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Integrated Planning and Coordinated Allocation of DG and DSTATCOM Considering Radial Distribution Network Reconfiguration

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Abstract: In order to enhance the operational efficacy of distribution power networks (DPNs) across techno economic and environmental aspects within a real-time operational framework, meticulous regulation of active as well as 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 Distributed generations (DGs) along with Distribution Static Synchronous Compensators (DSTATCOMs) for single-objective in the IEEE 33-bus radial distribution systems (RDSs). Several case studies demonstrate that simultaneous NR and DGs along with DSTATCOM allocation is the most effective solution for reduction of network active power losses ultimately reduces operational costs and emission. The results further demonstrates the superiority in terms of convergence characteristics, solution robustness and global optimality of the CTLBO algorithm under complex , multi-criteria constraints for NR and DGs along with DSTATCOM allocation in RDS against established bio-inspired metaheuristics such as the Gravitational Search Algorithm (GSA), Fireworks algorithm (FWA), Harmony Search Algorithm (HSA), Genetic Algorithm (GA) and Refined genetic algorithm (RGA).

Keywords CTLBO, Distributed Generation, DSTATCOM, Network reconfiguration, Radial distribution systems.

1. Introduction

The increasing demand of electrical energy, coupled with the limitations of conventional power generation and transmission systems, has necessitated the modernization of distribution networks. Distribution systems, particularly radial distribution network such as the IEEE 33-bus systems, often suffer from high power losses due to nature of high R/X ratio, poor voltage profile, and reduced system reliability due to their long radial structure and unidirectional power flow. To overcome these challenges, the integration of advance technologies such as Distributed Generation (Samala et. al., 2020; Khan et. al., 2022), Distribution Static Compensator (DSTATCOM) (Yuvaraj et. al., 2017; Salimon et. al., 2023) and network reconfiguration (Pegado et. al., 2019; Otuo et.al., 2023) has emerged as an effective solution.

Distributed Generation units, when optimally placed and sized, can significantly reduce active and reactive power losses, improve voltage stability, and enhance the overall efficiency of the distribution network. Similarly, DSTATCOM, a shunt-connected FACTS devices, provides dynamic reactive power support, thereby improving voltage regulation, power factor, and system reliability under varying load conditions. In addition, network reconfiguration, which involves changing the open/closed status of tie/sectional switches in the distribution

network, offers an economical method to minimize power losses and balance load distribution without requiring additional infrastructure.
The optimal allocation of DGs and DSTATCOMs, combined with effective reconfiguration strategies, ensures benefits (Yuvaraj et. al., 2018; Shaheen et al. 2022; Salkuti et al.,2022; Kannemadugu et al. 2025; Weqar et al. 2018) such as:

- Minimizes of active and reactive power losses.
- Enhance voltage stability and power quality.
- Improves reliability and security of the radial network.
- Better utilization of existing distribution infrastructure.

Hence, the coordinated planning and optimal allocation of these technologies in a 33-bus radial distribution network is essential for achieving an efficient, reliable, and sustainable modern power distribution network.

Table 1 Addressed the summary of several literatures presented on DGs DSTATCOM placement in distribution networks have methods, objective of finding and research gaps.

Authors / Year	Method / Algorithm	Focus Area	Test System	Key Outcomes
Marjani et al., 2018	MOPSO + TOPSIS	DSTATCOM + Reconfiguration	IEEE (33-bus & 69-bus)	Loss minimization, voltage profile improvement, better loadability through multi-objective optimization
Reddy et al., 2023	PLI method	DG + DSTATCOM	IEEE 33-bus	Effective loss reduction via combined DG and D-FACTS using PLI
Tolabi et al., 2015	Fuzzy-ACO	Reconfiguration + PV + DSTATCOM	IEEE 33-bus	Simultaneous PV & DSTATCOM placement with reconfiguration reduces losses and improves voltage profile more than separate methods
Dash et al., 2021	SAR (Search & Rescue algorithm)	DG + DSTATCOM + Reconfiguration	IEEE 33-bus	Improved loss reduction using coordinated allocation with SAR metaheuristic
Balamurugan et al., 2018	Whale Optimization (WOA)	DSTATCOM sizing & placement	IEEE 69-bus	Effective voltage profile improvement and loss reduction via DSTATCOM allocation
Amin et al., 2022	Gorilla troop's optimizer (GTO)	PV-DG + DSTATCOM	94-bis	Improves total annual cost, the system voltage deviations, and the system stability.
Razavi et al., 2020	Stochastic DNR + improved CSA	Daily Reconfiguration with renewables	IEEE 33-bus	Multi-objective optimization (loss, voltage, reliability, cost) under renewable uncertainty
Sirat et al., 2019	DG placement under stochastic DG nature	DG uncertainty modeling	IEEE 33-bus	Considerable cost and loss reduction by modeling wind, solar, biomass DGs stochastically
El-Zonkoly et al., 2011	PSO for multi-DG integration	DG placement	IEEE 33-bus (and others)	Loss, MVA flow, and intake reductions; voltage stability margin improved
Sambaiah et al., 2020	GOA (Grasshopper)	DG + Reconfiguration + DSTATCOM	IEEE 33-bus (also 69,118)	Loss and voltage profile improved with combined reconfiguration, DG, DSTATCOM & PV
Chinnaraj et al., 2020	CSA (Cuckoo Search Algorithm)	DG + DSTATCOM	IEEE 33-bus & 136-bus	Joint allocation improved voltage profile and reduced losses
Chinnaraj & Kumar et al., 2020	LSF + LSA-SM	DG + DSTATCOM	IEEE 33-bus and 69-bus	Both loss and voltage profile enhanced through combined planning
Injeti et al., 2020	PSO + BO (Butterfly Optimization)	DG + PEV presence	IEEE 33-bus	Reduced daily power loss and improved voltage with DG considering PEV loads
Balu et al., 2021	SPBO (Student Psychology-Based)	DG allocation	IEEE 33-bus, 69-bus, 136-bus unlabeled	Loss and VSI minimization effective across systems
Alam et al., 2018	MINLP	DG integration	IEEE 33-bus & 69-bus	Significant loss reduction and voltage improvement with optimally allocated

				DGs
El-Arini et al., 2024	GWO + DG + Reconfiguration + Capacitor Banks	Multi-tech coordinated planning	IEEE 33-bus & others	Excellent performance in simultaneous optimization of DG, reconfiguration, and capacitors
Mohamed et al., 2022	IGWO + Sensitivity Factors	DG + DSTATCOM	IEEE 33-bus	Reduced computational burdens with coordinated planning considering load modelling
Da Silva et al., 2008	Group Teaching Optimization (GTO)	DG + DSTATCOM	IEEE 33-bus	Improved DISCO voltage stability and maximized combined DISCO–DG owner cost–benefit through coordinated DG and DSTATCOM planning
Kannemadugu et al., 2025	Genetic Algorithm (GA)	DG + SVC	IEEE 38-bus	Reduced real and reactive power losses and improved voltage profile and system stability via optimal DG–SVC integration
Shukla et al., 2023	Multi-Objective Particle Swarm Optimization (MOPSO)	DG + Shunt Capacitors	IEEE 33-bus and IEEE 69-bus	Achieved up to 94.8% power loss reduction and significant voltage stability improvement through optimal simultaneous and independent DG–capacitor placement

2. Research Aim and Motivation

Many articles are reported, integration of distributed power resources to DPNs marks improvement in VP (Patel et al., 2025; Das et.al., 2008; Haldar et.al., 2015) line loadability improvement (Yaghoobi et al., 2018; Hung et. al., 2014; Quadri et al., 2018; Moravej et. al., 2013), post fault fast voltage recovery (Yaghoobi et. al., 2018), reduction in APL (Haldar et.al., 2015; Luo et al., 2018; Lakervi et. al., 1996), effect on greenhouse gas (Quadri et al., 2018) and voltage stability index improvement (Quadri & Bhowmick et. al., 2018; Solati et al., 2025)]. Further, concurrent reconfiguration (RE) of network and allocation of scattered energy storage (Santos et al., 2017) considerably enhance the penetration of DGs in distribution networks. In this perspective, limited investigative research literature are available to show the impact of simultaneous allocation of DGs, DSTATCOMs and radial network reconfiguration in the DNs. Therefore, this paper deals with detailed analysis on the impact of the allocation of DGs, DSTATCOMs and radial network reconfigurations in the DPNs. This investigation aims to provide complete solutions for DGs, DSTATCOMs locations, capacities, and network topologies under maximum load conditions. This paper uses a nature inspired CTLBO technique for reconfiguration of distribution network and placement of multiple DGs and DSTATCOMs in the distribution systems. The usefulness of the suggested method is validated on the IEEE 33-bus RDS by placing DGs and DSTATCOMs along with network reconfiguration optimally for 33-bus network.

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

i. Siting and sizing of DGs and DSTATCOMs for single-objective to maximize DPNOs benefits.
ii. Impact of simultaneous NR, DGs, and DSTATCOM allocation on network performance.
iii. Seven case studies presented here with maximum loading pattern (1.0 p.u.) for IEEE 33-bus RDS.
iv. Comparative results using CTLBO vs. Gravitational Search Algorithm (GSA), Fireworks algorithm (FWA), Harmony Search Algorithm [HSA], Genetic Algorithm (Imran et al., 2014) and refined genetic algorithm (RGA) considering performance indices: APL, QPL VP improvement, and voltage stability index.

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

3. 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 jth 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.

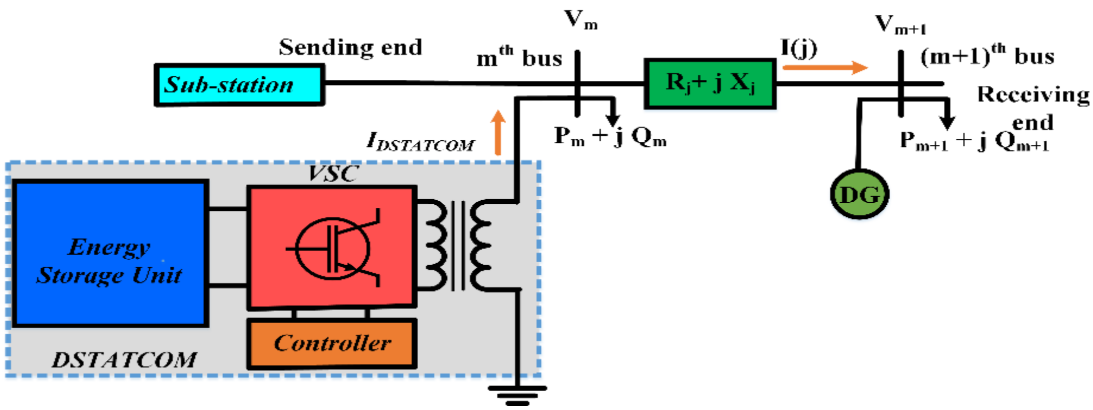

Figure 1 Schematic of a radial distribution network section with DSTATCOM showing line parameters, bus voltages, and load connections.

3.1 Single Objective function (SOF)

The objective of optimally placed DSTATCOMs in RDS is to decrease the network APL, 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,

Table 2. The mathematical descriptions of the single objective functions

Parameter/objectives	Description / Formulation	Equation
Active Power Loss (P_{loss})	$P_{loss} = \sum_{j=1}^{nb} I_j^2 R_j$ Where $I_j = \sum_{k=1}^{m}(P_{Lm}^2 + Q_{Lm}^2)/\|V_m^2\|$	(1)
SOF-1	$F_1 = Minimize\ P_{loss}$	(2)
After DGs and DSTATCOMs Allocation	$P_{Lm} = P_{LDm} - P_{DGm}$ $Q_{Lm} = Q_{LDm} - Q_{DGm}$	(3)
Constraints	Active & Reactive Power Balance: $P_{substation} = P_{loss} + P_D + P_{DGs}$	(4)
	$Q_{substation} + Q_{DSTATCOM} = Q_{loss} + Q_D$	(5)
	$Q_{loss} = \sum_{j=1}^{nb} I_j^2 X_j$	(6)
	Voltage Limits: $0.90\ p.u. \leq V_m \leq 1.05\ p.u.$ $i = 1,2,3,4 \ldots\ldots n$	(7)
	Line Thermal Limits: $I_j \leq I_j^{max}$	(8)
	Injected Active (P_m) and Reactive (Q_m) Power Limits: $P_m^{min} \leq P_m \leq P_m^{max}$ $where\ 0 \leq P_m \leq 3\ MW$; $Q_m^{min} \leq Q_m \leq Q_m^{max}$ $where\ 0 \leq Q_m \leq 3\ MVAr$	(9)

The effect of DGs and 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.

4. 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. In this work, network radiality is tested using a spanning tree methodology based on graph theory, as detailed in (Quadri et al., 2018). 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 to 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 (Quadri et al., 2018).

The Comprehensive Teaching–Learning-Based Optimization (CTLBO) algorithm teaching and learning phase can expressed as Table 3 (Quadri & Bhowmick et al., 2018).

5. Process to find optimal size and location of DGs, DSTATCOMs

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

5.1 Implementation of CTLBO for SOF in distribution network at nominal load

This section describe the implementation of CTLBO algorithm for the allocation of DSTATCOMs to satisfy the various single objective function 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.

Table 3. Overview of the Comprehensive Teaching–Learning-Based Optimization (CTLBO) Algorithm

Phase	Mathematical Representation	Equation
Teaching Phase	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_{Teacher,u} - T_F X_{worst})$	(10)
	$T_F = \left(1/_{rand}\right)^a$	(11)
Learning Phase	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_v - X_w) \quad if\ F(X_v) < F(X_w)$	(12)
	$X_{new,u}^{HMS} = X_{old,u}^{HMS} + rand * (X_w - X_v) \quad if\ F(X_v) > F(X_w)$	(13)

Table 4. Parameters values for Proposed CTLBO algorithm

Parameter	Value
Teaching Factor Rate 'a'	0.2
Solution Vector (SV)	100
Maximum Iteration for Case 1, 2, 3, 4	200
Maximum Iteration for Case 5, 6, 7, 8	500

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,

$$SV = \Big[\underset{DSTATCOM\ Location}{\overleftrightarrow{DSL_1^1 \quad DSL_2^1}} \quad \underset{DSTATCOM\ size}{\overleftrightarrow{DSS_1^1 \quad DSS_2^1}}\Big] \tag{14}$$

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,

$$SV = \Big[\underset{Open\ Switches}{\overleftrightarrow{DST_1^1 \quad DTL_2^1}} \quad \underset{DSTATCOM\ Location}{\overleftrightarrow{DSL_1^1 \quad DSL_2^1}} \quad \underset{DSTATCOM\ size}{\overleftrightarrow{DSS_1^1 \quad DSS_2^1}}\Big] \tag{15}$$

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 (16) as shown below.

$$X_i = X_{i,min} + rand * \left(X_{i,min} - X_{i,max}\right) \quad where\ i = 1,2,3 \dots N \tag{16}$$

SVM (solution vector matrix) is given below,

$$SVM = \begin{bmatrix} X_1^1 & X_2^1 & X_3^1 & \dots & X_{N-1}^1 & X_N^1 \\ X_1^2 & X_2^2 & X_3^2 & & X_{N-1}^2 & X_N^2 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ X_1^{SVS-1} & X_2^{SVS-1} & X_3^{SVS-1} & \dots & X_{N-1}^{SVS-1} & X_N^{SVS-1} \\ X_1^{SVS} & X_2^{SVS} & X_3^{SVS} & & X_{N-1}^{SVS} & X_N^{SVS} \end{bmatrix} \tag{17}$$

Step 2) Generate new solution vector.

After initialization using eqn. (16) of the CTLBO algorithm, SVM is generated according to eqn. (10), (12), & (13) while satisfying all the constraints given in eqn. (4)-(9) with parameters values for proposed CTLBO algorithm in Table 4.

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.

5.2 Algorithm for multi-DGs and DSTATCOMs allocation

The processes used to assign DGs, DSTATCOMs and perform network reconfiguration using the CTLBO algorithm to explore a single objective for network active power loss minimization is shown in Figure 3

6. Case Studies and Results

6.1 Selection of the Number of DSTATCOMS in 33-bus Radial Distribution Network

The optimal allocation of number of DSTATCOMs in 33-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 listed in Table 5 has been analyzed.

For the 33-bus system, as illustrated in Figure 2, the deployment of 1, 2, 3, 4, and 5 DGs results in power loss reductions of 48.7 %, 57.6%, 64.74%, 67.46% and 67.98% respectively. The deployment of 1, 2, 3, 4, and 5 DSTATCOMs results in power loss reductions of 29.14 %, 32.82%, 34.84%, 34.98% and 35.17% respectively. From the graph, it is obvious that the majority of the enhancements in both power loss reduction happens with the allocation of up to 3 DGs. Beyond this, the incremental benefits become marginal. Therefore, for practical and further study are limited up to three DGs and DSTATCOM units.

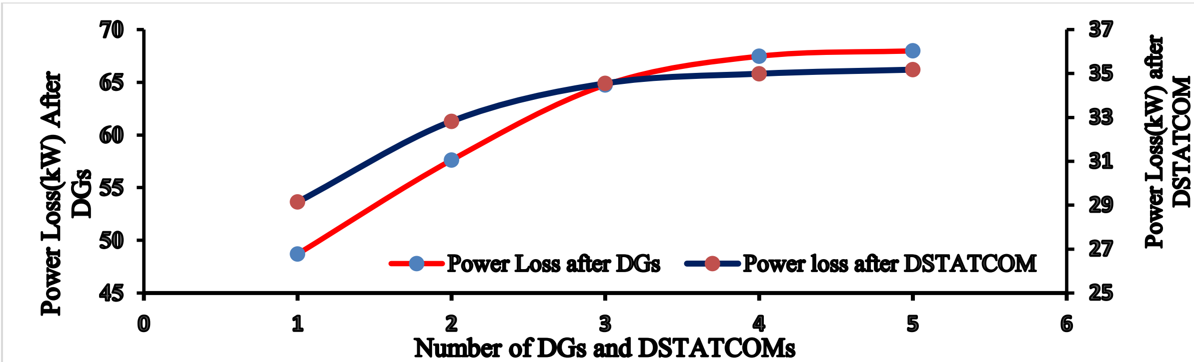

Figure 2 Active power losses after integrating DGs and DSTATCOMs

6.2 DGs and DSTATCOMs allocation along with reconfiguration in Radial Distribution systems

In this section, the IEEE 33-bus RDS is used to allocate numerous DGs and DSTATCOMs allocation along with reconfiguration as efficiently as possible. First, using the CTLBO optimization technique, the optimal positions and sizes of several DGs and DSTATCOMs are determined while taking peak load into account. The SOF taken into consideration for the RDS is used to determine the optimal number of 3 DGS and 3 DSTATCOMs. The usefulness of the suggested approach for numerous DGs and DSTATCOMs deployment in the IEEE 33-bus RDS is confirmed by comparing the results with those of a number of 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 8GB 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: The system's initial condition.
Case 2: Only reconfiguration of the network to reduce active power losses.
Case 3: Allocation of DGs alone.
Case 4: Allocation of DSTATCOMs alone.
Case 5: Allocation of simultaneous DGs and DSTATCOMs.
Case 6: Allocating DGs and reconfiguring the network simultaneously.
Case 7: Allocating DSTATCOM and reconfiguring the network simultaneously Allocation of DSTATCOMs alone.
Case 8: Allocating DGs, DSTATCOM and reconfiguring the network simultaneously.

6.3 IEEE 33-bus RDS

In [42], the comprehensive network specification is provided. It consists of 37 branches, 3 laterals, 33 buses and five tie switches that are kept open. 12.66 kV is the nominal voltage rating. The RDS's nominal load demands are 2.3MVAr and 3.72 MW, respectively. The initial network configuration APL is 202.677 kW while RPL is 135.1409 kVAr. The base case VSI of this initial configuration RDS is 0.667168 (Quadri & Bhowmick et al., 2018). The Network initial base case KVA is 1000 KVA. The finding corresponding to the 33-bus RDS's APL reduction are given in Table 6.

8. Results and Discussion

Table 6 indicates that, in the initial network configuration i.e. Case 1, the network's power loss is 202.667 kW when every tie-switch is open. Case 2 shows that the RDS has the minimal APL of 139.55kW for the APL minimization target when tie-switches 7, 9, 14, 32, and 37 are opened while maintaining the network radiality. Additionally, it is noted that in case 3, placing 3 DGs with appropriate capabilities results in a 64.74% reduction in APL and 63.45% reduction in RPL. Among all the conditions shown in Table 6 and Table 7, Case 8 i.e. simultaneous NR, optimal DGs and DSTATCOMs siting and sizing gives the greatest active power loss reduction i.e. 96.17% and reactive power loss reduction of 95.37% followed by Case 5 where active power loss reduction i.e. 94.27% and reactive power loss reduction of 92.85% as seen in Figure 4. Hence, it is evident that instead of placing type III DGs along with network reconfiguration in the network, it is better to place DGs and DSTATCOMs simultaneously along with reconfigured network for maximizing power loss reduction in the network. It can be seen from Figure 4 that prior to the installation of DGs and DSTATCOMs all active and reactive power requirements are supplied by the substation. However, the introduction of DGs and DSTATCOMs into the network facilitates local fulfilment of active and 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 active and reactive power management. The minimum bus voltage in the network without DGs and DSTATCOMs for Case 1 is 0.91309 p.u. (at 18th bus), as shown in Figure 4. Furthermore, for Case 5, it improved to 0.9922 p.u. (at 8th bus). After 3 DGs and 3 DSTATCOMs along with reconfigured network for Case 8, it rises to 0.99287 p.u. (at 13th bus). The complete voltage profile of 33-bus radial distribution network for all the eight cases shown in Figure 5. It is evident from the convergence characteristics of CTLBO algorithm as shown in Figure 6 (a) that the best solutions obtained for case 2, case 3 and case 4 within 200 iterations while the best solutions obtained for case 5, case 6, case 7 and case 8 within 500 iterations as shown in Figure 6 (b).

Table 5. Performance Indices for DSTATCOM allocation evaluation impact on RDS (Rao et al., 2013)

Performance Indices	Formulation
Active Power Loss Reduction (APLR) (%)	$APLR = \left(\frac{APL_b - APL_{DSTATCOM}}{APL_b}\right) X\,100$
Reactive Power Loss Reduction (RPLR) (%)	$RPLR = \left(\frac{RPL_b - RPL_{DSTATCOM}}{RPL_b}\right) X\,100$
Voltage Stability Index (VSI)	$VSI_{m+1} = \lvert V_m \rvert^4 - 4\{P_{m+1}X_j - Q_{m+1}R_j\}^2 - 4\{P_{m+1}R_j + Q_{m+1}X_j\}\lvert V_m \rvert^2$

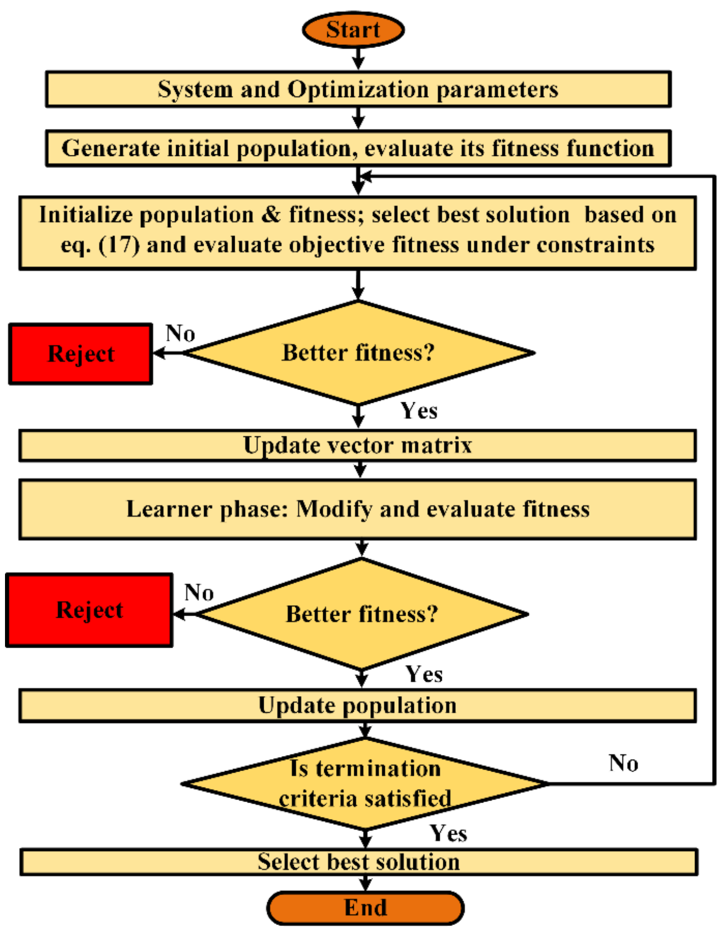

Figure 3 Flowchart of CTLBO-based DG and DSTATCOM placement for minimizing power losses.

9. Comparative Analysis Discussion

It is evident from the Table 8, that CTLBO gives better result for Case 2, Case 4 and Case 6 in comparison to GSA (Salkuti et al.,2022), FWA (Imran et al., 2014), HSA, GA and RGA (Rao et al., 2013) algorithms-based solutions. In Table 9, it is obvious that CLTBO having better result i.e. 94.27% and 96.17% for Case 5 and Case 8 respectively in comparison to GSA (Salkuti et al., 2022) algorithms-based solutions which is 68.43% and 66.89% for Case 5 and Case 8 respectively.

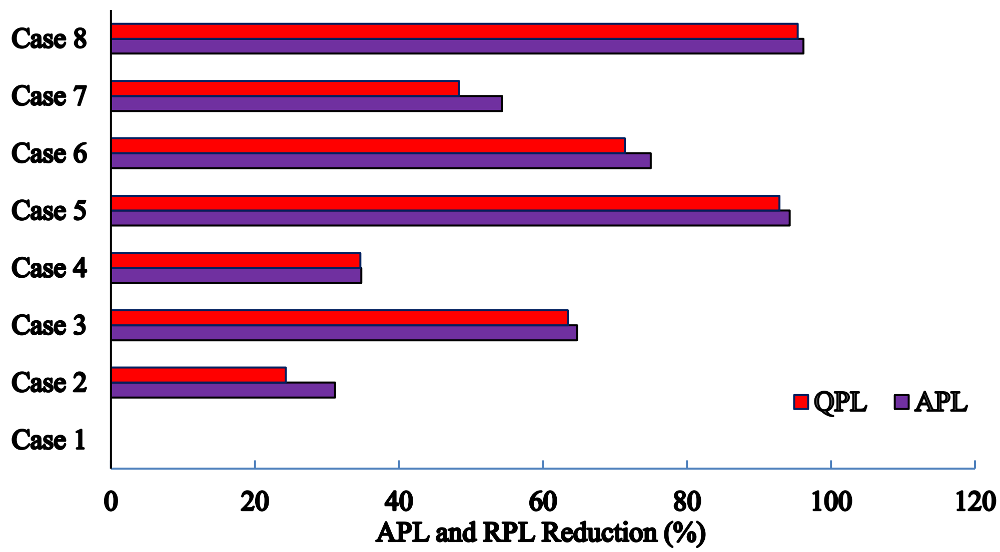

Figure 4 Active and reactive power losses in the 33-bus distribution system for different cases, showing effects of DGs, DSTATCOMs, and network reconfiguration.

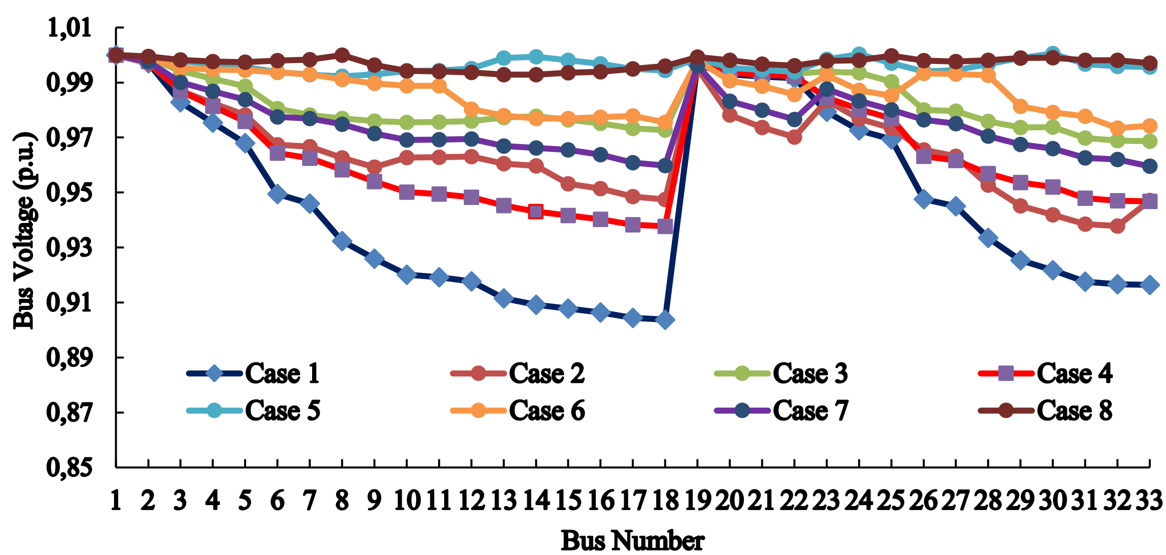

Figure 5 Voltage profile of the 33-bus radial distribution network for all eight cases, showing improvements after DG, DSTATCOM placement, and network reconfiguration.

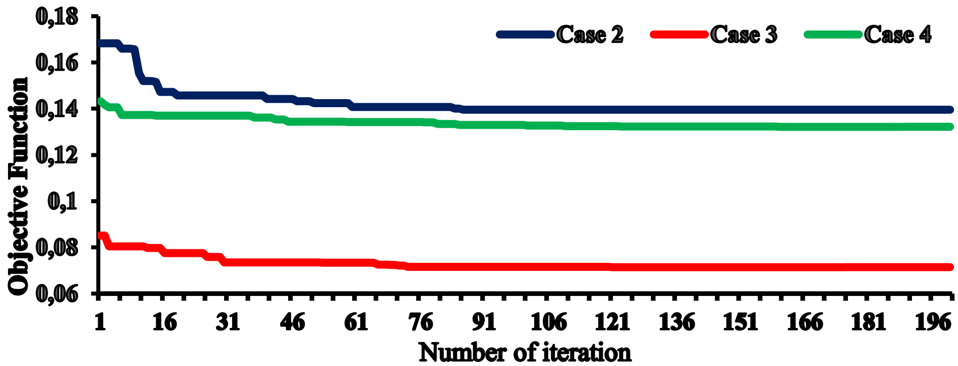

Figure 6 (a) Convergence Characteristics of CTLBO algorithm for case 2, case 3 and case 4

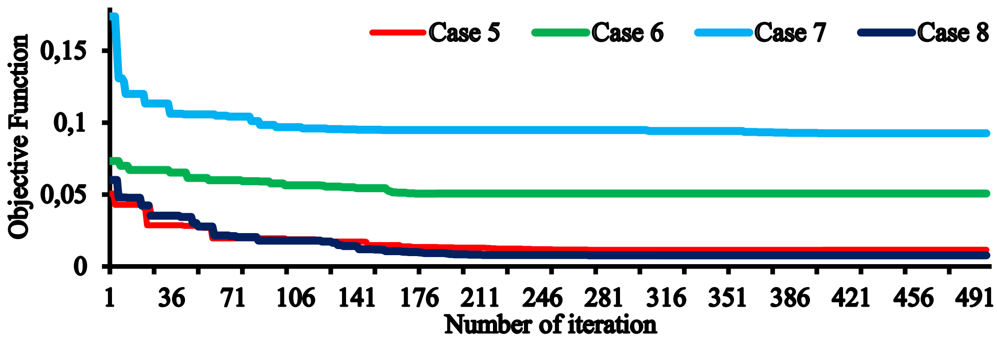

Figure 6 (b) Convergence Characteristics of CTLBO algorithm for case 5, case 6, case 7 and case 8

Table 6. Simulation results using proposed method for 33-bus RDS for power loss minimization

	Case 1	Case 2	Case 3	Case 4
	Base Case	Only RE	Only DG	Only DSTATCOM
Open Switch	33, 34, 35, 36, 37	7, 9, 14, 32, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
DG size (MW) /	-	-	0.7539789(14)	-
(Bus No.)	-	-	1.0994388(24)	-
	-	-	1.071416(30)	-
DSTATCOM size	-	-	-	0.3786869 (13)
(MVAr) /(Bus	-	-	-	0.5442038 (24)
No.)	-	-	-	1.036668 (30)
APL (kW)	202.677	139.551	71.457	132.1724
QPL (kVAr)	135.140	102.304	49.3908	88.3305
VI (p.u.)	0.69511 (18)	0.77359 (27)	0.88039(33)	0.77324(18)
Vmin (p.u.)	0.91309 (18)	0.93782 (32)	0.96865(33)	0.93773(18)

Table 7. Simulation results using proposed method for 33-bus RDS for power loss minimization

	Case 5	Case 6	Case 7	Case 8
	Only DG and DSTATCOM	Both RE and DG	Both RE and DSTATCOM	Both RE, DG and DSTATCOM
Open Switch	33, 34, 35, 36, 37	11, 28, 31, 33, 34	7, 9, 14, 32, 37	5, 13, 20, 26, 35
DG size (MW) /	0.747697/ (14)	0.956938/ (7)	-	1.1002 / (8)
(Bus No.)	1.078236/ (24)	0.722951 / (17)	-	1.1285 / (25)
	1.048484/ (30)	1.279589/ (25)	-	0.82439 / (32)
DSTATCOM	0.365476/ (13)	-	0.9595211/ (8)	0.56978 / (8)
size (MVAr) /	0.518525/ (24)	-	0.5239252/ (24)	0.41614 / (24)
(Bus No.)	1.014679/ (30)	-	0.96284007/ (30)	1.0631 / (30)
APL(kW)	11.61465	50.717546	92.5846329	7.758331
QPL (kVAr)	9.665727	38.720157	69.8161129	6.2627060
VI (p.u.)	0.969266 (8)	0.8976197 (16)	0.83747914 (16)	0.97206(31)
Vmin (p.u.)	0.992226 (8)	0.97343637(32)	0.959521149 (33)	0.99287 (13)

Table 8. Comparison of Simulation results using CTLBO algorithm for 33-bus RDS

		Case 2	Case 3	Case 6
		Only RE	Only DG	Only RE and DG
CTLBO	Open Switch	7, 9, 14, 32, 37	33 34 35 36 37	11, 28, 31, 33, 34
	DGsize (MW)	-	2.92483	2.959479
	APL(kW)	139.551	71.457	50.717
	Vmin (p.u.)	0.93782 (32)	0.96865(33)	0.97343 (32)
GSA (Salkuti et al.,2022)	Open Switch	7, 9, 14, 28, 37	33, 34, 35, 36, 37	7, 10, 14, 32, 34
	DGsize (MW)	-	2979.4	3051.8
	APL(kW)	138.62	78.16	62.93
	Vmin (p.u.)	0.9412 (32)	0.9653 (33)	0.9692 (32)
FWA **(**Imran et al., 2014)	Open Switch	7, 9, 14, 28, 32	33, 34, 35, 36, 37	7, 11, 14, 28, 32
	DGsize (MW)	-	1.7938	1.6841
	APL(kW)	139.98	88.68	67.11
	Vmin (p.u.)	0.9413	0.9680	0.9713
HSA (Rao et al., 2013)	Open Switch	7, 9, 14, 32, 37	33, 34, 35, 36, 37	7, 10, 14, 28, 32
	DGsize (MW)		1.7256	1.6684
	APL(kW)	138.06	96.76	73.05
	Vmin (p.u.)	0.9342	0.9670	0.9700
GA (Rao et al., 2013)	Open Switch	9, 28, 33, 34, 36	33, 34, 35, 36, 37	7, 10, 28, 32, 34
	DGsize (MW)		1.6044	1.9633
	APL(kW)	141.60	100.1	75.13
	Vmin (p.u.)	0.9310	0.9605	0.9677
RGA (Rao et al., 2013)	Open Switch	7, 9, 14, 32, 37	33, 34, 35, 36, 37	7, 9, 12, 27, 32
	DGsize (MW)		1.777	1.774
	APL(kW)	139.46	97.60	74.32
	Vmin (p.u.)	0.9315	0.9687	0.9691

Table 9. Comparison of Simulation results using CTLBO algorithm for 33-bus RDS

		Case 5	Case 7	Case 8
		Only DG and DSTATCOM	Both RE and DSTATCOM	Both RE, DG and DSTATCOM
CTLBO	Open Switch	33, 34, 35, 36, 37	7, 9, 14, 32, 37	5, 13, 20, 26, 35
	DGsize (MW)	2.874417	-	3.05309
	DSTATCOM Size (KVAr)	1.89868	2.44628637	2.04902
	APL(kW)	11.61465	92.5846	7.758331
	Vmin (p.u.)	0.992226 (8)	0.95952 (33)	0.99287 (13)
GSA(Salkuti et al.,2022)	Open Switch	33, 34, 35, 36, 37	7, 14, 28, 33, 36	7, 11, 26, 32, 33
	DGsize (MW)	3040.7	-	3108.4
	DSTATCOM Size (KVAr)	1125.8	1125.8	1182.6
	APL(kW)	63.96	78.32	67.11
	Vmin (p.u.)	0.9649(18)	0.9610(18)	0.9735(18)

10. Merits and Limitations of CTLBO Algorithm

The proposed CTLBO algorithm gives the advantages of metaheuristic technique by incorporating the better exploration and fast convergence capability. This hybrid approach demonstrates, enhanced performance in the allocation of Distributed Generators (DGs), DSTATCOMs 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 Gravitational Search Algorithm (GSA), Fireworks algorithm (FWA), Harmony Search Algorithm [HSA], Genetic Algorithm and Refined genetic algorithm (RGA) (Rao et al., 2013) 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 DGs and DSTATCOMs allocation and network reconfiguration are listed in Table 4.

11. Conclusion

This study recommends an optimization framework based on the TLBO algorithm for simultaneous network reconfiguration, Distributed Generations and optimal allocation of Distribution Static Compensator in IEEE 33-bus RDS. Simulation results validate that the simultaneous implementation of network reconfiguration, Distributed Generations 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, DGs and DSTATCOM units is essential for minimizing power loss. Comparative analysis confirms that the proposed CTLBO-based approach attains superior results in terms of power loss when, benchmarked against several existing soft computing techniques. Since, the CTLBO algorithm in this work has been applied to deterministic loading conditions with single objective under various system constraints, it holds substantial potential for extension to distributed network planning. Such applications involve a high number of decision variables and constraints, mainly due to the inherent uncertainties associated with distributed energy resources and real-time load fluctuations.

Nomenclature

DNO	Distribution Network Operator	**FWA**	Fireworks algorithm
DGs	Distributed Generations	**FWA**	Harmony Search Algorithm
CTLBO	Comprehensive Teaching-Learning based Optimization	**NR**	network reconfiguration
DSTATCOMs	Distribution Static Synchronous Compensators	**RE**	Reconfiguration
RDS	Radial distribution systems	**GSA**	Gravitational Search Algorithm
GA	Genetic Algorithm	**RGA**	Refined genetic algorithm
DS	distribution systems	**SOF**	Single Objective Function
VP	Voltage Profile	**APLR**	Active Power Loss Reduction
RPL	Reactive Power Loss	**RPLR**	Reactive Power Loss Reduction
APL	Active Power Loss	**FACTS**	Flexible Alternating Current Transmission System
VSI	Voltage Stability Index	P_{loss}	Active power loss
R_j	Resistance of j^{th} branch	X_j	Reactance of j^{th} branch
V_m	m^{th} node voltage	I_j	Current through j^{th} branch
P_D	Total active power demand	Q_D	Total reactive power demand
P_{Lm}	Total active power at node 'm'	Q_{Lm}	Total reactive power at node 'm'
P_{LDm}	Total active power load demand at node 'm'	Q_{LDm}	Total reactive power load demand at node 'm'
P_{DGm}	Total active power injected by DGS at node 'm'	Q_{DGm}	Total reactive power injected by DGS at node 'm'
P_{DGs}	Total active power injected by DGS	$Q_{DSTATCOM}$	Total reactive power injected by DSTATCOMs
$X_{new,u}^{HMS}$	New variable value of u^{th} solution vector	$X_{old,u}^{HMS}$	Old variable value of u^{th} solution vector
$rand$	Random variable between '0' and '1'	X_{worst}	Worst solution variable vector of previous iteration
X_v	Variable of randomly selected v^{th} solution vector	X_w	Variable of randomly selected w^{th} solution vector
$F(X_v)$	Fitness value of v^{th} solution vector		

Declaration of Ethical Standards

As the author of this study, I declare that all ethical standards complied.

Credit Authorship Contribution Statement

I. A. Quadri: writing—original draft, visualization, software, methodology, investigation, formal analysis, data curation, validation, project administration;

Declaration of Competing Interest

Not applicable

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Availability of data and materials

All the relevant data is included in the manuscript.

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