Modal Analysis and Stability Enhancement of 150 kV Sulselrabar Electrical System using PSS and RFB based on Cuckoo Search Algorithm

Muhammad Ruswandi Djalal[1], Herlambang Setiadi[2], Dwi Lastomo[3], and Muh. Yusuf Yunus[4]

[1,4]Department of Mechanical Engineering,
State Polytechnic of Ujung Pandang, Makassar, Indonesia
[2]School of Information Technology & Electrical Engineering,
The University of Queensland Brisbane, Australia
[3]Department of Automation Electrical Engineering,
Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.
[4]PUI-PT Mechatronics and Industrial Automation,
Research Center Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.
[1]wandi@poliupg.ac.id, [2]h.setiadi@uq.edu.au, [3]dtomo23@gmail.com,
[4]yusuf_yunus@poliupg.ac.id

Abstract: Small signal stability is one of the factor to assesst the reliability of a power system. Small signal stability is related to the ability of a power system to maintain synchronization after being exposed by small disturbance. In Indonesia, the reliability of power system is one of the important aspect that has to be achieved. However, very scant attention has been paid on studied small signal stability performance on Indonesia electricity. Hence, this paper studied the small signal stability analysis and its enhancement. 150 kV Sulselrabar interconnected power system is used as test system. To enhance the performance of the system designing coordinated controller of power system stabilizer (PSS) and redox flow batteries (RFB) using cuckoo search algorithm (CSA) is conducted. Eigenvalue, damping ratio, participation factor analysis, and time domain simulation is performed to assess the small signal stability performance and the successfulness of the CSA to optimize the PSS and RFB parameter. From the cases studies, it is found that 150 kV Sulselrabar has 12 local mode and 4 inter-area mode. Furthermore, the coordinated controller between PSS and RFB based on CSA could enhance the small signal stability performance of 150 kV Sulselrabar interconnected system indicated by higher damping, smallest overshoot and fastest settling time.

Keywords: Modal analysis, eigenvalue, damping ratio, participation factor, PSS, RFB, CSA

1. Introduction

Electrical energy has becoming a role vital in the daily activities of modern society. Every years there are a significant increase of electrical energy demand that drive the power provider to provide sufficient and qualified electrical energy. The increasing load demand every years has led to several problem in the stability of power system. One particular stability that can effected by increasing load demand is small signal stability.

Small signal stability or low frequency oscillation is the ability of power system to maintain stable condition after small perturbation occurs. This instability has frequency oscillation ranging from 0.1 to 2 Hz [1, 2]. If this instability is not handled properly, the oscillation may grow larger and lead to loss of synchronization of the interconnected system [3]. Generally, this instability can be handle by installing damper windings on the rotor of the generator. However, over the time the performance can be decreased. Hence, additional controller such as power system stabilizer (PSS) can be solution to handle small signal stability problems [4]. However, PSS alone is not enough to stabilize the low frequency oscillation when load demand increase significantly. Hence, additional device such as redox flow batteries (RFB) can be used as additional controller to enhance the system performance.

Received: February 27th, 2017. Accepted: December 30th, 2017
DOI: 10.15676/ijeei.2017.9.4.12

150 kV Sulselrabar interconnected power system is one of the largest interconnected power system in Sulewesi Island on Indonesia. Small signal stability problem is potentially emerges on 150 kV Sulselrabar interconnected power systems. However, very scant attention has been paid on studying small signal stability performance of 150 kV Sulselrabar. Hence, it is necessary to deeply investigate the small signal stability performance and also enhance the system performance. The biggest challenge in here is how to design optimal coordination of RFB and PSS in large interconnected system such as 150 kV Sulselrabar. Generally, designing PSS and RFB are based on traditional mathematical approach with high complexity. This the complexity of designing PSS and RFB becoming even worse when those devices installed in large system. Hence, it is essential to utilize intelligence method such as metaheuristic algorithm for designing PSS and RFB.

In the last decade, metaheuristic algorithm has shown a good performance for solving complex engineering problems. There are many type of metaheuristic algorithm that has been used on complex engineering problems such as genetic algorithm, particle swarm optimization, artificial immune system, differential evolution algorithm and bacteria foraging algorithm [5-10]. In recent years, there is new type of metaheuristic algorithm that has shown a good performance for solving complex engineering problems, this algorithm is called cuckoo search algorithm (CSA). This algorithm has shown a better performance than particle swarm optimization and genetic algorithm [11]. Hence the main contribution of this paper are:

- Investigate, the small signal stability performance on 150 kV Sulselrabar.
- Finding the electromechanical mode (EM) including the associated generator that contribute to the EM.
- Mitigation of low frequency oscillation using coordinate control between PSS and RFB based on CSA.

The rest of the paper is organized as follow: Section II provides modeling of synchronous generator, exciter, governor, PSS and fundamental theory of small signal stability. Section III briefly explain CSA and designing coordinate control of PSS and RFB using CSA. Modal analysis and time domain simulation are presented in section IV. Section V highlights the contribution, conclusions and future directions of the research.

2. Fundamental Theory

A. Generator, exciter and governor modeling

In small signal stability study, the most important thing is capturing the dynamic behavior of the system. Hence, transforming the non-linear model of synchronous generator to linear model is essential. The linear model of synchronous generator is given by (1), this mathematical representation can be derived through DQ transformation. The detailed procedure for transforming non-linear synchronous generator to linear model by using DQ transformation can be found in [12].

$$\begin{bmatrix} \Delta v_d \\ -\Delta v_F \\ 0 \\ \Delta v_q \\ 0 \\ \Delta T_m \\ 0 \end{bmatrix} = -\begin{bmatrix} r & 0 & 0 & \omega_0 L_q & \omega_0 kM_Q & \lambda_{q0} & 0 \\ 0 & r_F & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 & 0 & 0 \\ -\omega_0 L_d & -\omega_0 kM_F & -\omega_0 kM_D & r & 0 & -\lambda_{d0} & 0 \\ 0 & 0 & 0 & 0 & r_Q & 0 & 0 \\ \frac{\lambda_{q0}-L_d i_{q0}}{3} & \frac{-kM_F i_{q0}}{3} & \frac{-kM_D i_{q0}}{3} & \frac{-kM_Q i_{d0}}{3} & \frac{kM_Q i_{d0}}{3} & -D & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_F \\ \Delta i_D \\ \Delta i_q \\ \Delta i_Q \\ \Delta \omega \\ \Delta \delta \end{bmatrix} - \begin{bmatrix} L_d & kM_F & kM_D & 0 & 0 & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_Q & 0 & 0 \\ 0 & 0 & 0 & kM_Q & L_Q & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\tau_j & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \dot{i}_d \\ \Delta \dot{i}_F \\ \Delta \dot{i}_D \\ \Delta \dot{i}_q \\ \Delta \dot{i}_Q \\ \Delta \dot{\omega} \\ \Delta \dot{\delta} \end{bmatrix} \tag{1}$$

For small signal stability study, the excitation system can be simply modeled as first order differential equation consisting of gain and time constant as shown in Figure 1. Furthermore, the governor on power system can also be modeled as first order time delay with gain as illustrated in Figure 2 [13].

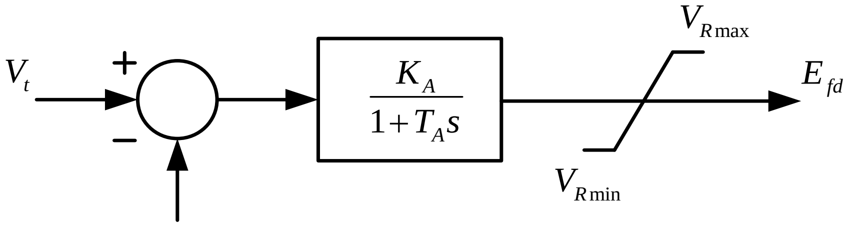

Figure 1. Exciter Block Diagram.

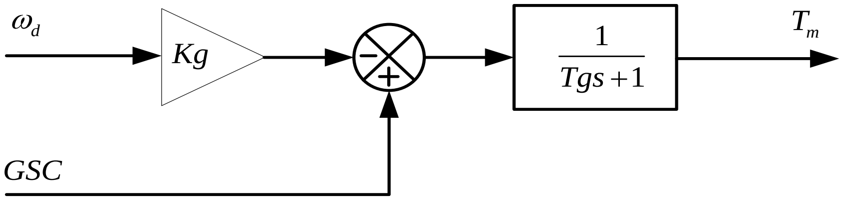

Figure 2. Governor Modelling.

B. Power System Stabilizer Modeling

Power system stabilizer (PSS) is additional controller in power system to mitigate oscillatory condition on power system. PSS is give additional signal to the excitation system to produce damping signals via electrical torque components. The input of PSS is rotor speed deviation while the output of PSS is additional control signal to the excitation system [14-17].

PSS consist of gain constant, washout process, lead lag process and saturation as shown in Figure. 3. The washout process modeled as first order time delay while the lead lag process comprises of second order differential equation [14-17].

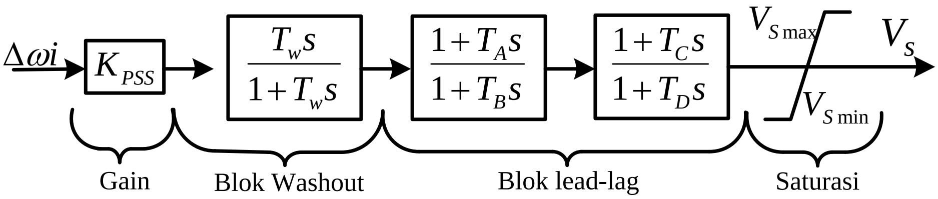

Figure 3. Block Diagram PSS.

C. Redox flow batteries modeling

Redox flow batteries (RFB) is one of the energy storage type that has becoming popular due to higher level capacity and quick response for providing active power to the system compared t the conventional battery. RFB is consisting of sulfuric acid with vanadium ion which are worked as negative and positive electrolytes ion. In this paper the purpose of RFB is providing active power to the grid by detecting rotor speed deviation of synchronous generator [18-20].

For small signal stability study, capturing dynamic model of RFB is crucial. The dynamic model of RFB can be presented as second-order differential equations as given in (2), while Figure. illustrates the schematic diagram of RFB. Where K_{ri} and T_{ri} are gain constant and time delay of the converter. ω and ΔP_{rfb} are rotor speed of generator and active power from the RFB, while K_{rfb} and T_{rfb} corresponded to the gain and time delay process of RFB [18-20].

$$\Delta P_{rfb} = \left\{ \omega \times K_{rfb} - \left(\frac{K_{ri}}{1+sT_{ri}} \right) \right\} \left(\frac{1}{1+sT_{di}} \right) \quad (2)$$

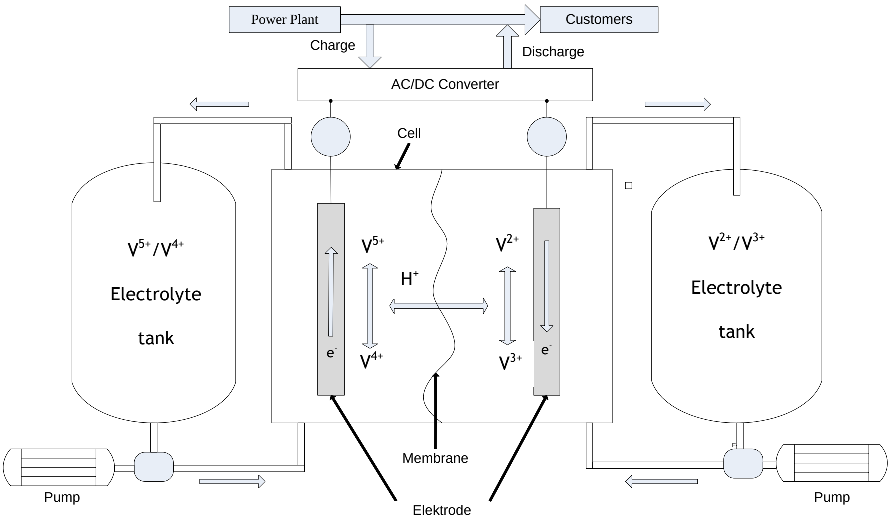

Figure 4. Schematic diagram of RFB.

D. Power system modeling

The dynamic characteristic of power system for low frequency oscillation study can be captured through differential and algebraic equation (DAE) as given in (3) and (4). In this study, multi-machine power system is considered to investigate the dynamic behaviors of local and inter-area modes [21, 22].

$$\dot{x} = f\left(x, y, u\right) \quad (3)$$

$$0 = g\left(x, y\right) \quad (4)$$

Where x and y corresponded to the state and algebraic variables respectively, while l and p related to the uncontrollable and controllable parameters. The load flow and other network parameter are included in algebraic equations, while machines and all others controller parameters are included on differential equations [21, 22].

E. Small signal stability

Small signal stability or low frequency oscillation is related to the ability of power system to remains on stable condition after being exposed by small perturbation. Small signal stability can be classified into two categorize namely local oscillation and global oscillation. Local oscillation is associated with the generator unit within a power plant with the rest of the system in that area with frequency ranging around 0.7-2 Hz. Global oscillation (inter-area mode) is related with generator unit in one area against generating units in another area, with typical frequency oscillation ranging from 0.1-0.7 Hz. Small signal stability analysis can be easily investigate through state space representation as given in (5) and (6) by linearizing equation (3) and (4) [23-25].

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (5)$$

$$\Delta y = C\Delta x + D\Delta u \quad (6)$$

Where Δx is a vector of state variables. Δy represents a vector of algebraic variables. Δu corresponded to the input vector. *A* and *B* are plant matrix and control or input matrix, respectively. While output matrix and feedforward matrix are denoted by *C* and *D*, respectively. Eigenvalue that can be calculated using (7), can be used to investigate the stability of the system [23-25].

$$\det\left(sI - A\right) = 0 \quad (7)$$

Where I is the identity matrix, and λ is eigenvalues of matrix A_{sys}. Moreover, complex eigenvalue carried information about frequency oscillation (f) and damping ratio (ξ) which can be described as given in (8), (9), and (10) [23-25].

$$\lambda_i = \sigma_i \pm j\omega_i \tag{8}$$

$$f_i = \frac{\omega_i}{2\pi} \tag{9}$$

$$\xi = \frac{-\sigma_i}{\sqrt{-\sigma_i^2 + -\omega_i^2}} \tag{10}$$

To investigate the contribution of particular state variables in a mode, participation factor analysis can be used. Participation factor can be determined using (11) [26, 27].

$$P_{ij} = \phi_{ij}\psi_{ij} \tag{11}$$

Where ϕ and ψ represent the right and left eigenvector, respectively. The product of right and left eigenvector provides dimensionless net participation of the state variables in a specific modes [26, 27].

3. Design PSS and RFB based on CSA

A. Cuckoo search algorithm

Cuckoo Search is a metaheuristic method inspired by the behavior / habits of daily living cuckoo in giving a birth. This method was developed by Xin-She Yang and Deb in 2009 and can be used as an optimization method to determine the global optimum value both minimum and maximum. There are four assumption in utilizing CSA as optimization method [28, 29]:

- Each cuckoo puts one egg at one time in a random nest.
- Each egg (including a nesting bird's egg) in the nest represent the solution, while the cuckoo bird egg represents a new solution. The goal is to use a new, better solution to replace a poor solution. If in one nest there is more than one cuckoo bird egg, this algorithm will be too broad and more difficult. Hence, each cuckoo parent just entrust one egg to the owner of the nest.
- The best nest with the best egg quality (solution) will survive until the next generation and became the set of solution.
- The number of nest targets has been fixed, and the owner of the nest can detect the foreign egg with the possibility 0 to 1. In this case, the owner of the nest may throw away the foreign egg or leave the nest and create a new nest.

Cuckoo has a unique behavior called levy flight that is not possessed by other bird. Levy flight can be presented as given in (12) with $\mu > 0$ is a minimum steps and γ is scale parameters [28, 29].

$$L(s,\gamma,\mu) = \begin{cases} \sqrt{\frac{\gamma}{2\pi}} \exp\left[-\frac{\gamma}{2(s-\mu)^{3/2}}\right]\frac{1}{(s-\mu)^{3/2}}, 0 < \mu < s < \infty \\ 0 \end{cases} \tag{12}$$

B. Tuning PSS and RFB procedure

Figure 5 shows the research flowchart, in this paper, the CSA is used as method for designing optimal coordination of PSS and RFB. Comprehensive damping index (CDI) is used as CSA objective function with minimum and maximum value of PSS and RFB parameter as the constraint. This objective function can be presented as given in (13), while the maximum and minimum value of PSS and RFB parameter is given on Table 1 [30].

$$CDI = \sum_{i=1}^{n}(1-\xi_i) \tag{13}$$

Table 1. Constraint of PSS and RFB parameters

No	Parameter	Lower Limit	Upper Limit
1	K_{rfb}	10	100
2	K_{pss}	10	50
3	T_1	0	0.05
4	T_2	0	0.05
5	T_3	0	1
6	T_4	0	2
7	Tw	10	

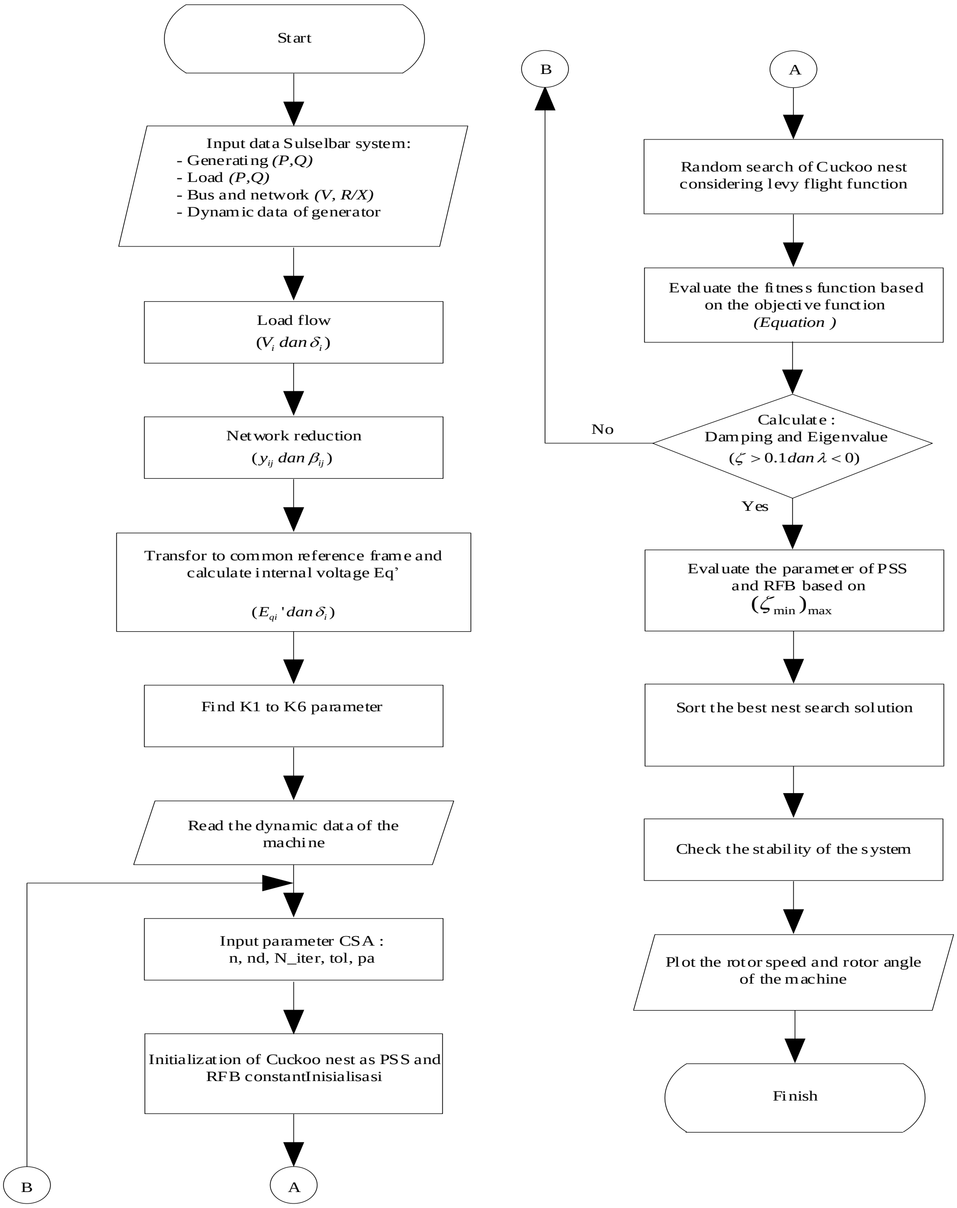

Figure 5. Research flowchart.

4. Results and Simulations

Two case studies is reported in this paper in an attempt to investigate the small signal stability performance and its enhancement using coordinated control of PSS and RFB. The case studies are carried using MATLAB/SIMULINK environment. 150 kV Sulselrabar interconnected power system is considered as a test system, the detailed parameter of 150 kV Sulselrabar can be found in [31]. The system consists of sixteen generator bus and 21 load bus as shown in Figure. 6, each generator modeled into ninth order model with exciter and governor. Hence, the total state variables in this system is one hundred and forty four state variables.

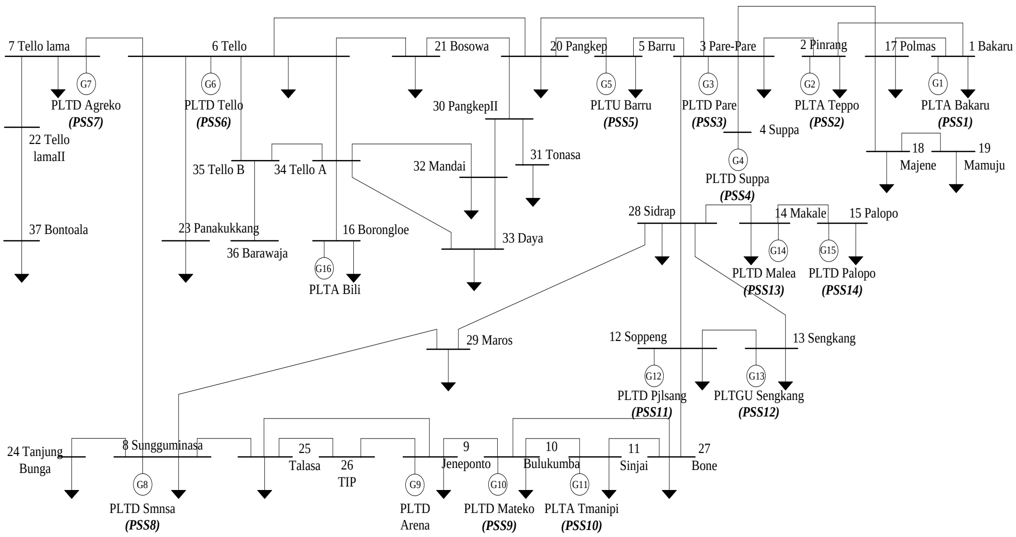

Figure 6. The one line diagram of 150 kV Sulselrabar

A. Case study 1

Table 2. Electromechanical mode of 150 kV Sulselrabar.

Mode	Eigenvalue	Damping (%)	Frequency (Hz)	Participation Factor
Inter-area 1	-0.3298±4.0807i	8.06	0.6495	G2G4G5G10G11G12G13G14G15
Inter-area 2	-0.4462±4.6039i	9.65	0.7327	G9G10G11G14G15
Inter-area 3	-0.5050±4.5408i	11.05	0.7227	G5G7G14G15
Inter-area 4	-0.5121±4.5346i	11.22	0.7217	G5G6G14G15
Local 1	-1.0027±9.4221i	10.58	1.4996	G1G3
Local 2	-1.0063±8.4356i	11.85	1.3536	G1G2G3G4G13
Local 3	-1.0503±7.0818i	14.67	1.1271	G2G4G12G13
Local 4	-0.8538±6.9707i	12.16	1.1094	G6
Local 5	-1.4621±6.0617i	23.45	0.9647	G2G4
Local 6	-0.8004±5.2783i	14.99	0.8401	G2G4G9G10G11G12G13G15
Local 7	-1.2472±5.8457i	20.87	0.9304	G8
Local 8	-1.1604±5.7432i	19.81	0.9141	G2G3G12G14
Local 9	-0.9248±5.4296i	16.79	0.8641	G2G4G9G10G11G12G13G15
Local 10	-0.9911±5.4670i	17.84	0.8701	G16
Local 11	-1.1221±5.5885i	19.69	0.8894	G2G9G10G12
Local 12	-1.1511±5.6598i	19.93	0.9008	G10G12G14G15

This case study is focused on, investigate the important mode on small signal stability analysis of power system which is the electromechanical mode (EM). Table 2 illustrates the modal analysis of electromechanical mode in 150 kV Sulselrabar interconnected power system. It is observed that the test system has 4 inter-area mode and 12 local mode. It is noticeable that all of damping value on local mode are above 10%, while the minimum damping requirement is 5%. Hence the local mode in the test system are robust again disturbance due to higher value of the system. Moreover, the oscillation of the local mode are fast enough to find the steady state condition. However for inter-area mode, the probability of the damping performance to fall under 5% when perturbation occurs is high. It is because there are two modes that the damping value are under 10%. Moreover, Table also provide which generator participate in the particular modes through participation factor analysis. Furthermore, to mitigate the probability of the damping performance fall under 5%, adding additional controller such as PSS and additional device such as RFB are essential.

B. Case study 2

Table 3. Electromechanical mode of 150 kV Sulselrabar under different scenarios.

Mode	No PSS	PSS RFB	PSS RFB Cuckoo
Inter-Area	-0.3298±4.0807i	-0.3480±4.1576i	-2.0596±2.2050i
	-0.4462±4.6039i	-0.4091±4.8645i	-0.6886±4.0953i
	-0.5050±4.5408i	-0.5243±4.7465i	-0.5579±4.6337i
	-0.5121±4.5346i	-0.5133±4.5343i	-0.5140±4.5338i
Local	-1.0027±9.4221i	-1.0009±9.4134i	-0.9985±9.3882i
	-1.0063±8.4356i	-2.2602±4.4635i	-1.1238±8.3879i
	-1.0503±7.0818i	-1.0703±8.4320i	-1.8739±7.1439i
	-0.8538±6.9707i	-0.8527±6.9688i	-5.2144±2.9247i
	-1.4621±6.0617i	-1.4367±7.6142i	-1.4940±6.3323i
	-0.8004±5.2783i	-0.8898±5.5111i	-0.8533±6.9712i
	-1.2472±5.8457i	-1.2500±5.9814i	-1.3520±5.6354i
	-1.1604±5.7432i	-1.2481±5.8467i	-1.2481±5.8425i
	-0.9248±5.4296i	-0.9300±5.4967i	-1.0055±5.3427i
	-0.9911±5.4670i	-0.9907±5.4673i	-0.9920±5.4661i
	-1.1221±5.5885i	-1.1381±5.7031i	-1.6097±5.3753i
	-1.1511±5.6598i	-1.1543±5.6987i	-1.4592±5.4420i

Table 3. Damping of electromechanical mode of 150 kV Sulselrabar under different scenarios.

Mode	No PSS	PSS RFB	PSS RFB Cuckoo
Inter-Area	8.06	8.34	68.26
	9.65	8.38	16.58
	11.05	10.98	11.95
	11.22	11.25	11.26
Local	10.58	10.57	10.58
	11.85	45.18	13.28
	14.67	12.59	25.37
	12.16	12.15	87.22
	23.45	18.54	22.96
	14.99	15.94	12.15
	20.87	20.46	23.33
	19.81	20.88	20.89
	16.79	16.68	18.50
	17.84	17.93	17.86
	19.69	19.57	28.69
	19.93	19.57	25.90

The second case study was focused on enhancement of small signal stability performance of the system by adding PSS and RFB. Base on the participation factor in case study 1, for inter-area with damping value less than 5% the contributed generators are coming from G2, G4, G5, G9, G10, G11, G12, G13, G14, and G15. Based on the [32, 33] the minimum PSS that can be installed is half of the generator number. Hence, for this study, the PSS is installed to the G2, G4, G5, G9, G10, G11, G12, G13, G14, and G15. Furthermore, from Table 2 it can be observed that G2 contribute to the half oscillation modes. Hence, it is essential to add RFB in the G2 to enhance the small signal stability performance of the system.

To get the best coordination between PSS and RFB an optimization method called CSA is used. Tables 3 and 4 show the eigenvalue and the damping performance of different scenarios. It can be seen that by adding PSS and RFB the eigenvalue of the system move towards left-half plane. This condition can be happened due to increasing damping performance of the system. Furthermore, the best damping performance is achieved when CSA is employed as optimization method for tuning parameter of PSS and RFB.

To validate and verify the modal analysis study, time domain simulation is carried out by giving 0.01 step input of load. Figure 7 illustrates the oscillatory condition of rotor speed in G2, it can be seen that, system with PSS and RFB experience lower oscillation than base case system. It is also observed that the best oscillatory condition is provided by system with PSS and RFB based on CSA indicated by smallest overshoot and fastest settling time. Figure. 8 shows the rotor angle response of G2 under different scenarios. Lower oscillatory condition are also observed in the rotor angle response of the G2. Moreover Table shows the detailed features of overshoot and settling time of rotor speed and rotor angle of G2. According to [34], the maximum settling time of small signal stability is around 10 second. Hence, only system with PSS and RFB based on CSA is capable to achieve this standard.

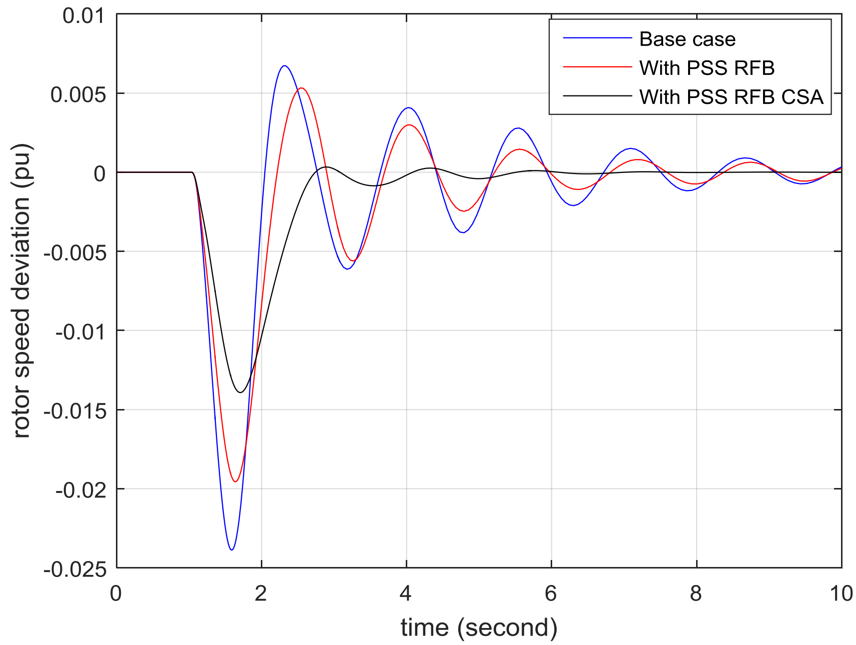

Figure 7. Rotor speed deviation (Δω) G2.

Table 3. Detailed featured of rotor speed overshoot and settling time.

Cases	Base case	PSS RFB	PSS RFB CSA
Overshoot	-0.02387	-0.01956	-0.01393
Settling time	>10	>10	6.843

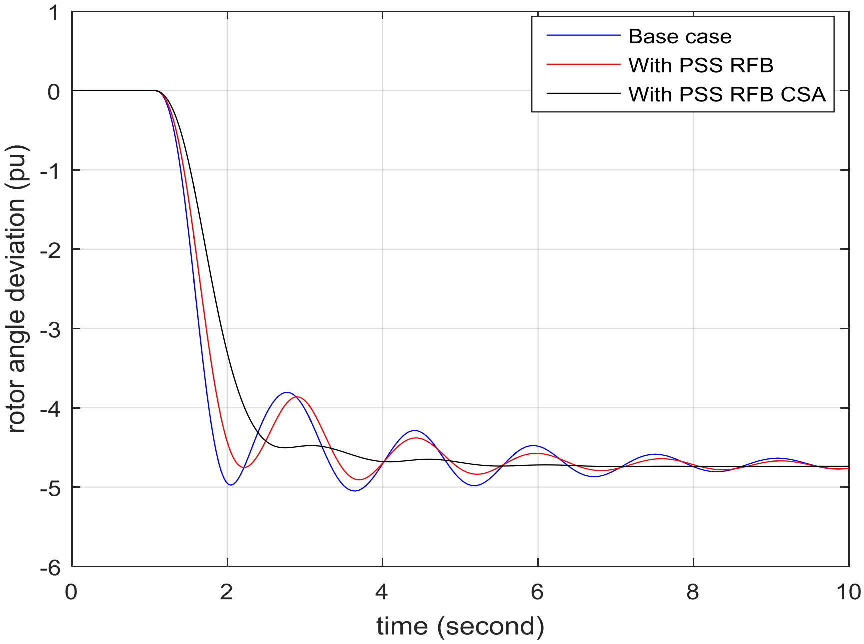

Figure 8. Rotor angle deviation of G2.

Table 3. Detailed featured of rotor angle overshoot and settling time.

Cases	Base case	PSS RFB	PSS RFB CSA
Overshoot	-0.275	-0.054	0
Settling time	>10	>10	6.017

5. Conclusions

This paper investigated the small signal stability performance of 150 kV Sulselrabar by using modal analysis. This paper also proposed a method to enhance the small signal stability performance of the test system using coordinate controller between PSS and RFB based on CSA. From the investigated study cases, it is found that the test system consist of four inter-area mode and eleven local mode. It is also found that the damping performance of the test system can be categorized as well damped damping. However, there are two inter-area mode that has possibility to become critical damping.

It is also observed that, the small signal stability performance of the test system is increased, when PSS and RFB is installed in the system. It is also noticeable that the best performance is shown by system with PSS and RFB based on CSA indicated by smallest overshoot and fastest settling time. Further research need to be conducted by integrated RESs in the system and assess the small signal stability performance. Designing wide area power oscillation damping can be considered to handle the oscillation coming from several sources. Moreover, utilizing another metaheuristic algorithm such as grey wolf algorithm, bat algorithm can be considered for designing PSS and RFB.

6. Acknowledgement

The author would like to express his gratitute to Prof. Imam Robandi (Sepuluh Nopember Institute of Technology), and Dr.Eng. Ardyono Priyadi (Sepuluh Nopember Institute of Technology), for the discussion on this topic. PT. PLN (Persero) Wilayah Makassar for providing all of data that used in this research.

7. References

[1] A. U. Krismanto and N. Mithulananthan, "Identification of Modal Interaction and Small Signal Stability in Autonomous Microgrid Operation," *IET Generation Transmission & Distribution*, 2017.

[2] H. Setiadi, A. U. Krismanto, N. Mithulananthan, and M. Hossain, "Modal interaction of power systems with high penetration of renewable energy and BES systems," *International Journal of Electrical Power & Energy Systems*, vol. 97, pp. 385-395, 2018.

[3] H. Setiadi and K. O. Jones, "Power System Design using Firefly Algorithm for Dynamic Stability Enhancement," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 1, pp. 446-455, 2016.

[4] N. Mithulananthan, C. A. Canizares, J. Reeve, and G. J. Rogers, "Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations," *IEEE Transactions on Power Systems*, vol. 18, pp. 786-792, 2003.

[5] S. Panda and N. Padhy, "Robust power system stabilizer design using particle swarm optimization technique," *Fuel*, vol. 337, p. 14723, 2008.

[6] E. Ali and S. Abd-Elazim, "TCSC damping controller design based on bacteria foraging optimization algorithm for a multimachine power system," *International Journal of Electrical Power & Energy Systems*, vol. 37, pp. 23-30, 2012.

[7] S. Ganguly and D. Samajpati, "Distributed Generation Allocation on Radial Distribution Networks Under Uncertainties of Load and Generation Using Genetic Algorithm," *IEEE Transactions on Sustainable Energy*, vol. 6, pp. 688-697, 2015.

[8] M. Abdillah, H. Setiadi, A. B. Reihara, K. Mahmoud, I. W. Farid, and A. Soeprijanto, "Optimal selection of LQR parameter using AIS for LFC in a multi-area power system," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, vol. 7, pp. 93-104, 2016.

[9] D. Lastomo, H. Setiadi, and M. R. Djalal, "Optimization Pitch Angle Controller of Rocket System using Improved Differential Evolution Algorithm," *International Journal of Advances in Intelligent Informatics*, vol. 3, 2017.

[10] V. Vakula and K. Sudha, "Design of differential evolution algorithm-based robust fuzzy logic power system stabiliser using minimum rule base," *IET generation, transmission & distribution*, vol. 6, pp. 121-132, 2012.

[11] X.-S. Yang, *Cuckoo search and firefly algorithm: Theory and applications* vol. 516: Springer, 2013.

[12] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*. United State of America: John Wiley & Sons, 2003.

[13] M. R. Djalal, D. Ajiatmo, A. Imran, and I. Robandi, "Desain Optimal Kontroler PID Motor DC Menggunakan Cuckoo Search Algorithm," *SENTIA 2015*, vol. 7, 2015.

[14] D. L. E. Swann, "Applying power system stabilizers part-I: general concepts," *IEEE Trans Power Ap Syst*, vol. 100, pp. 3017-3024, 1981.

[15] P. Kundur, M. Klein, G. Rogers, and M. S. Zywno, "Application of power system stabilizers for enhancement of overall system stability," *IEEE Transactions on Power Systems*, vol. 4, pp. 614-626, 1989.

[16] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," *IEEE Std 421.5-2016 (Revision of IEEE Std 421.5-2005)*, pp. 1-207, 2016.

[17] M. Y. Yunus, M. R. Djalal, and Marhatang, "Optimal Design Power System Stabilizer Using Firefly Algorithm in Interconnected 150 kV Sulselrabar System, Indonesia," *International Review of Electrical Engineering (IREE)*, vol. 12, pp. 250-259, 2017.

[18] I. Chidambaram and B. Paramasivam, "Control performance standards based load-frequency controller considering redox flow batteries coordinate with interline power flow controller," *Journal of Power Sources*, vol. 219, pp. 292-304, 2012.

[19] R. Shankar, K. Chatterjee, and R. Bhushan, "Impact of energy storage system on load frequency control for diverse sources of interconnected power system in deregulated power

environment," *International Journal of Electrical Power & Energy Systems,* vol. 79, pp. 11-26, 7// 2016.
[20] M. Taufik, D. Lastomo, and H. Setiadi, "Small-disturbance angle stability enhancement using intelligent redox flow batteries," in *2017 4th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, 2017, pp. 1-6.
[21] K. Prasertwong, N. Mithulananthan, and D. Thakur, "Understanding low-frequency oscillation in power systems," *International Journal of Electrical Engineering Education,* vol. 47, pp. 248-262, 2010.
[22] D. Lastomo, H. Setiadi, and M. R. Djalal, "Optimization of SMES and TCSC using particle swarm optimization for oscillation mitigation in a multi machines power system," *Journal of Mechatronics, Electrical Power, and Vehicular Technology,* vol. 8, pp. 11-21, 2017.
[23] A. Krismanto, N. Mithulananthan, and I. Kamwa, "Oscillatory Stability Assessment of Microgrid in Autonomous Operation with Uncertainties," *IET Renewable Power Generation,* 2017.
[24] D. Lastomo, H. Setiadi, M. Faisal, A. Ashfahani, G. Bangga, G. Hutomo*, et al.*, "The effects of energy storages on small signal stability of a power system," in *2017 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, 2017, pp. 52-57.
[25] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control* vol. 7: McGraw-hill New York, 1994.
[26] A. U. Krismanto, N. Mithulananthan, and O. Krause, "Microgrid impact on low frequency oscillation and resonance in power system," in *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, 2016, pp. 424-429.
[27] H. Setiadi, A. U. Krismanto, and N. Mithulananthan, "Influence of BES system on local and inter-area oscillation of power system with high penetration of PV plants," in *Applied System Innovation (ICASI), 2017 International Conference on*, 2017, pp. 1-4.
[28] A. H. Gandomi, X.-S. Yang, and A. H. Alavi, "Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems," *Engineering with computers,* vol. 29, pp. 17-35, 2013.
[29] M. R. Djalal, H. Setiadi, and A. Imran, "Frequency stability improvement of micro hydro power system using hybrid SMES and CES based on Cuckoo search algorithm," *2017,* vol. 8, p. 9, 2017-12-28 2017.
[30] A. El-Zonkoly, A. Khalil, and N. Ahmied, "Optimal tunning of lead-lag and fuzzy logic power system stabilizers using particle swarm optimization," *Expert Systems with Applications,* vol. 36, pp. 2097-2106, 2009.
[31] M. R. Djalal, H. Nawir, H. Setiadi, and A. Imran, "An Approach Transient Stability Analysis Using Equivalent Impedance Modified in 150 kV South of Sulawesi System," *JEEE-U (Journal of Electrical and Electronic Engineering-UMSIDA),* vol. 1, pp. 1-7, 2017.
[32] K. Sebaa and M. Boudour, "Optimal locations and tuning of robust power system stabilizer using genetic algorithms," *Electric Power Systems Research,* vol. 79, pp. 406-416, 2009.
[33] M. Eslami, H. Shareef, A. Mohamed, and M. Khajehzadeh, "An efficient particle swarm optimization technique with chaotic sequence for optimal tuning and placement of PSS in power systems," *International Journal of Electrical Power & Energy Systems,* vol. 43, pp. 1467-1478, 2012.
[34] J. Paserba, "Analysis and control of power system oscillation," *CIGRE special publication,* vol. 38, 1996.

Muhammad Ruswandi Djalal was born in Makassar on March 11, 1990. He received bachelor degree from State Polytechnic of Ujung Pandang (Makassar, Indonesia), majors in Energy Generation Engineering in 2012. Then, master degree from Sepuluh Nopember Institute of Technology, (ITS Surabaya, Indonesia), majors in Power System Engineering in 2015. His research about, Power System Stability, Operation and Control, Renewable Energy and Artificial Intelligent. Now, He is lecturer at State Polytechnic of Ujung Pandang (PNUP). The author can be contacted at Department of Mechanical Engineering, Energy Generation Study Programs PNUP, Jl. Perintis Kemerdekaan 7 km.10, Makassar 90245 or at wandi@poliupg.ac.id.

Herlambang Setiadi was born in Sidoarjo, on November 29, 1990. He received bachelor degree from Sepuluh Nopember Institute of Technology (Surabaya, Indonesia) majors in Power System Engineering in 2014. Then, master degree from Liverpool John Moores University (Liverpool, United Kingdom), majors in Electrical Power and Control Engineering in 2015. His research interest include small signal stability in power systems, renewable energy integration and metaheuristic algorithm. The Author can be contacted at h.setiadi@uq.edu.au.

Dwi Lastomo was born in Surakarta, on maret 23, 1987. He received bachelor and master degree from Sepuluh Nopember Institute of Technology Surabaya (Indonesia), majors in Department of Physics Engineering in 2010. Then, master degree majors in Electrical Engineering in 2015. His research about, Power Electronics, Renewable Energy, Power System Operation and Control, Artificial Intelligent and Power Quality. Currently, He is lecturer at Department of Automation Electrical Engineering, Institut Teknologi Sepuluh Nopember, Indonesia. The author can be contacted at Department of Automation Electrical Engineering, Jalan Raya ITS, Keputih, Sukolilo, Surabaya, Indonesia or at dtomo23@gmail.com.

Muhammad Yusuf Yunus was born in Sinjai, on august 20, 1980. He received bachelor degree from Polytechnic Surabaya (Indonesia), majors in Electrical Engineering in 2004. Then, master degree from Hasanuddin University, (Makassar, Indonesia), majors in Electrical Engineering in 2015. His research about, Power Quality, Image Processing, Renewable Energy, Artificial Intelligent and Partial Discharge. He is Leader in Power System Simulation Laboratory in State Polytechnic of Ujung Pandang. Now, He is lecturer at PNUP. The author can be contacted at Department of Mechanical Engineering, Energy Generation Study Programs PNUP, Jl. Perintis Kemerdekaan 7 km.10, Makassar 90245 or at yusuf_yunus@poliupg.ac.id.