Power System Stability Enhancement Using Grasshopper Optimization Approach and PSSs

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Abstract**:** A new meta-heuristic algorithm namely Grasshopper Optimization Approach (GOA) for Power System Stabilizer (PSS) design problem is investigated in this paper. The parameters of PSSs are optimized by GOA to minimize the time domain objective function. The performance of the designed GOA based PSSs (GOAPSS) has been has been compared with Differential Evolution (DE) based PSSs (DEPSS) and the Particle Swarm Optimization (PSO) based PSSs (PSOPSS) under various loading events. The results of the proposed GOAPSS are confirmed via eigenvalues, damping ratio, time domain analysis, and performance indices. Moreover, the robustness of the GOA in getting good damping characteristics is verified.

KeyWords: Power System Stabilizers; Grasshopper Optimization Algorithm; Particle Swarm Optimization; Differential Evolution; Power System Stability; Low Frequency Oscillations.

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1. Introduction

Power system stability is one of the recent significant issues in the analysis of power systems [1]. One of the compulsory instances of this is an interconnected power system. The heavily loaded long tie-lines could account for a variety of stability issues [2]. This leads to the inclination of most researchers towards designing a suitable Power System Stabilizer (PSS).

Recently, a lot of research work is based on an area called "Heuristics from Nature" in which the analogies of nature or social systems are being utilized [3]. These techniques when used in the research community can prove their capability of finding optimal solutions of multi-model, non-differentiable and complex objective functions. Various new algorithms have been used for designing a PSS as Differential Evolution (DE) [4], Particle Swarm Optimization (PSO) [5], Bacterial Swarm Optimization (BSO) [6-7], Harmony Search Approach (HSA) [8-9], Bacterial Foraging (BF) [10-11], Bat Algorithm (BA) [12-13], Water Cycle Approach (WCA) [14], Backtracking Search Approach (BSA) [15-16], Grey Wolf Approach (GWA) [17], Whale Optimization Approach (WOA) [18], Cuckoo Search Approach (CSA) [19-20], Flower Pollination Approach (FPA) [21], Genetic Approach (GA) [22], Kidney-Inspired Approach (KIA) [23], etc. All of these algorithms are based upon Artificial Intelligence (AI).

A new nature-inspired technique inspired from social activities of grasshoppers is introduced by Mirjalili. The technique is termed as Grasshopper Optimization Approach (GOA) [24]. Because of its simplicity, avoiding the high local optimum value as well as gradient-free mechanism, and inspiration by nature, it has been commonly implemented these days. Therefore, the effectiveness of implementing the proposed approach to handle real-life issues is evaluated. The solutions must be upgraded in nature-inspired algorithms until the end criterion is met. Alongside this the optimization procedure partitioned in two stages named exploration and exploitation. Exploration relates to the algorithm's tendency to have randomized behaviour to change the solutions. Large variations in solutions lead to more search space exploration and subsequently discovery of its promising areas. However, as an approach tends to exploit, solutions usually encounter smaller-scale variations and tend to search locally. An appropriate exploration and exploitation balance can lead to the search for the global optimum of a specified optimization problem. It is evident from [24] that the GOA method gives improved results as compared with several optimization techniques. Previous works clearly reflect the growing interest of the researchers in designing PSS when it comes to stability improvement. Further, the GOA technique has not been used.

2. Mathematical Problem Formulation

2.1 Power System Model

Generally, a power system can be established by a group of nonlinear differential equations as:

$$\dot{X} = f\,(X, U) \qquad (1)$$

Where X and U are the vectors of the state variables and of input variables. In this study, X =

$[\delta, \omega, E_q', E_{fd}, V_f]^T$ and U is the output of PSSs. E_q', E_{fd} and V_f are the internal, the field, and excitation voltages respectively. Also, δ and ω are the rotor angle and speed, respectively.

In the design of PSS, the state equation of a power system can be formalized as:

$$\dot{X} = AX + BU \tag{2}$$

2.2 PSS Structure

Due to the ease of online tuning, power system companies prefer the structure of conventional PSS (CPSS). The appropriate selection of the CPSS parameters results in satisfactory performance during the system disturbances. The CPSS can be modeled as:

$$\Delta U_i = K_i \frac{ST_W}{(1+ST_W)}\left[\frac{(1+ST_{1i})}{(1+ST_{2i})}\frac{(1+ST_{3i})}{(1+ST_{4i})}\right]\Delta\omega_i \tag{3}$$

Fig. 1. shows the block diagram of CPSS and excitation system. The model of CPSS contains a limiter, a gain, a dynamic compensator and washout filter. To avoid the delay between the excitation and the electric torque, two lead-lag circuits are included [1, 2]. In this paper, the time constants T_{1i}, and T_{3i}, and the gain K_i are optimized by GOA to reduce a time domain objective function.

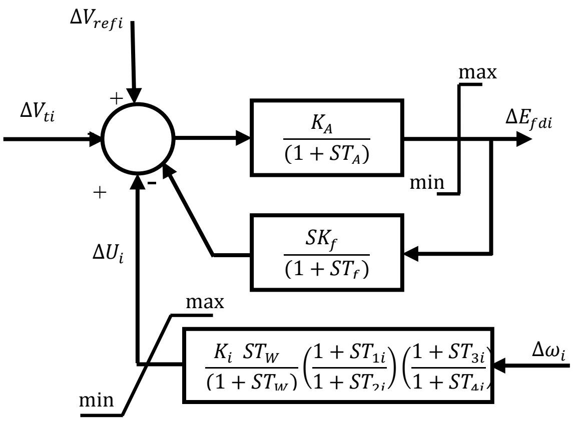

Fig. 1. Block diagram of i^{th} CPSS with excitation system.

2.3 Test System

A multimachine system that consists of three generators and nine buses is considered here. The system data and loading events are given in [2, 25].

3. Grasshopper Optimization Approach

GOA is an intelligence approach presented by Mirjalili [24]. It is a population based method which imitates grasshopper swarming behaviour. It is an insect pest since its destructive effect on crops. Its life has two stages, nymph and adulthood. For the nymph stage, the insects have no wings so they move slowly but after growing up they become adults with wings that allow them to move very fast covering a large scale area. Grasshopper swarming might be considered as the largest one among all creatures as it is a nightmare for farmers [26].

In the swarming process, there is a larval phase which is characterized by slow movement with small grasshopper steps but for adults long-rang and abrupt movements. In the food seeking process, grasshoppers follow two strategies, exploration and exploitation. Each grasshopper represents a solution, the next position X_j is influenced by the social interaction between grasshopper and the other one S_j, gravity force G_j and wind advection A_j as shown in the following equation:

$$X_j = S_j + G_j + A_j \tag{4}$$

Social interaction can be calculated by the following equation:

$$S_j = \sum_{k=1}^{N} s(d_{ik}).\ \hat{d}_{ik} \qquad k \neq i \tag{5}$$

$$d_{ik} = |X_k - X_i| \quad and \quad \hat{d}_{ik} = \frac{X_k - X_i}{d_{ik}} \tag{6}$$

Where N is no. of grasshoppers, d_{ik} is the distance from grasshopper k to grasshopper i and s is the strength of attraction and repulsion forces between grasshoppers. Since repulsion force appears when distance between grasshoppers between zero and 2.079 units, while at a distance of 2.079 neither repulsion or attraction force as it is a comfortable zone. Attraction force increases at a distance greater than 2.079 until reach 4 then it decreases and after 10 there will be no forces. Form the previous, the interval should be from 1 to 4 and s calculated as following:

$$s(r) = ae^{\frac{r}{l}} - e^{-r} \tag{7}$$

Where a is the intensity of attraction and l is the attractive length scale.

Gravity force can be calculated by the following equation:

$$G_j = g\hat{e}_g \tag{8}$$

Where g is a gravitational constant and $\hat{e}_g$ is the center of the earth unit vector.

Wind advection force A_j can be determined by the following equation:

$$A_j = u\hat{e}_w \tag{9}$$

Where u is a drift constant and $\hat{e}_u$ is the wind direction unit vector.

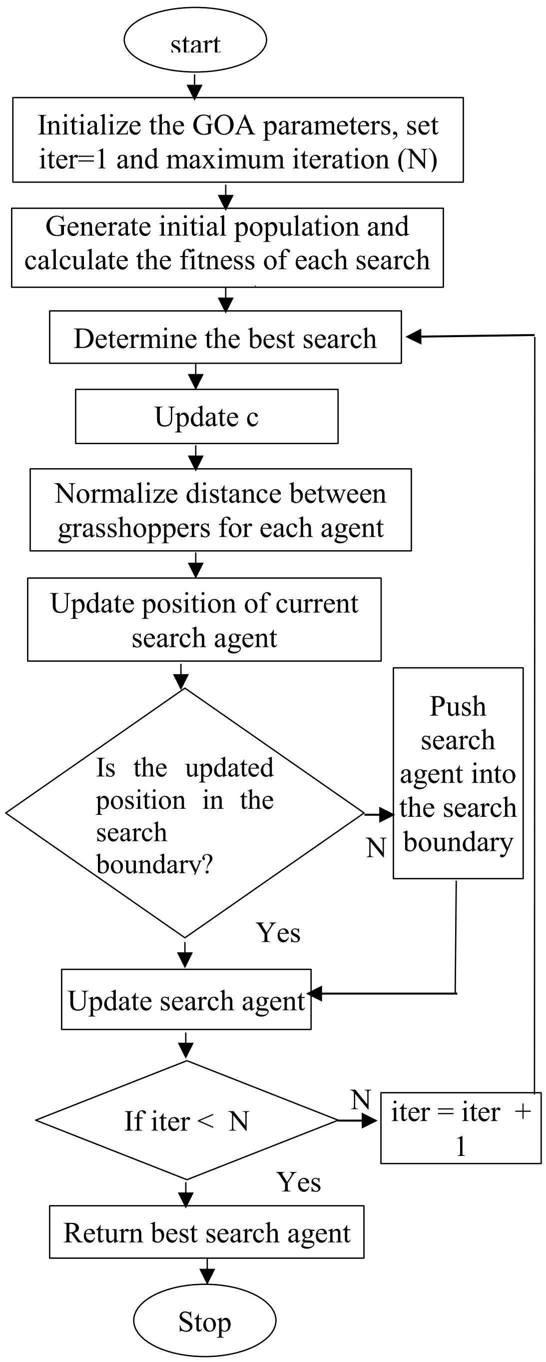

Fig. 2. Flow chart of the GOA.

Equation (4) will be represented as following:

$$X_j = \sum_{k=1}^{N}\left(ae^{\frac{r}{l}} - e^{-r}\right)(|X_k - X_i|).\ \frac{X_k - X_i}{d_{ik}} - g\hat{e}_g + u\hat{e}_w \qquad k \neq i \qquad (10)$$

To avoid comfortable zone and global optimum, the grasshopper position will be

$$X_j^d = c\left[\sum_{k=1}^{N} c\left(\frac{ub_d - lb_d}{2}\right) s\left(\left|X_k^d - X_i^d\right|\right).\ \frac{X_k - X_i}{d_{ik}}\right] + \hat{T}_d \qquad (11)$$

Where ub_d and lb_d represent upper and lower bounds respectively in D^th^ dimension, $\hat{T}_d$ is the target value assuming wind direction tends towards target and c is decreasing constant to minimize all zones neglecting gravity [26].

$$c = cmax - l\frac{cmax - cmin}{L} \qquad (12)$$

l is the current iteration, cmin=10^{-5} , cmax= 1 and L is the maximum number of iterations. Fig. 2 shows the flowchart of GOA. In addition, other recent applications for GOA can be found in [27- 28].

4. Objective Function

An Integral Time Absolute Error (ITAE) of the speed deviation of a generator is considered as the proposed objective function. It can be written as:

$$J = \int_{0}^{t_{sim}} t\left\{\left|\Delta\omega_{12}\right| + \left|\Delta\omega_{23}\right| + \left|\Delta\omega_{13}\right|\right\}dt \qquad (13)$$

The lower and upper limits of the stabilizer gain are [1- 50]. Also, these limits are [0.06 -1.0] for T_{1i} and T_{3i}. Other time constants T_{2i} and T_{4i} are fixed at 0.05 second. GOA searches for the optimal parameters of PSSs to enhance the damping behaviour and reduce the overshoot and settling time of the system response.

5. Results and Analysis

The eigenvalues and their damping ratios of mechanical modes are given in Table (1) for three various loading conditions and different approaches. It is obvious that the damping factors corresponding to GOAPSS have improved to be (σ=-1.12,- 1.19,- 1.32) and the eigenvalues have been shifted to the left of S plane. Moreover, the damping ratios related to GOAPSS are greater than other controllers. Thus, GOAPSS gives better damping performance compared with DEPSS and PSOPSS. Also, the parameters of each controller using GOA, DE and PSO are shown in Table (2).

5.1 Response for light load event:

The effectiveness of the decided controller is proved by setting a 3 phase fault near bus 7 of 6 cycle at 1 second. The system response is shown in Fig. 3 for light load event. It is obvious that the system responses with the decided GOAPSS are better than PSOPSS and DEPSS. Also, the settling times are 2.2, 3.2, and 3.5 second with GOAPSS, DEPSS, and PSOPSS respectively. The decided controller is competent to assign appropriate damping characteristics compared with DEPSS and PSOPSS.

Table (1) Mechanical modes and ζ for various loading events and approaches.

	PSO PSS	DE PSS	GOA PSS
Light load	-0.22±0.67j, 0.31	-1.06±0.66j,0.85	-1.12±0.64j,0.87
	-2.43±4.01j, 0.51	-3.75±6.23j,0.51	-6.3±6.34j, 0.70
	-3.45±7.1j,0.44	-3.65±5.94j,0.52	-3.33±5.12j,0.54
Normal load	-0.36±0.72j,0.37	-1.12±0.68j,0.85	-1.19±0.69j,0.87
	-2.41±4.32j,0.48	-4.29±7.0j,0.52	-6.9±6.88j,0.71
	-3.64±8.17j,0.41	-4.21±8.02j,0.46	-3.37±5.24j,0.54
Heavy load	-0.35±0.89j,0.36	-1.19±0.71j,0.86	-1.32±0.72j,0.88
	-1.99±4.31j,0.42	-3.52±6.7j,0.47	-7.99±5.34j,0.83
	-3.8±8.9j,0.39	-3.06±5.15j,0.51	-4.65±7.29j,0.54

Table (2) Parameters of controllers for several approaches.

	GOA	DE	PSO
PSS_1	K=42.128	K=27.4566	K=17.4736
	T_1=0.5436	T_1=0.5264	T_1=0.4224
	T_3=0.428	T_3=0.7578	T_3=0.7853
PSS_2	K=9.4211	K=7.9983	K=6.3649
	T_1=0.4723	T_1=0.3108	T_1=0.5542
	T_3=0.1643	T_3=0.1469	T_3=0.3231
PSS_3	K=5.2641	K=4.7541	K=7.8875
	T_1=0.3234	T_1=0.5361	T_1=0.5668
	T_3=0.1861	T_3=0.3931	T_3=0.4567

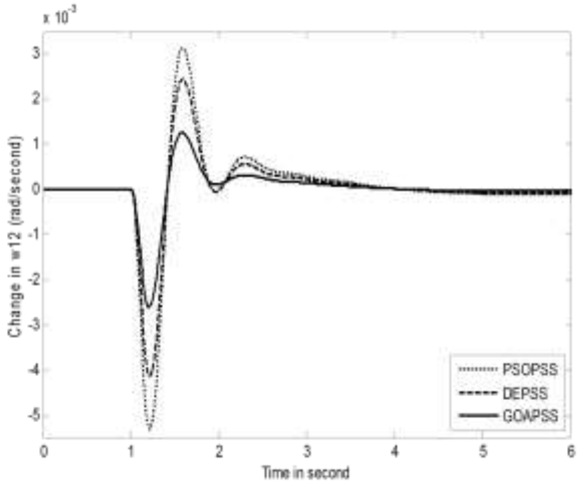

Fig. 3. Change of $\Delta\omega_{12}$ for light load event.

5.2 Response for normal load event:

The system response under normal loading is given in Fig. 4. From this response, the damping behaviour has been improved by the decided GOAPSS. The settling times of these responses are T_S =2.4, 3.1, and 3.2 second for GOAPSS, DEPSS, and PSOPSS respectively. Also, the decided GOAPSS outlasts DEPSS and PSOPSS in mitigating oscillations and shortening settling time. Hence, the decided GOAPSS expands the system stability limit.

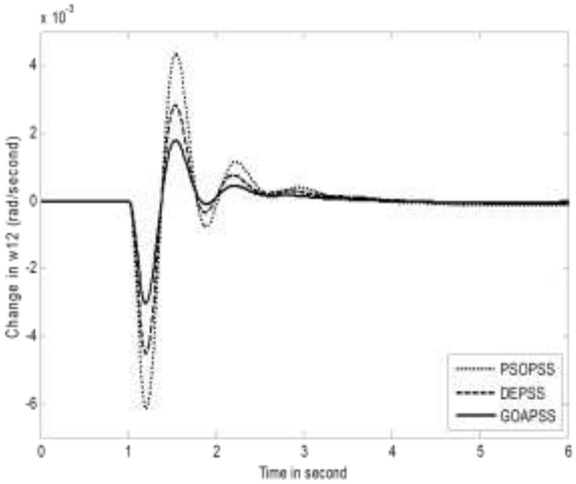

Fig. 4. Change of $\Delta\omega_{12}$ for normal load event.

5.3 Response for heavy load event:

Fig. 5, gives the response for heavy loading event. The superiority of the GOAPSS in attenuating system oscillations and minimizing the settling time are indicated. Also, the settling times of these oscillations are T_S =2.5, 3.1, and 3.3 second for GOAPSS, DEPSS, and PSOPSS respectively. Hence, the GOAPSS controller largely develops the system stability and increases the damping behaviour of the power system. Moreover, the settling times of the decided GOAPSS are shorter than these in [5, 12, and 19].

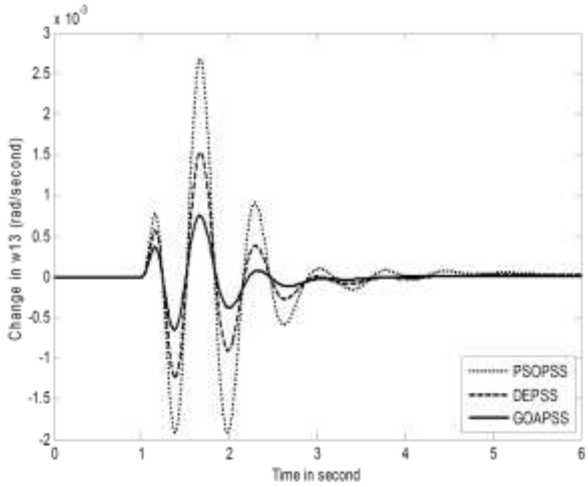

Fig. 5. Change of $\Delta\omega_{13}$ for heavy load event.

5.4 Response under small disturbance

The responses of $\Delta\omega_{13}$ are given in Fig. 6 due to 0.2 step increase in mechanical torque of machine 1 like a small disturbance. It is clear from these figures, GOAPSS presents supreme damping and acquires the best behaviour compared with DEPSS and PSOPSS.

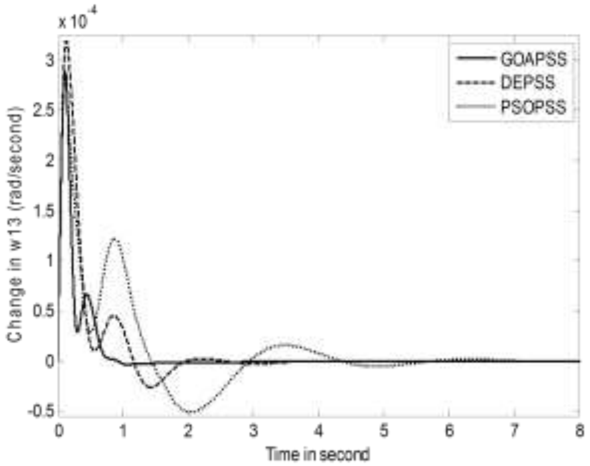

Fig. 6. Change of $\Delta\omega_{13}$ for small disturbance.

5.5 Performance indices

To assign the superiority of the decided GOAPSS, some performance indices: the Integral of Absolute value of the Error (IAE), and ITAE are considered as:

$$IAE = \int_{0}^{20} \left(|\Delta w_{12}| + |\Delta w_{23}| + |\Delta w_{13}| \right) dt \tag{14}$$

$$ITAE = \int_{0}^{20} t \left(|\Delta w_{12}| + |\Delta w_{23}| + |\Delta w_{13}| \right) dt \tag{15}$$

The weaker the value of indices have, the more supreme the system response is. Numeral results of performance indices for various events are given in Table (3). It is obvious that the values of these indices with the GOAPSS are junior compared with those of DEPSS and PSOPSS. This asserts that the speed deviations of all generators, settling time, and overshoot, are extremely diminished by setting the decided GOA based tuned PSSs.

Table (3) Performance indices for several approaches.

	IAE * 10^{-4}			ITAE * 10^{-4}		
	PSO	DE	GOA	PSO	DE	GOA
Light event	0.2663	0.1484	0.0451	0.4642	0.4148	0.2746
Normal event	0.3973	0.2648	0.0657	0.7756	0.7551	0.6001
Heavy event	0.5686	0.4126	0.1001	0.9729	0.9406	0.8407

6. Conclusions

GOA is introduced in this paper for optimal designing of PSSs parameters as minimizing the proposed time domain objective function. An ITAE of the generator speed is considered as the objective function to enhance the system stability. Simulation results evidence the superiority of the decided GOAPSS in assigning good damping behaviour to system oscillations for several loading events. Moreover, the decided GOAPSS affirms its efficacy than PSOPSS and DEPSS through some indices. Coordination of PSS and FACT controller with GOA is the future scope of this work.

References

[1] P. Kundur, "*Power System Stability and Control*", McGraw-Hill, 1994.

[2] P. M. Anderson and A. A. Fouad, "*Power System Control and Stability*", Wiley-IEEE Press, 2nd edition, 2002.

[3] X. Yang, "*Engineering Optimization: An Introduction with Metaheuristics Applications*", Wiley, 2010.

[4] Z. Wang, C. Y. Chung, K. P. Wong, and C. T. Tse, "*Robust Power System Stabilizer Design under Multi-Operating Conditions Using Differential Evolution*", IET Generation, Transmission & Distribution, Vol. 2, No. 5 , 2008, pp. 690-700.

[5] H. Shayeghi, H. A. Shayanfar, A. Safari, and R. Aghmasheh, "*A Robust PSSs Design Using PSO in a Multimachine Environment*", Int. J. of Energy Conversion and Management, Vol. 51, No. 4, 2010, pp. 696-702.

[6] E. S. Ali, and S. M. Abd-Elazim, "*Coordinated Design of PSSs and TCSC via Bacterial Swarm Optimization Algorithm in a Multimachine Power System*", Int. J. of Electrical Power and Energy Systems, Vol. 36, No. 1, March 2012, pp. 84-92.

[7] S. M. Abd-Elazim, and E. S. Ali, "*A Hybrid Particle Swarm Optimization and Bacterial Foraging for Optimal Power System Stabilizers Design*", Int. J. of Electrical Power and Energy Systems, Vol. 46, No. 1, March 2013, pp. 334-341.

[8] K. A. Hameed, and S. Palani, "*Robust Design of Power System Stabilizer Using Harmony Search Algorithm*", ATKAFF, Vol. 55, No. 2, 2014, pp. 162-169.

[9] D. Chitara, K. R. Niazi, A. Swarnkar, and N. Gupta, "*Multimachine Power System Stabilizer Tuning Using Harmony Search Algorithm*", 2016 Int. Conf. on Electrical Power and Energy Systems (ICEPES), 14-16 Dec. 2016.

[10] E. S. Ali, and S. M. Abd-Elazim, "*Coordinated Design of PSSs and SVC via Bacteria Foraging Optimization Algorithm in a Multimachine Power System*", Int. J. of Electrical Power and Energy Systems, Vol. 41, No. 1, Oct. 2012, pp. 44-53.

[11] E. S. Ali, and S. M. Abd-Elazim, "*Power System Stability Enhancement via Bacteria Foraging Optimization Algorithm*", Int. Arabian Journal for

Science and Engineering, Vol. 38, No. 3, March 2013, pp. 599-611.

[12] E. Ali, "*Optimization of Power System Stabilizers Using BAT Search Algorithm*", Int. J. of Electrical Power and Energy Systems, Vol. 61, No. C, Oct. 2014, pp. 683-690.

[13] D. K. Sambariya, R. Gupta, and R. Prasad, "*Design of Optimal Input–Output Scaling Factors based Fuzzy PSS Using Bat Algorithm*", Engineering Science and Technology, an Int. J., Vol. 19, Issue 2, June 2016, pp. 991-1002.

[14] N. Ghaffarzadeh, "*Water Cycle Algorithm Based Power System Stabilizer Robust Design for Power Systems*", J. of Electrical Engineering, Vol. 66, No. 2, 2015, pp. 91-96.

[15] M. Shafiullah, M. A. Abido, and L. S. Coelho, "*Design of Robust PSS in Multimachine Power Systems Using Backtracking Search Algorithm*", In Proceedings of the 18th Int. Conf. on Intelligent System Application to Power Systems (ISAP), Sep. 2015, pp.1-6.

[16] N. Niamul Islam, M. A. Hannan, A. Mohamed, and H. Shareef, "*Improved Power System Stability Using Backtracking Search Algorithm for Coordination Design of PSS and TCSC Damping Controller*", PLOS ONE, Vol. 11, No.1, January 2016, pp. e0146277.

[17] M. R. Shakarami, I. F. Davoudkhani, "*Wide-Area Power System Stabilizer Design based on Grey Wolf Optimization Algorithm Considering The Time Delay*", Electric Power Systems Research, Vol. 133, April 2016, pp. 149-159.

[18] N. A. M. Kamari, I. Musirin, Z. Othman, and S. A. Halim "*PSS Based Angle Stability Improvement Using Whale Optimization Approach*", Indonesian J. of Electrical Engineering and Computer Science, Vol. 8, No. 2, Nov. 2017, pp. 382 -390.

[19] S. M. Abd-Elazim, and E. S. Ali, "*Optimal Power System Stabilizers Design via Cuckoo Search Algorithm*", Int. J. of Electrical Power and Energy Systems, Vol. 75 C, Feb. 2016, pp. 99-107.

[20] D. Chitara, K. R. Niazi. A. Swarnkar, and N. Gupta, "*Cuckoo Search Optimization Algorithm for Designing of a Multimachine Power System Stabilizer*", IEEE Transactions on Industry Applications, Vol. 54, No. 4, 2018, pp. 3056 - 3065.

[21] S. Venkateswarlu1, M. Janaki, and R. Thirumalaivasan, "*Design of Power System Stabilizer Using Flower Pollination Algorithm*", Int. J. of Engineering & Technology, 7 (4.10), 2018, pp.177-181.

[22] M. Shafiullah, M. J. Rana, M. S. Alam, and M. A. Abido, "*Online Tuning of Power System Stabilizer Employing Genetic Programming for Stability Enhancement*", J. of Electrical Systems and Information Technology, Vol. 5, 2018, pp. 287-299.

[23] S. Ekinci, A. Demiroren, and B. Hekimoglu, "*Parameter Optimization of Power System Stabilizers via Kidney-Inspired Algorithm*", *Trans. Inst. Meas. Control*, Vol. 41, No. 5, 2019, pp. 1405-1417.

[24] S. Saremi, S. Mirjalili, and A. Lewis, "*Grasshopper Optimization Algorithm: Theory and Application*", Advances in Engineering Software, Vol. 105, 2017, pp.30-47.

[25] S. M. Abd-Elazim, and E. S. Ali, "*A Hybrid Particle Swarm Optimization and Bacterial Foraging for Power System Stability Enhancement*", Int. J. of Complexity, Vol. 21, No. 2, November/December 2015, pp. 245- 255.

[26] S. Arora, and P. Anand, "*Chaotic Grasshopper Optimization Algorithm for Global Optimization*", Neural Computing and Applications, 2019, Vol. 31, No. 8, pp. 4385- 4405, https://doi.org/10.1007/s00521-018- 3343-2.

[27] H. Jia, C. Lang, D. Oliva, W. Song and X. Peng, "*Hybrid Grasshopper Optimization Algorithm and Differential Evolution for Multilevel Satellite Image Segmentation*", Remote Sens., Vol. 11, 2019, pp. 1134.

[28] L. Zhang, Q. Guo, M. Liu, N. Yang, R. Gao, and B. Sobhani, "*Optimal Dispatch of Dynamic Power and Heat Considering Load Management, Water Pump System, and Renewable Resources by Grasshopper Optimization Algorithm*", Journal of Energy Storage, Vol. 57, 2023, 106166.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.