A Simulated Annealing Based Power System Stabilizer

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Abstract: Power System Stabilizers (PSS) are used to generate supplementary damping control signals for the excitation system in order to damp the Low Frequency Oscillations (LFO) of the electric power system. The PSS is usually designed based on classical control approaches but this Conventional PSS (CPSS) has some problems. To overcome the drawbacks of CPSS, numerous techniques have been proposed in literatures. In this paper a PID type PSS is considered for damping electric power system oscillations. The parameters of this PID type PSS are tuned based on Simulated Annealing (SA) optimization method. The proposed PSS (SA-PSS) is evaluated against the conventional power system stabilizer (CPSS) at a single machine infinite bus power system considering system parametric uncertainties. The simulation results clearly indicate the effectiveness and validity of the proposed method.

Key words: Power System Stabilizer, Low Frequency Oscillations, Simulated Annealing, PID type Power System Stabilizer

INTRODUCTION

Large electric power systems are complex nonlinear systems and often exhibit low frequency electromechanical oscillations due to insufficient damping caused by adverse operating. These oscillations with small magnitude and low frequency often persist for long periods of time and in some cases they even present limitations on power transfer capability (Liu et al., 2005). In analyzing and controlling the power system’s stability, two distinct types of system oscillations are recognized. One is associated with generators at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as “intra-area mode” oscillations. The second type is associated with swinging of many machines in an area of the system against machines in other areas. This is referred to as “inter-area mode” oscillations. Power System Stabilizers (PSS) are used to generate supplementary control signals for the excitation system in order to damp both types of oscillations (Liu et al., 2005). The widely used Conventional Power System Stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead-lag compensator. The parameters of CPSS are determined based on the linearized model of the power system. Providing good damping over a wide operating range, the CPSS parameters should be fine tuned in response to both types of oscillations. Since power systems are highly nonlinear systems, with configurations and parameters which alter through time, the CPSS design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. Therefore, an adaptive PSS which considers the nonlinear nature of the plant and adapts to the changes in the environment is required for the power system (Liu et al., 2005). In order to improve the performance of CPSSs, numerous techniques have been proposed for designing them, such as intelligent optimization methods (Linda and Nair, 2010; Yassami et al., 2010; Sumathi et al., 2007; Jiang et al., 2008; Sudha et al., 2009) and Fuzzy logic method (Hwang et al., 2008; Dubey, 2007). Also many other different techniques have been reported by Chatterjee et al. (2009) and Nambu and Ohsawa (1996) and the application of robust control methods for designing PSS has been presented by Gupta et al., (2005), Mocwane and Folly (2007), Sil et al., (2009) and Bouhamida et al., (2005).

This paper deals with a design method for the stability enhancement of a single machine infinite bus power system using PID type PSS which its parameters are tuned using Simulated Annealing (SA-PSS). To show effectiveness of the new PID type SA-PSS, this method is compared with the CPSS. Simulation results show
that the proposed method guarantees robust performance under a wide range of operating conditions.

2. System under Study:
   Fig. 1 shows a single machine infinite bus power system (Kundur, 1993). The static excitation system has been considered as model type IEEE-ST1A.

Fig. 1: A single machine infinite bus power system.

3. Dynamic Model of the System:
   3.1. Non-linear Dynamic Model:
   A non-linear dynamic model of the system is derived by disregarding the resistances and the transients of generator, transformers and transmission lines (Kundur, 1993). The nonlinear dynamic model of the system is given as (1).

\[
\begin{align*}
\dot{\delta} &= \omega_0 (\omega - 1) \\
\dot{E}_q^' &= \frac{(-E_q + E_{id})}{T_d}
\end{align*}
\]

\[
\dot{E}_{id} = \frac{-E_{id} + K_e (V_{ref} - V_i)}{T_a}
\]

\[
\begin{align*}
\Delta \dot{\delta} &= \omega_0 \Delta \omega \\
\Delta \dot{\omega} &= \frac{-\Delta P - D \Delta \omega}{M} \\
\Delta E_q^' &= (-\Delta E_q + \Delta E_{id})/T_d' \\
\Delta E_{id} &= -\left(\frac{1}{T_a}\right) \Delta E_{id} - \left(\frac{K_e}{T_a}\right) \Delta V
\end{align*}
\]

(2)

Fig. 2 shows the block diagram model of the system. This model is known as Heffron-Phillips model (Kundur, 1993). The model has some constants denoted by \(K_e\). These constants are functions of the system parameters and the nominal operating condition. The nominal operating condition is given in the appendix.

3.2. Linear dynamic model
   A linear dynamic model of the system is obtained by linearizing the non-linear dynamic model around the nominal operating condition. The linearized model of the system is obtained as (2) (Kundur, 1993).

3.3. Dynamic Model of the System in the State-space Form:
   The dynamic model of the system in the state-space form is obtained as (3) (Kundur, 1993).
4. Analysis:

In the nominal operating condition, the Eigen values of the system are obtained using analysis the state-space model of the system presented in (3) and these Eigen values are listed in Table 1. It is clearly seen that the system has two unstable poles at the right half plane and therefore the system is unstable and needs to Power System Stabilizer (PSS) for stability.

\[
\begin{bmatrix}
\Delta \dot{\delta} \\
\Delta \dot{\omega} \\
\Delta \dot{E}_q \\
\Delta \dot{E}_d
\end{bmatrix} =
\begin{bmatrix}
0 & \omega_0 & 0 & 0 \\
-K_1 & 0 & -K_2 & M \\
K_4 & 0 & K_5 & \frac{1}{T_d} \\
-K_\alpha K_5 & 0 & -K_\alpha K_\delta \frac{1}{T_\alpha} & -\frac{1}{T_\alpha}
\end{bmatrix}
\times
\begin{bmatrix}
\Delta \dot{\delta} \\
\Delta \dot{\omega} \\
\Delta \dot{E}_q \\
\Delta \dot{E}_d
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 & 0 \\
\frac{1}{M} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\times
\begin{bmatrix}
\Delta T_m \\
\Delta V_{ref}
\end{bmatrix}
\tag{3}
\]

Table 1: The Eigen values of the closed loop system.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>λ1</td>
<td>λ2</td>
<td>λ3</td>
<td>λ4</td>
</tr>
<tr>
<td>-4.2797</td>
<td>-46.3666</td>
<td>0.1009</td>
<td>j4.758</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Power System Stabilizer:

A Power System Stabilizer (PSS) is provided to improve the damping of power system oscillations. Power system stabilizer provides an electrical damping torque (\(\Delta T_m\)) in phase with the speed deviation (\(\Delta \omega\)) in order to improve damping of power system oscillations (Kundur, 1993). As referred before, many different methods have been applied to design power system stabilizers so far. In this paper a new optimal method based on the SA is considered to tuning parameters of the PID type PSS. In the next section, the proposed method is briefly introduced.

6. The Proposed Method:

In this paper SA method is considered for tuning PID type PSS. For more introductions, the SA method is briefly introduced in the following subsection.

6.1. Simulated Annealing:

In the early 1980s the method of simulated annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes
its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, \( f \), associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

\[
T \leq \exp\left(\frac{(f_{\text{old}} - f_{\text{new}})}{T}\right)
\]

(4)

Where, \( r \) is a uniform random number and \( T \) is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable set as (5).

\[
P_{\text{new}} = dP_{\text{old}}
\]

(5)

The variable \( d \) is either uniformly or normally distributed about \( P_{\text{old}} \). This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of \( T \) and \( d \) decrease by a certain percent and the algorithm repeats. The algorithm stops when \( T = 0 \). The decrease in \( T \) is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is \( T_0 \) and the ending temperature is \( T_N \), then the temperature at step \( n \) is given by (6).

\[
T_n = f(T_0, T_N, N, n)
\]

(6)

Where, \( f \) decreases with time. Some potential cooling schedules are as follows:
1. Linearly decreasing: \( T_n = T_0 - \frac{n(T_0 - T_N)}{N} \)
2. Geometrically decreasing: \( T_n = 0.99 \cdot T_{n-1} \)
3. Hayjek optimal: \( T_n = \frac{c}{\log(1+n)} \), where \( c \) is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems (Randy and Sue, 2004).

7. Design Methodology:

In this section the PID type PSS parameters tuning based on the SA is presented. The PID type PSS configuration is as (7).

\[
\text{PID - PSS} = K_p + \frac{K_i}{S} + K_d S
\]

(7)

The parameter \( \Delta E_{\text{ref}} \) is modulated to output of PSS and speed deviation \( D\omega \) is considered as input to PSS. The optimum values of \( K_p, K_i \) and \( K_d \) which minimize an array of different performance indexes are accurately computed using SA. In this study the performance index is considered as (8). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE).

\[
\text{ITAE} = \int_0^t |\Delta \omega| dt
\]

(8)

The parameter "\( t \)" in performance index is the simulation time. It is clear to understand that the controller with lower performance index is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in the reference mechanical torque (DTm) is assumed and the performance index is minimized using SA. It should be noted that SA algorithm is run several times and then optimal set of PSS parameters is selected. The optimum values of the parameters \( K_p, K_i \) and \( K_d \) are obtained using SA and summarized in the Table 2.
Table 2: Obtained parameters of PID-PSS using SA.

<table>
<thead>
<tr>
<th>PID Parameters</th>
<th>$K_p$</th>
<th>$K_i$</th>
<th>$K_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtained Value</td>
<td>69.2031</td>
<td>55.8721</td>
<td>14.2297</td>
</tr>
</tbody>
</table>

8. Simulation Results:

In this section, the proposed SA-PSS is applied to the under study system (single machine infinite bus power system). To show effectiveness of the proposed optimal SA-PSS, A classical lead-lag PSS based on phase compensation technique (CPSS) is considered for comparing purposes.

The detailed step-by-step procedure for computing the parameters of the classical lead-lag PSS (CPSS) using phase compensation technique is presented in (Kundur, 1993). Here, the CPSS has been designed and obtained as (9).

$$CPSS = \frac{38(0.4012S+1)}{(0.1S+1)}$$

In order to study the PSS performance under system uncertainties (controller robustness), three operating conditions are considered as follow:

i: Nominal operating condition
ii: Heavy operating condition (20% changing parameters from their typical values)
iii: Very heavy operating condition (50% changing parameters from their typical values)

In the nominal operating condition, the Eigen values of the system with CPSS and SA-PSS are obtained and listed in Table 3. It is clear to see that the Eigen values of the system with SA-PSS are farther than the imaginary axis and the system stability margin is more than CPSS method.

Table 3: The Eigen values of system with different PSSs.

<table>
<thead>
<tr>
<th>SA-PSS</th>
<th>CPSS</th>
<th>Without PSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.7109</td>
<td>-3.4256</td>
<td></td>
</tr>
<tr>
<td>-4.8291</td>
<td>-4.0503</td>
<td>-4.2797</td>
</tr>
<tr>
<td>-4.8821</td>
<td>-46.3704</td>
<td>-46.366</td>
</tr>
<tr>
<td>-49.6121</td>
<td>-3.2991 + j57.32</td>
<td>-0.1009 + j4.758</td>
</tr>
<tr>
<td>-432.8194</td>
<td>-3.2991 - j57.32</td>
<td>-0.1009 - j4.758</td>
</tr>
</tbody>
</table>

Also to demonstrate the robustness performance of the proposed method, The ITAE is calculated following a 10% step change in the reference mechanical torque ($DT_m$) at all operating conditions (Nominal, heavy and Very heavy) and results are shown at Table 4. Following step change at $DT_m$, the SA-PSS has better performance than the CPSS at all operating conditions. Where, the SA-PSS has lower ITAE index in comparison with CPSS, therefore the SA-PSS can damp power system oscillations more successfully.

It can be more useful to show responses in figures. Fig. 3 shows $\omega$ at nominal, heavy and very heavy operating conditions following 10% step change in the reference mechanical torque ($DT_m$). It is clear to see that between all operating conditions, the SA-PSS has better performance than the other method in mitigating oscillations. SA-PSS characteristics in the damping power system oscillations are in the range of acceptable. Eventually between two methods, the SA-PSS has a very significant better performance than CPSS. The CPSS ability in damping power system oscillations goes to unstable and large oscillations with changing system operating conditions and under heavy loads.

Table 4: The calculated ITAE.

<table>
<thead>
<tr>
<th>SA-PSS</th>
<th>CPSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal operating condition</td>
<td>$3.9123 \times 10^4$</td>
</tr>
<tr>
<td>Heavy operating condition</td>
<td>$3.1288 \times 10^4$</td>
</tr>
<tr>
<td>Very heavy operating condition</td>
<td>$4.3455 \times 10^4$</td>
</tr>
</tbody>
</table>

9. Conclusions:

In this paper a new optimal PID type PSS based on SA (SA-PSS) method has been successfully proposed. The design strategy includes enough flexibility to set the desired level of stability and performance, and to consider the practical constraints by introducing appropriate uncertainties. Also the final designed SA-PSS is low order and its implementation is easy and cheap. The proposed method was applied to a typical single
machine infinite bus power system containing system parametric uncertainties and various loads conditions. The simulation results demonstrated that the designed SA-PSS is capable of guaranteeing the robust stability and robust performance of the power system under a wide range of system uncertainties.

Fig. 3: Dynamic responses $\omega$ following 0.1 step in the reference mechanical torque ($T_m$)
   a: Nominal operating condition b: Heavy operating condition c: Very heavy operating condition.
Nomenclature:

\( \omega \): Synchronous speed.

\( \delta \): Synchronous angle.

\( P_{m} \): Input mechanical power.

\( P_{e} \): Output electrical power.

\( M \): Inertia.

\( E_{q} \): q axis voltage.

\( E_{ref} \): Field voltage.

\( E_{q}^{\prime} \): Transient voltage of q axis.

\( T_{do}^{\prime} \): Transient time constant of q axis.

\( K_{a} \): Excitation system gain.

\( T_{a} \): Excitation system time constant.

\( V_{t} \): Terminals voltage.

\( V_{ref} \): Reference voltage of excitation system.

\( T_{m} \): Mechanical torque.

PSS: Power System Stabilizer.

SA: Simulated Annealing.

CPSS: Conventional Power System Stabilizer.


ITAE: Integral of the Time multiplied Absolute value of the Error.

Appendix:

The nominal parameters and operating conditions of the system are listed in Table 5.

| Table 5: The nominal system parameters. |
| Generator | M = 10 Mj/MVA | X_s = 1.6 p.u. | T_{do}= 7.5 s | X_{q} = 1.68 p.u. |
| Excitation system | K_a = 50 | X_d = 0.3 p.u. | T_a = 0.02 s |
| Transformer | X_{tr} = 0.1 p.u. | |
| Transmission lines | X_{te1} = 0.5 p.u. | X_{te2} = 0.9 p.u. | Operating |
| condition | V_{t} =1.05 p.u. | P=1 p.u. | Q=0.2 p.u. |

REFERENCES


