Optimal Coordinated Voltage Control in Distribution Systems with Smart Inverter-Interfaced Solar PV Penetration: A Discrete Jellyfish Search Algorithm Approach

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Received: 20.06.2023 Accepted:03.08.2023

Abstract- The intermittent nature of photovoltaic power causes a voltage control issue. This study evaluates the effect that the smart inverter capabilities of a photovoltaic (PV) based distributed generator (DG) have on voltage regulation. In high-penetrated PV-based DG in distribution systems, a coordinated voltage control (CVC) technique is suggested in this paper. This method makes use of both conventional voltage regulating devices and the coordinated reactive power capabilities of smart inverters to reduce voltage violations brought on by the intermittent nature of photovoltaic energy. The objective of this study is to reduce energy losses while keeping voltage within reasonable bounds. A discrete jellyfish search algorithm is presented to attain the best optimization. With the help of the IEEE 33 bus distribution system, the suggested solution is validated. The evaluation's conclusions show that the proposed approach significantly reduces the active and reactive power losses by 22.28% and 13.68% compared to the base network, maintaining the voltage within permissible limits.

Keywords Coordinated Voltage Control; solar photovoltaic generation; distribution network; smart inverter.

Nomenclature

Set/index		
h	:	hour
Nb	:	Total number of buses
Ω_{PV}, Ω_{CB}	:	Set of PV and capacitor banks (CBs) mounted buses
parameters		
V_{min}, V_{max}	:	voltage magnitude limits
Δq_i^{cb}	:	capacitor bank step change at i^{th} bus
Variables		
$Q_{loss,i}^h$, $P_{loss,i}^h$	:	Losses in reactive and active power at h^{th} hour respectively in a branch linked to the i^{th} bus
P_{grid}^h, Q_{grid}^h	:	Grid active power and reactive power drawn from substation at h^{th} hour respectively
$P_{dem,i}^h$, $Q_{dem,i}^h$	:	demand of active and reactive power at h^{th} hour at i^{th} bus respectively
$Q_{CB,i}^h$	:	Capacitor bank reactive power injection at h^{th} hour at i^{th} bus
$P_{PV,i}^h$, $Q_{PV,i}^h$	:	PV-smart inverter active power and reactive power at h^{th} hour at i^{th} bus
$Q_{PV,i}^{max}$	:	PV-smart inverter maximum reactive power
st_i^h	:	OLTC tap step change at h^{th} hour at i^{th} bus
V_i^h	:	voltage magnitude at h^{th} hour at i^{th} bus
tap^h	:	OLTC transformer tap position

1. Introduction

1.1. Motivation

In recent times, the deployment of renewable energy sources in distribution systems has seen tremendous growth, driven by their eco-friendly nature [1] [2] [3]. However, the operation of a low voltage (LV) grid with significant solar photovoltaic (PV) generation penetration [4] [5] [6] can severely impact the distribution system. Several challenges arise from this situation, including increased voltage levels, higher energy losses, greater energy consumption, bidirectional power flow, and fluctuations in power flow [7] [8] [9]. To tackle these issues, volt/VAR control (VVC) has been implemented, relying on conventional voltage control devices such as capacitor banks (CBs) and on-load tap-changing transformers (OLTC) [10] [11] [12] [13] [14]. Nevertheless, the frequent use of these conventional devices could lead to a shorter useful lifetime. On the other hand, smart inverters have gained attention due to their flexibility and adaptability. The variable working modes of smart inverters used in PV generation have made them increasingly popular [15], and they have proven successful in providing reactive power adjustment during non-operational times [16] [17]. However, an improper coordinated approach between the operation of conventional and advanced voltage control devices can have negative consequences for the system [18] [19]. Hence, the present literature emphasizes the necessity for an optimal coordinated voltage control, taking into account smart inverter interfaced solar PV penetration.

1.2. Literature Survey

The significant impact of Distributed Generators (DGs) on power losses and voltage profiles has been extensively discussed in [20]-[23], utilizing various metaheuristic methods. İn [20] [21] adopted the network reconfiguration scheme for loss minmization. In [22], the significant impact of DGs on power loss minimization was solved using power loss sensitivity index and a non-linear programming solver. In [23] loss allocation in radial DN branch oriented approach disscused. In [24], the impact of high penetration of renewable generation in low voltage systems on network losses and voltage conditions in a low voltage network was investigated. A comprehensive review has been presented in [25] for volt-var control to support the penetration of RES into the distribution systems. In [26], a honey bee mating optimization based on an upgraded chaotic scheme was suggested to approximate the active power scheduling of DGs, the reactive power dispatch of capacitors, and the OLTC tap locations. In [27], a genetic algorithm (GA) was adopted to enhance the performance of VVC devices in active distribution networks. İn [28], both energy loss and peak load reduction in the distribution network were optimized using a non-dominated sorting genetic algorithm (NSGA-II). In this [29] algorithm discussed the fast convergence as been implemented to optimize the active and reactive power losses of distribution networks by finding the optimal allocation of distributed generations and capacitor bank in the networks. To ensure the efficient activation of voltage-regulated control devices in distribution networks, authors in [30] adopted a particle swarm evolutionary method. In [31], a coordinated strategy including static VAR compensators and on-load tap changers (OLTCs) was suggested to reduce total line losses in the distribution network. In [32], particle swarm optimization (PSO) was suggested to choose the best configuration for VVC devices while considering scattered energy into reason to minimize energy loss in the distribution network. The utilization of Grey Wolf Optimization was implemented in [33] to ascertain the scheduling of reactive power allocation for both Dispatchable and Non-dispatchable Distributed Generators (DGs). In this [34] study drawn the conclusion of without DG, with DG, diffrent DG models.

However, despite being mentioned in the literature [1]–[34], these studies had overlooked the evaluation of smart inverters' reactive power capability in voltage regulation. In [35], the focus was on reducing losses and voltage variations by efficiently scheduling reactive power from OLTCs, shunt capacitors, and PV inverters. The potential energy savings achieved by integrating VVC strategies with solar PV inverters were explored in [36]. Furthermore, in [37][38], PV inverters were equipped with voltage control loops to maintain appropriate voltage levels, accomplished by either supplying or absorbing reactive power in the presence of high PV penetration in distribution networks.

In fact, most studies have neglected the significance of reactive power injection in [39] loss minimization and voltage management in favour of concentrating largely on the active power from PV-DGs. These devices are frequently run autonomously, as well. A coordinated voltage control (CVC) technique has been proposed to meet these restrictions in order to decrease losses and control voltage. In order to address problems, this technique combines conventional voltage control devices with smart inverter-interfaced PV-DG. In addition, the effects of various load types, including constant power and voltage-dependent loads, have been investigated. In [40] controlled the voltage by three-phase step voltage regulators. The active and reactive power output of PVs are coordinated by whale optimization algorithm.

1.3 Contributions

The following are the primary contributions of the current paper:

- Through the use of a coordinated VVC system, a time series model has been created to reduce power loss and voltage changes.
- A coordinated voltage control mechanism has been established considering both conventional and cutting-edge VVC regulating devices.
- Discrete Jellyfish Searching Optimisation (DJSO) has been used to improve the scheduling of the CVC problem without relaxing or linearization. The efficiency and effectiveness of the suggested strategy are greatly increased by this optimisation method.
- The influence of high PV deployment on voltage regulation has been studied, illuminating the need for advanced control techniques and disclosing information regarding the impact of high PV dispersion on voltage regulation.
- Its authentication on IEEE 33 bus distribution systems has shown the approach's applicability and efficacy in real-world circumstances.

1.4. Structure of Paper

This paper is structured as follows: The research issue that is being looked into is designated in Section 2. Section 3 describes the suggested solution algorithm.further, the use of the coordinated voltage control (CVC) and the discrete jellyfish search optimisation technique is described. The results are fully summarised in Section 4 along with remarks. Section 5 concludes by outlining the study's findings.

2. Problem Formulation

2.1. Objective Function

In this paper, minimization of energy losses is considered as fitness function as given in (1)

$$OF_1 = \sum_{h=1}^{T}\left(\sum_{i=1}^{Nb}\left|P_{loss,i}^{h} + jQ_{loss,i}^{h}\right|\right) \tag{1}$$

Decision variables

The OLTC transformer taps, CB switching steps, and reactive power settings on the PV smart inverter are the primary decision variables for the CVC problem

- OLTC transformer tap position of (tap^h)
- shunt capacitor banks step position (st_i^h)
- reactive power from PV smart inverter $(Q_{PV,i}^h)$

$$X = \left[tap^h, st_i^h, Q_{PV,i}^h\right] \tag{2}$$

2.2 constraints

- Active power and reactive power balance limits in the network

$$P_{grid}^h - \sum_{i=1}^{Nb} P_{loss,i}^h - \sum_{i=1}^{Nb} P_{dem,i}^h + \sum_{i\in\Omega_{pv}} P_{PV,i}^h = 0 \tag{3}$$

$$Q_{grid}^h - \sum_{i=1}^{Nb} Q_{loss,i}^h - \sum_{i=1}^{Nb} Q_{dem,i}^h + \sum_{i\in\Omega_{CB}} Q_{CB,i}^h + \sum_{i\in\Omega_{pv}} Q_{PV,i}^h = 0 \tag{4}$$

- System voltage magnitude limits

$$V^{min} \le V_I^h \le V^{max} \tag{5}$$

- Tap settings of OLTC transformer limits

$$a^h = 1 + tap^h \frac{\Delta tap_{step}}{100} \tag{6}$$

here,

$$tap^h \in \{tap^{min} \ldots -2, -1, 0, 1, 2, \ldots .\, tap^{max}\}$$

- Capacitor banks (CBs) limits

$$Q_{CB,i}^h = st_i^h \Delta q_i^{cb}; i \in \Omega_{CB} \tag{7}$$

Where, $st_i^h \in \{0, 1, \ldots\ldots st_i^{max}\}$

- PV smart inverter reactive power limit

$$Q_{PV,i}^h = \sqrt{\left(\left(S_{pv,i}^{max}\right)^2 - \left(P_{pv,i}^h\right)^2\right)} \tag{8}$$

$$-Q_{PV,i}^{max} \le Q_{PV,i}^h \le Q_{PV,i}^{max} \tag{9}$$

- Voltage dependent load models

$$P_{dem,i}^h = P_{dem,i}^{nom,h}\left[Z_i^p\left(\frac{V_i}{V^n}\right)^2 + I_i^p\left(\frac{V_i}{V^n}\right) + P_i^p\right] \tag{10}$$

$$Q_{dem,i}^h = Q_{dem,i}^{nom,h}\left[Z_i^q\left(\frac{V_i}{V^n}\right)^2 + I_i^q\left(\frac{V_i}{V^n}\right) + P_i^q\right] \tag{11}$$

3. Overview of Jellyfish Searching Algorithm (JSA)

The Jellyfish Searching Optimisation (JSO) algorithm [41] uses jellyfish movement patterns to solve optimisation issues. It effectively explores complex search spaces by combining local exploitation and random exploration algorithms. JSO uses a population of solution agents that interact and adapt across iterations, much like jellyfish swimming in a decentralised fashion. A fitness evaluation function directs these agents as they travel arbitrarily through the solution space. The sharing of information between nearby agents is how local exploitation is accomplished. Due to its decentralised structure and parallelizability, JSO is a good choice for resolving a variety of optimisation issues, including those involving high-dimensional and multimodal environments. In many different fields, it has demonstrated promising performance. There are different stages of JSO as describe below

Ocean current: The ocean current, which is controlled by the direction specified by Eq. (12), is the thing that attracts jellyfish because of its plentiful food source.

$$\overrightarrow{trend} = Y^* - \beta \times rand(0,1) \times \mu \tag{12}$$

Where Y* is the swarm's best location and μ is the jellyfish mean location

Eq. (13) provides each jellyfish new location, which is influenced by several factors including the coefficient of distribution (β) which is connected to the span of the vector $\overrightarrow{trend}$.

$$Y_i(iter + 1) = Y_i(iter) + rand(0,1) \times \overrightarrow{trend} \tag{13}$$

Jellyfish swarm: When moving in swarms, jellyfish can move in two different ways: passively (type A) or actively (type B). When a jellyfish swarm first forms, it typically exhibits type A motion, which gradually changes to type B motion over time. Eq. (14) is utilised to determine each jellyfish's updated location in accordance with motion of Type A scheme, This involves jellyfish moving around their own spaces.

$$Y_i(iter + 1) = Y_i(iter) + \gamma \times rand(0,1) \times (U_B - L_B) \tag{14}$$

Where U_B and L_B represent the upper and lower bounds of search spaces, respectively, and $\gamma > 0$ refers to a motion coefficient that measures the amount of motion that occurs around jellyfish sites.

In simulations of jellyfish swarms, Type B comprises a jellyfish *i* moving either towards or away from a jellyfish *j*. To determine the motion's direction, a jellyfish *j* different than jellyfish i is randomly selected, and a vector is made from jellyfish *i* to jellyfish *j*. Jellyfish *i* will travel towards jellyfish *j* if the amount of food at jellyfish *j*'s position is greater than it is at jellyfish *i*'s location. Jellyfish *i*, on the other hand, migrate away from jellyfish *j* if the amount of food there is lower than it is there. Because of this, each jellyfish can relocate to a more advantageous spot within the swarm to acquire nourishment. The updated location of a jellyfish and its direction of travel are both simulated using Eqs. (15) and (16), respectively.

$$\overrightarrow{Direction} = \begin{cases} Y_j(iter) - Y_i(iter) & if\ f(Y_i) \ge f(Y_j) \\ Y_j(iter) - Y_i(iter) & if\ f(Y_i) < f(Y_j) \end{cases} \tag{15}$$

$$Y_i(iter+1) = Y_i(iter) + rand(0,1) \times \overrightarrow{Direction} \qquad (16)$$

Time control mechanism: The type of motion in the jellyfish swarm, as well as the jellyfish's migrations towards the ocean current, are both controlled by the time control mechanism. It is composed of a constant value (C_0) and a time control purpose, indicated as *c(iter)*. The time control action is a random number generated by Eq. (17), which over time decreases from 1 to 0. The jellyfish will migrate with the ocean current when *c(iter)*is greater than C_0, and they will move within the swarm when *c(iter)* is less than C_0. This value is kept to 0.5. This strategy guarantees the efficiency of the time control mechanism and enables the jellyfish to travel in a regulated manner, depending on the value of *c(iter)*, either within the swarm or towards the ocean current.

$$c(iter) = \left|\left(1 - \frac{iter}{iter_{max}}\right) \times (2 \times rand(0,1) - 1)\right| \qquad (17)$$

where iter is the number of iterations and $iter_{\max}$ is the number of iterations up to a maximum.

Boundary Conditions: In the event that a jellyfish ventures external the search area's bounds, Eq. (18) will be used to bring it back to the opposite boundary.

$$\begin{Bmatrix} Y'_{i,d} = \left(Y_{i,d} - U_{B,d}\right) + L_{B,d} \quad if\ Y_{i,d} > U_{B,d} \\ Y'_{i,d} = \left(Y_{i,d} - L_{B,d}\right) + U_{B,d} \quad if\ Y_{i,d} < L_{B,d} \end{Bmatrix} \qquad (18)$$

The d^{th} dimension of the i^{th} jellyfish's location is denoted by $Y_{i,d}$ in this context, while $Y'_{i,d}$ denotes the modified location after boundary restrictions have been taken into consideration. Particularly, $U_{B,d}$ upper and $L_{B,d}$ lower bounds in the d^{th} dimension of the search space.

Discrete JSA

The Jellyfish Search Algorithm (JSA) is frequently used to solve continuous optimisation issues. Due to its intrinsic coding structure, it cannot be used directly to resolve discrete optimisation issues, such the VVO problem. The JSA code has to undergo a number of changes as a result for it to be able to tackle the current optimisation issue. The JSA code was altered twice to enable the discrete optimisation problem known as the CVC problem to be solved.

- First, the nearest integer value for each variable was chosen to perform integer random initialization.
- Second, using the bracket function stated in Eq. (19), the solution variables produced for the dth dimension using Equation (16), $Y_{i,d}(iter+1)$, were rounded off to the nearest integer value.

$$\begin{Bmatrix} Y^m_{i,d}(iter+1) = \left[Y_{i,d}(iter+1)\right], d: 1 \to n \\ Y_{i,d}(iter+1) \in \Re\ and\ Y^m_{i,d}(iter+1) \in Z \end{Bmatrix} \qquad (19)$$

Table 1 shows the proposed pseudo-algorithm for the CVC in distribution network with smart inverter interfaced solar PV penetration problem.

Table 1. Pseudo algorithm

Begin
Define the objective function f(X) using Eq.(1), X is decision variable as given in Eq.(2)
Set the maximum number of population size(nps) and maximum iteration
Initilaise population of jelly fish Xi (i=1,2,….nps) using discrete population
Determine the amount of food X_i, and fitness function f(X) using Eq.(1)
Identify the jellyfish at the spot that has the most food currently (X*)
Initlaize iter: iter=1
Repeat
For i=1: nps **do**
Determine the time control *c(iter)* using Eq. (17)
If c(t)> 0.5: Jellyfish will float together with the ocean current **then**
1) Ocean current could be determined by using Eq.(12)
2) Updated location can be find by Eq.(13)
Else: jellyfish swim within the swarm.
if (rand(0,1)>(1-c(t))) **then**
Type A motion has been exhibits
Updated location can be find by using Eq.(14)
Else
Type B motion has been exhibits
Updated location can be find by using Eq.(16)
End if
End if
check limits and determine the f(X) using Eq.(1) at updated location X_i
End for
Update the iteration
Until stop criterion is met (iter>itermax)
Output the best results and visualization
End

4. Results and Observations

The MATLAB environment has been used to implement the recommended coordinated voltage control method. The control method's effectiveness has been examined, and it has been applied to the IEEE 33 bus distribution system. For this bus system, exact load and line data were gathered from [42]. OLTC, CBs, and PV smart inverters are examples of control components that are not present in the original system. The parameters of both modified test systems are shown in Table 2. The load profile and PV generation output over a 24-hour period are shown in Figure 1.

Table 2. Details of case system

Voltage	12.66 KV
OLTC transformer tap	-16 to 16 taps
active power consumption	3715 kW
reactive power consumption	2300 kVAR
Capacitor bank allocation buses	5, 3, 10, 24, 15
Capacitor bank capacity	600 kVAR

PV-DG mounted buses (size in kVA)	15 (750),17 (950), 33 (750)
tolerable voltage limits	From 0.95 to 1.05 per unit

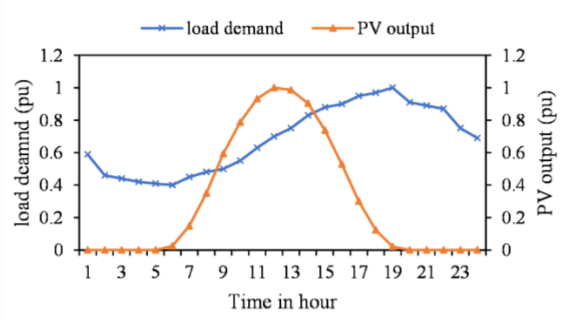

Fig. 1 Load and PV generation: Forecasted output

4.1 Effectiveness of Proposed Algorithm

The proposed DJSO optimization has been utilized to minimize overall power loss while keeping the voltage profile within permissible limit. Four scenarios have been researched and are listed in Table 3 to demonstrate the effects of corresponding operation of various devices such smart inverter interfaced PV-DG, OLTC, and SCBs. Case 1 is the base case no PV integration has been considered. Case 2, high PV penetration has considered. The usage of the traditional VVC devices (OLTC and CBs) is present in Case 3 as well, making it similar to Case 2 in many ways. A PV-DG with a smart inverter is also included in Case 4 along with standard VVC devices.

Table 3. Cases studied

Cases	PV-DG	OLTC	SCBs	PV-DG with SI
Case 1	No	No	No	No
Case 2	Yes	No	No	No
Case 3	Yes	Yes	Yes	No
Case 4	Yes	Yes	Yes	Yes

No- denotes not considered, Yes- denotes considered

4.2 IEEE 33 Bus Distribution System Under Voltage Dependent Load

A overview of the findings for several cases is shown in Table 4. Comparing case 1 to case 2, real power losses are down 3.26% and reactive power losses are down 1.17%. The magnitudes of the voltage measured at the minimum and highest points are 0.919 pu and 1.0533 pu, respectively, which are outside the ranges of acceptable voltage. The unchecked high penetration of PV is to blame for this. Comparing example 3 to case 1, actual power losses drop by 19.06% and reactive power losses by 12.04%. This enhancement is made possible by managing conventional legacy VVC components like OLTCs and shunt capacitor banks. Last but not least, case 4 experiences a reduction in both actual and reactive power losses of 22.28% and 13.68%, respectively, compared to instance 1. This decrease is made possible by the use of conventional, legacy VVC equipment and the reactive power adjustment offered by PV-DG with smart inverters.

Table 4. 33 bus system: Results under various cases

Parameters	Case 1	Case 2	Case 3	Case 4
Apparent energy losses (kVAh)	2465.79	2401.64	2051.67	1985.50
energy losses reduction (%)		2.60	16.79	19.48
Active energy losses (kWh)	2042.68	1976.02	1653.28	1587.67
active energy losses reduction (%)	----	3.26	19.06	22.28
Reactive energy losses (kVARh)	1381.16	1365	1214.91	1192.28
reactive energy losses reduction (%)		1.17	12.04	13.68
Minimum. voltage (pu)	0.91615	0.919	0.945	0.95
Maximum voltage (pu)	1	1.0533	1.05	1.05

The best reactive dispatch of PV-DG using a smart inverter is shown in Figure 3. Given that the inverter's entire capacity is only being used for active power generation at 12:00, it is noteworthy that there is no reactive absorption or injection at that time. However, in the remaining hours, there is a chance for reactive power injection/absorption, which is reliant on the PV smart inverter's capability, as shown in Figure 2. The positive and negative sides reflect the injection and consumption of reactive power into the distribution network. The tap position of the OLTC for cases 3 and 4 is shown in Figure 3. In case 4, the tap position is kept higher, which reduces losses and improves voltage regulation, it is noticed.

The switching of shunt capacitor banks under various conditions is shown in Figure 4 throughout the day.

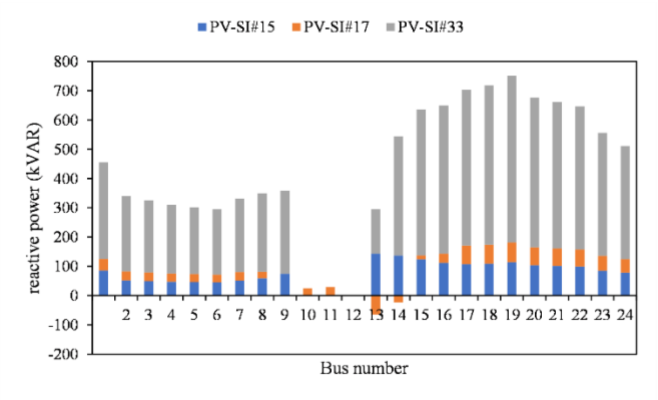

Fig. 2. PV smart Inverter: Reactive power injection and absorption under case 4

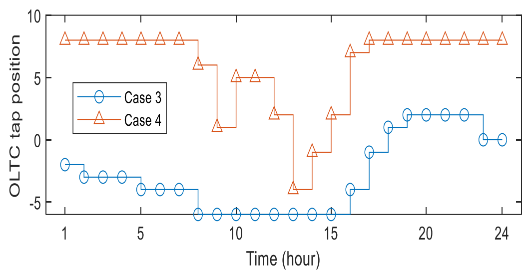

Fig. 3. OLTC transformer tap position in 24 hour under case 4

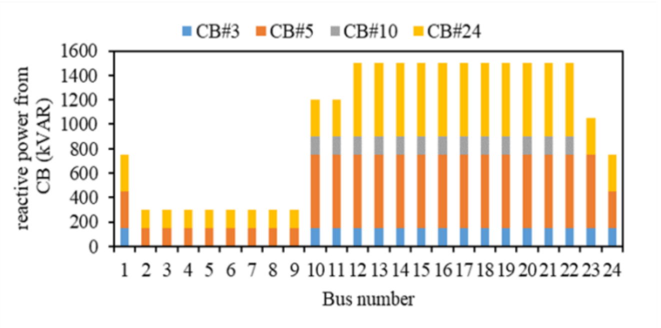

Fig. 4. CBs steps operation in 24 hour under case 4

4.3 Voltage Behavior During the Hour of Maximum PV Generation:

Figure 1 shows that at 12:00, PV generation peaked. Figure 5 shows the system's voltage behaviors under various conditions. When there is no PV generation, as in scenario 1, the voltage profile goes below the minimum voltage threshold. In contrast, instance 2's significant PV penetration causes the voltage profile to go over the permitted maximum voltage. The operation of conventional voltage control devices, however, ensures that in case 3, the voltage magnitude stays within acceptable bounds. Additionally, case 4 shows an increase in voltage magnitude. The efficient use of both traditional and modern voltage control technology is attributed with this achievement.

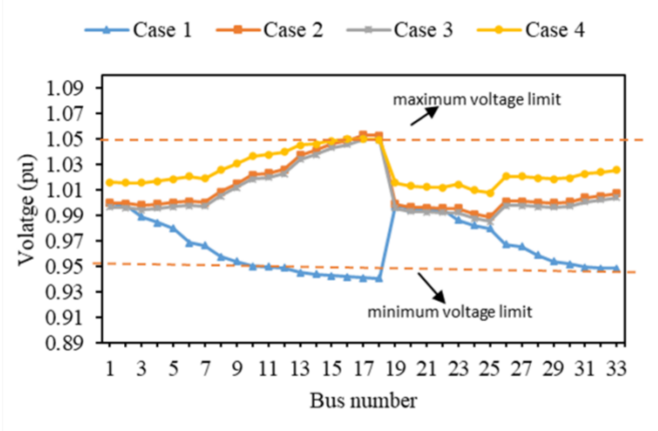

Fig. 5. Voltage profile at hour 12:00 for different cases

4.4 Voltage Behavior at Peak Loading Hour Point

The greatest loading period is seen at 19:00 in Figure 1. Figure 6 shows the system's voltage behaviours under various conditions. When there is no generation, the voltage profile falls below the minimum voltage threshold. The voltage profile in case 2 reaches the minimum voltage limit because there is no PV generation at 19:00. The operation of conventional voltage control devices, however, ensures that in case 3, the voltage magnitude stays within acceptable bounds. Additionally, case 4 shows an increase in voltage magnitude. This development is credited to the successful operation of both conventional and cutting-edge voltage control equipment.

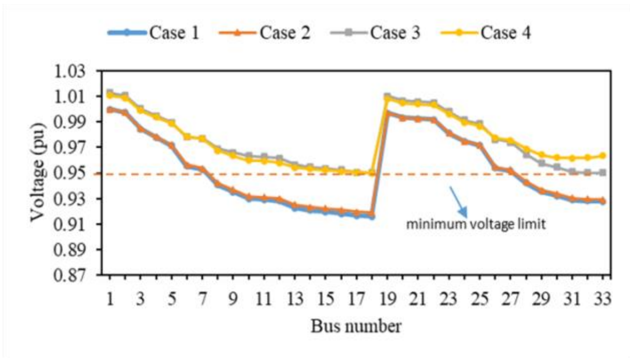

Fig. 6. Voltage profile at hour 19:00 for different cases

4.5 Comparison of Different Algorithms

Numerous cases have assessed the proposed DJSO (Discrete Jellyfish Searching Optimisation). For this system, a population size of 50 and a maximum iteration of 100 were used for all algorithms. Due to its complexity, case 4 was chosen to compare the performance of the several algorithms: Dandelion Optimizer Algorithm (DOA), Marine Predator Algorithm (MPA), Particle Swarm Optimisation (PSO), grey wolf optimisation (GWO), JSO (Jellyfish Searching Optimisation), and DJSO. Figure 8 shows the convergence patterns of these metaheuristic algorithms. In contrast to the DOA, MPA, PSO, GWO, and JSO, which converge to values of 2801.23 kVAh, 2759.79 kVAh, 2698.45 kVAh, 2510.98 kVAh, and 2498.23 kVAh, respectively, the suggested DJSO converges to a minimal energy losses value of 2465.8 kVAh. The best, mean, and worst values obtained by various metaheuristic methods are shown in Table 5. Notably, DJSO performs better than the other algorithms in every way. It can be argued that considerable advancements have been made by adding the proposed algorithm and using integer values in the traditional JSA (Jellyfish Searching Algorithm).

Table 5. Comparative analysis

Algorithm	DOA [24]	MPA [29]	PSO [18]	JSO [30]	GWO [20]	Proposed DJSO
Best	2801.23	2759.79	2698.45	2510.98	2498.23	2465.8
Average	3062.33	2985.623	2885.137	2756.39	2712.12	2644.82
Worst	5187.42	5150.812	4730.586	4753.76	4753.85	4414.45
Standard deviation	527.5054	502.1717	438.0233	495.801	475.623	420.028
Computation time (sec)	89	82	70	79	72	58

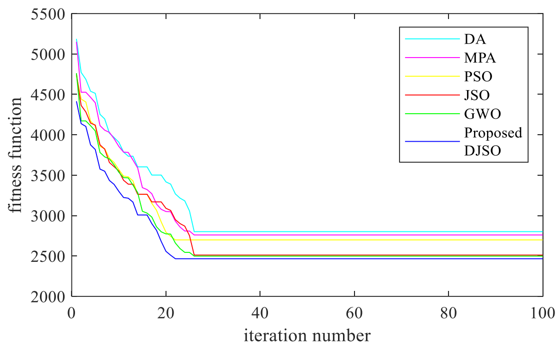

Fig. 7 convergence pattern of different algorithms

4.6 Sensitivity Analysis of the Proposed Model

This study performed sensitivity analysis on maximum number of iterations (it_{max}) and number of population (N) to assess their impact on the problem formulation and objective function (equation 1). 100 runs were conducted for each parameter set, employing statistical methods to determine DJSO's performance sensitivity. Mean values and standard deviations were subsequently calculated.

$$f(x_{avg}) = \frac{\sum_{k=1}^{100} f(x_b^k)}{100} \tag{20}$$

$$STD = \sqrt{\frac{\sum_{k=1}^{100}\left(f(x_b^k) - f(x_{avg})\right)^2}{100-1}} \tag{21}$$

The sensitivity analysis was performed using MATLAB (R2022b – Academic Version). In this analysis, $f(x_m)$ denotes the average value obtained from 100 runs, while $f(x_b^k)$ represents the best global solution obtained during each run. The standard deviation is denoted as STD. The simulations were carried out on a computer equipped with an AMD RYZEN 5 processor and 8 GB RAM.

4.6.1 Variation in Maximum Number of Iterations (it^{max})

In our investigation, we examined it_{max} from 10 to 500 while keeping N constant at 50. Table 6 displays the best, worst, mean, and standard deviation of the objective function. Notably, at itmax = 100, there was no significant change in performance (best, mean, and standard deviation). Therefore, iter 100 was chosen as the fixed value for this problem.

Table 6. Variation in it^{max} with N is constant =50

it_{max}	Best	Worst	Mean	Standard deviation
10	3082.250	5518.063	3306.025	525.035
20	2835.670	5076.617	3041.513	482.936
50	2589.090	4635.154	2776.950	440.500
75	2478.129	4436.500	2657.911	417.405
100	**2465.800**	**4414.450**	**2644.820**	**420.028**
150	2465.798	4414.450	2644.794	419.944
200	2465.775	4414.432	2644.714	419.524
300	2465.775	4414.428	2644.688	415.329
400	2465.775	4414.424	2644.661	411.176
500	2465.775	4414.410	2644.635	411.171

4.6.2 Variation in Population Size (N)

Table 7 illustrates the impact of population size on DJSO's performance, with itmax fixed at 500. As diversity increases, efficiency and effectiveness improve. However, larger population sizes result in higher computational burden. Notably, after 50 population, statistical performance remains consistent, indicating a threshold beyond which further increases do not significantly affect the best, mean, and standard deviations.

Table 7. variation in population size, it^{max} is constant =100

Population size (N)	Best	Worst	Mean	Standard deviation

5	3205.540	5738.785	3306.025	525.03
25	2712.380	4855.895	2909.302	462.03
50	**2465.800**	**4414.450**	**2644.820**	**420.02**
100	2465.775	4414.16	2644.556	420.02
200	2465.726	4414.318	2644.635	419.73
300	2465.578	4413.964	2644.291	416.24
400	2465.307	4413.567	2642.704	399.02
500	2464.814	4395.468	2631.596	386.00

4.7. Wilcoxon's Rank-sum Test and ANOVA Test

A thorough analysis, encompassing both non-parametric and parametric statistical approaches. The non-parametric analysis utilized Wilcoxon's rank-sum test to facilitate pairwise comparisons against a benchmark algorithm. Meanwhile, the parametric analysis employed the ANOVA test for multiple comparisons of the optimization algorithms.

Wilcoxon's rank-sum test provided valuable p-values, enabling the assessment of the fitness values of the two algorithms. A p-value less than 0.05 indicated the superiority of the first algorithm, DJSO, while a p-value greater than 0.05 favored the second algorithm. Accordingly, DJSO was designated as the first algorithm, and the other algorithms were classified as the second in Table 8. The results from Table 8 unequivocally demonstrated DJSO's superior performance over the other algorithms, thereby validating the efficacy of the proposed technique.

Table 8. wilconxon's test results

Sl no	Methods	p-values
1	DJSO vs. DA	1.26E-26
2	DJSO vs. MPA	2.97E-20
3	DJSO vs. PSO	2.22E-18
4	DJSO vs. JSO	3.06369E-14
5	DJSO vs. GWO	1.75902E-14

Furthermore, the ANOVA test compared the median values of the optimization algorithms, aiming to identify any significant differences. The authors conducted the ANOVA test for the problem formulated in Section 2, utilizing DJSO along with the other five reported approaches. Fig. 8 visually presented the variation of minimum values observed in 30 simulation runs. Consistently, the ANOVA test results showcased DJSO's superior performance compared to the other five algorithms for the present problem. This robust validation further strengthened the claim that DJSO outperformed the other algorithms, as supported by the ANOVA test.

In conclusion, both the Wilcoxon's rank-sum test and the ANOVA test consistently substantiated the assertion that DJSO exhibited greater effectiveness than the other optimization algorithms in addressing the problem outlined in the paper. The comprehensive statistical analyses conducted by the authors provide strong evidence of the superiority of DJSO, affirming the validity of the proposed technique.

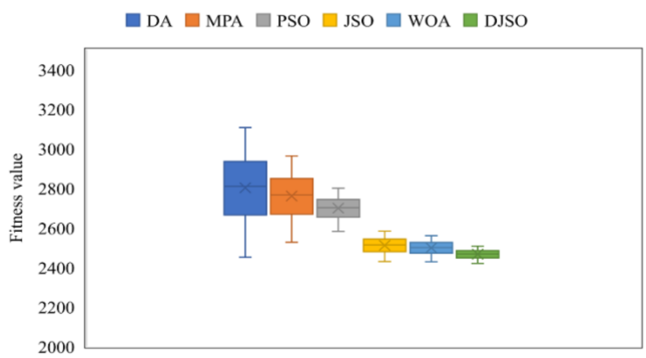

Fig. 8 Anova Test Results

5. Conclusion

In this study, we propose a coordinated voltage control (CVC) mechanism aimed at achieving both voltage regulation and loss minimization. The test results demonstrate the effectiveness of the suggested CVC methodology in regulating voltage and reducing losses. To enhance the distribution system's reactive power supply, we explore the widespread utilization of PV smart inverters. Properly coordinating the functioning of voltage and VAR control (VVC) devices with PV smart inverters can lead to significantly higher energy savings compared to traditional VVC techniques. Our evaluation focuses on a 33 bus distribution system, and the conclusions reveal a remarkable reduction in active and reactive power losses by 22.28% and 13.68%, respectively, when compared to the base network. Notably, the proposed approach successfully maintains voltage within permissible limits, ranging from 0.95 per unit (pu) to 1.05 pu, even during periods of high PV penetration in the system. The findings further indicate that the performance of the proposed Discrete Jellyfish search optimization (DJSO) algorithm surpasses that of existing algorithms.

Future research directions could encompass cost analysis, networked microgrid operations, network reconfiguration, and the integration of distributed energy resources as integral components of this methodology. Exploring these aspects could lead to even greater advancements in voltage control and loss reduction for distribution systems.

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