RESEARCH ARTICLE **ISSN 2738-9898 (Print) ISSN 2738-9901 (Online)**

Voltage Regulation in Distribution Network with Penetration of Renewable Energy Sources Using Different Metaheuristic Algorithms

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Received : 02 November 2025; Received in revised form : 10 March, 2026; Accepted : 23 March, 2026; Published: 31 July, 2026

Abstract

Power distribution systems, traditionally managed through centralized and vertically integrated structures, often employ radial topologies or weakly interconnected networks with high resistance-to-reactance (R/X) ratios. These configurations lead to undesirable voltage profiles along with power loss. The photovoltaic (PV) based distributed generation can cause voltage control issues. The optimization framework for coordination of reactive power injection of smart inverters and tap operations of on-load tap changers (OLTCs) is proposed. The primary objective of this study is to minimize the voltage deviations and power loss in the distribution network after penetration of photovoltaic. To achieve the best results three metaheuristic algorithms: Genetic Algorithm (GA), Snake Optimization (SO) and Modified Snake Optimization (MSO) were used. It was found that SO and MSO have better optimal results compared to GA. In terms of computational time, SO was the fastest, followed by GA, whereas MSO required the longest time due to its additional mechanisms of exploration and exploitation. The proposed method is tested on IEEE 33 bus system and validated on 42 bus 11 kV radial distribution feeder using MATLAB. Results demonstrate that active energy loss and reactive energy loss are reduced by 25.78% and 18.73% respectively in IEEE 33 bus system. On the 42 bus 11 kV radial distribution feeder, active energy loss reduction of 5.16% and reactive energy loss reduction of 10.84% are achieved. This method also indicates that the coordination of reactive power outputs of PVs and OLTC facilitates better voltage magnitude profile after penetration of PVs in 11 kV distribution network.

Keywords

Distributed Generation, Genetic Algorithms, Modified Snake Optimization, Power Distribution Systems, Renewable Energy Sources, Voltage Regulation

1. Introduction

The increasing use of photovoltaic (PV) based distributed generation (DGs) in medium voltage (MV) grids has the potential to significantly impact the distribution system's operation. To address these challenges, Volt/VAR control (VVC) utilizing voltage control devices presents itself as a viable solution [1–2]. Traditional voltage control devices, including capacitor banks (CBs) and on load tap changer (OLTC) transformers, have long been utilized to achieve conventional VVC. However, their frequent use results in a shortened lifespan. In contrast, smart inverter interfaced PV generation is gaining traction due to its adaptable modes of operation, such as volt/var mode [3]. As a result, utilizing smart inverters for VVC presents itself as a promising alternative. By effectively utilizing these inverters, the MV grid can be stabilized without causing damage to the voltage control devices. Additionally, their adaptable modes of operation can help lessen the negative impact of high diffusion levels of PV-based DGs on the MV grid.

The research work addresses the subject of high DG allocation and volt VAR control. It offers helpful insights into the issues that are connected with integrating large volumes of distributed generation into electrical network as well as potential solutions to those challenges. The authors of [4] used the Cuckoo Search algorithm to enhance the benefits of the Static Var Compensator (SVC) and synchronous generator (SG) controller at the port of the induction generator (IG) in order to minimise frequency and terminal voltage variations. This was accomplished by improving the gains of the SG controller and the SVC. The results of the investigation revealed that the method is effective in resolving the DNR issue. The authors of the article [5] suggested using the Artificial Hummingbird Algorithm (AHA) to optimise the location and capacities of renewable distributed generators sources within a power system. The strategy that was suggested took into account a number of different goals, such as lowering total cost and emissions, reducing voltage deviation, and enhancing voltage stability, all while taking into account the uncertainties connected with the loading and RDG output power. Daily volt/var control was performed in [6], and various type of load model and their effect on energy losses in distribution network have been studied under VVO framework in [7]. Optimal reactive power dispatching from PV inverters, capacitor banks, and OLTCs in a distribution system was accomplished in [8] to minimize loss and voltage deviation. In [9], a voltage control loop was implemented in PV inverters to keep the voltage within acceptable bounds by absorbing or supplying reactive power. In [10], the limiting factors for photovoltaic penetration in radial distribution systems were presented.

Novel approaches to voltage management in active distribution networks (ADNs) are required due to the dynamic changes in power distribution systems that are being driven by the increasing integration of renewable energy sources (RESs).

Recent research has focused extensively on leveraging photovoltaic (PV) inverter reactive power capability to enhance voltage regulation and minimize power losses in distribution networks. Maintaining voltage levels within acceptable operational limits can be effectively achieved through reactive power control, where PV inverters play a crucial role by producing or absorbing reactive power as needed. A decentralized approach introduced in [11] employs linear decision rules based on PV real power output under an adjustable robust optimization framework, enabling optimal voltage and loss management through convex quadratic programming. This method provides a robust and computationally efficient alternative to traditional control schemes, though its dependence on accurate PV output forecasts limits its reliability under uncertain solar conditions.

Building on this, [12] presents a distributed framework for Conservation Voltage Reduction (CVR) in systems with high PV penetration, coordinating inverter operation with traditional voltage regulation devices using a modified Alternating Direction Method of Multipliers (ADMM) to address non-convex optimization issues efficiently.

Similarly, [13] proposes a multi-period reactive power and voltage optimization technique using

Benders decomposition and a model predictive control (MPC)-based rolling optimization framework, effectively coordinating On-Load Tap Changers (OLTCs) and PVs for fast, smooth voltage control transitions.

In [14], a multi-objective optimization framework is developed to coordinate reactive power support from smart inverters and OLTC operations in multi-phase unbalanced networks. The formulation uses a novel power-flow linearization to convexify the problem and solve it using mixed-integer linear programming (MILP), achieving significant reductions in voltage deviation and tap operations. Decentralized control strategies have also gained prominence, as demonstrated in [15], where a near-optimal local reactive power dispatch method achieves comparable performance to centralized optimization while being suitable for real-time applications in complex systems with variable PV penetration.

Metaheuristic and evolutionary algorithms have been increasingly applied to optimize inverter Volt/Var characteristics. Reference [16] utilizes a multi-objective Genetic Algorithm (GA) to optimize smart inverter Volt/Var curves for voltage profile improvement and loss reduction, while [17] and [18] extend GA-based frameworks to coordinate LTCs, switched capacitors (SCs), and inverters. These studies collectively highlight the potential of genetic algorithms in efficiently managing voltage fluctuations and enhancing distribution network performance.

Beyond GA-based methods, heuristic optimization techniques such as the Grey Wolf Optimizer (GWO) [19], pattern search [20], and harmony search algorithms [21] have been explored to coordinate reactive power sources, voltage regulators, and inverter operations. These approaches demonstrate the growing emphasis on hybrid and cooperative control mechanisms that integrate traditional devices and modern inverter-based resources for enhanced grid stability. However, issues such as parameter sensitivity and convergence challenges still pose limitations for practical deployment.

To further improve control efficiency, [22] introduces a Mutation Fuzzy Adaptive Particle Swarm Optimization (MF-APSO) algorithm that effectively balances overvoltage mitigation and loss reduction, outperforming traditional approaches. A similar direction is taken in [23], where a multi-stage, multi-objective Volt/Var control (VVC) strategy combines planning and real-time operations through Discrete Multi-Objective Particle Swarm Optimization (DMOPSO) and adaptive Volt/Var droop control, providing robust performance under uncertainty in load and PV forecasts.

An extended Volt/Var co-optimization strategy for low-voltage networks is presented in [24], which coordinates medium-voltage switched capacitors and low-voltage inverters through improved load-flow and modified Particle Swarm Optimization (MPSO) methods. Likewise, [25] focuses on optimizing smart inverter functions to reduce voltage deviation and network losses in real systems, demonstrating the effectiveness of adaptive inverter control in practical scenarios.

Recent developments have also incorporated newer metaheuristic algorithms for enhanced coordination of distributed resources.

For instance, the Sparrow Search Algorithm (SSA) [26] optimizes OLTCs, voltage regulators, and capacitors to minimize voltage imbalance and variation in unbalanced systems. Similarly, [27] introduces a hierarchically coordinated VVC method using droop-controlled PV inverters, optimized through Taguchi's orthogonal array design, to reduce voltage deviation and power loss under variable PV output conditions. Finally, [28] integrates multiple distributed voltage control devices using a GA-based optimization strategy to achieve optimal system-level voltage management in PV-rich networks.

The integration of photovoltaic (PV) based distributed generation (DG) into Medium voltage (MV) grids presents both opportunities and challenges. While traditional voltage control devices (such as capacitor banks and on load tap changer transformers) have limitations due to frequent use and shortened lifespans, smart inverter interfaced PV generation offers adaptable modes of operation and a promising alternative for Volt/VAR control (VVC). However, existing research primarily focuses on active power injection from PV-based DGs, neglecting the reactive power capability of smart inverters for voltage management. Coordinated voltage control strategies for voltage regulation in PV-based DGs have yet to be fully explored.

The contributions of this study can be summarized as follows:

- A coordinated multi-stage voltage control methodology has been suggested, which takes into account both traditional and advanced VVC devices.
- A PV smart inverter control approach for local reactive power voltage (Q-V) has been proposed, which enhances the voltage control capability of PV-based DG systems.
- The impact of penetration of PV-based DG on the voltage profile and power loss in active distribution networks have been explored. This analysis provides insights into the effect of PV penetration on voltage control and power loss and highlights the need for advanced control techniques.
- The proposed coordinated approach has been verified on established 33 bus distribution systems. This verification demonstrates the practicality and effectiveness of the proposed approach in real-world scenarios.

2. Methodology

2.1 The process of managing PVs' reactive power and OLTC

The flow chart of managing PVs' reactive power and OLTC is shown in Figure 1. System data, forecasted load data and PVs output are given as input to the system taken into consideration. Then the limits for tap operation and inverter reactive power are set.

The taps of OLTC are allowed to change in the range between -8 to 8 with the tap step of 1.25%. The number of tap positions are 1 to 17 and the normal tap position is 9.

The reactive power that the inverters can inject/absorb to the system is obtained according the power generated by the PVs and reactive power limit can be calculated as:

$$Q_{PV}^{lim} = \sqrt{(S_{PV}^{max})^2 - (P_{PV})^2} \quad (1)$$

Here, Q_{PV}^{lim} shows the maximum and minimum limit values of the reactive powers that PV can support. P_{PV} and Q_{PV} represent the active and reactive power outputs of the PV respectively and S_{PV}^{max} represents the maximum apparent power of the PVs. The permissible voltage limit is taken as 0.95 to 1.05 pu.

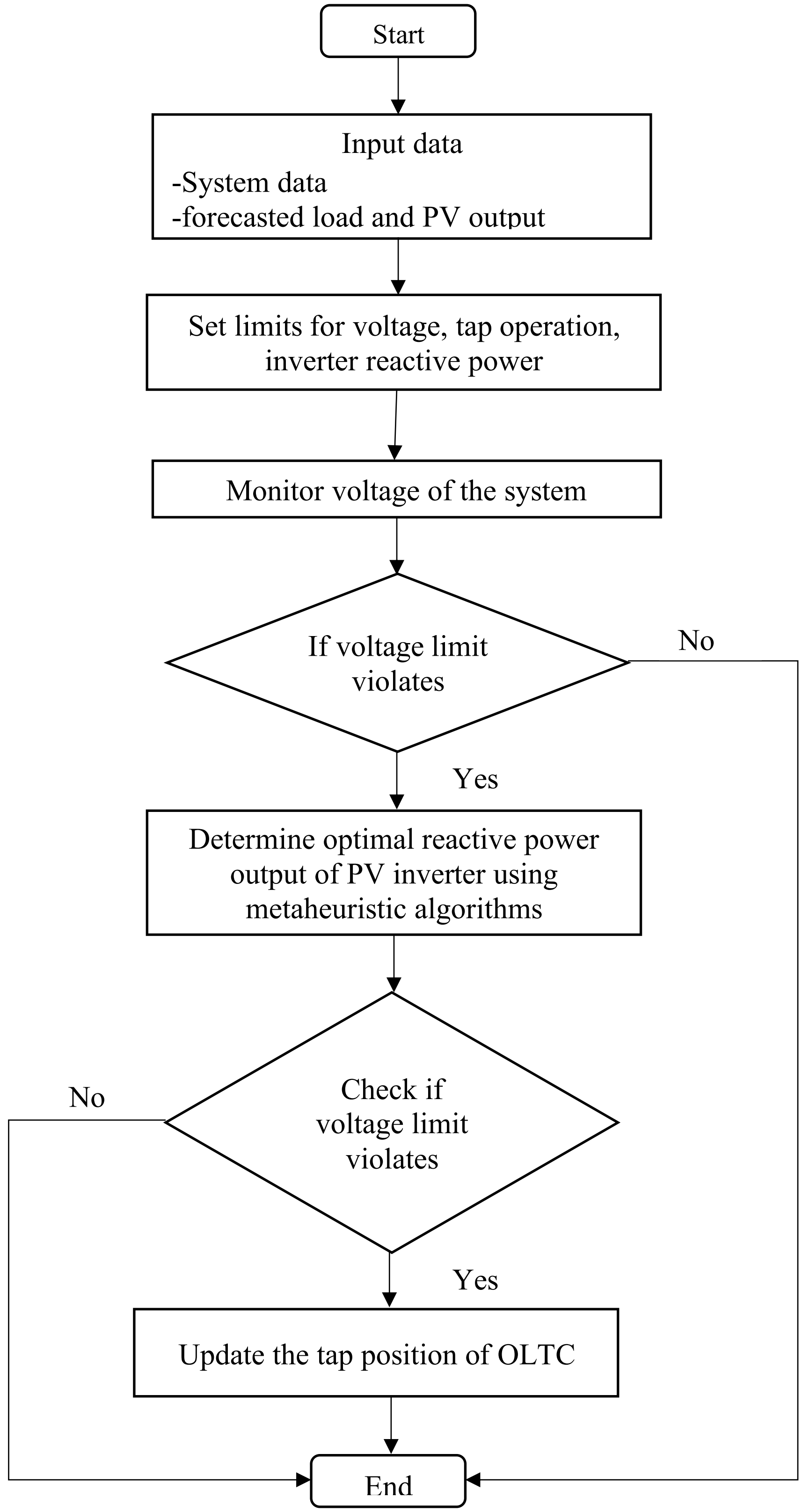

Figure 1: Flow chart for managing PVs' reactive power and OLTC

The voltage of each bus of the system is monitored and if the voltage of any bus violates the permissible limit, the reactive power output of the PV inverters are either injected to the system or absorbed from the system whose optimal values are determined by using different Algorithms (MSO, SO and GA). After reactive power output from the PV inverter, again the bus voltages are checked. If any of the bus voltage violates the permissible voltage limit again, then the tap position of the OLTC is updated.

The proposed coordinated voltage control is a novel solution that addresses the challenges of voltage regulation and power loss in active distribution networks. At an hourly level, the centralized control technique assigns the slowly controlled voltage devices, such as on-load tap changers (OLTCs), as well as quickly controlled voltage devices like PV inverter with reactive power control capability. However, OLTCs are not suitable for handling sudden changes in renewable generation or load dynamics due to their slow reaction times. Therefore, the local control scheme handles the scheduling of fast-acting devices within each hour, which provides assistance against abrupt changes in voltage and responds more quickly.

The proposed coordinated voltage control strategy offers an effective solution to the challenges of coordinated Volt-VAR regulation in active distribution networks. The suggested approach ensures efficient voltage control by incorporating both conventional and cutting-edge VVC devices. Moreover, it provides a better choice for practitioners who are seeking a coordinated Volt-VAR regulation strategy that eliminates voltage violations and power loss minimization in distribution network. The efficacy of the proposed architecture was verified through the established 33 bus distribution system. Overall, the study presents an important contribution to the field of active distribution network research by offering a new and effective approach to coordinated Volt-VAR regulation.

The power capability curve as shown in Figure 2, is a graphical representation of the limits within which an inverter can operate in terms of real and reactive power.

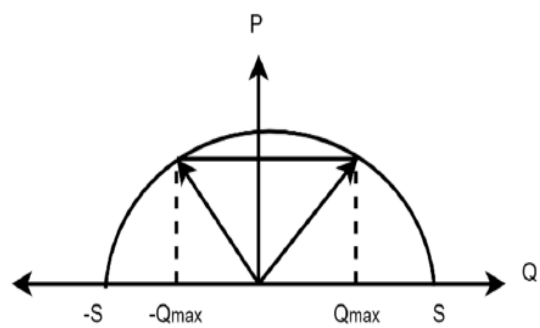

Figure 2: Power Capability curve [26]

There is a limit on the amount of reactive power (Q) the device can produce or absorb. As the active power increases, the available reactive power decreases, and vice versa. This is due to the fact that the device has a fixed total apparent power, and an increase in one component (P or Q) reduces the available capacity for the other.

Figure 3 denotes Volt-VAR curve with dead band and without dead band. If the local voltage is between V_1 and V_2 (low voltage), the inverter injects reactive power to raise the voltage. If the voltage is between V_3 and V_4 (high voltage), the inverter absorbs reactive power to reduce the voltage. In between V_2 and V_3, the inverter does not provide reactive power as the voltage is within an acceptable range.

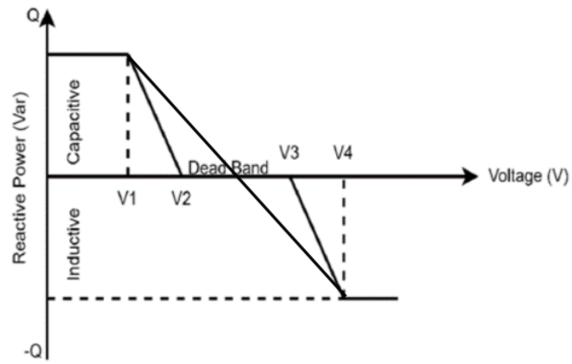

Figure 3: Volt-VAR curve [26]

A Volt-VAR curve without a dead band is a control strategy used by inverters to continuously adjust reactive power (VARs) in response to changes in the grid voltage without any "neutral zone" where no reactive power is injected or absorbed.

The reactive power injection or absorption is proportional to the voltage deviation. As the voltage moves away from the nominal value (e.g., 1.0 pu), the inverter adjusts its reactive power output continuously. With no dead band, the slope of the Volt-VAR curve is usually more aggressive to ensure that even small voltage deviations result in reactive power changes.

The X-axis represents the grid voltage in per unit (pu), with 1.0 pu being the nominal voltage. The Y-axis represents the reactive power (Q), with positive values indicating reactive power injection (to raise voltage) and negative values indicating reactive power absorption (to lower voltage).

The single line diagram of IEEE 33 bus system is shown in Figure 4. It is assumed that PV's are installed at buses 15, 17 and 33.

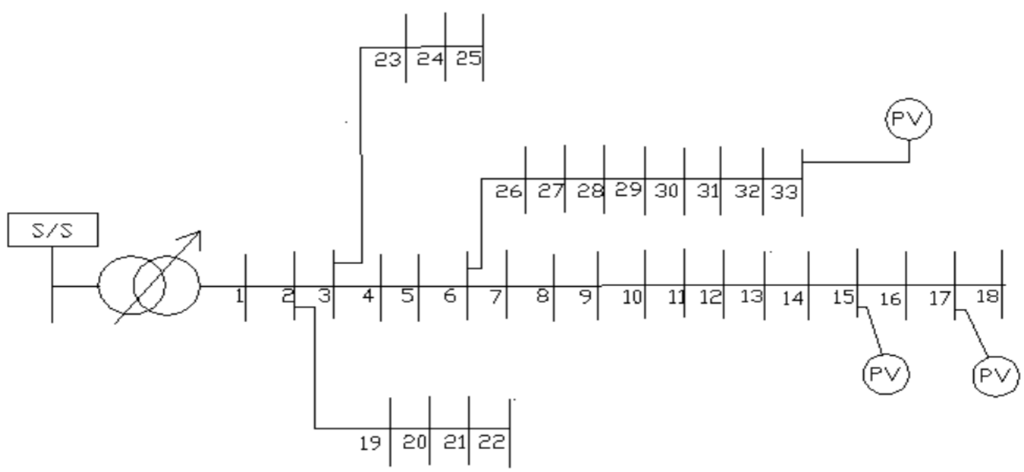

Figure 4: single line diagram of IEEE 33 bus distribution system

Similarly, the single line diagram of 42 bus radial distribution feeder is shown in Figure 5. It is assumed that PVs are installed at buses 20, 22 and 40.

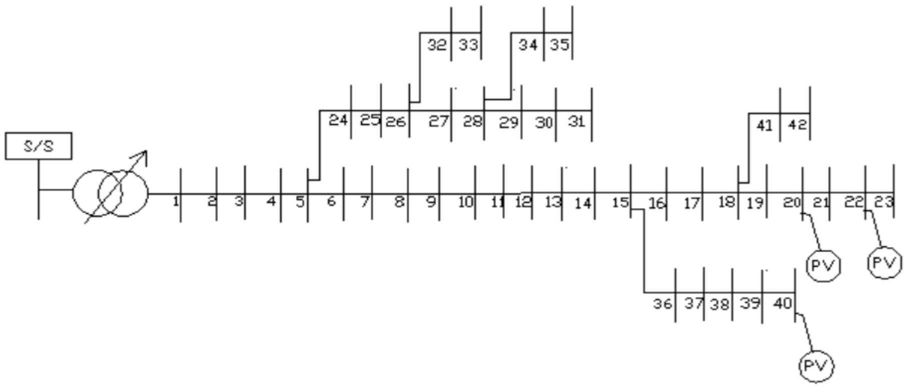

Figure 5: Single line diagram of 42 bus radial distribution feeder

Additionally, the forecasted load data over 24 hour has been plotted in figure 6 for IEEE 33 bus distribution system. The load is forecasted as maximum at 8 pm and minimum at 8 am. The maximum load of the distribution system is 5.65 MVA and minimum load of the system is 3.67 MVA.

The forecasted load data over 24 hour has been plotted in Figure 7 for 42 bus radial distribution feeder. The load is forecasted as maximum at 10 pm and minimum at 9 am.

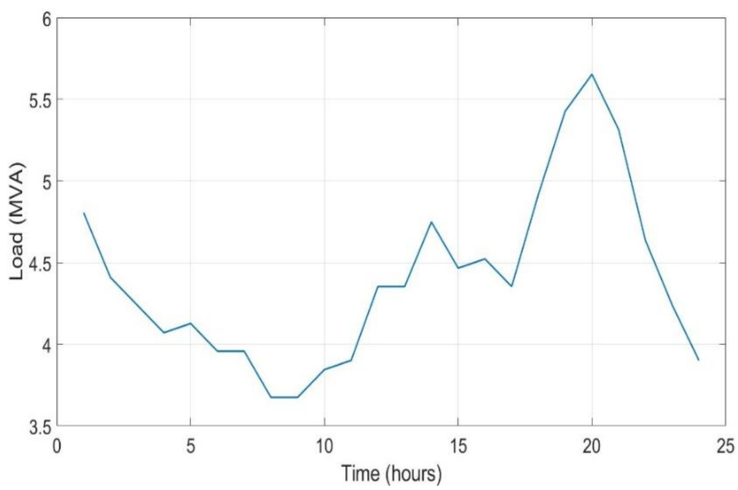

Figure 6: Forecasted load data over 24 hours (For IEEE 33 bus)

The maximum load of 42 bus radial distribution system considered for case study is 4.678 MVA and minimum load of the system is 3.041 MVA.

Morning Hours (0-6 AM), the PV generation is essentially zero during these early hours, which is expected since there is no sunlight at night. Mid-morning to Early Afternoon (7 AM - 12 PM), the PV generation starts to increase gradually as the sun rises, with the values increasing steadily.

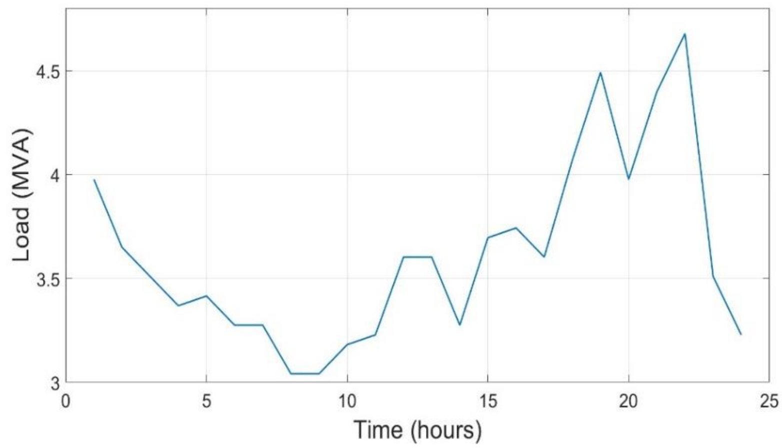

Figure 7: Forecasted load data over 24 hours (For 42 bus Radial Distribution Feeder)

Peak Hours (12 PM - 5 PM), the PV generation reaches its peak during these hours, corresponding to the period when sunlight is most intense. Evening Hours (5 PM - 7 PM), the PV generation drops back to zero. The PV generation values follow a typical daily solar irradiance pattern, with values increasing as the sun rises, peaking around noon, and decreasing as the sun sets. This is consistent with the behaviour of solar PV systems that depend on sunlight to generate electricity. The load values show minor fluctuations during most of the day, indicating a relatively steady demand for energy. However, the significant spike late in the evening suggests a surge in energy consumption, which might be due to increased usage of electrical appliances, lighting, or other activities occurring after dark.

To assess the effectiveness of the voltage control, Modified Snake Optimization, Snake Optimization and Genetic Algorithm are used for optimization of reactive power output of PV inverter to minimize the voltage deviation and power loss in distribution network.

Problem Formulation

Power loss reduction and voltage profile improvement form the objective function of this study.

Loss minimization

The total real power losses on the feeder can be computed as:

$$P_{Loss}=\sum_{i=1}^{Nb} R_i \mathrm{x} I_i^2 \quad (2)$$

Also the cumulative reactive power losses can be calculated as:

$$Q_{Loss}=\sum_{i=1}^{Nb} X_i \mathrm{x} I_i^2 \quad (3)$$

Where P_{Loss} and Q_{Loss} are the two objective functions related to minimization of the system power loss, I_i is the line current, R_i is the i^{th} line resistance and N_b denotes the branches in the system.

Voltage profile improvement

The next objective focuses on enhancing the voltage profile of Radial Distribution Network, expressed through the aggregate voltage variation index as follows formula:

$$V_{Deviation} = \sum_{i=1}^{N} \left| V_i - V_{ref} \right| \quad (4)$$

Where V_i is the i[th] bus voltage, N is the number of system bus, V_{ref} is the reference voltage.

General Objective Function

The multi-objective function is transformed using the weighted sum method into a single objective function where w_1 and w_2 are weighting factors.

$$F = w_1(P_{Loss} + Q_{Loss}) + w_2\, V_{Deviation} \quad (5)$$

The weighted sum method is advantageous for its simplicity especially when applied to convex problems. Equal weight settings are done i.e. $w_1 = 0.5$ and $w_2 = 0.5$

System Operational Limits

Active and reactive power equilibrium limits

$$P_{grid}^{h} - \sum_{i=1}^{Nb} P_{loss,i}^{h} - \sum_{i=1}^{Nb} P_{dem,i}^{h} + \sum_{i\in\Omega_{PV}} P_{PV,i}^{h} = 0 \quad (6)$$

$$Q_{grid}^{h} - \sum_{i=1}^{Nb} Q_{loss,i}^{h} - \sum_{i=1}^{Nb} Q_{dem,i}^{h} + \sum_{i\in\Omega_{PV}} Q_{PVDST,i}^{h} = 0 \quad (7)$$

Onload tap changing (OLTC) transformer settings limit

$$T^{min} \le T_i \le T^{max} \quad (8)$$

Reactive power limit of PV smart inverter

$$-Q_{PV}^{lim} \le Q_{PV} \le Q_{PV}^{lim} \quad (9)$$

$$Q_{PV}^{lim} = \sqrt{(S_{PV}^{max})^2 - (P_{PV})^2} \quad (10)$$

Where P_{PV} and Q_{PV} represent the active and reactive power outputs of the PV, respectively, S_{PV}^{max} represents the maximum apparent power of the PV, Q_{PV}^{lim} shows the minimum and maximum limit values of the reactive power that PV can support, T_i represents the tap position of the OLTC, T^{min} represents the minimum position and T^{max} represents the maximum position.

Reactive power output of PV inverter as population: [Q_{PV1}, Q_{PV2}, Q_{PV3}]. Each candidate solution in metaheuristic represents a vector of PV reactive power.

2.2 Genetic Algorithm (GA)

A Genetic Algorithm (GA) is a powerful optimization technique inspired by the principles of natural selection and evolution. GA involves the process of evolution by working with a population of potential solutions, which undergo cycles of selection, crossover, and mutation to evolve towards optimal or near-optimal solutions.

The algorithm starts with an initial population of individuals, where each individual represents a potential solution to the optimization problem. These individuals are typically encoded as chromosomes, often represented as binary strings, but they can also be real numbers or other data structures depending on the problem. The initial population is usually generated randomly to explore a broad range of possible solutions. At each iteration, called a generation, the quality of each individual is assessed using a fitness function. This fitness function evaluates how well an individual solves the problem, with higher fitness values corresponding to better solutions. The fitness values then guide the selection process, where individuals with higher fitness are more likely to be chosen to create offspring for the next generation. Selection can be done using various methods, such as roulette wheel selection, tournament selection, or rank-based selection and the flow chart is shown in Figure 8.

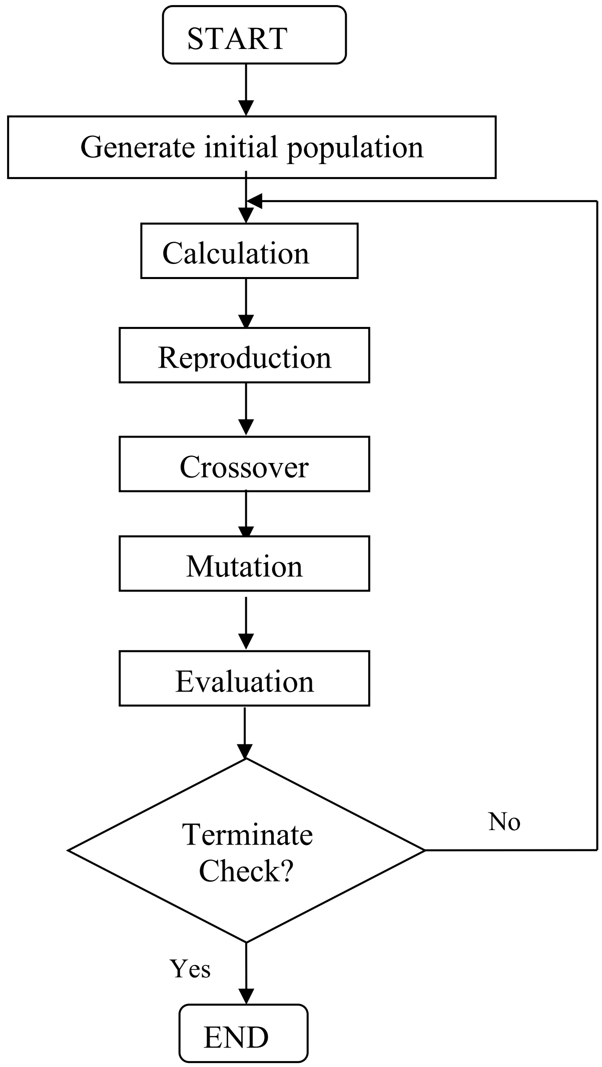

Figure 8: Genetic algorithm flow chart

Crossover (recombination) is then applied to selected individuals, where genetic material from two parents is combined to produce offspring. This creates new solutions by mixing the properties of different individuals. Mutation introduces small random changes to some individuals, helping to maintain diversity in the population and preventing premature convergence to suboptimal solutions. The next generation is formed by replacing some or all of the population with the new offspring.

2.3 Snake Optimization (SO)

Snake Optimization (SO) is designed to solve complex and nonlinear optimization problems by mimicking the hunting, mating, and survival behaviors of snakes in nature. Like other nature-inspired algorithms, SO aims to find the global optimum by balancing exploration (searching new areas) and exploitation (refining known good areas). However, SO is unique in that it classifies the population into male and female snakes, each with different behavioral patterns, and incorporates natural processes such as energy consumption, role division, and mating for offspring generation. Due to its simplicity, fast convergence, and strong global search ability, SO has proven to be highly effective for solving problems in power systems, especially for minimizing power losses and improving voltage profiles in distribution networks. The flow chart of SO is shown in Figure 9.

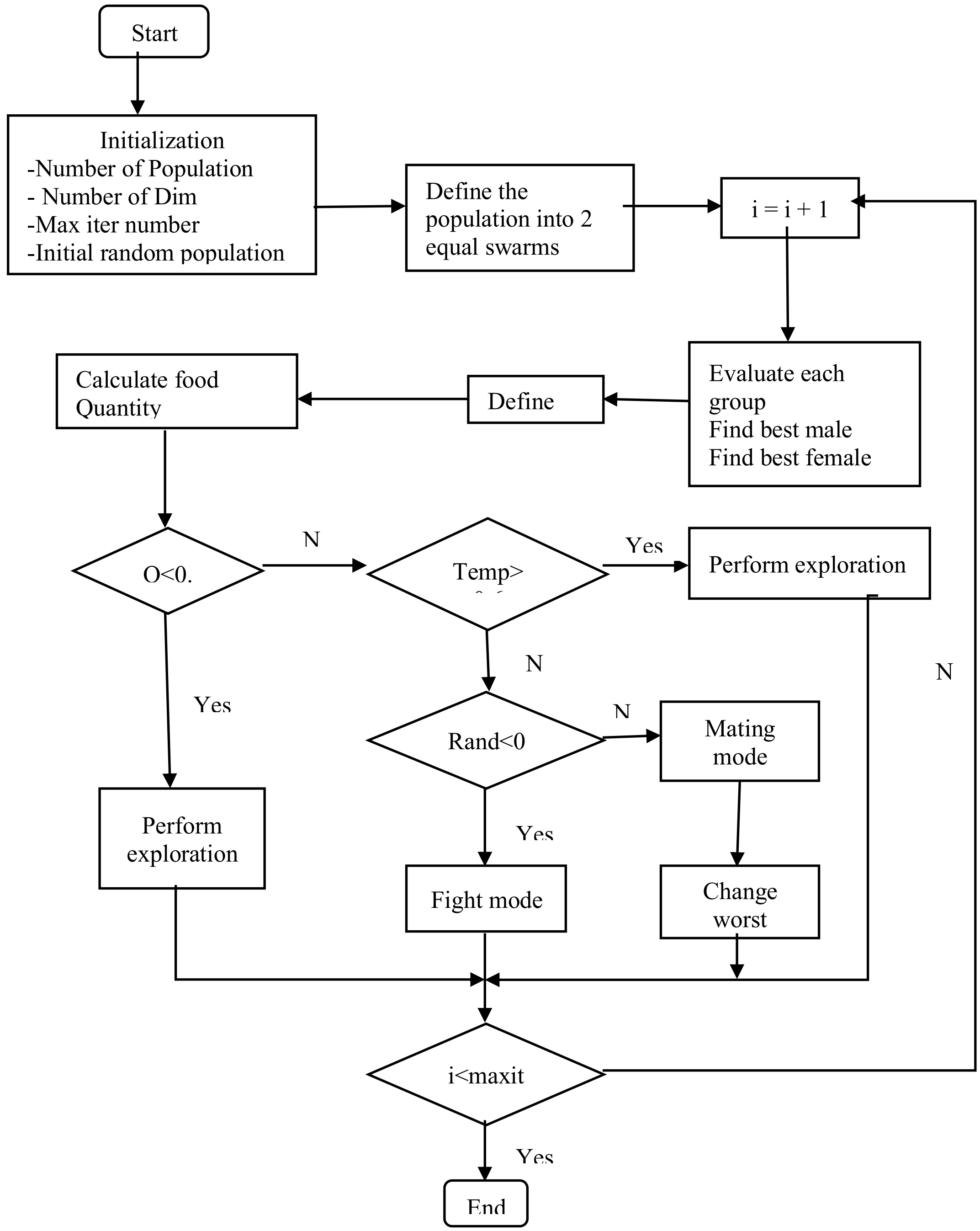

Figure 9: Flow chart of SO

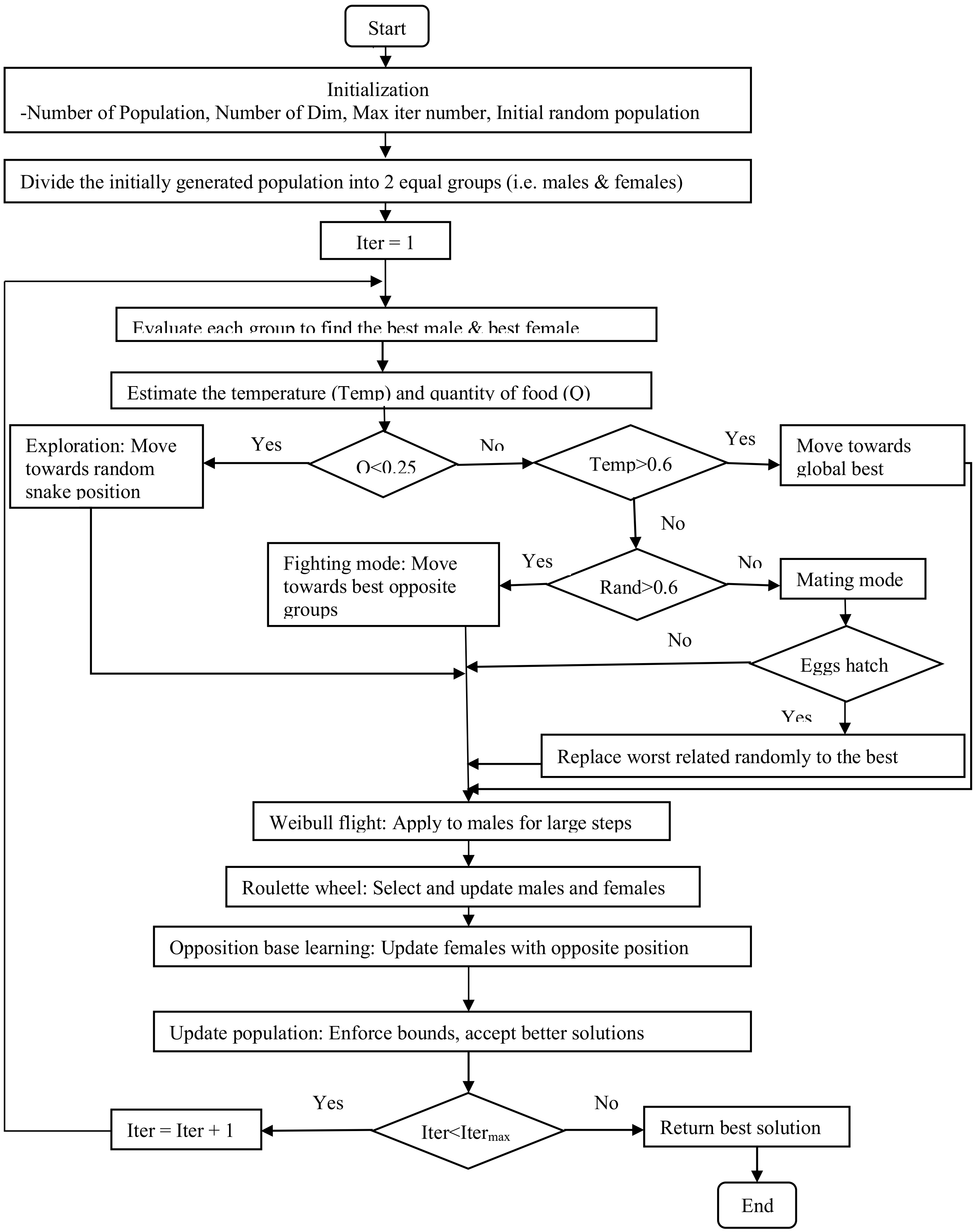

Figure 10: Flow chart of MSO

2.4 Modified Snake Optimization (MSO)

Modified Snake Optimization (MSO) is an advanced version of the original Snake Optimization (SO) algorithm, enhanced to improve convergence speed, solution quality, and global search capability. While the original SO algorithm was inspired by the hunting, movement, and mating behaviors of snakes, the MSO builds upon these mechanisms by introducing additional techniques such as Weibull flight, adaptive role switching, and dynamic exploitation control. These enhancements enable MSO to more effectively explore complex solution spaces and escape local optima. MSO is particularly suitable for multi-objective and non-linear optimization problems such as those found in power systems, including power loss minimization, voltage profile improvement, and optimal control of reactive power sources like PV-DSTATCOMs. The flow chart of MSO is shown in Figure 10.

3. Results and Discussion

In this section, the outcomes and discussions of the research study are presented. The proposed method of coordinated voltage control has been implemented using the MATLAB and evaluated on a laptop featuring an Intel® Core™ i5-1135G7 processor at 2.40 GHz, 8 GB of RAM, and a 256 GB SSD. The control strategy was tested on both the IEEE 33-bus system and a real-world 42-bus radial distribution feeder. Table 1 summarizes the details of the bus systems, considering OLTC and PV-based DGs.

Table 1: Details of test systems

Parameters	Test system 1	Test System 2
Bus system	IEEE 33 bus	42 bus Radial Distribution feeder
Voltage	11 KV	11 kV
Maximum power demand (MVA)	5.65 MVA	4.678 MVA
PV plant mounted locations	15, 17, 33	20, 22, 40
PV plant capacity (MVA)	1, 1.5, 1	1, 1.5, 1
allowable voltage bounds	0.95 pu to1.05 pu	0.95 pu to1.05 pu

In this paper, the performance of three different metaheuristic algorithms, namely GA, SO and MSO have been evaluated. In Figure 11 and 12, the convergence pattern for IEEE 33 bus system and 42 bus radial distribution system of each algorithm are depicted. In table 2, mean, standard deviation and computation time for each algorithms are shown.

Table 2: Comparison of mean, standard deviation and computational time of GA, SO and MSO (IEEE 33 bus)

Parameters	GA	SO	MSO
Mean	0.5587	0.5582	0.5582
Standard deviation	0.0013	0	0
Computational time (Seconds)	5.2327	4.8355	13.7272

From the Table 2, the performance of three algorithms can be compared. The mean fitness values for GA, SO and MSO are 0.5587, 0.5582 and 0.5582 respectively which indicate that SO and MSO have better optimal results compared to GA. The standard deviation reflects the stability of the algorithms. SO and MSO both have a deviation of 0 which means they consistently produced the same optimal results across multiple runs while GA showed minor variability. In terms of computational time, SO was the fastest (4.8355 seconds), followed by GA (5.2327 seconds), whereas MSO required the longest time (13.7272 seconds) due to its additional mechanisms of exploration and exploitation.

From the convergence pattern of GA, SO and MSO for IEEE 33 bus system, it is observed that all three algorithms achieved the same fitness value of 0.558183 but at different iterations i.e. 63, 34 and 11 respectively. This shows that while all three reached the same optimal solution, their convergence speeds varied significantly. GA took the longest iteration due to its gradual evolutionary process. SO converged faster through efficient cooperation and movement strategies. MSO achieved the fastest best fitness, demonstrating its enhanced exploration-exploitation balance and superior convergence efficiency. Hence MSO outperformed GA and SO in terms of number of iterations required and optimization effectiveness while maintaining the same final accuracy. Similarly from the convergence pattern for 42 bus radial distribution system, it is observed that GA required more iterations followed by SO and MSO. MSO reached the best solution at the least iterations demonstrating superior convergence ability and search efficiency. Overall, MSO showed the best optimization performance compared to GA and SO.

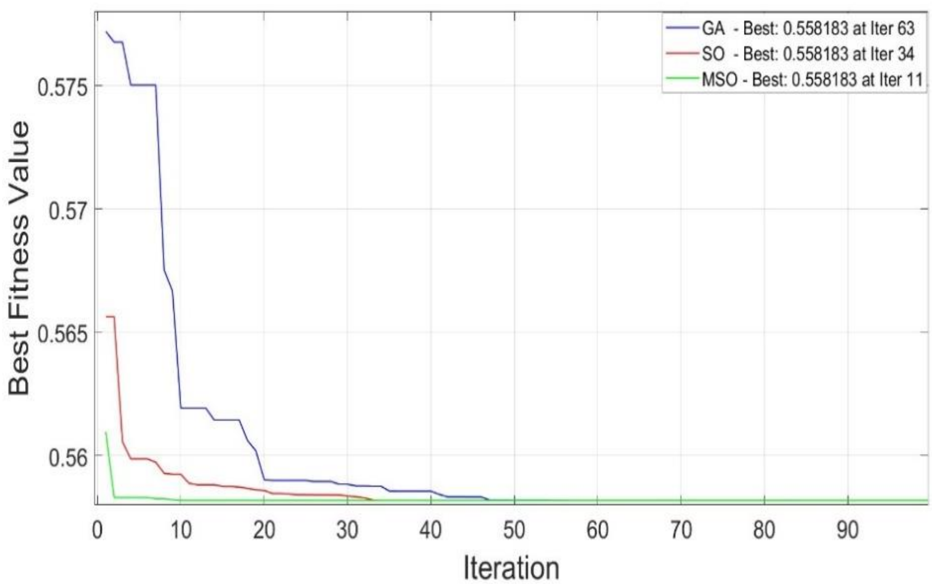

Figure 11: Convergence pattern of different algorithms for IEEE 33 bus system

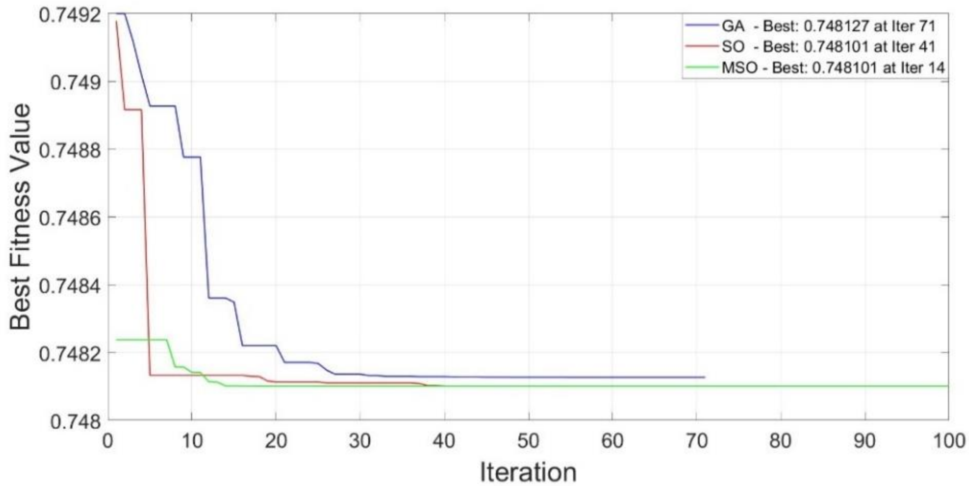

Figure 12: Convergence pattern of different algorithms for 42 bus radial distribution system

For IEEE 33 bus test system and 42 bus radial distribution feeder, results obtained for following four different cases are analysed and discussed.

Case 1: no integration of photovoltaic (PV) energy.

Case 2: penetration of PV with no voltage control.

Case 3: inverter based PVs as voltage control device.

Case 4: both OLTC and inverter based PVs as voltage control devices.

3.1 For test system (IEEE 33 bus system)

Figure 13 shows the bus voltage of the system before PV penetration. In this case OLTC tap position is set to normal position.

To handle PV penetration, it is assumed that PVs are installed at buses 15, 17 and 33 with maximum power that the PV can generate are 1 MVA, 1.5 MVA and 1 MVA respectively. The permissible voltage limit is taken as 0.95 pu to 1.05 pu.

Figure 14 is the graph that represents the behaviour of the system when there is PV penetration with no voltage control. Lines in the figure represents voltage magnitude for each time interval. From figure it can be seen that at various times of the day, the bus voltages are not within the permissible limit.

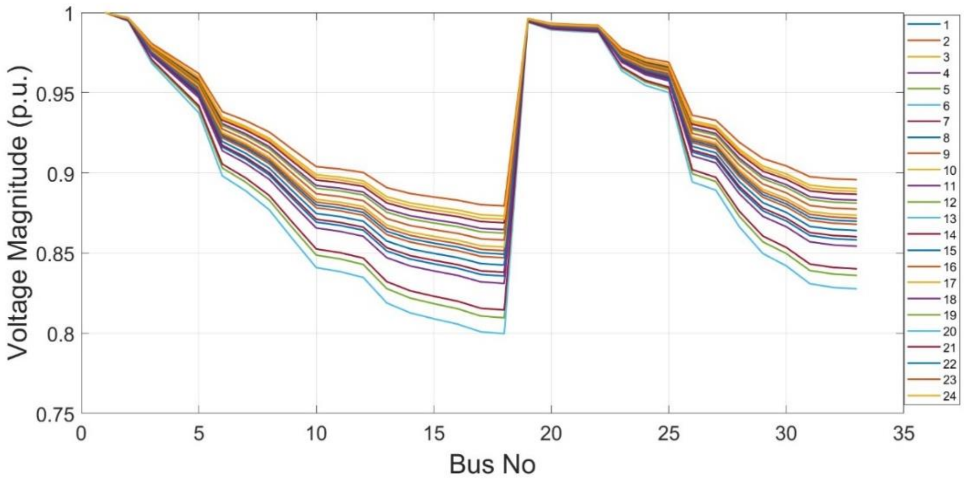

Figure 13: Bus voltage magnitude of the system for 33 bus system

The minimum voltage is 0.7997 pu at Bus 18 and maximum voltage is 1.057 pu at Bus 17. Since the voltages at some buses violate the permissible voltage limit, reactive power should be absorbed/injected to the system.

In figure 15, reactive power outputs of PVs installed at buses 15, 17 and 33 are illustrated. It is seen that the reactive power support from PVs decreases when the real power output from the PVs increases. It is also seen that PV inverters start to absorb the reactive power from the system and inject reactive power to the system so that voltage deviation and power loss in the system will be minimum.

The voltage deviations in the system after reactive power output by PV inverter is represented in Figure 16. Still the maximum voltage at Bus17 (i.e. 1.065) and minimum voltage at Bus 31 (i.e. 0.9030 pu) are not within the the permissible limit. The voltages of some buses are also not in permissible limit.

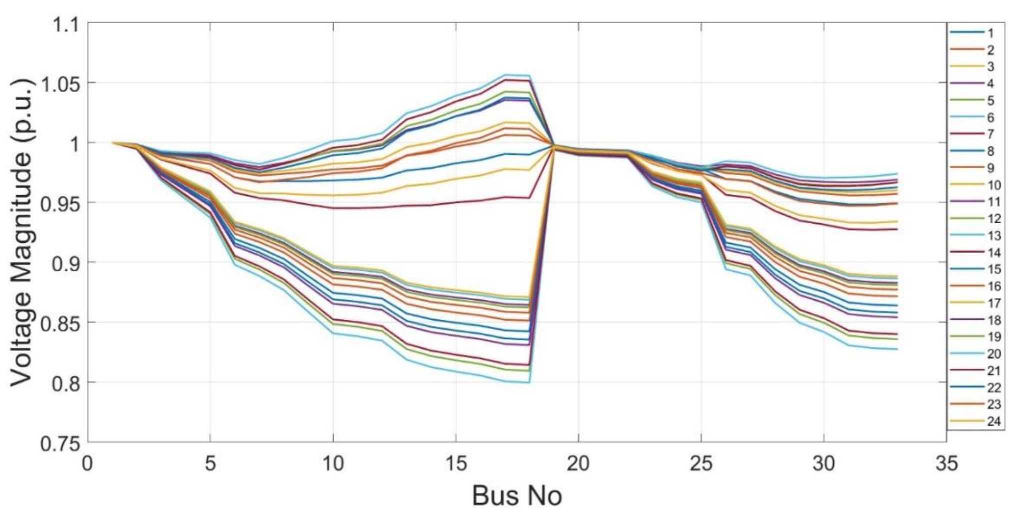

Figure 14: Bus voltage magnitude with no control after PV penetration for 33 bus system

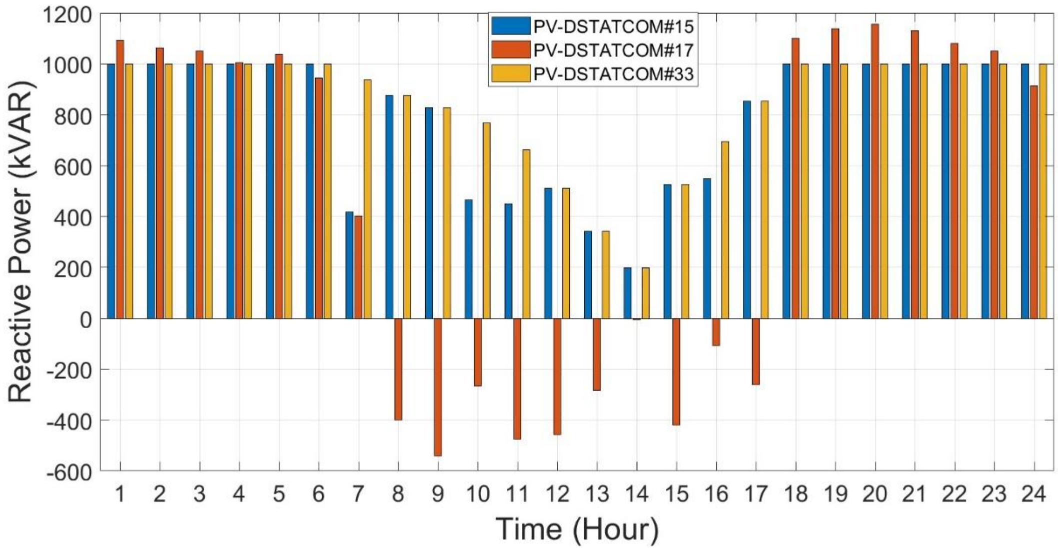

Figure 15: Reactive power injection/absorption by PV-DSTATCOM for 33 bus system

The tap changes for the tap changer transformer is illustrated in the graph shown in Figure 17. The taps of OLTC are allowed to change in the range between -8 to 8, each with 1.25% steps. The number of tap positions are 1 to 17 and tap position 9 is the normal tap position. The number of tap changes for this case is 4. In this case, the optimal reactive power absorbed or injected by PV inverters installed at various buses are not able to increase the minimum voltage to permissible limit when load is maximum at night. The tap position of OLTC is increased to position 11 and still the voltages of some buses are below the permissible limit so position of OLTC is increased up to 13 at 20:00 and again decreased to11 at 24:00, so that the voltage will be in the permissible limit.

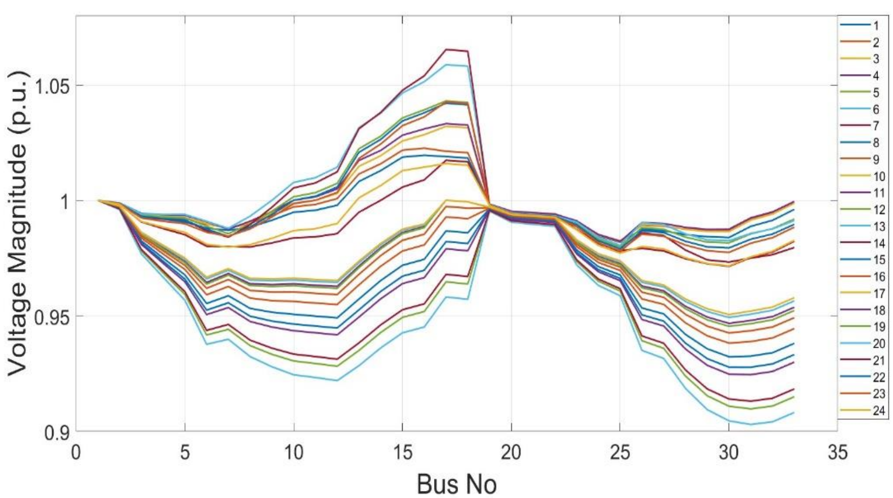

Figure 16: Bus voltage magnitude after reactive power outputs by PV inverters for 33 bus system

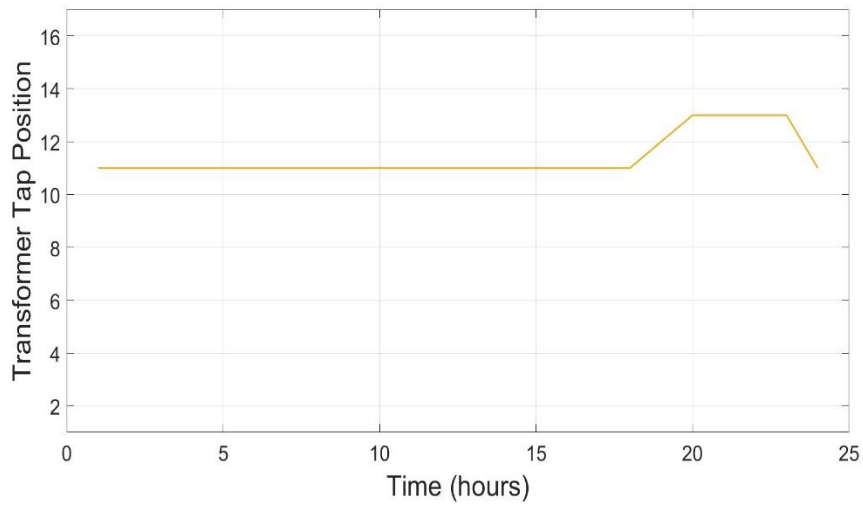

Figure 17: Tap position for OLTC for 33 bus system

The voltage profile obtained when reactive power outputs of PV inverter and OLTC both are used for the voltage control is represented by the graph in Figure 18. In this case, the minimum voltage is 0.9520 pu at Bus 31 and maximum voltage is 1.050 pu at Bus 19. All the bus voltages are within the permissible voltage limit. This is the best voltage profile that is obtained by coordination of inverter based PVs and OLTC of the transformer.

The active and reactive power losses of the IEEE 33 bus system were examined in four different cases and results were plotted in Figure 19 and 20. It can be seen that losses were highest in case 1, when there was no integration of photovoltaic energy. However the losses were significantly reduced with the integration of PV as shown in case 2. In case 3, the losses were further reduced after injection/absorption by PV inverter. In case 4, the implementation of PV inverter in association with OLTC led to a significant reduction in losses.

The outcomes under various cases for 33 bus system is shown in Table 3. Active energy losses and reactive energy losses in the system have been reduced by 14.39% and 11.42% respectively in case 2 compared to case 1. However, it was discovered that the minimum and maximum voltage magnitude violated the voltage permissible limit. In case 3, by the injection/absorption of reactive power by inverter results in reduction of active energy losses by 21.76% and reactive energy losses by 12.65% compared to case 1.

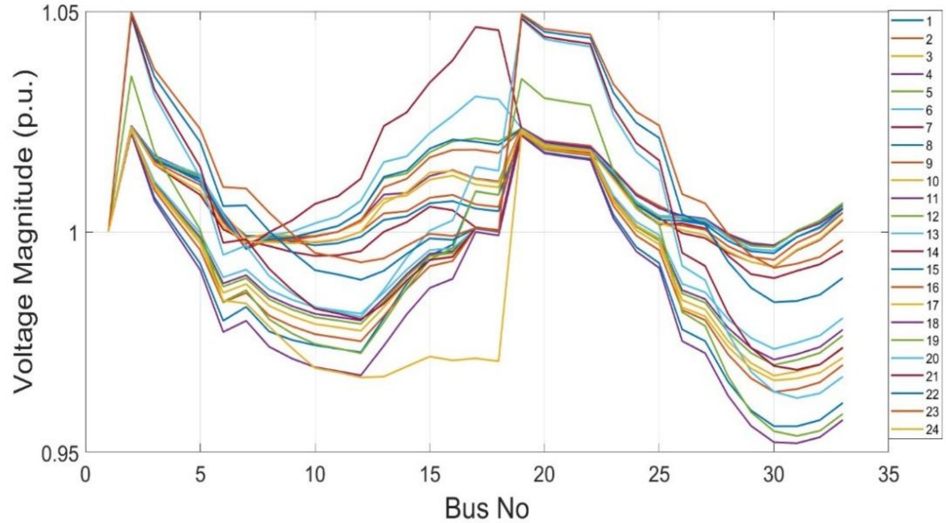

Figure 18: Voltage profile when reactive power outputs of PV inverter and OLTC both are used for the voltage control

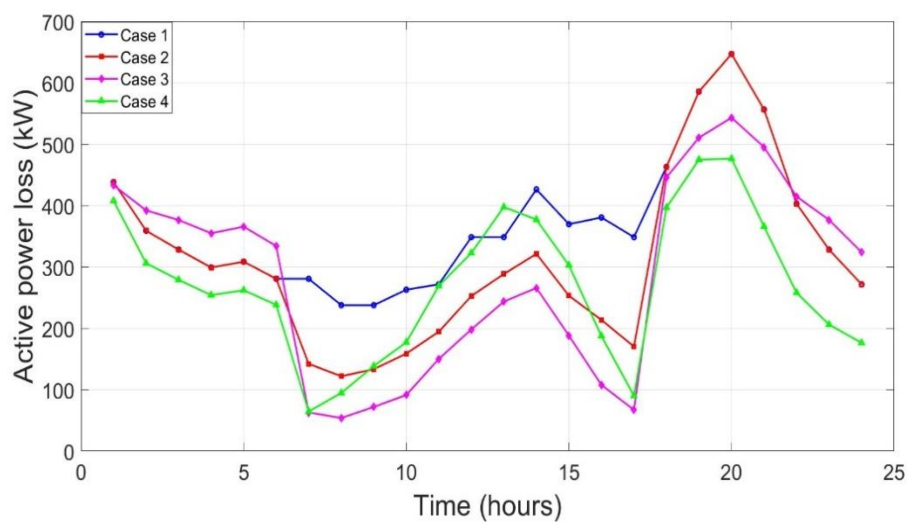

Figure 19: Active power loss under four different cases for 33 bus system

In the last scenario, case 4, active energy loss has been reduced by 25.78% and reactive energy losses have been decreased by 18.13% compared to case 1 due to functioning of reactive power correction provided by PV-DSTATCOM in addition to OLTC.

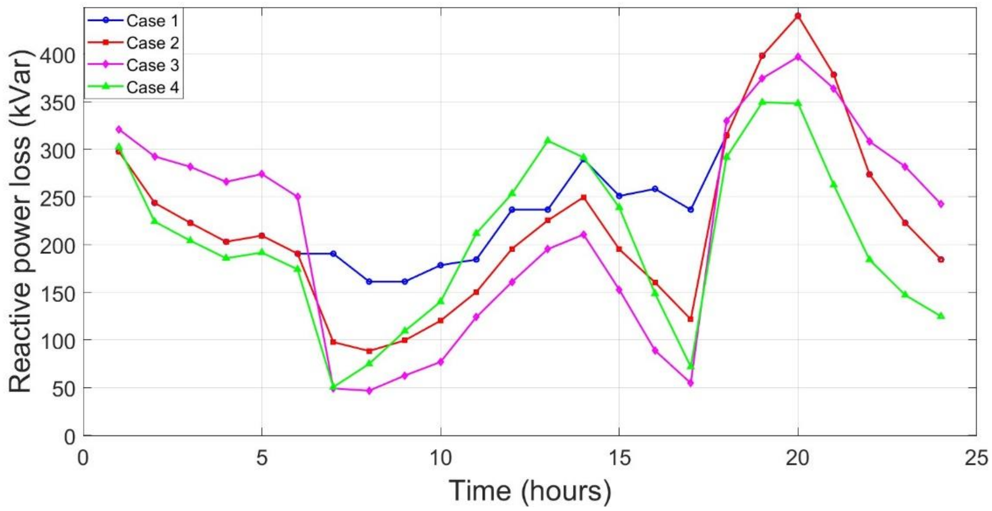

Figure 20: Reactive power loss under four different cases for 33 bus system

Table 3: Outcomes under various cases for 33 bus system

Parameter	Case 1	Case 2	Case 3	Case 4
Active Energy Loss (kWh)	8777.24	7514.54	6866.93	6514.09
Percentage reduction in active energy losses (%)		14.39	21.76	25.78
Reactive Energy Loss (kVARh)	5965.50	5284.51	5210.87	4883.81
Percentage reduction in reactive energy losses (%)		11.42	12.65	18.13
Min. Voltage (p.u.)	0.7997	0.7997	0.9030	0.9520
Max. Voltage (p.u)	1.000	1.057	1.065	1.050

3.2 For test system (42 bus Radial Distribution Feeder of Bhairahawa Substation)

Figure 21 shows the bus voltages of the 42 bus Radial Distribution Feeder before PV penetration. In this case OLTC tap position is set to normal position.

To handle PV penetration, it is assumed that PVs are installed at buses 20, 22 and 40 with maximum power that the PV can generate are 1 MVA, 1.5 MVA and 1 MVA respectively. The permissible voltage limit is taken as 0.95 pu to 1.05 pu.

Figure 22 is the graph that represents the behaviour of the system when there is PV penetration with no voltage control. Lines in the figure represents voltage magnitude for each time interval. The minimum voltage is 0.7932 pu at Bus 23 and maximum voltage is 1.053 pu at Bus 22. Since the voltages at some buses violate the permissible voltage limit, reactive power should be absorbed/injected to the system.

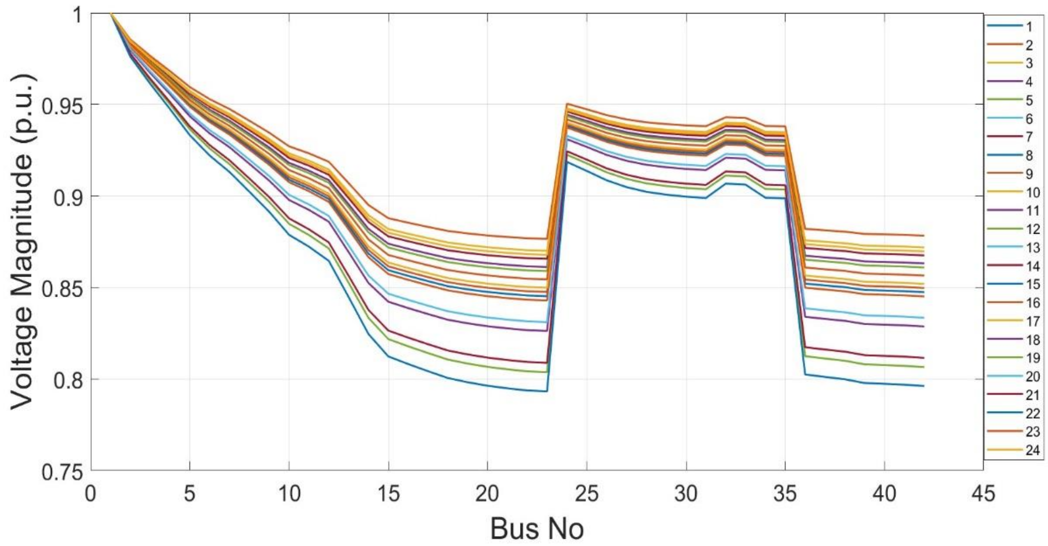

Figure 21: Bus voltage magnitude of the system for 42 bus radial distribution feeder

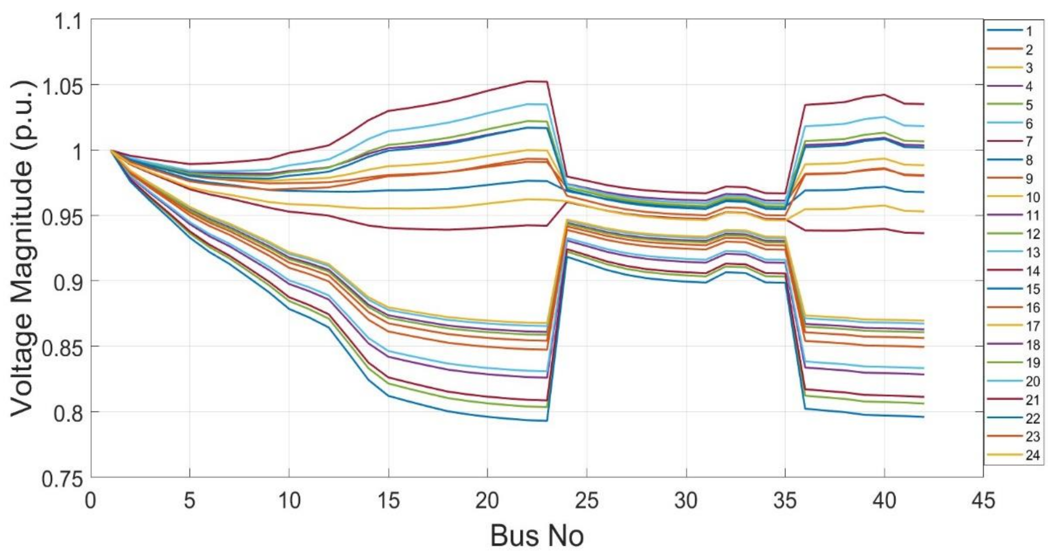

Figure 22: Bus voltage magnitude with no control after PV penetration for 42 bus radial distribution feeder

In Figure 23, reactive power outputs of PV installed at bus 20, 22 and 40 are illustrated. It is seen that the reactive power support from PVs decreases when the real power output from the PVs increases. It is also seen that PV inverters start to absorb the reactive power from the system and inject reactive power to the system so that voltage deviation and power loss in the system will be minimum.

The voltage deviations in the system after reactive power output by PV inverter is represented in Figure 24. In this case, all the bus voltages are below the permissible limit of allowable upper voltage bound but the voltages of some buses are below the permissible limit. The maximum voltage is at Bus 22 (i.e. 1.033 pu) and minimum voltage is at Bus 36 (i.e. 0.9110 pu) which violates the lower allowable permissible limit of the voltage. The voltages of some buses are also not in permissible limit.

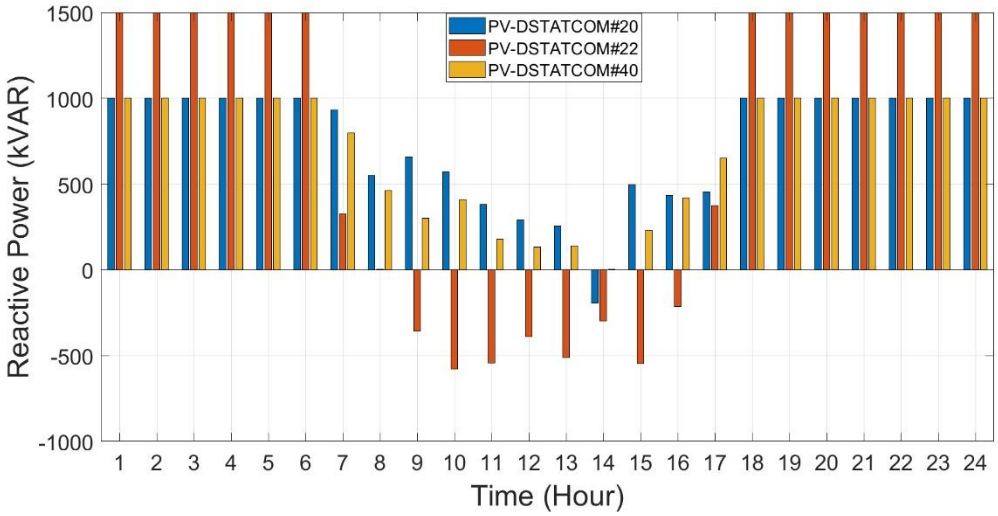

Figure 23: Reactive power injection/absorption by PV-DSTATCOM for 42 bus radial distribution feeder

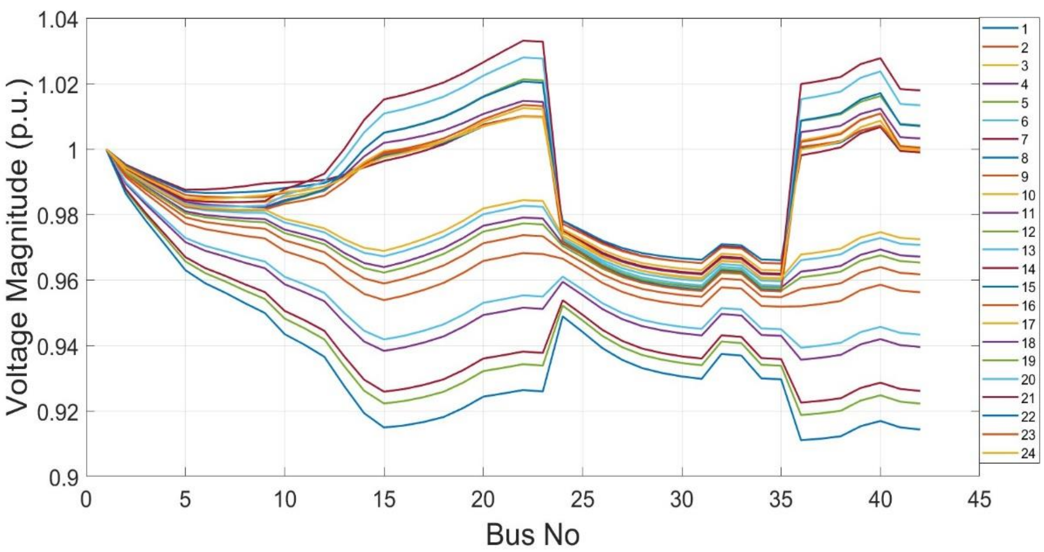

Figure 24: Bus voltage magnitude after reactive power outputs by PV inverters for 42 bus radial distribution feeder

The tap changes for the tap changer transformer is illustrated in the graph shown in Figure 25. The tap position of OLTC is increased to position 10 and still the voltages of some buses are below the permissible limit so position of OLTC is increased up to position 12 so that the voltage will be in the permissible limit.

In this case, the optimal reactive power absorbed or injected by PV inverters installed at various buses are not able to maintain voltage to permissible limit. So, operation of OLTC is required at different times.

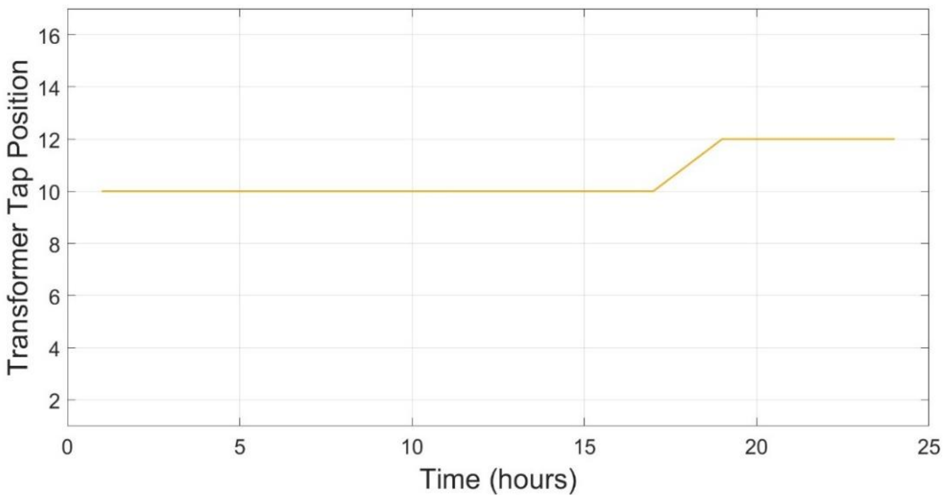

Figure 25: Tap position for OLTC for 42 bus radial distribution feeder

The voltage profile obtained when reactive power outputs of PV inverter and OLTC both are used for the voltage control is represented by the graph in figure 26. In this case, the minimum voltage is 0.9533 pu at Bus 36 and maximum voltage is 1.039 pu at Bus 22. All the bus voltages are within the permissible voltage limit. This is the best voltage profile that is obtained by coordination of inverter based PVs and OLTC of the transformer.

The active and reactive energy losses of the 42 bus radial distribution feeder were examined in four different cases and results were plotted in Figure 27 and 28. It can be seen that losses were highest in case 1, when there was no integration of photovoltaic energy.

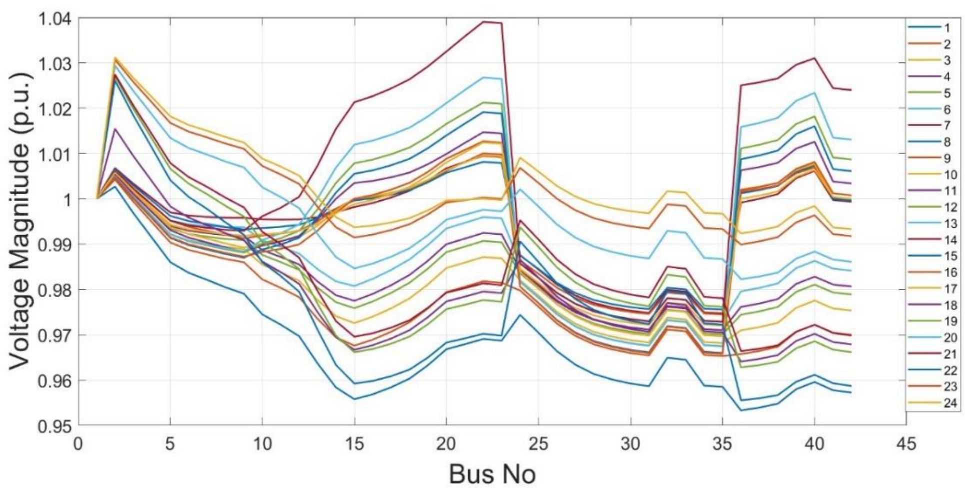

Figure 26: Voltage profile when reactive power outputs of PV inverter and OLTC both are used for the voltage control for 42 bus radial distribution feeder

However the losses were significantly reduced with the integration of PV as shown in case 2. In case 4, the losses increase in comparison to case 2 but reduce as compared to case 1 after injection/absorption by PV inverter and OLTC operation.

Active energy losses and reactive energy losses in the system have been reduced by 17.24% and 18.49% respectively in case 2 compared to case 1. However, it is discovered that the minimum voltage is 0.7932 pu and maximum voltage is 1.053 pu which are not within the permissible limit. The voltage improves further in case 3 i.e. maximum and minimum voltages are 1.033 pu and 0.9110 pu respectively but still the minimum voltage is below the permissible limit. In this case, loss increase slightly compared to case 2. In case 4, active energy losses and reactive energy losses in the system are reduced by 5.16% and 10.84% respectively as compared to case 1. In this case, the maximum and minimum voltage magnitudes are 1.039 pu and 0.9533 pu which are within the permissible limit.

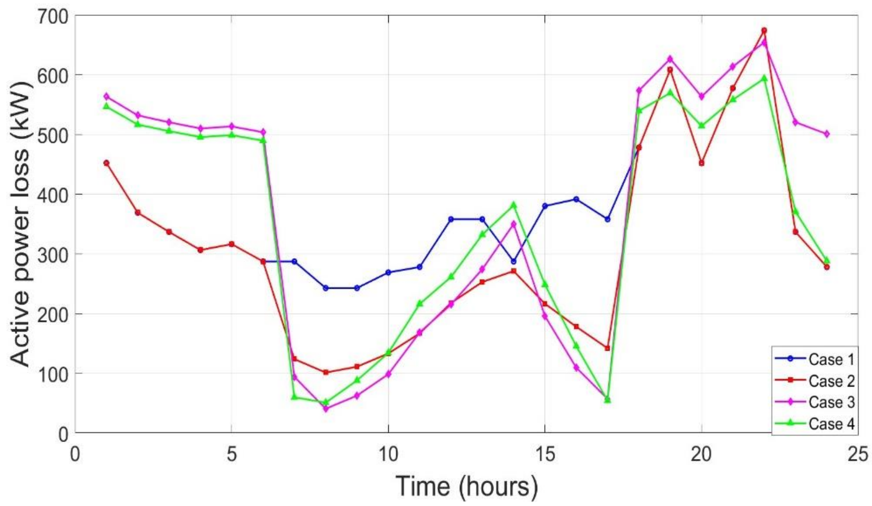

Figure 27: Active power loss under four cases for 42 bus radial distribution feeder

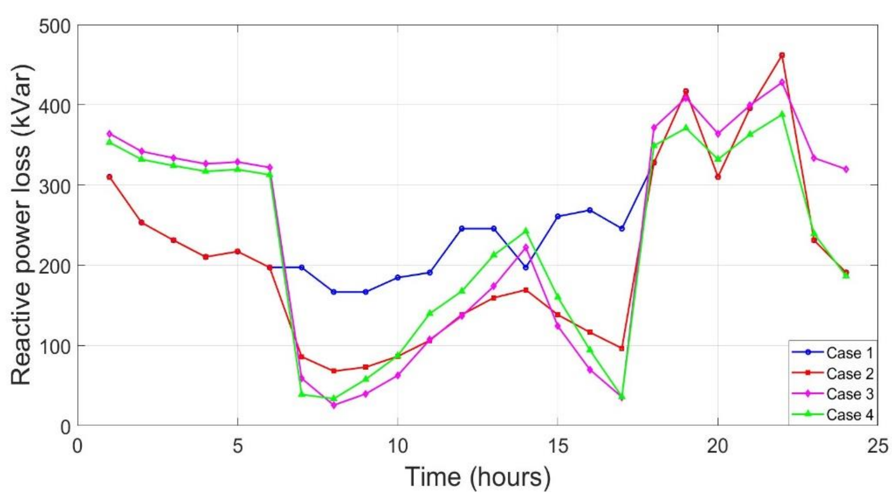

Figure 28: Reactive power loss under four cases for 42 bus radial distribution feeder

The outcomes under various cases for 42 bus radial distribution feeder is shown in Table 4.

Table 4: Outcomes under various cases for 42 bus radial distribution feeder

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Active Energy Loss (kWh)	8917.98	7380.35	8804.03	8457.89
Percentage reduction in active energy losses (%)		17.24	1.28	5.16
Reactive Energy Loss (kVARh)	6124.73	4992.55	5668.04	5461.02
Percentage reduction in reactive energy losses (%)		18.49	7.46	10.84
Min. Voltage (p.u.)	0.7932	0.7932	0.9110	0.9533
Max. Voltage (p.u)	1.000	1.053	1.033	1.039

4. Conclusions

In this paper, a coordinated voltage control with power loss minimization has been proposed, and its effectiveness has been evaluated. The study showcases the potential of the proposed approach to achieve the goal of voltage control when there is penetration of Renewable Energy Sources in distribution network than the conventional technique by effectively combining both conventional device (OLTC) and PV smart inverters. To optimize the proposed approach, three different metaheuristic algorithms namely GA, SO and MSO has been used and tested on the IEEE 33 bus test system and 42 bus radial distribution feeder.

The results demonstrate that active energy loss and reactive energy loss are reduced by 25.78% and 18.73% respectively in IEEE 33 bus system. On the 42 bus 11 kV radial distribution feeder, active energy loss reduction of 5.16% and reactive energy loss reduction of 10.84% are achieved. The findings of this research suggest that the proposed methodology is a viable and efficient solution for voltage control in distribution systems along with power loss minimization.

Conflicts of Interest Statement

The authors declare no conflicts of interest for this study.

Data Availability Statement

The data supporting the findings of this study are presented in the manuscript. Additional data will be provided upon request.

References

1. Mataifa H, Krishnamurthy S, Kriger C. Volt/VAR optimization: a survey of classical and heuristic optimization methods. IEEE Access 2022:13379–99.
2. Jabr RA. Robust Volt/VAr control with photovoltaics. IEEE Trans Power Syst; 2019. p. 1–1.
3. Smith JW, Sunderman W, Dugan R, Seal B. Smart inverter volt/var control functions for high penetration of PV on distribution systems. In: In 2021 IEEE/PES Power Systems Conference and Exposition. p. 1–6.
4. Mehta P, Bhatt P, Pandya V. Optimized coordinated control of frequency and voltage for distributed generating system using Cuckoo Search Algorithm. Ain Shams Eng J 2019;9(4):1855–64.

5. Ramadan A, Ebeed M, Kamel S, Ahmed EM, Tostado-Véliz M. Optimal allocation of renewable DGs using artificial hummingbird algorithm under uncertainty conditions. Ain Shams Eng J 2023;14(2):101872.
6. Malekpour AR, Niknam T. A probabilistic multi-objective daily Volt/Var control at distribution networks including renewable energy sources. Energy 2021;36 (5):3477–88.
7. Satsangi S, Kumbhar GB. Effect of load models on energy loss reduction using volt-var optimization. In: Proc. Nat. Power Syst. Conf.; 2021. p. 1–6.
8. Chen Y, Strothers M, Benigni A. All-day coordinated optimal scheduling in distribution grids with PV penetration. Electr Pow Syst Res 2019; 164:112–22.
9. Jahangiri P, Aliprantis DC. Distributed volt/VAr control by PV inverters. IEEE Trans Power Syst. 2013;28(3):3429–39.
10. Shayani RA, Oliveira MAG. Photovoltaic generation penetration limits in radial distribution systems. IEEE Trans Power Syst. 2011; 26(3): 1625-31
11. Jabr, R.A. Linear decision rules for control of reactive power by distributed photovoltaic generators. IEEE Trans. Power Syst. 2017, 33, 2165–2174.
12. Zhang, Q.; Dehghanpour, K.;Wang, Z. Distributed CVR in Unbalanced Distribution Systems with PV Penetration. IEEE Trans. Smart Grid 2019, 10, 5308–5319.
13. Ge, X.; Shen, L.; Zheng, C.; Li, P.; Dou, X. A Decoupling Rolling Multi-Period Power and Voltage Optimization Strategy in Active Distribution Networks. Energies 2020, 13, 5789.
14. Li, C.; Disfani, V.R.; Haghi, H.V.; Kleissl, J. Coordination of OLTC and smart inverters for optimal voltage regulation of unbalanced distribution networks. Electr. Power Syst. Res. 2020, 187, 106498.
15. Kundu, S.; Backhaus, S.; Hiskens, I.A. Distributed control of reactive power from photovoltaic inverters. In Proceedings of the 2013 IEEE International Symposium on Circuits and Systems (ISCAS), Beijing, China, 19–23May 2013; IEEE: Piscataway, NJ, USA, 2023.
16. Jafari, M.; Olowu, T.O.; Sarwat, A.I. Optimal smart inverters volt-var curve selection with a multi-objective volt-var optimization using evolutionary algorithm approach. In Proceedings of the 2018 North American Power Symposium (NAPS), Fargo, ND, USA, 9–11 September 2018; IEEE: Piscataway, NJ, USA, 2018.
17. Olowu, T.O.; Jafari, M.; Sarwat, A.I. A multi-objective optimization technique for volt-var control with high pv penetration using genetic algorithm. In Proceedings of the 2018 North American Power Symposium (NAPS), Fargo, ND, USA, 9–11 September 2018; IEEE: Piscataway, NJ, USA, 2018.
18. Lee, H.; Kim, J.-C.; Cho, S.-M. Optimal Volt–Var Curve Setting of a Smart Inverter for Improving Its Performance in a Distribution System. IEEE Access 2020, 8, 157931–157945.
19. Ceylan, O.; Liu, G.; Tomsovic, K. Coordinated distribution network control of tap changer transformers, capacitors and PV inverters. Electr. Eng. 2017, 100, 1133–1146.
20. Chen, Y.; Strothers, M.; Benigni, A. Day-ahead optimal scheduling of PV inverters and OLTC in distribution feeders. In Proceedings of the 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, USA, 17–21 July 2016; IEEE: Piscataway, NJ, USA, 2016.
21. Ceylan, O.; Liu, G.; Xu, Y.; Tomsovic, K. Distribution system voltage regulation by distributed energy resources. In Proceedings of the 2014 North American power symposium (NAPS), Pullman, WA, USA, 7–9 September 2014; IEEE: Piscataway, NJ, USA, 2014.

22. Yang, H.-T.; Liao, J.-T. MF-APSO-Based Multiobjective Optimization for PV System Reactive Power Regulation. IEEE Trans. Sustain. Energy 2015, 6, 1346–1355.
23. Singh, S.; Pamshetti, V.B.; Thakur, A.K. Multistage Multiobjective Volt/VAR Control for Smart Grid-Enabled CVR with Solar PV Penetration. IEEE Syst. J. 2021, 15, 2767–2778.
24. Su, X.; Liu, J.; Tian, S.; Ling, P.; Fu, Y.; Wei, S.; SiMa, C. A multi-stage coordinated volt-Var optimization for integrated and unbalanced radial distribution networks. Energies 2020, 13, 4877.
25. Lee, H.-J.; Yoon, K.-H.; Shin, J.-W.; Kim, J.-C.; Cho, S.-M. Optimal Parameters of Volt–Var Function in Smart Inverters for Improving System Performance. Energies 2020, 13, 2294.
26. Lee, Y.-D.; Lin, W.-C.; Jiang, J.-L.; Cai, J.-H.; Huang, W.-T.; Yao, K.-C. Optimal Individual Phase Voltage Regulation Strategies in Active Distribution Networks with High PV Penetration Using the Sparrow Search Algorithm. Energies 2021, 14, 8370.
27. Xu, R.; Zhang, C.; Xu, Y.; Dong, Z.; Zhang, R. Multi-Objective Hierarchically-Coordinated Volt/Var Control for Active Distribution Networks with Droop-Controlled PV Inverters. IEEE Trans. Smart Grid 2022, 13, 998–1011.
28. Senjyu, T.; Miyazato, Y.; Yona, A.; Urasaki, N.; Funabashi, T. Optimal Distribution Voltage Control and Coordination with Distributed Generation. IEEE Trans. Power Deliv. 2008, 23, 1236–1242.