

# A novel approach for Volt-VAR optimization in Radial Distribution System Using Modified Tuna Swarm Optimization

Deepak Porwal, Sanjiv Kumar Jain, Ashish Kumar Soni, Manoj Fozdar, and Rajive Tiwari

**Abstract**—Distributed Generation integrated with Volt-VAR Optimization (VVO) is crucial for dependable and cost-effective distribution grid operations. Energy management strategies are essential to ensure demand, enhance system performance, and guarantee the proper operation of renewable energy-based hybrid systems. In recent years, DG has rapidly gained recognition for its potential to optimize power demands. This work proposes the Modified Tuna Swarm Optimization (MTSO) based swarm intelligence technique to redesign the Radial Distribution network (RDN) for voltage profile improvement and power losses reduction. With 0.9742 p.u. voltage, the proposed MTSO has successfully reduced active and reactive power losses to 105.47kW and 88.25kVAR, respectively in 33-bus system. With 0.9913p.u. voltage, the suggested MTSO reduced the 69-bus's active and reactive power losses to 68.47kW and 47.25kVAR, respectively.

**Keywords**—Energy storage systems(ESS); Network Reconfiguration; Radial Distribution Network; Volt-VAR optimization

## I. INTRODUCTION

VOLT/VAR optimization involves synchronizing VAR control devices and voltage regulating equipment, including substation On Load Tap Changers(OLTC) and voltage regulators(VRs), to achieve one or more predefined objectives like, network loss reduction, voltage profile enhancement keeping the operational constraints maintained like voltage magnitude profile and line flow limits[1-2]. The optimal position and alteration of DG size will add greater advantage like improving reliability, voltage control through cost, voltage stability and network loss reduction [3-4]. The proper placement and alteration of DG size in electric distributed network is a compound and wide range Mixed Integer Non-linear Programming (MINLP) issue [5]. The issue to DG placement and size alteration has been resolved in various ways. These solved ways are mainly categorized into two overall types. 1<sup>st</sup> method is by the optimization techniques. Ex Ant Lion Optimization Algorithm (ALOA) and Backtracking Search Optimization Algorithm (BSOA). The prime goal intends to decrease the line losses with regards to different conditions such as DG real power generation limit, voltage limit, DG position constraint, and power balance constraint. 2<sup>nd</sup> method is the analytical technique [6]. For example, the analytical expression

and the technique elicited from the particular loss formula are put forward to compute the best optimal location and alteration

DG size [7]. In the viewpoint of developing algorithms, the convergence is not taken into accounts as a result of the non-iterative nature of the analytical optimization methods that falls under classic optimization techniques. But the different ceaseless parameters in the optimization course are repeatedly matched in an algorithm and that improves the calculation cost and reduces the computational performance [8].

In distinct distribution grids various techniques are used to optimally place DGs. The loss of power depreciation was accomplished through suitable placement and altering size of DGs in IEEE 75, 16 and 37-bus systems utilizing genetic algorithm(GA) [9]. Total power loss in IEEE 69 and 33- bus networks is reduced by suitable position and size alteration of DGs utilizing sensitivity test. But not a single-method is successful in the proper position of DG to tact all issues at once [10-12]. A hybrid algorithm PSO(Particle Swarm Optimization) and SQP(Sequential Quadratic Programming) was utilized to decrease the time with enhanced convergence [13]. It is observed that the suggested technique overcome the voltage deflection, power loss, network loss and convergence successfully. To ensure dependable and effective operation of distribution systems, sophisticated optimization approaches must be developed because the unpredictable and intermittent nature of DG outputs might result in voltage fluctuations and power quality problems[14-20].

In order to optimize the technical and financial advantages of VVO, the suggested method seeks to identify the best positions, sizes, and operating conditions for Energy storage systems while guaranteeing adherence to operational and grid restrictions. Utilities may minimize energy losses, lower peak demand, and increase overall system efficiency by coordinating DG and ESS outputs with VVO. This will ultimately result in a more resilient and sustainable energy infrastructure[21-25].

Following are the major contribution of this paper,

- This work is unique in that it suggests optimally placing the ESS by utilizing the recently discovered Tuna Swarm Optimization technique to solve issues of voltage instability and power loss mitigation.

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- The MTSO was evaluated against IEEE 33 and 69 RDN to determine its efficacy. It gives better results compared to other existing traditional methods.

The following describes the structure of this study: Arithmetic equations are defined using the suggested MTSO approach in Section 2. The results analysis comparison is presented in Section 3. Lastly, the conclusion part is discussed in Section 4.

## II. PROPOSED METHOD

This paper's main goal is to determine the best suitable way to control the ESS in order to enhance the power system's performance in terms of voltage stability and power loss. Fig. 1 shows the suggested approach's block diagram.

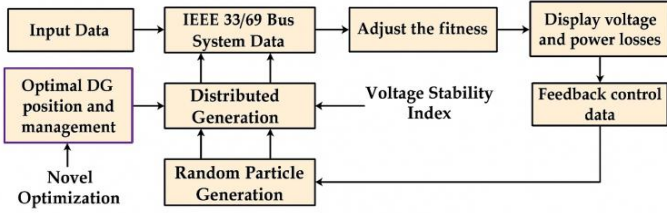


Fig. 1. Block diagram representation of MTSO based optimal ESS management

Step 1: Initialize the optimization process with pre-defined common control variables.

Step 2: Read bus and line data for the IEEE-33/69 bus test distribution system.

Step 3: Generate random particles and perform load flow analysis to evaluate their feasibility.

Step 4: Calculate the fitness function values (power loss and voltage profile) for each particle.

Step 5: Identify the particle with the best fitness values and update the system data for the next consecutive iteration.

Step 6: Repeat the power flow analysis using the optimized algorithm to determine the best fitness values.

Step 7: For ESS management, randomly select a location and evaluate its fitness values. Evaluate the optimal location of ESS to control real and reactive power values.

Step 8: Using the proposed method, optimally manage ESS with the best values obtained, and evaluate multi-objectives with proper placement of DG.

### A. Modified Tuna Swarm Optimization

With the present methods, huge search areas, time requirements, and reaching optimal solutions remain challenging issues in large systems. In response to the current algorithm development, this paper suggests an MTSO based on search space reduction for every iteration phase. The visual representation of multi-objective functions in RDS is shown in Fig. 2.

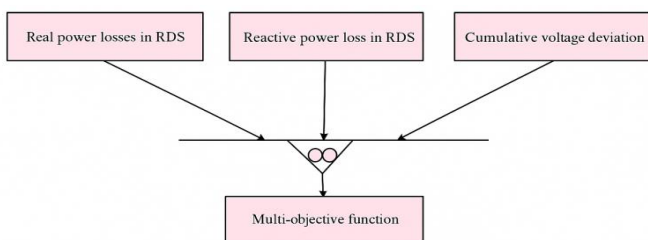


Fig. 2. Representation of Multi-objective function

### B. Mathematical Formula

The mathematical derivation of the suggested algorithm is thoroughly discussed in this section.

#### Initialization

Like the majority of swarm-based meta-heuristics, MTSO begins the optimization procedure by uniformly generating beginning populations at random in exploring space,

$$X_i^{int} = rand \cdot (ub - lb) + lb, \quad i = 1, 2, \dots, N_p, \quad (1)$$

where  $X_i^{int}$  is the  $i^{th}$  initial individual,  $N_p$  denotes tuna population number,  $l_b$  and  $U_b$  are the lower and upper limits of the search area, and  $rand$  is a random vector distributed uniformly with a range of 0 to 1.

#### Spiral Foraging

The calculation for the spiral foraging method is as follows, based on the aforementioned guidelines:

$$X_i^{t+1} \begin{cases} \alpha_1 \cdot (X_{best}^t + \beta \cdot |X_{best}^t - X_i^t|) + \alpha_2 \cdot X_i^t, & i = 1, \\ \alpha_1 \cdot (X_{best}^t + \beta \cdot |X_{best}^t - X_i^t|) + \alpha_2 \cdot X_{i-1}^t, & i = 2, 3, \dots, NP, \end{cases} \quad (2)$$

$$\alpha_1 = a + (1 - a) \cdot \frac{t}{t_{max}}, \quad (3)$$

$$\alpha_2 = (1 - a) - (1 - a) \cdot \frac{t}{t_{max}}, \quad (4)$$

$$\beta = e^{bl} \cdot \cos(2\pi b), \quad (5)$$

$$l = e^{3 \cos((t_{max} + 1/t) - 1)\pi}, \quad (6)$$

where  $X_i^{t+1}$  is the  $i^{th}$  individual  $(t + 1)^{th}$  iteration,  $X_{best}^t$  refers current optimal individual. At first phase, the amount to which tuna tracks the optimal individual solution and the previous available individual is determined by the constants  $t$ ,  $t_{max}$  and  $b$ .  $\alpha_1$  and  $\alpha_2$  control the weight coefficients which regulate the propensity of individuals tunas to move closer to the ideal private and the earlier individualized, respectively.

The spiral search allows MTSO to travel the globe and eases for each individual to search a larger region. The calculation details are as follows:

$$X_i^{t+1} = \begin{cases} \alpha_1 \cdot (X_{rand}^t + \beta \cdot |X_{rand}^t - X_i^t|) + \alpha_2 \cdot X_i^t, & i = 1, \\ \alpha_1 \cdot (X_{rand}^t + \beta \cdot |X_{rand}^t - X_i^t|) + \alpha_2 \cdot X_{i-1}^t, & i = 2, 3, \dots, NP, \end{cases} \quad (7)$$

where  $X_{rand}^t$  refers randomly generated reference point.

MTSO changes the spiral foraging based reference points from random to ideal individuals as the number of iterations grows. Lastly, the spiral foraging method's full computational structure looks like this:

$$X_i^{t+1} = \begin{cases} \alpha_1 \cdot (X_{rand}^t + \beta \cdot |X_{rand}^t - X_i^t|) + \alpha_2 \cdot X_i^t, & \text{if } rand < \frac{t}{t_{max}} \\ \alpha_1 \cdot (X_{rand}^t + \beta \cdot |X_{rand}^t - X_i^t|) + \alpha_2 \cdot X_{i-1}^t, & \text{if } rand \geq \frac{t}{t_{max}} \end{cases} \quad (8)$$

Parabolic Foraging

Tunas work together to create both a spiral and a parabolic pattern when feeding. Tuna creates a parabolic form by utilizing food as their reference point. Tuna also search their nearby surroundings for nourishment. These two techniques are applied simultaneously, assuming that the probability of their selection for each is 50%. The following are the calculation's details:

$$X_i^{t+1} = \begin{cases} X_{best}^t + rand.(X_{best}^t - X_i^t) + TF.P^2.(X_{best}^t - X_i^t), & \text{if } rand < 0.5, \\ TF.P^2.X_i^t, & \text{if } rand \geq 0.5, \end{cases} \quad (9)$$

$$P = \left(1 - \frac{t}{t_{max}}\right)^{(t/t_{max})} \quad (10)$$

where *TF* refers random number 1 or -1.

Fig. 3 provides a detailed explanation of the MTSO technique.

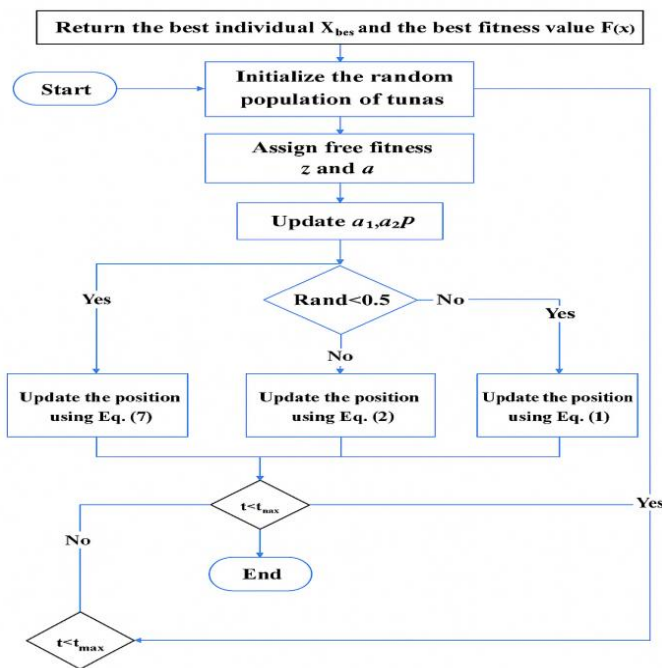


Fig. 3. Flowchart of MTSO

III. RESULT AND DISCUSSION

This study utilized MATLAB 2024a, running on a Windows operating system with a 2.7 GHz i7-7500U CPU and 16 GB of RAM, to achieve optimal ESS placement. The efficacy of the proposed method is tested on the IEEE-33 and 69-bus systems, demonstrating its in achieving optimal network reconfiguration.

A. Performance Analysis of power factor scenario

Table I summarizes DG performance at unity PF, highlighting the improvements offered by the suggested technique. Notably, the incorporation of DGs at lagging and unity Power Factor (PF) results in reduced losses compared to the base case model without DG. The voltage magnitude profile at unity PF is depicted in Fig. 4.

TABLE I  
PERFORMANCE ANALYSIS OF DG AT UNITY PF

Parameters	Without DG	Existing methods with DG	Proposed Methodology
Location	--	30	25
DG rating (kW)	--	1542.7	1412.6
Minimum bus voltage(p.u.)	0.904	0.925	0.935
active power loss(kW)	211	125.166	116.1102

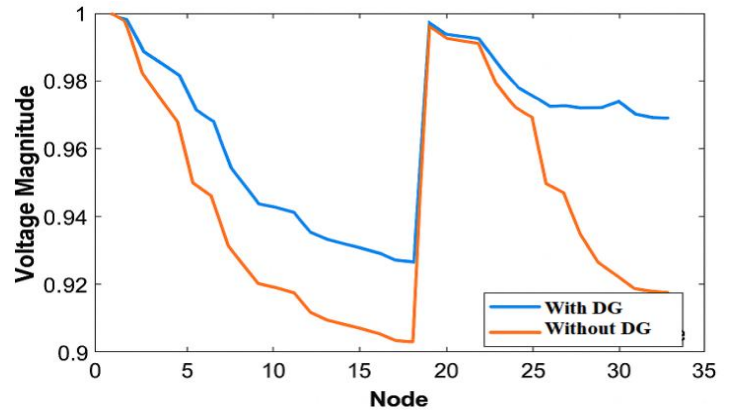


Fig. 4. Voltage Magnitude comparison without and with DG at unity PF

B. Results Analysis of 33-bus System

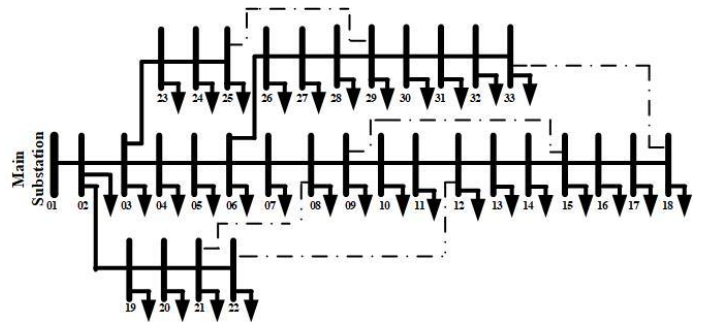


Fig. 5. Single line diagram representation of 33-bus System

Fig. 5 shows the single-line representation of the IEEE-33 bus system. The simulated results are analyzed using the suggested methodology.

Case test 1: Only one DG is examined.

Case test 2: Two DGs are examined.

Case test 3: Three DGs are under investigation.

Case test 4: Three ESS are taken into account.

Case 1 is investigated utilizing only 1 DG incorporated in the 33-bus system, yielding a suggested model that is lower than the previous DG. The performance analysis of the case test 1 results study is shown in Table II.

TABLE II  
PERFORMANCE ANALYSIS OF TEST CASE 1

Case test 1	Without DG	Proposed Methodology
Location	-----	33
Rating	-----	0.15 MW
Active power loss	202.68 kW	106.41 kW
Percentage loss reduction	-----	47.49%

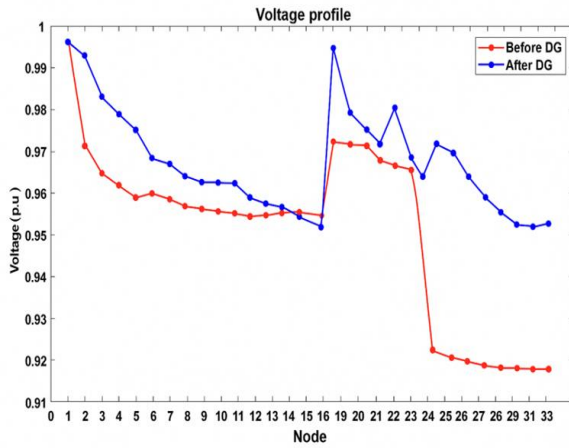


Fig. 6. Voltage profile for test case 1

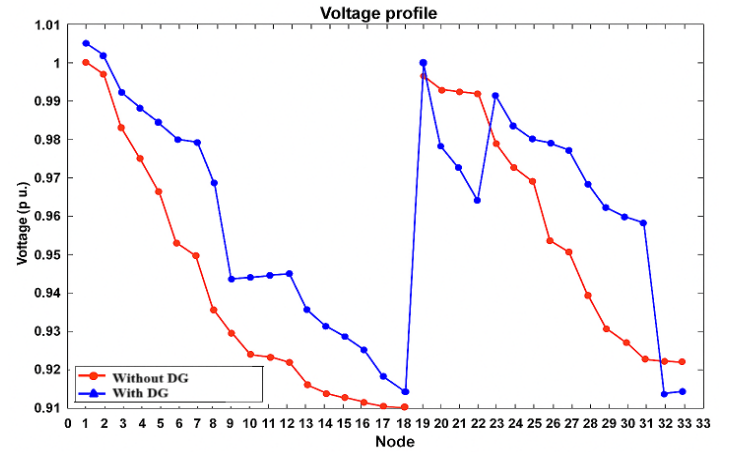


Fig. 8. Voltage Magnitude profile of case 3

The behavior of case test 2 performance with 2 DGs results is shown in Table III. A graphical representation of the voltage profile of the case 2 investigation is shown in Figure 7.

TABLE III  
TEST PERFORMANCE ANALYSIS OF CASE 2

Case test 2	Without DGs	Proposed Methodology
Active power loss	202.68 kW	96.73 kW
Reduction	-----	52.27 %
Minimum voltage	0.91075pu	0.911981pu
Size	-----	1.13 MW (25, 30)

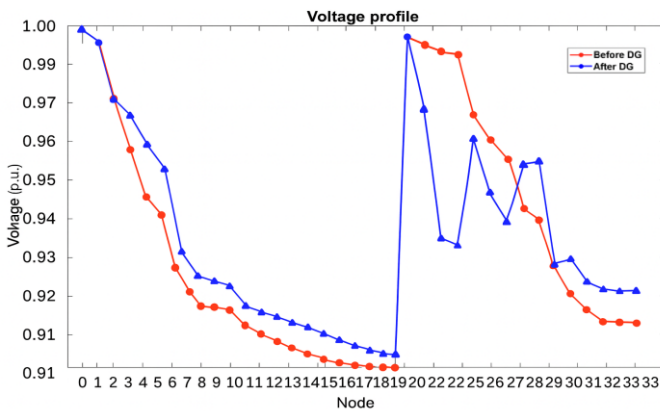


Fig. 7. Voltage stability for case 2

For analyzing before DG and proposed results in case 3, passed 33 bus system with DG and its behavior is presented in Table IV. Fig. 8 illustrates the voltage stability graph.

TABLE IV  
PERFORMANCE ANALYSIS OF CASE 3

Test case 3	Without DGs	Proposed Methodology
Size (position of DG)	-----	1.1251 (21), 1.2433 (33), 0.2385 (29)
Active power loss	202.68 kW	57.27 kW
Percentage loss reduction	-----	71.74 %
Voltage	0.91075 p.u.	0.9847p.u.

TABLE V  
COMPARATIVE ANALYSIS TABLE FOR ESS

Parameters	Without ESS	With ESS
Active power loss	202.68 kW	105.47 kW
Percentage loss reduction	-----	47.96 %
Rating(ESS location)	-----	1.10 kW 1.09 kW 1.13 kW (31, 15, 22)

The network losses are the main reason for the exaggerated ESS position and sizing. The maximum candidate buses in this study are initialized or modified using the suggested methodology, which determines the findings as minimized, ranging from 202.68 KW to 105.47 KW, or 47.96% of the total loss reduction.

### C. Results of 69-bus System

Standard IEEE-69 bus test distribution system is taken in this paper as shown in fig.9. It has 68 lines with bus 1 connected as main substation. Base voltage of 12.66kV and base MVA of 10MVA are taken. The total active and reactive power load of system is 3801.85kW and 2694.6kVAr respectively.

The simulation results are contrasted with the other alternative approaches results to validate the presentation of the suggested strategy.

Case test 1: Only 1 DG is examined.

Case test 2: 2 DGs are examined.

Case test 3: 3 DGs are under investigation.

Case test 4: 3 ESSs are taken into account.

In the first scenario, one DG bus system is used; The performance results are shown in Table VI. The results of case test 1 are shown in Fig. 10.

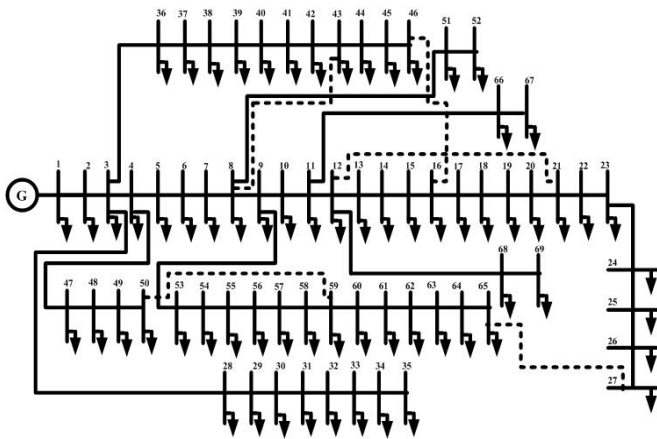


Fig. 9. Representation of 69-bus system

TABLE VI  
PERFORMANCE ANALYSIS OF CASE 1

Parameters	Base case scenario	Proposed methodology
Active power loss	224.98 kW	116.51 kW
Percentage loss Reduction	-----	48.21 %
Size	-----	0.11 MW
Minimum voltage(p.u.)	0.905 p.u.	0.943 p.u.

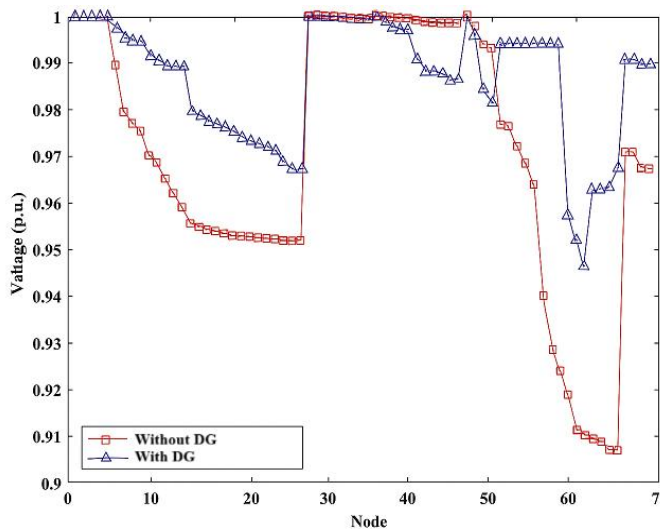


Fig. 10. Voltage magnitude profile for test case 1

For case test 2, the Type 2 DG is employed through 69 bus system. The outcome analysis of case 2 are shown in Table VII. Fig. 11 illustrates the result of case test 2.

TABLE VII  
PERFORMANCE ANALYSIS OF CASE 2

Parameters	Base case values	Proposed Methodology
Active power loss	224.98 kW	98.932 kW
Percentage loss reduction	-----	56.02 %
Minimum voltage(p.u.)	0.90919 (p.u.)	0.94693(p.u.)
Rating (Location DG)	4 kW	4 kW (39, 51)

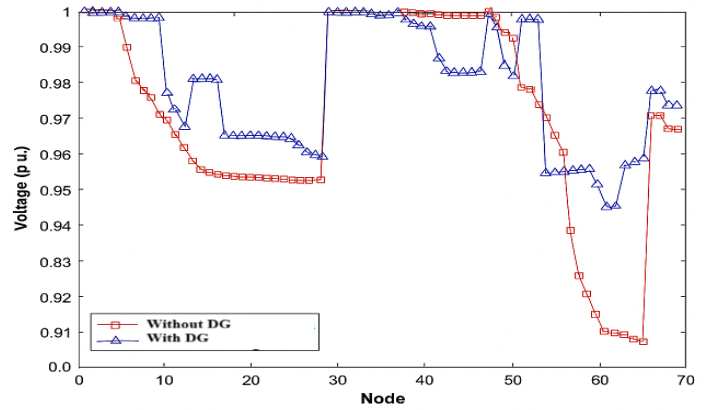


Fig. 11. Voltage profile for test case 2

The optimal Distributed Generation (DG) magnitude with network reconfiguration in IEEE 69 Radial Distribution Network is presented in Table VII. The results indicate that buses 39 and 51 are the most suitable positions for DG placement, with an optimal magnitude of 0.4 MW. This strategic placement of DGs yields a major reduction in real power loss, decreasing by 56.02% from 224.6 kW to 98.9326 kW. Fig. 11 illustrates the voltage stability graph, demonstrating the efficiency of the suggested technique in obtaining the optimal location and capacity sizing of DG units. Notably, the IEEE 69 system with multiple DG units exhibit reduced power loss compared to the base configuration.

TABLE VIII  
PERFORMANCE ANALYSIS OF CASE 3

Parameters	Base Values	Proposed
Active power loss	224.98 kW	74.26 kW
Reduction	-----	66.99 %
Rating (DG location)	-----	0.4 MW (23, 44, 55)
Minimum voltage(p.u.)	0.909p.u.	0.9721p.u.

Table VIII shows the ideal DG size in IEEE 69-Radial distribution network. The voltage magnitude is shown in fig. 12. Buses 23, 44, and 55 have been identified as the best bus positions for DG placement, having 0.4 MW magnitude. As a result, active power loss drops by 66.99%, from 224.6 to 74.2615 kW. Table IX shows the comparative table for ESS in 69 bus system.

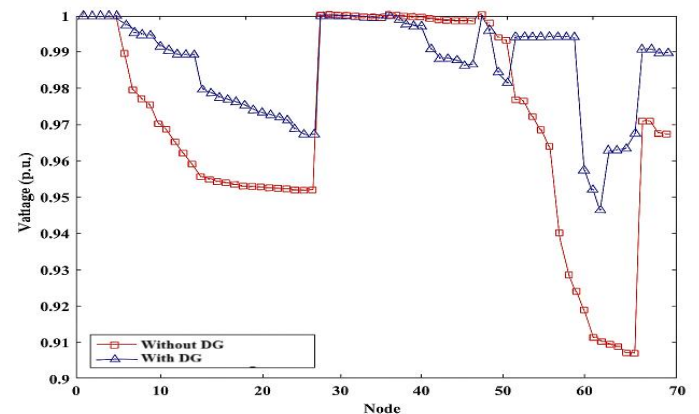


Fig. 12. Voltage profile analysis for test case 3

TABLE IX  
COMPARATIVE TABLE FOR ESS IN 69 BUS SYSTEM

Test scenario	Without ESS	With ESS
Active power loss	224.9804 kW	68.47 kW
Percentage loss reduction	-----	69.56 %
Size (position of ESS)	-----	0.9 kW 1.22 kW 1.05 kW (45, 37, 58)

TABLE X  
COMPARATIVE ANALYSIS OF EXISTING TECHNIQUES

Scenario	MOPSO(Multi-Objective Particle Swarm Optimization) method [26]	Proposed MTSO
Case 1	Voltage magnitude= 0.942p.u.  Active power loss = 99.35kW Percentage loss reduction = 55.85 %	Voltage = 0.959p.u.  Active power loss = 92.585kW  Reduction = 61.19%
Case 2	Voltage = 0.961p.u.  Loss = 51.30 kW Reduction = 77.2 %	Voltage = 0.956p.u.  Loss = 45.1239 kW Reduction = 79.19%
Case 3	DG rating (location) = 1.07(61), 0.36 (60), 0.46 (62) Voltage = 0.974p.u. Loss = 40.30 kW Reduction = 82.08 %	DG rating (location) = 0.4 (23), 0.4 (44), 0.4 (55) Voltage = 0.9629p.u. Loss = 32.5833 kW Reduction = 89.46 %

Table X presents the entire process for the comparison analysis. A number of ESS's voltage stability is displayed. According to Table XI, the suggested approach lowers the active power loss from 224.98 kW to 30.10 kW, resulting in a 93.9529 percent reduction in total loss. Table XII presents the comparative study of ESS.

TABLE XI  
ANALYSIS WITH MULTIPLE DG UNITS

Case 4	Existing Method [21]	Proposed
Voltage	0.9673 pu	0.97276 pu
Loss	224.9804 KW	30.108 KW
Reduction	-----	93.9529 %
Size (position of DG)	0.13 (24), 0.45 (45), 0.77 (58)	0.2, 0.172, 0.824 (23, 53, 61)

TABLE XII  
ASSESSMENT FOR MULTIPLE DG UNITS

Scenario	Existing Firefly Algorithm [16]	Existing WOA [19]	Proposed
Position	7, 22	7, 15	35, 59
Size (MW)	0.37 & 0.72	0.67, 1.50	0.31, 0.59
Loss (kW)	51.42	51.15	48.23

#### IV. CONCLUSION

This paper presented a novel optimization technique for voltage profile enhancement and power loss reduction in radial distribution system. It focused on developing and evaluating an optimal Volt-Var strategy for total real power loss minimization in radial distribution networks. A Modified Tuna Swarm Optimization (MTSO)-based optimal strategy was proposed to minimize overall active power losses while handling the optimal RDS reconfiguration issue. The effectiveness of MTSO is validated using two RDS systems, consisting of 33 and 69 nodes. The results show that the proposed approach is a reliable tool for power system operators to solve the optimal ESS placement problem for RDS, reducing real power losses. The analysis of the 33-bus system shows that the proposed MTSO reduces real and reactive power losses by up to 105.47 kW and 88.25 kVAr, respectively, with a voltage of 0.9742 p.u. Similarly, for the 69-bus system, the proposed MTSO achieves reductions of 68.47 kW and 47.25 kVAr in active and reactive power losses, respectively, with a voltage of 0.9913 p.u. Future research may include more complex test cases, including line outage situations and larger RDS.

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