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Optimal Placement Of Facts Devices Through Hybrid Optimization Algorithm To Improve Power System Operation

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Abstract: This paper presents a hybrid optimization framework for the optimal placement and sizing of Flexible Alternating Current Transmission System (FACTS) devices to enhance power system stability, reliability, and quality. Two FACTS devices, the Unified Power Quality Conditioner (UPQC) and the Thyristor-Controlled Series Compensator (TCSC), are employed to mitigate voltage instability, power losses, and harmonic distortion. The proposed hybrid technique integrates the Improved Grey Wolf Optimization (IGWO) with Cuckoo Search Optimization (CSO) and Improved Grey Wolf Optimization (IGWO) with Opposition-Based Learning (OBL), forming hybrid algorithms. The optimization aims to minimize active power loss, total bus voltage deviation and operating cost (OC), while improving the Voltage Stability Index (VSI). Both single-objective and multi-objective formulations are considered, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP) are utilized to identify optimal trade-offs among objectives. The algorithm is tested on IEEE 33-bus and IEEE 69-bus systems using MATLAB. Comparative analyses with GWO, IGWO, and CSO demonstrate that the hybrid IGWO–CSO method and IGWO–OBL method outperforms existing algorithms in convergence speed, accuracy, and overall system performance. The results validate its effectiveness in optimally deploying FACTS devices for improved power quality and economic operation.

Index Terms – Power Quality, Hybrid Optimization, FACTS Devices, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) ,Analytical Hierarchy Process (AHP).

I. INTRODUCTION

The rapid growth of electrical energy demand and the increasing complexity of modern power distribution systems have led to significant challenges in maintaining voltage stability, minimizing power losses, and ensuring high power quality. Power systems are frequently subjected to voltage fluctuations, harmonic distortions, and reliability issues due to nonlinear loads and dynamic operating conditions. These issues adversely affect system performance and can lead to inefficient energy utilization. To overcome these challenges, Flexible Alternating Current Transmission System (FACTS) devices have emerged as an effective solution for improving controllability, enhancing stability, and optimizing power flow within electrical networks.[1]

Among various FACTS devices, the Unified Power Quality Conditioner (UPQC) and the Thyristor-Controlled Series Compensator (TCSC) have demonstrated remarkable capabilities in mitigating voltage disturbances, reducing harmonic distortion, and improving overall power system reliability. However, the performance of these devices strongly depends on their optimal placement and sizing within the power network. Determining the optimal configuration involves solving a highly nonlinear and multi-objective optimization problem that balances technical and economic parameters such as power loss, Total voltage deviation and operating cost (OC).To address this complexity, metaheuristic optimization algorithms have been widely applied due to their ability to find near-global optimal solutions efficiently. This research proposes two hybrid optimization algorithms Improved Grey Wolf Optimization combined with Cuckoo Search Optimization (IGWO–CSO) and Improved Grey Wolf Optimization combined with Opposition-Based Learning (IGWO–OBL). These hybrid approaches enhance exploration and exploitation capabilities, preventing premature convergence and improving solution quality. [2]

II. PROBLEM STATEMENT

Modern power distribution networks are increasingly challenged by issues such as voltage instability, high power losses, and poor power quality arising from nonlinear loads, system expansion, and growing electricity demand. Flexible Alternating Current Transmission System (FACTS) devices, particularly the Unified Power Quality Conditioner (UPQC) and the Thyristor-Controlled Series Compensator (TCSC), can effectively enhance voltage regulation, minimize losses, and improve system stability. However, the effectiveness of these devices greatly depends on their optimal placement and sizing within the power network. The optimal allocation of FACTS devices is a complex, nonlinear, and multi-objective optimization problem involving conflicting goals such as minimizing active power losses, total voltage deviation and operating costs while improving the Voltage Stability Index (VSI). Conventional optimization techniques often struggle with such problems due to their slow convergence and tendency to become trapped in local optima. Although metaheuristic algorithms like Grey Wolf Optimization (GWO), Improved Grey Wolf Optimization (IGWO), and Cuckoo Search Optimization (CSO) have shown potential, they still face limitations in exploration and convergence efficiency. Hence, there is a need for a robust hybrid optimization approach that effectively combines these algorithms' strengths to achieve faster convergence, improved accuracy, and better system performance in optimal FACTS device placement.

III. PROBLEM FORMULATION

The objective function is mathematically expressed as a multi-objective function, considering appropriate weights for each factor. Constraints such as bus voltage limits, line capacity, and the operational constraints of UPQC are included. By comparing the results of traditional optimisation methods with hybrid techniques such as Improved Grey Wolf Optimization (IGWO) combined with Opposition-Based Learning (OBL), the study highlights the effectiveness of hybrid approaches.[3]

The optimisation problem involves single and multi-objective scenarios.

3.1 Single objective Optimization for placement and sizing of UPQC

Single-objective function is to minimise a specific factor (e.g., power loss) while ensuring that constraints on other system parameters, such as voltage stability and installation costs, are upheld. This analysis will focus on the performance of UPQC in enhancing the voltage stability index (VSI) and reducing total power losses, while also taking into account the costs associated with UPQC installation.

Voltage Stability Index (VSI) Improvement

The Voltage Stability Index for bus i is defined as,

$$\mathrm{VSI_i} = \frac{|V_i|^4}{4(P_i^2+Q_i^2)(R_{ij}^2+X_{ij}^2)} \quad (1).$$

The VSI enhancement objective is expressed as

$$F_{VSI} = \max\left(1 - \frac{\mathrm{VSI_i}}{\mathrm{VSI_{max}}}, 0\right) \quad (2)$$

Where $\mathrm{VSI_{max}}$ is the desired maximum VSI threshold.

Total Power Loss Minimization

The power loss minimisation is expressed as

$$F_{loss} = \sum_{k=1}^{N_{lines}} R_k \left(\frac{P_k^2+Q_k^2}{|V_K|^2}\right) \quad (3)$$

UPQC Installation Cost Minimization

The cost of a Unified Power Quality Conditioner (UPQC) can be expressed mathematically as:

$$F_{cost} = C_{fixed} + C_{var} \cdot S_{UPQC} \quad (4)$$

3.2 Mono objective Optimization for placement and sizing of TCSC

In this paper, the optimization problem of TCSC is conducted in two ways which includes mono objective optimisation and multi objective optimisation along with constraints [14].

3.2.1 Minimization of Active power loss, Total voltage deviation and operating cost (OC)

In this study, three objective functions are taken into account. These objectives include minimization of power system operating costs, active power loss, and bus voltage deviation in power systems . The optimization problem can be expressed by (5) to (9).

$$\min F = [F_{PL}(x), F_{TVD}(x), F_{OC}(x)] \quad (5)$$

$$F_{PL} = \sum_{k=1}^{L} G_k[Vb_m^2 + Vb_n^2 - 2Vb_mVb_n\cos(\delta_{mn})] \quad (6)$$

$$F_{TVD} = \sum_{m=1}^{N}[Vb_m - 1]^2 \quad (7)$$

$$F_{OC} = (real\ power\ loss) \times 0.09 \times 365 \times 24 \quad (8)$$

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \quad (9)$$

Where F_{pl} , G_k , Vb_m, Vb_n, δ_{mn} and L represents Active power loss function, Conductance of the transmission line voltage magnitudes at buses m and n, Voltage angle difference between buses m , n and Total number of transmission lines respectively F_{TVD}, Vb_m and N represents Total bus voltage deviation function, Voltage magnitude at bus m and Total number of buses respectively. F_{PL}, F_{TVD} and F_{OC} are the objective functions for power loss, voltage deviation and operating cost respectively, 0.09represents the cost associated with the power losses measure in $/KWhr , 365 denotes the number of days in a year, 24 is the hours of the day, C_{TCSC} indicates the TCSC installation cost[2].

3.3 Multi objective Optimization for placement and sizing of UPQC

The objective is to optimize the placement and sizing of UPQC to improve power quality and system performance which include

Minimisation of Total power losses

$$f_1 = P_{loss} = \sum_{i=1}^{N} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}) \quad (10)$$

Where g_{ij} is the conductance of the line between buses i and j and θ_{ij} is the phase angle difference

Improvement of Voltage Stability Index(VSI)

Enhance system robustness under varying load conditions

$$f_2 = \sum_{i=1}^{N}\left(\frac{4V_i(V_{nom}-V_i}{V_{nom}^2}\right) \quad (11)$$

Where V_i is the voltage magnitude at bus i, V_{nom} is the nominal voltage and N is the number of buses

Minimization of UPQC Installation Cost (C)

The cost of installation and operation of UPQC

$$f_3 = a + b.S_{UPQC} + c.S_{UPQC} \quad (12)$$

Where S_{UPQC} =Apparent power rating of UPQC

a,b,c installation and operational cost coefficients.

The multi-objective optimisation combines the above objectives into a weighted fitness function:

Weighted sum fitness function

$$f(x) = w_1f_1 + w_2f_2 + w_3f_3 \quad (13)$$

Where w_1, w_2 and , w_3 are the assigned weights with relative importance.
f_1, f_2 and f_3 are the Total power loss minimization , voltage stability index improvement and UPQC cost minimization respectively.

3.4 Multi-objective Optimization for placement and sizing of TCSC

In multi objective optimisation for placing TCSC the considered objectives are minimized simultaneously. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach is used in this paper to find the best compromise solution from the obtained non-dominated solutions [14].

In the mono-objective function form, the objective functions under consideration are optimized concurrently through their combination into one objective function F is expressed in (13).

$$F = w1 \cdot J1 + w2 \cdot J2 + w3 \cdot J3 \quad (14)$$

In this equation, w1, w2, and w3 represent the weight coefficients that quantify the contribution of each term within the fitness function.

$$J_1 = \frac{PL\_TCSC}{PL\_base}, J_2 = \frac{TVD\_TCSC}{TVD\_base}, J_3 = \frac{OC\_TCSC}{OC\_base} \quad (15)$$

In this context, PL_{TCSC} and PL_{base} represent the real power losses associated with the integration and non-integration of TCSC controller into the power system. Similarly, TVD_{TCSC} and TVD_{base} denote the Total voltage deviations experienced with and without the installation of TCSC controller. Furthermore, OC_{TCSC} and OC_{base} indicate the system operating costs incurred with and without the installation of TCSC controller [19],[20].

3.4.1 TOPSIS method

The TOPSIS is an effective decision making approach that employs qualitative priority ranking to classify alternatives and identify the optimal solution. This strategy seeks to clarify alternatives that are both closest to the positive suitable solution distant away from the negative ideal solution [14]. There are two types of criteria in this method: cost criteria (lower value is better) and profit criteria (higher value is better). The negative ideal solution reduces the benefit and increases the cost criteria. The positive ideal solution, on the other hand, increases the benefit criteria while decreasing the cost criteria [15]. The approach for the TOPSIS technique is as follows.

1.Formation and normalization of the decision matrix. Let X =X=(x_{ij}) be a decision matrix containing the optimal set solutions where i = {1, 2, …, n}, j= {1, 2, ..., m}, n represents the number of Pareto optimal alternatives, and m denotes the number of goals. Since the objectives are usually presented with various units, this step is used to convert the objectives into a non-dimensional scale r_{ij} as expressed in (15).

$$r_{ij} = {x_{ij}} \Big/ \sqrt{\sum_{i=1}^{m} x_{ij}^2} \quad (16)$$

compute the weighted normalised decision matrix as expressed in (17).

$$k_{ij} = w_j r_{ij} \quad (17)$$

Where w_j signifies the j^{th} objectives relative importance, $\sum_{j=1} w_j = 1$. Weights are computed using the Analytical Hierarchy Process (AHP) procedure. Identifying the ideal negative and positive solutions. To identify $A+$ and $A-$, utilise following equations as expressed in (18) & (19).

$$A^+ = (k_1^+, k_2^+, \dots \dots k_n^+) = \left(\max k_{ij} \,\middle|\, \mathrm{j} \in I, \left(\max k_{ij} \,\middle|\, \mathrm{j} \in \mathrm{j},\right)\right) \quad (18)$$

$$A^- = (k_1^-, k_2^-, \dots \dots k_n^-) = \left(\max k_{ij} \,\middle|\, \mathrm{j} \in I, \left(\max k_{ij} \,\middle|\, \mathrm{j} \in \mathrm{J},\right)\right) \quad (19)$$

Where j and I indicate cost and benefit criteria respectively.

2.Determination of the distance between each alternative and the positive and negative ideal alternatives. It is possible to obtain the distance of the i_{th} alternative from the ideal positive solution (d_i^+) and the separation of ith solution from the ideal negative solution (d_i^-) as following equations as expressed in (20) & (21).

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(k_{ij} - k_j^+)^2} \quad (20)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}(k_{ij} - k_j^-)^2} \quad (21)$$

3.Arranging the relative nearness to the positive ideal solution.The relative closeness (C_i) of the i_{th} alternative with respect to A^+ is defined as expressed in (22).

$$C_i = \frac{d_i^-}{d_i^- + d_i^+} \quad (22)$$

Where $0 < C_i < 1$

Finally the preferred solution is one with a value of C_i close to 1.

3.4.2 Analytical Hierarchy Process (AHP)

The AHP is an efficient method that is widely used for comprehensive multi-objective evaluations [16]. In this paper, the AHP is used for the optimal determination of the weights in as expressed in (23) utilizing the following procedure Construction of pairwise comparison matrix [S], which is a square matrix formed by comparing the importance of each objective with the other as expressed in (23). The off-diagonal elements S are integer numbers in range 1–9. A higher value means that the index associated with it is more significant [17].

$$S=\begin{bmatrix} 1 & s_{ij} & . & . & s_{im} \\ 1/s_{ij} & 1 & . & . & s_{jm} \\ \vdots & . & . & . & . \\ 1/s_{mi} & 1/s_{mj} & . & . & 1 \end{bmatrix} \quad (23)$$

1. Calculation of the weight of objectives as expressed in (23)

$$w_i = \frac{\sqrt[m]{\pi_{j=1}^{m} s_{ij}}}{\sum_{i=1}^{m} \sqrt[m]{\pi_{j=1}^{m} s_{ij}}} \; (i = 1,2, \ldots, m) \quad (24)$$

2.checking the consistency of the matrix[S] as expressed in (24)

$$I_{CR} = \frac{I_{CI}}{I_{RI}} = \frac{\lambda_{max} - m}{(m-1)I_{RI}} < 0.1 \quad (25)$$

where I_{CR} is the index consistency ratio, I_{RI} indicates a random index, and I_{CI} denotes the index consistency[18]. The I_{RI} value is affected by the number of objective functions, as displayed in Table 1. The λmax represents the maximum eigenvalue of the matrix S, which can be defined as expressed in (25)

$$[S][W] = \lambda_{max}[W] \quad (26)$$

Where $W = [w_1, w_2, \ldots \ldots w_m]^T$

No of objectives	1	2	3	4	5	6	7
I_{RI}	0.00	0.00	0.58	0.91	1.12	1.24	1.32

Table 1. The values of the index I_{RI}

3.5 Constraints

The constraints described below are applicable to the optimization problems under consideration [16]

$$QG^m - QD^m - \sum_{n=1}^{Nb} V_m V_n [G_{mn} \sin(\delta_{mn}) + B_{mn} \cos(\delta_{mn})] = 0 \quad (27)$$

QG^m, QD^m indicate the reactive power generated and demanded at bus m and and n, Nb is number of buses.

$$PG^m - PD^m - \sum_{n=1}^{Nb} V_m V_n [G_{mn} \cos(\delta_{mn}) + B_{mn} \sin(\delta_{mn})] = 0 \quad (28)$$

PG^m, PD^m refers to active power generated and demanded at bus m and n, Nb is number of buses.

B_{mn}, G_{mn} represents the transfer susceptance and conductance between m and n buses.

$$V_{mn}^{min} \leq V_{mn} \leq V_{mn}^{max} \quad (29)$$

Where V_{mn}^{min}, V_{mn}^{max} voltage minimum and maximum at m,n bus.

$$S_{mn} \leq S_{mn}^{max} \quad (30)$$

S_{mn} denotes apparent power transmitted in the mn line, S_{mn}^{max} maximum allowable apparent power transmitted in the mn line

$$X_{TCSC}^{min} \leq X_{TCSC} \leq X_{TCSC}^{max} \quad (31)$$

Where $X_{TCSC}^{min}, X_{TCSC}^{max}$ and TCSC lowest and highest reactance limits.

$$Q_{TCSC}^{min} \leq Q_{TCSC} \leq Q_{TCSC}^{max} \quad (32)$$

Where $Q_{TCSC}^{min}, Q_{TCSC}^{max}$ and TCSC lowest and highest reactive power constraints.

IV. ALGORITHM OF IGWO-OBL HYBRID OPTIMISATION

The Improved Grey Wolf Optimization (IGWO) integrated with Opposition-Based Learning (OBL) is a hybrid optimisation approach that enhances the standard GWO by improving its exploration and exploitation capabilities. The incorporation of OBL helps in accelerating convergence and avoiding local optima by considering both the current solution and its opposite. The steps for the IGWO-OBL hybrid optimisation algorithm for the optimal placement and sizing of UPQC are described below which includes initialization, Iterative Optimisation Process and Termination Criteria.

Initialization parameters include 'N' candidate selection number of wolves, Decision variables include $x_{location}, S_{UPQC}$ and Q_{UPQC} .The maximum number of iteration i.e, Max Iter. The control parameter α that linearly decreases from 2 to 0.The opposite solution describes Computation of opposite candidates for enhanced search space exploration

Step 1: Randomly generate the initial population of wolves $X_i(t) = [x_{i1}, x_{i2}, \ldots x_{iD}]$,where each wolf $x_{i1} = [x_{location}, S_{UPQC}, Q_{UPQC}]$.

Step 2: Evaluate the fitness of each wolf based on the objective function $f(x) = w_1 f_1 + w_2 f_2 + w_3 f_3$.Where $w_1, w_2$and , w_3 are the assigned weights with relative importance.f_1, f_2 and f_3 are the Total power loss minimization, voltage stability index improvement and UPQC cost minimization respectively

Step 3: Determine the top three wolves α Best solution,β Second-best solution and δ Third-best solution.

Step 4: Compute the opposite population $X_{opposite}$ using opposition-based learning$x_{opposite,i} = LB + UB - x_i$,where LB and UB are the lower and upper bounds of the decision variables. Evaluate $X_{opposite}$ and replace less fit wolves in X with fitter wolves from $X_{opposite}$.

Step 5: Update the positions of wolves, each wolf updates its position based on its distance to α, β, and δ. Compute the attraction coefficients $A = 2a.r - a$, $C = 2.r$ where a linearly decreases from 2 to 0 over iterations. r is a random number in [0,1].

V. IGWO-CSO HYBRID OPTIMIZATION

The Improved Grey Wolf Optimization (IGWO)[21] and Cuckoo Search Optimization (CSO)[22] hybrid approach integrates the exploitation capabilities of IGWO with the exploration efficiency of CSO.

5.1 Hybrid Algorithm Process

- IGWO Phase: Wolves update positions based on their hierarchy (alpha, beta and delta).
- CSO Phase: New nests are explored using Levy flights and discovery probability.
- Dynamic Switching: The algorithm adaptively switches between IGWO and CSO based on iteration count to ensure diversity and convergence.

5.2 Hybrid Update Equations

The IGWO update is:

$$X_i^{new} = X_i^{old} + A.\left|C.X_{best} - X_i^{old}\right| \quad (33)$$

Where X_i^{new} is the updated wolf position,X_{best} is the best solution found,A and C are mentioned as Coefficient vectors controlling exploration and exploitations

A=$2a.r_1 - a$,where a decreases linearly from 2 to 0
C=$2.r_2$ where $r_1$and r_2 describes random numbers in the range [0,1]

The CSO update is:

$$X_{new} = X_{best} + \alpha.Levy() \quad (34)$$

where X_{new}mentions New Position of the nest X_{best}describes position of the best nest found so far. α Represents scaling factor $Levy()$ descibes Levy Flight behaviour.

5.3 Integration of Both Techniques

- IGWO refines solutions using leadership-based search.
- CSO enhances diversity through random exploration.
- Averaging-based nest updates improve solution accuracy.

The final CSO update:

$$x_i^{t1+1} = x_i^{t1} + \alpha levy(\lambda) \quad (35)$$
$$levy(\lambda) = t1^{-\lambda} \quad (36)$$

Whereas the community hierarchy selection is determined by fitness.Wherever $X_\alpha = 1^{st}$ hunt agent, $X_\beta = 2^{nd}$ hunt agent and $X_\delta = 3^{rd}$ hunt agent. By alternating IGWO and CSO, the hybrid algorithm achieves faster convergence, better exploration, and improved solution quality for TCSC placement in power systems.

VI. RESULTS AND DISCUSSION

In order to recognize the effectiveness and applicability of the IGWO-OBL technique and IGWO-CSO technique, the IEEE 33 and 69 bus systems have been tested to find the optimum sitting and capacity of the FACTS controller. The results of the proposed IGWO-OBL approach are compared with GWO, IGWO,CSO algorithms to verify the performance of the proposed IGWO-OBL approach over other reported methods for the optimum allocation of the UPQC. The results of the proposed IGWO-CSO approach are compared with GWO, IGWO algorithms to verify the performance of the proposed IGWO-CSO approach over other reported methods for the optimum allocation of the TCSC.In terms of the objective function formulation, the optimization problem is carried out with two cases: (1) Single-objective optimization and (2) multi-objective optimization. The optimization problems are implemented on the two tested systems as the following.

6.1.1 Performance Evaluation on the IEEE 33-Bus System

The IEEE 33-bus single line diagram is illustrated in Fig. 1, this radial distribution network is composed of 33 nodes numbered from 1 to 33 and 32 lines. Its base voltage is set at 12.66 kV.

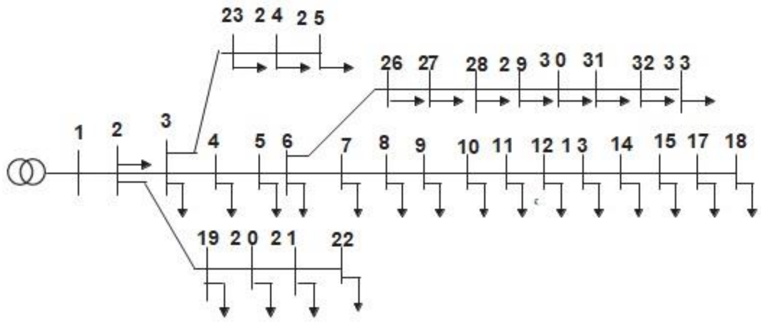


Figure 1 Single line diagram of the IEEE 33-bus system

6.1.1.1 Single-objective optimization

Each objective function is performed individually on the IEEE 33-bus system with UPQC installation scenario. Table 2 provides the optimal UPQC controller settings obtained from the proposed algorithms to improve the voltage stability index and reduce power losses of the IEEE 33-bus system.

Table 2: The optimal solution of all algorithms for improves the voltage stability index; minify the active power losses and system operating cost at installation of UPQC in IEEE 33 bus system

ALGORITHMS	LOC (bus)	Voltage Stability Index (VSI) (p.u)	LOC (bus)	PL (MW)	LOC (bus)	OC($)
GWO	6	0.76	10	6.94	26	5.674×10^6
IGWO	6	0.77	10	6.89	26	5.653×10^6
CSO	6	0.76	10	6.87	26	5.662×10^6
IGWO-OBL	6	0.78	10	6.85	26	5.643×10^6

As shown in Table 2, in the case to improve the voltage stability index and reduce power losses as an individual objective function, the integration of UPQC in the power system based on the different tested techniques reduced the total actual power losses from 7.22 MW to 6.85 MW.

The proposed IGWO-OBL technique provides the global minimum value of total power losses compared to the other methods. In addition, in the case improving the voltage stability index of the system as an individual objective function, the UPQC installation in the power system based on the proposed algorithms, IGWO-OBL algorithm, improving the voltage stability index from 0.71 p.u to 0.78 p.u . Without optimal UPQC installation, these values were 0.71 p.u, 7.22 M.W, 5.871×10^6 $, respectively. Table 2 shows the individual objective function of minimizing the operational Cost (OC) based on UPQC installation in the power system. The OC of the power system is 5.871×10^6 $ without the installation of UPQC device. The results show that the integration of UPQC based on the proposed IGWO-OBL algorithm at bus 6 reduces the OC to 5.643×10^6 $. It is noted that the IGWO-OBL algorithm provides a better and faster solution than any other optimization technique. It is also observed that the IGWO-OBL algorithm finds the global optimum in a small number of iterations compared to the other algorithms.

6.1.1.2 Mono-objective optimization

Each objective function is performed individually on the IEEE 33-bus system with TCSC installation scenario. Table 3. provides the optimal TCSC controller settings obtained from the proposed algorithms to improve the voltage stability index and reduce power losses of the IEEE 33-bus system.

Table 3. The optimal solution of all algorithms for improves the voltage stability index; minify the active power losses and system operating cost at installation of TCSC in IEEE 33 bus system

ALGORITHMS	LOC (bus)	Size (MVAR)	PL (MW)	LOC (bus)	Size (MVAR)	TVD (p.u)	LOC (bus)	Size (MVAR)	OC($)
GWO	6	-57.97	7.614	8	-73.12	0.0264	11	-38.423	5.699×10^6
IGWO	6	-56.13	7.523	8	-73.00	0.0254	11	-34.843	5.636×10^6
IGWO-CSO	6	-55.48	7.412	8	-71.74	0.0249	11	-33.639	5.548×10^6

Table 3 presents the optimal settings of the TCSC controller obtained based on various proposed algorithms to minimize the active power losses and voltage division of the IEEE33 bus system. From Table 3, in the case of minimizing total power losses as the individual objective function, the installation of the TCSC in the power system based on the IGWO-CSO algorithm reduced total actual power losses from 7.859 to 7.412 MW. The installation of the TCSC in the power system based on the GWO, IGWO and IGWO-CSO algorithms reduces the Total voltage deviation from 0.0274 to 0.0264 p.u ,0.0254p.u and 0.0249 p.u respectively. The optimal solution of all algorithms to minimize the OC based on the integration of TCSC in the power system is shown in Table 3. In this case, the proposed GWO, IGWO and IGWO-CSO algorithms techniques minimize the OC to 5.669×10^6, 5.636×10^6 and 5.548×10^6 $ respectively. In contrast with other algorithms, the optimal sitting and capacity of the TCSC based on the IGWO-CSO algorithm approach resulted in a simultaneous reduction of the TVD and OC to the minimum values. In conclusion, although the IGWO-CSO algorithm has the best results with the power losses objective function, it has the highest values with VD and OC objective functions. As shown in Figs. 2(a ,b and c) the IGWO-CSO algorithm exhibits the best performance during the optimization process. The IGWO-CSO algorithm finds the global optima in fewer numbers of iterations than other algorithms.

6.1.1.3. Multi-objective optimization

In multi-objective function via the proposed techniques are performed to improve the voltage stability index ,minify the power losses and system operating cost. The multi-objective function plays an important role in the performance of the optimization technique process for ensuring the global minimum. This issue can be achieved only based on the optimal evaluating of the weighting factors of the proposed fitness function. Therefore, the IGWO-OBL algorithm has been carried out via multi-objective function (F) using to evaluate the most suitable weighting factors' values via selecting the optimum capacity and sitting of the SVC as a case study. In this regard, for the 33-bus IEEE system, Table 4 illustrates the variation of the targeted quantities values (VSI, PL and OC) with changes in the weighting factors' values. The most applicable weighting factors are 0.1, 0.1, and 0.8 these values simultaneously ensure the balance between VSI, PL and OC values with the lowest capacity of the UPQC device installation, unlike all cases in Table 4.

Table 4. The optimal solution of all algorithms at different values of weight factors by the installation of UPQC for multi-objective optimization problem in IEEE 33 bus system

Weighting factors	LOCATION	Function	VSI(p.u)	PL(M.W)	O.C($)
(1,0,0)	8	2.579	0.68	6.718	6.193×10^6
(0.8,0.1,0.1)	8	0.955	0.61	6.716	6.231×10^6
(0.1,0.8,0.1)	8	0.968	0.68	6.774	6.917×10^6
(0.1, 0.1, 0.8)	8	0.865	0.77	6.881	5.663×10^6
(0.7,0.2,0.1)	8	0.931	0.65	6.734	6.495×10^6
(0.2,0.7,0.1)	8	0.931	0.66	6.772	6.917×10^6
(0.2,0.1,0.7)	8	0.968	0.61	6.872	5.689×10^6
(0.6,0.3,0.1)	8	0.956	0.68	6.756	6.761×10^6
(0.3,0.6,0.1)	8	0.978	0.66	6.774	6.917×10^6
(0.1,0.3,0.6)	8	0.935	0.61	6.846	5.715×10^6
(0.6,0.2,0.2)	8	0.921	0.66	6.726	6.209×10^6
(0.2,0.2,0.6)	8	0.927	0.63	6.802	5.781×10^6
(0.2,0.6,0.2)	8	0.926	0.61	6.774	6.917×10^6
(0.5,0.1,0.4)	8	0.918	0.67	6.794	5.797×10^6
(0.5,0.4,0.1)	8	0.922	0.62	6.774	6.917×10^6
(0.5,0.2,0.3)	8	0.917	0.64	6.740	6.009×10^6
(0.5,0.3,0.2)	8	0.921	0.63	6.729	6.417×10^6
(0.1,0.5,0.4)	8	0.965	0.68	6.726	6.335×10^6
(0.4,0.1,0.5)	8	0.952	0.64	6.832	5.731×10^6
(0.3,0.5,0.2)	8	0.942	0.65	6.767	5.859×10^6
(0.2,0.3,0.5)	8	0.924	0.64	6.743	5.990×10^6

In this section, all tested programs determined the optimum allocation of the UPQC in the IEEE 33-bus system to improve voltage stability index, minimize active power losses and system operating cost at the same time using as multi-objective function (F). As illustrated from Table 5. the optimal installation of the UPQC at bus 8, based on GWO,IGWO,CSO and IGWO-OBL techniques is resulting in to improve voltage stability index, reduction of active power losses and system operating cost to be 0.71 p.u to 0.77 p.u ,7.22 M.W to 6.88 M.W and 5.871×10^6 $ to 5.663×10^6 $ respectively.

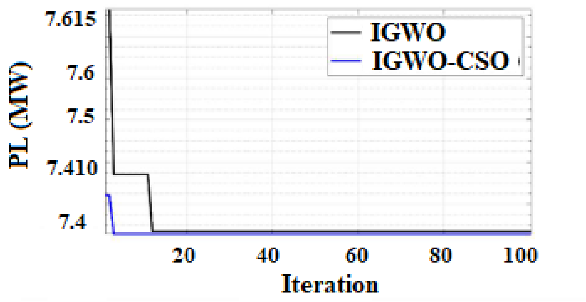
Without optimal UPQC installation, these values were 0.71 p.u, 7.22 M.W, 5.871×10^6 $, respectively. The IGWO-OBL algorithm finds a global optimum solution faster than other algorithms and has achieved the optimum global minimum value of F.

Table 5. The optimal solution of all algorithms for minimization of the multi-objective optimization problem at the installation of UPQC in IEEE 33 bus system

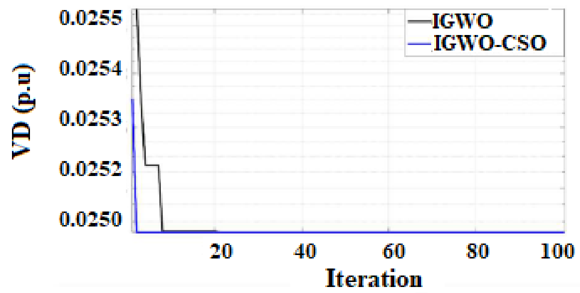
ALGORITHMS	LOC(bus)	VSI(p.u)	PL(M.W)	O.C($)
GWO	8	0.61	6.99	5.839×10^6
IGWO	8	0.67	6.97	5.781×10^6
CSO	8	0.62	6.92	5.797×10^6
IGWO-OBL	8	0.77	6.88	5.663×10^6

6.1.1.4 Multi-objective optimization

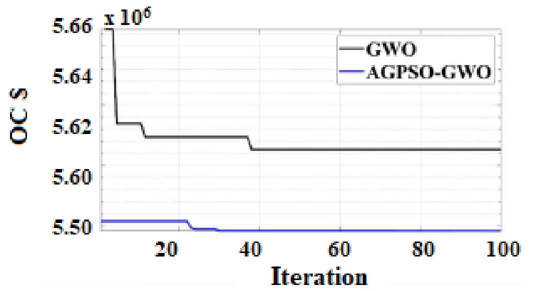
In this chapter, the multi-objective function via the proposed techniques are performed to minify the active power losses, Total voltage deviation, and system operating cost simultaneously in TCSC installation. The multi-objective function plays an important role in the performance of the optimization technique process for ensuring the global minimum. This issue can be achieved only based on the optimal evaluating of the weighting factors of the proposed fitness function. Therefore, the IGWO-CSO algorithm has been carried out via multi-objective function (F) using to evaluate the most suitable weighting factors' values via selecting the optimum capacity and sitting of the TCSC as a case study. In this regard, for the 33-bus IEEE system, Table 6. illustrates the variation of the targeted quantities values (PL, TVD, and OC) with changes in the weighting factors' values. The most applicable weighting factors are 0.1, 0.1, and 0.8; these values simultaneously ensure the balance between PL, VD, and OC values with the lowest capacity of the TCSC device installation, unlike all cases in Table 6.



(a)



(b)



(c)

Fig 2. a) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm in IEEE 33 bus system.to minimize PL(MW) in comparison with IGWO. b) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize VD(p.u) in comparison with IGWO. c) b) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize OC ($) in comparison with IGWO.

Table 6. The optimal solution of all algorithms at different values of weight factors by the installation of TCSC for multi-objective optimization problem.

Weighting factors	LOC (bus)	Function (F)	Size (MVAR)	TVD (p.u)	PL(M.W)	O.C($)
(1,0,0)	6	2.5675	-56.954	0.0271	7.626	6.293×10^6
(0.8,0.1,0.1)	6	0.7721	-55.121	0.0272	7.760	6.120×10^6
(0.1,0.8,0.1)	6	0.6735	-62.107	0.0248	7.774	6.827×10^6
(0.1, 0.1, 0.8)	6	0.8377	-29.568	0.0234	7.496	5.693×10^6
(0.7,0.2,0.1)	6	0.7322	-53.491	0.0151	7.732	6.385×10^6
(0.2,0.7,0.1)	6	0.5298	-62.011	0.0138	7.776	6.827×10^6
(0.2,0.1,0.7)	6	0.8223	-31.691	0.0226	7.872	5.872×10^6
(0.6,0.3,0.1)	6	0.7008	-68.659	0.0142	7.756	6.869×10^6

(0.3,0.6,0.1)	6	0.5541	-63.121	0.0139	7.774	6.816×10^6
(0.1,0.3,0.6)	6	0.8173	-32.039	0.0221	7.864	5.861×10^6
(0.6,0.2,0.2)	6	0.7500	-56.487	0.0173	7.726	6.109×10^6
(0.2,0.2,0.6)	6	0.8116	-36.772	0.0208	7.802	5.812×10^6
(0.2,0.6,0.2)	6	0.6448	-63.111	0.0147	7.774	6.817×10^6
(0.5,0.1,0.4)	6	0.7657	-48.824	0.0216	7.791	5.681×10^6
(0.5,0.4,0.1)	6	0.7214	-63.011	0.0147	7.774	6.817×10^6
(0.5,0.2,0.3)	6	0.6700	-48.542	0.0182	7.729	6.009×10^6
(0.5,0.3,0.2)	6	0.8115	-51.231	0.0165	7.726	6.327×10^6
(0.1,0.5,0.4)	6	0.9126	-49.124	0.0168	7.832	6.345×10^6
(0.4,0.1,0.5)	6	0.7164	-35.323	0.0216	7.726	5.831×10^6
(0.3,0.5,0.2)	6	0.7759	-72.663	0.0152	7.767	6.759×10^6
(0.2,0.3,0.5)	6	0.7654	-48.898	0.0189	7.743	6.990×10^6

As seen from Table 7. the optimal sittings of the TCSC based on IGWO-CSO algorithms is resulting in a reduction of active power losses, total bus voltage deviation, and system operating costs to 7.496 MW, 0. 0242 p.u, and 5.693×10^6\$, respectively. The optimal placement of the TCSC is the connection to line 6 with a size −29.568 MVAR. Whereas, the IGWO-CSO algorithm provided the largest size of the TCSC resulted in a minimum PL value that required the minimum OC value compared to the other algorithms. As depicted the IGWO-CSO algorithm shows the best performance and achieved the optimum global minimum value of F during the optimization process, among other algorithms.

Table 7. The optimal solution of all algorithms for minimization of the multi-objective optimization problem at the installation of TCSC .

ALGORITHMS	LOC (bus)	Function (F)	Size (MVAR)	TVD (p.u)	PL (M.W)	O.C ($)
GWO	6	0.8387	-29.7136	0.262	7.652	5.782×10^6
IGWO	6	0.8397	-29.9490	0.251	7.547	5.765×10^6
IGWO-CSO	6	0.8377	-29.5681	0.242	7.496	5.693×10^6

The IGWO-CSO algorithm is employed in this scenario to instantaneously mitigate the considered objectives. Due to these competing goals, the Pareto-optimal front solutions are stored for every iteration. To extract the best compromise solution from the final archive values, TOPSIS and AHP methods have been used. Table 8 presents the AHP method's pairwise comparison matrix. The optimal weight values obtained are 0.6667, 0.2222, and 0.1111.

Table 8 Pairwise Comparison Matrix

	OC	PL	TVD
OC	1	3	6
PL	1/3	1	2
TVD	1/6	1/2	1

Table 9. shows the optimum size and location of the TCSC device based on the IGWO-CSO algorithm to achieve the minimum value of the optimization problem. As shown in Table 9, the proposed method successfully defines the optimal TCSC position and rating, resulting in all objective values that are less than those obtained without TCSC installation. The reductions in TVD, PL, and OC are 0.247p.u, 7.273 MW, and 5.714×10^6\$, respectively.

Table 9. The Optimal Solution Determined by the TOPSIS Method from Pareto-Front Obtained IGWO-CSO Algorithm.

LOC (bus)	Size (MVAR)	TVD (p.u)	PL (M.W)	O.C ($)
8	-39.30	0.247	7.273	5.714×10^{6}

6.1.1.5 Evaluation of the results using statistical methods

To illustrate the robustness of the IGWO-CSO method, a statistical performance assessment is conducted for all methods. The mathematical expressions corresponding to the assessment criteria are presented in Table 10.

Table 10 Criteria of evaluations of the proposed techniques for IEEE 33 bus system

Criteria	Equation
Relative error (RE)	$\frac{\sum_{i=1}^{nr}(F_i - F_{min})}{F_{min}}.100\%$
Mean absolute error(MAE)	$\frac{\sum_{i=1}^{nr}(F_i - F_{min})}{nr}$
Root mean square error (RMSE)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - F_{min})^2}{nr}}$
Standard deviation (S.D)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - \overline{F_{min}})^2}{nr}}$

The numerical values corresponding to the evaluation criteria for all algorithms utilized in the installation of TCSC within the IEEE 33 bus system, aimed at optimizing the multi-objective function, are presented in Table 11.

Table 11. Numerical values for criteria of evaluations for IEEE 33 bus system

Installation of TCSC			
Criteria	Technique		
	GWO	IGWO	IGWO-CSO
Relative error (RE)	2.1235×10^{-7}	3.0707×10^{-10}	1.2054×10^{-12}
Mean absolute error(MAE)	2.0371×10^{-9}	3.9683×10^{-12}	1.0651×10^{-14}
Root mean square error (RMSE)	1.5585×10^{-8}	8.5037×10^{-12}	3.8231×10^{-14}
Standard deviation (S.D)	1.5365×10^{-8}	7.7851×10^{-7}	3.7867×10^{-14}

The data presented in Table 11. demonstrates that the proposed IGWO-CSO algorithm exhibits superior performance in accurately determining the optimal allocation of TCSC controller within the IEEE 33-bus power system, when compared to other proposed techniques.

6.1.2 Evaluating Performance on the IEEE 69 bus system

The IEEE69-bus single line diagram is shown in Fig.3. This radial distribution network is composed of 69 bus numbered from 1 to 69 and 68 lines. The system voltage base and Volt-Ampere base are chosen to be 12 kV and 100 MVA, respectively.

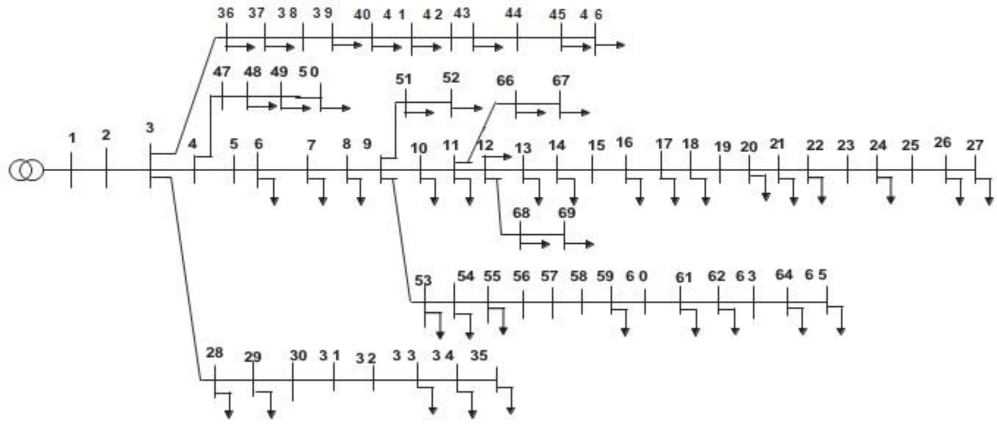


Figure 3. Single line diagram of the IEEE 69-bus system

6.1.2.1 Single-objective optimization

Table 12. displays the optimal settings of the UPQC device for improve voltage stability index, minimize active power losses of the IEEE 69 bus system based on different proposed techniques. The installation of the UPQC at bus 61 location the IGWO-OBL algorithm reduced the power losses from 122.86 to 120.439 MW and improve voltage stability index from 0.81 to 0.99 p.u with high capacities values as compared to other algorithms. The non-optimized location of UPQC controller results in poor objective values such as Voltage p.u,stability index ,power loss and operating cost yields 0.81 p.u , 122.86 M.W and 5.7567 $\times 10^6$ respectively. Whereas the non-optimum UPQC location result in higher objective values than the optimized location. According to the GWO, IGWO, and CSO algorithms PL(MW) value is 122.794,121.69 and122.552 MW, respectively. In comparison, the optimal location OF UPQC using the GWO, IGWO, and CSO algorithms to improve voltage stability index 0.91, 0.88, and 0.90 p.u respectively.

Table 12. The optimal solution of all algorithms for improves the voltage stability index to minimise the active power losses and system operating cost at installation of UPQC in IEEE 69 bus system

ALGORITHMS	LOC (bus)	Voltage Stability Index (VSI) (p.u)	LOC (bus)	PL (MW)	LOC (bus)	OC($)
GWO	61	0.91	65	122.794	64	5.7446×10^6
IGWO	61	0.88	65	121.169	64	5.7394×10^6
CSO	61	0.90	65	122.552	64	5.7241×10^6
IGWO-OBL	61	0.99	65	120.439	64	5.6675×10^6

The optimal solution of all algorithms to minimize the OC based on the location of UPQC is shown in Table 12. The installation of the UPQC based on the GWO, IGWO, and CSO algorithms minimizes the OC to 5.7446×10^6 ,5.7394×10^6 and 5.7241×10^6 $. On the other hand, the optimum location and size of the UPQC based on the IGWO-OBL technique resulted in the OC value to 5.6675×10^6 $.

6.1.2.2 Mono-objective optimization

Each objective function is performed individually on the IEEE 69-bus system with TCSC installation scenario. Table 13. provides the optimal TCSC controller settings obtained from the proposed algorithms to improve the voltage stability index and reduce power losses of the IEEE 69-bus system.

Table 13. Presents the optimal settings of the TCSC controller obtained based on various proposed algorithms to minimize the active power losses and voltage division of the IEEE 69 bus system. From Table 13, in the case of minimizing total power losses as the individual objective function, the installation of the

TCSC in the power system based on the IGWO-CSO algorithm reduced total actual power losses from 133.86 to 130.439 MW. The installation of the TCSC in the power system based on the GWO, IGWO and IGWO-CSO algorithms reduces the Total voltage deviation from 0.0762 to 0.0747 p.u, 0.0743 p.u and 0.0716 p.u respectively. The optimal solution of all algorithms to minimize the OC based on the integration of TCSC in the power system is shown in Table 13.

Table 13. The optimal solution of all algorithms for improves the voltage stability index, reduce active power losses and system operating cost at installation of TCSC in IEEE 69 bus system

ALGORITHMS	LOC (bus)	Size (MVAR)	PL (MW)	LOC (bus)	Size (MVAR)	TVD (p.u)	LOC (bus)	Size (MVAR)	OC($)
GWO	52	-13.375	132.71	21	-20.476	0.0747	38	-27.966	1.0452×10^8
IGWO	52	-13.365	131.69	21	-18.327	0.0743	38	-26.811	1.0350×10^8
IGWO-CSO	52	-12.745	130.43	21	-17.412	0.0716	38	-24.532	1.0337×10^8

In this case, the proposed GWO, IGWO and IGWO-CSO algorithms techniques minimize the OC to 1.0452×10^8, 1.0350×10^8 and 1.0337×10^8 $ respectively. In contrast with other algorithms, the optimal sitting and capacity of the TCSC based on the IGWO-CSO algorithm approach resulted in a simultaneous reduction of the TVD and OC to the minimum values. In conclusion, although the IGWO-CSO algorithm has the best results with the power losses objective function it has the highest values with TVD and OC objective functions. As shown in Figs. 3(a, b and c) the IGWO-CSO algorithm exhibits the best performance during the optimization process. The IGWO-CSO algorithm finds the global optima in fewer numbers of iterations than other algorithms.

6.1.2.3 Multi-objective optimization

In this chapter, the UPQC is installed in the IEEE 69-bus system to minimize the considered multi-objective function. Table 14. illustrates the minimum value of the PL that is 121.792 MW. This issue can be achieved by installing the UPQC in the system based on the IGWO-OBL algorithm. IGWO-OBL technique achieved the optimal global solutions compared to other algorithms by installing UPQC at bus 61.

Table 14. The optimal solution of all algorithms at different values of weight factors by the installation of UPQC for multi-objective optimization problem in IEEE 69 bus system

Weighting factors	LOC (bus)	Function	VSI (p.u)	PL (M.W)	O.C($)
(1,0,0)	61	2.945	0.77	123.107	5.8234×10^6
(0.8,0.1,0.1)	61	0.892	0.78	122.914	5.8334×10^6
(0.1,0.8,0.1)	61	0.6745	0.76	123.531	5.8102×10^6
(0.1, 0.1, 0.8)	61	0.8455	0.89	121.792	5.7214×10^6
(0.7,0.2,0.1)	61	0.9331	0.71	123.078	5.8804×10^6
(0.2,0.7,0.1)	61	0.7284	0.71	123.495	5.7731×10^6
(0.2,0.1,0.7)	61	0.8225	0.76	122.822	5.7631×10^6
(0.6,0.3,0.1)	61	0.9112	0.77	122.209	5.7532×10^6
(0.3,0.6,0.1)	61	0.7763	0.76	123.216	5.7433×10^6
(0.1,0.3,0.6)	61	0.9292	0.71	123.446	5.7641×10^6
(0.6,0.2,0.2)	61	0.9693	0.75	122.973	5.8041×10^6
(0.2,0.2,0.6)	61	0.9685	0.78	123.402	5.8052×10^6
(0.2,0.6,0.2)	61	0.9681	0.76	122.854	5.8121×10^6

(0.5,0.1,0.4)	61	0.9685	0.77	123.305	5.8164×10^6
(0.5,0.4,0.1)	61	0.9680	0.76	123.014	5.8127×10^6
(0.5,0.2,0.3)	61	0.9678	0.75	123.157	5.8389×10^6
(0.5,0.3,0.2)	61	0.9851	0.73	123.455	5.7473×10^6
(0.1,0.5,0.4)	61	0.9692	0.75	123.843	5.7379×10^6
(0.4,0.1,0.5)	61	0.9684	0.77	123.331	5.7526×10^6
(0.3,0.5,0.2)	61	0.9683	0.76	123.155	5.8354×10^6
(0.2,0.3,0.5)	61	0.9582	0.78	123.676	5.8269×10^6

According to the optimal UPQC setting based on the IGWO-OBL algorithm, the system's voltage stability index and operating costs were reduced to 0.89 pu and 5.7214×10^6 \$, respectively. The IGWO-OBL algorithm finds the global optimum solution faster than the other algorithms.

Table 15. The optimal solution of all algorithms for minimization of the multi-objective optimization problem at the installation of UPQC in IEEE 69 bus system.

ALGORITHMS	LOC(bus)	VSI(p.u)	PL(M.W)	O.C($)
GWO	61	0.75	122.972	5.7539×10^6
IGWO	61	0.78	122.828	5.7481×10^6
CSO	61	0.74	122.855	5.7436×10^6
IGWO-OBL	61	0.89	121.791	5.7214×10^6

In this section, all tested programs determined the optimum allocation of the UPQC in the IEEE 69-bus system to improve voltage stability index, minimize active power losses and system operating cost at the same time using the multi-objective function (F). As illustrated from Table 15. the optimal installation of the UPQC at bus 61, based on GWO,IGWO,CSO and IGWO-OBL techniques is resulting in to improve voltage stability index, reduction of active power losses and system operating cost to be 0.81 p.u to 0.89 p.u ,122.861 M.W to 121.79 M.W and 5.7567×10^6 \$ to 5.7214×10^6 \$ respectively. Without optimal UPQC installation, these values were 0.81 p.u, 122.861 M.W, 5.7567×10^6 \$, respectively. The IGWO-OBL algorithm finds a global optimum solution faster than other algorithms and has achieved the optimum global minimum value of F.

6.1.2.4 Multi-objective optimization

In this chapter, the multi-objective function via the proposed techniques are performed to minify the active power losses, Total voltage deviation, and system operating cost simultaneously in TCSC installation. The multi-objective function plays an important role in the performance of the optimization technique process for ensuring the global minimum. This issue can be achieved only based on the optimal evaluating of the weighting factors of the proposed fitness function. Therefore, the IGWO-CSO algorithm has been carried out via multi-objective function (F) to evaluate the most suitable weighting factors' values via selecting the optimum capacity and sitting of the TCSC as a case study. In this regard, for the 69-bus IEEE system, Table 16. illustrates the variation of the targeted quantities values (PL, TVD, and OC) with changes in the weighting factors' values. The most applicable weighting factors are 0.1, 0.1, and 0.8; these values simultaneously ensure the balance between PL, VD, and OC values with the lowest capacity of the TCSC device installation, unlike all cases in Table 5.0

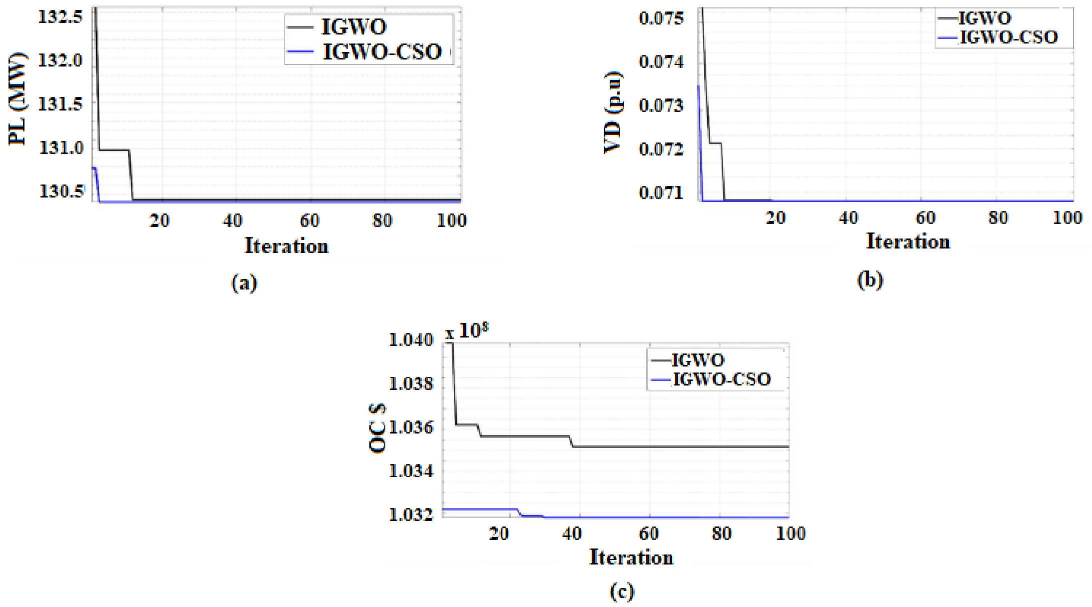


Fig 3. a) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm in IEEE 69 bus system.to minimize PL(MW) in comparison with IGWO. b) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize TVD(p.u) in comparison with IGWO. c) Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize OC ($) in comparison with IGWO.

As seen from Table 17, the optimal sittings of the TCSC based on IGWO-CSO algorithms is resulting in a reduction of active power losses, total bus voltage deviation, and system operating costs to 131.791 MW, 0.743 p.u, and 1.0392×10^8\$, respectively. The optimal placement of the TCSC is the connection to line 52 with a size −14.207 MVAR. Whereas, the IGWO-CSO algorithm provided the largest size of the TCSC resulted in a minimum PL value that required the minimum OC value compared to the other algorithms. As depicted the IGWO-CSO algorithm shows the best performance and achieved the optimum global minimum value of F during the optimization process, among other algorithms.

Table 16. The optimal solution of all algorithms at different values of weight factors by the installation of TCSC for multi-objective optimization problem.

Weighting factors	LOC (bus)	Function (F)	Size (MVAR)	TVD (p.u)	PL(M.W)	O.C($)
(1,0,0)	52	2.845	-35.3705	0.0711	133.103	1.0441×10^8
(0.8,0.1,0.1)	52	0.884	-33.396	0.0720	132.914	1.0411×10^8
(0.1,0.8,0.1)	52	0.855	-53.332	0.0706	133.439	1.0511×10^8
(0.1, 0.1, 0.8)	52	0.887	-14.207	0.0743	131.741	1.0392×10^8
(0.7,0.2,0.1)	52	0.878	-52.796	0.0712	133.074	1.0448×10^8
(0.2,0.7,0.1)	52	0.853	-60.872	0.0706	133.497	1.0538×10^8
(0.2,0.1,0.7)	52	0.885	-22.431	0.0730	132.623	1.0588×10^8
(0.6,0.3,0.1)	52	0.872	-51.121	0.0709	133.101	1.0575×10^8
(0.3,0.6,0.1)	52	0.852	-60.120	0.0706	133.429	1.0628×10^8
(0.1,0.3,0.6)	52	0.885	-24.827	0.0729	132.826	1.0488×10^8
(0.6,0.2,0.2)	52	0.878	-42.566	0.0713	133.024	1.0439×10^8
(0.2,0.2,0.6)	52	0.881	-38.881	0.0716	132.877	1.0426×10^8
(0.2,0.6,0.2)	52	0.852	-59.468	0.0706	133.201	1.0618×10^8
(0.5,0.1,0.4)	52	0.886	-28.868	0.0725	132.857	1.0467×10^8
(0.5,0.4,0.1)	52	0.865	-54.572	0.0707	133.307	1.0497×10^8
(0.5,0.2,0.3)	52	0.880	-38.723	0.0715	133.004	1.0632×10^8

(0.5,0.3,0.2)	52	0.882	-48.061	0.0710	133.157	1.0539×10^8
(0.1,0.5,0.4)	52	0.861	-59.381	0.0706	133.453	1.0494×10^8
(0.4,0.1,0.5)	52	0.885	-27.811	0.0726	132.841	1.0503×10^8
(0.3,0.5,0.2)	52	0.858	-56.660	0.0707	133.330	1.0522×10^8
(0.2,0.3,0.5)	52	0.874	-41.620	0.0711	133.051	1.0533×10^8

Table 17. The optimal solution of all algorithms for minimization of the multi-objective optimization problem at the installation of TCSC .

ALGORITHMS	LOC (bus)	Function (F)	Size (MVAR)	TVD (p.u)	PL (M.W)	O.C ($)
GWO	52	0.894	-15.827	0.747	132.794	1.0426×10^8
IGWO	52	0.890	-15.912	0.744	132.697	1.0411×10^8
IGWO-CSO	52	0.887	-14.207	0.743	131.791	1.0392×10^8

The IGWO-CSO algorithm is employed in this scenario to instantaneously mitigate the considered objectives. Due to these competing goals, the Pareto-optimal front solutions are stored for every iteration. To extract the best compromise solution from the final archive values, TOPSIS and AHP methods have been used. Table 18 presents the AHP method's pairwise comparison matrix. The optimal weight values obtained are 0.6667, 0.2222, and 0.1111.

Table 18. Pairwise Comparison Matrix

	OC	PL	TVD
OC	1	3	6
PL	1/3	1	2
TVD	1/6	1/2	1

Table 19. shows the optimum size and location of the TCSC device based on the IGWO-CSO algorithm to achieve the minimum value of the optimization problem. As shown in Table 19, the proposed method successfully defines the optimal TCSC position and rating, resulting in all objective values that are less than those obtained without TCSC installation. The reductions in TVD, PL, and OC are 0.745 p.u,132.78 M.W and 1.0402×10^8\$, respectively.

Table 19. The Optimal Solution Determined by the TOPSIS Method from Pareto-Front Obtained IGWO-CSO Algorithm.

LOC (bus)	Size (MVAR)	TVD (p.u)	PL (M.W)	O.C ($)
51	-14.2667	0.745	132.78	1.0402×10^8

6.1.2.5 Evaluation of the results using statistical methods

A statistical performance assessment is conducted for all methods to illustrate the robustness of the IGWO-CSO method . The mathematical expressions associated with the assessment criteria are detailed in Table 20.

Table 20. Criteria of evaluations of the proposed techniques for IEEE 69 bus system

Criteria	Equation
Relative error (RE)	$\frac{\sum_{i=1}^{nr}(F_i - F_{min})}{F_{min}}.100\%$
Mean absolute error(MAE)	$\frac{\sum_{i=1}^{nr}(F_i - F_{min})}{nr}$
Root mean square error (RMSE)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - F_{min})^2}{nr}}$
Standard deviation (S.D)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - \overline{F_{min}})^2}{nr}}$

The numerical values associated with the evaluation criteria for all algorithms employed in the installation of TCSC within the IEEE 69 bus system, intended for the optimization of the multi-objective function, are detailed in Table 20. The data shown in Table 21. indicates that the proposed IGWO-CSO algorithm outperforms other techniques in accurately determining the optimal allocation of TCSC within the IEEE 69-bus power system.

Table 21 Numerical values for criteria of evaluations for IEEE 69 bus system

Installation of TCSC			
criteria	Technique		
	GWO	IGWO	IGWO-CSO
Relative error (RE)	1.5525×10^{-12}	5.3818×10^{-13}	1.8643×10^{-13}
Mean absolute error(MAE)	1.5566×10^{-12}	5.2515×10^{-15}	1.8244×10^{-15}
Root mean square error (RMSE)	1.5753×10^{-12}	1.2483×10^{-14}	2.8140×10^{-15}
Standard deviation (S.D)	2.1402×10^{-12}	8.5240×10^{-15}	2.1201×10^{-15}

VII. CONCLUSION

This research presented a hybrid optimization framework for the optimal placement and sizing of Flexible Alternating Current Transmission System (FACTS) devices to enhance the performance of power distribution networks. Two hybrid algorithms—Improved Grey Wolf Optimization combined with Cuckoo Search Optimization (IGWO–CSO) and Improved Grey Wolf Optimization integrated with Opposition-Based Learning (IGWO–OBL)—were developed to overcome the limitations of conventional metaheuristic techniques. The proposed methods aimed to minimize active power losses, voltage deviation, total harmonic distortion (THD), and operating costs while improving the Voltage Stability Index (VSI) and overall system reliability. The algorithms were implemented and validated on IEEE 33-bus and IEEE 69-bus systems using MATLAB/MATPOWER. Comparative analyses with existing algorithms such as GWO, IGWO, and CSO demonstrated that the proposed hybrid methods achieved superior convergence speed, solution accuracy, and stability. The results confirm that integrating hybrid metaheuristic optimization techniques significantly improves the effectiveness of FACTS device allocation, thereby enhancing voltage regulation, power quality, and economic operation. Future research may focus on extending the proposed approach to large-scale, real-time power systems and incorporating renewable energy sources for improved sustainability and adaptive control in smart grid environments.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

Conceptualization, L.Vamsi Narasimha Rao; Methodology, L.Vamsi Narasimha Rao; Validation, L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Formal analysis L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Investigation, L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Resources, L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Data curation, L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Writing—original draft preparation, L.Vamsi Narasimha Rao; Writing—Review and Editing, L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Visualization; L.Vamsi Narasimha Rao, P.S.Prakash, and M.Veera kumari; Supervision; P.S.Prakash, and M.Veera kumari

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