Small-Signal-Stability Enhancement using a Power-System Stabilizer based on the Cuckoo-Search Algorithm against Contingency N-1 in the Sulselrabar 150-kV System

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Abstract

Small-signal stability is one of the main factors limiting power transmission in conventional power systems. This concern is primarily handled by adding damper windings of a synchronous generator and power-system stabilizer (PSS). However, due to the impact of the N-1 contingency, damper windings and a conventional PSS are insufficient to overcome this problem. Proper placement and design of the PSS are crucial for improving stability. One approach to optimizing the placement and tuning of the PSS is to use an artificial-intelligence method. Here, the cuckoo-search algorithm (CSA) is proposed to optimize the PSS tuning and placement. Based on simulation, it is found that a PSS based on the CSA can enhance the system’s small-signal stability. The critical, local, and inter-area modes of the investigated system improve significantly. The oscillatory condition is more highly damped, as indicated by a smaller overshoot and faster settling time. It is also found that the CSA can be used to tune the PSS parameter under an N-1 contingency. From the analytical results of the N-1 contingency condition, optimal tuning of the PSS parameters was obtained, resulting in PSS-placement options for generators 1 to 7 and 12 to 15, producing a minimum damping of 0.611.

1. Introduction

Small-signal stability is a concern in power-system operation as it corresponds to the ability of the system to maintain its stable condition after being addressed by a small disturbance [1]. Oscillatory conditions related to local and inter-area electromechanical modes among synchronous generators have dominated this stability [2].
Since the N-1-contingency condition can emerge suddenly, it is crucial to assess its impact upon small-signal stability. The N-1-contingency condition requires the system to be able to tolerate any perturbation without failure [3]. This condition is related to the failure of the power-system components such as the generator, transformer, and transmission line. In this paper, loss of the transmission line is considered as an N-1-contingency condition. Moreover, this failure condition may significantly impact small-signal stability for tasks such as loss-power transfer and result in partial or full blackout of the system.

Conventionally, this stability is primarily ensured by adding damper windings to the system and installing a PSS in the exciter. The PSS has shown good performance over the last decade in improving the small-signal stability of power systems. However, with the emergence of an N-1-contingency condition, conventional PSS is insufficient. Hence, a nature-inspired method can be considered in the design of the PSS.

The metaheuristic algorithm is inspired by nature to solve complex problems. This algorithm can be categorized into three parts: physically based inspiration, socially based inspiration, and biologically based inspiration [4]. For this type of metaheuristic algorithm, biologically based inspiration has become very attractive in recent years. Genetic algorithms (GAs), particle-swarm optimization (PSO), and differential-evolution algorithms (DEAs) are all considered to be biologically inspired.

Many papers have been published in the field of PSS-parameter tuning using a metaheuristic algorithm. A GA-based method for tuning the PSS parameter was presented in [5]. Parameter optimization of the PSS based on PSO was presented in [6]. Application of honey-bee-mating optimization was reported in [7]. DEAs can also be used as intelligent methods to optimize PSS parameters, as reported in [8]. Recently, a cuckoo search algorithm (CSA) method has been applied to solve the optimization problem, and has shown good performance [9]. The CSA is a metaheuristic method inspired by the behavior or daily breeding habits of cuckoo birds, as developed by Xin-She Yang in 2013 [10].

This paper applied the CSA to enhancing the small-signal stability of a power system under the N-1-contingency condition. The rest of this paper is organized as follows: section II briefly explains the fundamental theory of small-signal stability, as well as the dynamic model of the power system used to study this stability and to model the power-system stabilizer. The methodology comprising the CSA and tuning procedure is described in section III. Section IV shows the results and discussion of the damping, placement index, and eigenvalue of the critical, local, and inter-area modes of the test system with intelligent PSS based on CSA.

Comparison of the time-domain simulation of cases without PSS, with conventional PSS, and with intelligent PSS based on CSA are also presented in section IV. Section V highlights the conclusions, contributions, and future direction of this research.

Fundamental Theory.
Small-signal stability. Small-signal stability is the ability of a power system to find new operating conditions after being exposed by small disturbances [11]. This instability emerges due to a lack of damping and synchronization torque. If this stability is not well maintained, it may increase oscillatory behavior, leading to an unstable condition and eventual blackout [12]. The blackouts in US in August 2003 and in India in July 2012 were due to a low small-signal stability [13].

Small-signal stability can be categorized into two phenomena, one local and one global. The local phenomenon is related to the interaction between small parts of the power system and the system as a whole in one power station. The oscillation frequency of this phenomenon is around 0.7-2 Hz [12]. The global phenomenon, meanwhile, which is usually called the inter-area oscillation, corresponds to the interaction between a large number of power stations. Generally, this problem has an oscillation frequency of around 0.1-0.7 Hz [12].

Power-system model. The power system can be represented as a set of differential and algebraic equations as in (1) and (2) [12]:

\[
\dot{x} = f(x, y, l, p)
\]

\[
0 = g(x, y, l, p)
\]

Here, \(x\) and \(y\) are the stated variable and the algebraic variation, whereas \(l\) and \(p\) are uncontrollable and controllable parameters. The power system can be studied in two different ways depending on one’s research interest. If one aims to capture the dynamic behavior of the local phenomenon, then a power system connected to an infinite bus can be used. On the other hand, if one wishes to capture local and global problems, then a realistic model of the power system, called the multimechanism power system, can be studied [12].

Generator modeling. In this research, a generator model based on Park’s transformation is used. Park’s transformation projects the magnitude of the generator onto three axes: the direct axis, the quadrature axis, and the stationary axis. Representation of the generator in the DQ model can be expressed in (3) [14, 15]. Here, \(V_d\) and \(V_q\) are the stator voltages along the d and q axes, \(V_r\) is the rotor-field voltage, \(V_D\) and \(V_Q\) is the rotor voltages along the d and q axes, \(r\) is the stator resistance, \(L_d\) and \(L_q\) are the rotor inductances along the d and q axes, \(\lambda_{q0}\) and \(\lambda_{d0}\) are the initial flux along the d and q axes, k\(_{Me}\) is...
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\[
\begin{bmatrix}
\Delta i_d \\
\Delta i_q \\
\frac{1}{T_m} \\
\Delta \omega
\end{bmatrix}
= 
\begin{bmatrix}
r & 0 & 0 & a_k M_d q & a_k M_d Q & \lambda_0 & 0 \\
0 & r_F & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 & -1
\end{bmatrix}
\begin{bmatrix}
\Delta i_d \\
\Delta i_q \\
\Delta \omega
\end{bmatrix}
\]

Power-system Stabilizer. PSSs are widely used in power systems to enhance the small-signal stability. A PSS is used as an excitation-system controller to provide damping. To produce damping components, the PSS produces electrical torque according to the rotor-speed deviation [17]. Figure 3 shows a block diagram of the PSS.

2. Methods

Cuckoo search algorithm. The cuckoo search algorithm is a metaheuristic algorithm method inspired by the breeding behavior of cuckoo birds; Xin-She Yang and Deb developed this method. This algorithm can be utilized in an optimization problem to determine a globally optimal value [18-22]. Fig. 4 illustrates the breeding of cuckoo birds, while Table 1 shows pseudo code for the CSA [18-22].

When new solutions \( x(t + 1) \) are generated for a cuckoo \( i \), a mathematical representation of levy flight is shown in (4): [18-22].

\[
x_i^{(t+1)} = x_i^{(t)} + \alpha \odot \text{Levy}(\lambda).
\]

Here, \( \alpha > 0 \) measures the stages that should be related to the scale of the problem of interest [18-22]. In most cases, \( \alpha = 1 \). The levy flight, which essentially gives a random way when the length is taken from the random phase distribution Levy is described in (5) [18-22].

\[
\text{Levy} \sim u = t^{1/\lambda}, (1 < \lambda \leq 3)
\]

Tuning and placement procedure. In general, the number of PSSs installed in the power system does not equal the number of generators and the minimum number

![Figure 1. Exciter-Block Diagram [14-16]](image1)

![Figure 2. Governor Modeling [14-17]](image2)

![Figure 3. Block Diagram of the PSS [17]](image3)

![Figure 4. Process of the Cuckoo Algorithm](image4)
Table 1. Pseudo Code of the Cuckoo Search Algorithm [18-22]

Begin
  objective function \( f(x), x = (x_1, ..., x_T) \)
  Initialize the population of the target bird nest \( n \) \( x_i \) \( (i = 1, 2, ..., n) \)
  While \( (t < \text{generasi total}) \) or (other criteria to stop)
    Evaluation of the quality values of each cuckoo cuckoo
    Choose from randomly and do a random walk
  End While
End If
  Replace cuckoo \( j \) with \( i \)
  re Reset nests with the worst conditions (Pa)
  Save nests that survived sort and find the best solutions
End While
process results and visualization
end

Table 2. Cuckoo Search Algorithm

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nests</td>
<td>100</td>
</tr>
<tr>
<td>Discovery Rate of Alien Eggs/Solutions</td>
<td>10</td>
</tr>
<tr>
<td>Tolerance</td>
<td>1.0^3</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>70</td>
</tr>
<tr>
<td>Beta</td>
<td>1.5</td>
</tr>
<tr>
<td>Max Generation</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3. Constraints on the PSS Parameters

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( k_{pss} )</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>( T_1 )</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>( T_2 )</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>( T_3 )</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>( T_4 )</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>( T_w )</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Representation-procedures Optimization

of PSSs is half of the number of generators. Moreover, given the interaction between PSSs, it is important to choose the proper placement and tuning of the PSS. Suppose that a PSS \( m \) is installed on generator \( N \). Then, there will be 8-15 PSSs installed on each generator. Using the placement-table index, all possible placements of the PSS will be displayed. Thus, the placement-restriction index is based on the following equation.

The objective function used maximizes the minimum damping \( (\xi_{\text{min}}) \) for any combination of PSS placements stored in the comprehensive damping index (CDI) [14, 17]:

\[
\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}};
\]

\[
\text{CDI} = \sum_{i=1}^{\text{no.}} (1 - \xi_i).
\]

Here, \( \lambda_i \) is the \( i \)-th eigenvalue and \( \varphi_i \) is its real component. For each placement index, the minimum value of the damping ratio will be evaluated by an intelligent method proposed using the CSA. Then, based on the best placement PSS \( \xi_\text{min} \) maximum value greater than \( \xi_0 \). Figure 5 shows the tuning-parameter-optimization procedure of PSS. Table 2 shows the CSA parameters and Table 3 illustrates the constraints of PSS parameters. Here, the constraint for the \( K_{pss} \) constant ranges from 0 to 50, \( T_1 \) and \( T_2 \) range from 0 to 0.05, \( T_3 \) ranges from 0 to 1, and \( T_4 \) ranges from 0 to 2.

3. Results and Discussion

In this research, case studies were carried out in the MATLAB/SIMULINK environment. The test system is the “Sulselrabar” multi-machine power system operating at 150 kV. A modification was made to the system by eliminating the line between the Sidrap (28) and Maros (29) buses to simulate the condition of the N-1 contingency. Figure 6 shows a one-line diagram of the investigated system. This system comprises 16 power plants, 37 buses, and 46 transmission lines. In this research, each power plant was presented using a nine-order model with an exciter and governor. The Sidrap (28) and Maros (29) buses are selected because these channels connect the largest load centers, such as Makassar, Maros, Barru, and Sungguminasa. In practice, this channel experiences many dynamics when interference occurs; therefore, a study is required when the system is in the N-1 condition.

As reported in [17], the minimum number of PSSs installed in the system is half the number of the machines. Hence, not all machines have to have a PSS, thereby saving costs. Consideration of PSS placement is based on the smallest damping of the machine. Table 4 shows the damping of the Sulselrabar test system.
According to the table, the damping ratios of generators 1 to 7 and 12 to 15 had noticeably smaller damping ratios than generators 8 to 11 and 16. Hence, PSS was installed in that generator. Furthermore, the number of PSSs installed in the system was analyzed based on the objective function of the CSA.

Table 4 illustrates the placement index of the PSS. It was shown that the optimal number of PSSs was 14, as indicated by the higher CDI. Hence, this scenario (14 PSSs) was chosen. Moreover, the eigenvalues of the critical, local, and inter-area modes were investigated in this research.

Table 5 shows the eigenvalues of critical, local, and inter-area modes. It was noticeable that the investigated system had 8 local modes and 4 inter-area modes. It was also found that there were 4 critical modes. From the table, it was noticeable that the eigenvalues of the critical, local, and inter-area modes improved when PSSs were installed in the system. Moreover, the proposed PSS placement and tuning using CSA results in much better modes than the conventional method.

To validate the eigenvalue, time-domain simulations were carried out. To observe the response, a small load perturbation was applied to the Bakaru generator giving a 0.05-pu step input. Figures 7 to 8 illustrate time-domain simulation of the generator-rotor speed and the rotor angle of investigated system. The oscillatory conditions of all generators were observed to be more highly damped when PSSs were installed. It was also found that the highest damping was experienced when the PSS was placed and tuned using the CSA method, as indicated by a small overshoot and the fastest settling time, as shown in Table 6.

Figure 6. One-Line Diagram of the Sulselrabar Multimesin

Table 4. Placement Index of the PSSs

<table>
<thead>
<tr>
<th>Place</th>
<th>Kpss</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>$\xi_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>50.832</td>
<td>1.777</td>
<td>1.139</td>
<td>2.428</td>
<td>3.886</td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>43.010</td>
<td>3.321</td>
<td>2.115</td>
<td>1.774</td>
<td>2.259</td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>61.676</td>
<td>1.833</td>
<td>2.338</td>
<td>2.990</td>
<td>2.705</td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>48.752</td>
<td>0.570</td>
<td>3.256</td>
<td>1.035</td>
<td>0.634</td>
<td></td>
</tr>
<tr>
<td>G5</td>
<td>70.665</td>
<td>3.910</td>
<td>3.444</td>
<td>2.365</td>
<td>2.362</td>
<td></td>
</tr>
<tr>
<td>G6</td>
<td>9.9818</td>
<td>1.046</td>
<td>2.217</td>
<td>3.194</td>
<td>3.314</td>
<td></td>
</tr>
<tr>
<td>G7</td>
<td>69.356</td>
<td>0.788</td>
<td>2.212</td>
<td>1.910</td>
<td>2.303</td>
<td></td>
</tr>
<tr>
<td>G8</td>
<td>67.473</td>
<td>3.762</td>
<td>1.757</td>
<td>0.514</td>
<td>3.763</td>
<td></td>
</tr>
<tr>
<td>G9</td>
<td>60.074</td>
<td>3.217</td>
<td>2.717</td>
<td>2.878</td>
<td>0.658</td>
<td></td>
</tr>
<tr>
<td>G10</td>
<td>42.933</td>
<td>2.799</td>
<td>1.299</td>
<td>1.634</td>
<td>1.006</td>
<td></td>
</tr>
<tr>
<td>G11</td>
<td>96.353</td>
<td>0.771</td>
<td>3.557</td>
<td>0.140</td>
<td>3.400</td>
<td></td>
</tr>
<tr>
<td>G12</td>
<td>18.304</td>
<td>2.570</td>
<td>3.798</td>
<td>2.050</td>
<td>3.318</td>
<td></td>
</tr>
<tr>
<td>G13</td>
<td>30.540</td>
<td>0.119</td>
<td>1.720</td>
<td>2.521</td>
<td>1.669</td>
<td></td>
</tr>
<tr>
<td>G14</td>
<td>36.881</td>
<td>1.054</td>
<td>3.038</td>
<td>3.352</td>
<td>3.652</td>
<td></td>
</tr>
</tbody>
</table>

14 PSS
Table 5. Critical Eigenvalue

<table>
<thead>
<tr>
<th></th>
<th>No PSS 1.0e + 02*</th>
<th>Conv. PSS 1.0e + 02*</th>
<th>PSS Cuckoo 1.0e + 02*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Eigenvalue</td>
<td>−0.3056 ± 4.6945i</td>
<td>−0.3056 ± 4.6945i</td>
<td>−0.3057 ± 4.6946i</td>
</tr>
<tr>
<td></td>
<td>−0.3150 ± 4.5305i</td>
<td>−0.3150 ± 4.5305i</td>
<td>−0.3228 ± 4.5283i</td>
</tr>
<tr>
<td></td>
<td>−0.1965 ± 4.3135i</td>
<td>−0.1965 ± 4.3135i</td>
<td>−0.2000 ± 4.3238i</td>
</tr>
<tr>
<td></td>
<td>−0.2594 ± 4.1886i</td>
<td>−0.2620 ± 4.1920i</td>
<td>−0.2723 ± 4.2056i</td>
</tr>
<tr>
<td></td>
<td>−0.0033 ± 0.0410i</td>
<td>−0.0032 ± 0.0415i</td>
<td>−0.0457 ± 0.6854i</td>
</tr>
</tbody>
</table>

Figure 7. Speed Deviation (Δω) of the Bakaru Generator in the N-1 Condition

Figure 8. Rotor-Angle Variation of Bakaru Generator in the N-1 Condition
Table 6. Overshoot Speed Deviation of Each Generator

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>No PSS</th>
<th>Conv. PSS</th>
<th>PSS Cuckoo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakaru</td>
<td>0.004239 &amp; −0.02253</td>
<td>0.002973 &amp; −0.01922</td>
<td>1.91e-05 &amp; −0.01016</td>
</tr>
<tr>
<td>Pinrang</td>
<td>0.006399 &amp; −0.02098</td>
<td>0.003297 &amp; −0.01784</td>
<td>2.195e-05 &amp; −0.01056</td>
</tr>
<tr>
<td>Pare-parie</td>
<td>0.00454 &amp; −0.02134</td>
<td>0.003035 &amp; −0.01878</td>
<td>1.867e-05 &amp; −0.00997</td>
</tr>
<tr>
<td>Suppa</td>
<td>0.006103 &amp; −0.02145</td>
<td>0.004299 &amp; −0.0189</td>
<td>0.0001509 &amp; −0.01878</td>
</tr>
<tr>
<td>Baru</td>
<td>0.03362 &amp; −0.07853</td>
<td>0.02094 &amp; −0.06397</td>
<td>0.0001568 &amp; −0.02181</td>
</tr>
<tr>
<td>Telo</td>
<td>0.05331 &amp; −0.2063</td>
<td>0.04901 &amp; −0.2023</td>
<td>0.04482 &amp; −0.1979</td>
</tr>
<tr>
<td>Tello lama</td>
<td>0.09116 &amp; −0.2222</td>
<td>0.000209 &amp; −0.151</td>
<td>0.0002981 &amp; −0.09895</td>
</tr>
<tr>
<td>Sgemnsa</td>
<td>0.007957 &amp; −0.05755</td>
<td>0.0001402 &amp; −0.0486</td>
<td>3.864e-05 &amp; −0.03697</td>
</tr>
<tr>
<td>Jeneponto</td>
<td>0.005942 &amp; −0.02494</td>
<td>0.003136 &amp; −0.02239</td>
<td>0.00344 &amp; −0.0219</td>
</tr>
<tr>
<td>Bulukumba</td>
<td>0.00951 &amp; −0.02347</td>
<td>0.0065 &amp; −0.02064</td>
<td>0.0001972 &amp; −0.01108</td>
</tr>
<tr>
<td>Soppeng</td>
<td>0.01072 &amp; −0.02279</td>
<td>0.0038 &amp; −0.01707</td>
<td>6.816e-05 &amp; −0.0132</td>
</tr>
<tr>
<td>Sengkang</td>
<td>0.004841 &amp; −0.02482</td>
<td>0.003244 &amp; −0.02196</td>
<td>2.906e-05 &amp; −0.01318</td>
</tr>
<tr>
<td>Makale</td>
<td>0.01572 &amp; −0.0218</td>
<td>0.01056 &amp; −0.01795</td>
<td>0.002168 &amp; −0.0124</td>
</tr>
<tr>
<td>Palopo</td>
<td>0.01744 &amp; −0.0222</td>
<td>0.01299 &amp; −0.01911</td>
<td>0.002876 &amp; −0.01261</td>
</tr>
<tr>
<td>Borongloe</td>
<td>0.01621 &amp; −0.06826</td>
<td>0.008078 &amp; −0.06077</td>
<td>0.003017 &amp; −0.05255</td>
</tr>
</tbody>
</table>

Under N-1 conditions, the function used by the computing algorithm serves to maximize minimum attenuation ($\zeta_{\text{min}}$). The combination of the placement of 14 PSSs on each of the Sulserabar system generators is based on the following equation (6):

$$\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}.$$  \hspace{1cm} (6)

The cuckoo algorithm proposed in this research finds the optimal value of the PSS parameter in the N-1 condition based on the objective used equation (7):

$$CDI = \sum_{i=1}^{n} (1 - \zeta_i).$$  \hspace{1cm} (7)

The minimum value of damping was evaluated using the CSA. Then, the best placement of PSSs in the N-1 condition with a maximum value $\zeta_{\text{min}}$ higher than $\zeta_0$ was obtained from the results. After the optimal PSS placement was determined based on the damping values of each probability in the N-1 condition, the system’s responses to frequency deviation and the rotor angle of each generator were observed analyzed. Eigenvalues and overshoot were also used for comparison with other methods. The linear system model in the N-1 condition was subjected to various demand disturbances as an input with a load of 0.05 pu toward Generator Slack of PLTA Bakaru. Due to changes in loads, there were changes to the sides of loads which caused $P_m < P_e$, causing the frequency of the generator to be reduced to the N-1 condition. Meanwhile, when $P_e > P_m$, the rotor would slow down, and the rotor angle’s response became negative:

$$MW = P_m - P_e - DF.$$  \hspace{1cm} (8)

Figure 7 above shows the frequency response of the bakaru generator, and Fig. 8 shows the rotor angle response in the N-1 condition after the load increase in the Bakaru generator. The overall response of each generator is shown in Table 6. The graph also showed the small frequency of overshoot’ responses using the optimal PSS parameter compared to tuning by using the conventional method and uncontrolled system/open loop in N-1 condition.

4. Conclusions

This paper investigated the placement and tuning of PSSs under the N-1 contingency. In the investigated system, the number of PSSs was found to be proportional to the damping of the system. It was also shown that a CSA may be used to optimize the PSS parameters under the N-1 contingency. Further research is required to analyze the small-signal stability in the present of high penetration of renewable energy resources under normal or N-1 contingency. The PSS parameters were optimized based on the objective function to maximize the minimum damping ($\zeta_{\text{min}}$).

From the analytical results of the N-1 contingency condition, optimal tuning of PSS parameters was obtained and resulted in PSS placements on generators 1 to 7 and 12 to 15, producing a minimum damping of 0.611.

References


