

Voltage Stability Assessment of Radial Distribution Systems Including Optimal Allocation of Distributed Generators

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ABSTRACT

Assessment of power systems voltage stability is considered an important assignment for the operation and planning of power system. In this paper, a voltage stability study using Continuous Power Flow (CPF) is introduced to evaluate the impact of Distribution Generator (DG) on radial distribution systems. On the way to allocate the DG, a hybrid between the Voltage Stability Index (VSI) and Whale Optimization Algorithm (WOA) is developed. The main purpose of using VSI is to find the most sensitive buses for allocating the DG in the system. Hence, Fuzzy logic control with the Normalized VSI (NVSI) and the voltage magnitude at each bus are used to determine the candidate buses. However, the best DG size is calculated using WOA. Four standard radial distribution systems are used in this paper; 12, 33, 69, and 85-bus. The developed hybrid optimization method is compared with other existing analytical and metaheuristic optimization techniques to prove its efficiency. The results prove the ability of the developed method in the allocation of DG. In addition, the influence of the DG integration on enhancing the voltage stability through injecting the proper active and reactive powers is studied.

KEYWORDS

Whale Optimization Algorithm, Fuzzy Logic Controller, Voltage Stability Index, Optimal DG Placement.

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I. INTRODUCTION

RECENTLY, the complexity of the power system has been increased to align the expansion of the total load demand due to the economic and environmental constraints [1]. Power systems could be viewed as complex systems due to their structure which includes many types of components such as controlling, measuring, and monitoring devices. Hence, the increase of the load may lead to disturbance occurrence in the power system which brings an unallowable reduction in the voltage level and raises the probability of voltage instability which affects the power system operation.

Voltage stability is defined as the ability of the power system to keep the voltage of all buses at the acceptable range under abnormal conditions [1]. The probability of the voltage instability increases when there is no chance to recover the loads by the active or reactive power demand which causes the voltage collapse [2].

The voltage stability assessment has been considered as the main problem in power system monitoring [1] [3]. Considerable attention has been paid to determine maximum power system load ability limit before voltage collapse occurs [4] [5].

Voltage collapse is identified as a strongly decaying in the power system voltage level [2]. Voltage collapse could bring an unexpected

shortage in the power system. Some countries challenged the voltage collapse phenomenon such as France, Japan, Sweden, and Germany [6]. Correspondingly, voltage stability indices (VSIs) have been presented to identify the most sensitive bus in the system that can lead to voltage instability [7].

To overcome the voltage instability and voltage collapse problems, many studies have been proposed and presented [8] [9]. However, the integration of distributed generators (DGs) with the power system increases power system reliability and decreases power losses. Consequently, the best solution has been addressed in the literature and is to use the active and reactive power of the DG which is connected at a suitable location to operate systems with maximum economic and reliability and enhance the performance of power system [10]. Therefore, accurate indices are required by the power systems utilities to clarify the possibility of the voltage collapse occurring, then the utilities tend to use a compensation device such as a DG [8] [11].

Currently, several research works have been presented to optimally allocate DGs in the power system. Numerous optimization techniques have been used subjected to different objective functions to increase the advantages of DGs, for instance, power loss decline, voltage profile improvement, and voltage stability [12]. DG allocation problem using optimization can be classified into many different categories based on objective functions, constraints, and the type of algorithms [13].

Two main algorithms have been frequently used in the DG allocation problem [13]. The first algorithm is the analytical method, it is a simple method that implements a mathematical formulation to

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maximize or minimize an objective function by changing the main control variables [14]. Many analytical indices have been applied to allocate the DG into distribution systems. The minimization of power loss using an analytical technique was presented in [15]. Loss sensitivity factor (LSF) has been used to find the most sensitive bus in the system subject to the change in the active or reactive power [16]. Furthermore, the power stability index (PSI) and voltage stability index (VSI) have been introduced to integrate DG in the distribution network. These two stability indices have been applied to recognize the most sensitive buses which could cause instability with increasing the load [17].

The second algorithm is the metaheuristic optimization algorithm, which attempts to generate all possible solutions from an initial set of solutions. A genetic algorithm (GA) has been used to optimally place the DG in distribution system [18]. Particle swarm optimization has been applied in [19]. Cuckoo Search Algorithm (CSA) has been applied in references [20] [21] to decrease the power loss and improve the voltage profile. For the multiobjective optimization problem, and NSGA II has been introduced in [22] to simultaneously minimize the power loss and maximize the VSI. Metaheuristic optimization techniques are intelligent based optimization methods [23] [24]. The main advantage of the metaheuristic techniques is the ability to handle complex problems without going so far in the problem details [13]. However, these algorithms take an uncertain time of convergence based on the search space limits and may trap in the local optima [13].

To overcome the drawback of the metaheuristic optimization technique and decrease its search space, a hybrid optimization technique can be implemented. Hence, this paper presents a hybrid between analytical VSI and a modern heuristic optimization technique named Whale Optimization Algorithm (WOA). WOA proved its efficiency as a nature-inspired based technique in comparison to the other methods [25]. The VSI is mathematically formulated, then a fuzzy logic controller is implemented using the normalized VSI and voltage magnitude at each node to arrange the system buses according to the fuzzy weighting output. The highest output weighting buses are chosen to be the candidate buses to the DG placement. Finally, the WOA is used to compute the optimal location and size of injected active and reactive powers of the DG to minimize the total power losses. The MATLAB environment is used to formulate and evaluate the objective function. The DG influence on the voltage stability is traced with PV curve analysis that performed using the continuation power flow (CPF) using PSAT package. The developed method is tested on 12, 33, 69, and 85 radial distribution systems, the results prove that using the optimal allocation of the DG increases the voltage stability.

The paper structure is prepared as follows: Section II addresses the mathematical formulation of the problem which includes the objective function, VSI, fuzzy logic controller, and WOA. The optimization process of allocating DG is introduced in Section III. The simulation results and discussion based on the study test system are presented in Section IV. Finally, Section V presents the conclusion.

II. MATHEMATICAL PROBLEM FORMULATIONS

In this section, the main objective function and the mathematical formulation for the VSI with the fuzzy logic controller and the metaheuristic WOA are presented.

A. Objective Function

In this paper, the main purpose of the DG connection in the distribution system is to reduce the power losses P_{loss} hence, the objective function F can be expressed as.

$$F = \min (P_{loss}) \quad (1)$$

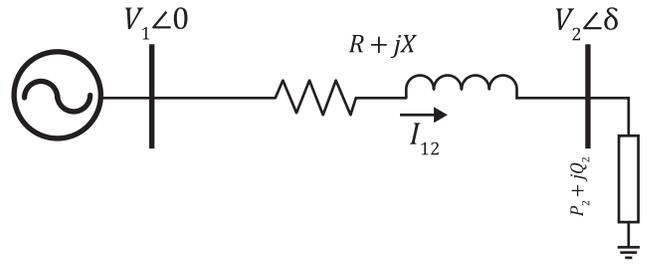


Fig. 1 Equivalent circuit model.

Where, for each two linked buses, j , the power loss P_{loss_z} can be calculated using the resistance R_j and the current I_z passing through the branch z as follows:

$$P_{loss_z} = R_j I_z^2 \quad (2)$$

To calculate the overall active power loss in the distribution system, a summation of the losses in all system branches n_{br} are added as follows:

$$P_{loss} = \sum_{z=1}^{n_{br}} P_{loss_z} \quad (3)$$

B. Implementation of Voltage Stability Index VSI

To obtain a mathematical formulation for VSI, simple implementation for the radial distribution system consists of two buses is used as presented in Fig 1. The figure shows that the power transfers from bus 1 (where the source is connected) over a transmission line have an impedance $R_{12} + jX_{12}$ to the load connected at bus 2. The load consuming active and reactive power $P_2 + jQ_2$.

In this case, the load current at bus 2 is the same branch current passing between 1 and 2, hence the branch current I_{12} is expressed as follows:

$$I_{12} = \left[\frac{P_2 + jQ_2}{V_2 \angle \delta} \right]^* \quad (4)$$

Hence, the voltage V_2 can be calculated using the voltage V_1 and the voltage drop across the line as :

$$V_2 \angle \delta = V_1 \angle 0 - (R_{12} + jX_{12}) I_{12} \quad (5)$$

Using the current in (4) then eq (5) can be rewritten as:

$$V_2 \angle \delta = V_1 \angle 0 - (R_{12} + jX_{12}) \left(\frac{P_2 - jQ_2}{V_2 \angle -\delta} \right) \quad (6)$$

$$\text{Reorganize the eq (6) using multiplication with } V_2 \angle -\delta \\ V_2^2 = (V_1 V_2 \cos(\delta) - jV_1 V_2 \sin(\delta)) - (R_{12} + jX_{12})(P_2 - jQ_2) \quad (7)$$

Separate the real and imaginary parts

$$\begin{aligned} V_2^2 + P_2 R_{12} + Q_2 X_{12} &= V_1 V_2 \cos \delta \\ P_2 X_{12} - Q_2 R_{12} &= -V_1 V_2 \sin \delta \end{aligned} \quad (8)$$

$$\text{Let } \delta \approx 0 \text{ and } R_{12} = \frac{P_2 X_{12}}{Q_2}$$

$$V_2^2 - V_2 V_1 + \left(\frac{P_2^2}{Q_2} + Q_2 \right) X_{12} = 0 \quad (9)$$

Equation (9) can be solved as a quadratic equation and for stable bus voltages condition, $b^2 - 4ac \geq 0$.

Finally, the VSI can be obtained as follows:

$$VSI = \frac{4X}{V_1^2} \left(\frac{P_2^2}{Q_2} + Q_2 \right) \leq 1 \quad (10)$$

For normal operation, the system can be considered a stable as long as the $VSI < 1$. So, the system is more stable when the VSI value is close to zero. Consequently, the node with a maximum value of the VSI is the most sensitive node in the system and should be chosen as the optimal DG location.

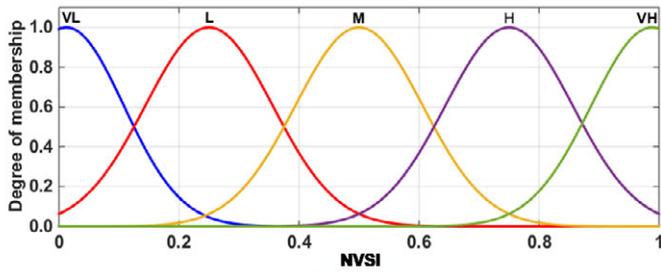
C. Candidate Buses Using the Fuzzy Logic Controller

The candidate buses are arranged using a fuzzy logic controller. The fuzzy controller is implemented with two inputs and one output. The first input is NVSI and can be expressed as follows:

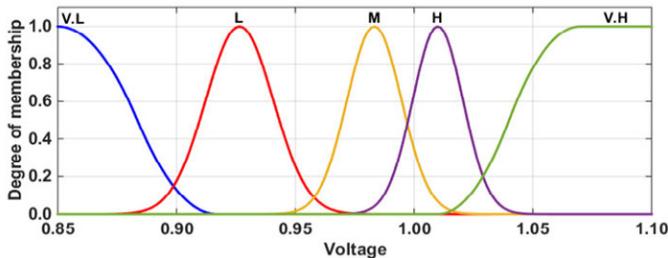
$$NVSI_i = \frac{VSI_i - VSI_{max}}{VSI_{max} - VSI_{min}} \quad (11)$$

where all $NVSI_i$ are between $[0,1]$.

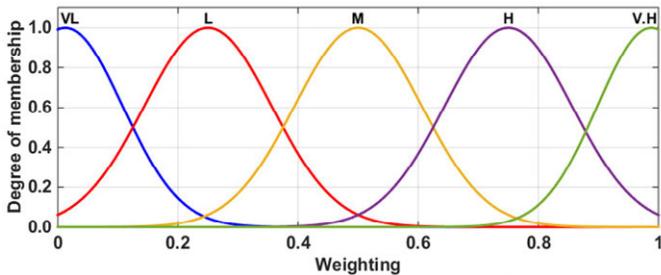
Five membership functions are utilized to represent the $NVSI_i$ as illustrated in Fig. 2.a. Also, the second input is the voltage profile at each node and represented with five membership functions as presented in Fig 2.b. The fuzzy output is calculated using predetermined rules based on (IF, Then). The output degree is shown in the surface plot in Fig. 3. Hence, each bus obtains a weighting value then these values are listed in descending order as a candidate bus.



(a) Membership function for NVSI.



(b) Membership function for voltage magnitude.



(c) Membership function for weighting.

Fig. 2. Fuzzy inputs and output memberships.

(VL= Very Low, L= Low, M= Medium, H= High, and VH= Very High)

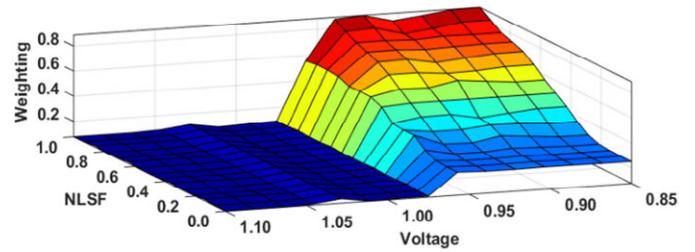


Fig. 3. Fuzzy rules output in 3 D plot.

D. Overview of Whale Optimization Algorithm (WOA)

WOA is a metaheuristic optimization technique that has been recently introduced by S. Mirjalili in [25]. The performance of WOA has been validated using 29 optimization benchmark functions and 6 structural design problems. Results show the efficiency of WOA in comparison with some nature-inspired algorithms [25]. In fact, the WOA simulates the hunting behavior of humpback whales. These whales are characterized by a bubble net feeding technique for hunting their prey.

In consequence, three stages have been utilized to mathematically represent the hunting procedure of the whales as described below:

1. Search for Prey

In order to imitate the random movement of the whales in case of their searching, a random search whale X^{rand} is used to update the position of the whales as follows:

$$X^{k+1} = X^{rand} - A \cdot D \quad (12)$$

$$D = |C \cdot X^{rand} - X^k| \quad (13)$$

where, X^k is the current position of the whale at iteration k , and X^{k+1} is the updated position for the next iteration. D represents the distance from the random search agent X^{rand} to X^k .

A is a random value with prespecified limits $[-a, a]$ where coefficient a is reducing from 2 to 0, then A can be expressed with the following formula:

$$A = 2a \cdot r - a \quad (14)$$

$$a = 2 - k(2 / K_{max}) \quad (15)$$

where, r is a random number in the range of $[0, 1]$, then C can be computed as:

$$C = 2 \cdot r \quad (16)$$

2. Encircling Prey

The mathematical formulation for encircling the prey by the whale can be adopted using the next equations:

$$X^{k+1} = X^* - A \cdot D \quad (17)$$

$$D = |C \cdot X^* - X^k| \quad (18)$$

The whales use a spiral-shaped in to encircle the prey, this shape can be mathematically presented as:

$$X^{k+1} = D' \cdot e^{bl} \cdot \cos(2\pi l) + X^* \quad (19)$$

$$D' = |X^* - X^k| \quad (20)$$

In this case, D' describes the absolute distance value between X^k (current whale position) and the best position X^* . b implements the formula of the logarithmic spiral. l is a random number with a range $[-1, 1]$.

3. Bubble Net Hunting

Two whale movements have been used to formulate the bubble net hunting, the first movement uses the encircling prey by applying (17), where the second uses the spiral shape as described in (19). The transition between those two movements can occur using a random probability parameter p as follows:

$$X^{k+1} = \begin{cases} X^* - A \cdot D, & p < 0.5 \\ D' \cdot e^{bl} \cdot \cos(2\pi l) + X^*, & p \geq 0.5 \end{cases} \quad (21)$$

The overall WOA is presented in the pseudocode shown in Fig. 4.

Initialize a set of random search whales $X_i = (X_{i1}, X_{i2}, \dots, X_{in})$.

within the limits $X_L \leq X_i \leq X^U$

Calculate the objective function for each search whale

Store the best solution X^*

While ($k < K_{max}$)

for each search whale X_i

Update the parameters A , a , and C using (14), (15), and (16) respectively

$p = rand$

$l = rand$

If $1 < p < 0.5$

If $2 |A| < 1$

Update the whale's positions using (17), and (18)

else if $2 |A| \geq 1$

Choose a random whale X^{rand}

Update the whale's positions using (12), and (13)

end if 2

else if $1 < p \geq 0.5$

Update the whale's positions using (19), and (20)

end if 1

Calculate the objective function

Update the best solution X^*

$K = K + 1$

end while

return the final best solution stored X^*

Fig. 4. Pseudocode of WOA.

III. VOLTAGE STABILITY ASSESSMENT WITH DG ALLOCATION

The assessment of the power system voltage stability with optimal allocation of the DG is described in the flowchart shown in Fig. 5. The overall process is concluded in the main following steps:

Step 1: Read the system data (line data and load data) and define the objective function.

Step 2: Run the power flow and obtain the voltage magnitude and angle for all buses.

Step 3: Compute the VSI for each node and calculate the $NVSI_i$.

Step 4: Apply the fuzzy logic controller to arrange the candidate buses.

Step 5: Randomly initialize a set of search whales with the candidate buses, WOA parameters, and Max. number of iterations K_{max} .

Step 6: Run power flow and calculate the objective function for each search whale and store the best solution.

Step 7: For each search whale, update the parameters a , A , C , l and p .

Step 8: Calculate the objective function for each search agent.

Step 9: Update the best solution.

Step 10: If $k < K_{max}$, repeat Step 5.

Step 11: Return the stored best solution obtained so far.

Step 12: Use the best solution as the optimal size and location for the DG.

Step 13: Run the continuation power flow and assess the power system voltage stability by tracing the PV curve.

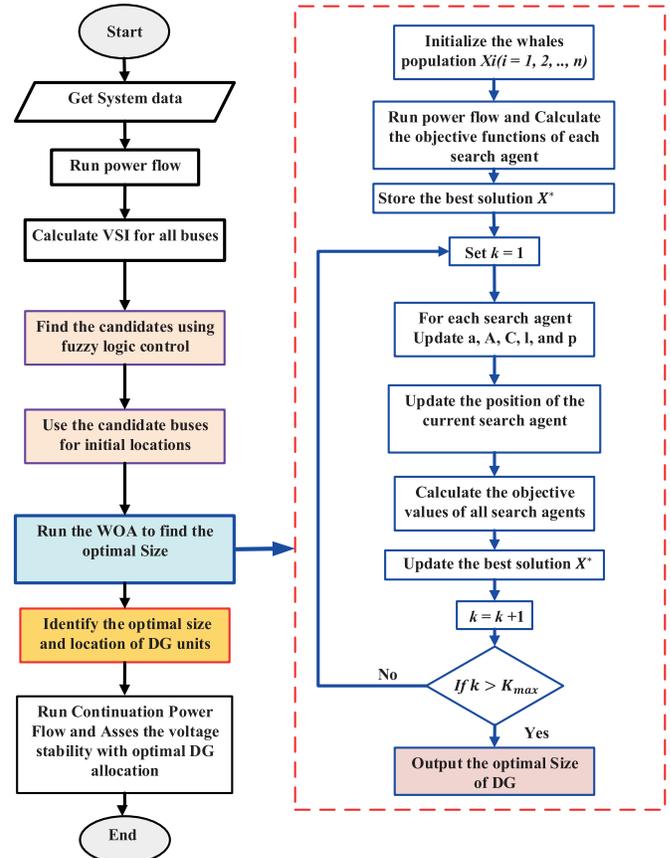


Fig. 5. Flowchart for voltage stability assessment with optimal DG allocation.

IV. RESULTS AND DISCUSSION

In this section, the performance of the proposed hybrid VSI and WOA technique is tested using 12, 33, 69, and 85 radial distribution systems. The feasibility and efficiency of hybrid VSI and WOA to optimally allocate DG in radial distribution systems are proved compared with other well-known optimization techniques. All simulations have been carried out using MATLAB M-files. WOA parameters are set as; the number of agents = 100, the maximum number of iterations = 50. The following four cases have been considered for the DG allocation and voltage stability assessment in the studied systems:

1. Case 1: No DG unit is connected.
2. Case 2: One DG unit that injects only active power is connected.
3. Case 3: One DG unit that injects only reactive power is connected.
4. Case 4: One DG unit that injects active and reactive powers is connected.

A. 12-bus Radial Distribution System

The distribution system can be found in [26]. The system consists of 12 buses and 11 branches. The fuzzy logic controller using the NVSI

and voltage profile is applied to the 12-bus system. Table I summarizes the ordering of the candidate buses. For each branch, VSI is calculated then the NVSI is adopted as the first input of the fuzzy logic controller. The voltage at the end of each branch bus is used as the second input as presented in the table. As seen in the table, branch 8 has the highest VSI and NVSI and it receives bus 9 that has 0.9473 p.u voltage. Respecting to the fuzzy rules this bus is considered the highest output hence, the fuzzy weighting output is 0.8210. The same process is performed in all buses and the order of candidate buses is shown in Table I.

TABLE I. CANDIDATE BUS ORDERING USING FUZZY LOGIC CONTROL

Branch ID	VSI	NVSI	Receive Bus	Voltage	Fuzzy output	Bus order
1	0.00180	0.334	2	0.9943	0.0888	9
2	0.00138	0.233	3	0.9890	0.0806	11
3	0.00325	0.674	4	0.9806	0.0859	10
4	0.00274	0.555	5	0.9698	0.1314	7
5	0.00067	0.065	6	0.9665	0.1264	8
6	0.00162	0.291	7	0.9637	0.2178	6
7	0.00389	0.826	8	0.9553	0.6337	2
8	0.00463	1.000	9	0.9473	0.8210	1
9	0.00213	0.412	10	0.9445	0.4003	3
10	0.00132	0.220	11	0.9436	0.2710	4
11	0.00039	0.000	12	0.9434	0.2534	5

1. DG Allocation

In the base case (Case 1), the power flow results of the 12-bus system indicate that the active and reactive power losses are 20.7138 kW and 8.0411 kVAR, respectively. The minimum voltage bus is reported at bus 12 with 0.9434 p.u. After applying the fuzzy logic controller using NVSI and the voltage magnitude, the WOA is applied to find the final size at the candidates' buses which give the minimum power loss.

Table II gives the optimal sizes and locations of three DG cases. For Case 2, the optimal size is calculated using the WOA and its value is 235.5 kW, as shown in Table II, and the total power loss decreases to 10.774 kW with Loss Reduction (LR) reaching 47.98 %. The minimum voltage, in this case, is 0.9835 at bus 7.

At Case 3, where 210.21 kVAR reactive power is injected at bus 9, the LR is 39.25% and the minimum voltage reports at bus 12 with 0.9563 p. u. A significant LR is obtained in Case 4 due to the active and reactive power injection. The LR is 84.76 % and the minimum voltage bus is 7 with 0.9907 p.u. Overall enhancement in the voltage profile in the three cases is illustrated in Fig 6. A considerable enhancement is achieved at Case 4.

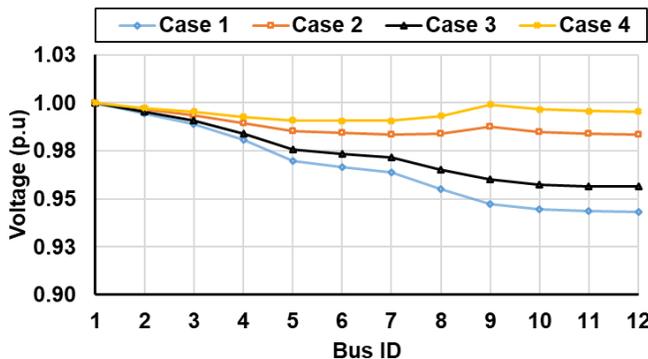


Fig. 6. Voltage profile of 12-bus at different case studies.

The convergence characteristic for the hybrid VSI and WOA for the three case studies (Case 2, Case 3, and Case 4) is presented in Fig. 7. It is clear that WOA converged fast due to decreasing the search space through the fuzzy process applied with the VSI.

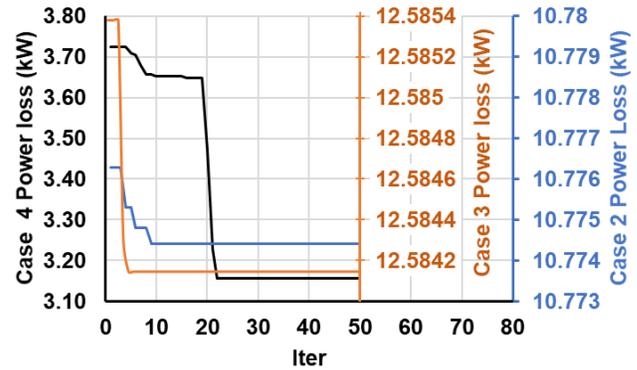


Fig. 7. Convergence characteristics of the WOA for 12-bus at different case studies.

TABLE II. DG ALLOCATION IN 12- BUS SYSTEM AT DIFFERENT CASE STUDIES

DG Location		Case 1	Case 2	Case 3	Case 4
DG Location		-	9	9	9
DG Size	kW	-	235.50	-	230.82
	kVAR	-	-	210.21	213.93
PL (kW)		20.714	10.774	12.584	3.157
QL (kVAR)		8.041	4.125	4.824	1.108
Min bus voltage		12	7	12	7
Vmin (p.u)		0.9434	0.9835	0.9563	0.9907
LR %		0.00	47.98	39.25	84.76
Lambda max		5.31	5.96	6.54	6.31

2. Voltage Stability Assessment

In this section, the PV curve is obtained with the CPF using the PSAT package to evaluate the voltage stability of the radial distribution system with DG allocation. Fig. 8 shows the PV curves for the four case studies at bus 12 which is the minimum bus voltage. It can observe that in Case 1 the maximum lambda loading is 5.31%. In Case 2, the loading factor increases to 5.96%, which demonstrates the influence of the active power of the DG. However, the maximum loading lambda is achieved at Case 3 which equals 6.54% and this is due to the injected DG reactive power. Finally, the impact of the active and reactive power injected by the DG on the PV curve is carried out in Case 4 and the reported Lambda max is 6.31%.

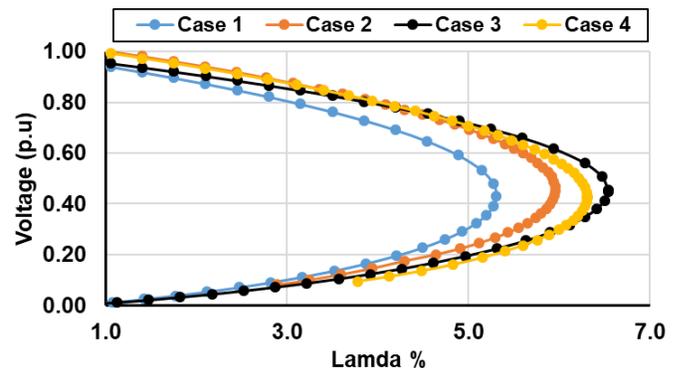


Fig. 8. PV curve for 12-bus at different case studies.

B. 33-Bus Radial Distribution System

The second system used to validate the proposed method is the 33-bus radial distribution system. The complete depiction of this test system involves the line and load data that can be obtained in [27]. The fuzzy logic controller with the NVSI and voltage magnitude is applied to this system and the highest candidates' buses are 7 and 30. However, during the search process with the WOA and the updating positions, buses 6 and 30 are found to be the best buses for DG allocation as summarized in Table III.

1. DG Allocation

Table III presents the optimal sizes and locations of the three cases of DG allocations. In Case 1, the power loss is 210.986kW and it decreases to 111.019 kW, 151.365 kW, and 67.855 kW at Case 2, Case 3, and Case 4, respectively. The voltage profile has a significant enhancement in Case 4 as shown in Fig. 9 where the minimum voltage is reported at bus 18, which equals 0.9584 p.u.

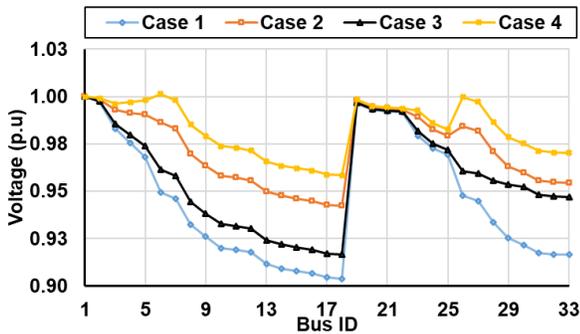


Fig. 9. Voltage profile of 33-bus at different case studies.

The convergence characteristics of the proposed method are displayed in Fig 10. Case 4 needed the highest number of iterations to converge because it searches for the active and reactive powers to minimize the power loss.

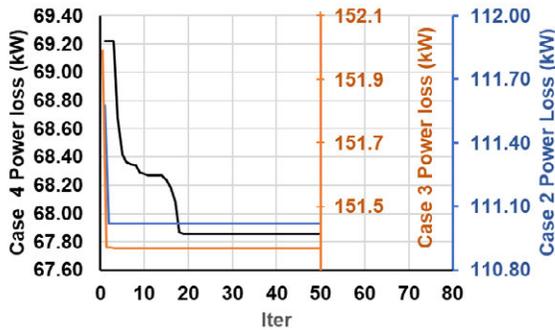


Fig. 10. Convergence characteristics of the WOA for 33-bus at different case studies.

TABLE III. DG ALLOCATION IN 33-BUS SYSTEM AT DIFFERENT CASE STUDIES

	Case 1	Case 2	Case 3	Case 4
DG Location	-	6	30	6
DG Size	kW	-	2590.21	2558.92
	kVAR	-	-	1258.013
PL (kW)	210.986	111.019	151.365	67.855
QL (kVAR)	143.127	81.717	103.890	54.840
Min bus voltage	18	18	18	18
Vmin (p.u)	0.9038	0.9424	0.9165	0.9584
LR %	0.00	47.38	28.26	67.84
Lambda max	3.40	3.72	3.90	3.86

2. Voltage Stability Assessment

The PV curve for bus 18, which is the minimum bus voltage at Case 1, is exhibited in Fig. 11 in different case studies. From this figure, it can be observed that the highest lambda is achieved at Case 3 which reaches 3.90% where it was 3.40% in Case 1. The lambda max is 3.72 % and 3.86 % at Case 2 and Case 4, respectively.

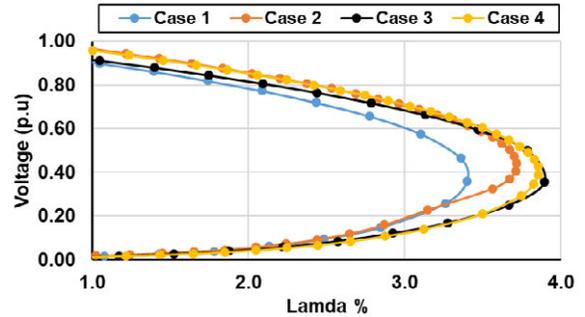


Fig. 11. PV curve for 33-bus at different case studies.

C. 69-Bus Radial Distribution System

This system consists of 69 radial connected buses and 68 branches, the single line diagram and the line and load data is available in [28]. In this system, the highest order candidate bus obtained by the fuzzy logic controller is bus 61, hence it is chosen by the WOA to be the optimal location for the DG in the three case studies.

1. DG Allocation

Table IV presents the base case results of the 69-bus system where the power loss is 224.95 kW, the reactive power loss is 102.146 kVAR, and the minimum voltage is 0.9092 at bus 65. However, with connected three DG types at three case studies, the active power LR reaches 63.02, 32.43, and 89.71 at Case 2, Case 3, and Case 4, respectively. Also, the voltage profile achieves a significant improvement as shown in Fig. 12. Fig 13 demonstrates the convergence characteristics of the proposed method and it is clear that the WOA converged at a low number of iterations.

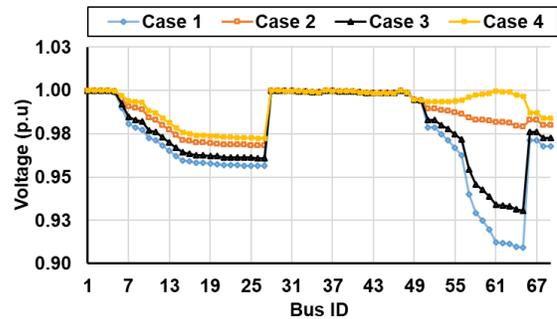


Fig. 12. Voltage profile of 69-bus at different case studies.

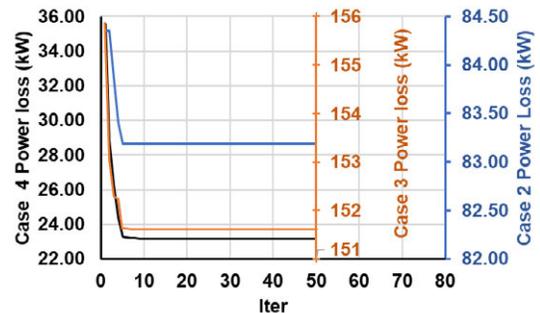


Fig. 13. Convergence characteristics of the WOA for 69-bus at different case studies.

TABLE IV. DG ALLOCATION IN 69- BUS SYSTEM AT DIFFERENT CASE STUDIES

		Case 1	Case 2	Case 3	Case 4
DG Location		-	61	61	61
DG Size	kW	-	1872.63	-	1828.24
	kVAR	-	-	1329.90	1300.73
PL (kW)		224.950	83.189	152.005	23.146
QL (kVAR)		102.146	40.522	70.489	14.370
Min bus voltage		65	27	65	27
Vmin (p.u)		0.9092	0.9683	0.9307	0.9725
LR %		0.00	63.02	32.43	89.71
Lambda max		3.21	3.95	4.02	4.24

2. Voltage Stability Assessment

Fig. 14 reveals the PV curves for bus 65 at different case studies, the highest lambda max is 4.24 % attained at Case 4 where the impact of the DG integration on the voltage stability is clearly assessed using the PV curve.

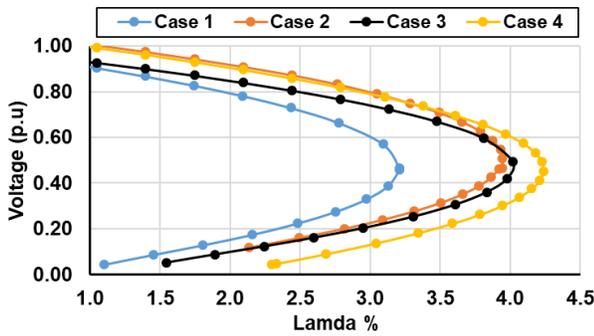


Fig. 14. PV curve for 69-bus at different case studies.

D. 85-Bus Radial Distribution System

This system considers a large and long radial distribution system. The system includes 85 buses and 84 branches and the overall data can be obtained from [29]. Bus 8 has the highest order weighting based on the fuzzy logic controller so that this bus is considered the optimal location for DG location at the different case studies.

1. DG Allocation

Due to the length of this system, the power loss is 315.973 kW and the lowest voltage is 0.8714 p.u at bus 54 as given in Table V. By applying the proposed VSI and WOA at three DG allocation cases, the Power loss decrease to 175.470, kW 180.548 kW, and 62.576 kW with LR 44.47%, 42.86 %, and 80.20 % at Case 2, Case 3, and Case 4 respectively. Also, the voltage at bus 54 increases to 0.9283 p.u, 0.9108 p.u, and 0.9616 p.u at Case 2, Case 3, and Case 4, respectively. The enhancement in the voltage profiles for all buses is presented in Fig. 15.

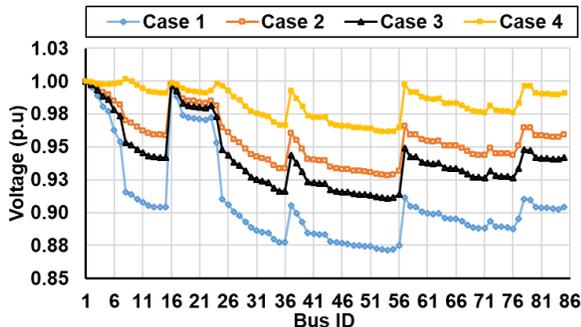


Fig. 15. Voltage profile of 85-bus at different case studies.

Fig. 16 proves the efficiency of the WOA in allocating the DG at different case studies in the large-scale distribution system with low iteration numbers.

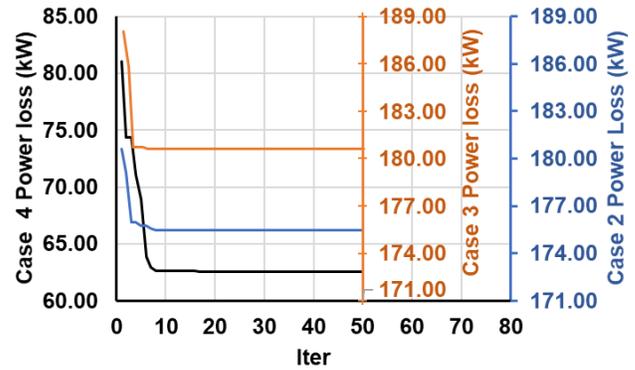


Fig. 16. Convergence characteristics of the WOA for 85-bus at different case studies.

TABLE V. DG ALLOCATION IN 85- BUS SYSTEM AT DIFFERENT CASE STUDIES

		Case 1	Case 2	Case 3	Case 4
DG Location		-	8	8	8
DG Size	kW	-	2373.78	-	2268.50
	kVAR	-	-	2332.77	2259.11
PL (kW)		315.973	175.470	180.548	62.576
QL (kVAR)		198.701	104.385	107.276	27.997
Min bus voltage		54	54	54	54
Vmin (p.u)		0.8714	0.9283	0.9108	0.9616
LR %		0.00	44.47	42.86	80.20
Lambda max		2.55	2.74	3.29	2.94

2. Voltage Stability Assessment

Similarly, the PV curve for the 85-bus is drawn using the CPF at different case studies of DG integration as exhibited in Fig. 17. The base case lambda max of this system is 2.55 % and this value increased to 2.74 % when connecting DG at bus 8 with 2373.78 kW. Furthermore, a considerable increase in the lambda is accomplished at Case 2 with 2332.77 kVAR connected on bus 8. Finally, at Case 4 the lambda reaches 2.94 % with 2268.5 kW and 2259.11 kVAR at the same bus.

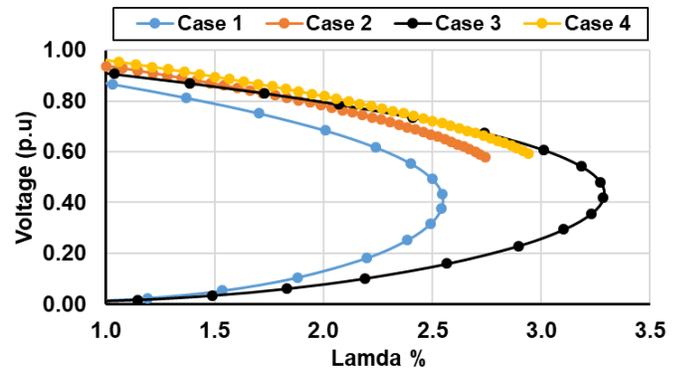


Fig. 17. PV curve for 85-bus at different case studies.

E. Result comparison

To demonstrate the efficiency of the developed method, a comparison is performed with other optimization techniques mentioned in the literature such as; analytical technique [15], PSO [12], CS [21],

NSGA-II [22]. As presented in Table VI, the proposed method has the highest LR compared to all techniques. However, for the maximum loading factor the proposed method gives the highest loading factor in 12- bus that equals 6.31 %. Also, the same lambda max in 69-bus is given by the proposed method and NSGA II which reaches 4.24%. The maximum loading factor in 33-bus is given by the CS algorithm. In addition, for 85-bus the NSGA II has the maximum lambda 2.94 %.

TABLE VI. RESULT COMPARISON WITH OTHER OPTIMIZATION TECHNIQUES

Method		12-bus	33-bus	69-bus	85-bus
Proposed method VSI and WOA	DG location	9	6	61	8
	DG size (kVA)	314.71	3106.14	2243.73	3201.5
	LR %	84.76	67.84	89.71	80.20
	Lambda max %	6.31	3.86	4.24	2.94
Analytical technique [15]	DG location	9	6	61	8
	DG size (kVA)	227.15	2490.78	1807.8	22088.6
	LR %	47.95	47.31	62.95	44.28
	Lambda max %	5.92	3.70	3.92	2.88
NSGA-II [22]	DG location	8	7	61	25
	DG size (kVA)	435	3715	2663.8	2484.5
	LR %	33.97	35.92	53.8	42.75
	Lambda max %	6.08	3.88	4.24	2.96
PSO [12]	DG location	9	7	61	
	DG size (kVA)	253.9	2895.1	2026.4	
	LR %	47.7	45.55	62.65	
	Lambda max %	6.03	3.78	4.03	
CS [21]	DG location		61		
	DG size (kVA)		2200		
	LR %		62.8		
	Lambda max %		4.06		

V. CONCLUSION

In this paper, an assessment of power systems voltage stability with DG integration using CPF has been presented. A hybrid between VSI and WOA has been developed to place the DG in the radial distribution system. NVSI and voltage magnitude at each node has been modeled with the fuzzy logic controller to find the candidate buses which are the most sensitive buses to allocate the DG. Finally, the optimal size and location have been achieved using the WOA. The developed method has been tested using the 12, 33, 69 and 85 bus radial distribution systems. To present the effectiveness of the developed method, a comparison with existing techniques has been accomplished. The obtained results proved the efficiency and capability of the developed optimization technique for selecting the optimal DG location and size using the voltage stability index. In addition, a significant increase in the loadability has been obtained with integrating DG that injects both active and reactive powers. The extended work of this paper is to improve the exploration and exploitation phases of the WOA by hybridizing with other metaheuristic optimization techniques.

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