An integrated approach for optimal placement and tuning of power system stabilizer in multi-machine systems

Vahid Keumarsi *, Mohsen Simab, Ghazanfar Shahgholian

Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
Department of Electrical Engineering, College of Engineering, Fars Science and Research Branch, Islamic Azad University, Fars, Iran

ABSTRACT

In this paper, a hybrid approach for tuning and placement of power system stabilizers (PSS) in multi-machine power systems is provided with the aim of reducing low-frequency oscillations (LFO) and improving power system dynamic stability with wide range of changes in system parameters and operating point of the system. PSS parameters are adjusted using Particle Swarm Optimization algorithm (PSO), and using Takagi–Sugeno (TS) fuzzy, optimal location for the PSS is determined. The employed fuzzy system has two inputs, the real part and the damping coefficient of network eigenvalues. The results of test on a grid four machine-two area sample, show optimal performance of the proposed method in improving system stability and reducing low-frequency oscillations of local and inter-area modes.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The power system is a complex and nonlinear system. Mechanical nature of the power systems produces low-frequency oscillations (LFO) in the system, which will negatively affect the stability and performance of the system and will restrict the capacity of the transmission line [1]. In order to solve this problem, a supplementary controller is employed in the excitation system of the generators. This supplementary controller, known as PSS, is widely used to reduce the LFO and improve system stability [2]. Many new intelligent methods such as neural networks [3] and fuzzy logic [4,5] have been used in PSS design. Modern control methods such as adaptive control have also been used in PSS design [6]. In [7], an approach based on state feedback control is presented for tuning PSS parameters. Pole placement has also been employed to design PSS for multi-machine power systems in coordination with FACTS devices [8]. In [9], PSO was used to tune PSS for interconnected power systems. In [10], the use of adaptive neuro-fuzzy inference was proposed for PSS design to enhance the damping issue of the conventional PSSs. Bacterial swarm optimization is the other approach used for the design of PSS in coordination with thyristor controlled series capacitor (TCSC) for multi-machine power systems [11]. A fuzzy PI Takagi–Sugeno stabilizer is presented in [12]. An optimal power system stabilizer (OPSS) based on second-order linear regulator with conventional lead-lag compensation structure is also proposed in [13]. The modified particle optimization (MPSO) is the other method proposed to adjust the stabilizer parameters [14].

In [15] presented a method to determine the optimal location and the number of multi-machine power system stabilizers (PSSs) using participation factor (PF) and genetic algorithm (GA). A type-2 fuzzy logic power system stabilizer with differential evolution algorithm presented in [16]. In [17], the design of a conventional power system stabilizer (CPSS) is carried out using the bat algorithm (BA). In [18] presents an enhanced indirect adaptive fuzzy sliding mode based power system stabilizer for damping local and inter-area modes of oscillations for multi-machine power systems. In [19] presented a new technique named cultural algorithms (CAs) to tune the PSS parameters. In [20] present the design and implementation of Power System Stabilizers in a multi-machine power system based on innovative evolutionary algorithm overtly as Breeder Genetic Algorithm with Adaptive Mutation.

This paper presents a hybrid approach to tune and place PSSs in multi-machine systems. PSS parameters are adjusted using PSO algorithm, according to the operating point of the network. The optimal location for PSS installation is then determined by fuzzy Takagi–Sugeno (TS) system. The fuzzy system has two inputs, the real part and the damping coefficient of network eigenvalues.
Network eigenvalues are obtained by the linearization of differential–algebraic equations of the power system. The experimental results on a four machine-two area network show the good performance of the proposed method improving system stability and reducing low frequency oscillations of local and inter-area modes.

Power system modeling equations are presented in section ‘Power system modelling’ and the algorithm used for tuning and placement of PSSs is given in section ‘PSS tuning and placement’. Simulation results and conclusions are described in sections ‘Experimental results and Conclusion’, respectively.

**Power system modelling**

In order to analyze the power system, linearization of Differential–Algebraic Equations (DAE) around the operating point is used [21].

**Generator equations**

For each generator, the following fourth-order model has been considered:

\[
\frac{d\delta_i}{dt} = \omega_i - \omega_s
\]

\[
\frac{d\omega_i}{dt} = \frac{T_M}{M_i} (E_{qi} - X_{qi}I_{qi})I_{qi} - \frac{(E_{di} + X_{di}I_{di})I_{di}}{M_i} - D_i(\omega_i - \omega_s)
\]

\[
\frac{dE_{qi}}{dt} = -\frac{E_{qi}}{T_{dqi}} - \frac{(X_{qi} - X'_{qi})I_{qi}}{T_{dqi}} + E_{di}
\]

\[
\frac{dE_{di}}{dt} = -\frac{E_{di}}{T_{dqi}} + \frac{l_q}{l_{q0}}(X_{qi} - X'_{qi})
\]

**Exciter equation**

Exciter equation is:

\[
\frac{dE_{dli}}{dt} = -\frac{E_{dli}}{T_{dli}} - \frac{(X_{di} - X'_{di})I_{dli}}{T_{dli}} + E_{dhi}
\]

A detailed description of all symbols and quantities can be found in [21]. By the linearization of the power system equation, explained in [21], and by the addition of PSS equations, the power system model is:

\[
\Delta \dot{x} = A \Delta x + B \Delta u
\]

\[
\Delta y = C \Delta x + D \Delta u
\]

where \(A\) is the state variables matrix, \(B\) is the input matrix, \(C\) is the output matrix, \(D\) is the feed-forward matrix, \(x\) is the vector of state variables, \(u\) is the vector of control inputs, and \(y\) is the output. Here, the goal of PSS design is to place the eigenvalues of matrix \(A\) in the left half of the complex plane. Eigenvalues of the system can be evaluated from matrix \(A\):

\[
\lambda_i = \sigma_i + j\omega_i
\]

where \(i = 1, 2, 3, \ldots, n\) and \(n\) denotes the total number of eigenvalues. The eigenvalues may be real or complex. The imaginary part of the complex eigenvalue \((\omega)\) is the radian frequency of the oscillations and the real part \((\sigma)\) is the decrement rate. Then, the damping ratio \((\xi)\) of the \(j\)th eigenvalue is defined with the following equation:

\[
\xi_j = \frac{-\sigma_j}{\sqrt{\sigma_j^2 + \omega_j^2}}
\]

**PSS structure**

The PSSs used here possess a conventional lead-lag structure and have speed deviation input [22–24]. The Gain of stabilizer \((K_{PSS})\) determines the amount of damping created by PSS. Like a high-pass filter with time constant \(T_w\), the Filtering block (washout) passes the cross speed deviations and blocks steady-state values of the speed. The two-level compensation blocks provide an appropriate lead characteristic, in order to compensate the lag characteristic between the input excitation control and the electrical torque of the generator. Five parameters of PSS, including \(T_1\)-\(T_4\) (time constant) and \(K_{PSS}\), are optimized by PSO algorithm and \(T_w\) is considered to be constant. Fig. 1 shows the PSS structure.

**PSS tuning and placement**

The classical PSS tuning methods are usually used for specific frequency and operating point, and hence, any change in system operating point degrades the performance of PSS. In this paper, Particle Swarm Optimization algorithm (PSO) is used to adjust PSS parameters.

**Particle Swarm Optimization (PSO) algorithm**

PSO is an evolutionary computation algorithm, inspired from the nature and based on repetition [25]. The PSO algorithm is composed of fixed number of particles taking random initial values. Two values are assigned to each particle, position \((X_i^k)\) and velocity \((V_i^k)\). These particles repetitively move in the \(n\)-dimensional space (corresponding to the number of parameters) to look for new possible answer choices by calculating the optimality of each particle based on the objective function. At each step, the best position of each particle \((pbest_i^k)\) and the best position among all particles \((gbest_i^k)\) are stored. New speed \((V_i^{k+1})\) and new position \((X_i^{k+1})\) of each particle will be updated using following equations [26]:

\[
V_i^{k+1} = w \times V_i^k + c_1 \times r_1 \times (pbest_i^k - X_i^k) + c_2 \times r_2 \times (gbest_i^k - X_i^k)
\]

\[
X_i^{k+1} = X_i^k + V_i^{k+1}
\]

where \(c_1\) and \(c_2\) are positive numbers illustrating the weight of the acceleration of each term, guiding each particle toward the best individual \((pbest)\) and the best swarm \((gbest)\) positions, \(r_1\) and \(r_2\) are two random number in the range [0.1], and \(w\) is the inertia calculated by the following equation [26]:

\[
w = w_{\text{max}} - \left(\frac{w_{\text{max}} - w_{\text{min}}}{k_{\text{max}}}\right) \times k
\]

where \(w_{\text{max}}\) and \(w_{\text{min}}\) are the maximum and minimum values of \(w\), \(k_{\text{max}}\) is the maximum number of iterations and \(k\) is the current iteration number.

**Objective function**

The Stability of a power system can be determined based on its eigenvalues. Eigenvalues with large negative real parts ensure system stability, the overshoot and oscillations values are determined.
by the damping coefficient of the system, where any increase in the damping coefficient reduces oscillations and improves the stability of the system. In this paper, the objective function is a combination of the two indices; the damping coefficient and the real part of eigenvalues, which are considered as follows [27]:

\[ J = J_1 + \alpha J_2 \quad (\alpha = 10) \]  

\[ J_1 = \sum_{i=1}^{n} (\sigma_i - \sigma_0)^2 \quad \text{for} \quad \sigma_i \geq \sigma_0, \quad (\sigma_0 = -3) \]  

\[ J_2 = \sum_{i=1}^{n} (\zeta_i - \zeta_0)^2 \quad \text{for} \quad \zeta_i \leq \zeta_0, \quad (\zeta_0 = 0.3) \]

\( n \) denotes the total number of eigenvalues. Term \( J_1 \) in the objective function controls the real part (\( \sigma \)) of eigenvalues and generally leads the eigenvalues of the system to the left side of imaginary axis in an area less than \( \sigma_0 \). The term \( J_2 \) in the objective function brings the damping (\( \zeta \)) of eigenvalues to the desired damping (\( \zeta_0 \)) and controls the overshoot of the system. Value of \( \alpha \) obtained by experimentation and considered constant equal to 10 [27].

**Optimal PSS placement using TS fuzzy**

Optimal PSS locating in multi-machine systems is an important issue which can improve PSS performance and increase dynamic stability of the power system. The TS fuzzy system is suited for mathematical analysis such as nonlinear systems modeling [28]. The output of a TS fuzzy system is defined as a function of inputs:

\[ \text{If } x_1 = M \text{ and } x_2 = L \text{ then output } = ax_1 + bx_2 + c \]  

\[ (a, b, c) \text{ are constants. In this paper, the TS fuzzy system determines the optimal location for PSS installation by proper design of membership functions and fuzzy rules. The zero-order TS fuzzy system } (a, b = 0) \text{ is used, and thus the output of each rule is a constant. The TS fuzzy system inputs are the damping coefficient and the real part of power system eigenvalues. Five linguistic variables were considered for each input. The membership functions of the damping coefficient and the real part inputs can be seen in Figs. 2 and 3, respectively. Also, the 25 rules defined for fuzzy output are shown in Table 1. In this paper, it is assumed that a fixed number of PSSs, } k \text{, are installed among the } m \text{ generators of the network. Various cases of PSS location in network, defined as position index variable } (\text{PlaceIndex}), \text{ are obtained by enumeration of } k \text{ stabilizers among } m \text{ generators. The maximum possible value for PlaceIndex is obtained by Eq. (17):}

\[ \text{PlaceIndex}_{\text{max}} = \binom{k}{m} = \frac{m!}{k!(m-k)!} \]  

\[ 1 \leq \text{PlaceIndex} \leq \text{PlaceIndex}_{\text{max}} \]  

In order to determine the best location for PSS, all possible locations are determined by (17) and (18) and are stored in PlaceIndex variable. Then, according to the algorithm shown in Fig. 5, enumeration of variable PlaceIndex is performed for each PlaceIndex. In each enumeration step, after tuning PSS parameters, the eigenvalues of the system are calculated and sorted based on the least damping. The first eight eigenvalues (corresponding to the quantity of mechanical modes), having the least damping coefficients are sent to the fuzzy system. Receiving the damping coefficient and the real part of eigenvalues by the fuzzy system as inputs, it calculates the \( \text{out}(i) \), output corresponding to the \( i \)th eigenvalue. Also FuzzyPlace\((k)\), corresponding to the \( k \)th placeIndex at each enumeration step, can be calculated using Eq. (19):

\[ \text{FuzzyPlace}(k) = 10\text{out}(i) + 8\text{out}(i+1) + 6\text{out}(i+2) + \ldots + \text{out}(8) \]  

for \( i = 1, 2, 3, \ldots, 8 \)

The variable FuzzyPlace\((k)\) indicates the fitness of the \( k \)th for installing PSS and a large FuzzyPlace\((k)\) shows a better place for PSS installation. Finally, the best place for PSS installation is determined based on the maximum value of FuzzyPlace\((k)\). The algorithm used PSS tuning and finding its location can be observed in Fig. 5.

**Experimental results**

In order to study the performance of the proposed method, the four machine-two area network shown in Fig. 4 is simulated. This benchmark system is introduced to study inter-area oscillations and their effects on the system dynamic stability. It consists of two areas, each having two generators. The two areas are connected by a double communication line. About 400 MW of power is transferred through the communication lines between the two areas. All the simulations have been carried out by Matlab software. In this system, there are two generation areas, which have two loads interconnected by transmission lines. Details of the power system can be seen in Reference [29].

**PSS tuning**

The results of using PSO algorithm to tune the stabilizer parameters (PSOPSS) are compared with those of using classical methods (CPSS) and Genetic Algorithm (GAPSS). PSO and GA parameters...
considered in this comparison can be seen in Table 2. Eigenvalues and the damping coefficients of network modes for cases of no stabilizers (No PSS), CPSS, PSOPSS and GAPSS are illustrated in Table 3.

It can be seen that in NoPSS case, some of the network modes have very weak damping. Moving up to the CPSS case, relative improvement in the weak modes of network is observed, suggesting the positive impact of PSS on network stability. As the results show, optimizing PSS parameters, significantly improves the damping of network modes. It can also be observed that using PSO algorithm results in more favorable results than using other methods to tune PSS parameters.

Fig. 4. Network four machine-two areas.

Fig. 5. Simultaneous PSS tuning and locating algorithm.
Table 2
PSO and GA parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PSO</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoPSS</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Iter</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>c1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>c2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>α max</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>P crossover</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>P mutation</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 3
Eigenvalues and damping coefficients.

<table>
<thead>
<tr>
<th>Method</th>
<th>Eigenvalues</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoPSS</td>
<td>–0.0907 ± 4.3183i</td>
<td>0.0210</td>
</tr>
<tr>
<td></td>
<td>–0.2851 ± 6.1351i</td>
<td>0.0464</td>
</tr>
<tr>
<td></td>
<td>–0.4054 ± 6.2126i</td>
<td>0.0651</td>
</tr>
<tr>
<td>CPSS</td>
<td>–0.4708 ± 4.4266i</td>
<td>0.1058</td>
</tr>
<tr>
<td></td>
<td>–0.7694 ± 6.3661i</td>
<td>0.1200</td>
</tr>
<tr>
<td></td>
<td>–0.7954 ± 6.3383i</td>
<td>0.1245</td>
</tr>
<tr>
<td>GAPSS</td>
<td>–2.5545 ± 8.6985i</td>
<td>0.2818</td>
</tr>
<tr>
<td></td>
<td>–2.5440 ± 7.8648i</td>
<td>0.3078</td>
</tr>
<tr>
<td></td>
<td>–3.0023 ± 8.1775i</td>
<td>0.3446</td>
</tr>
<tr>
<td>PSOPSS</td>
<td>–2.9973 ± 7.9819i</td>
<td>0.3515</td>
</tr>
<tr>
<td></td>
<td>–2.9764 ± 7.1223i</td>
<td>0.3856</td>
</tr>
<tr>
<td></td>
<td>–3.5894 ± 8.1883i</td>
<td>0.4015</td>
</tr>
</tbody>
</table>

PSS locating

As a common rule, not all the generators in a network are equipped by PSSs, but the minimum number of PSSs used in a network equals to half of the total generators used in it [30]. In this paper, one, two and three PSSs are considered for the power system. The optimal location for installing PSSs in each case is presented in Table 4, obtained using the TS fuzzy system. The 3rd column of the table shows the fitness value of each PlaceIndex, with larger values showing better locations for PSS. As observed in Table 4, generators G1, G3, G4 are the best PSS locations for the case of using three generators, while generators G1, G3 and generator G1 are the best places for PSS installation for the cases of using two and one generator, respectively. The tuned PSS parameters in each case, best installation position, and the least network damping coefficient are summarized in Table 5.

As observed in Table 5, the minimum damping coefficients in cases of using one and two PSSs in network are 0.047 and 0.067, respectively, suggesting a network with weakly damping modes. These values increase to 0.151, a suitable value, for the case of using three PSSs and 0.352 when using four PSSs. As a conclusion, installing three PSSs in the network yields to acceptable damping of oscillatory and weak network modes.

Time domain simulations

In order to study the performance of the proposed algorithm in setting and placing PSSs in power systems, some time domain simulations have been performed on the network under study. Meanwhile, to investigate the proposed method performance when the operating point of the system changes, two different operating cases are considered for the system (Table 6).

PSS tuning

All generators of the studied network are equipped by PSSs. Dynamic behavior fluctuations of inter-area modes are depicted in Figs. 6 and 7 with different methods of setting PSS parameters, including CPSS, GAPSS, PSOPSS and without PSS simulations.

According to Figs. 6 and 7 tuning PSS parameters by PSO algorithm provides suitable results and results in more favorable damping for network compared to the use of CPSS and GAPSS. Analyzing system eigenvalues, shown in Table 3, in combination with the dynamical simulation performed, suggests the good performance of the proposed PSOPSS method tuning PSS, improving damping and reducing local and inter-area network oscillations.

PSS locating

In order to study the performance of the proposed method finding the best location for PSS, some time domain simulations has been applied to the network under study. The experiments were performed for the cases of installing two and three PSSs in the network.

Investigating the speeds of generators. Figs. 8–15, show the speeds of generators with three and two PSSs in the network for different installation locations and load conditions in the network.

According to Figs. 8–15, the best locations for installing three and two PSSs in the network are generators G1, G3, G4.
Inter-area modes. Figs. 16–21, show inter-area oscillations \((w_1 - w_3)\) and \((w_2 - w_3)\), with three and two PSSs in the network with different installation locations and loading conditions.
Figs. 20 and 21, show inter-area oscillations \((w_1-w_3)\) and \((w_2-w_3)\), with two PSSs installed:

Figs. 16–21 confirm the previously obtained optimized locations for installing three and two PSSs in the network. Time domain simulations, shown in Figs. 8–21, introduce generators G1, G3, G4, and G1, G3 as the best installing locations in the network for the cases of using three and two PSSs, respectively. By comparing these results to Table 4, which shows the installing locations determined using fuzzy systems, the optimal performance of the proposed fuzzy method to determine the best places for PSSs in the system.
is confirmed. In order to study the performance of the proposed method improving system stability, reducing local and inter-area oscillations of the system, a simulation assuming three PSSs installed in the network is performed. PSS parameters and optimized installation locations are determined by the proposed algorithm, and PSSs are installed on the generators G1, G3, G4. Figs. 22–25 show the speeds of generators and inter-area oscillations for cases of no PSS and three PSSs installed. Figs. 22–25 show the favorable performance of the proposed method setting and placing PSSs in the network with the aim of improving the system dynamic stability.

Conclusions

In this paper, a hybrid approach for simultaneous PSS setting and placing in multi-machine systems is proposed. PSS parameters are adjusted using PSO optimization algorithm and the optimal PSS installation locations are determined by Takagi–Sugeno fuzzy system. The TS fuzzy system employs damping coefficients and real parts of network eigenvalues as its two inputs. A sample four-machine, two-area network is employed to investigate the effectiveness of the proposed method, in different operating point conditions. Analysis of the system eigenvalues and dynamic simulation of the network, confirmed optimal performance of the proposed method (PSOPSS) setting PSS parameters and improving damping modes (particularly mechanical oscillating modes), compared to the cases of use of classical methods (CPSS) and Genetic Algorithm (GAPSS). The proposed fuzzy method was applied to determine the PSS installation locations, and the obtained results showed optimal performance of the proposed method to simultaneously determine the best PSS adjustments and installation locations, providing appropriate damping for the system. The proposed method is robust against changes in network operating point, improves dynamic performance of the network, reduces local and inter-area low-frequency oscillations of the system, and is suitable for a wide range of power systems.

References