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IET Renewable Power Generation

ORIGINAL RESEARCH

Analysis of reactive power loadability and management of flexible alternating current transmission system devices in a distribution grid using whale optimization algorithm

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Abstract

The optimal injection of reactive power to minimize power loss and manage voltage profiles is a difficult task that must be addressed and managed effectively for the power system's reliability. The distribution network indices like voltage stability, loss minimization, and power quality enhancement can be improved by the effective management of reactive power regulation. Aside from its interaction with reactive power management, the best location and sizing in a cost-effective strategy have an impact on overall performance. As a broadly accepted swarm intelligence method in various engineering fields due to its simple assembly, less entails operator constraints, wild convergence speed, and better harmonizing ability between exploration and exploitation faces, the Whale Optimization Algorithm (WOA) is used in conjunction with a Flexible Alternating Current Transmission System (FACTS) device in this paper to manage reactive power effectively. The WOA was implemented and compared with Differential Evolution (DE), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) at 100%, 150%, and 200% load in the IEEE 30 test system. The results reveal that the suggested WOA produces a greater impact on cost management, power loss, and reactive power balance than any previous evolutionary algorithm.

1 | INTRODUCTION

1.1 | Background

The modern electric power system is quite prolonged concerning the requirement of the twenty-first century, where there is the inclusion of more renewable energy resources and critical parts. Quality of electric power is one of the most prolific keywords in utilities and for end-users of electric power. The stability issues in the distribution system are associated with the phrase 'reactive power management' or Volt-Amps Reactive (VAR), which controls the superintend coordination of the reactive power of the alternating current (AC) system implementation [1]. The keyword 'reactive power management' is

TABLE 1 Correlation of basic types of FACTS controllers and their impact on different applications

Compensators	Compensator type	Power flow performance	Transient stability	Cost analysis	Voltage regulation
Fixed capacitor	Static	Medium	Medium	Very low	Small
TCSC	Static	Medium	Strong	Average	Medium
SVC	Dynamic	Small	Strong	Average	Strong
STATCOM	Static	Fast	Strong	High	Average

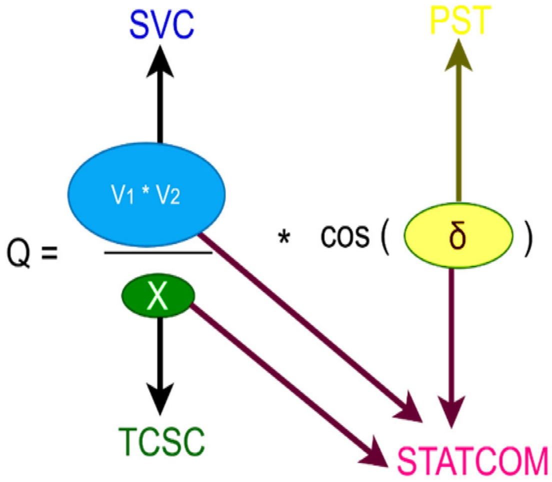

FIGURE 1 The regulator constraints of FACTS devices in reactive power management.

also linked with voltage support, load management, harmonic elimination, and voltage fluctuation. Thus, the application of reactive power compensators such as flexible alternating current transmission system (FACTS) devices boosts the AC system's performance technically and economically. The reactive power flow analysis between two buses with bus voltages V_1 and V_2 with respective phase angles is depicted in Equation (1).

$$Q = \frac{-V_1^2}{X} + \frac{V_1 V_2}{X} \cos\delta \tag{1}$$

The performance of the reactive power is affected by the bus voltages, and the angle differences are delimited below 35° [2]. Furthermore, the striking objective of FACTS devices with the controlled constraints for the performance analysis is crucial from the electrical system operation point of view. Figure 1 enlists the controlled parameters of FACTS devices in an electrical system operation.

The impact of different control factors (voltage and phase angle) on reactive power planning with FACTS devices is deliberated in [3]. Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Compensator (TCSC), and Static VAR Compensator (SVC), along with Phase Shifting Transformer (PST), are considered for the reactive power planning as sketched in Figure 1. The detailed comparison of those is explained in Table 1. The increased productivity for all utility customers is the underlying theme that connects all the reasons for raised concern about the quality of the power. Therefore, the FACTS device must be connected to the distribution system in a way that prevents the degradation of power quality and its dependability, which allows for the use of concurrent optimization techniques for device placement [4].

1.2 | Literature review

The selection of FACTS devices depends on their envisioned use [5]. Series compensator family devices such as the TCSC [6] control the impedance factor. Similarly, the parallel compensator family promotes reactive power support. At the same time, the series-shunt controller amends both system parameters as illustrated in [7]. Generally, the optimal placement of FACTS devices, the capacity of FACTS devices, and the general classification of FACTS devices are the major concerns in the selection of FACTS devices.

A comparison of FACTS devices is deliberated in Table 1. It can be perceived from Table 1 that STATCOM is a strong contender among other FACTS devices. The installation cost of STATCOM is higher than other FACTS devices. But the voltage stability is more secure with the SVC than STATCOM. But when a fixed capacitor is combined with any of the FACTS devices, it produces an improved outcome compared with single FACTS devices.

Furthermore, several authors have devised different approaches suitable for the optimal placement of FACTS devices. The best placement and rating of FACTS devices are analyzed using analytic approaches, conventional optimization, metaheuristic optimization, and hybrid methods [6]. In [7], the optimal placement of the SVC, TCSC [8], and Static Compensator (STATCOM) is focused, and a distributed voltage control is achieved by providing reactive power resources. The IEEE 30 bus test system is used in the experimental analysis through different optimization approaches. Then evolutionary programming is considered to determine the optimal location of the SVC, TCSC, and STATCOM [9].

Further, in [10], congestion management in the deregulated power system with optimal placements of TCSC [11] and STATCOM is described. This work proposed congestion management in cost and location without including other reactive power management. In addition, they observed the IEEE 14 test system in this work. At the same time, more comparison work is noted and explained in this work.

A stimulating study using the Controller Hardware-in-the-Loop (CHIP) is performed in [8]. The STATCOM used for this work focuses on grid services such as power flow control, harmonic mitigation, and oscillation fluctuation.

Although the Available Transfer Capacity (ATC), another major key factor, is determined by the location, size, and cost of its low-cost energy transfer to the load characteristics. Furthermore, the allocation of multiple FACTS devices, such as the SVC, TCSC, unified power flow controller, and STATCOM, is empowered by ATC, as described in [9]. A novel reactive power control using the photovoltaic (PV)-STATCOM entitled [10]. The response time of the proposed work is two times faster than the common STATCOM. Then in [11], a distributional locational marginal pricing in the distribution network is explained. But no FACTS devices are mentioned in this work. In [12], the adaptive neuro-fuzzy inference system (ANFIS)-Particle Swarm Optimization (PSO) and ANFIS-Genetic Algorithm (GA) have been proposed for the stability management of the STATCOM. Test results show that stability and voltage control have improved so far by using this new technique.

'Distribution generation' (DG) stands for one of the strongest keywords of the modern power grid. In general, the voltage stability of the DG demands the upper and the lower operational limit to circumvent the voltage fluctuation. As a result, reactive power planning incorporated with resilience to voltage stability is followed by power quality support. Both the PSO and GA recommend minimizing the objective function of DG performance of the STATCOM, which is introduced in [13]. This hybrid proposal reduces the annual cost minimization in the distribution network. Installation of the renewable energy-based distribution network using PSO through STATCOM is explained in [14]. Loss reduction and cost management are the major concern dealt with in this paper.

The IEEE 30 test system is used for this analysis. The optimal placement of multiple STATCOMs for voltage stability is also analyzed in this work. Simultaneous operation of PSO and continuous power flow (CPF) provide apt results. In [15], conventional reactive power dispatch studies the TCSC and SVC presented. This study emphasizes the implementation loss of FACTS devices. An efficient and reliable evolutionary approach is portrayed in [16]. Fuel cost minimization is also discussed in this work in addition to reactive power control.

Furthermore, a comprehensive learning PSO is used for the reactive power dispatch (RPD) as illustrated in [17]. The Gravitational Search Algorithm with the RPD study is explained in [18]. Studies with the STATCOM and RPD have not been conducted so far. Reactive power support based on cost analysis presented in [19] and the voltage profile enhancement depends on the reactive power support with a minimum transmission loss. RPD [20] is a key grid service that provides optimal reactive power flow, power loss, and voltage fluctuation in the system as considered in [21]. Both the TCSC and SVC are observed in the IEEE 30 bus used for the RPD. Reactive power planning associated with different evolutionary algorithms adopts a cost-effective strategy in distribution networks revealed in [22]. A detailed comparison investigation of reactive power planning utilized with PSO [23], Evolutionary Particle Swarm Optimization (EPSO) [24], Hybrid PSO (HPSO), and finally adaptive PSO (APSO) [25] delivered with the best cost-effective value in this work.

Further, bio-inspired algorithms implement the reactive power planning for the cost minimization executed in [27]. This work comes up with the option GWO-PSO positioned as the best combo for optimal reactive power planning [28]. In this work, multi-objective optimal power flow with FACTS devices is marked in detail by taking real and reactive power limits, voltage, and line flow limits, and the FACTS devices operational limit, as explained in [26]. FACTS location, voltage rating, and sizing are the major goals analysed by different IEEE test systems achieved in [27]. The PSO and GA are also proposed in this work. However, the optimal allocation of different parameters of DG is not debated.

1.3 | Research gap and motivation

The best location of different FACTS devices [28] at the weak bus, which is decided through sensitivity analysis and speedy determination of the sizing of these devices, has not been proposed yet. The Whale Optimization Algorithm (WOA) for the optimal sizing of the STATCOM [29] in the presence of other FACTS devices such as the SVC and TCSC in a distribution network has never been dealt with in the literature yet. This work proposes a sensitivity analysis performed primarily by the L_{mn} index and PV curves construction of the load bus, thus governing the ideal location for the SVC and TCSC. PV curves generate the weak bus because of their sensitive nature towards voltage fluctuation. The location of the STATCOM is determined by the WOA. Furthermore, the results from the WOA are also compared with the results from GA, PSO, and DE (differential evolution) [3]. The optimal synchronization of the reactive power management using the optimal distribution of FACTS devices resolute with existing reactive power sources such as transformer tap setting and reactive power from the generator.

1.4 | Contribution and paper organization

The goal of the proposed work is to identify ways to reduce operational costs, which include reactive power costs and FACTS device installation costs. The fitness function used in this work is the reactive power rating achieved by the generator and transformer tap changing. Reactive power sources that were already in place were used in this work for cost- and placement-effective placement. The impact of FACTS devices on reactive power management and cost supervision using the best placement of FACTS devices with WOA in the distribution network is the research question that is highlighted in this work.

The following is a summary of the paper: Introduction is provided in Section 1, and modelling of FACTS devices is described in Section 2 to determine whether the custom power devices considered in this work are cost-effective in a distribution network system. The best locations for FACTS devices are described in Section 3. Additionally, Section 4 shows the mathematical formulation and how the suggested algorithm is used in the proposed work followed by results and discussion in Section 5. The conclusions are drawn in Section 6 along with limitation and future research scope.

2 | MODELLING OF FACTS DEVICES

FACTS controllers are faster when compared with other controller performances because of their response time, cost, and efficiency [28]. The shunt is enabled by the FACTS controller SVC, and the series compensator performance is enhanced by the TCSC. The STATCOM is a shunt-connected static compensator and is well established for its faster response in voltage stability along with reactive power compensation. In this work, these FACTS controllers focus on reactive power management and voltage stability enhancement in the distribution system.

2.1 | Modelling of the TCSC

The inductive and capacitive compensation depends on the firing angle of the thyristor [30]. As a series compensator, it works on system impendence performance. TCSC modelling is performed by L_{mn} index which provides both best position and effective cost management in a distribution network system. The mathematical prototype of TSCS is depicted in Figure A1 of Appendix A.

In TCSC, the power flow equations from ith to jth and jth to the ith bus with corresponding active and reactive power are given below in Equations (2) to (5):

$$P_{\mathrm{ij}} = V_{\mathrm{i}}^{2}\ R - V_{\mathrm{i}}V_{\mathrm{j}}R\cos\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) - V_{\mathrm{i}}V_{\mathrm{j}}\sin\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) \quad (2)$$

$$Q_{\mathrm{ij}} = -\mathrm{V}_{\mathrm{i}}^{2}\ X - V_{\mathrm{i}}V_{\mathrm{j}}R\sin\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) - V_{\mathrm{i}}V_{\mathrm{j}}X\cos\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) \quad (3)$$

$$P_{\mathrm{ji}} = V_{\mathrm{j}}^{2}\ R - V_{\mathrm{j}}V_{\mathrm{i}}X\cos\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) - V_{\mathrm{j}}V_{\mathrm{i}}\sin\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) \quad (4)$$

$$Q_{\mathrm{ji}} = -V_{\mathrm{i}}^{2}\ X - V_{\mathrm{j}}V_{\mathrm{i}}R\sin\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) - V_{\mathrm{i}}V_{\mathrm{j}}X\cos\left(\delta_{\mathrm{i}} - \delta_{\mathrm{j}}\right) \quad (5)$$

2.2 | Modelling of the SVC

Ideally, the SVC is a variable impedance device that enables the consequent thyristor which is established in the development of high-voltage direct current technology. The rate of change of voltage is the same as for a step-down transformer because it works on both the thyristor mode and the extra-high voltage line [31]. The chief characteristic of the SVC is that it either injects or absorbs reactive power when connected to the shunt [32]. The SVC works in both inductive and capacitive regions. In the inductive region, the SVC injects reactive power in a capacitive mode where it absorbs reactive power. The mathematical prototype of SVC is depicted in Figure A2 of Appendix A. Let us assume that SVC is coupled at bus and the estimated reactive power at the bus is given by Equation (6) [33].

$$Q_{\mathrm{SVC}} = Q_{\mathrm{S}} = -V_{\mathrm{s}}^{2}\ B_{\mathrm{SVC}} \quad (6)$$

The linearized equation taking B_{SVC} as a state variable is represented as in Equation (7).

$$\begin{bmatrix} \Delta P_{\mathrm{s}} \\ \Delta Q_{\mathrm{s}} \end{bmatrix}^{(\mathrm{i})} = \begin{bmatrix} 0 & 0 \\ 0 & \mathbf{Q}_{\mathrm{s}} \end{bmatrix}^{(\mathrm{i})} \begin{bmatrix} \Delta Q_{\mathrm{s}} \\ \delta Q_{\mathrm{SVC}}/B_{\mathrm{SVC}} \end{bmatrix}^{(\mathrm{i})} \quad (7)$$

2.3 | Modelling of STATCOM

The STATCOM belongs to the second class of FACTS devices which are mainly used for the shunt reactive power controller. The STATCOM [34] works following the principles of self-communication inverter and draws reactive power from the supply. The STATCOM [34] works following the principles of self-communication inverter and draws reactive power from the supply. Thus, the reactive power regulation using the STATCOM gives better results than other FACTS controllers. The power flow equation of the STATCOM is depicted as follows and the schematic representation of STATCOM can be seen in Figure A3 of Appendix A. The voltage source is mathematically represented as Equation (8).

$$E_{vR} = V_{vR}\ \ (cos\ \delta_{vR} + jsin\ \delta_{vR}) \quad (8)$$

The corresponding real and reactive power is illustrated in Equations (9) to (12).

$$P_{k} = V_{k}V_{vR}\left[G_{vR}\cos\left(\theta_{k} - \delta_{vR}\right) + B_{vR}sin\left(\theta_{k} - \delta_{vR}\right) + V_{k}^{2}G_{vR}\ldots\ldots\ldots\right] \quad (9)$$

$$Q_{k} = -V_{k}V_{vR}\left[G_{vR}\sin\left(\theta_{k} - \delta_{vR}\right) - B_{vR}cos\left(\theta_{k} - \delta_{vR}\right) - V_{k}^{2}G_{vR}\ldots\ldots\ldots\right] \quad (10)$$

$$P_{vR} = V_{k}V_{vR}\left[G_{vR}\cos\left(\theta_{k} - \delta_{vR}\right) + B_{vR}sin\left(\theta_{k} - \delta_{vR}\right) + V_{k}^{2}G_{vR}\ldots\ldots\right] \quad (11)$$

$$Q_{vR} = -V_{k}V_{vR}\left[G_{vR}\sin\left(\theta_{k} - \delta_{vR}\right) - B_{vR}cos\left(\theta_{k} - \delta_{vR}\right) - V_{k}^{2}G_{vR}\ldots\ldots\right] \quad (12)$$

where G_{vR} is conductance of the Y BUS which includes the FACTS devices. B_{vR} is susceptance of the Y bus which includes the FACTS devices.

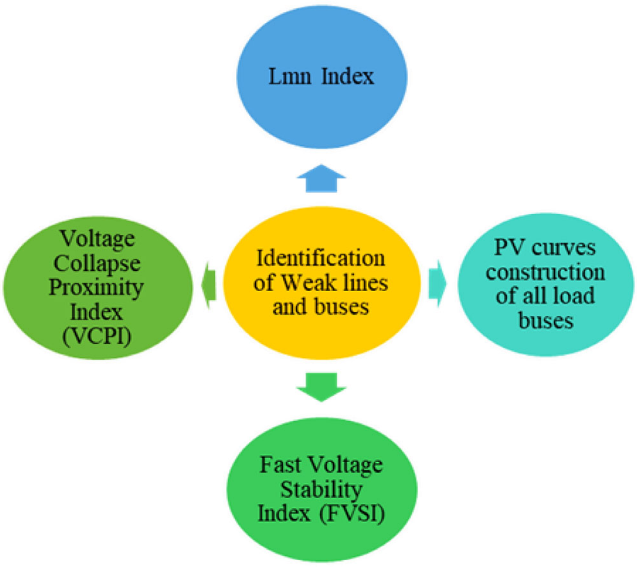

FIGURE 2 Taxonomy of identification of weak bus

3 | OPTIMAL PLACEMENT OF FACTS DEVICES

Generally, the optimal placement of FACTS devices [35] is entrusted with two factors such as power system topology and the demanded output. In this proposed work, the placement of the SVC modified with reactive power flow between the buses and the TCSC helps to control the real power flow by altering the impedance of the line. The STATCOM is performed in terms of voltage control of the system. Mostly, the FACTS devices [24] are located in the weak bus and the weak line. Identification of the weak bus and lines is performed by the L_{mn} index for the TCSC by constructing PV curves of all load buses for the SVC. The number of ways of deciding the weak bus and line is described in Figure 2.

In describing the identification of a weak bus, it is important to scrutinize the key characteristics of the L_{mn} index [36] as compensation for voltage collapse. From Figure 5, the next promising factor is the fast voltage stability index (FVSI) [37], whose response with reactive power in the base case is observed to be precise but is observed losing its accuracy with the change in reactive loading. Likewise, the voltage collapse proximity index (VCPI) depends on the real power, and different loadings develop imprecision in the system [38]. Thus, the L_{mn} index and the constructing PV curves are suitable for the identification of the weak bus.

3.1 | Optimum placement of the TCSC

The placement of the TCSC [39] depends on the L_{mn} index because of its indicator specialty to find the weak bus. The value of the L_{mn} index should be less than 1. If its value is closer to 1, the line will be in the critical stage. The mathematical expression for the L_{mn} index is described as follows in Equation (13) [40]:

$$L_{mn} = \frac{4XQ_r}{\left[V_s \, sin\,(\theta - \delta)\right]^2} \tag{13}$$

where X stands for the reactance of the line, Q_r depicts the reactive power, V_s represents the sending end voltage, and θ, δ show the difference in bus angle and the impedance angle.

3.2 | Optimum placement of the SVC

PV curves are used for this purpose. CPF methodology [41] is applied for the PV curve generation. In the CPF method, predictors and correctors generate outputs through all the loading points. In [42], the PV curve produces all load bus curves. The highest voltage fluctuation stands for the weak bus to recognize the SVC location with ease.

3.3 | Optimum placement of the STATCOM

For optimal placement of the STATCOM, those buses that transmit the higher voltage fluctuation are determined. Furthermore, the STATCOM is placed at this bus where the voltage needs to be controlled. The approach based on the sensitivity method is used for the location of the STATCOM controller [43]. The sensitivity index method is mathematically explained in Equation (14).

$$SI_i = \sum_{j=1}^{i} \frac{\partial V_j}{\partial Q_i} \tag{14}$$

Equation (14) represents the rate change of voltage fluctuation concerning the bus j and i. Bus with a larger SI value is selected as the best location for the STATCOM.

4 | PROBLEM FORMULATION AND OPTIMIZATION

4.1 | Mathematical problem formulation

The objective function of the optimal location of the TCSC, SVC, and STATCOM includes improvement in voltage profile, reduction of the total, real, and reactive power loss, and the operation cost of the system. Moreover, for an efficient outcome, the transformer tap setting and reactive power from generators are selected as fitness functions. The proposed objective function is summarized below in Equations (15) to (20).

$$f_1 = min\left[C_{Energy} + C_{FACTS}\right] \tag{15}$$

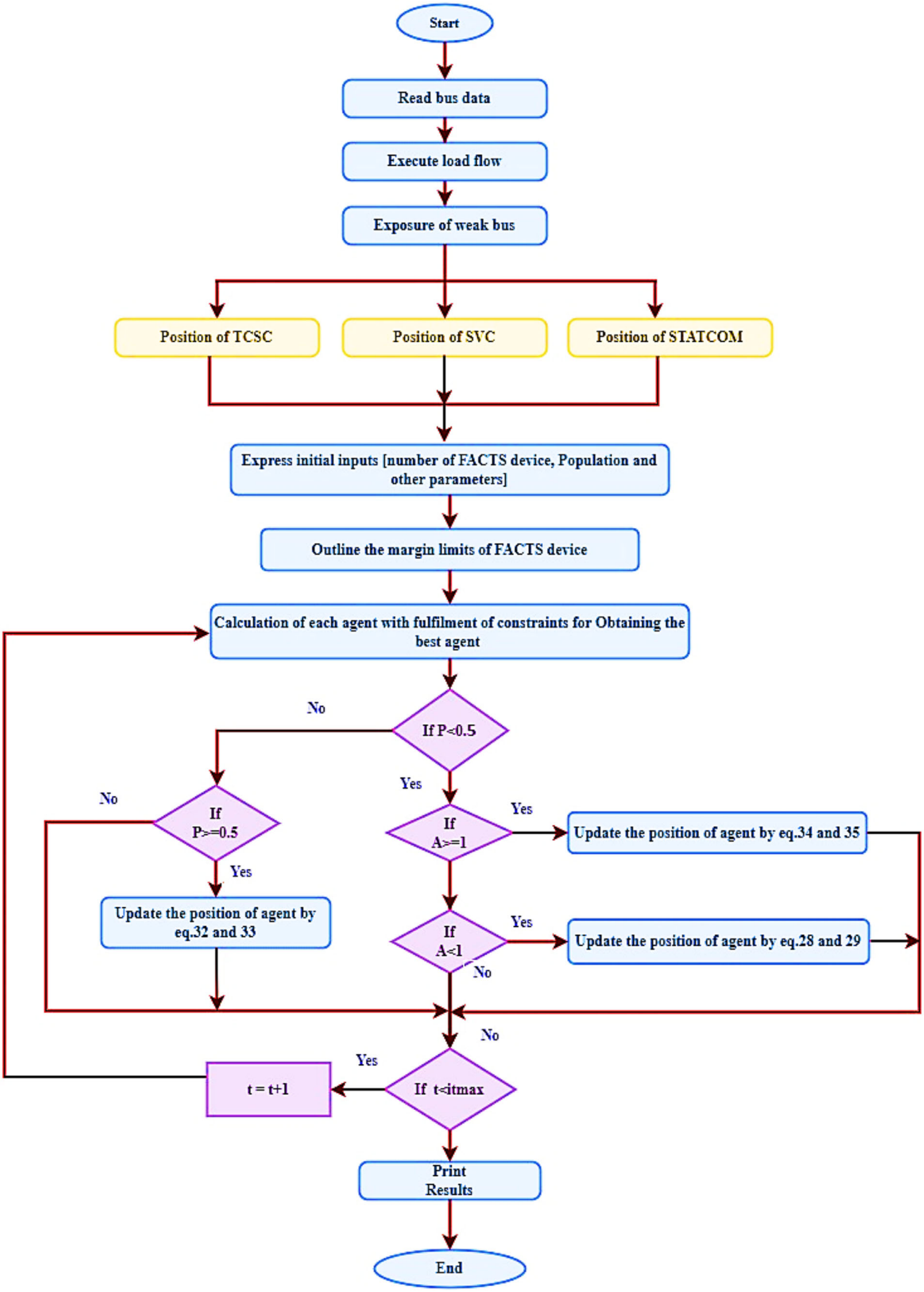

FIGURE 3 Flow chart of proposed WOA.

TCSC	SVC	STATCOM
5,24,28,41	4, 22, 20,28	23,11,9,10

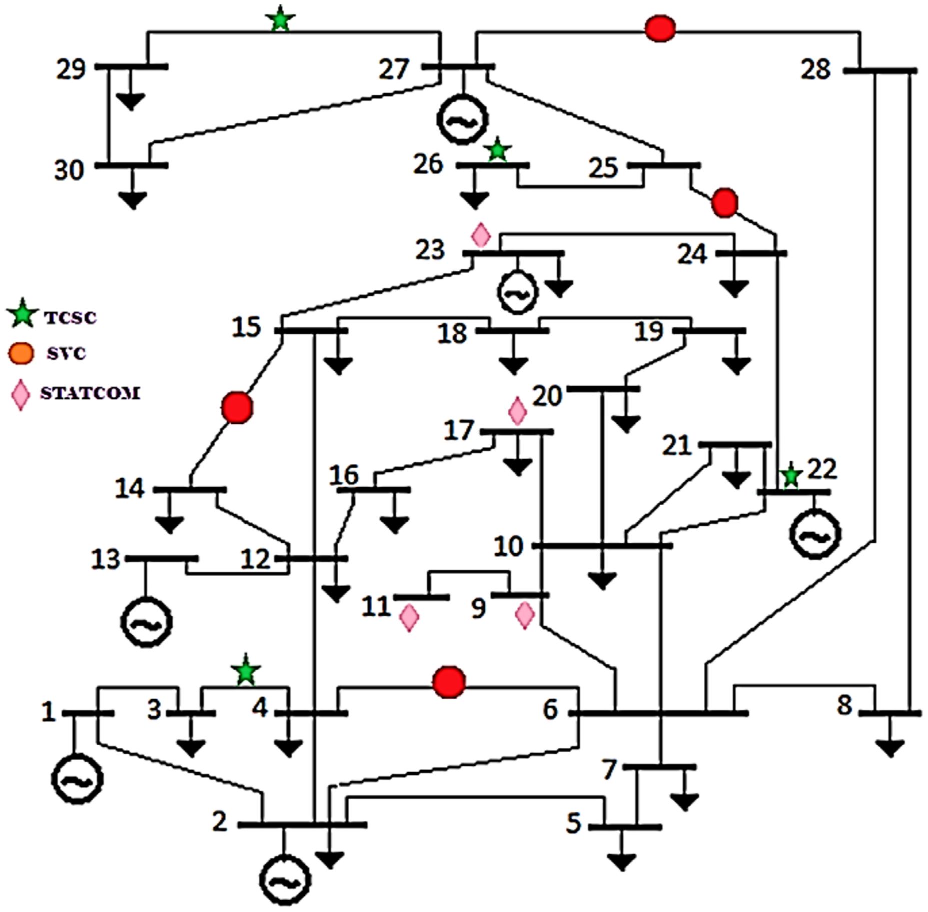

FIGURE 4 Optimal location of facts devices on the 30-bus test system

$$C_{Energy} = (Power\ Loss) \times \left(\frac{0.06\$}{kWh}\right) \times 10^5 \times 365 \times 24 \tag{16}$$

where energy loss cost is taken as 0.06 (\$/kWh). The fixed installed capacity of shunt capacitors is 1000 \$, for 1 year (365 days) and done in 24 h [44].

$$C_{FACTS} = C_{TCSC} + C_{SVC} + C_{STATCOM} \tag{17}$$

$$C_{TCSC} = 0.0015p^2 - 0.7130p + 153.75 \left(\frac{\$}{kVAr}\right) \tag{18}$$

$$C_{SVC} = 0.0015q^2 - 0.7130q + 127.38 \left(\frac{\$}{kVAr}\right) \tag{19}$$

$$\mathrm{C_{STATCOM}} = 553\left[0.0004\left(\left(Q^i_{statcom}\right)^2\right) - 0.3225Q^i_{statcom} + 127.38\right] \quad (\$/\mathrm{kVAr}) \tag{20}$$

The cost function of FACTS controllers, the SVC and TCSC, are analyzed in [4]. The cost function of the STATCOM [2] is depicted in Equation (20). The FACTS sizes are described as p, q, and $Q^i_{statcom}$.

4.2 | Constraints

The constraints chosen for the optimization are given in below in Equations (21) to (27).

Bus voltage constraints

$$0.95 \leq V_i \leq 1.05 \tag{21}$$

Thermal limit constraints

$$S_{min} \leq S_L \leq S_{max} \tag{22}$$

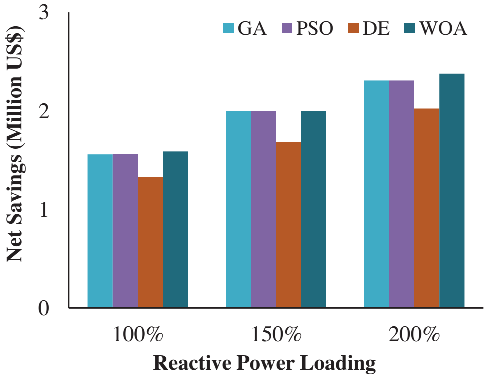

FIGURE 5 Net savings comparison between A and B at different reactive power loading with GA, PSO, DE, and WOA. Note: For detailed data refer to Figure A6 in Appendix A. DE, differential evolution; GA, genetic algorithm; PSO, particle swarm optimization; WOA, whale optimization algorithm.

Generator's reactive power supply constraints

$$Q_{g,min} \leq Q_g \leq Q_{g,max} \tag{23}$$

Transformer tap setting constraints

$$T_{i,min} \leq T_i \leq T_{i,max} \tag{24}$$

SVC size constraints

$$-0.9 \leq Z_{SVC} \leq 0.9 \ \ (\text{pu}) \tag{25}$$

Z_{SVC}—SVC size in pu
TCSC size constraints

$$-0.8X_L \leq X_{TCSC} \leq 0.2X_L \ \ (\text{pu}) \tag{26}$$

X_{TCSC}—size of TCSC in pu
STATCOM size constraints

$$Q_{min} \leq Q^{i}_{statcom} \leq Q_{max} \tag{27}$$

$Q^{i}_{statcom}$—size of STATCOM in pu

4.3 | Whale optimization algorithm (WOA)

The WOA's most significant advantage is that the optimization technique requires only one design parameter where as the the PSO and DE algorithms uses fewer steps. But the ideal solutions can only be determined if an algorithm can successfully achieve a good balance between the design parameters and steps for solving. In the literature, no other optimization is found to solve all optimization problems except the WOA [45]. The application analysis of WOA in ref [46] shows that it is very effective in electrical studies especially for power system problems. We study certain research work which focuses on IEEE 30 Bus system [3]. They tested the proposed study on IEEE-30 and IEEE- 57 bus systems. The results exhibit an improvement in voltage profile enhancement as well as the power loss reduction. The application of WOA in the electrical engineering domain enhances its reliability and accuracy by its capability of solving many unimodal as well as the low-dimensional complex problems. The trends towards the growth of meta-heuristic algorithms enhanced in recent years due to its potentials like (1) advanced structure, (2) dynamic condition flexibility, (3) fast convergence speed, and (4) solving convex problems. The number of publications and applications in different engineering fields is sketched in Figures A4 and A5 in Appendix A. Hence, we can find the trends towards WOA in the current scenario with different application levels. From the analysis of computer engineering and electrical engineering, fields dominate the WOA applications widely.

As per studies, whales are deliberated as massive beings possessing high intelligence with emotion. The WOA is inspired by the inimitable hunting nature of humpback whales. Usually, humpback whales proffer to hunt small fishes or krill located at the surface of the sea. The hunting trick is called bubble-net feeding [47]. Furthermore, by this method, they create an eccentric bubble with a circle or 9-shaped paths for hunting. The spiral bubble-net feeding operation is mathematically exhibited to execute optimization.

The following section deals with the mathematical model and optimization of the WOA:

- Encircling prey
- Exploitation phase (bubble net attacking method)
- Exploration phase (search for prey)

4.3.1 | Encircling prey

Humpback whales identify the location of the prey and encircle them with a 9-shaped circuit. Otherwise, they assume that their best candidate resolution is the prey. After fixing the best search agents, other search agents update their position for the best search agent. The mathematical expression for this operation is characterized by Equations (28) and (29):

$$D \ = \left| C.X_{a(t)} - X_t \right| \tag{28}$$

$$X \ \ (t+1) = X_{a(t)} \ - A \times D \tag{29}$$

where $X_{a(t)}$ deliberated the best solution position vector at each iteration, | | denote the absolute value, and X_t marks the location of the search agent. The vectors A and C are illustrated in Equations (30) and (31):

$$A \ = \ 2a \times r_1 - a \tag{30}$$

$$C \ = \ 2r_2 \tag{31}$$

where 'a' is linearly decreased from 2 to 0 and r_1 and r_2 describe random vector with limit [0, 1].

TABLE 2 Procedures of WOA

The procedure of the WOA
Step 1: Read the line and load data of the system and perform the load flow.
Step 2: Identify the weak bus.
Step 3: Generate the population size of the FACTS device
Step 4: Define the boundary limits for the selected FACTS devices.
Step 5: Determine the power loss.
Step 6: Select the finest solution.
Step 7: Update the position of the humpback whale using (28) and (35).
Step 8: Determine the losses for the updated position.
Step 9: Restitute the current best solution with the updated value. If the value is excluded, then the current best solution goes back to step 7.
Step 10: If the maximum number of iterations is fulfilled, then display the results.

TABLE 3 The modified IEEE 30 bus system with optimal location facts devices

TCSC	SVC	STATCOM
5,24,28,41	4, 22, 20,28	23,11,9,10

TABLE 4 A probe into total reactive power with different algorithms in the modified IEEE 30 bus system

Reactive power loading (%)	Wdevices	GA with FACTS devices	PSO with FACTS devices	DE with FACTS devices	WOA with FACTS devices
100	−0.29940	−0.41970	−3.58220	−0.36140	−0.61040
150	−0.18500	−0.48420	−1.15100	−1.18640	−0.22220
200	−0.28620	−1.31660	−2.51700	−1.84570	−2.14000

TABLE 5 Control indicators experimented using different optimization algorithms for the 30-bus system

Control variables	GA with FACTS devices	PSO with FACTS devices	DE with FACTS devices	WOA with FACTS devices
Q (2)	0.2876	0.6000	−0.5090	0.6000
Q (5)	0.2764	0.0000	−0.1307	0.6250
Q (8)	0.0729	0.0000	0.3955	0.5000
Q (11)	0.1865	0.4000	0.3031	0.0029
Q (13)	0.0812	0.0000	0.0000	0.0177
Tap (11)	0.9290	0.9439	0.9021	0.9000
Tap (12)	0.9136	0.9000	0.9658	0.9448
Tap (15)	0.9501	0.9000	0.9007	0.9000
Tap (36)	0.9217	0.9326	0.9211	0.9285
TCSC (24)	0.0185	0.0000	0.0800	0.0800
TCSC (41)	0.0002	0.0419	0.0800	0.0800
TCSC (28)	0.0016	0.1049	0.0797	0.0800
TCSC (5)	0.0009	0.1368	0.0800	0.0800
SVC (22)	0.1906	0.0000	0.0663	0.0524
SVC (4)	0.0051	0.0000	0.1492	0.1544
SVC (28)	0.0486	0.0000	0.1498	0.2000
SVC (20)	0.0000	0.0000	0.0225	0.0145
STATCOM (23)	0.0181	0.110	0.2410	0.0311
STATCOM (11)	0.0030	0.0340	0.004	0.0051
STATCOM (17)	0.0240	0.103	0.031	0.049
STATCOM (9)	0.08	0.1588	0.1368	0.08
Power Loss	0.0499	0.0538	0.0485	**0.0493**
Total cost	3.1297×10^6	3.3671×10^6	3.0984×10^6	$\mathbf{3.0669 \times 10^6}$

4.3.2 | Exploitation phase

Bubble-net feeding behaviour is mathematically modelled by two approaches (1) Shrinking encircling approach; and (2) Spiral updating position.

In the shrinking encircling approach, the value of A is decreased by the value of a. Hence, the value of A is stable in the interval of $[-a, a]$. For example, the value of A is $[-1, 1]$, where −1 represents the original agent position and 1 represents the current best position [48].

In Spiral updating position approach, the distance measurements between the humpback whale (x, y) and prey (x^*, y^*) are calculated. Then a helix-shaped movement of whales generates a spiral Equation (32) as follows:

$$X_{(t+1)} = D^* \times e^{bt} \times \cos(2\pi rl) \times X_{a(t)} \tag{32}$$

where b is a constant for determining the shape of the spiral, l a random number ranging from [−1,1], and $D^* = |X_{a(t)} - X_t|$ denote the distance between whale and prey. The movement of the humpback whale is either within a shrinking circle or a spiral-shaped path simultaneously. The probability of this movement is assumed as 50%. The mathematical model for this particular probability is given in Equation (33).

$$X_{(t+1)} = \begin{cases} X_{B(t)} - A \times D & if\ p < 0.5 \\ D^* \times e^{bt} \times \cos(2\pi rl) \times X_{a(t)} & if\ p \geq 0.5 \end{cases} \tag{33}$$

where p demonstrates the arbitrary value ranging from [0,1].

4.3.3 | Exploration phase

To provide a global search, the humpback whale discovers the superlative resolution and updates its position based on an alternative randomly selected search agent. Its limit lies in between [>1/<1]. The mathematical model is shown below.

$$D = |CX_r - X| \tag{34}$$

$$X\ (t+1) = X_r - A \times D \tag{35}$$

where X_r is the position vector of the arbitrarily selected search agent.

TABLE 6 Implementation with and without facts devices in the 30-test bus system in power loss and operating cost

Reactive power loading (%)	Power loss (pu)	Operational cost fuelled by energy loss ($) (A)	Power loss by FACTS devices (pu)	The algorithm used for the optimization	Operational cost ($) (B)	Rate of FACTS devices ($)
100	0.0711	3,737,016	0.0406	GA	2.1786×10^7	44,664
			0.0406	PSO	2.1771×10^7	43,064
			0.0445	DE	2.4052×10^7	66,280
			0.039	WOA	2.1481×10^7	98,260
150	0.0974	5,120,900	0.0585	GA	3.1222×10^7	47,440
			0.0584	PSO	3.1222×10^7	52,700
			0.0639	DE	3.4361×10^7	77,516
			0.0581	WOA	3.1224×10^7	68,700
200	0.1294	6,800,100	0.0839	GA	4.4915×10^7	81,716
			0.0839	PSO	4.4915×10^7	81,716
			0.0891	DE	4.7774×10^7	94,304
			0.0824	WOA	4.4231×10^7	92,056

Thus, whale optimization is considered the global search optimization algorithm. Generally, the optimal sizing of FACTS controllers by the WOA depends on the dimensions of the search agent. A comprehensive stepwise procedure of WOA is shown in Table 2. Figure 3 illustrates the proposed flowchart of WOA for optimum sizing of FACTS devices.

5 | RESULTS AND DISCUSSIONS

The proposed method of optimal sizing of FACTS devices is applied to the IEEE 30 bus system [49]. The obtained results and discussion are described below. The test bid becomes more efficient as progress is made in creating competitive reactive power markets. On a personal computer with 8 GB RAM, all simulations are performed using the MATLAB 2017b computing environment.

5.1 | Case study with 30 test bus system

Six generating units and transmission lines at buses 2, 5, 8, 11, 13, and 41, respectively, belong to the typical IEEE 30 test bus system. Then, the branches (6–9, 6–10, 4–12, and 27–28) are furnished with a tap-changing transformer (bus 10), and the shunt capacitors (bus 24) are connected to the test system. Meanwhile, bus 1 is considered the slack. In addition, the net active power required is 2.834 MW, and the reactive power required is 1.263 MVAR at a base of 100 MVA for this work. The power loss of reactive power planning is 7.11 MW, and its operating cost is3.737018×10^6. Furthermore, Table 3 describes the location details of FACTS in buses. TCSCs are placed in 25, 41, 28, and 5 which are sensed as the weak bus by the power flow analysis scheme. This work points out that SVCs are optimally placed in 22, 4, 28, and 20 buses by constructing the PV curve method, and the STATCOM is placed at bus 23 by using the sensitivity analysis. The number of search agents is considered 40 for this proposed work.

The one-line diagram of the IEEE 30 bus test system with the optimal placement of FACTS devices is elucidated in Figure 4. In Table 4, the impact of total reactive power loss on different FACTS devices is explained. It found that the total reactive power loss was lower after FACTS and WOA installation in the system [50]. The reactive power loss gradually decreases with an effective cost gain with WOA through different reactive loading (−0.61040, −0.22220, −2.140000) described in Table 4. Control variables experimented with using the GA, PSO, DE, and WOA are depicted in Table 5. From Table 5, each control parameter described the optimal placement, and all the parameters are perfectly placed for the dynamic cost minimization. It is detected that power loss and operational cost declined to 0.0493 and 3.0669×10^6, respectively.

Table 6 explicates a comparative cost study between the presence of FACTS devices and the absence of FACTS devices using the GA, PSO, DE, and WOA. The test results deliberated that WOA generates an operative cost study as compared to other algorithms. Furthermore, Figure 5 shows the net savings at different reactive loadings with the GA, PSO, DE, and WOA. It shows that the proposed whale optimization gives improved results as compared with the different algorithms mentioned in this work, thus enabling better economic savings. Table 7 illustrates the scrutiny of operating cost subsequently by 30 different trials by different optimization techniques. From this table, it can be identified that the WOA produces the best cost management when compared with the GA, PSO, and DE. The total operating cost of 2.0569×10^6 $ is delivered by the WOA.

Figure 6 shows the variation in operating cost with production for different reactive power loading (100%, 150%, and

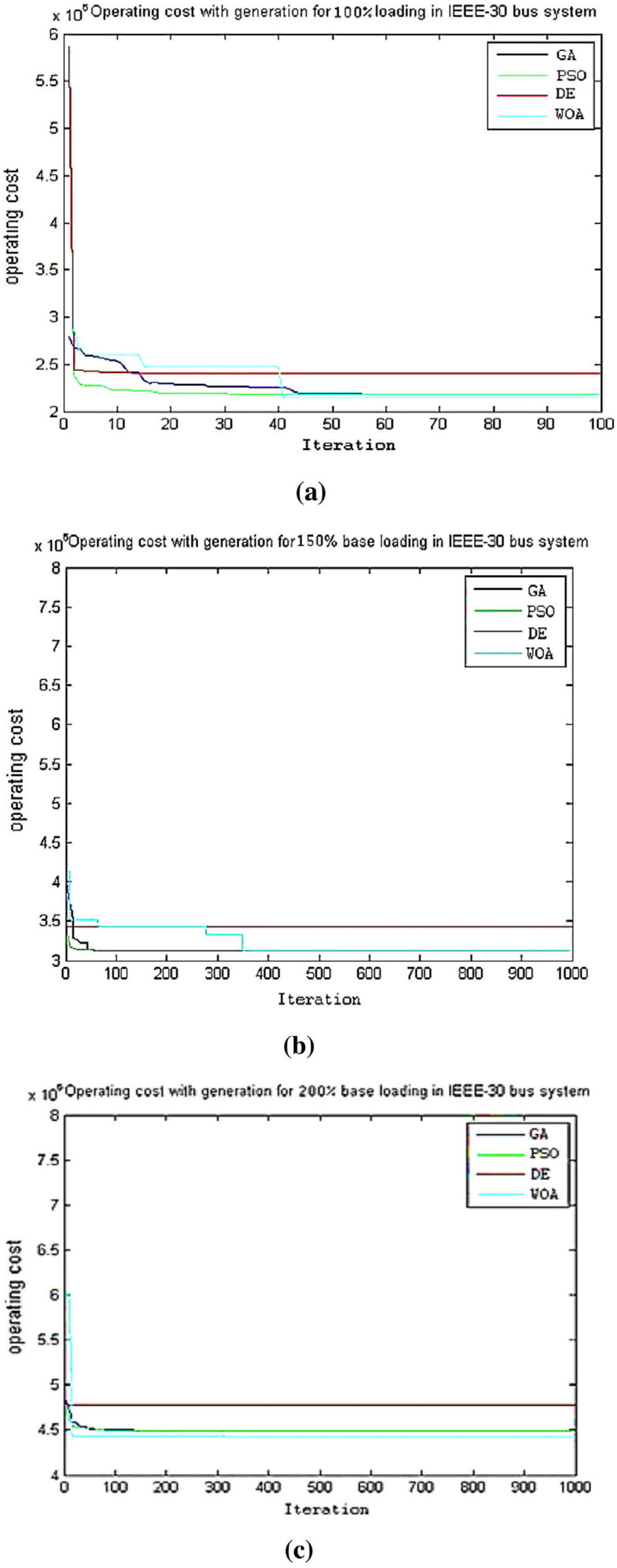

FIGURE 6 Operating cost with production for different reactive power loading using the GA, PSO, DE, and WOA. (a) 100%, (b) 150%, (c) 200%

TABLE 7 Scrutiny of operational cost after different trials by diverse optimization techniques

	Total operational cost (in $)		
Algorithm	**High**	**Low**	**Medium**
GA	2.0995×10^7	2.0889×10^7	2.0817×10^7
PSO	2.0974×10^7	2.1062×10^7	2.0998×10^7
DE	2.0681×10^7	2.0992×10^7	2.0987×10^7
WOA	2.0569×10^7	2.0053×10^7	2.0760×10^7

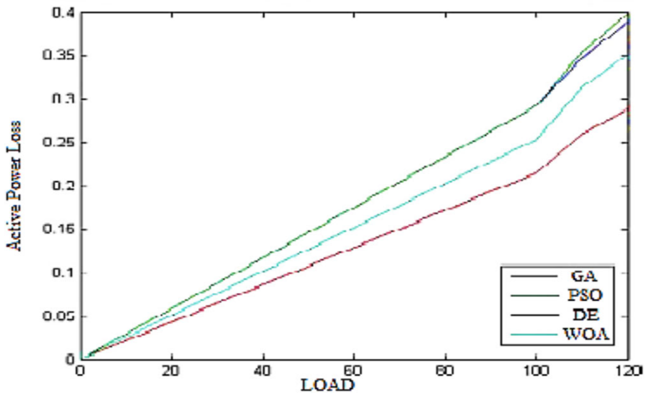

FIGURE 7 Active power loss using the GA, PSO, DE, and WOA

200%) using the GA, PSO, DE, and WOA. From Figure 6, it can be seen that the operating cost of the test system was deducted by 3.36% when optimized using WOA.

Figure 7 depicts the active power loss of the test system, and it can be observed that the WOA reduces the power loss by 4.93%. Hence WOA is suitable for power loss other than GA, PSO, and DE by its quick convergence time.

From the simulations the following inference has arrived

- It found that the total reactive power loss is reduced with the optimal setting of FACTS devices using WOA. The reactive power loss gradually decreased with an effective cost gain with WOA through different reactive loading (−0.61040, −0.22220, −2.140000) which is described in Table 4.
- Compared with GA, PSO, and DE, WOA reduces the total power loss and total operating cost by 4.93% and 3.36 %, respectively.
- The effectiveness of the WOA is validated with various load conditions and results confirmed that WOA is performed better compared with GA, PSO, and DE optimization algorithms.

5.2 | ANOVA test

The ANOVA test [51] embedded with every optimization problem for the study of variance of the system as well as the operating cost. As per the procedure of the ANOVA, the value of $k = 4$ because the suggested work utilized GA, PSO, DE, and WOA with 30 different trials ($n = 30$). The test results are featured in Table 7.

6 | CONCLUSION

In conclusion, this paper suggests a novel approach for the best positioning and sizing of various FACTS device types using the coordination of various reactive power loads. The construction of the PV curve and sensitivity approaches, as well as the placement of the TCSC, SVC, and STATCOM, are all guided by the Lmn index. Once the weak bus has been located, FACTS devices are positioned using a WOA to assess their suitability for optimization, and the results are then modified using the GA, PSO, and DE algorithms. The objective functions of the proposed work are listed as cost management and power loss (total operational cost of the system). Additionally, an IEEE 30 test system is used to evaluate the proposed methodology.

According to the results of WOA optimization, the WOA is effective for reducing losses and produces the best results, with a total operating cost of 3.0669×10^6. Reactive loading has a positive effect on FACTS device rate (92,056 $) and cost reduction. The lowest cost of all the approaches is provided by various load abilities. As a result, the WOA explains that it can be the best algorithm for scheduling FACTS devices optimally while effectively managing costs.

While optimizing the operating cost and location of the system, the system's dependability and security were not considered. There are a restricted number of FACTS devices, which is considered. The incorporation of various FACTS devices comparable to UPFC, Interline Power Flow Controller (IPFC), and DSTATCOM is part of the study's future scope.

AUTHOR CONTRIBUTIONS

Honey Baby: Conceptualization; Methodology; Formal analysis; Writing-original draft; Writing-review & editing. Jayaraj Jayakumar: Conceptualization; Resources Validation; Supervision; Writing-review & editing. Mobi Mathew: Formal analysis; Validation. Mohamed G. Hussien: Writing-review & editing. Nallapaneni Manoj Kumar: Conceptualization; Funding acquisition; Resources; Validation; Writing-review & editing

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

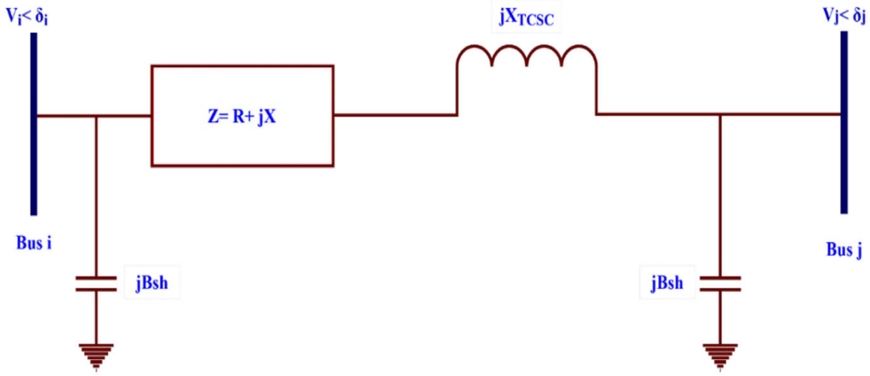


FIGURE A1 Mathematical prototype of TCSC.

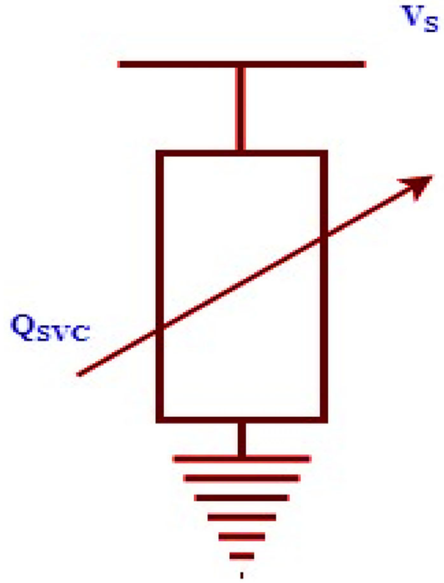


FIGURE A2 Mathematical prototype of SVC

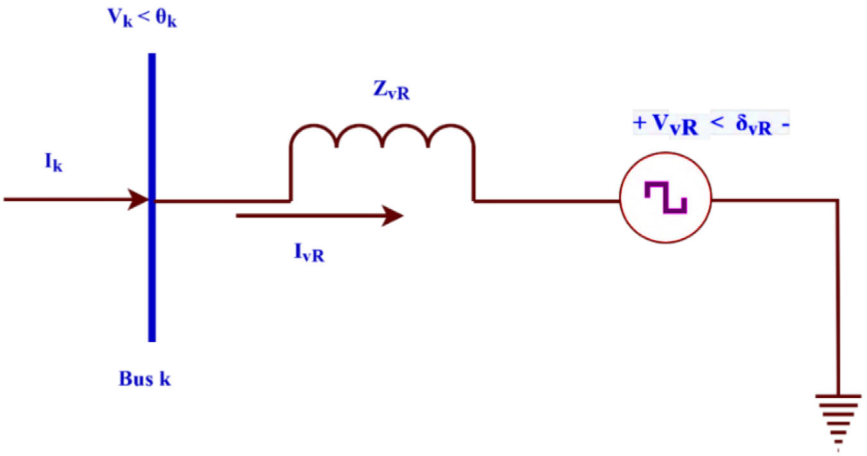


FIGURE A3 Mathematical model of STATCOM

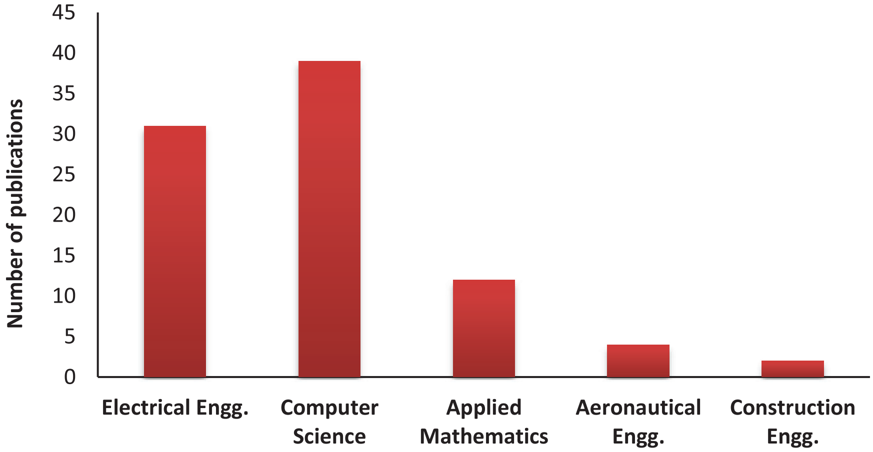


FIGURE A4 Number of publications of WOA in different engineering fields

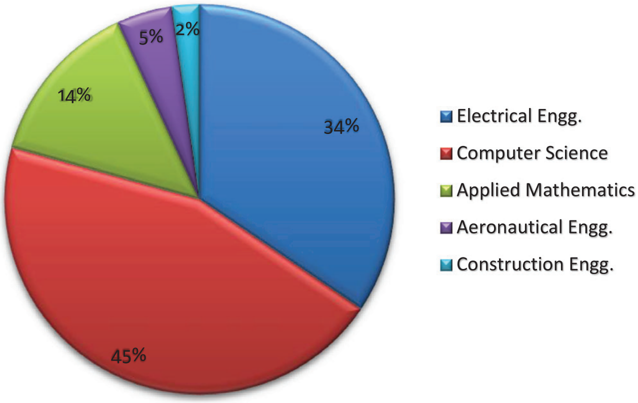
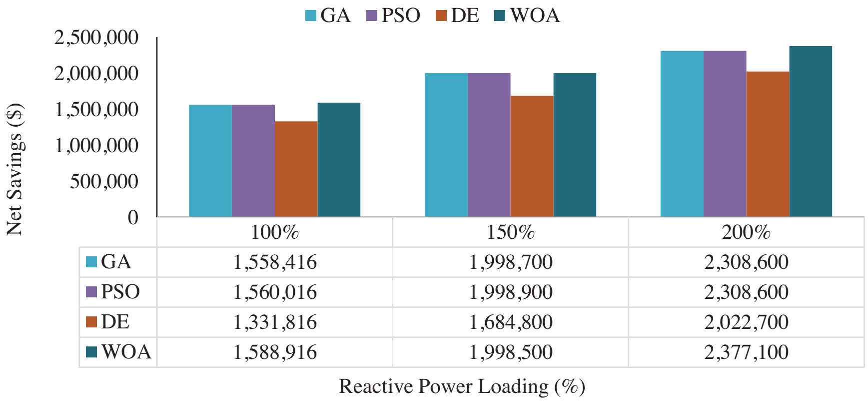


FIGURE A5 Application of WOA in different engineering fields



	100%	150%	200%
GA	1,558,416	1,998,700	2,308,600
PSO	1,560,016	1,998,900	2,308,600
DE	1,331,816	1,684,800	2,022,700
WOA	1,588,916	1,998,500	2,377,100

FIGURE A6 Net savings comparison between *A* and *B* at different reactive power loading with GA, PSO, DE, and WOA