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Intelligent Control of Compensating Devices for Power Quality Enhancement in Radial Network

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Abstract: In order to enhance the operational efficacy of distribution networks (DPNs) across technical, economic, and environmental aspects within a real-time operational framework, meticulous regulation of reactive power is imperative. In the present study, a comprehensive teaching-learning-based optimization (CTLBO) algorithm is employed for network reconfiguration (NR) and optimal allocation of distribution static synchronous compensators (DSTATCOMs) for a single objective, along with 24-h practical load profiles in the IEEE 33-bus and 69-bus radial distribution systems (RDSs). Several case studies demonstrate that simultaneous NR and DSTATCOM allocation is the most effective solution for the reduction of system losses, operational costs, and emissions. The results further demonstrate the superiority in terms of convergence characteristics, solution robustness, and global optimality of the CTLBO algorithm under complex, multi-criteria constraints for NR and DSTATCOM allocation in RDS against established bio-inspired metaheuristics such as the Immune Algorithm (IA), Bat Algorithm (BA), and Bacterial Foraging Optimization Algorithm (BFOA).

Keywords: DSTATCOM; CTLBO; network reconfiguration; radial distribution systems

1. Background and Challenges

Nowadays, rapid integration of distributed generation (DG) resources, renewable energy sources (RESs), and electric vehicles (EVs) into distribution power networks (DPNs) has significantly transformed the operational landscape of next-generation power systems. This proliferation, driven by reducing the CO_2 and consumer-level energy participation, has significantly altered the operational framework of distribution systems, compelling distribution power network operators (DPNOs) to adopt advanced strategies for ensuring techno-economic optimality and operational resilience. Some DPNOs have employed classical measures such as fixed/switched capacitor banks [1,2], network reconfiguration [3–5], and demand/load management [6,7] to improve voltage stability, reduce losses, and enhance overall efficiency. However, the increased penetration of intermittent RES-based DGs and stochastic EV charging patterns [8–10] has introduced a new class of power quality (PQ) challenges [11,12] and operational uncertainties. Since distribution systems are primarily resistive, variations in load demand have a significant effect on several variables such as:

a. Voltage profile (VP) degradation and instability
b. Total harmonic distortion current and voltage [13]
c. Power losses and stability issues

Table 1 summarizes the literature presented on DSTATCOM Placement in Distribution Networks, including methods, objectives, and research gaps.

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Table 1. DSTATCOM placement in distribution networks (DNs).

Ref. No.	Method/Approach	Test System(s)	Objective(s)	Key Contributions	Limitations
[14]	Analysis of unbalanced load and intermittency	DNs	Losses, stability, VP, THD impact	Highlighted DG challenges	Not solution-focused
[15]	Intermittent resource impact analysis	DNs	Power quality challenges	Contextual background	Not optimization-oriented
[16–19]	Shunt capacitors placement methods	DNs	Reactive compensation	Earliest mitigation approach	Static, slow response
[20,21]	FACTS and CPD applications	DNs	Power quality and reliability	Positioned DSTATCOM as an advanced CPD	High-level overview
[22]	SVC implementations	DNs	Reactive support	CPD alternative	Not focused on placement
[23]	DSTATCOM usage	DNs	Reactive compensation	Benefits listed	No placement strategy
[24–26]	Optimization for network reconfiguration + DG placement	DNs	Enhance stability, power quality; Optimal DG sizing & allocation	Reactive power compensation	DG-only focus excludes DSTATCOM; FACTS devices not considered
[16,27,28]	DSTATCOM impact on PF, VP, THD	DNs	Quality improvement	Validated fast, dynamic behavior	Not optimization-specific
[29,30]	Location optimization necessity	DNs	Reliability and viability	Emphasized placement relevance	Not methodological
[31–33]	Analytical placement via indices	IEEE 33-bus	Loss, VP improvement	Quick, simplified placement	Single DSTATCOM only
[34]	Energy and cost savings analysis	DNs	Savings via DSTATCOM	Quantitative benefits	Single device focus
[35]	Voltage stability index method	IEEE 33-bus	Loss & VP improvement	Stability-based placement	Single DSTATCOM
[36]	CPLS, FVSI, PSI, VSI methods	38-bus meshed DNs	Sensitivity-based placement	CPLS and PSI are more effective	Single DSTATCOM
[37]	Immune Algorithm (IA)	IEEE 33, 69-bus	Loss, cost, VP optimization	IA > GA	Optimal device number not considered
[38]	DE + network reconfiguration	69, 83-bus	APL, VP optimization	DE > PSO	No real loading modeling
[39]	Binary Gravitational Search (BGSA)	47-bus DNs	Reliability enhancement	Improved reliability	Single DSTATCOM
[40]	Improved Cat Swarm Optimization (ICSO)	69-bus DNs	Energy loss, VP improvement	ICSO > CSO & PSO	One DSTATCOM only
[41]	Harmony Search (HS)	IEEE 33-bus	Energy savings	HS > IA on cost savings	Constant load, single device
[42]	Fuzzy and ACO/PSO/GA hybrids	IEEE 33-bus, Taiwan DNs	DG and DSTATCOM placement	Enhanced adaptability	Only a single DG and DSTATCOM
[43]	IC and Nelder-Mead hybrid	IEEE 30-bus	Loss & stability	Multi-objective approach	No comparative analysis

1.1. Research Aim and Motivation

Many researchers show that integration of distributed energy resources in distribution networks marks improvement in VP [16–18], line loadability improvement post fault fast voltage recovery, reduction in APL [18], effect on greenhouse gas and voltage stability index improvement [44–53]. Further, concurrent reconfiguration of network and allocation of scattered energy storage [49,51] considerably enhances the penetration of DG in distribution networks. In this perspective, in comparison to DGs, limited investigative research literature is available to show the impact of the allocation of DSTATCOMs on network operational cost saving and emission saving in the DN. This investigation aims to provide complete solutions for network topologies, DSTATCOM locations, and its capacities under varying load conditions. Therefore, this paper initially deals with analysis for selection of optimal number of DSTATCOMs in the DPNs. The nature inspired CTLBO algorithm's exploration and exploitation capability for global solution has already been tested on several standard mathematical benchmark functions and DG allocation in 33-bus, 69-bus and 118-bus distribution networks [50]. Hence, reconfiguration of distribution network along with placement of multiple DSTATCOMs in the distribution systems implemented using a CTLBO technique. The usefulness of the suggested CTLBO algorithm is further implemented by considering a 24-h load profile on the IEEE 33-bus and 69-bus RDS to validate its real-world application.

The summary of the analysis carried out in this paper is as follows:

(1) Modification in teaching factor (T_F) in the Teachers phase of the algorithm greatly enhances the exploration and exploitation capabilities of CTLBO compared to several TLBO modifications that avoid local minima trapping and ensure global real-world solutions.
(2) Siting and sizing of DSTATCOMs for a single objective to maximize DPNOs benefits demonstrates the CTLBO algorithm capabilities of handling mixed integer variables and constrained optimization problems for a 33-bus radial distribution network.

(3) Graphical-based load flow approach (BIBV/BCBV matrix) further reduces computational time for DSTATCOM allocation in the distribution network.
(4) Identification of the optimal number of DSTATCOMs for each DPN for maximum economic gains.
(5) Local reactive power management by DSTATCOMs significantly enhances the power transfer capability of the distribution network.
(6) The study demonstrates the huge savings in emissions of SO_2, NO_X, and CO_2 because of optimal NR and DSTATCOM allocation in the radial distribution network.
(7) Simulation results validate that the simultaneous network reconfiguration and DSTATCOMs allocation yields the most promising outcomes in terms of objective function performance for IEEE 33-bus and 69-bus RDS.
(8) The simulation result validates a noticeable enhancement in the performance indices like: APL, VP improvement, yearly energy savings, cost savings, and emission reduction because of the CTLBO algorithm in comparison to IA, BA, BFOA, and ICSO algorithms.

The remaining paper is structured as follows: Section 2 details the modeling of DSTATCOM by considering single objective functions. Section 3 describes the CTLBO algorithm. Section 4 illustrates the procedure for the allocation of DSTATCOMs. Section 5 explains the results and the comparative analysis with other existing methods. Conclusions and future scope of work are reported in Section 6.

1.2. Problem Formulation

Here, a typical radial DPN is described in Figure 1. R_j & X_j are the resistances and the reactances, respectively, of the *j*th line between bus m and m + 1. The loads associated at buses m and m + 1 are $P_m + jQ_m$ and $P_{m+1} + jQ_{m+1}$, respectively. V_m and V_{m+1} are the respective voltages at node m and m + 1, respectively.

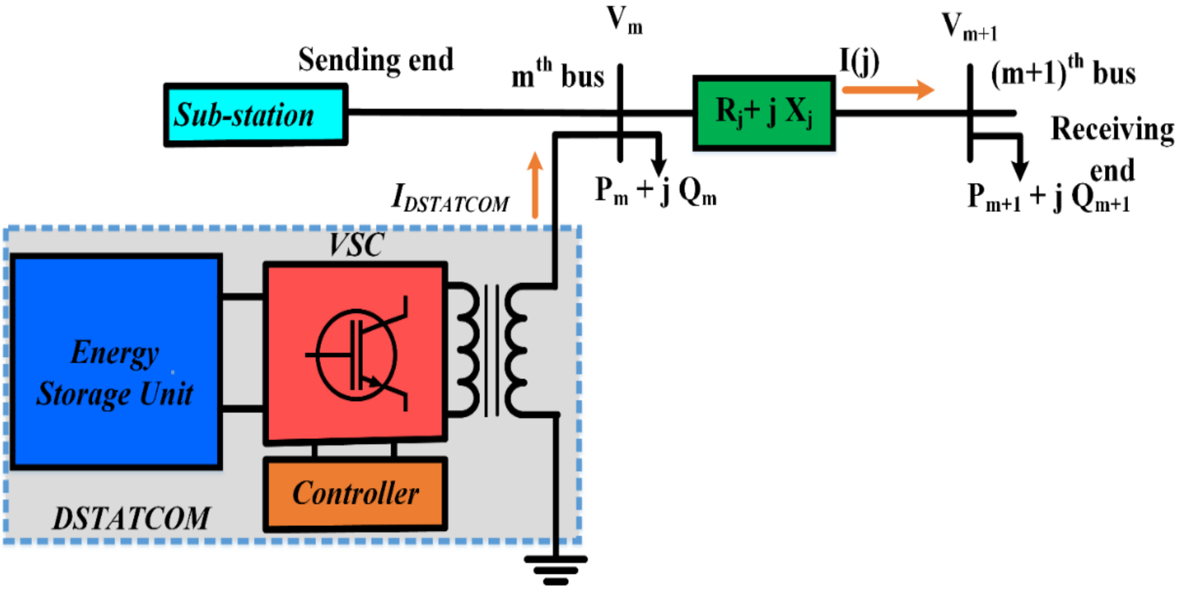


Figure 1. Network section of the *j*th line between buses 'm' and '(m + 1)' with DSTATCOM.

2. Optimal Allocation of DSTATCOM and DGs

2.1. Single Objective Function (SOF)

The objective of optimally placed DSTATCOMs in RDS is to decrease the network APL and enhance the voltage stability index and voltage profile while maintaining all the constraints within its limit. Explanations of all the Single objective functions are as follows, the effect of DSTATCOM allocation in the DPNs are computed using the indices addressed in Table 2.

The VSI functions as an indicator of the network's proximity to voltage failure; improving VSI toward unity reflects enhanced voltage stability margins. The VDI captures the cumulative deviation of bus voltages from their nominal values across the network, with an ideal value of zero signifying optimal voltage regulation. The Qualified Load Index (QLI) [47] represents the network's loadability potential, where higher values indicate increased capacity to accommodate load demand without compromising voltage or stability constraints.

Table 2. The mathematical descriptions of the single objective functions.

Parameter/Objectives	Description/Formulation	Equations
Real Power Loss (P_{loss})	$P_{loss} = \sum_{j=1}^{nb} I_j^2 R_j$ Where $I_j = \sum_{k=1}^{m} (P_{Lk}^2 + Q_{Lk}^2)/\lvert V_k^2 \rvert$	(1)
SOF-1	$F_1 = \text{Minimize } P_{loss}$	(2)
After DSTATCOM Allocation	$Q_{Lk} = Q_{Lk} - Q_{DSk}$	(3)
Total Annual Cost Saving (TACS)	$TACS = 365.\left(K_e \sum_{i=1}^{24} T_i * P_{loss,i} - K_e \sum_{i=1}^{24} T_i * P_{loss,i}^{with\ D-STATCOM}\right) - \sum_{i=1}^{24} K_{ci} * \left(Cost_{D-STATCOM_{year,i}}\right)$	(4)
SOF-2	$F_2 = \text{Maximization (TACS)}$	(5)
Emission Saving (ES) [54]	$\text{Emission without DSTATCOM} = (P_{total\ load} + P_{loss,base}).ER.8760$	(6)
	$\text{Emission with DSTATCOM} = (P_{total\ load} + P_{loss,with\ DSTATCOM}).ER.8760$	(7)
	$\text{Yearly Saving ES} = (P_{loss,base} - P_{loss,with\ DSTATCOM}).ER.8760$	(8)
	$ES = E - E^{DS}$	(9)
Cost of DSTATCOM	$Cost_{DSTATCOM_{year,i}} = Cost_{DSTATCOM_i} \frac{(1+AR)^{n_{D-STATCOM}} * AR}{(1+AR)^{n_{D-STATCOM}} - 1}$	(10)
Constraints	Active & Reactive Power Balance: $P_{substation} = P_{loss} + P_D$	(11)
	$Q_{substation} + Q_{DSTATCOM} = Q_{loss} + Q_D$	(12)
	$Q_{loss} = \sum_{j=1}^{nb} I_j^2 X_j$	(13)
	Voltage Limits: $0.90\ p.u. \le V_m \le 1.05\ p.u.$ $i = 1,2,3,4 \ldots \ldots n$	(14)
	Line Thermal Limits: $I_j \le I_j^{max}$	(15)
	Injected Reactive Power Limits: $Q_m^{min} \le Q_m \le Q_m^{max}$ where $0 \le Q_m \le 3$ MVAr	(16)

2.2. Radiality of Distribution Network and CTLBO Algorithm

After network reconfiguration, it is essential to ensure that the distribution system remains a radial topology by properly opening or closing tie and sectionalizing switches. This paper tests network radiality using a spanning tree methodology based on graph theory, as detailed in [3]. The confirmation is accomplished using the MATLAB command 'graphisspantree (D)', where 'D' denotes the adjacency matrix of the distribution network of the undirected graph. If 'D' resembles a valid spanning tree, the command returns a logical value of '1', representing that the network remains radial. The adjacency matrix 'D' consists of binary entries, where '1' characterizes the existence of a branch between two nodes and '0' specifies its absence [3].

The CTLBO algorithm [50] is a nature-inspired algorithm derived from the TLBO algorithm [54], which is a population-based meta-heuristic optimization technique having two phases, as shown in Table 3,

(1) Teaching Phase: In this phase, the teacher (the best-performing solution) improves the knowledge of the students (other solutions). The new solutions of teaching phase is obtained using Equation (17).
(2) Learner Phase: In this phase, students interact with each other to enhance their knowledge using Equations (19) and (20).

In TLBO algorithm T_F is randomly selected as either 1(no information transfer) or 2 (complete information transfer) but practically it is possible to have knowledge transfer value between '1' and '2'. So T_F is modified as per Equation (18). The parameters values for proposed CTLBO algorithm are as shown in Table 4.

Table 3. Overview of the CTLBO algorithm.

Phase	Mathematical Representation	Equations
Teaching Phase	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_{Teacher,u} - T_F X_{worst,u})$	(17)
	$T_F = \left(1/_{rand}\right)^a$	(18)
Learning Phase	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_v - X_w) \quad \text{if } F(X_v) < F(X_w)$	(19)
	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_w - X_v) \quad \text{if } F(X_v) > F(X_w)$	(20)

The best solution retained in each iteration after completing these two phases and finally global solution obtained using process defined in flowchart shown in Figure 2.

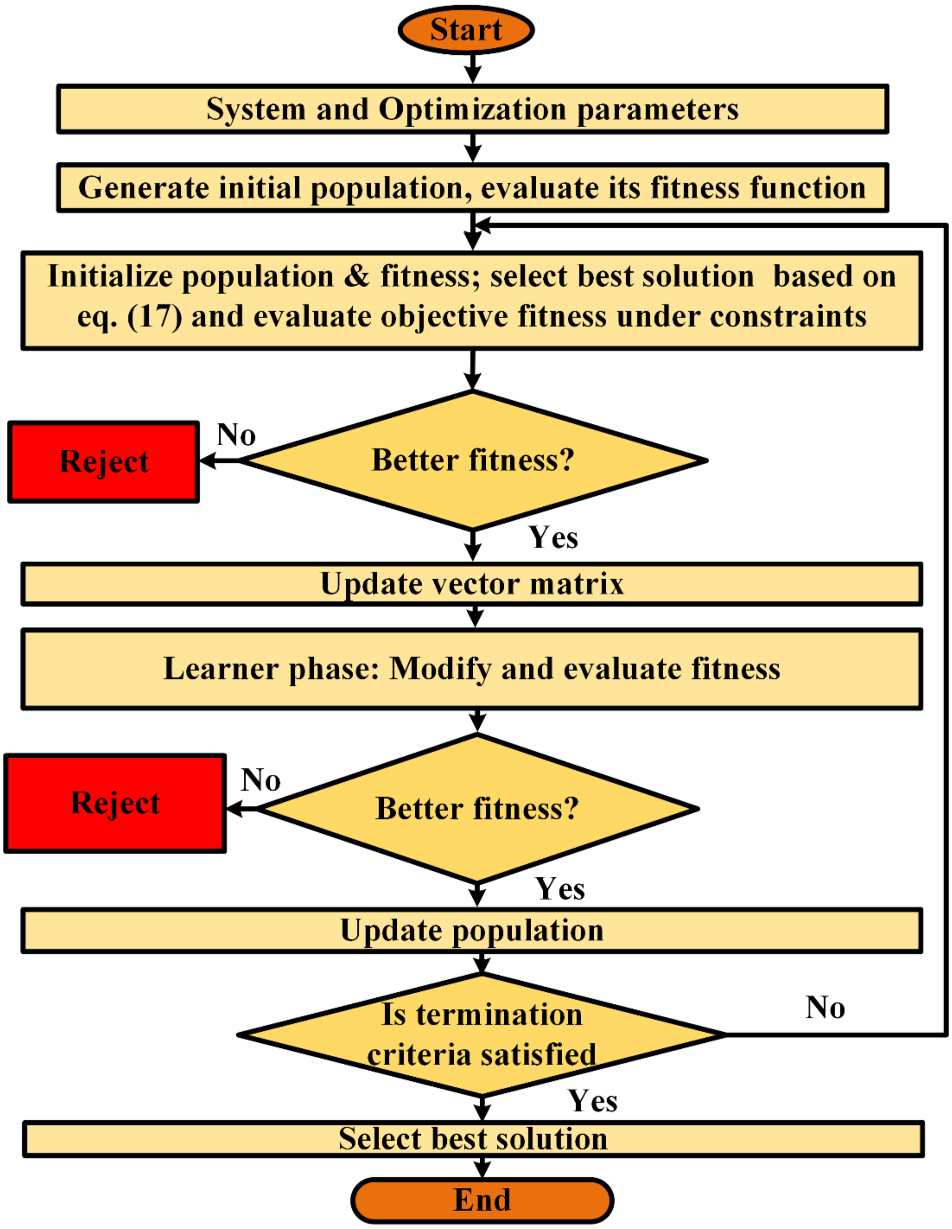


Figure 2. Flowchart of the proposed method.

Table 4. Parameters values for proposed CTLBO algorithm.

Parameters	Standards
Teaching Factor Rate 'a'	0.2
Solution Vector (SV)	100
Maximum Iteration for Case 1,2,3	100
Maximum Iteration for Case 4, 5	500

3. Process to Find the Optimal Size and Location of DSTATCOM

The main aim is to optimize network APL (P_{loss}) by injecting or absorbing reactive power ($Q_{DSTATCOM}$) in the distribution networks. The suggested approach ensures the optimal size and placement of multiple DSTATCOMs as given below.

3.1. Implementation of CTLBO for SOF in the Distribution Network at Nominal Load

This section describes the implementation of CTLBO algorithm for allocating DSTATCOMs to satisfy the various single objective functions while meeting all the constraints requirement. In this paper, multiple DSTATCOMs are placed in the RDS to minimize real power loss, annual energy, and cost savings using CTLBO. Allocation of DSTATCOMs in RDS for APL minimization is based on nominal load level.

For the allocation of DSTATCOMs without reconfiguration of the network, the quantity of variables in the solution vector (SV) will be twice of the number of as shown below,

$$SV = \left[\underbrace{\overleftrightarrow{\mathrm{DSL}_1^1 \quad \mathrm{DSL}_2^1}}_{\text{DSTATCOM Location}} \quad \underbrace{\overleftrightarrow{\mathrm{DSS}_1^1 \quad \mathrm{DSS}_2^1}}_{\text{DSTATCOM size}} \right] \tag{21}$$

where DSL_1^1, DSL_2^1 are discrete variables (DSTATCOMs site) and DSS_1^1, DSS_2^1 are continuous variables (DSTATCOMs size) in MVAr.

Representation of simultaneous reconfiguration, DSTATCOMs allocation and DSTATCOMs sizing in SV is presented as shown below,

$$SV = \left[\underbrace{\overleftrightarrow{\mathrm{DST}_1^1 \quad \mathrm{DTL}_2^1}}_{\text{Open Switches}} \quad \underbrace{\overleftrightarrow{\mathrm{DSL}_1^1 \quad \mathrm{DSL}_2^1}}_{\text{DSTATCOM Location}} \quad \underbrace{\overleftrightarrow{\mathrm{DSS}_1^1 \quad \mathrm{DSS}_2^1}}_{\text{DSTATCOM size}} \right] \tag{22}$$

where DST_1^1, DST_2^1 are open tie/sectionalizing switches. Radiality of DN is confirmed by either opening of the sectionalizing switches or closing tie-switches.

The aforesaid sequence of steps is implemented to achieve the desired objective by placing DSTATCOMs in the distribution networks.

Step 1: First solution vector matrix generation.

In solution vector matrix (SVM) each row shows a set of solutions for the defined objective function $F(X_i)$ in particular optimization problem. Each decision variable (X_i) is computed using Equation (23) as shown below.

$$X_i = X_{i,min} + rand * (X_{i,min} - X_{i,max}) \quad \text{where } i = 1,2,3 \ldots N \tag{23}$$

SVM (solution vector matrix) is given below,

$$SVM = \begin{bmatrix} X_1^1 & X_2^1 & X_3^1 & \ldots & X_{N-1}^1 & X_N^1 \\ X_1^2 & X_2^2 & X_3^2 & & X_{N-1}^2 & X_N^2 \\ \vdots & \vdots & \vdots & \ldots & \vdots & \vdots \\ X_1^{SVS-1} & X_2^{SVS-1} & X_3^{SVS-1} & \ldots & X_{N-1}^{SVS-1} & X_N^{SVS-1} \\ X_1^{SVS} & X_2^{SVS} & X_3^{SVS} & & X_{N-1}^{SVS} & X_N^{SVS} \end{bmatrix} \tag{24}$$

Step 2: Generate a new solution vector.

After initialization using Equation (23) of the CTLBO algorithm, SVM (Solution vector matrix) is generated according to Equations (17), (19) and (20) while satisfying all the constraints given in Equations (11)–(16).

Step 3: Updating the solution vector matrix

The fitness is calculated for each solution vector to achieve the objective. If the fitness of SV corresponding to $X_{new,i}$ is better than that of $X_{old,i}$, the SVM is updated. Until the termination condition is met, the SVM creation and updating process is repeated. The objective function is said to achieve by the solution vector that has the highest fitness value in the SVM.

3.2. Annual Cost and Energy Savings for Useful Load

This section details the steps to employ DSTATCOM units in the DPNs to maximize cost savings and minimize energy loss.

In order to minimize APL at the nominal load (1.0 p.u.), Firstly the DSTATCOMs sizes and location is determined. The load demand curve [53] is used to calculate the DSTATCOM outputs. Lastly, the DSTATCOM output patterns are used to calculate the annual energy losses and cost reductions. To determine the yearly energy saving for 24-h load demand, the following procedures are taken,

Step 1: Use the previously described approach to determine the optimal capacities and position of the DSTATCOM unit at the peak load level.
Step 2: Determine the DSTATCOM unit's output at the optimal location at time't' as shown below, where p.u. demand(t) is the load demand in p.u. at that moment,

$$Q_{DSTATCOM,k} = p.u.demand(t)\ x\ Q_{DSTATCOM,k}^{max} \tag{25}$$

Step 3: With each DSTATCOM output i.e., $Q_{DSTATCOM,k}$, acquired in step 2, run the power flow algorithm to get the total annual energy loss, (E_{loss}) as indicated below:

$$E_{loss} = 365 \sum_{t=1}^{24} P_{loss}^{t} \tag{26}$$

In this case P_{loss}^{t} represents the active power loss at time't' with reactiveh power injections from the DSTATCOMs.
Step 4: Determine the TACS using Equation (4) for cost saving per year.

3.3. Algorithm for Multi-DSTATCOM Allocation

The processes used to assign DSTATCOMs and perform network reconfiguration using the CTLBO algorithm to explore a single-objective for network active power loss minimization and maximum cost saving is shown in Figure 2.

4. Case Studies and Results

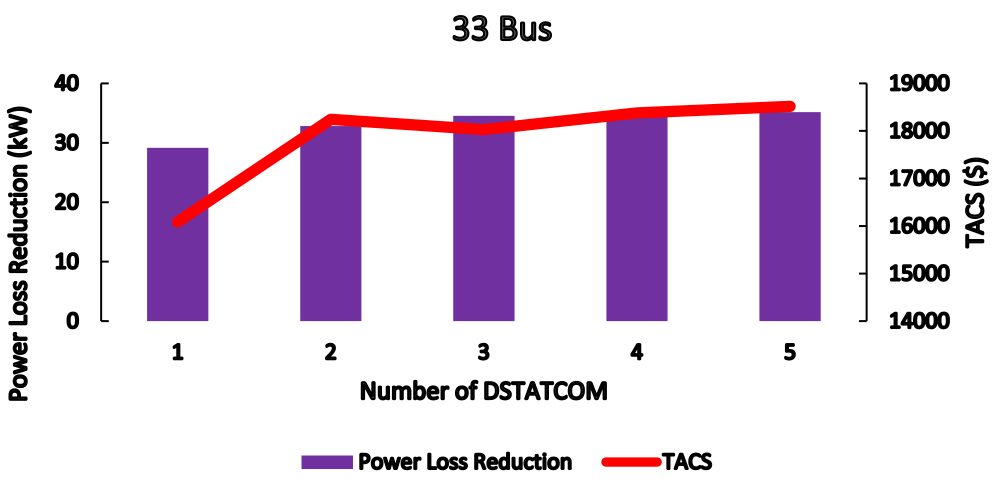
4.1. Selection of the Number of DSTATCOMS in 33-bus and 69-bus Radial Distribution Networks

The optimal allocation of the number of DSTATCOMs in 33-bus and 69-bus RDNs has been carried out with the objectives of maximizing power loss reduction and emission savings using CTLBO optimization technique while considering peak load. The impact of varying the number of DSTATCOMs (ranging from 1 to 5) on system performance has been analyzed.

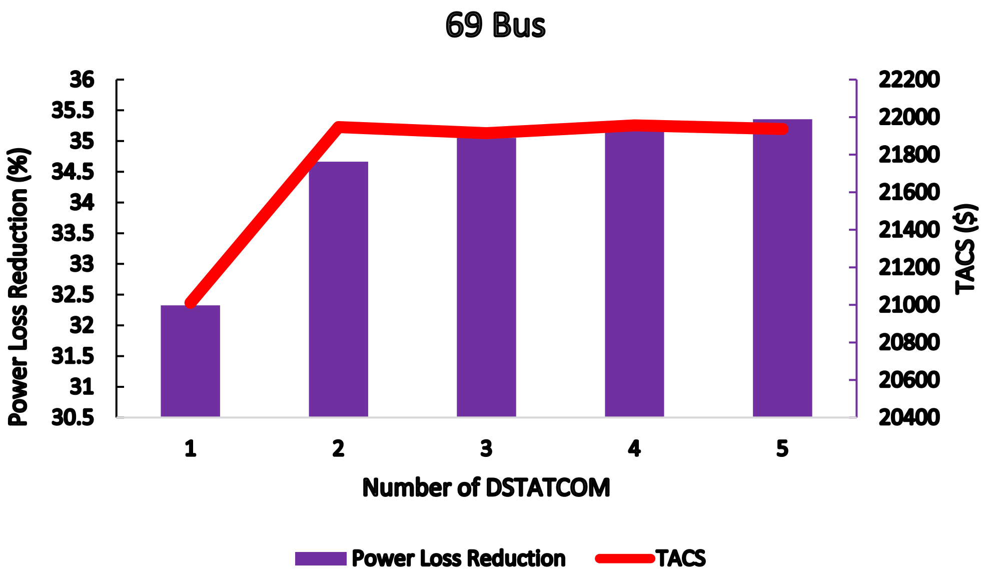
For the 33-bus system, as illustrated in Figure 3a, the deployment of 1, 2, 3, 4, and 5 DSTATCOMs results in power loss reductions of 29%, 33%, 34.5% and 35.17% respectively. Corresponding TACS are observed to be $16,086.76, $18,242.38, $18,027.08, $18,376.92, and $18,516.2 respectively.

Similarly, for the 69-bus system, Figure 3b indicates that the installation of 1, 2, 3, 4, and 5 DSTATCOMs leads to power loss reductions of 32%, 34.5%, 35%, 35.2% and 35.3% with associated TACS of $21,011.07, $21,947.16, $21,915.02, $21,956.26, and $21,937.25, respectively.

From the graph, it is obvious that the majority of the enhancements in both power loss reduction and cost savings happen with the allocation of up to 3 DSTATCOMs. Beyond this, the incremental benefits become marginal. Therefore, for practical and financial concerns, further studies are limited to three DSTATCOM units.



(a)



(**b**)

Figure 3. (**a**) Effect of DSTATCOM number on Power Loss and TACS for 33-bus RDS; (**b**) Effect of DSTATCOM number on Power Loss and TACS for 69-bus RDS.

4.2. DSTATCOMs Allocation in Radial Distribution Systems

In this section, the IEEE 33-bus and 69-bus RDS are used to allocate numerous DSTATCOMs as efficiently as possible. First, using the CTLBO optimization technique, the optimal positions and sizes of several DSTATCOMs are determined while taking peak load into account. Then, using Equations (4), (9) and (26), yearly energy savings, TACS, and ES are calculated. The SOF taken into consideration for the RDS is used to determine the optimal number of DSTATCOM. The usefulness of the suggested approach for numerous DSTATCOM deployments in the IEEE 33-bus and 69-bus RDS is confirmed by comparing the results with those of several other soft computing algorithms. The suggested approach was put into practice using MATLAB R2015a on a desktop PC with an Intel i5-4570 processor, 3.2 GHz, and 8 GB of RAM.

The efficacy of the CTLBO optimization technique is demonstrated through the analysis of two RDS, namely 33-bus and 69-bus. The following cases are applied while comparing the outcomes:

Case 1: Initial condition of the system's
Case 2: Only reconfiguration of the network to reduce active power losses.
Case 3: Allocation of DSTATCOMs alone.
Case 4: DSTATCOM allocation following network reconfiguration.
Case 5: Allocating DSTATCOM and reconfiguring the network simultaneously.

5. Analysis of Case Studies and Discussion

5.1. IEEE 33-bus RDS

The reactive power management in the IEEE 33-bus is carried out using CTLBO algorithm for network reconfiguration and efficient DSTATCOM allocation. In [55], the comprehensive network specification is provided. It consists of 37 branches, 3 laterals, 33 buses and five tie switches (33–37) that are kept open. 12.66 kV is the nominal voltage rating. The RDS's nominal load demands are 2.3 MVAr and 3.72 MW, respectively. The Network's initial base case KVA is 1000 KVA.

5.1.1. Case 1: RDS without NR and DSTATCOM

In case 1 load flow is carried out for the initial network configuration or base case, where distribution network is without DSTATCOM and NR. Here, all tie-switches are kept open i.e., 33, 34, 35, 36, and 37 which gives 202.67 kW APL while RPL is 135.1409 kVAr. The base case VSI of this initial configuration RDS is 0.667168 [56]. Equations (4) and (9) are used to calculate the network's energy loss and TACS based on the characteristics listed in Table 5. The power loss in the 33-bus distribution network will causes emission of 26,175.015 tons of pollutant mentioned in Table 6. The minimum voltage for base case is 0.91309 at 18th bus. The other performance indices (Table 7) are shown in Table 8.

Table 5. Parameter setting for cost calculation [57].

$Cost_{DSTATCOM_i}$ (US$/kVAr)	$n_{DSTATCOM}$ (year)	AR	K_e (US$/kWh)
50	30	0.1	0.06

Table 6. Emission data [58].

Source	Emission Rate (ER) (kg/MWh)		
	NO_X	CO_2	SO_2
Grid	2.2952	921.25	3.5834

Table 7. Performance Indices for DSTATCOM allocation evaluation impact on RDS [57].

Performance Indices	Formulation
Emission Saving (ES)(Ton)	$ES = E_b - E_{DSTATCOM}$
Voltage Stability Index (VSI)	$VSI_{m+1} = \lvert V_m\rvert^4 - 4\{P_{m+1}X_j - Q_{m+1}R_j\}^2 - 4\{P_{m+1}R_j + Q_{m+1}X_j\}\lvert V_m\rvert^2$
Active Power Loss Reduction (APLR) (%)	$APLR = \left(\frac{APL_b - APL_{DSTATCOM}}{APL_b}\right) X\,100$
Voltage Deviation Index (VDI) (p.u.)	$VDI = \sum_{i=1}^{n} (1 - \lvert V\rvert_{i,DSTATCOM})^2$
Reactive Power Loss Reduction (RPLR) (%)	$RPLR = \left(\frac{RPL_b - RPL_{DSTATCOM}}{RPL_b}\right) \times 100$
Qualified Load-Index (QLI)	$QLI = \sum_{i=1}^{n} \lvert V\rvert_i \,.\, Load_i$
Total Bus Violate Voltage Boundary (TBVVB)	TBVVB = 0 $TBVVB = \sum_{i=1}^{n}$ if $\lvert V\rvert_i < \lvert V\rvert_{min}$ or $\lvert V\rvert_i > \lvert V\rvert_{max}$ $TBVVB + 1$ end

Table 8. Simulation results using proposed method for 33-bus RDS for power loss minimization.

	Case 1	Case 2	Case 3	Case 4	Case 5
Open Switch	33, 34, 35, 36, 37	7, 9, 14, 32, 37	33, 34, 35, 36, 37	7, 9, 14, 32, 37	7, 9, 14, 36, 37
No. of DSTATCOM	-	-	2	1	1
Size (Location) MVAr (Bus No.)	-	-	0.46886 (12)	1.02834 (30)	1.07023 (30)
	-	-	1.05775 (30)		
APL (kW)	202.677	139.553	135.7530	101.818	101.0188
RPL (kVAr)	135.1409	102.3049	90.5464	77.3081	75.3696
EL (kWh)	1,248,443.0528	864,733.1989	840,960.3743	632,642.3927	627,806.5746
ELC ($)	74,906.5831	51,883.9919	50,457.6224	37,958.5435	37,668.3944
DSTATCOM cost ($)	-	-	6713.8693	4522.5000	4706.7518
TACS ($)	-	23,022.5912	17,735.0913	32,425.5395	32,531.4369
Emission (Ton)	26,175.015	25,819.2666	25,797.226	25,604.0886	25,599.6051
ES (Ton)	-	355.7484	377.7888	570.9264	575.4098
QLI (p.u.)	3.5311	3.58408	3.5841	3.60868	3.61032
VSI (p.u.)	0.6951	0.77358	0.7683	0.78938	0.79327
VDI (p.u.)	0.1171	0.04869	0.0561	0.03483	0.031390
TBVVB	0	0	0	0	0
APLR (%)	-	31.1466	33.020	49.7632	50.1577
RPLR (%)	-	24.2649	32.998	42.7944	44.2288
MinVoltage (p.u.)	0.91309 (18)	0.9378 (32)	0.9362 (18)	0.9475 (33)	0.95447 (18)

5.1.2. Case 2: RDS with Network Reconfiguration

In the Case 2, only network reconfiguration is done. Table 8 also represent the results for case-2. The optimum result obtained for this case using CTLBO algorithm yield significant reduction in APL i.e., 139.55 kW and 355.74 tons of emission reductions in comparison to case 1, for the APL minimization target, when tie-switches 7, 9, 14, 32, and 37 are opened while maintaining the network radiality. The obtained result gives APL reduction and emission saving of 31.15% and 86.33% respectively. Due to reconfiguration only, the minimum voltage rises to 0.9378 p.u. at 32th bus.

5.1.3. Case 3: RDS with DSTATCOMs

Here, DSTATCOMs without network reconfigurations are installed in the 33-bus network. it is noted that in case 3, placing only two DSTATCOMs (at 12th and 30th bus) with appropriate capabilities results in the greatest network annual operating cost saving of $17,735.0913, along with a 33.02% reduction in APL and an increase in emission reductions of 377.78 tons as shown in Table 8. After DSTATCOMs allocation, the minimum network voltage rises up to 0.9362 p.u. at 18th bus.

5.1.4. Case 4: DSTATCOMs Allocation after Network Reconfiguration

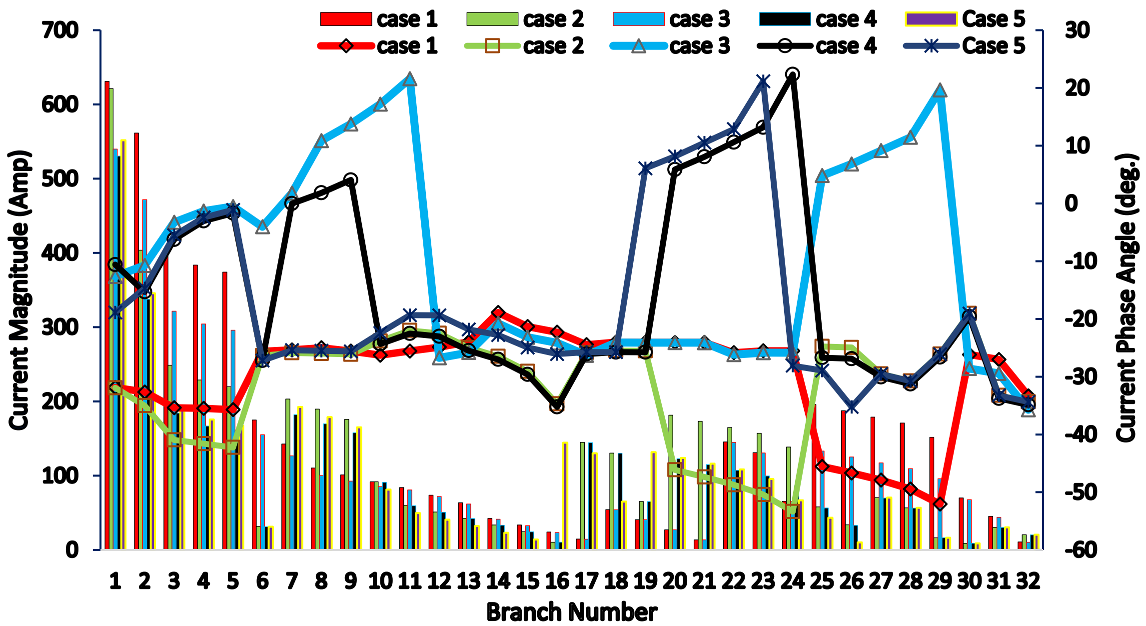
In Case 4, optimal reconfiguration is done first i.e., tie/sectional switches 7, 9, 14, 32, and 37 are opened, then DSTATCOMs are installed. The simulation result shown in Table 8, indicates that the greatest operational cost savings of $32,425.53 can be achieved by placing a single DSTATCOM following network reconfiguration. The APL and emission saving observed in this case are 49.6% and 570.92 tons respectively, less than case 1. The minimum network voltage rises to 0.9475 p.u. at 33th bus.

5.1.5. Case 5: Simultaneous DSTATCOMs Allocation and Network Reconfiguration

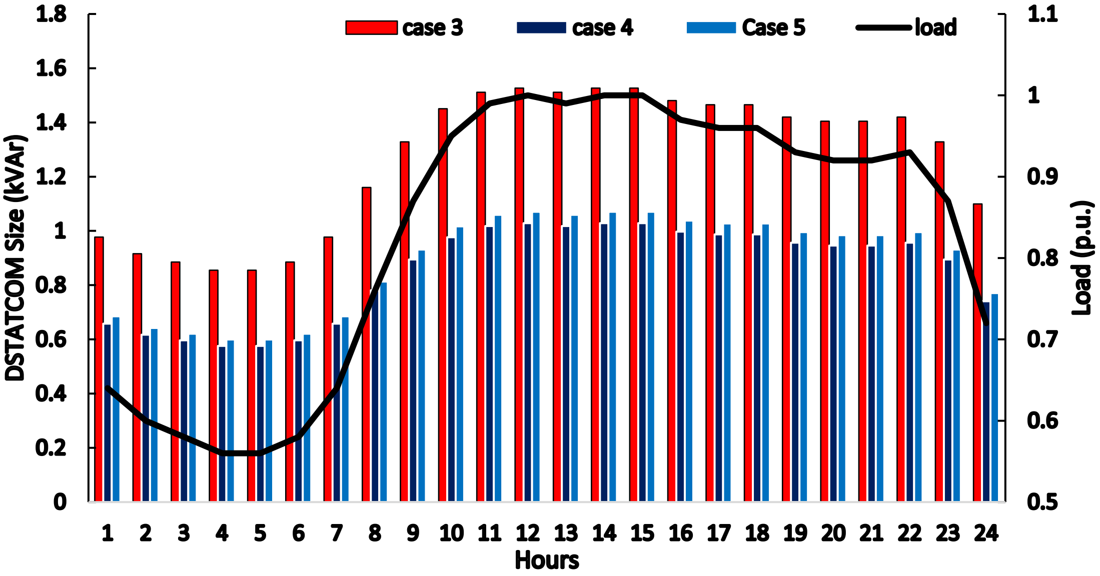
However, in Case 5, the simultaneous reconfiguration and DSTATCOM allocation further improve the APL reduction to 101.02 kW and the operational cost savings of $32,531.53. The case 5, yields maximum benefits out of all cases i.e., maximum emission saving 575.41 ton, minimum voltages rise to 0.95447 at 18th bus, VSI rises to 0.79327 p.u., 50.12% APL reduction etc. as shown in Table 8.

5.1.6. Comparative Results and Other Discussion

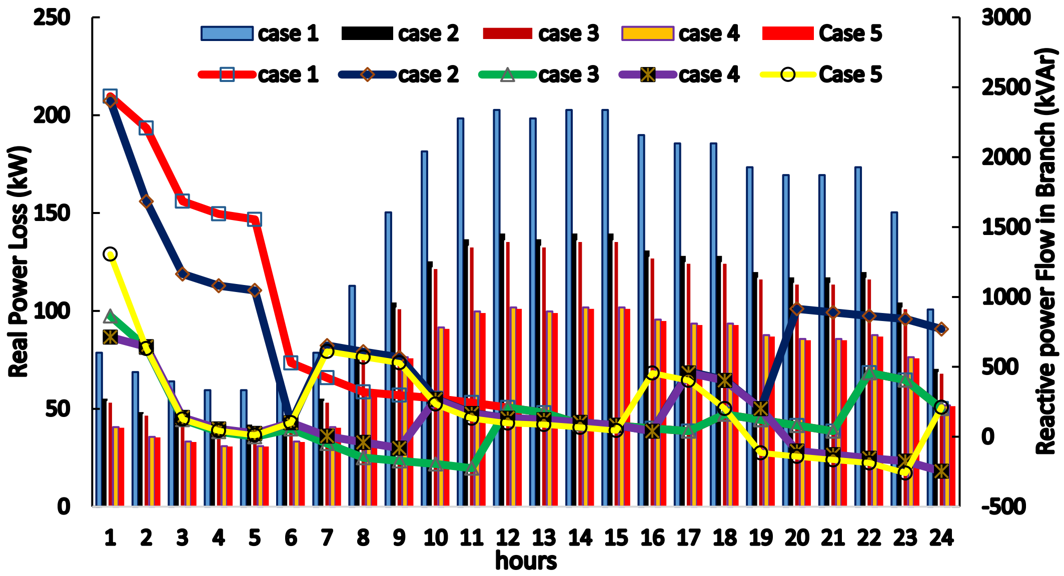
Additionally, Tables 9–12 show that the network's operating cost saving and power loss reduction increase significantly when the number of DSTATCOMs increases up to three. It can be seen from Figure 4a that prior to the installation of DSTATCOMs, all reactive power requirements are supplied by the substation. However, introducing DSTATCOMs into the network facilitates local fulfillment of reactive power demand. As a result, the flow of reactive power in different lines across the network is reversed. The DNs active power flow capacity is enhanced via local reactive power management. The reactive power compensation in the network causes the branch current phase angle to changes greatly, even though their amplitude only slightly changes, as seen in Figure 4a. The minimum bus voltage in the network without DSTATCOM is 0.91309 p.u. (at 18th bus), as shown in Figure 4d. After 2 DSTATCOMs are installed, it rises to 0.936243 p.u. (at 18th bus). Furthermore, for Case 5, it improved to 0.95447 p.u. (at 18th bus). Figure 4b shows reactive power injected by the DSTATCOMs in the network for 24-h load demand as depicted in Figure 4b. Figure 4c demonstrate the 24-h power loss in the 33-bus network for all the Cases under consideration.



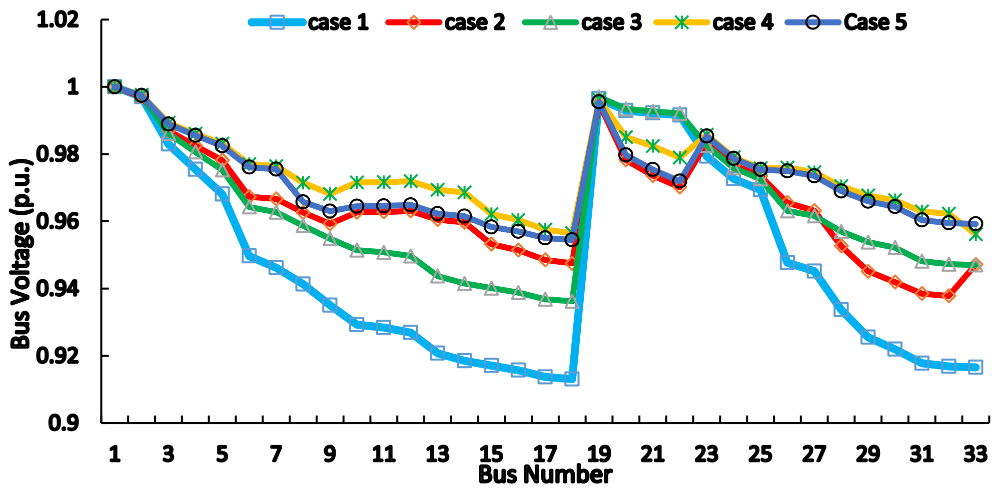
(**a**)



(**b**)



(**c**)



(**d**)

Figure 4. (**a**) Branch current and its corresponding phase angle for power loss minimization for 33-bus; (**b**) Hourly Reactive power injected by DSTATCOMs for power loss minimization and load profile for 33-bus; (**c**) Hourly Real power loss and reactive power flow in branch for power loss minimization in 33-bus; (**d**) Voltage profile of 33-bus for all the cases.

The voltage profile of the network is shown in Figure 4d for all the cases under consideration. Following the installation of 1 and 2 DSTATCOMs for case 3, the proposed algorithm obtains the least active power losses, 143.6016 kW and 135.753 kW as shown in Tables 11–13 in comparison to the BFOA [59], BA [60], ICA [61], and HFACO [41] algorithms-based solutions.

Table 9. Simulation results for TACS maximization for 33-bus RDS.

	Case 3				
Open Switch	33, 34, 35, 36, 37				
Number of DSTATCOM	1	2	3	4	5
Size (Location) MVAr (Bus No.)	1.08263 (30)	0.31447 (14)	0.19895 (8)	0.198947 (8)	0.178328 (8)
		0.95121 (30)	0.25437 (14)	0.254379 (14)	0.254380 (14)
			0.89402 (30)	0.69939 (30)	0.138438 (25)
				0.194087 (32)	0.693006 (30)
					0.1940879 (32)
APL (kW)	144.63079	137.1904	135.7712	135.3968	133.719
RPL (kVAr)	96.71742	91.3411	90.3221	89.9566	88.8626
EL (kWh)	894,608.6125	849,409.4762	840,786.7641	838,507.1302	828,134.7484
ELC ($)	53,676.5167	50,964.5685	50,447.2058	50,310.4278	49,688.0849
DSTATCOM cost ($)	4761.2992	5566.2834	5925.4844	5923.0722	6413.1546
TACS ($)	16,468.7671	18,375.7311	18,533.8928	18,673.0830	18,805.3435
Emission (Ton)	25,846.9649	25,805.0595	25,797.0652	25,794.9516	25,785.3351
ES (Ton)	328.0500	369.9554	377.9498	380.0633	389.6798
QLI (p.u.)	3.5685	3.5771	3.5783	3.57900	3.5802
VSI (p.u.)	0.72904	0.764873	0.76537	0.76538	0.76510
VDI (p.u.)	0.07526	0.062398	0.06135	0.06082	0.06077
TBVVB	0	0	0	0	0
APLR (%)	28.63977	32.3108	33.0110	33.1957	34.0232
RPLR (%)	28.43217	32.4104	33.1644	33.4349	34.2444
MinVoltage (p.u.)	0.92403 (18)	0.93518 (18)	0.93533 (18)	0.93534 (18)	0.93525 (18)

Table 10. Simulation results for TACS maximization for 33-bus RDS.

	Case 4				
Open Switch	7, 9, 14, 32, 37				
No. of DSTATCOM	1	2	3	4	5
Size (Location) MVAr (Bus No.)	0.85468 (30)	0.17888 (17)	0.14269 (14)	0.141403 (14)	0.055630 (9)
		0.85154 (30)	0.14137 (18)	0.140608 (18)	0.132449 (14)
			0.84970 (30)	0.135403 (25)	0.114094 (18)
				0.834725 (30)	0.134823 (25)
					0.834439 (30)
APL (kW)	102.8491	98.6193	96.4796	94.7383	94.4560
RPL (kVAr)	77.7878	73.8687	71.7985	70.6681	70.4053
EL (kWh)	638,935.0106	612,952.9470	599,777.5798	588,978.5470	587,248.5505
ELC ($)	38,336.1006	36,777.1768	35,986.6547	35,338.7128	35,234.9130
DSTATCOM cost($)	3758.8017	4531.6866	4986.1689	8775.6716	5591.6148
TACS ($)	32,811.6807	33,597.7196	33,933.7594	34,061.1184	34,080.0552
Emission (Ton)	25,609.9226	25,585.8339	25,573.6186	25,563.6066	25,562.0026
ES (Ton)	565.0923	589.1810	601.3963	611.4084	613.0123
QLI(p.u.)	3.6047	3.61079	3.61325	3.61455	3.61486
VSI (p.u.)	0.78921	0.82234	0.82492	0.82660	0.82680
VDI(p.u.)	0.03664	0.03021	0.02825	0.02809	0.02789
TBVVB	0	0	0	0	0
APLR (%)	49.2546	51.3416	52.3973	53.2565	53.3958
RPLR (%)	42.4394	45.3394	46.8713	47.7078	47.9022
MinVoltage (p.u.)	0.94745(33)	0.95815 (33)	0.95833 (33)	0.95825 (32)	0.95825 (32)

Table 11. Comparison of Simulation results using CTLBO algorithm for 33-bus RDS.

	Case 3			
Algorithm	BFOA [59]	IA [62]	BA [60]	CTLBO
Open Switch	33, 34, 35, 36, 37			
No. of DSTATCOM	1	1	1	1
Size (Location) MVAr (Bus No.)	1102.7 (30)	0.96249 (12)	1.150 (30)	1.2527 (30)
APL (kW)	144.38	171.79	143.97	143.6016
RPL (kVAr)		115.26	96.47	96.3378
QLI (p.u.)	-			3.5740
VSI (p.u.)	0.7228	0.79311	0.7242	0.7340
VDI (p.u.)	-	-	-	0.07013
APLR (%)	28.76	15.24	28.97	29.147
RPLR (%)	-	14.78	28.67	28.713
MinVoltage (p.u.)	0.9240	0.9258	0.9244	0.9256 (18)

Table 12. Comparison of Simulation results using CTLBO algorithm for 33-bus RDS.

	Case 3			
Algorithm	ICA [61]	BFOA [59]	BA [60]	CTLBO
Open Switch	33, 34, 35, 36, 37			
No. of DSTATCOM	2	2	2	2
Size (Location) MVAr (Bus No.)	0.455 (10)	0.600 (10)	0.450 (10)	0.46886 (12)
	1.005(30)	1.200(30)	0.995 (30)	1.05778 (30)
APL (kW)	140.24	137.50	146.73	135.7530
RPL (kVAr)	93.67	92.01	95.63	90.5464
QLI (p.u.)	-	-	-	3.5841
VSI (p.u.)	-	-	-	0.7683
VDI (p.u.)	-	-	-	0.0561
APLR (%)	30.31	32.15	27.60	33.020
RPLR (%)	30.73	31.96	29.28	32.998
MinVoltage (p.u.)	0.9301	0.9289	0.9299	0.9362 (18)

Table 13. Comparison of Simulation results using CTLBO algorithm for 33-bus RDS.

	Case 5		
Algorithm	HFACO [41]	BFOA [59]	CTLBO
Open Switch	7, 9, 14, 32, 37	11, 28, 30, 33, 34	7, 9, 14, 36, 37
No. of DSTATCOM	1	1	1
Size (Location) MVAr (Bus No.)	0.98 (10)	1.1102 (10)	1.07023 (30)
APL (kW)	110.22	118.1	101.0188
RPL (kVAr)	-	-	75.3696
QLI(p.u.)	-		3.61032
VSI (p.u.)	-	-	0.79327
VDI (p.u.)	-	-	0.031390
APLR (%)	45.61	41.73	50.1577
RPLR (%)	-	-	44.2288
MinVoltage (p.u.)	-	0.9423	0.95447 (18)

5.2. 69-bus RDS

The CTLBO algorithm is now applied for network reconfiguration and DSTATCOM allocation in the 69-bus RDS. The comprehensive specifications are provided in reference [50]. The system comprises 69 buses, 7 laterals, and 73 branches, which includes five tie-switches that are typically maintained in an open position. The nominal voltage rating is set at 12.66 kV. The expected load demand on the RDS is 3.8 MW and 2.69 MVAr.

5.2.1. Case 1: RDS without NR and DSTATCOM

In case 1 load flow is carried out for the initial network configuration or base case, where distribution network is without DSTATCOM and NR. Here, all tie-switches are kept open i.e., 69, 70, 71, 72, and 73 which gives 224.89 kW APL while RPL is 102.11 kVAr. The base case VSI of this initial configuration RDS is 0.68332 [56]. The minimum voltage for base case is 0.90919 at 65th bus. The other performance indices (Table 7) are shown in Table 14. The power loss in the 69-bus distribution network will causes emission of 26,879.98 tons of pollutant mentioned in Table 14.

5.2.2. Case 2: RDS with Network Reconfiguration

In the Case 2, only network reconfiguration is done. Table 14 also represent the results for case-2. The optimum result obtained for this case using CTLBO algorithm yield significant reduction in APL i.e., 98.5717 kW and 713.8086 tons of emission reductions in comparison to case 1, for the APL minimization target, when tie/sectional switches 14, 56, 69–71 are opened while maintaining the network radiality. The obtained result gives APL reduction and emission saving of 56.17% and 97.35% respectively. Due to reconfiguration only the minimum voltage rises to 0.9494 p.u. at 61th bus. Only reconfiguration results in annual operating cost saving of $46,194.86.

5.2.3. Case 3: RDS with DSTATCOMs

Here, DSTATCOMs without network reconfigurations are installed in the 33-bus network. it is noted that in case 3, placing only two DSTATCOMs (at 17th and 61th bus) with appropriate capabilities results in the greatest network annual operating cost saving of $21,462.48, along with a 34.91% reduction in APL and an increase in emission reductions of 442.771 tons as shown in Table 14. After DSTATCOMs allocation, the minimum network voltage rises up to 0.93113 p.u. at 65th bus.

Table 14. Simulation results for APL minimization for 69-bus RDS.

	Case 1	Case 2	Case 3	Case 4	Case 5
Open Switch	69, 70, 71, 72, 73	14, 56, 61, 69, 70	69, 70, 71, 72, 73	14, 56, 61, 69, 70	14, 56, 61, 69, 70
No. of DSTATCOM	-	-	2	2	2
Size (Location)			0.36041 (17)	1.03819 (61)	1.03819 (61)
MVAr (Bus No.)			1.27498 (61)	0.34179 (64)	0.34179 (64)
APL (kW)	224.8974	98.5717	146.379	67.3899	67.3899
RPL (kVAr)	102.1156	92.0240	68.2097	62.7666	62.7666
EL (kWh)	1,381,327.9423	611,413.5998	903,748.9191	419,399.2101	419,399.2101
ELC ($)	82,879.6765	36,684.8159	54,224.9351	25,163.9526	25,163.9526
DSTATCOM cost ($)	-		7192.2586	6069.04997	6069.04997
TACS ($)	-	46,194.8606	21,462.4827	51,646.6739	51,646.6739
Emission (Ton)	26,879.9838	26,166.1742	26,437.2066	25,988.1521	25,988.1521
ES (Ton)	-	713.8096	442.7771	891.8316	891.8316
QLI (p.u.)	3.61844	3.69671	3.6621	3.73063	3.73063
VSI (p.u.)	0.68332	0.83082	0.75170	0.88647	0.88647
VDI(p.u.)	0.09924	0.02436	0.05731	0.01242	0.01242
TBVVB	0	0	0	0	0
APLR (%)	-	56.1701	34.9121	70.0349	70.0349
RPLR (%)	-	9.8825	33.2034	38.5337	38.5337
MinVoltage (p.u.)	0.90919 (65)	0.94947 (61)	0.93113 (65)	0.96683 (61)	0.96683 (61)

5.2.4. Case 4: DSTATCOMs Allocation after Network Reconfiguration

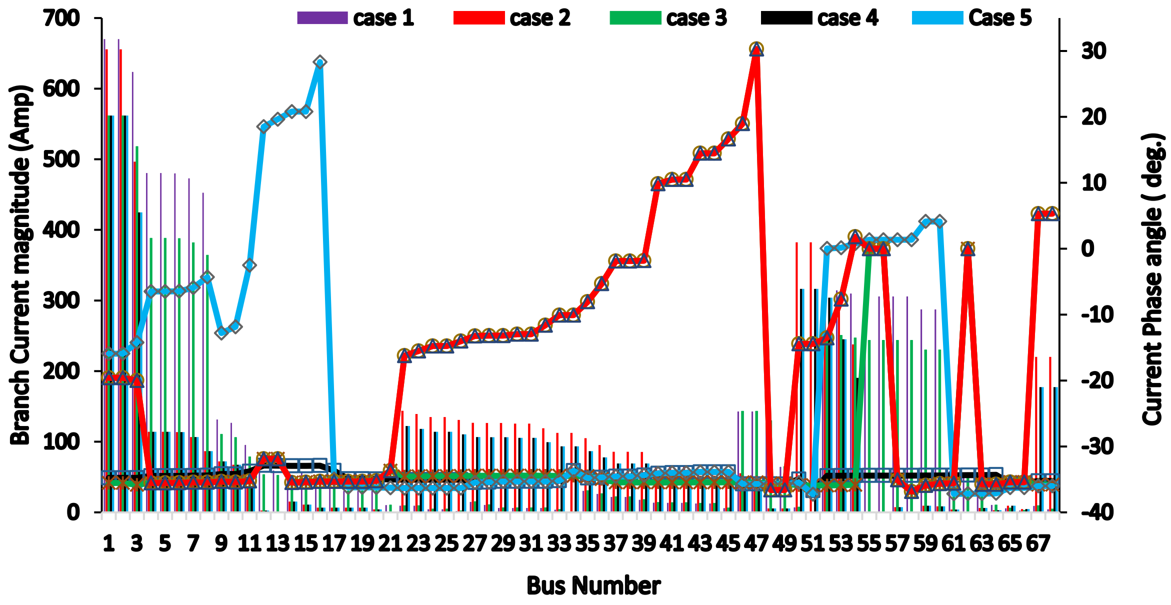
In Case 4, optimal reconfiguration is done first i.e., tie/ sectional switches 14, 56, 61, 69, and 70 are opened, then DSTATCOMs are installed. The simulation result shown in Table 14, indicates that the greatest operational cost savings of $51,646.67 can be achieved by placing a two DSTATCOMs following network reconfiguration. The APL and emission saving observed in this case are 70.03%, 891.83 tons respectively, less than case 1. The minimum network voltage rises to 0.9475 p.u. at 33th bus.

5.2.5. Case 5: Simultaneous DSTATCOMs Allocation and Network Reconfiguration

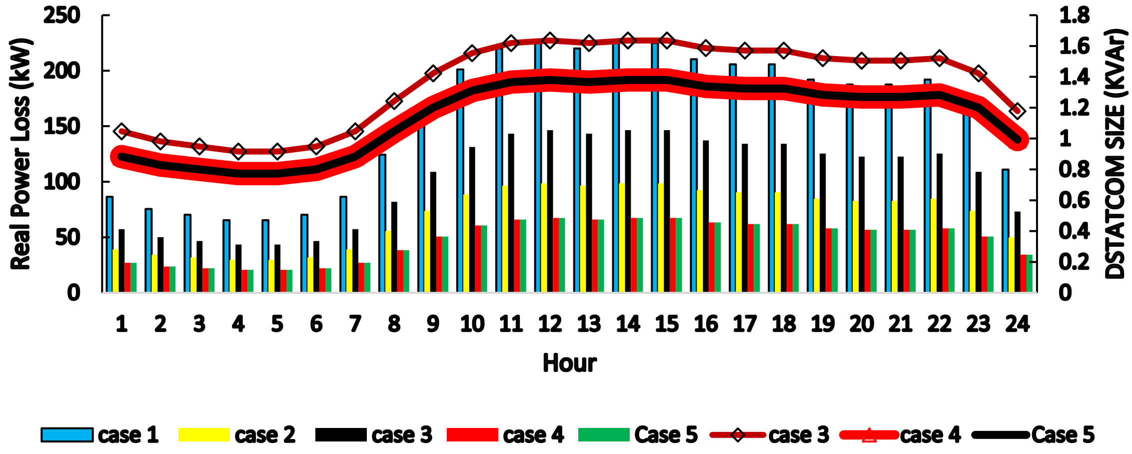
However, in Case 5, the simultaneous reconfiguration and DSTATCOM allocation further improve the APL reduction to 67.38 kW and the operational cost savings of $51,646.67. The case 5, yields maximum benefits i.e., maximum emission saving 981.83 tons, minimum voltages rise to 0.96683 at 61th bus, VSI rises to 0.88647 p.u., 70.03% APL reduction etc. as shown in Table 14.

5.2.6. Comparative Results and Other Discussion

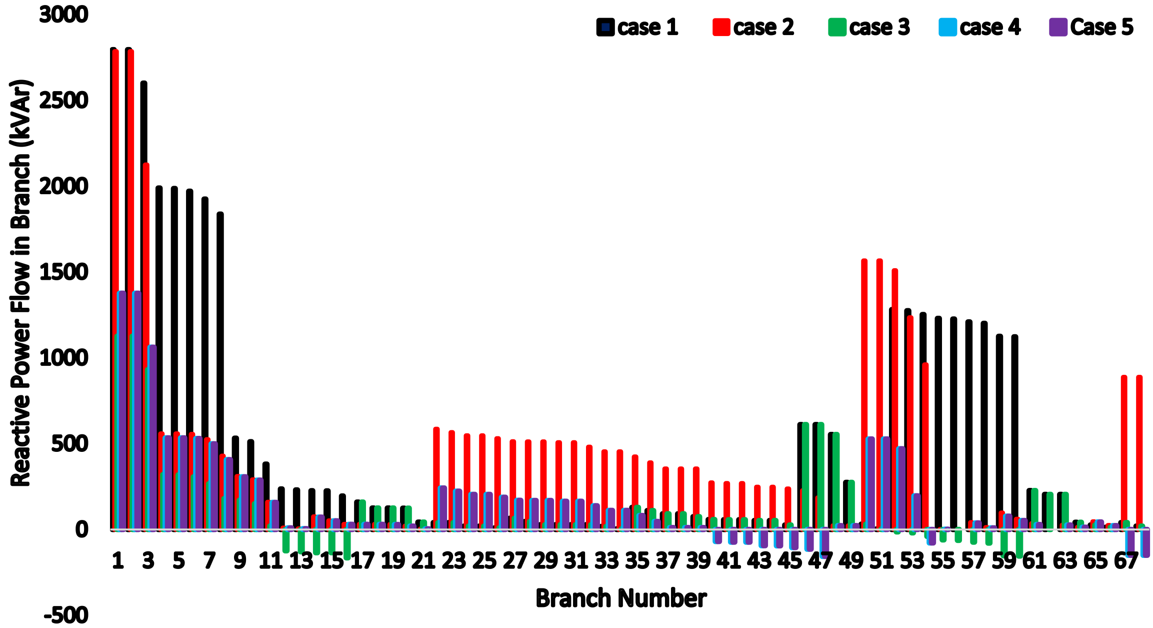
As depicted in Figure 5c, prior to the installation of DSTATCOMs, all reactive power requirements are supplied from the substation, whereas the introduction of DSTATCOM into the network facilitates the local fulfilment of reactive power demand. Figure 5a illustrate that while the magnitudes of the branch currents experience only slight changes, their phase angle exhibit significant alterations because of DSTATCOMs. As depicted in Figure 5d, the minimum bus voltage for initial network configuration is recorded at 0.90919 p.u. (at 65th bus), rises to 0.93113 p.u. on same bus, following the installation of '2 DSTATCOMs'. However, for case 5, the minimum bus voltage of the network is further increased to 0.96683 p.u. (at 61st bus). Figure 5b depicts reactive power injections by '2 DSTATCOMs' corresponding to the actual line loading over a 24-h period, as shown in Figure 5b. Figure 5b demonstrate the 24-h power loss in the 69-bus network for all the Cases under consideration. Equations (4) and (9) are used to calculate the network's energy loss and TACS based on the characteristics listed in Table 7. The voltage profile of the network is shown in Figure 5d for all the cases under consideration. Following the installation of 1 and 2 DSTATCOMs for case 3, the proposed algorithm obtains the least active power losses, 151.958 kW and 146.379 kW as shown in Tables 15–17 in comparison to the DE [38], BFOA [59], BA [60], ICA [61], and CSOA [63] algorithms based solutions, in the 69-bus RDS for Case 3, when compared to BFOA [59], Bat Algorithm (BA) [60], and Imperialist Competitive Algorithm (ICA) [61]. Table 15, indicates that a significant decrease in the APL is attained when the concurrently appropriate tie-switches/isolator are kept opened and allocate DSTATCOMs within the network.


case 1
case 2
case 3
case 4
Case 5
Branch Current magnitude (Amp)
Current Phase angle (deg.)
Bus Number

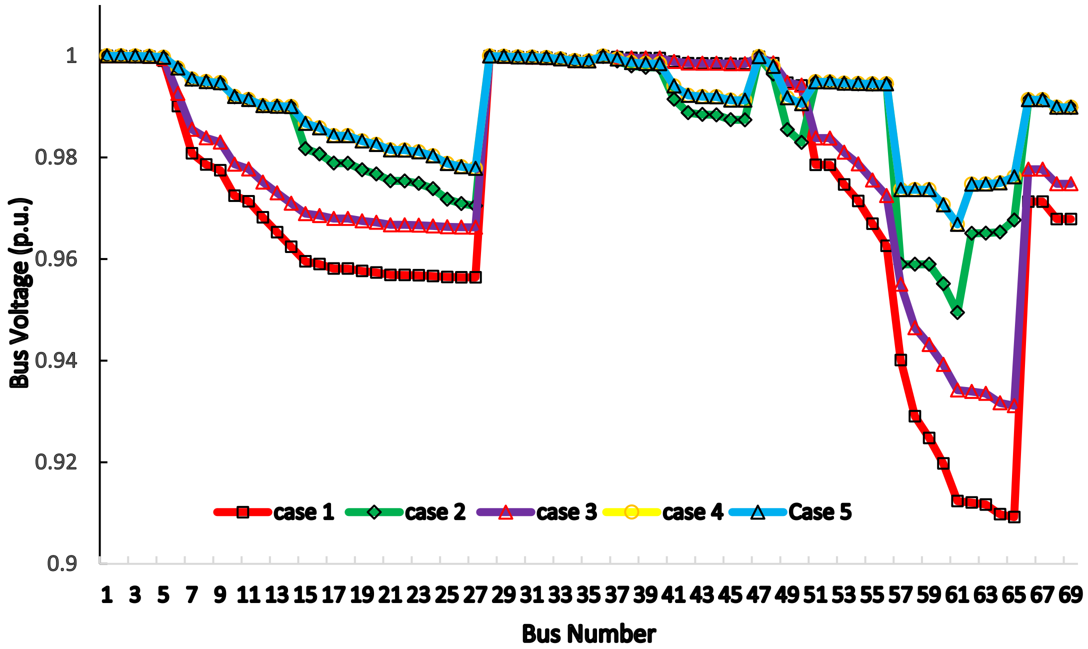
(**a**)


Real Power Loss (kW)
DSTATCOM SIZE (KVAr)
Hour
case 1
case 2
case 3
case 4
Case 5
case 3
case 4
Case 5

(**b**)


case 1
case 2
case 3
case 4
Case 5
Reactive Power Flow in Branch (kVAr)
Branch Number

(**c**)



(**d**)

Figure 5. (**a**) Branch current and its corresponding phase angle for power loss minimization in 69-bus for all the cases; (**b**) Hourly Real power loss in each branch and DSTATCOMs size for power loss minimization in 69-bus for all the cases; (**c**) Hourly Reactive power injected by DSTATCOMs for power loss minimization in 69-bus for all the cases; (**d**) Voltage profile of 69-bus for all the cases.

Table 15. Comparison of Simulation results for 69-bus RDS.

	Case 3			
Algorithm	BA [60]	IA [64]	CSOA [63]	CTLBO
Open Switch	68, 69, 70, 71, 72			
No. of DSTATCOM	1	1	1	1
Size (Location) MVAr (Bus No.)	1.150 (61)	1.7044 (61)	1.200 (61)	1.32982 (61)
APL (kW)	153.36	157.5	152.95	151.958
APLR (%)	32.02	30	31.9	32.4315
RPL (kVAr)	-	72.4	96.47	70.4638
RPLR (%)	30.27	29.2	-	30.9959
VDI (p.u.)	-	-	-	0.06397
VSI (p.u.)	0.7375	0.7561	0.7356	0.75041
QLI (p.u.)	-	-	-	3.6585
MinVoltage (p.u.)	0.9278	0.9353	0.9285	0.93073 (65)

Table 16. Comparison of Simulation results for 69-bus RDS.

	Case 3			
Algorithm	ICA [62]	BA [60]	BFOA [59]	CTLBO
Open Switch	68, 69, 70, 71, 72			
No. of DSTATCOM	2	2	2	2
Size (Location) MVAr (Bus No.)	0.0.375 (15)	0.330 (15)	0.480 (15)	0.36041 (17)
	1.280 (61)	1.220 (61)	1.430 (61)	1.27498 (61)
APL (kW)	147.35	146.73	148.07	146.379
RPL (kVAr)	72.382	68.73	68.76	68.2097
QLI (p.u.)	-			3.6621
VSI (p.u.)	-	0.7418	0.7512	0.75170
VDI (p.u.)	-	-	-	0.05731
APLR (%)	34.60	34.78	34.19	34.9121
RPLR (%)	29.17	33.04	32.72	33.2034
MinVoltage (p.u.)	0.9324	0.9299	0.9332	0.93113 (65)

Table 17. Comparison of Simulation results for 33-bus RDS.

	Case 5	
Algorithm	DE [38]	CTLBO
Open Switch	13, 59, 63, 70, 71	14, 57, 63, 69, 70
No. of DSTATCOM	1	1
Size (Location) MVAr (Bus No.)	0.924 (61)	1.06268 (61)
APL (kW)	78.59	73.16635
RPL (kVAr)	84.23	67.4086
QLI (p.u.)	-	3.72539
VSI (p.u.)	-	0.87101
VDI (p.u.)	-	0.016625
APLR (%)	55.64	67.4663
RPLR (%)	17.51	33.9878
MinVoltage (p.u.)	0.9632	0.96609 (62)

5.2.7. Computational Performance

Table 18 provides a summary of the average computation times for the proposed CTLBO algorithm across various case studies involving the allocation of one or two DTATCOM units. The algorithm was executed in MATLAB R2015a on desktop systems equipped with an Intel Core i5-4570 CPU, 3.2 GHz, and 8 GB of RAM. Each result represents the average computation time over 150 iterations and 10 independent runs. In Case 3 of the 33-bus radial distribution systems, the proposed CTLBO algorithm exhibits low computational time compared to the Bat Algorithm (BA) [60]. And it is nearly 50% lower than the Bacterial Foraging Optimization Algorithm (BFOA) [59]. Furthermore, it significantly outperforms the Immune Algorithm (IA) [62] and Genetic Algorithm (GA) [33], achieving approximately 75% reduction in computational time. The CTLBO approach also demonstrates better performance than the Imperialist Competitive Algorithm (ICA) [61]

Table 18. Comparison of computational time for DSTATCOM allocation in distribution network.

.	**33-bus**					**69-bus**					
	IA	**BA**	**GA**	**BFOA**	**CTLBO**	**BFOA**	**GA**	**ICA**	**BA**	**ICA**	**CTLBO**
No. of DSTATCOMs	1	1	1	1	2	2	1	2	2	2	2
DSTATCOM penetration level (%)	41.82	50	48.44	48.13	54.2	71	71.3	61.52	42.75	61.52	60.8
Computational time (s)	21.22	7.2	24.15	12.14	7.18	11.06	45.58	9.37	10.6	9.37	7.85

5.2.8. Merits and Limitations of the CTLBO Algorithm

The proposed CTLBO algorithm gives the advantages of a metaheuristic technique by incorporating better exploration and fast convergence capability. This hybrid approach demonstrates, enhanced performance in the allocation of Type-II Distributed Generators (DGs) and network reconfiguration of the distribution systems.

The CTLBO algorithm meritoriously manages mixed-integer decision variables where DG location and network reconfiguration parameters are discrete, and DG sizes are continuous along with system constraints, including bus voltage limits and DSTATCOM capacity limits. Comparative results shows that the CTLBO overtakes existing methods such as the Imperialist Competitive Algorithm (ICA), Bat Algorithm (BA), and Bacteria Foraging Optimization Algorithm (BFOA) in terms of solution quality and constraint handling capability.

Though the standard TLBO algorithm is nearly parameter independent, the CTLBO requires proper tuning to achieve global optimization and accelerated convergence. Accordingly, more simulations were conducted to identify optimal parameter setting. The final tuned parameters used for DSTATCOM allocation and network reconfiguration are listed in Table 4.

6. Conclusions and Future Scope of Work

This study recommends an optimization framework based on the CTLBO algorithm for simultaneous network reconfiguration and optimal allocation of the Distribution Static Compensator in IEEE 33-bus and 69-bus RDS. Simulation results validate that the simultaneous implementation of network reconfiguration and DSTATCOMs yields the most promising outcomes in terms of objective function performance. The addition of DSTATCOMs in distribution lines, remarkably alters reverse power flow patterns, thereby increasing the overall power transfer capability of the system.

The outcomes further validate that determining the optimal number of DSTATCOM units is essential for minimizing annual operational expenses, with power loss minimization considered as a constraint. Realistic 24-h load profiles are used to capture daily load variations across both distribution networks. Comparative analysis confirms that the proposed CTLBO-based approach attains superior results in terms of annual energy savings, cost efficiency, emission reduction, and computational time when, benchmarked against several existing soft computing techniques.

The CTLBO algorithm in this work has been applied to deterministic, single-objective scenarios, it holds substantial potential for extension to distributed network planning. Future work may focus on multi-objective, incorporating uncertainties from DERs and load variability through stochastic modelling. The algorithm can also be adapted for real-time control, dynamic network reconfiguration, and integration with machine learning for improved adaptability. Its scalability makes it suitable for large scale smart grids, including applications in microgrid coordination and peer-to-peer energy trading.

Author Contributions

I.A.Q.: writing—original draft, visualization, software, methodology, investigation, formal analysis, data curation, project administration; N.K.: writing—review & editing, supervision, validation; S.A.: writing—review & editing, visualization. All authors have read and agreed to the published version of the manuscript.

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All the relevant data is included in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Nomenclature

IA	Immune Algorithm9pt
ICSO	Improved Cuckoo Search Optimization
SOF	Single Objective Function
BA	Bat Algorithm
CTLBO	Teaching Learning Based Optimization
BFOA	Bacterial Foraging Optimization Algorithm
APLR	Active Power Loss Reduction
TACS	Total Annual Cost Saving
ER	Emission Rate
P_{loss}^{DS}	Power Loss
ES	Emission Saving
P_{loss}	Active Power Loss
RPLR	Reactive Power Loss Reduction
QLI	Qualified Load-Index
TCVVB	Total Bus Violate Voltage Boundary
VDI	Voltage Deviation Index
SV	Solution Vector
N	Number of Solution variables
NI	Number of improvisations
DPNO	Distribution Power Network Operator
PQ	Power Quality
VP	Voltage Profile
DGS	Distributed Generation System
THD	Total Harmonic Distortion
DS	Distribution System
APL	Active Power Loss
RPL	Reactive Power Loss
DSTATCOM	Distribution Static Compensator

CPD	Custom Power Devices
SVC	Static Var Compensator
FACTS	Flexible Alternating Current Transmission System
VSI	Voltage Stability Index
FVSI	Fast Voltage Stability Index
CPLS	Combined Power Loss Sensitivity
PSI	Proposed Stability Index
RDS	Radial Distribution System
$X_{i,min}, X_{i,max}$	Minimum and maximum values of decision variables

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