Optimal Tuning and Comparison of Different Power System Stabilizers Using Different Performance Indices Via Jaya Algorithm

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Abstract - In this paper, a powerful optimization algorithm is used for optimal tuning of different types of PSS to stabilize a synchronous machine connected to an infinite bus. The robustness of each controller has been evaluated via four different types of error criteria and the coefficients optimized by the Jaya algorithm which provides reasonable solution. By analyzing the results based on the solutions given by Jaya algorithm, the excellency of this algorithm in solving such problem are obvious. The capability of each controller for damping, when acting alone, may be matter of concern, too. Finally results obtained for each controller due to different criteria, have been compared to show the operational results of each controller.

Keywords: Fractional Order PID (FOPID), Jaya Algorithm, PID, Power System Stabilizer

1 Introduction

Service continuity is one of the most important features of a power system. This means that the power system must remain a reliable power source even after being subjected to a disturbance or occurrence of a fault [1]. The main reasons which cause instability in a power system are local oscillations between generators exist in the same power plant, oscillations caused by neighboring power plants and global oscillations of unstable generators connected to the same grid. It’s obvious that these oscillations (even at low frequency) have negative effects on power transferred in transmission lines. Disturbances such as sudden load changes or faults lead to an imbalance between electrical power delivered by the generator and the mechanical power being produced by the turbine. The imbalance results in a shaft torque with an accelerating or decelerating effect on the shaft line. So considering the problem of transient stability which concerns maintaining synchronism between generators in the case of a severe disturbance, is necessary [2].

The basic role of a Power System Stabilizer (PSS) is damping of such power oscillations, by producing electrical torque using the excitation system. Lead-Lag, PID and Fractional Order PID (FOPID), are different types of PSSs, to name a few.

One of the commonly used PSS is lead-lag compensator. Although new types may operate better in real-world, i.e. industrial applications, but they show robust performances for various operating conditions and are easy to implement [3]. Beyond choosing one type of PSS, tuning its parameters can be considered as a problem, too. From this point of view there has been so many works provided in the literature about tuning PSS parameters. Approaches differ from modern control theory [2,4-6], to random heuristic methods, such as Tabu search, genetic algorithms, chaotic optimization algorithm, rule based bacteria foraging and particle swarm optimization, teaching and learning based optimization and bat optimization for achieving the optimal PSS parameters which give us the optimal recovery condition of a power system after a disturbance [7-11].

Despite the significant number of recently proposed algorithms that have been used for optimizing the PSS parameters, there might be a fundamental question about using and testing different algorithms. For answering to this question we refer to the so-called No Free Lunch (NFL) theorem [12]. This theorem challenges the ability of a single algorithm for solving the optimization problem. So, success of an algorithm in solving a specific set of problems does not guarantee solving all optimization problems with different type and nature. In this regard, we have used Jaya algorithm to optimize the parameters of the applied PPS in the system. Jaya is a simple and powerful optimization algorithm which have the ability to solve whether constrained or unconstrained optimization problems. The fundamental concept of algorithm is that the solution obtained for a problem should move towards the best solution and should avoid the worst solution. This does not need any algorithm-specific control parameters except common control parameters [13]. Furthermore, we have used three types of PSS, Lead-Lag, PID and FOPID for our system and after optimization the results have been compared regarding different error criteria, including Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral of the Time-Weighted Absolute Error (ITAE) and Integral of Time multiplied by the Squared Error (ITSE).
2 Power system modelling and PSS design

In the next two sections presented below, we have provided the model of the power system and its complete block diagram which can be used for simulations.

2.1 Power system model

For the stability analysis a Single Machine connected to an Infinite Bus (SMIB) through transmission line has been adopted. The system includes synchronous generator which is connected to a power grid (infinite bus) via a transmission line. Exciter Automatic Voltage Regulator (AVR) is one of the equipment used in generator [14]. Figure 1 shows a schematic diagram for the test system. System data are given in Ref. [15].

![Fig. 1. Single line diagram of SMIB](image)

2.2 Block diagram of Simulink model

We have considered synchronous generator by model 1.1, i.e. containing field circuit and one equivalent damper winding on the q axis (4th - order model). Due to linearizing the nonlinear model for an operating condition, a linear dynamic model can be obtained. Block diagram of the linearized dynamic model of the SMIB power system with PSS is shown in Fig. 2. \( K1, K2, \ldots, K6 \) are Heffron-Phillips constants that can be easily obtained by data presented in Ref. [15].

![Fig. 2. Block diagram of the linearized dynamic model of the SMIB](image)

The linearized equations can be rewritten in the state space form as follows:

\[
\begin{align*}
\Delta x &= A \Delta x + B \Delta u \\
y &= C \Delta x
\end{align*}
\]

Where, A, B and C are the system, input and measurement matrices, respectively. The overall linearized state-space model of the power system (SMIB including PSS) has been developed using the state-space equations and is provided in [15]. Note that, as \( D \) is a zero matrix, it has not been mentioned in the above equation.

3 Proposed stabilizers

Here, three kind of power system stabilizers which have been used in this investigation, are discussed.

3.1 Lead-Lag power system stabilizer

The transfer function of commonly used structure of the PSS that implemented in this study is given by the relationship below. It comprises of a block of \( K_{PSS} \) gain followed by a high-pass filter (so called washout filter) of time constant \( T_w \) and lead-lag structured phase compensation blocks with time constants \( T_1 \) and \( T_2 \). It is to be noted that the reduction of the power system oscillations after a wide perturbation in order to enhance the stability of power system is one of the reasons for suggesting stabilizers designation. The output of stabilizer is a voltage signal that adds supplementary control loops to the generator AVR, i.e. input voltage signal of the exciter system. The input signal of such a structure is usually the deviation of the synchronous speed \( \Delta \omega \) [16-18].

\[
U(s) = K_{PSS} \frac{1 + sT_1}{1 + sT_2} \Delta \omega(s)
\] (3)

It is worth noting that in this study, the time constant \( T_w \) is considered as 10.0 s.

3.2 PID type power system stabilizer

The main application of a PID type power system stabilizer is to create a proper torque on the rotor of the generator in order to compensate the phase lag between the machine electrical torque and the exciter input. The transfer function of the PID-PSS is given by:

\[
U(s) = \left[ K_p + \frac{K_i}{s} + K_d s \right] \Delta \omega(s)
\] (4)

3.3 FOPID type power system stabilizer

To improve the robustness and performance of PID control systems, Podlubny has proposed an extension to the PID controllers, which can be called PI\(^\lambda\)D\(^\mu\) (FOPID) controller because of involving a differentiator of order \( \mu \) and integrator of order \( \lambda \). Many applications have been provided for this controller and detailed information about it is presented in the literature [19]. The commonly used concept for the fractional differintegral, is the Riemann-Liouville (RL) definition. The transfer function of FOPID can be written as follows:

\[
G(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu}
\] (5)

In this work, a comparison based on the different types of PSS and either PI\(^\lambda\)D\(^\mu\) controller is considered in order to see which one can prove greater damping of power system. To assess the robustness of each controller we have not combined them together and same signal washout filter is used for all of them.
The transfer function of the FOPID-PSS to modulate the excitation voltage is given by:

\[ \frac{U(s)}{\Delta \omega(s)} = [K_p + K_i s^{-\lambda} + K_d s^\mu] \]

(6)

Below you can see Simulink implementation of FOPID, in which coefficient “a” and “b” represent “\( \lambda \)” and “\( \mu \)”, respectively.

![Simulink implementation of FOPID](image)

**Fig. 3.** Simulink implementation of FOPID

### 4 Objective function

In this article, we used performance indices including Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral of the Time-weighted Absolute Error (ITAE), Integral of Time multiplied by the Squared Error (ITSE), to minimize the error signal; in other terms minimize the overshoots and settling time in power system oscillations, and compare them to find the best suitable one, where, Jaya algorithm has been applied to minimize the values provided by the objective functions of the system that is given by:

\[ IAE = \int_0^{t_s} |e(t)|dt \]

(7)

\[ ITAE = \int_0^{t_s} t \times |e(t)|dt \]

(8)

\[ ISE = \int_0^{t_s} e(t)^2 dt \]

(9)

\[ ITSE = \int_0^{t_s} t \times e(t)^2 dt \]

(10)

Where, \( t_s \) is total simulation time.

### 5 Proposed algorithm

Regarding to success of the TLBO algorithm, another algorithm-specific parameter-less algorithm is proposed in this paper [14]. As we remember from TLBO algorithm, there are two phases, one is teacher phase and the other is learner phase. But, Jaya algorithm has only one phase and it is very easy to use, whether the problem is constrained or unconstrained. Thus, the working of the proposed algorithm is much different from that of the TLBO algorithm.

Imagine \( f(x) \) as the objective function to be minimized, with four error criteria (i.e. IAE, ITAE, ISE, ITSE). At any iteration \( i \), ‘\( m \)’ indicates the number of design variables (i.e. \( j=1,2,\ldots,m \)) and ‘\( n \)’ indicates the number of candidate solutions (i.e. population size, \( k=1,2,\ldots,n \)). Amongst the entire candidate solutions, best candidate \( best \) obtains the best value of \( f(x) \) (i.e. \( f(x)_{best} \)) and the worst candidate \( worst \) obtains the worst value of \( f(x) \) (i.e. \( f(x)_{worst} \)). If \( X_j,k,i \) is the value of the \( j \)th variable for the \( k \)th candidate during the \( i \)th iteration, then the modification of its value will be done by Eq. (11).

\[ X_j,k,i = X_j,k,i + r_{1,j,i} (X_{best,i} - X_j,k,i) - r_{2,j,i} (X_{worst,i} - X_j,k,i) \]

(11)

where, \( X_{best,i} \) and \( X_{worst,i} \) show the value of the variable \( j \) for the best and worst candidate, respectively. \( X_{j,k,i} \) is the updated value of \( X_{j,k,i} \) while \( r_{1,j,i} \) and \( r_{2,j,i} \) are the two random numbers for the \( j \)th variable during the \( i \)th iteration in the range \([0,1] \). The term “\( r_{1,j,i} (X_{best,i} - X_j,k,i) \)” indicates the willing of the solution to move closer to the best solution and the term “\( -r_{2,j,i} (X_{worst,i} - X_j,k,i) \)” indicates the willing of the solution to avoid the worst solution. \( X_{j,k,i} \) is accepted if it gives better function value. All the accepted function values at the end of iteration are maintained and these values become the input to the next iteration. The flowchart of the proposed algorithm can be seen in Fig. 4. The main idea behind the name of Jaya algorithm is the fact that, the algorithm has the willing get closer to success (i.e. obtaining the best solution) and tries to move away from failure (i.e. avoiding the worst solution). Reaching the best solution somehow considered as achieving victory and hence it is named as **Jaya** (a Sanskrit word meaning **victory**).

**Fig. 4.** The Flowchart of the proposed algorithm

### 6 Results and discussions

By simulating system using the data provided here, it can be seen that the system is in a stable condition. In another word, system will regain its stability after being subjected to a change in \( T_m \). Results are obtained after 0.01 p.u. change in \( T_m \) and by using different kinds of controllers and objective functions. Robustness of each controller is compared due to different objective functions. It is to be noted that each criterion has its
own feature (lower or higher overshoot and settling time). Therefore, choosing a controller depends on the needs we want to meet, i.e. we should try to reach to an equilibrium point regarding so called cost and benefit of our system. As there are many works available in the area of these controllers in the literature, for the sake of brevity, we just provided a comparison of this controller due to different scenarios.

Figure 5 shows rotor speed deviation of lead-lag power system stabilizer simulation results which compare 4 types of objective function for this kind of PSS. In Table 1 the coefficients obtained via the algorithm for lead-lag PSS and the result of objective function (cost) using these coefficients is provided. Consider that the lower and upper limits of coefficient which specified in the algorithm are as follows:

\[
0.001 < K_{PSS} < 15 \\
0.001 < T_1 < 10 \\
0.001 < T_2 < 10 
\]

![Fig. 5. Comparison of lead-lag PSS evaluated by different criteria](image)

As it can be seen from Fig. 5 the lowest overshoot and settling time belongs to ISE and ITAE criterion, respectively.

Table 1. Coefficients obtained via the algorithm and cost for lead-lag PSS

<table>
<thead>
<tr>
<th>Coef. Criteria</th>
<th>( K_P )</th>
<th>( K_I )</th>
<th>( K_D )</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAE</td>
<td>15</td>
<td>1.4409</td>
<td>5.8991</td>
<td>3.50E-05</td>
</tr>
<tr>
<td>ITAE</td>
<td>15</td>
<td>1.4475</td>
<td>5.2364</td>
<td>8.55E-06</td>
</tr>
<tr>
<td>ISE</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>2.23E-09</td>
</tr>
<tr>
<td>ITSE</td>
<td>15</td>
<td>15</td>
<td>8.6846</td>
<td>4.46E-10</td>
</tr>
</tbody>
</table>

![Fig. 6. Comparison of PID PSS evaluated by different criteria](image)

As it can be seen from Fig. 5 the lowest overshoot and settling time belongs to ISE and ITAE criterion, respectively.

Figure 6 shows that the lowest overshoot and settling time belongs to ISE and ITAE criterion, respectively.

Table 2. Coefficients obtained via the algorithm and cost for PID PSS

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Figure 7 shows FOPID power system stabilizer simulation results, comparing 4 type of objective function for this kind of PSS. In Table 3 the coefficients obtained via the algorithm for FOPID PSS and the result of objective function (cost) using these coefficients is provided. Consider that the lower and upper limits of coefficient which specified in the algorithm are as follows:

\[
1 < K_P < 15 \\
1 < K_I < 15 \\
1 < K_D < 15 \\
0.1 < \lambda < 1 \\
0.1 < \mu < 1 
\]

![Fig. 7. Comparison of FOPID PSS evaluated by different criteria](image)
From Fig. 8 it can be seen that PID and lead-lag controllers perform in the same manner. But, the FOPID shows a different manner that we see a decrease in overshoot by a factor of about 8 while the settling time increases in contrast.

It’s clearly obvious from Fig. 9 that the three applied controller have same overshoot but FOPID damps the power oscillations faster than other two controllers.

As Fig. 10 shows, PID controller has the highest overshoot and the lowest settling time belongs to this controller, too. Lead-Lag controller lowers the overshoot by a factor of 3 but its settling time increases. Although the FOPID controller has the least overshoot but it has the most settling time among others. Finally in Fig. 11, while PID and lead-lag controllers have the same overshoot, FOPID decreases the overshoot by a factor of 7. In contrast lower overshoot and its settling time is increased.
7 Conclusion

In this article, we have applied a newly presented optimization algorithm named Jaya, to determine and compare robustness of commonly used and newly presented power system stabilizers using performance indices (PI) including IAE, ISE, ITAE and ITSE. The coefficients and the results of objective functions which obtained using algorithm are presented in Tables 1-3 and the deviation of rotor speed regarding 0.01 p.u. change in \( \Delta g \) with the given system data are shown in Figs. 5-11. It is clearly obvious that the algorithm works well in solving our stability problem by providing reasonable coefficients. Thus, regarding to the needed criteria (i.e. lower rise time, smaller over shoot and etc.), one can choose the appropriate controller. In addition, the newly proposed FOPID controller shows high capability in damping. Further study can be made on practical implementation of these controllers and comparing simulational results with real-world.

References

Biographies

Heidar Ali Shayanfar received the B.S. and M.S.E. degrees in Electrical Engineering in 1973 and 1979, respectively. He received his Ph.D. degree in Electrical Engineering from Michigan State University, U.S.A., in 1981. Currently, he is a Full Professor in Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research Interests are in the Area of Application of Artificial Intelligence to Power System Control Design, Dynamic Load Modeling, Power System Observability Studies, Voltage Collapse, Congestion Management in a Restructured Power System, Reliability Improvement in Distribution Systems, Reactive Pricing in Deregulated Power Systems and Smart Grids. He has published more than 220 papers in international journals and 300 papers in conference proceedings. He is a member of the Iranian Association of Electrical and Electronic Engineers and IEEE.

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