Series and shunt FACTS controllers based optimal reactive power dispatch

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Article Info

Article history:

Received Jun 7, 2023
Revised Nov 15, 2023
Accepted Nov 28, 2023

Keywords:

Active power loss
Operating cost
SVC
TCSC
Whale optimization algorithm

ABSTRACT

Optimal reactive power dispatch involves the determination and management of reactive power resources in a power system to maintain voltage stability, improve power transfer capability, and minimize system losses. Reactive power is essential for maintaining voltage levels within acceptable limits and ensuring the reliable operation of electrical networks. The whale optimization algorithm (WOA) has been proposed to obtain the optimal location of flexible alternating current transmission system (FACTS) components. The efficacy of WOA is tested using conventional IEEE 14 and 30 bus test systems. Static var compensator (SVC) is used as shunt and the thyristor-controlled series capacitor (TCSC) as a series FACTS controller. The analysis is carried out for both the systems with and without FACTS controllers. Optimization techniques are applied to select the optimal control parameters. The suggested strategy is compared to other contemporary techniques such as particle swarm optimization (PSO) and grey wolf optimization (GWO). At various loading situations, the WOA-based technique outperforms other two techniques.

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1. INTRODUCTION

Due to rising power consumption, the electrical networks are becoming more complicated day by day. The deficit power demand can be fulfilled either by building new transmission lines or by increasing the performance of the existing system. The construction of transmission lines is not recommended because of economic and environmental factors. It is also critical to make effective use of existing transmission lines. Flexible alternating current transmission system (FACTS) controllers are installed in the current power system to increase the power transmission line's maximum transfer capacity.

This literature review aims to investigate and summarize the existing research on reactive power planning of IEEE 14 and 30 bus systems using metaheuristic techniques. FACTS devices offer significant benefits in terms of grid control [1], stability [2], and system security [3]. Power system stability is also achieved by incorporating FACTS devices [4]. The several FACTS controller types are described in [5]. Different strategies can be used to optimize reactive power, however most of them are being suffered from premature convergence [6]. Evolutionary approaches provide a higher potential for reliable and cost-effective power system operation [7]. The FACTS devices' allotment procedures are classified as heuristic or analytical [8]. FACTS devices are used to discuss the optimal power flow model [9]–[11]. A series compensator is used to address a power flow control approach [12]. FACTS based power flow analysis are explained in [13]. The reactive power planning (RPP) challenges are described in [14]. A unique technique for optimally positioning FACTS controllers in multi-objective issues is explored [15]. A novel sine cosine algorithm is used in [16] to address the minimizing of loss and running cost. The selection of weak buses is determined for establishing a reactive power supply. The operating cost is minimized in IEEE 14 [17] and 30 bus [18], [19]. On the basis of the steady state model of these controllers, the control of power flow is investigated in [20]. The ideal position for the FACTS controllers is chosen using a loss sensitivity and performance index sensitivity technique [21]. By strategically placing a static var compensator (SVC) on the grid, a multi-objective problem involving increasing system loading and reducing power loss was solved [22]. Fuzzy-SVC controller is suggested in [23] to improve the system's transient stability. A modified differential algorithm based on statistical analysis is proposed in [24] for optimal reactive power dispatch. Though several research works have been done for minimization of losses by incorporating FACTS controllers, still there are scope for improvement by using some promising and efficient techniques. In this work, the whale optimization algorithm (WOA) has been implemented for loss and cost optimization.

2. PROBLEM FORMULATION

The primary objective in this study is to minimize the losses satisfying some constraints. The power loss can be expressed using (1).

$$P_L = \sum_{k=1}^{l} G_k [{V_a}^2 + {V_b}^2 - 2V_a V_b \cos(\delta_a - \delta_b)] \tag{1}$$

Where, line number is denoted by l, G_k denotes conductance of kth line, V_a and V_b denotes the respective voltage of buses a and b; δ_a and δ_b are the respective voltage angle of buses a and b.

The equality restrictions definition using (2) and (3).

$$P_{G_x} - P_{D_x} - V_a \sum_{b=1}^{n_b} V_b [G_{ab} \cos(\delta_a - \delta_b) + B_{ab} \sin(\delta_a - \delta_b)] = 0, x = 1,2, \ldots n_b \tag{2}$$

$$Q_{G_x} - Q_{D_x} - V_a \sum_{b=1}^{n_b} V_b [G_{ab} \sin(\delta_a - \delta_b) - B_{ab} \cos(\delta_a - \delta_b)] = 0, x = 1,2, \ldots n_b \tag{3}$$

Where n_b is bus number P_{G_x} and Q_{G_x} indicates both active and reactive power generated. P_{D_x} and Q_{D_x} denotes active and reactive power demand; G_{ab} and B_{ab} denotes respective conductance and susceptance between buses a and b.

The inequality limitations are defined as generator's voltage limits and reactive power limit given by (4) and (5).

$$V_G{}^{min} \leq V_G \leq V_G{}^{max} \tag{4}$$

$$Q_G{}^{min} \leq Q_G \leq Q_G{}^{max} \tag{5}$$

Transformer tap setting limits are determined by (6).

$$t^{min} \leq t \leq t^{max} \tag{6}$$

The shunt capacitor's var output limit is determined by (7).

$$Q_C{}^{min} \leq Q_C \leq Q_C{}^{max} \tag{7}$$

The SVC limit is given by (8).

$$Q_{SVC_x}{}^{min} \leq Q_{SVC_x} \leq Q_{SVC_x}{}^{max} \tag{8}$$

The operating cost is expressed by (9).

$$C_{Operating} = P_{Loss} \times 0.06 \times 10^5 \times 365 \times 24 \tag{9}$$

3. OPTIMAL POSITIONING OF FACTS CONTROLLERS

Power flow analysis is used to determine the position of FACTS controllers in the transmission line. The SVC locations are identified as the weak buses. High reactive power lines are considered for thyristor-controlled series capacitor (TCSC) deployment. Table 1 shows the position of FACTS controllers in the systems considered. In a conventional IEEE 14 test system, bus numbers 10, 13, and 14 are assigned to SVC, whereas line number 7 is assigned to TCSC. The SVC is deployed on buses 21, 7, 17, and 15 in IEEE 30 bus system, whereas the TCSC is located on lines 5, 25, 41, and 28.

Table 1. Location of FACTS controllers

Standard	Line number for TCSC placement	Buses for SVC placement
IEEE 14	7	10,13,14
IEEE 30	5, 25, 28, 41	7, 15, 17, 21

4. WOA METHOD

It is a nature-inspired optimization technique based on the social behavior of humpback whales [25]. It mimics the hunting strategy of whales, where a leader whale guides a group to locate prey. In WOA, potential solutions are represented as a population of whales, with the best solution being the leader. Whales move towards the leader to improve their fitness, and as the optimization process progresses, they gradually converge towards the global optimum. The algorithm incorporates exploration and exploitation phases, balancing exploration of new areas and exploitation of promising regions. WOA is applied in various optimization problems to find optimal solutions efficiently. The humpback whale's hunting techniques include searching and encircling the target, and feeding bubble-net.

4.1. Searching and encircling target

When hunting, whales simulate searching and encircling prey. Whales move towards the prey (optimal solution) while maintaining a balance between exploration and exploitation. The leader whale guides the group's movements, ultimately converging towards the prey by encircling it to find the optimal solution in the search space. This process can be expressed mathematically in (10) and (11).

$$\vec{D} = \left|\vec{P}.\overrightarrow{X^*}(t) - \vec{X}\,(t)\right| \tag{10}$$

$$\vec{X}(t+1) = \overrightarrow{X^*}(t) - \vec{Q}.\vec{D} \tag{11}$$

Where $\vec{D}$ represents the distance between whale and target, t is the current iteration, and the position vector is represented by $\vec{X}$. Vectors $\vec{Q}$ and $\vec{P}$ are shown in (12) and (13).

$$\vec{Q} = 2\vec{q}.\vec{r} - \vec{q} \tag{12}$$

$$\vec{P} = 2.\vec{r} \tag{13}$$

$\vec{q}$ is reduced from two to zero.

4.2. Bubble-net feeding method

The difference between whale and prey is estimated by (14).

$$\vec{X}(t+1) = \vec{D}.e^{kl}\cos(2\pi l) + \overrightarrow{X^*}(t) \tag{14}$$

Where, $\vec{D} = \left|\overrightarrow{X^*}(t) - \vec{X}\,(t)\right|$; l is any value in [-1,1]; k is a constant. The formula for the updated whale location is expressed as (15).

$$\vec{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \vec{Q}.\vec{D} & if\ m < 0.5 \\ \overrightarrow{D'}.\ e^{kl}\ \cos(2\pi l) + \overrightarrow{X^*}(t) & if\ m \geq 0.5 \end{cases} \tag{15}$$

m is any number in the range [0,1].

4.3. Search for prey process

The exploration is achieved by $\vec{B}$ and given in (16) and (17).

$$\vec{D} = \vec{P}\,\vec{X}_{rand} - \vec{X} \tag{16}$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{Q}.\vec{D} \quad (17)$$

$\vec{X}_{rand}$ is a random position vector.

5. RESULTS AND DISCUSSION

IEEE 14 and 30 bus systems with varying loading are used to examine the effectiveness of WOA for loss reduction. For a performance comparison, particle swarm optimization (PSO) and grey wolf optimization (GWO), two promising algorithms, are taken into account. The simulation is run in MATLAB 2019a software, and the graphical comparisons are analyzed. Power flow study identifies the buses 10, 13, and 14 as weak nodes, and these buses are the ones that will receive SVC installation. The seventh line is seen to be the most pertinent for the TCSC site. The comparison of active power loss (APL), operational costs, and % loss reduction under different active and reactive loadings of the IEEE 14 bus system are shown, respectively, in Tables 2-4. The loss convergence graph of an IEEE 14 bus system is shown in Figures 1-3 for active and reactive loading levels of base, 110%, and 120%. It is evident from the table, WOA reduces loss, cost, and hence percentage loss reduction significantly with respect to PSO and GWO.

Table 2. Analysis of losses before and after incorporating FACTS controllers under different loadings in IEEE 14 bus

Loading (%)	APL before incorporating FACTS controllers (p.u.)	APL after incorporating FACTS controllers (p.u.)		
		PSO	GWO	WOA
100	0.1554	0.132769	0.131942	0.040762
110	0.1973	0.1651	0.16392	0.05006
120	0.2295	0.2012	0.1992	0.0670

Table 3. Analysis of operating cost using PSO, GWO, and WOA based approaches in IEEE 14 bus system

Loading (%)	Operating Cost before incorporating FACTS controllers ($)	Operating Cost after incorporating FACTS controllers × 10^5 in $		
		PSO	GWO	WOA
100	8173080	6978338.64	6934871.52	2142450.72
110	10375344	855878.4	8615635.2	2631153.6
120	15452640	1043020.8	10469952	3521520

Table 4. Loss reduction in percentage at various loadings using PSO, GWO, and WOA methods in IEEE 14 bus system

Loading (%)	PSO	GWO	WOA
100	14.665	15.149	73.786
110	16.362	16.96	74.36
120	12.292	13.164	70.793

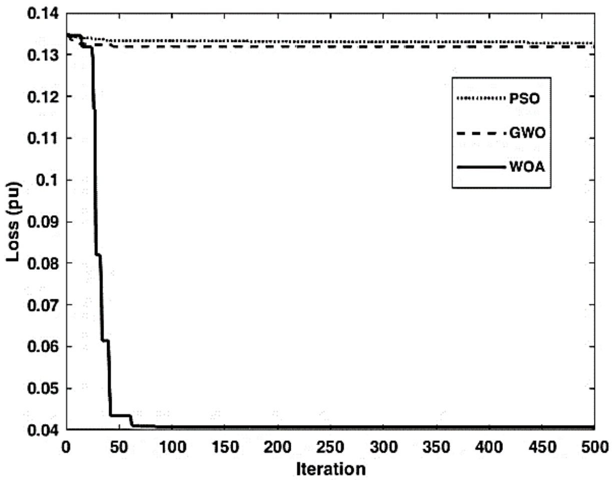

Figure 1. Loss convergence curve of IEEE 14 bus under 100% loading

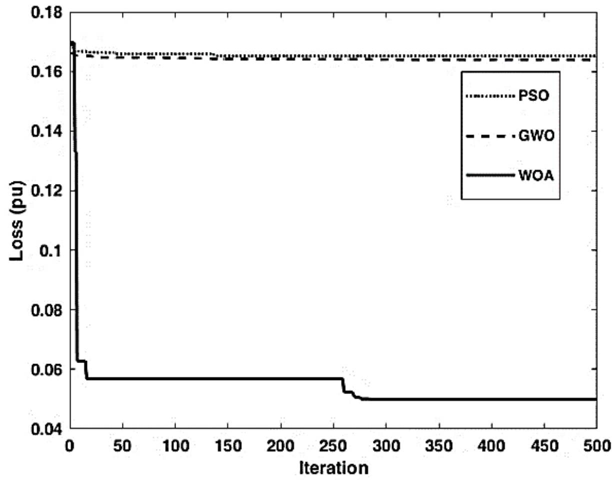

Figure 2. Loss convergence curve of IEEE 14 bus under 110% loading

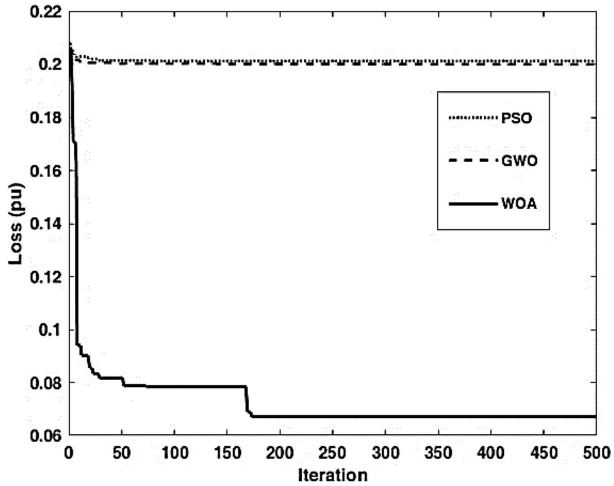

Figure 3. Loss convergence curve of IEEE 14 bus under 120% loading

Tables 5-7 compares, respectively, the losses, operational cost, and percentage loss reduction at various active and reactive loadings of IEEE 30 bus system. Figures 4-6 shows the loss convergence graph of an IEEE 30 bus system at base, 110%, and 120% active and reactive loading. It is evident from the Tables 5-7, WOA reduces loss, cost and hence percentage loss reduction significantly as compared to PSO and GWO.

Table 5. Analysis of losses with and without FACTS controllers under different loadings in IEEE-30 bus

Loading (%)	APL before incorporating FACTS controllers (p.u.)	APL after incorporating FACTS controllers (p.u.)		
		PSO	GWO	WOA
100	0.0719	0.069653	0.069138	0.068914
110	0.0970	0.094756	0.094513	0.094122
120	0.1288	0.12473	0.12369	0.080357

Table 6. Comparison of operating cost using PSO, GWO, and WOA based approaches in IEEE 30 bus system

Loading (%)	Operating cost before incorporating FACTS controllers ($)	Operating cost after incorporating FACTS controllers $\times 10^5$ in $		
		PSO	GWO	WOA
100	3779064	3660961.68	3633893.28	357250.176
4110	5098320	4980375.36	4967603.28	4946947.2
120	6769728	6555808.8	6501146.4	42235639.2

Table 7. Loss reduction in percentage at various loadings using PSO, GWO, and WOA methods in IEEE-30 bus system

Loading (%)	PSO	GWO	WOA
100	3.125	3.841	4.152
110	2.313	2.563	2.969
120	3.159	3.967	37.61

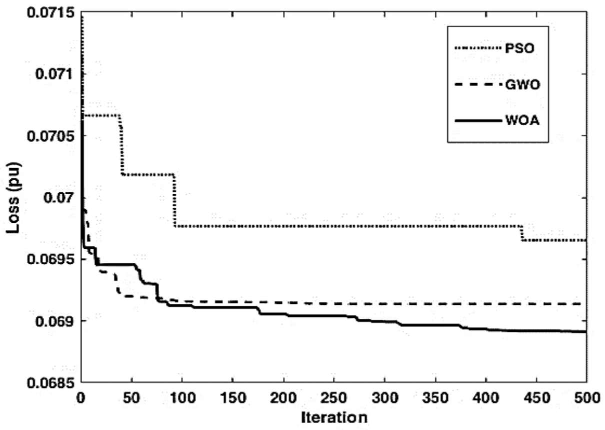

Figure 4. Loss convergence curve of IEEE 30 bus under 100% loading

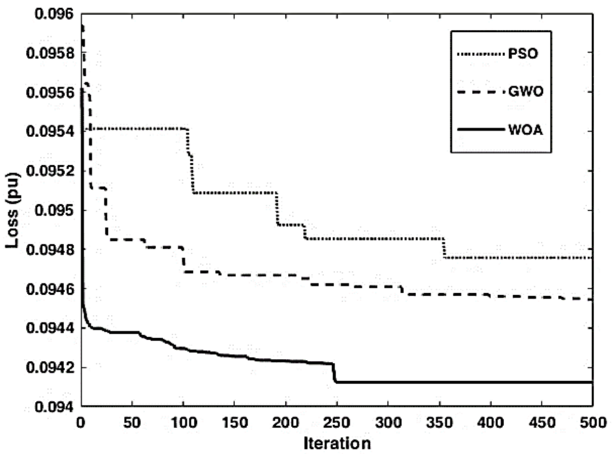

Figure 5. Loss convergence curve of IEEE 30 bus under 110% loading

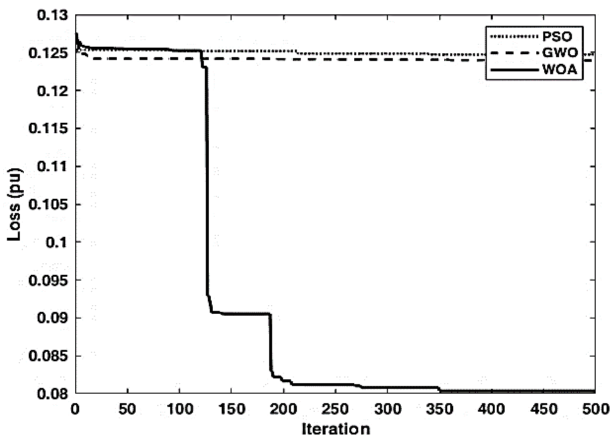

Figure 6. Loss convergence curve of IEEE 30 bus under 120% loading

6. CONCLUSION

The optimal placement of FACTS devices for reactive power planning requires a detailed power system analysis, including load flow studies, and voltage stability analysis. In this study, the efficacy of the WOA is analyzed by considering the IEEE 14 and 30 bus system. The outcomes of optimization approaches based on PSO and GWO are compared to the outcomes of a WOA-based approach. It has been observed from the result that WOA outperforms PSO and GWO in IEEE 14 and 30 bus systems under base, 110% and 120% loading. Active power loss and hence operating expenses are greatly reduced in both the IEEE 14 and 30 bus systems. As a result, it can be suggested that WOA is a superior optimization technique for volt amperes reactive (VAR) planning of power systems. This work may be extended for higher test bus system to achieve better performance in terms of operating cost and voltage stability.

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