determine that this system has unstable eigenvalues. The frequency responses of generators are given in (11) to (13) and Fig. 11.
the stabilizer. Therefore, $\beta$ is considered 30 degrees. Based on the proposed method, central frequency is also considered to be 3.5 Hz. In the next stage, the gain of PSS should be calculated. In this study, the PSS gain is obtained from the root-locus diagram and regards the desired amount of the damping ratio ($\xi=0.15$). Finally, by addition of the pole and zero of the stabilizer, the root-locus of generators 1, 2 and 3 are shown in Figs 12, 13, and 14. According to the results of the root locus, it can be observed that PSS increases system damping, so that the refraction angle of roots which are close to the imaginary axis is 180 degrees. Fig. 15 shows the frequency response of generator 1 after applying the stabilizer.

After applying the stabilizer, the suitable condition of the problem is satisfied, i.e., the phase margin is about 40 degrees and the refraction angle occurred at 22 rad/sec with a slope close to 180 degrees. Therefore, the designed compensator will provide suitable damping in the system.

The effectiveness of the proposed PSS design is shown in Figs. 16 and 17 with small disturbances, such as a 10% step change in $V_{ref}$ in GEN3.

To evaluate the performance of the designed compensator, a three-phase short circuit is considered for the three machines system. This fault happened at the first second in bus 7 and after 100 ms it will be cleared. Figs. 18 and 19 show the impact of a three-phase short circuit fault before and after applying a stabilizer on the voltage of buses 7 and 8. The electrical power response of generator 3 for a 3φ self-cleared is shown in Fig. 20. Fig. 21 shows transferred power between bus 7 and bus 8 respectively after the three-phase fault and after applying the stabilizer. The PSS data are shown in Table 5.1 for the three machines system.

<table>
<thead>
<tr>
<th>$G$</th>
<th>$\beta$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$K_{PSS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>0.0803</td>
<td>0.0257</td>
<td>49</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>0.08735</td>
<td>0.0236</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>0.15</td>
<td>0.01</td>
<td>3</td>
</tr>
</tbody>
</table>
5.2. Five-Generator Ten-bus System

This system is shown in Fig. 22 [31]. Due to the critical eigenvalues of Table 5.2, it is observed that the system has 4 oscillating modes where its damping ratio is less than 2.0. Figs 23 and 24 indicate frequency responses of generators 1, 2, 3, 4 and 5. Generators 2, 3 and 5 have the resonance peak in their frequency responses.

In order to adjust the parameters of the stabilizer, the reactance of the transformer should be changed step by step and complex eigenvalues of the matrix should be evaluated. Figs. 25, 26, and 27 show the reactance changes of generators 2, 3 and 5.

Fig. 25 shows that as $x_t$ is increased, pole $-1.250 \pm j9.430$ move in negative direction of real axis, and pole $-1.935 \pm j5.760$ move in positive direction of real axis. Consequently, pole $-1.935 \pm j5.760$ is the dominant pole and this pole should be restricted by complex zero of the compensator. Fig. 26 shows that $-0.850 \pm j10.750$ is the dominant pole and this pole should be restricted by complex zero of the compensator. Fig. 27 shows that $-2.256 \pm j4.835$ is the dominant pole and this pole should be restricted by complex zero of the compensator. Here, a stabilizer is designed for generator 5 and the complete procedure of design is studied. The algorithms and design procedures of the other generators are the same as for generator 5. In the first step it should be determined how much of required phases margin is provided by transfer function $G_E(s)$, then the rest of the required phase margin should be compensated by the stabilizer. For this purpose, the frequency response of generator 5 is plotted and the gain margin is calculated. In Fig. 28 it can be observed that the phase margin of this generator is about 9 degrees. For this purpose, the parameters $T_1$, $T_2$, $\omega_n$ and $\xi$ should be adjusted so that the required 40 degrees will be compensated. Hence, as can be seen in Figs. 29 and 30, five different states are

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$\omega_n$</th>
<th>$\xi$</th>
<th>Phase margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>0.01</td>
<td>7.7</td>
<td>0.4</td>
<td>9.35</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.05</td>
<td>11</td>
<td>0.4</td>
<td>13.4</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.08</td>
<td>15</td>
<td>0.5</td>
<td>21.9</td>
</tr>
<tr>
<td>4</td>
<td>0.01</td>
<td>0.1</td>
<td>18</td>
<td>0.6</td>
<td>24.2</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.1</td>
<td>22</td>
<td>0.4</td>
<td>39.4</td>
</tr>
</tbody>
</table>
evaluated. Finally, in the fifth state, the system phase margin reaches 40 degrees. Data on the adjustment and phase margin of each state are given in Table 5.2.

The PSS data are shown in Table 5.2 for the five machines system.

Fig. 31 shows the roots locus of GEN-5 in the fifth state. It is observed that the zeros are close to the complex poles and compensated.

5.3. Ten-Generator 39 Bus System

This system is taken from Padiyar [32]. In this system, PSS is modeled for all generators except generator number 2 that is modeled as the external network model (infinite bus). In this system frequency responses of generators have no resonance peak. The characteristics of the designed stabilizer parameters are given in Table 5.2. To evaluate the effectiveness of the obtained adjustment, different loading conditions are examined in the system. Three scenarios of low load, medium load and heavy load are considered for the system load level.

In Fig. 32 slip speed of GEN-8 is considered at normal and heavy load condition without PSS, by a 10% change in mechanical torque. It is shown that slip speed of GEN-8 at the normal condition starts to oscillate, but after a while it will be damped. Now, slip speed response of GEN-8 to 10% step in $T_m$ is considered at heavy loading conditions with PSS.

Fig. 33 shows slip speed of this generator's response to a 10% step change in mechanical torque, at heavy condition with and without the proposed PSS. It can be seen that slip speed variations caused by a 10% step change in mechanical torque are damped after a while with the proposed PSS.

Under light loading condition, slip speed variation of GEN-6 for a 10% step change in $\Delta T_m$ that occurred at second 5, before and after applying the stabilizer is shown in Fig. 34. The performance of the proposed PSS is shown in Fig. 34. The slip speed variations of GEN-6 with PSS designed based on the proposed method damps in a shorter time compared to the situation without PSS.

6. Stabilizer design based on PI Controller for Three-Machines Power System

PI controller is designed for the three generators of the three machines system, and the results of the PI controller
parameters are given in Table 6 for the three machines system. A three phase fault is implemented on bus 3. Fig. 35 shows slip speed responses of GEN-1 to GEN-3 for a 3φ fault in the presence of the designed stabilizer based on the general structure of the PSS. Fig. 36 shows the slip speed responses of GEN-1 to GEN-3 for a 3φ fault in the presence of the PI controller.

By comparing Figs. 34 and 35, it can be observed that the PI controller partially improves system damping conditions, but it cannot completely eliminate the low frequency oscillations. In fact, this type of controller has a major impact on the steady-state behavior of the system and it improves steady-state error. Thus, if the low-frequency oscillation is low and oscillatory modes are local, using the PI controller can have a desirable effect on system stability.

7. Conclusions

In this paper, the dynamic equations are linearized by considering the high voltage bus of the step-up transformer instead of infinite bus voltage, and all the measurements are local and it does not require overall calculation of system parameters such as equivalent external reactance. The power system stabilizer based on the root locus and frequency response method is used to increase stability and to damp oscillations of 3, 5, and 10 machines systems. The results of these test systems when small disturbances like a 10% step change in \( V_{ref} \) or a big disturbance like a 3φ fault are applied to the system show the performance of the proposed PSS. However, by using the designed stabilizer, the oscillations will be damped. The results of slip speed response in the three machines system show the superiority of the PSS with lead-lag controller over the PSS with PI controller.

<table>
<thead>
<tr>
<th>G</th>
<th>( K_i )</th>
<th>( K_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.002</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Acknowledgments

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Figure 36: Slip speed responses of GEN-1 to 3 for a 3φ fault with PI controller.


