

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.

Abstrak

Peningkatan Kestabilan Sinyal Kecil Menggunakan Power System Stabilizer Berbasis Algoritma Burung Cuckoo pada Kontingensi N-1 Sistem 150 kV Sulselrabar. Stabilitas sinyal kecil adalah salah satu faktor utama yang membatasi transmisi daya dalam sistem tenaga konvensional. Penanganan stabilitas ditangani dengan menambahkan *Damper Winding* pada generator sinkron dan Power System Stabilizer (PSS). Namun, karena dampak kontingensi N-1, *Damper Winding* dan PSS konvensional tidak cukup untuk mengatasi masalah ini. Penempatan dan desain PSS yang tepat sangat penting untuk meningkatkan kontribusinya terhadap stabilitas. Salah satu pendekatan untuk mengoptimalkan penempatan dan penyetelan PSS adalah menggunakan metode kecerdasan buatan. Dalam tulisan ini, Cuckoo search algorithm (CSA) diusulkan untuk menyelesaikan optimalisasi tuning dan penempatan PSS. Dari hasil simulasi, ditemukan bahwa PSS berdasarkan CSA dapat meningkatkan stabilitas sinyal kecil dari sistem. Critical mode, lokal dan inter-area dari sistem yang diteliti meningkat secara signifikan. Kondisi osilasi lebih teredam ditunjukkan oleh overshoot kecil dan waktu penyelesaian yang lebih cepat. Ditemukan juga bahwa CSA dapat menjadi metode untuk menyetel parameter PSS di bawah N-1 kontingensi. Dari hasil analisis kondisi kontingensi N-1, penyetelan parameter PSS optimal diperoleh, dan menghasilkan opsi penempatan PSS pada generator 1 hingga 7, dan 12 hingga 15, yang menghasilkan redaman minimum 0,611.

Keywords: acetylide, conductivity, IDE, semiconductor, thiourea

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 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]:

$$\dot{x} = f(x, y, l, p) \quad (1)$$

$$0 = g(x, y, l, p) \quad (2)$$

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 multi-machine 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_F 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, λ_{q0} and λ_{d0} are the initial flux along the d and q axes, kM_F is

$$\begin{bmatrix} \Delta v_d \\ -\Delta v_F \\ 0 \\ \Delta v_q \\ 0 \\ \Delta T_m \\ 0 \end{bmatrix} = - \begin{bmatrix} r & 0 & 0 & \omega_0 L_q & \omega_0 k M_Q & \lambda_{q0} & 0 \\ 0 & r_F & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 & 0 & 0 \\ -\omega_0 L_d & -\omega_0 k M_F & -\omega_0 k M_D & r & 0 & -\lambda_{d0} & 0 \\ 0 & 0 & 0 & 0 & r_Q & 0 & 0 \\ \frac{\lambda_{q0} - L_d i_{q0}}{3} & \frac{-k M_F i_{q0}}{3} & \frac{-k M_D i_{q0}}{3} & \frac{-k M_Q i_{d0}}{3} & \frac{k M_Q i_{d0}}{3} & -D & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_F \\ \Delta i_D \\ \Delta i_q \\ \Delta i_Q \\ \Delta \omega \\ \Delta \delta \end{bmatrix} - \begin{bmatrix} L_d & k M_F & k M_D & 0 & 0 & 0 & 0 \\ k M_F & L_F & M_R & 0 & 0 & 0 & 0 \\ k M_D & M_R & L_D & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_q & k M_Q & 0 & 0 \\ 0 & 0 & 0 & k M_Q & L_Q & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\tau_j & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_F \\ \Delta i_D \\ \Delta i_q \\ \Delta i_Q \\ \Delta \omega \\ \Delta \delta \end{bmatrix} \quad (3)$$

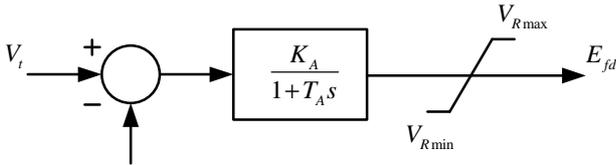


Figure 1. Exciter-Block Diagram [14-16]

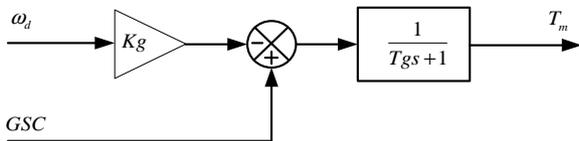


Figure 2. Governor Modeling [14-17]

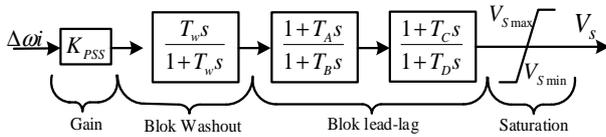


Figure 3. Block Diagram of the PSS [17]

the rotating magnetic field, M_D and M_Q are the mutual inductances, Δi_d and Δi_q are the stator currents along the d and q axes, Δi_F is the rotor-field current, Δi_D and Δi_Q are the rotor currents along the d and q axes, $\Delta \omega$ is the generator-speed change, and $\Delta \delta$ is the generator rotor-angle change.

Exciter modeling. The function of an excitation system is to regulate the generator-output variables. For small-signal-stability analysis, the excitation system can be represented as a first-order delay with a gain constant. This is called the fast-exciter model. Figure 1 shows a block diagram of the fast-exciter model for this research [14, 15].

Governor modeling. The purpose of the governor is to regulate the mechanical torque of the generator. The fluctuation of mechanical torque in the governor corresponds to the generator speed, load variation, and speed-reference variation. Figure 2 illustrates a block diagram of the governor [14-16].

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].

$$x_i^{(t+1)} = x_i^{(t)} + \alpha \oplus Levy(\lambda). \quad (4)$$

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].

$$Levy \sim u = t^\lambda, (1 < \lambda \leq 3) \quad (5)$$

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 4. Process of the Cuckoo Algorithm

Table 1. Pseudo Code of the Cuckoo Search Algorithm [18-22]

```

Begin
  objective function  $f(x)$ ,  $x = (x_1, \dots, x_n)^T$ 
  Initialize the population of the target bird nest  $n_i$  ( $i = 1, 2, \dots, n$ )

  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

  if ( $F_i > F_j$ )
    Replace cuckoo  $j$  with  $i$ 

  End If
  re Reset nests with the worst conditions ( $P_a$ )
  Save nests that survived sort and find the best solutions

  End While
  process results and visualization
end
  
```

Table 2. Cuckoo Search Algorithm

Parameters	Values
Number of Nests	100
Discovery Rate of Alien Eggs/Solutions	10
Tolerance	1.0^{-5}
Number of Parameters	70
Beta	1.5
Max Generation	50

Table 3. Constraints on the PSS Parameters

No	Parameter	Lower Limit	Upper Limit
1	K_{pss}	10	50
2	T_1	0	0.05
3	T_2	0	0.05
4	T_3	0	1
5	T_4	0	2
6	T_w	10	

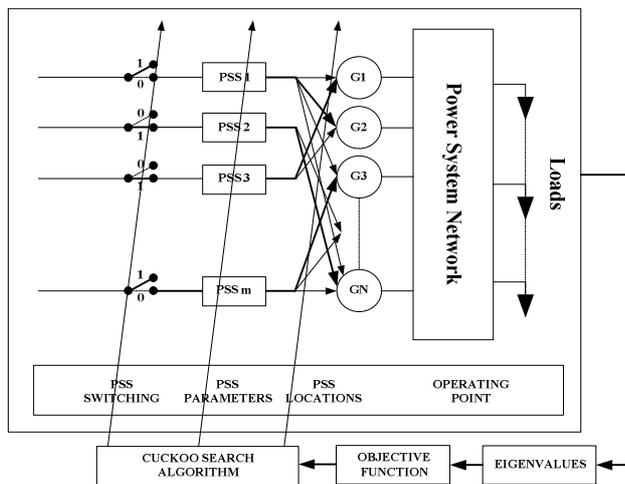


Figure 5. Representation-procedures Optimization

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 (ζ_{\min}) for any combination of PSS placements stored in the comprehensive damping index (CDI) [14, 17]:

$$\xi_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}; \quad (6)$$

$$CDI = \sum_{i=1}^n (1 - \xi_i). \quad (7)$$

Here, λ_i is the i -th eigenvalue and σ_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 ζ_{\min} maximum value greater than ζ_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 ‘‘Sulselbar’’ 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 Sulselbar test system.

According to the table, the damping ratios of generators 1 to 7 and 12 to15 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 show 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.

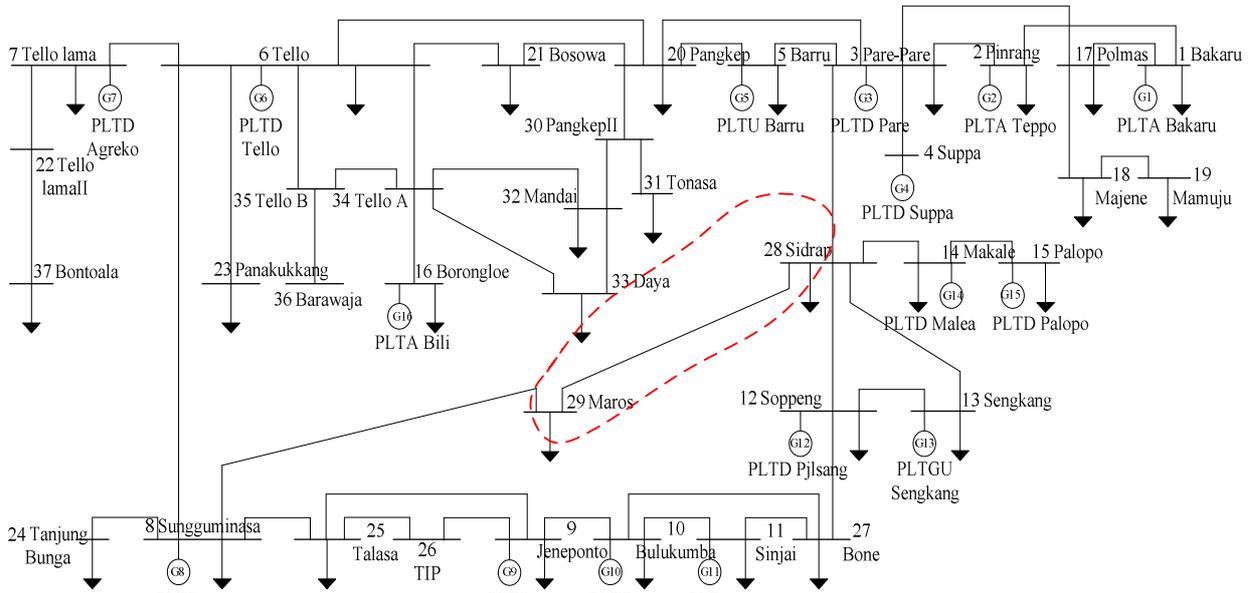


Figure 6. One-Line Diagram of the Sulselrabar Multimesin

Table 4. Placement Index of the PSSs

	Place	Kpss	T1	T2	T3	T4	ξ_{min}
14 PSS	G1	50.832	1.777	1.139	2.428	3.886	0.611
	G2	43.010	3.321	2.115	1.774	2.259	
	G3	61.676	1.833	2.338	2.990	2.705	
	G4	48.752	0.570	3.256	1.035	0.634	
	G5	70.665	3.910	3.444	2.365	2.362	
	G6	9.9818	1.046	2.217	3.194	3.314	
	G7	69.356	0.788	2.212	1.910	2.303	
	G8	67.473	3.762	1.757	0.514	3.763	
	G10	59.074	3.217	2.717	2.878	0.658	
	G11	42.933	2.799	1.299	1.634	1.006	
	G12	96.353	0.771	3.557	0.140	3.400	
	G13	18.504	2.570	3.798	2.050	3.318	
	G14	30.540	0.119	1.720	2.521	1.669	
	G15	36.881	1.054	3.038	3.352	3.652	

Table 5. Critical Eigenvalue

No PSS (1.0e + 02*)	Conv. PSS (1.0e + 02*)	PSS Cuckoo (1.0e + 02*)
-0.3056 ± 4.6945i	-0.3056 ± 4.6945i	-0.3057 ± 4.6946i
-0.3150 ± 4.5305i	-0.3150 ± 4.5305i	-0.3228 ± 4.5283i
-0.1965 ± 4.3135i	-0.1965 ± 4.3135i	-0.2000 ± 4.3238i
-0.2594 ± 4.1886i	-0.2620 ± 4.1920i	-0.2723 ± 4.2056i
-0.0033 ± 0.0410i	-0.0032 ± 0.0415i	-0.0457 ± 0.6854i

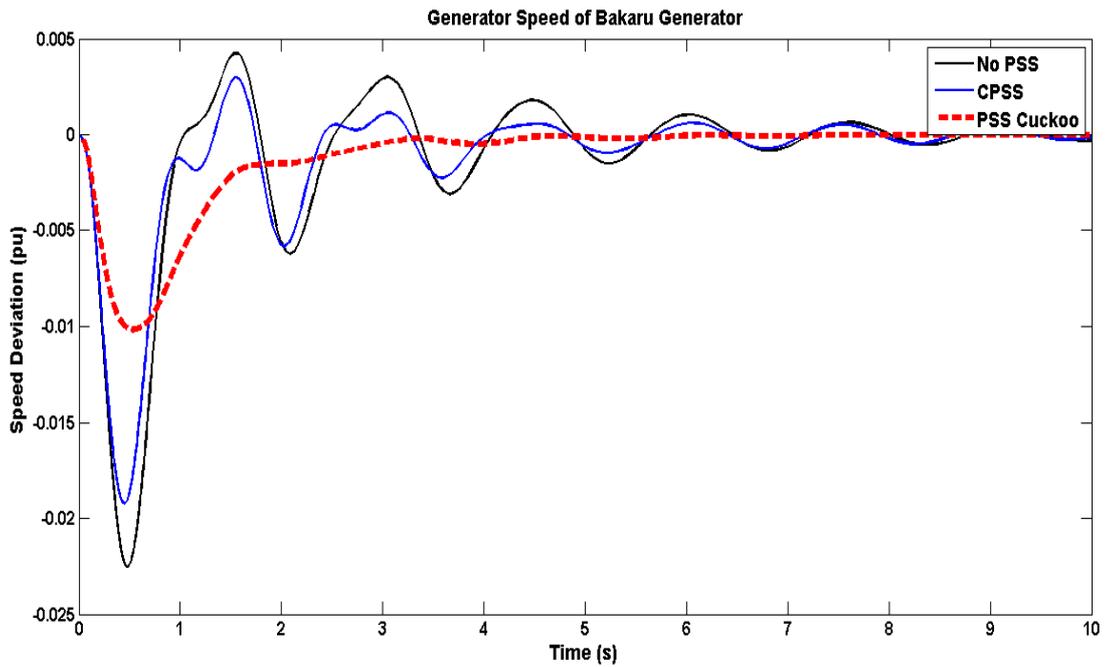


Figure 7. Speed Deviation ($\Delta\omega$) of the Bakuru Generator in the N-1 Condition

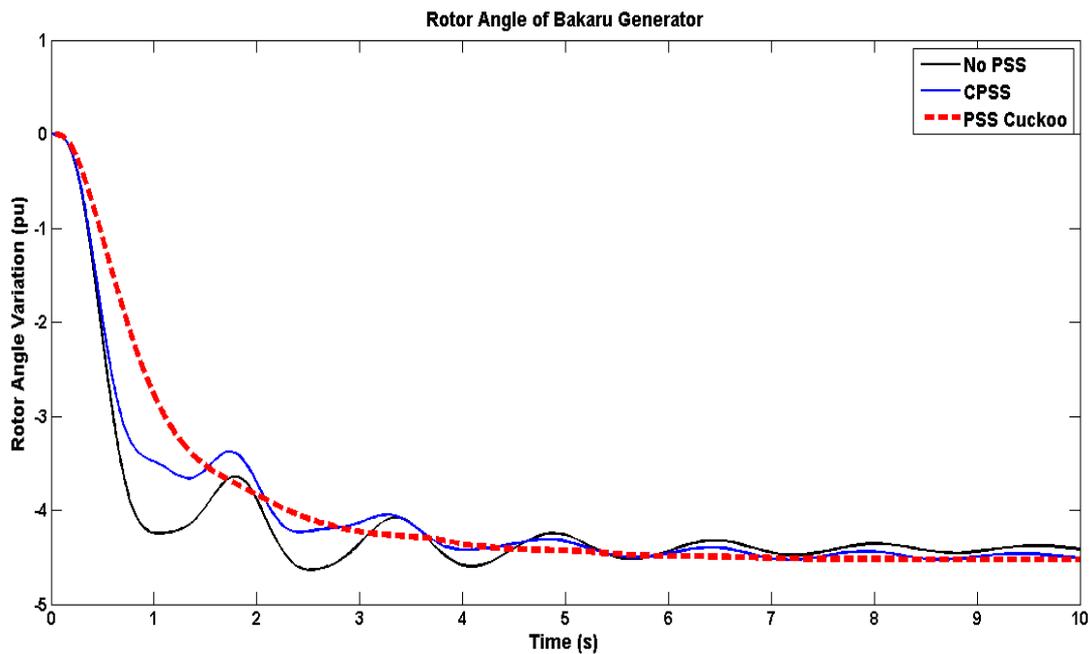


Figure 8. Rotor-Angle Variation of Bakuru Generator in the N-1 Condition

Table 6. Overshoot Speed Deviation of Each Generator

Power Plant	No PSS	Conv. PSS	PSS Cuckoo
Bakaru	0.004239 & -0.02253	0.002973 & -0.01922	1.91e-05 & -0.01016
Pinrang	0.006399 & -0.02098	0.003297 & -0.01784	2.195e-05 & -0.01056
Pare-pare	0.00454 & -0.02134	0.003035 & -0.01878	1.867e-05 & -0.0097
Suppa	0.006103 & -0.02145	0.004299 & -0.0189	0.0001509 & -0.01878
Barru	0.03362 & -0.07853	0.02094 & -0.06397	0.0001568 & -0.02181
Tello	0.05331 & -0.2063	0.04901 & -0.2023	0.04482 & -0.1979
Tello lama	0.09116 & -0.2222	0.000209 & -0.151	0.0002981 & -0.09895
Sgmnsa	0.007957 & -0.05755	0.0001402 & -0.0486	3.864e-05 & -0.03697
Jeneponto	0.005942 & -0.02494	0.003136 & -0.02239	0.00344 & -0.0219
Bulukumba	0.00951 & -0.02347	0.0065 & -0.02064	0.0001972 & -0.01108
Sinjai	0.01689 & -0.0249	0.01335 & -0.02206	1.72e-05 & -0.01248
Soppeng	0.01072 & -0.02279	0.0038 & -0.01707	6.816e-05 & -0.0132
Sengkang	0.004841 & -0.02482	0.003244 & -0.02196	2.296e-05 & -0.01318
Makale	0.01572 & -0.0218	0.01056 & -0.01795	0.002168 & -0.0124
Palopo	0.01744 & -0.0222	0.01299 & -0.01911	0.002876 & -0.01261
Borongloe	0.01621 & -0.06826	0.008078 & -0.06077	0.003017 & -0.05255

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

$$\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (6)$$

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):

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

The minimum value of damping was evaluated using the CSA. Then, the best placement of the PSSs in the N-1 condition with a maximum value ζ_{\min} higher than ζ_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 and 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:

$$M\dot{W} = P_m - P_e - DF \quad (8)$$

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 (ζ_{\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.

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