ARCHIVES OF ELECTRICAL ENGINEERING VOL. 71(2), pp. 397–407 (2022)

DOI 10.24425/aee.2022.140718

A novel approach for power system stabilizer control parameter selection: a case-study on two-area four-machine system

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(Received: 10.08.2021, revised: 03.01.2022)

Abstract: This paper proposes a power system stabilizer (PSS) with optimal controller parameters for damping low-frequency power oscillations in the power system. A novel meta-heuristic, weighted grey wolf optimizer (WGWO) has been proposed, it is a variant of the grey wolf optimizer (GWO). The proposed WGWO algorithm has been executed in the selection of controller parameters of a PSS in a multi-area power system. A two-area four-machine test system has been considered for the performance evaluation of an optimally tuned PSS. A multi-objective function based on system eigenvalues has been minimized for obtained optimal controller parameters. The damping characteristics and eigenvalue location in the proposed approach have been compared with the other state-of-the-art methods, which illustrates the effectiveness of the proposed approach.

Key words: grey wolf optimizer, power system stabilizer, optimization, stability

1. Introduction

The quality of power supply to the load ends in an interconnected power system is a challenge for the operators. This is mainly because there are multiple forms of generating stations in the system where traditional thermal and nuclear plants can be regulated by operating conditions, and solar, wind, and other generator plants are weather dependent [1, 2]. It needs continuous monitoring at both generating and load ends. These continuous fluctuating operating conditions will lead to the injection of different frequency oscillations in the system [3]. The role of automatic voltage regulators (AVRs), power system stabilizers (PSSs) is vital, where placements of flexible alternating current transmission system (FACTS) controllers have also been recommended in

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the literature. The parameter settings of these controllers play also a prominently vital role, for which various tuning algorithms are proposed in the literature [4, 5]. It has been observed that there are various novel methods proposed in the literature for effective damping of low-frequency power oscillations in a power network. The damping controller parameters have been optimally selected in coordination with the other controllers, resulting in superior characteristics over the conventional method of the parameter selection [6, 7].

Recently, there is hardly any power system network that incorporates only a PSS as a controller, rather a coordinated system of a PSS and FACTS is being used. FACTS devices are capable of increasing the power transfer capacity of transmission lines under a wide range of operating conditions either by changing transmission line parameters (inductance and capacitance) or injecting reactive power into the transmission lines [8–10]. The main problem with these FACTS devices is that they are extremely parameter sensitive. It means a minute change in such a parameter can lead to the completely different behaviour of these devices. Also, as the network size of an interconnected power system is usually extremely large, placing FACTS devices in each transmission line will not be cost-effective. The parameters to be handled will also be very large [11–13]. Along with this, maintaining proper coordination between them will not be an easy task too. So, several authors have come up with the idea of proper placements of these devices like in [14–16].

The application of meta-heuristic algorithms is increasing in proportion to the complexity of research problems. Various algorithms were used in electrical engineering-related research problems, for example, economic load dispatch problems [17], optimal power flow [18], or electrical machines [19, 21–23]. The grey wolf optimizer (GWO) is one of the most commonly used algorithms in the literature. It has been successfully applied to line-start induction motors [24], low-power-line-start motors [22], and PM synchronous motors [21]. Further, the non-linear variations have been incorporated into the GWO and improved its performance characteristics in the application of electromagnetic devices [19]. Based on the various studies, this paper proposes a new variant of the grey wolf optimizer (GWO) based on the weighting function with a better balance between exploration and exploitation phases as well as faster convergence towards the optimal solution. The proposed WGWO algorithm is applied for tuning PSS controller parameters (time constants and gain). Hence, this paper mainly covers,

- Stability analysis on a test power network with optimal PSS parameters.
- Proposing a new variant of a GWO algorithm.
- Performance evaluation based on eigenvalue studies and system damping behaviour against system disturbances.

The paper is arranged as follows: the proposed WGWO algorithm has been described in section 2, two-area four-machine test system modelling and objective function formulation has been presented in section 3, the damping nature for the system responses with the proposed approach is analyzed in section 4 followed by conclusions drawn from the study.

2. Proposed WGWO algorithm

Recently, the grey wolf optimizer (GWO) is a popular meta-heuristic algorithm [25] for various engineering problems. The hunting behavior of grey wolves has been mathematically modelled as α, β, and δ groups based on their social hierarchy. The key restrictions of a GWO

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algorithm [26] can be summarized as local optimality is often a result of being stuck in dead-end solutions. A second effect is the contraction of the population, which reduces the potential of the GWO to move away from the local optimum. The weighted GWO (WGWO), a variant of the GWO, is put forth in this section to address these problems. The new feature includes a new search method, the result of choosing and modifying the current stage. The detailed algorithm formulation is expressed as follows:

The prey surrounded by a group of wolves is represented in (1), (2). A distance vector of different wolf groups with respect to the prey can be written as

$$\left.\begin{aligned} \vec{D}_\alpha &= \left|\vec{C}_1\vec{X}_\beta(t) - \vec{X}(t)\right| \\ \vec{D}_\beta &= \left|\vec{C}_2\vec{X}_\beta(t) - \vec{X}(t)\right| \\ \vec{D}_\delta &= \left|\vec{C}_3\vec{X}_\delta(t) - \vec{X}(t)\right| \end{aligned}\right\}. \tag{1}$$

The encircling nature of grey wolves can be expressed as in (3) by considering factors in (2) which are functions of some random vector, $(\vec{r})$, in the range [0, 1], and iteration count, (t).

$$\vec{A} = (2\vec{a}\,\vec{r}) - \vec{a}, \qquad \vec{a} = 2 - t_{\text{present}}\left(\frac{2}{t_{\text{total}}}\right), \qquad \vec{C} = 2\vec{r}, \tag{2}$$

$$\left.\begin{aligned} \vec{X}_1 &= \vec{X}_\alpha - \vec{A}_1\vec{D}_\alpha \\ \vec{X}_2 &= \vec{X}_\beta - \vec{A}_2\vec{D}_\beta \\ \vec{X}_3 &= \vec{X}_\delta - \vec{A}_3\vec{D}_\delta \end{aligned}\right\}. \tag{3}$$

As in the standard GWO approach, α, β, and δ groups are responsible for attracting other grey wolfs towards the optimal solution. Hence these α, β, and δ groups are utilized to update the positions of other grey wolfs. As a result, if the position of other grey wolfs updated based on either of the groups of grey wolfs, they may become trapped in local optima and cannot explore new areas in search space because their solution space significantly concentrates around α, β, and δ group solutions.

To tackle this issue, for the efficient search capability and balance between exploration and exploitation [27–29], weights have been defined in the proposed WGWO approach. Hence, the position update function can be derived using (4).

$$\vec{X}(t+1) = \frac{1}{\omega_1 + \omega_2 + \omega_3}\,\frac{\left(\omega_1 \cdot \vec{X}_1 + \omega_2 \cdot \vec{X}_2 + \omega_3 \cdot \vec{X}_3\right)}{3}, \tag{4}$$

where weights ω_1, ω_2, ω_3 provides the learning rates for α, β, and δ groups, respectively. These are defined as in (5).

$$\omega_1 = \frac{\left|\vec{X}_1\right|}{\left|\vec{X}_1\right| + \left|\vec{X}_2\right| + \left|\vec{X}_3\right|}, \qquad \omega_2 = \frac{\left|\vec{X}_2\right|}{\left|\vec{X}_1\right| + \left|\vec{X}_2\right| + \left|\vec{X}_3\right|}, \qquad \omega_3 = \frac{\left|\vec{X}_3\right|}{\left|\vec{X}_1\right| + \left|\vec{X}_2\right| + \left|\vec{X}_3\right|}. \tag{5}$$

Here $|\vec{X}|$ represents the Euclidian distance. The exploration and exploitation phases are controlled by the $\vec{a}$ magnitude in (2).

3. Mathematical model of test power system

The benchmark two-area four-machine system has been modelled by considering different components in the power network. It has been summarized as follows: for alternators, a sub-transient model is used. It consists of seven coils: one field coil, three-phase coils, one damper coil on the d-axis and two damper coils on the q-axis [30]. The terminal voltages of these coils, along with shaft angle and rotor speed, can be obtained by applying the KVL (Kirchhoff's Voltage Law) as:

$$v_a = i_a r_s + \frac{\mathrm{d}\lambda_a}{\mathrm{d}t}\,. \tag{6}$$

The above equation is applicable for all the three-phase coils of the armature with r_s being the stator (armature) coil resistance of that particular phase, i_a being the current flowing in that coil and λ_a being the flux crossing that phase coil. The voltage of the remaining coils can be found by applying the KVL to them as

$$v_{fd} = i_{fd} r_{fd} + \frac{\mathrm{d}\lambda_{fd}}{\mathrm{d}t}\,, \tag{7}$$

$$v_{1d} = i_{1d} r_{1d} + \frac{\mathrm{d}\lambda_{1d}}{\mathrm{d}t}\,, \qquad v_{1q} = i_{1q} r_{1q} + \frac{\mathrm{d}\lambda_{1q}}{\mathrm{d}t}\,, \qquad v_{2q} = i_{2q} r_{2q} + \frac{\mathrm{d}\lambda_{2q}}{\mathrm{d}t}\,. \tag{8}$$

The rotor speed can be derived by the following relation between electrical angle, (ω), and mechanical angle, (ω_{shaft}),

$$\left.\begin{aligned} \frac{\mathrm{d}\theta_{\text{shaft}}}{\mathrm{d}t} &= \omega_{\text{shaft}} = \frac{2}{P}\omega \\ J\left(\frac{2}{P}\right)\frac{\mathrm{d}\omega}{\mathrm{d}t} &= T_m - T_e - T_{fw} \end{aligned}\right\}, \tag{9}$$

where: P is the number of poles of the synchronous machine, T_m, T_e and T_{fw} represent the mechanical torque, electrical torque and field stored torque, respectively.

For the dynamic study of the synchronous machine, the shaft angle, (δ), needs to be defined as:

$$\delta \triangleq \frac{P}{2}\theta_{\text{shaft}} - \omega_s t. \tag{10}$$

The excitation system is incorporated with the synchronous alternator. In this article, a self-excited DC generator exciter has been used, whose scaled dynamic equation will be

$$T_E \frac{\mathrm{d}E_{fd}}{\mathrm{d}t} = -\left(K_{E_{\text{self}}} + S_E\left(E_{fd}\right)\right)E_{fd} + V_R\,, \tag{11}$$

$$K_{E_{\text{self}}} = \left(\frac{V_{\text{res}}}{E_{fd}}\right) - S_E\left(E_{fd}\right). \tag{12}$$

The equation representing the conventional PSS (CPSS) is

$$G_j(s)H_j(s) = \frac{K_{\text{PSS}_j}\left(sT_w\right)\left(1+sT_{1j}\right)\left(1+sT_{3j}\right)}{\left(1+sT_w\right)\left(1+sT_{2j}\right)\left(1+sT_{4j}\right)}\Delta\omega_{\text{elec}}(s). \tag{13}$$

The effective damping of low-frequency oscillations caused by different operating conditions depends on the gain and time constants selection in (13). The optimal values by the proposed WGWO algorithm can be achieved by minimizing the oscillating angular velocity, (ω), and maximizing the damping ratio, (ζ), of the different oscillating modes. Oscillating modes depend upon the eigenvalues of the characteristics equation of the power system. Each eigenvalue has two parts, real and imaginary. For a system of 'n' states, the following equation can be written:

$$\lambda_a = \mathrm{Re}\left[\lambda_a\right] + \mathrm{j}\,\mathrm{Im}\left[\lambda_a\right], \quad a = 1, 2, 3, \ldots, n, \tag{14}$$

and their corresponding damping ratio and oscillating frequency will be:

$$\varsigma_a = \frac{\mathrm{Re}\left[\lambda_a\right]}{|\lambda_a|}, \qquad f_{\mathrm{osc}_a} = \frac{|\mathrm{Im}\left[\lambda_a\right]|}{2\pi}. \tag{15}$$

The objective function can be formulated as:

$$\mathrm{ObjFn} = \left(\sum_{a=1}^{n} \left(\mathrm{Re}(\lambda_0) - \mathrm{Re}(\lambda_a)\right)^2 + \alpha \sum_{a=1}^{n} \left(\varsigma_0 - \varsigma_a\right)^2 \right), \tag{16}$$

where λ_0 and ζ_0 represent the threshold values of the damping ratio and eigenvalue real part.

Corresponding to the above objective function, the following are the constraints:

$$\left. \begin{array}{c} K_{PSS_j}^{\min} \le K_{PSS_j} \le K_{PSS_j}^{\max} \\ T_{a_j}^{\min} \le T_{a_j} \le T_{a_j}^{\max} \end{array} \right\}, \tag{17}$$

where j belongs to the generator number, where $a = 1, 2, 3, 4$, and maximum values of 2 and 50 are for the time constant and gain, respectively, whereas minimum values are 0.01 and 0.1.

4. Results and discussions

The performance of the PSS in damping oscillations has been investigated on the benchmark of a two-area four-machine system under a temporary three-phase fault condition for a duration of 0.1 s at $t = 1$ s in the first area. The optimal parameters obtained with the suggested WGWO algorithm, GWO, and butterfly optimization algorithm (BOA) have been listed in Table 1. All the considered algorithms have been validated under similar system hardware configurations and all the algorithms have considered 500 iterations for the optimal parameter selection with 30 search agents.

The optimal controller parameters obtained with the suggested GTO algorithm with the convergence characteristics as shown in Fig. 1. The balance between exploration and exploitation phases can be observed in Fig. 1 and resulted in minimal value over the total number of iterations.

The suggested algorithm has been developed with an aim to improve the damping characteristics through the eigenvalues. The eigenvalues with the traditional PSS settings and optimally tuned PSS settings with various algorithms have been listed in Table 2. Due to the temporary fault condition considered, the system eigenvalues represent oscillations in their states. There are

Table 1. Controller parameters tuned with WGWO algorithm

		K	T_1	T_2	T_3	T_4
Gen 1	GWO	6.845428	0.054031	0.954708	0.147582	0.156542
	BOA	10.40461	0.533423	0.351841	0.445511	0.100166
	WGWO	12.9766	0.25839	0.715922	0.27753	0.210477
Gen 2	GWO	50	0.044758	0.027421	0.259751	0.292216
	BOA	11.22141	0.242298	0.143817	0.399887	0.512919
	WGWO	14.36073	0.058524	0.020145	0.233384	0.121289
Gen 3	GWO	0.228428	0.011145	0.31342	0.667661	0.264126
	BOA	18.13538	0.421832	0.336861	0.131331	0.283483
	WGWO	4.953507	0.193727	0.471602	0.168824	0.125772
Gen 4	GWO	3.961443	0.913467	0.937595	0.31348	0.448423
	BOA	12.99604	0.128612	0.120114	0.181521	0.47514
	WGWO	11.57923	0.177017	0.436324	0.208057	0.189586

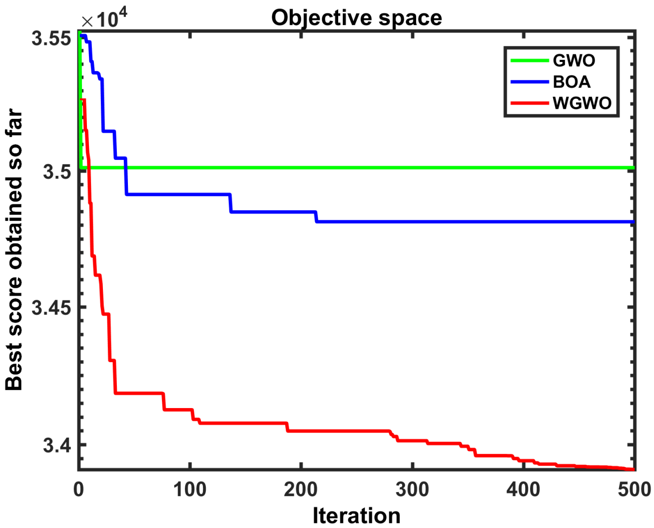

Fig. 1. Convergence characteristics of considered algorithms

negatively damped oscillations caused by the CPSS that may lead to unstable conditions as well. However, the system with the proposed WGWO-tuned PSS resulted in positive damping ratios, which will result in quick damping of the oscillations, over the other state-of-the-art algorithms. Further, the location of the eigenvalues has been depicted in Fig. 2.

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Table 2. Test system eigenvalues with oscillating frequencies

CPSS			GWO		
Eigen values	**Frequency (in Hertz)**	**Damping ratio (ζ)**	**Eigen values**	**Frequency (in Hertz)**	**Damping ratio (ζ)**
133.3641	0	–1	−90.5445+0.1145i	0.0173858	0.99669918
98.49633	0	–1	−3.2400 – 8.8647i	1.4154800	0.36167686
1.17455 + 67.9349i	10.8045771	–0.0172403	−3.6871 + 8.0633i	1.2854006	0.41656879
3.27688 + 26.4248i	4.2064869	–0.1232720	−2.5698 – 5.7357i	0.9169115	0.40886582
0.087572	0	–1	−2.1380 + 5.1560i	0.8166838	0.3854410
−0.01344 + 0.0301i	0.0048959	0.48052280	−1.5629 – 4.1812i	0.6567963	0.35155217
0.038577	0	–1	−0.6319 + 1.4735i	0.2352730	0.37608546
0.027505	0	–1			
0.01255	0	–1			
BOA			**WGWO**		
Eigen values	**Frequency (in Hertz)**	**Damping ratio (ζ)**	**Eigen values**	**Frequency (in Hertz)**	**Damping ratio (ζ)**
−7.3378 – 12.8658i	2.0468428	0.49542077	−90.9198+0.0992i	0.0157916	0.99999940
−8.3939 + 9.5604i	1.5209737	0.65977826	−4.7711+10.4819i	1.6675862	0.41427558
−2.9476 – 6.5331i	1.0393573	0.41126858	−4.2421 – 9.8124i	1.5610649	0.39682909
−2.3666 – 4.9645i	0.7898108	0.43031382	−9.7675 + 0.4086i	0.0650196	0.99912577
−0.7882 – 3.8440i	0.6115464	0.20087073	−2.8861 – 5.6890i	0.9050818	0.45241929
−1.0367 + 1.1093i	0.1764920	0.68278802	−1.0555 + 3.8154i	0.6070040	0.26662568
			−3.3009 – 3.3335i	0.5303391	0.70362038
			−1.5535 – 0.8885i	0.1413583	0.86805579

The analysis on the system can be further carried out based on the damping characteristics achieved in the system states. Figs. 3 to 4 represent the responses of the system states after the systems have been subjected to a temporary fault condition. Here, at $t = 1$ s, oscillations have been initiated in the torque angle, angular speed, active power delivered responses and post fault condition, they are being damped with the PSS. When comparing the CPSS and other methods with the proposed WGWO-based PSS, quicker damping can be observed once a fault has been cleared at $t = 1.1$ s.

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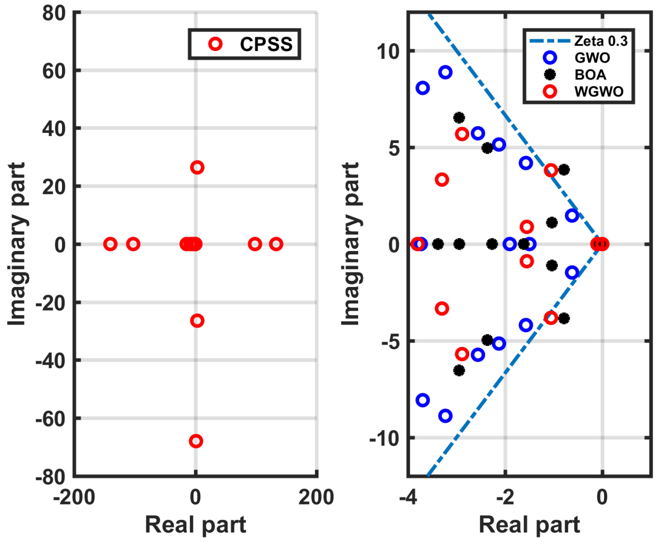

Fig. 2. The pictorial representation of eigenvalue location

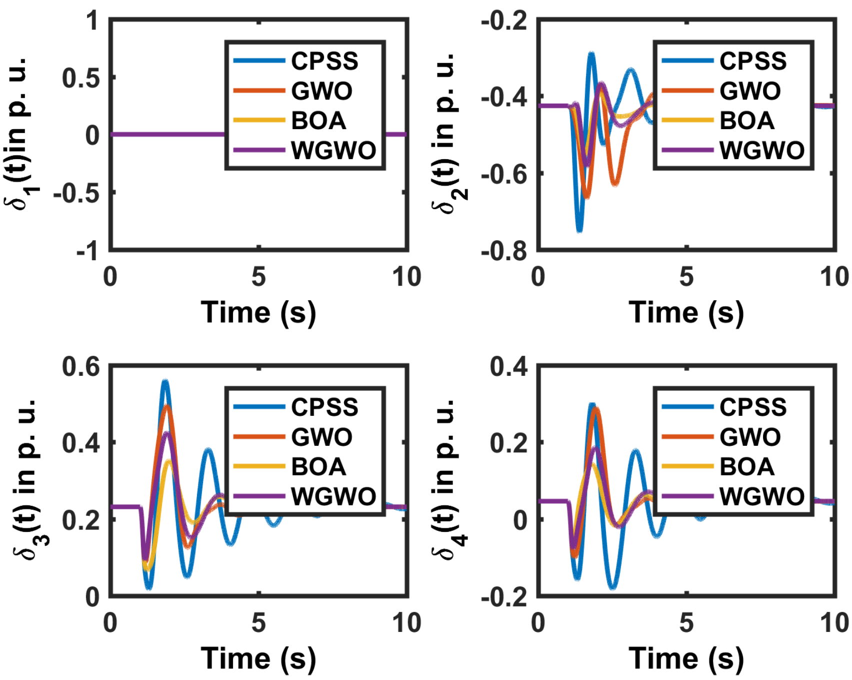

Fig. 3. The nature of oscillations in torque angle of four generators

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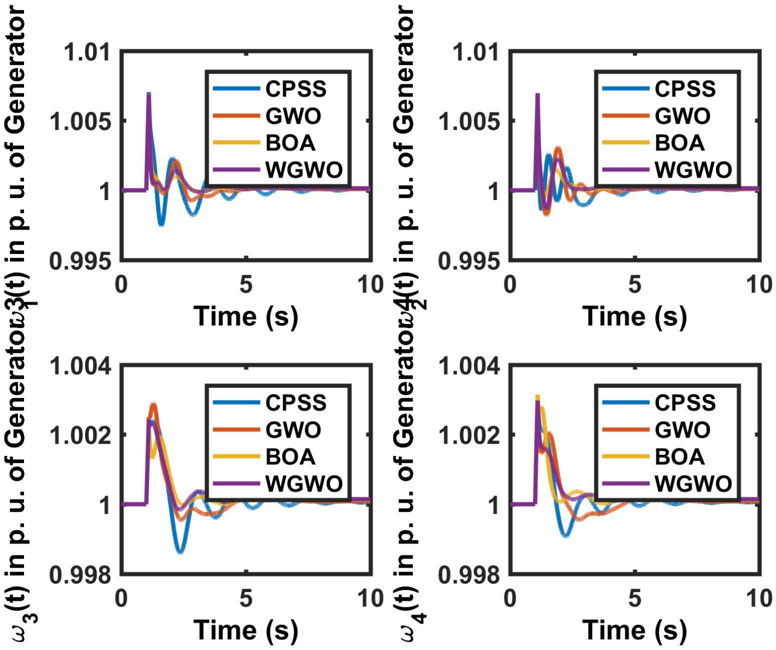

Fig. 4. The nature of oscillations in angular speed of four generators

5. Conclusions

A two-area four-machine power network has been investigated in this paper for power system oscillation damping. A novel weight function-based GWO approach has been proposed, which has an affinity to avoid stuck in local optima and can result in faster convergence characteristics over the total number of iterations. The optimal parameter selection of a PSS has been recommended through the WGWO algorithm. The suggested approach resulted in effective damping of system oscillations under temporary fault conditions. The eigenvalues resulted with the suggested approach represent higher damping ratios over state-of-the-art methods. The responses of the system states also proved that the proposed WGWO-based PSS resulted in quick damping of oscillation caused in the test system. Hence, the proposed WGWO algorithm can be recommended for the larger power systems for tuning controller performance, and the algorithm can be used in different areas of electrical engineering optimization problems. The proposed algorithm can be further extended to the other engineering problems as future work, also the non-linear variation of the “*a*” parameter may give better performance characteristics for some research problems.

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