Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Enhancing Operational Performance of Power System through Optimal Allocation of TCSC Using a Novel Hybrid Optimisation Technique

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ARTICLE INFO

Received: 15 Oct 2024

Revised: 29 Nov 2024

Accepted: 22 Dec 2024

ABSTRACT

This paper presents a novel hybrid optimization methodology integrating the Improved Grey Wolf Optimizer (IGWO) and Cuckoo Search Optimization (CSO) for the optimal placement and sizing of Thyristor-Controlled Series Compensators (TCSC) in power distribution networks. The proposed IGWO-CSO algorithm aims to enhance power system performance by minimizing active power loss, total bus voltage deviation and operating costs (OC). The optimization problem is formulated as a single-objective and multi-objective framework to ensure an effective trade-off between multiple power system parameters. To determine the optimal compromise solution in the multi-objective scenario, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP) are employed. The performance of the proposed approach is evaluated on the IEEE 33-bus and 69-bus systems using MATLAB with the MATPOWER package. Comparative analysis with Grey Wolf Optimization (GWO) and Improved Grey Wolf Optimization (IGWO) demonstrates that the IGWO-CSO hybrid method achieves superior results in terms of solution quality, convergence speed, and overall system performance. The results validate the efficiency of the proposed methodology in optimally placing TCSC devices to enhance power system stability and economic operation.

Keywords: Hybrid Optimization, Thyristor-Controlled Series Compensator (TCSC), Optimal Placement and Sizing, Multi-Objective Optimization, Power Loss Minimization, total bus voltage deviation, Operating Cost Reduction, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution),Analytical Hierarchy Process (AHP).

1. INTRODUCTION

The increasing complexity of modern power systems, coupled with growing electricity demand, necessitates the integration of advanced optimization techniques to enhance power system stability, efficiency, and cost-effectiveness [1]. One of the most effective solutions for improving power system performance is the deployment of Flexible AC Transmission System (FACTS) devices, such as the Thyristor-Controlled Series Compensator (TCSC)[2]. TCSC plays a crucial role in reducing transmission losses, optimizing power flow, minimizing voltage deviations, and alleviating line congestion. However, the benefits of TCSC largely depend on its optimal placement and sizing, which is a challenging multi-objective optimization problem due to the nonlinear and dynamic nature of power systems [3][4].

Hybrid optimization algorithms have proven to be highly effective in solving complex power system optimization problems. In this study, a novel hybrid optimization approach combining Improved Grey Wolf Optimizer (IGWO)

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and Cuckoo Search Optimization (CSO) is proposed to determine the optimal placement and sizing of TCSC in the IEEE 33-bus and IEEE 69-bus test systems [5]. The IGWO algorithm, an enhanced version of the standard Grey Wolf Optimizer (GWO), improves the balance between exploration and exploitation by incorporating adaptive weight strategies and a chaotic local search mechanism. On the other hand, Cuckoo Search Optimization (CSO), inspired by the brood parasitism behaviour of cuckoo birds, introduces an efficient Levy flight mechanism to enhance the global search capability and prevent premature convergence. The hybridization of IGWO and CSO leverages the strengths of both algorithms, ensuring faster convergence and improved solution accuracy.[6]

The key objectives of this research are:

1. Minimization of active power losses to enhance system efficiency.
2. Reduction of total bus voltage deviation to improve voltage stability.
3. Minimization of operating costs (OC) for economic power system operation.

To address the multi-objective nature[7] of the optimization problem, multi-criteria decision-making (MCDM) techniques such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP) are employed to determine the most optimal trade-off solution.[8] The proposed IGWO-CSO hybrid algorithm is implemented in MATLAB using the MATPOWER package[9], and its performance is evaluated through comparison with standard optimization algorithms[10], including Grey Wolf Optimization (GWO)[11], and Improved Grey Wolf Optimization (IGWO)[12]. The results demonstrate that the IGWO-CSO hybrid method outperforms existing techniques in terms of solution quality, convergence speed, and overall system performance, making it a promising approach for TCSC Controller optimal allocation [13].

The rest of this paper is organized as follows: Section II presents the mathematical modelling of TCSC and the problem formulation. Section III explains the problem formulation in detail. Section IV explains the IGWO-CSO hybrid algorithm in detail. Section V discusses the simulation results and comparative analysis. Finally, Section VI concludes the paper with conclusion.

2. MODELLING OF TCSC IN POWER SYSTEMS

The Thyristor-Controlled Series Compensator (TCSC) is a widely used FACTS device that enhances power system stability by modulating line impedance, improving voltage profile, and reducing transmission losses [11]. The TCSC consists of a series-connected capacitor and a thyristor-controlled reactor (TCR), allowing dynamic control over the effective reactance of a transmission line. By adjusting the thyristor firing angle, the TCSC can operate in capacitive, inductive, or bypass mode, thereby optimizing power flow and mitigating line congestion [12]. The mathematical representation of the TCSC reactance is given as follows:

$$X_{TCSC} = X_C + \frac{X_L}{1+(\alpha/\pi)} \tag{1}$$

Where X_C is capacitive reactance. X_L is Inductive reactance. α is the thyristor firing angle. The optimal placement of TCSC is crucial for improving voltage stability, minimizing active power losses, and enhancing economic operation of power systems.

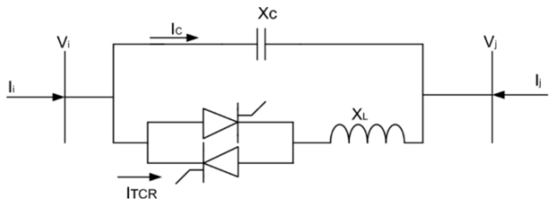

Figure 1. Schematic representation of a Thyristor Controlled Series Capacitor (TCSC).

The optimal placement of TCSC is crucial for improving voltage stability, minimizing active power losses, and enhancing economic operation of power systems. Figure 1 illustrates a schematic representation of a TCSC connected between Bus i and Bus j. The TCSC is represented as a variable reactance that is connected in series with the transmission line's impedance, as illustrated in Figure 2.

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/

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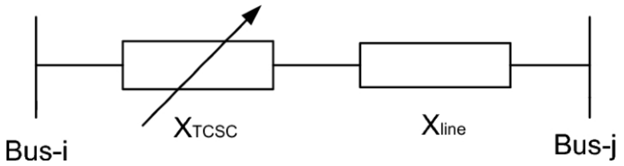

Figure 2. Equivalent Circuit of a Thyristor Controlled Series Capacitor (TCSC).

The incorporation of TCSC modifies the reactance of the line as outlined in equations (2) and (3).

$$Z_{TL} = R_{ij} + JX_{ij} \quad (2)$$

$$X_N = X_{ij} - X_{TCSC} \quad (3)$$

The equation (3) can be further simplified to produce equations (4) and (5), in which the ratio of the TCSC reactance to the line reactance prior to compensation determines the rate of compensation.

$$X_N = (1-\tau)X_{ij} \quad (4)$$

$$\tau = \frac{X_{TCSC}}{X_{ij}} \quad (5)$$

$$X_{TCSC} = X_{ij}.\tau \quad (6)$$

Where Z_{TL} is the impedance of the transmission line, R_{ij} and X_{ij} are the line's resistance and reactance respectively between buses I and j.X_N is the line reactance without compensation. X_{TCSC} is the reactance of TCSC and τ is the degree of compensation.The range of X_{TCSC} to avoid overcompensation is expressed in eq (7).

$$-0.8X_N \leq X_{TCSC} \leq 0.2X_N \quad (7)$$

3. PROBLEM FORMULATION

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

3.1 Mono-Objective Optimization, in which each of the specific objective functions is optimised independently of the others.

3.1.1 Optimisation problem formulation

In this study, three objective functions are taken into account. These objectives include minimisation of power system operating costs, active power loss, and bus voltage deviation in power systems [11]. The optimization problem can be expressed by (8) to (12).

$$\min F = [F_{PL}(x), F_{TVD}(x), F_{OC}(x)] \quad (8)$$

Active power loss minimization

The given equation represents the active power loss minimization in a power system network. It expresses the total real power loss F_{PL} in transmission lines expressed in (9) based on the bus voltages and conductance of the lines [19].

$$F_{PL} = \sum_{k=1}^{L} G_k [Vb_m^2 + Vb_n^2 - 2Vb_m Vb_n \cos(\delta_{mn})] \quad (9)$$

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.

Minimization of the total bus voltage deviation

Total Bus Voltage Deviation (TVD) Minimization objective function properly formatted expressed in (10)

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$$F_{TVD} = \sum_{m=1}^{N}[Vb_m - 1]^2 \tag{10}$$

Where F_{TVD}, Vb_m and N represents Total bus voltage deviation function, Voltage magnitude at bus m and Total number of buses respectively

Minimisation of operating cost(OC)

The OC function[2] is expressed in (11)

$$F_{OC} = (real\ power\ loss) \times 0.09 \times 365 \times 24 \tag{11}$$

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \tag{12}$$

where $F_{PL,}$ 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].

3.2 MULTI-OBJECTIVE OPTIMIZATION

In multi objective optimisation 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].

3.2.1 Multi-objective Function

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).

$$F = w1 \cdot J1 + w2 \cdot J2 + w3 \cdot J3 \tag{13}$$

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

$$J_1 = \frac{PL_{-TCSC}}{PL_{-base}}, J_2 = \frac{TVD_{-TCSC}}{TVD_{-base}}, J_3 = \frac{OC_{-TCSC}}{OC_{-base}} \tag{14}$$

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].

Multi-objective optimization, where 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[12]. This paper presents the optimisation problem addressed through two distinct approaches:

1.A mono-objective optimisation, where each of the Each specific objective function is optimised independently of the others.

2. Multi-objective optimisation involves the simultaneous minimisation of the identified objectives. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is employed in this study to identify the optimal compromise solution from the derived non-dominated solutions [15].

3.2.2 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.

Journal of Information Systems Engineering and Management
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e-ISSN: 2468-4376
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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).

$$r_{ij} = {x_{ij}}\Big/{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{15}$$

2.compute the weighted normalised decision matrix as expressed in (16).

$$k_{ij} = w_j r_{ij} \tag{16}$$

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 (17) & (18).

$$A^+ = (k_1^+, k_2^+, \dots \dots . k_n^+) = \left(\max k_{ij} \,\middle|\, \mathrm{j} \in I \,, \left(\max k_{ij} \,\middle|\, \mathrm{j} \in \mathrm{j} \,,\right)\right) \tag{17}$$

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

Where j and I indicate cost and benefit criteria respectively.

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 (19) & (20).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (k_{ij} - k_j^+)^2} \tag{19}$$

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

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 (21).

$$C_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{21}$$

Where 0< $C_i < 1$

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

3.2.3 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 (22). 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].

$$\mathrm{S}=\begin{bmatrix} 1 & s_{ij} & \cdot & \cdot & s_{im} \\ 1/s_{ij} & 1 & \vdots & \cdot & s_{jm} \\ \vdots & \cdot & \vdots & \cdot & \cdot \\ 1/s_{mi} & 1/s_{mj} & \cdot & \cdot & 1 \end{bmatrix} \tag{22}$$

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

$$w_i = \frac{\sqrt[m]{\pi_{j=1}^{m} s_{ij}}}{\sum_{i=1}^{m} \sqrt[m]{\pi_{j=1}^{m} s_{ij}}} \; (i = 1,2, \ldots, m) \tag{23}$$

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

$$I_{CR} = \frac{I_{CI}}{I_{RI}} = \frac{\lambda_{max} - m}{(m-1)I_{RI}} < 0.1 \tag{24}$$

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)

$$[S][W] = \lambda_{max}[W] \tag{25}$$

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}

3.3 Constraints

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

$$QG^m - QD^m - \sum_{n=1}^{Nb} V_m V_n [G_{mn} \sin(\delta_{mn}) + B_{mn} \cos(\delta_{mn})] = 0 \tag{26}$$

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

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

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.

$$V_{mn}^{min} \le V_{mn} \le V_{mn}^{max} \tag{28}$$

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

$$S_{mn} \le S_{mn}^{max} \tag{29}$$

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

$$X_{TCSC}^{min} \le X_{TCSC} \le X_{TCSC}^{max} \tag{30}$$

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

$$Q_{TCSC}^{min} \le Q_{TCSC} \le Q_{TCSC}^{max} \tag{31}$$

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

4. OPTIMISATION METHOD

4.1 Improved Grey Wolf Optimization (IGWO) Algorithm

The Improved Grey Wolf Optimization (IGWO) algorithm enhances the original GWO by balancing exploration and exploitation, reducing premature convergence and local optima trapping [21]. IGWO introduces Dimension-Learning-Based Hunting (DLBH) to improve search efficiency.

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e-ISSN: 2468-4376
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4.1.1 Wolf Position Initialization

Wolves are randomly initialized within the search space using:

$$X_{ij} = I_j + rand_j[0,1]x(u_j - l_j), i \in [1, N], j \in [1, D] \quad (32)$$

Where N is the number of wolves, D is the dimension, I_j and u_j are the lower and upper limits of the search space.

4.1.2 Neighbourhood and Distance Calculation

The neighbourhood of a wolf is determined by:

$$R_i(t) = \left\| X_j(t) - X_{j-GWO}(t+1) \right\| \quad (33)$$

$$N_i(t) = \left\{ X_j(t) | D_i \left(X_j(t), X_j(t) \right) \le R_i(t), X_j(t) gMatrix \right\} \quad (34)$$

Where D_i is the Euclidean distance between wolves.

4.1.3 Dimension-Learning Hunting (DLBH) Model

The new wolf position is updated as:

$$X_{iDLH,d}(t) = \left(X_{i,d}(t) + rand[0,1]x \left(X_{n,d}(t) - X_{r,d}(t) \right) \right) \quad (35)$$

Where $X_{iDLH,d}(t)$ is the new DLH-based position, and X_n, X_r are selected wolves.

The final update rule is

$$X_i(t+1) = \begin{Bmatrix} X_{i\,GWO}(t+1), if\ f(X_{i\,GWO}(t+1) < f(X_{iDLH,d}(t+1) \\ X_{iDLH,d}(t+1) \qquad otherwise \end{Bmatrix} \quad (36)$$

4.2 Cuckoo Search Optimization (CSO) Algorithm

Cuckoo Search Optimization (CSO) is inspired by cuckoo species brood parasitism behaviour. It employs Levy flights for exploration [22], [23].

4.2.1 Levy Flight Update

New candidate solutions are generated as

$$Y_i = Y_i - \gamma. \left| Y_i - Y_g \right| + levy(\lambda) \quad (37)$$

$$Y_i = Y_i + \frac{0.01\mu}{v^{1/\lambda}} \left(Y_i - Y_g \right) \quad (38)$$

Where Y_g is the global best solution,γ>0 is a step scaling factor,μ, v follow a normal distribution.

The Levy step size is given by

$$\sigma_u = \left[\frac{\sin\frac{\lambda\pi}{2}.\tau(1+\lambda)}{2^{(\lambda-1)/2}\lambda.\tau\left(\frac{1+\lambda}{2}\right)} \right]^{1/\lambda} \quad (39)$$

4.2.2 Discovery of New Nests

Cuckoos replace nests with a probability p_a

$$Y_i = \begin{Bmatrix} Y_i + m.\left(Y_j - Y_k \right), if\ p > p_a \\ Y_i, \qquad otherwise \end{Bmatrix} \quad (40)$$

Where Y_j, Y_k are randomly chosen solutions.

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e-ISSN: 2468-4376
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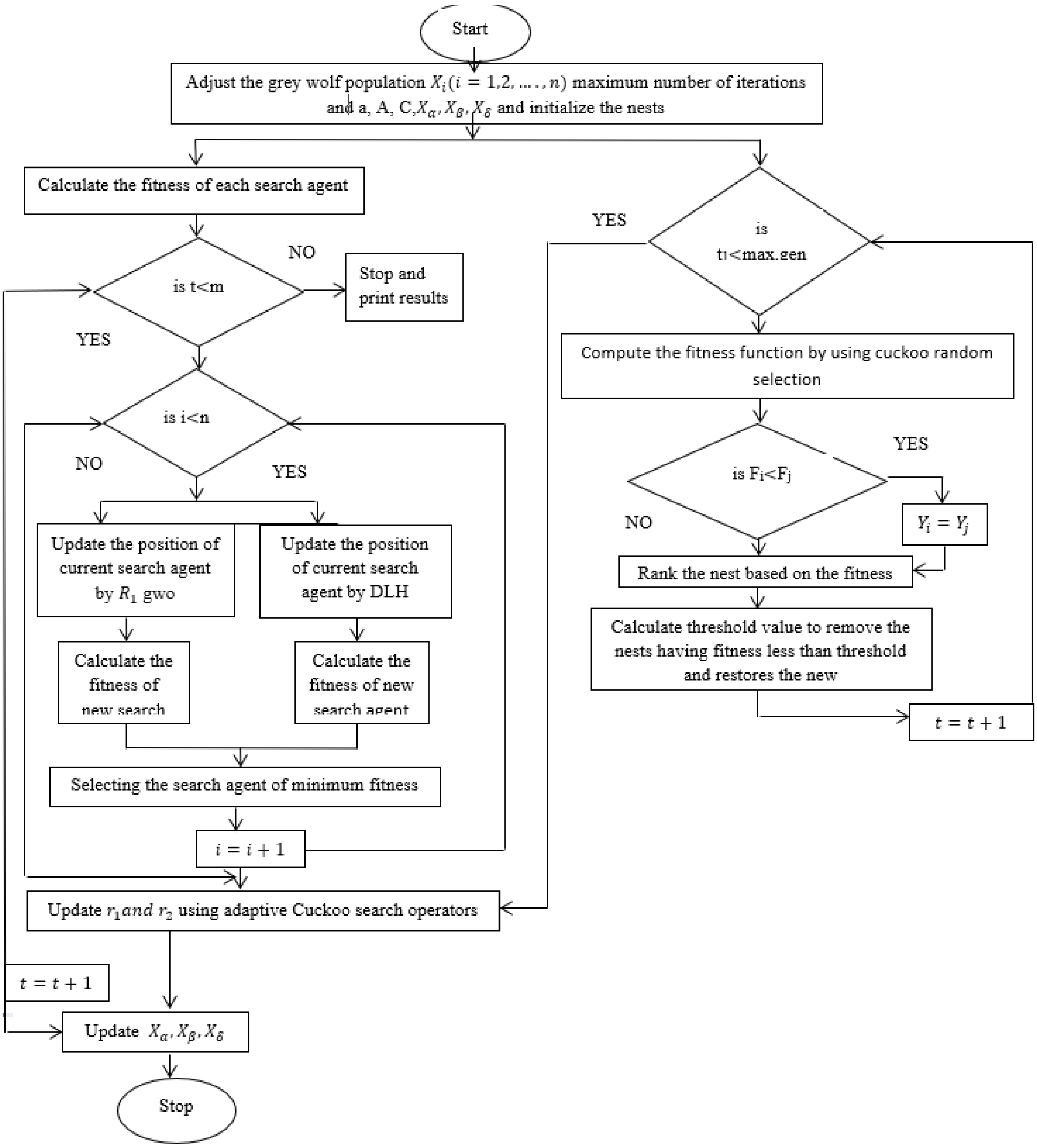
4.3 IGWO-CSO Hybrid Optimization

The Improved Grey Wolf Optimizer (IGWO)[21] and Cuckoo Search Optimization (CSO)[22] hybrid approach integrates the exploitation capabilities of IGWO with the exploration efficiency of CSO[23]. IGWO enhances the traditional Grey Wolf Optimizer (GWO) by reducing premature convergence and improving search diversity, while CSO's Levy flight-based exploration allows it to escape local optima. The IGWO-CSO hybrid algorithm alternates between IGWO and CSO to enhance both exploration and exploitation shown in figure 3.



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2024, 9(4s)
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4.3.1 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.

4.3.2 Hybrid Update Equations

The IGWO update is:

$$X_i^{new} = X_i^{old} + A.\left|C.X_{best} - X_i^{old}\right| \tag{41}$$

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:

$$X_{new} = X_{best} + \alpha.Levy() \tag{42}$$

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.

4.3.3 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:

$$x_i^{t1+1} = x_i^{t1} + \alpha levy(\lambda) \tag{43}$$

$$levy(\lambda) = t1^{-\lambda} \tag{44}$$

Whereas the community hierarchy selection is determined by fitness.Wherever X_α = 1st hunt agent, X_β = 2nd hunt agent and X_δ =3rd 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.

5. SIMULATION RESULTS

In order to assess the efficiency and flexibility of the IGWO-CSO Hybrid approach, in two cases the IEEE 33 bus system and IEEE 69 bus system has been studied to determine the optimal siting and capacity of the TCSC. The effectiveness of the proposed IGWO-CSO hybrid method is compared with GWO, IGWO algorithm in order to determine its performance in the optimal allocation of TCSC.The optimization problem is formulated in two cases: (1) mono-objective optimization and (2) multi-objective optimization. The optimization issues are implemented as follows [20].

5.1 IEEE 33 bus system

IEEE 33 bus system with mono-objective optimisation with TCSC and Without TCSC.Figure 4 illustrates the IEEE 33-bus single line diagram. This radial distribution network consists of 33 nodes, numbered from 1 to 33, and 32 lines. The base voltage is established at 12.66 kV.

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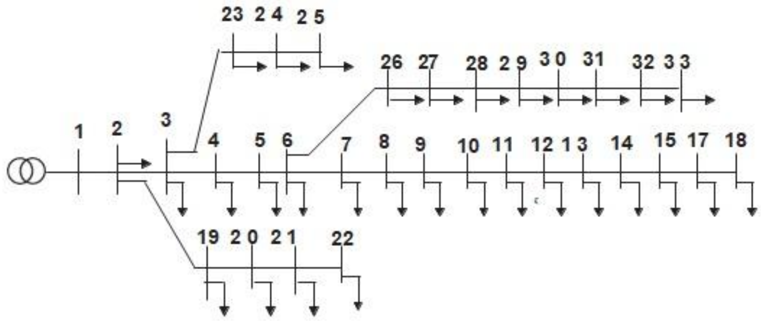

Figure 4. Single line diagram of the IEEE 33-bus system

5.1.1 Mono-objective optimisation

The TCSC device's optimal parameters for minimising the active power losses , total voltage division and operational cost is objective function of the IEEE 33 bus system without TCSC and with TCSC are illustrated in Table 2 and 3 which is based on various proposed techniques.

	P_L is the only objective function in (MW)	TVD is the only objective function in (p.u)	Operation cost (OC) is the objective function in ($)
Without TCSC	29.94	1.7000	2.2029×10^4

Table 2. The Optimal solution of all algorithms for Active Power Losses (PL), Total Voltage Deviation (TVD) and Operation Cost (OC) is the mono objective function in ($) without installation of TCSC in IEEE 33 Bus system

Table 2 displays the single objective function and TCSC is not installed in IEEE 33 bus system and shows the behaviour of power loss, Total voltage deviation and operation cost considered as 29.94 MW,1.7000 p.u and 2.2029×10^4 $ respectively. The non-optimum location of TCSC results in poor objective values. This non optimum location of TCSC controller results in poor objective values.

With TCSC installation									
Algorithms	**LOC. (bus)**	**TCSC Size (Mvar)**	**Active power loss PL(MW)**	**LOC. (bus)**	**TCSC Size (Mvar)**	**Total Voltage Deviation TVD(p.u)**	**LOC. (bus)**	**TCSC Size (Mvar)**	**Operation cost (OC) In $**
GWO	3	-0.15	27.9740	1	-0.15	1.6710	1	-0.15	2.1975×10^4
IGWO	9	-0.11	27.9796	2	-0.15	0.8769	2	-0.15	2.1980×10^4
IGWO-CSO	4	-0.7	27.8796	2	-0.15	0.9506	2	-0.15	2.1980×10^4

Table 3. The Optimal solution of all algorithms for Active Power Losses (PL), Total Voltage Deviation (TVD) and Operation Cost (OC) is the mono objective function in ($) with installation of TCSC in IEEE 33 Bus system

According to GWO, IGWO and IGWO-CSO algorithms, the PL value is minimised from 29.94MW to 27.9740 MW, 27.9796 MW and 27.8796 MW respectively .Table 3 demonstrates that in case of minimizing the Total voltage deviation of the system as single objective function, installation of TCSC based on GWO, IGWO, IGWO-CSO

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e-ISSN: 2468-4376
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reduces the total voltage deviation from 1.7000 p.u to 1.6710 p.u, 0.8769 p.u and 0.9506 p.u respectively. The optimal proposed location of the TCSC is at bus 1 and bus 2 with size -0.15MVAR reactance of the connected line. The optimal solution of all algorithms to minimize the OC based on the location of TCSC is shown in Table 3.The installation of TCSC based on the GWO and IGWO-CSO minimises the OC from 2.2029×10^4 \$ to 2.1975×10^4 \$ and 2.1980×10^4\$ respectively.

5.1.2 Multi-Objective Optimisation

This paper presents the application of proposed techniques to optimise a multi-objective function aimed at minimising active power losses, total voltage deviation, and system operating costs concurrently in the installation of TCSC. The multi-objective function is critical in the optimisation technique process, as it ensures the achievement of the global minimum. The resolution of this issue is contingent upon the optimal evaluation of the weighting factors associated with the proposed fitness function.

S.No	Weighting factors	Muti objective function (F)	Bus No	TCSC size (MVAR)	Operation cost (OC) In \$	PL(MW)	TVD(p.u)
1	(1,1,1)	2.5110	2	-0.15	2.1987×10^4	29.7400	0.9542
2	(0.8,0.1,0.1)	1.5444	1	-0.15	2.1990×10^4	29.8380	0.9518
3	(0.1,0.8,0.1)	1.8475	2	-0.15	2.1993×10^4	29.7360	0.9530
4	**(0.1, 0.1, 0.8)**	**1.1490**	**2**	**-0.15**	**2.1980×10^4**	**27.8796**	**0.9506**
5	(0.7,0.2,0.1)	1.5582	2	-0.15	2.2023×10^4	29.5320	0.9554
6	(0.2,0.7,0.1)	1.7993	2	-0.15	2.2026×10^4	29.4300	0.9566
7	(0.2,0.1,0.7)	1.2006	2	-0.15	2.2029×10^4	29.3280	0.9578
8	(0.6,0.3,0.1)	1.6064	2	-0.15	2.2020×10^4	29.2260	0.9590
9	(0.3,0.6,0.1)	1.7637	1	-0.15	2.2017×10^4	29.1240	0.9602
10	(0.1,0.3,0.6)	1.3486	2	-0.15	2.2014×10^4	29.0220	0.9614
11	(0.6,0.2,0.2)	1.5066	2	-0.15	2.2011×10^4	28.9200	0.9626
12	(0.2,0.2,0.6)	1.3004	2	-0.15	2.2008×10^4	28.8180	0.9638
13	(0.2,0.6,0.2)	1.6995	2	-0.15	2.2005×10^4	28.7160	0.9650
14	(0.5,0.1,0.4)	1.3553	2	-0.15	2.2002×10^4	28.6140	0.9662
15	(0.5,0.4,0.1)	1.6546	2	-0.15	2.1999×10^4	28.5120	0.9674
16	(0.5,0.2,0.3)	1.4550	2	-0.15	2.1996×10^4	28.4100	0.9686
17	(0.5,0.3,0.2)	1.5548	2	-0.15	2.1993×10^4	28.3080	0.9698
18	(0.1,0.5,0.4)	1.5481	2	-0.15	2.1990×10^4	28.2060	0.9710
19	(0.4,0.1,0.5)	1.3037	2	-0.15	2.1987×10^4	28.1040	0.9722
20	(0.3,0.5,0.2)	1.6513	2	-0.15	2.1984×10^4	28.0020	0.9734
21	(0.2,0.3,0.5)	1.4086	1	-0.15	2.1981×10^4	29.6340	0.9769

Table 4. The optimal solution of all algorithms at different values of weight factors by the installation of TCSC for multi objective optimisation problem in IEEE 33 Bus system

Consequently, the IGWO-CSO algorithm has been implemented through a multi-objective function (F) as defined in Eq. (13) to assess the most appropriate values for the weighting factors by determining the optimal capacity and placement of the TCSC in this case study. In this context, Table 4 presents the variation of the targeted quantities (PL, TVD, and OC) for the 33-bus IEEE system in relation to changes in the values of the weighting factors. The applicable weighting factors are 0.1, 0.1, and 0.8. These values ensure a balance between PL, TVD, and OC values while minimising the capacity of the TCSC device installation, in contrast to all cases presented in Table 4.

The IGWO-CSO algorithm is utilised in this context to promptly address the specified objectives as a

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2024, 9(4s)
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Bus No	TCSC Size(Mvar)	PL (MW)	VD(p.u)	OC($)
2	-0.15	27.9422	0.9605	2.1990×10^4

Table 5. The Optimal Solution Determined by the TOPSIS Method from Pareto-Front Obtained by the IGWO-CSO Hybrid Algorithm in IEEE 33 Bus system

result of these conflicting objectives, the solutions on the Pareto-optimal front are retained for each iteration. The TOPSIS and AHP methods have been employed to extract the optimal compromise solution from the final archive values.

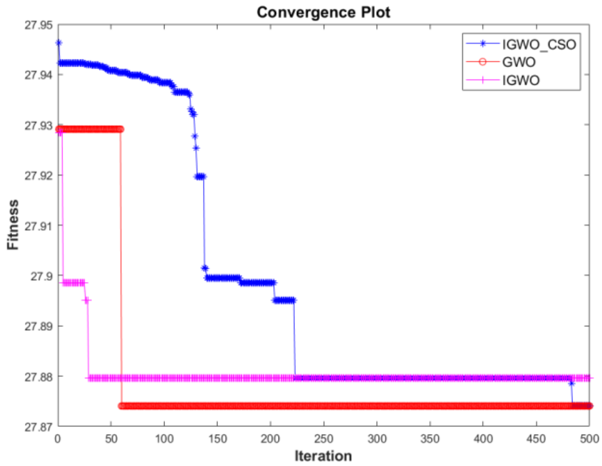

Figure 5. Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize PL(MW) in comparison with GWO and IGWO, in IEEE 33 Bus system

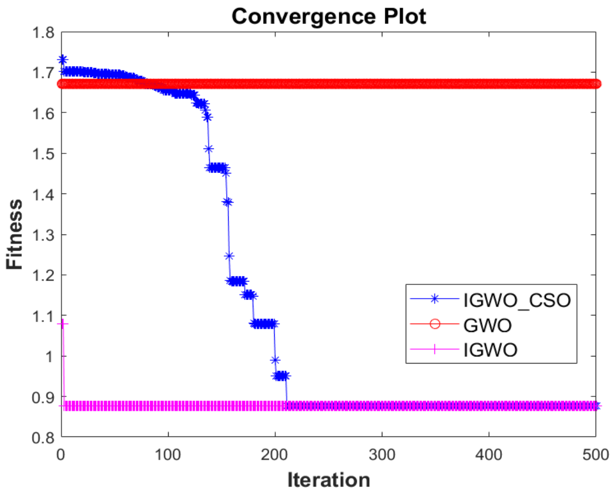

Figure 6. Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to diminish TVD(p.u) in comparison with GWO and IGWO, in IEEE 33 Bus system.

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e-ISSN: 2468-4376
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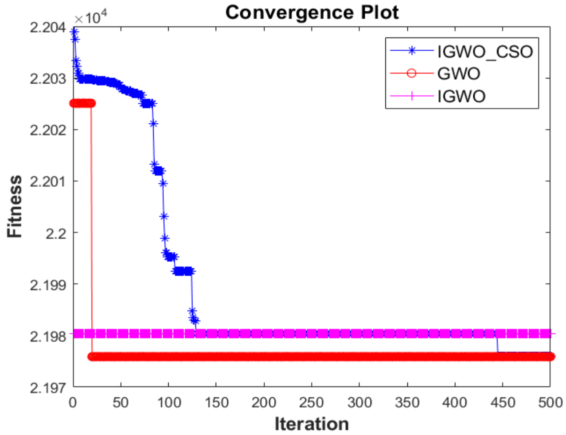

Figure 7. Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to reduce Operation cost OC ($) in comparison with GWO and IGWO in IEEE 33 Bus system

Table 5 presents the optimal size and placement of TCSC as determined by the IGWO-CSO algorithm, aimed at minimising the value of the optimisation problem. The data presented in Table 5 indicates that the proposed method effectively determines the optimal position and rating for the TCSC, leading to objective values that are lower than those achieved without the installation of TCSC. The reductions in PL , TVD and OC are 0.9605 p.u 27.9422 M.W , and 2.1990×10⁴$ respectively.

The data presented in Figs.5, 6 and 7 demonstrate that the IGWO-CSO technique achieves superior performance throughout the optimisation process. The IGWO-CSO algorithm identifies global optima with a reduced number of iterations when compared to alternative algorithms. The IGWO-CSO algorithms encountered a local optimum which results to reach the optimal global minimum values for the PL, TVD, and OC, as illustrated in Figs. 5, 6, and 7 respectively.

5.1.3 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 [24]. The mathematical expressions corresponding to the assessment criteria are presented in Table 6. The numerical values corresponding to the evaluation criteria for all algorithms utilised in the installation of TCSC within the IEEE 33 bus system, aimed at optimising the multi-objective function, are presented in Table 7. The data presented in Table 7 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.

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)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - \overline{F_{min}})^2}{nr}}$

Table 6. Criteria of evaluations of the proposed techniques for IEEE 33 bus system

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e-ISSN: 2468-4376
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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}

Table 7. Numerical values for criteria of evaluations for IEEE 33 bus system

5.2 IEEE 69 bus system

IEEE 69 bus system with mono-objective optimisation and multi objective optimisation with TCSC and Without TCSC. Figure 8 illustrates the single line diagram of the IEEE 69-bus system. The radial distribution network consists of 69 buses, numbered from 1 to 69, and includes 68 lines. The selected system voltage base is 12 kV, and the Volt-Ampere base is set at 100 MVA.

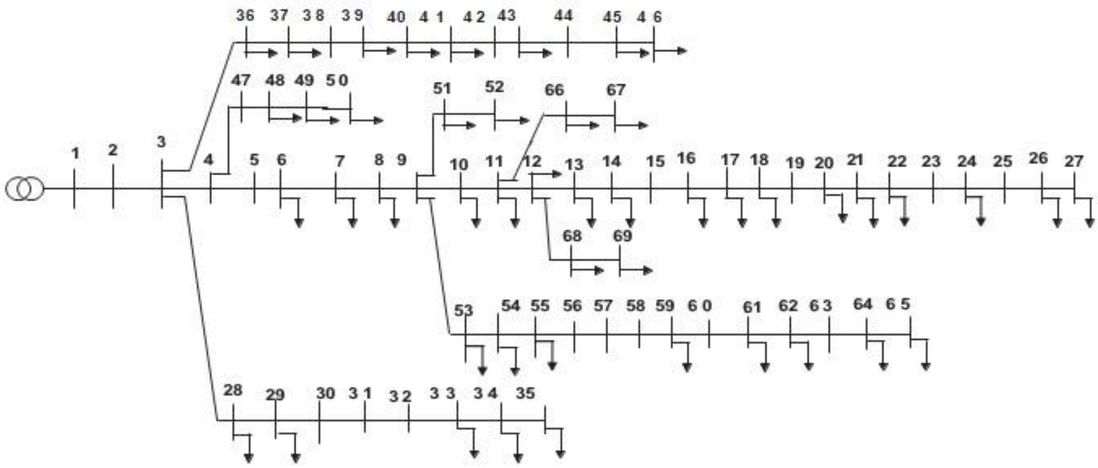

Figure 8. Single line diagram of the IEEE 69-bus system

5.2.1 Mono-Objective Optimisation

The TCSC device's optimal parameters for minimising the active power losses ,Total voltage division and operational cost is objective function of the IEEE 69 bus system without TCSC and with TCSC are illustrated in Table 8 and 9 which is based on various proposed techniques.

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e-ISSN: 2468-4376
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Without TCSC	PL is the only objective function in (MW)	TVD is the only objective function in (p.u)	Operation cost (OC) is the objective function in ($)
	53.8966	1.8367	4.1116×10^4

Table 8. The Optimal solution of all algorithms for active power losses , Total Voltage Deviation and Operation cost (OC) is the mono objective function in ($) without installation of TCSC in IEEE 69 Bus system

Table 8 presents the single objective function for the IEEE 69 bus system without the installation of TCSC. It illustrates the performance metrics, including power loss at 53.8966 MW, total voltage deviation at 1.8367 p.u, and operational cost at 4.1116×10^4 $. The suboptimal placement of the TCSC leads to unsatisfactory objective values. The suboptimal placement of the TCSC controller leads to unsatisfactory objective values.

With TCSC installation									
Algorithms	LOC. (bus)	TCSC Size (Mvar)	Active power loss PL(MW)	LOC. (bus)	TCSC Size (Mvar)	Total Voltage Deviation TVD (p.u)	LOC. (bus)	TCSC Size (Mvar)	Operation cost (OC) in $
GWO	1	-0.15	51.6886	10	-0.15	1.6692	5	-0.15	4.0916×10^4
IGWO	2	-0.15	51.6886	16	-0.15	1.8026	57	-0.15	4.0844×10^4
IGWO-CSO	2	-0.15	51.6886	6	-0.15	0.7445	1	-0.15	4.0794×10^4

Table 9. The Optimal solution of all algorithms for active power losses, Total Voltage Deviation and Operation cost (OC) is the mono objective function in ($) with installation of TCSC in IEEE 69 Bus system

Table 9 displays the optimal configurations of the TCSC controller derived from multiple proposed algorithms aimed at minimising active power losses and voltage division within the IEEE69 bus system. According to Table 9, when minimising total active power losses is considered as the individual objective function, the implementation of the TCSC in the power system utilising the IGWO-CSO algorithm resulted in a reduction of total actual power losses from 53.89 MW to 51.6886 MW. The installation of the TCSC in the power system utilising the GWO, IGWO, and IGWO-CSO algorithms results in a reduction of voltage deviation from 1.8367 p.u to 1.6692 p.u, 1.8026 p.u, and 0.7445 p.u. The proposed optimal location for the TCSC is situated between buses 10 and 16, with an optimal size of -0.15 Mvar for the reactance of the connected line. The optimal solution for all algorithms aimed at minimising the OC through the integration of TCSC within the power system is presented in Table 9. The proposed GWO, IGWO, and IGWO-CSO techniques result in a minimisation of the OC to $4.0794\times10^4$$. Compared to alternative algorithms, the optimal placement and capacity of the TCSC utilising the IGWO-CSO approach achieved a concurrent minimisation of both the Total voltage deviation (TVD) and the operating cost (OC).

5.2.2 Multi-Objective Optimisation

The optimal positioning and dimensions of the TCSC in the IEEE 69 bus system have been computed to minimise the multifaceted function delineated in Eq. (13). The IGWO-CSO method has been implemented using a multi-objective function (F) procedure to assess the optimal values of the weighting variables (w1, w2, w3) by determining the ideal capacity and placement of the TCSC, as demonstrated in Table 10. The findings from Table 10 indicate that variations in the weight factors result in alterations in the values of the goal quantities (PL, TVD, and OC). The

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e-ISSN: 2468-4376
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most relevant weighting factors are 0.1, 0.1, and 0.8, which guarantee a concurrent equilibrium among PL, TVD, and OC values while minimising TCSC capacity, OC, and PL, in contrast to all instances presented in Table 10.

S.No	Weighting factors	Muti objective function (F)	Bus No	TCSC size (MVAR)	Operation cost (OC) $	PL (MW)	TVD (p.u)
1	(1,1,1)	2.4039	5	-0.15	4.0916×10^4	51.7160	0.9765
2	(0.8,0.1,0.1)	1.4210	6	-0.15	4.0905×10^4	51.7400	0.9358
3	(0.1,0.8,0.1)	1.8351	6	-0.15	4.0894×10^4	51.7940	0.8951
4	**(0.1, 0.1, 0.8)**	1.1372	6	-0.15	4.0794×10^4	51.6886	0.7445
5	(0.7,0.2,0.1)	1.4801	6	-0.15	4.0872×10^4	51.9020	0.9765
6	(0.2,0.7,0.1)	1.7760	6	-0.15	4.0861×10^4	51.9560	0.9358
7	(0.2,0.1,0.7)	1.1778	6	-0.15	4.0850×10^4	52.0100	0.8951
8	(0.6,0.3,0.1)	1.5393	6	-0.15	4.0839×10^4	52.0640	0.8544
9	(0.3,0.6,0.1)	1.7168	6	-0.15	4.0828×10^4	52.1180	0.8137
10	(0.1,0.3,0.6)	1.3366	6	-0.15	4.0817×10^4	52.1720	1.2207
11	(0.6,0.2,0.2)	1.7812	12	-0.15	4.0806×10^4	52.2260	1.2614
12	(0.2,0.2,0.6)	1.2775	1	-0.105	4.0895×10^4	52.2800	1.3021
13	(0.2,0.6,0.2)	1.6763	3	-0.125	4.0874×10^4	52.3340	1.3428
14	(0.5,0.1,0.4)	1.2994	23	-0.15	4.0823×10^4	52.3880	1.3835
15	(0.5,0.4,0.1)	1.5985	3	-0.15	4.0882×10^4	52.4420	1.5870
16	(0.5,0.2,0.3)	1.3991	61	-0.15	4.0851×10^4	52.4960	1.5463
17	(0.5,0.3,0.2)	1.4988	13	-0.15	4.0840×10^4	52.5500	1.5056
18	(0.1,0.5,0.4)	1.5836	53	-0.15	4.0829×10^4	52.6040	1.4649
19	(0.4,0.1,0.5)	1.2588	6	-0.15	4.0818×10^4	52.6580	1.0172
20	(0.3,0.5,0.2)	1.6171	6	-0.15	4.0807×10^4	52.7120	1.0579
21	(0.2,0.3,0.5)	1.3772	11	-0.15	4.0883×10^4	52.7437	1.0986

Table 10. The optimal solution of all algorithms (GWO, IGWO, and IGWO-CSO) at different values of weight factors by the installation of TCSC for multi objective optimisation problem in IEEE 69 Bus system

The IGWO-CSO algorithm has been applied to efficiently tackle the multi-objective optimization problem. Given the conflicting nature of the objectives, solutions along the Pareto-optimal front are preserved at each iteration. To derive the most balanced compromise solution from the final set of solutions, the TOPSIS and AHP methods have been employed.

Bus No	TCSC Size (Mvar)	PL (MW)	TVD (p.u)	OC ($)
1	-0.103	51.7467	1.4522	4.0797×10^4

Table 11. The Optimal Solution Determined by the TOPSIS Method from Pareto-Front Obtained by the IGWO-CSO Hybrid Algorithm in IEEE 69Bus system.

Table11 illustrates the optimal placement and sizing of TCSC, as determined by the IGWO-CSO algorithm, with the goal of minimizing the overall optimization problem. The results presented in Table 11 demonstrate that the proposed method successfully identifies the optimal location and rating for the TCSC. This leads to notable improvements compared to the system without TCSC installation, with reductions observed in TVD, PL, and OC are 1.4522 p.u, 51.7467 MW and $4.0797 \times 10^4$$ respectively

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e-ISSN: 2468-4376
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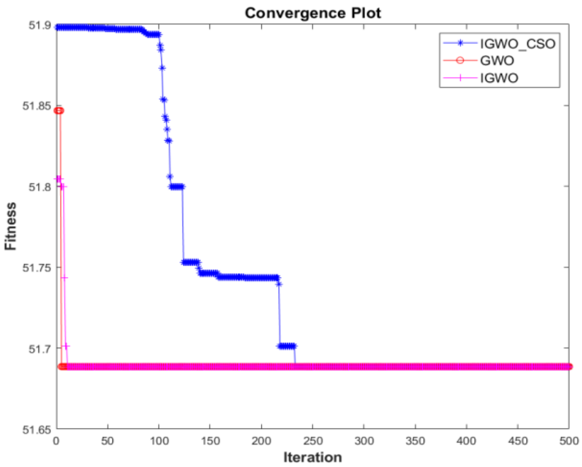

Figure 9. Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to minimize PL(MW) in comparison with GWO and IGWO, in IEEE 69 Bus system

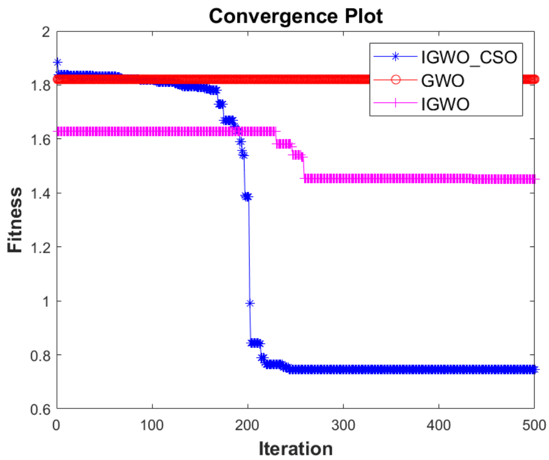

Figure 10.convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to diminish TVD(p.u) in comparison with GWO and IGWO, in IEEE 69 Bus system

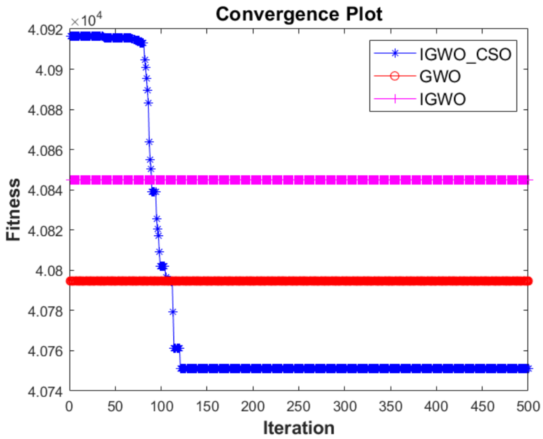

Figure 11. Convergence curves at TCSC installation along with IGWO-CSO hybrid algorithm to reduce Operation cost OC ($) in comparison with GWO and IGWO in IEEE 69 Bus system

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The data illustrated in Figures 9, 10 and 11 indicate that the IGWO-CSO technique exhibits enhanced performance during the optimisation process. The IGWO-CSO algorithm efficiently identifies global optima, requiring few iteration in comparison to other algorithms. The IGWO-CSO algorithm experienced a local optimum, which results to achieve the optimal global minimum values for the PL, TVD, and OC, as demonstrated in Figures 9, 10, and 11, respectively.

5.2.3 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 [24]. The mathematical expressions associated with the assessment criteria are detailed in Table 12.

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)	$\sqrt{\frac{\sum_{i=1}^{nr}(F_i - \overline{F_{min}})^2}{nr}}$

Table 12. Criteria of evaluations of the proposed techniques for IEEE 69 bus system

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 optimisation of the multi-objective function, are detailed in Table 12. The data shown in Table 13 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.

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}

Table 13. Numerical values for criteria of evaluations for IEEE 69 bus system

6. CONCLUSION

The integration of the Improved Grey Wolf Optimizer (IGWO) with Cuckoo Search Optimization (CSO) presents a robust and effective solution for the optimal placement and sizing of TCSC devices in power distribution networks. The proposed IGWO-CSO hybrid algorithm demonstrates significant improvements in minimizing active power loss, total voltage deviation, and operating costs compared to conventional methods. The application of multi-criteria decision-making tools such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytical Hierarchy Process (AHP) further enhances the robustness of the decision-making process in multi-objective optimization scenarios. These tools enable the identification of the most balanced and technically feasible solutions from the Pareto-optimal front, ensuring a practical trade-off among conflicting objectives. Extensive simulations carried out on standard IEEE 33-bus and 69-bus distribution systems using the MATPOWER package in MATLAB confirm the superior performance of the proposed IGWO-CSO hybrid algorithm when benchmarked against conventional GWO and standalone IGWO techniques. The hybrid approach not only delivers better-quality solutions but also demonstrates faster convergence and improved computational efficiency. These outcomes highlight the potential of the IGWO-CSO algorithm as a powerful tool for improving the operational stability, voltage profile, and economic performance of modern power distribution systems.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the authorities of Annamalai University for the facilities offered to carry out this work.

AUTHOR CONTRIBUTIONS

Conceptualization, L.Vamsi Narasimha Rao;methodology, L.Vamsi Narasimha Rao; software, 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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