Optimal DG Unit Placement and Sizing in Radial Distribution Network for Power Loss Minimization and Voltage Stability Enhancement

Benalia M'hamdi[1*], Madjid Teguar[2], Benaissa Tahar[3]

[1] Applied Automation and Industrial Diagnostics Laboratory, Faculty of Science and Technology, University of Djelfa, P. O. B. 3117, Djelfa, Algeria
[2] Electrical Research Laboratory (L.R.E), National Polytechnic School, 10 Rue des Frères OUDEK, El Harrach 16200, Algiers, Algeria
[3] Department of Electrical Engineering, Faculty of Science and Technology, University of Djelfa, P. O. B. 3117, Djelfa, Algeria
* Corresponding author, e-mail: mhbenalia@yahoo.fr

Abstract

The optimal allocation and size of decentralized generating units are essential to minimize power losses, while meeting the demand for active and reactive power in a distribution system. In other words, most of the total energy produced can be efficiently exploited by end users. In addition, if the DGs are of optimal size and location in the distribution system, the reliability, stability and efficiency of the power system are guaranteed. This paper focuses on reducing power losses and improving the voltage profile by accurately identifying the optimal location and sizing of Distributed Generation based on three indexes, namely the IVM Index Vector Method, the VDI Voltage Deviation Index and the VSI Voltage Stability Index. Two types of DGs were considered for the analysis: DGs operating with unit power factor and DGs operating with a lagging power factor. Three optimization algorithms are applied to determine the optimal sizes of decentralized generation units in a power distribution network which are GWO, WOA and PSO. The results obtained in this article show that the three algorithms give very similar values. DG at lagging power factor gives better results compared with those obtained with DGs at unity power factor. In terms of loss reduction and minimum bus voltage, the best results are obtained for the VSI index with a DG at a power factor of 0.9.

Keywords

Distributed Generation (DG), radial distribution system, voltage stability, power loss reduction

1 Introduction

Distribution networks are an important part of a power supply system since the supply of electricity to consumers is ensured by an efficient distribution system. In general, the radial distribution network has a high R / X ratio, which leads to more power losses and voltage drop. A large amount of total power losses in the power grid occurs in the distribution network accounting for about 13 % of the total network generation [1]. The minimization of power losses plays a crucial role in economic exploitation and the reduction of energy costs. In recent years, the use of Distributed Generation units in distributed radial networks has attracted the attention of many industrialists and researchers because of their effectiveness in reducing power losses and improving voltage stability. Generally, the DG term refers to the small scale electric power generators. Noting that,

the renewable energy-based DG has been growing rapidly worldwide in recent years due to its promising potential to reduce the share of fossil energy consumption in electricity production and to mitigate harmful carbon emissions [2, 3].

In general, the DG units can be classified in three types based on their ability to inject and absorb real and reactive powers: type I operates at unity power factor and injects active power (PV cells), type II injects reactive power (capacitors) and type III injects real power and injects or consumes reactive power(synchronous generators).

Based on the review of literature, deferent approaches based on classical, and meta-heuristics algorithms have been recently proposed for the optimal placement and sizing of DG units in a distribution system for power loss minimization and voltage stability enhancement.

In [4, 5], an analytical approach was proposed for DG Sizing and Sitting in radial distribution networks to reduce power losses.

This work has attempted to investigate the performance of the distribution system in the presence of two types of DG sources, DG at unity power factor and lagging power factor DG, to reduce power losses and voltage profile enhancement. For identification of the optimum location of DG the authors have used the Index Vector Method (IVM), Voltage Stability Index (VSI) and Voltage Deviation Index (VDI).

In this investigation, three optimization algorithms are applied to determine the optimal sizes of decentralized production units in a power distribution network namely the Grey Wolf Optimization Algorithm (GWO) [6], the Whale Optimization Algorithm (WOA) [7] and the Particle Swarm Optimization (PSO) [8]. The proposed method are tested on standard IEEE 33-bus and IEEE 69-bus test systems by considering loss minimization and voltage profile improvement.

2 Problem formulation

In this study, the optimal sizing and sitting of DG units in radial distribution networks is formulated as a multi-objective problem by considering as objectives the minimization of active power losses and improving the voltage profile and enhancing the voltage stability.

The mathematical construction of the Objective Function is given as:

$$OF = \text{Min}\left(f_1; f_2\right),$$

where f_1 and f_2 are the total system power loss and the bus voltage deviation respectively.

Firstly, the optimal location of DG is determined from the following concepts:
- Case (i) Index Vector Method
- Case (ii) Voltage Stability Index
- Case (iii) Voltage Deviation Index.

Secondly, the optimal location DG size is determined using the optimization algorithms.

2.1 The active power losses

Among the most important objectives of the implementation of sources in radial distribution networks is the reduction of total power losses. In radial distribution networks, each receiving bus is fed by solely one sending bus.

Well, the line active power losses between the receiving and sending end buses can be determinate as follows [1]:

$$P_L(i) = r_i |I_i|^2 = r_i \frac{\left(P_i^2 + Q_i^2\right)}{V_i^2}. \tag{1}$$

Therefore, the total system power loss (the first objective function) can be calculated as following [1]:

$$\sum_{i=2}^{N_{bus}} P_L(i) = \sum_{i=2}^{N_{bus}} r_i |I_i|^2 = \sum_{i=2}^{N_{bus}} r_i \frac{\left(P_i^2 + Q_i^2\right)}{V_i^2}, \tag{2}$$

where r_i is the line resistance connected between the sending end node i-1 and the receiving end node i; I current of branch i; V_i voltage of node i; P_i and Q_i active and reactive power load fed through node i.

So, the Total System Loss Reduction (TLR) can be calculated using the flowing Eq. (3):

$$TLR\ \% = \frac{\sum_{i=1}^{N_{bus}} P_{LwoutDG} - \sum_{i=1}^{N_{bus}} P_{LwDG}}{\sum_{i=1}^{N_{bus}} P_{LwoutDG}} \times 100\ \%, \tag{3}$$

where P_{LwDG} and $P_{LwoutDG}$ are the total line losses in the system with the employment of DG and without employment DG respectively.

2.2 Index Vector Method

Among the indices used to determine the optimal location of Distributed Generation, is the Index Vector Method (IVM) [9]. The IVM for bus i is given by:

$$IVM(i) = \frac{1}{V_i^2} + \frac{I_q(k)}{I_p(k)} + \frac{Q_{eff}(i)}{Q_T}. \tag{4}$$

$I_p(k)$, $I_q(k)$ are the real and imaginary parts of the current in the kth branch. $Q_{eff}(i)$ and $V(i)$ are the reactive load, the voltage at the ith bus. Q_T is the total reactive load.

To find the optimal locations for DG unit placement using IVM, firstly, store the buses with index arranged in decreasing order in a vector according to their positions. Secondly, select the buses with normalized voltage magnitudes less than 1.01. The bus with the highest Index and with normalized voltage magnitudes less than 1.01 are the best suitable locations for DG placement [9].

Normalized voltage magnitudes $V_{norm}(i)$ for the ith bus can be calculated by the following formula:

$$V_{norm}(i) = V_{norm}(i)/0.95, \tag{5}$$

where $V(i)$ is the base case voltage magnitude of the ith bus.

2.3 Voltage Stability Index

For proper operation and to prevent the system from the block out conditions, the stability must be maintained. Voltage stability is therefore one of the most important security indices. To find the most sensitive bus to voltage collapse in the system, Murty and Kumar in 2015 [3] proposed Voltage Stability Index (VSI) which can be defined at each node as follows:

$$\text{VSI}_{i+1} = \frac{4X_i}{V_i^2}\left(\frac{P_{i+1}^2}{Q_{i+1}} + Q_{i+1}\right), \qquad (6)$$

where VSI_i is the stability index for node i (2,3,..., N bus), P_i and Q_i are total active and reactive power load fed through at i bus, V_i is voltage of the ith node, X_i is reactance of the ith branch.

In order to attain the stable operation of the radial distribution system, the Voltage Stability Index (VSI) value should be less than unity. To avoid the possibility of voltage collapse, the VSI of all buses should become closer to zero. Buses with the highest VSI values are more sensitive and are candidates for DG placement [3].

2.4 Voltage Deviation Index

Maintaining bus voltage within acceptable limits is one of the most important criteria. The introduction of DGs into an existing radial network improves nodes voltage because DGs provide locally a portion of energy to the load and thus reduce losses in the feeders; therefore, the voltage deviation is improved.

The Voltage Deviation Index (VDI) for bus i can be formulated as given in the following [10, 11]:

$$\text{VDI}_i = \sum_i^{\text{NB}} |1 - V_i|, \qquad (7)$$

where V_i is the Voltage at the ith bus in (pu) and NB is the Number of Buses.

2.4.1 Constraints
- Equality Constraints: The equality constraints represent power balance equations. The power balance equation in transmission system in presence of Distributed Generation units can be expressed as follows:

$$\begin{cases} \sum_{i=1}^{NG} P_{Gi} + \sum_{i=1}^{ND} P_{DGi} = P_D + P_L \\ \sum_{i=1}^{NG} Q_{Gi} = Q_D + Q_L \end{cases}. \qquad (8)$$

- Inequality Constraints:
  - Voltage constraint: The voltage magnitude must keep within the specified limits at each bus:

$$V_{\min} \le V_i \le V_{\max}, \qquad (9)$$

  where $V_{\min}$ and $V_{\max}$ are respectively the lower and upper limits of the ith bus voltage.
  - Distributed Generation size constraint: The power generated by each DG unit must be less than the total active load of the system.

$$\begin{cases} P_{DGi}^{\min} \le P_{DGi} \le P_{DGi}^{\max} \\ Q_{DGi}^{\min} \le Q_{DGi} \le Q_{DGi}^{\max} \end{cases},$$

  where P_{DGi} and Q_{DGi} are the DG active and reactive power components injected at the ith bus.

3 Test systems description

In this study, the proposed algorithms are used to determine the optimal location and size of the DG unit and have been carried out on two different IEEE test networks namely the 33-bus [10-14] and the 69-bus [10, 14] radial distribution networks.

The IEEE 33-bus radial distribution network is shown in Fig. 1. It consists of thirty-three buses and thirty-two branches (lines), the total system load is 3.715 MW and 2.3 MVAr, its voltage level is 12.66 kV [12, 13]. The second one (Fig. 2) is 69-bus radial distribution network contains sixty nine buses, sixty eight lines with a total load of 3.80 MW and 2.69 MVAr [14]. The operating constrains in RDS with the algorithms parameters are listed in Table 1.

The IEEE 33 and 69-bus systems are examined as test cases with two types of DG units the first one operates at unity power factor, injects only real power and
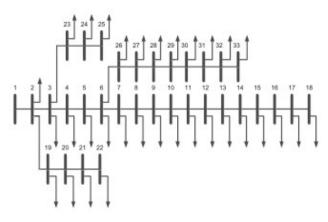

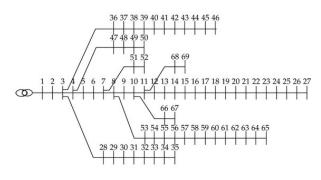**Fig. 1** Single-line diagram of IEEE 33-bus distribution system

Fig. 2 Single-line diagram of IEEE 69-bus distribution system

Table 1 The used parameters

Algorithm	GWO	WOA	PSO
Maximum iteration	500	500	500
Search agents No.	30	30	30
DG sizing limits	$0 \leq P_{DGi} \leq 5$ MW		
Voltage limits	$0.9 \leq V_i \leq 1.05$		

the second one operates at lagging power factor (0.9 pf lag) injects both active and reactive powers.

3.1 Results and discussion

3.1.1 Results using Index Vector Method

According to the Index Vector Method profile and the normalized voltage curves (Figs. 3 to 6), it is found that for the 33-bus system, buses 26 to 30 exhibits the highest vector method index and their normalized voltages are less than 1.01. Thus, these buses can be chosen as appropriate locations for DG units. In the present investigation, the node 30 is chosen as the optimal location of the DG unit installation (IVM has the maximum value). Similarly, for bus system 69, at node 61, the Index Vector Method reaches a maximum value of 2.412 and a normalized voltage of 0.919 pu which is less than 1.01 (Figs. 5 and 6). Thus, the node 61 is chosen as the optimal location of the DG.
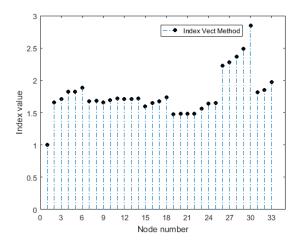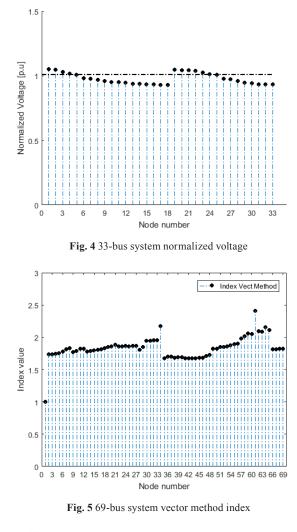

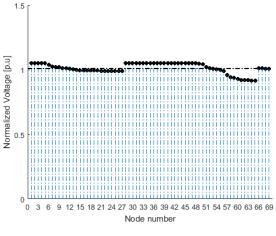Fig. 3 33-bus system vector method index

Fig. 4 33-bus system normalized voltage

Fig. 5 69-bus system vector method index

Fig. 6 69-bus system normalized voltage

3.1.2 Results for 33-bus test system using Index Vector Method

The presented investigation has been carried out on 33-bus radial distribution test system with a total active and reactive power demand of 3715 kW and 2300 kVAr. Without installation of DG units, the real and the reactive power losses are respectively 281.5877 kW and 187.9595 kVAR. Minimum

voltage before installation of DG unit is 0.882 pu at bus 18 as given in Table 2 and shown in Fig. 7. After placement at node 30 of the DG at unity power factor, the total power losses decrease, and reach the values of 151.6819 kW for active power and 106.913 kVAr for reactive power, which shows reductions of 46.13 % and 43.12 % respectively. After the installation of the DG, bus 18 is still at the minimum voltage of 0.918 pu. With DG at 0.9 lag power factor, the active and reactive power losses became 106.3945 kW and 77.0343 kVAr, which reveal reductions of 62.21 % and 59.02 % respectively. As shown in Table 2, it is observed from the results that the losses are lower with DG operating at 0.9 pf when compared to DG operating at unity pf. This is due to the fact that the locally produced reactive power decreases the reactive power called from the substation. Noted that the optimal DG size obtained at lagging

power factor 1.7995 MW is higher compared to the optimal size obtained at unity power factor 1.6319 MW. As shown in Fig. 7, the voltage profile is also improved with DG at lagging power factor. The minimum voltage obtained at bus 18 is 0.928 pu which is better compared to the voltage obtained with DG at unity power factor. It is therefore essential to note the impact of reactive power available in DG on losses reduction and voltage improvement. The results obtained for DG unit operating at unity power factor, are also given in Table 2 using three optimizer algorithms method (GWO, WOA and PSO).

Active and reactive power losses variation in each branch of the 33-bus system are shown in Figs. 8 and 9 for the two cases with no DG connected and with DG at unity and lagging power factor connected to the selected bus. For the IEEE 33-bus test system, the branches 2 and 5 have the highest losses, particularly in case without and with DG at unit power factor.
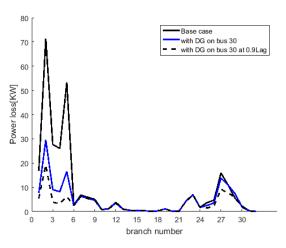
Table 2 Simulation results of 33-bus system

Methods	DG location		DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case	-		-	281.578	187.560	0.882
GWO	30	upf	1.6319	151.6819 (46.13)	106.913 (43.12)	0.918
		lag	1.7995	106.3945 (62.21)	77.0343 (59.015)	0.928
WOA	30	upf	1.6321	151.6909 (46.13)	106.9616 (43.09)	0.9186
		lag	1.7995	106.3664 (62.226)	77.1702 (58.94)	0.928
PSO	30	upf	1.6320	151.682 (46.13)	106.8708 (43.14)	0.9183
		lag	1.7995	106.3662 (62.23)	77.1704 (58.94)	0.928

Fig. 8 Active power line loss of the 33-bus system

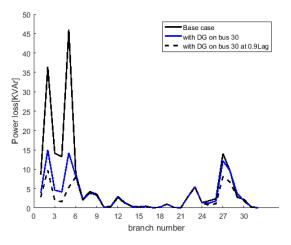**Fig. 7** Voltage profiles of the 33-bus system

Fig. 9 Reactive power line loss of the 33-bus system

3.1.3 Results for 69-bus test system using Index Vector Method

The results have been obtained for 69-bus test system for two types of DG units the first one operates at unity power factor and the second one operates at 0.9 pf lag and with a total active and reactive power demand of 3792 kW and 2694.1 kVAr. Without DG the real and the reactive power losses are 337.2778 kW and 150.6536 kVAr respectively and the voltage is at its minimum value of 0.869 pu at bus 65 as given in Table 3 and shown in Fig. 10. With the DG installation at bus 61, the active and the reactive power losses obtained are respectively 113.0785 kW and 54.3294 kVAr in case of DG operating at pf unit which presents reductions of 66.47 % and 63.93 % respectively compared to the case without DG installation and in case with DG operating at 0.9 pf lag, the active and the reactive
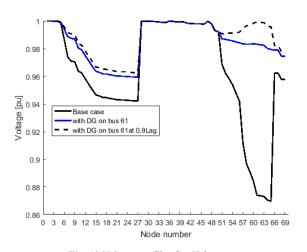
power losses obtained are 51.7467 kW and 28.0549 kVAr which presents reductions of 84.65 % and 81.37 % respectively compared to the case without DG installation. Noted that the losses are lower with DG operating at 0.9 pf when compared to DG operating at unity pf, this is due to the decrease in reactive power called from the substation and provided by the DG unit. As in the case of IEEE 33-bus system, the optimal DG size obtained for the 69-bus system at lagging power factor 2.0446 MW is higher compared to the optimal size obtained at unity power factor 1.9043 MW. As shown in Fig. 10, the profile of the voltage also improves with the installation of DG, in particular with that with a lagging power factor, the voltage is at its minimum value at bus 27 equal to 0.9594 pu for the DG with unit pf and equal to 0.9627 pu for the lag pf DG, as shown in Table 3.

Figs. 11 and 12 show the active and reactive power losses in each of the branches of the 69-bus system for the two cases where a DG is connected to the selected bus,
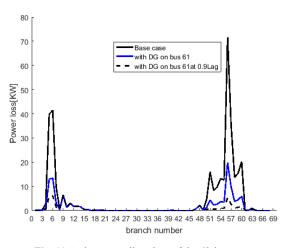
Table 3 Simulation results of 69-system

Methods	DG location		DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case				281.578	187.560	0.882
GWO	61	upf	1.9043	113.0785 (66.47)	54.3294 (63.93)	0.9594
		lag	2.0446	51.7467 (84.65)	28.0549 (81.37)	0.9627
WOA	61	upf	1.9043	113.0868 (66.47)	54.2342 (64.00)	0.9598
		lag	2.0446	51.7502 (84.66)	28.0638 (81.37)	0.9629
PSO	61	upf	1.9043	113.062 (66.478)	54.2726 (63.975)	0.9596
		lag	2.0446	51.7485 (84.657)	28.0791 (81.36)	0.9628

Fig. 11 Active power lines loss of the 69-bus system

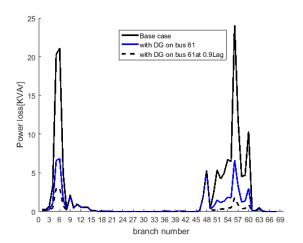**Fig. 10** Voltage profiles for 69-bus system

Fig. 12 Reactive power lines loss of the 69-bus system

in the case of a unit power factor and in the case of a lagging power factor and when no DG is connected. It is observed from the figures that, for the IEEE 69-bus test system, the branches 6 and 58 have the highest losses.

3.2 Results using Voltage Stability Index

The buses are sorted in descending order according to the Voltage Stability Index. For the 33-bus system, bus 6 has the highest Voltage Stability Index (the most sensitive bus to voltage collapse) of the network, so this bus is selected for the DG location; In addition, buses 18 and 33 are also selected for the simulation since they have the lowest voltage values. Similarly for the 69-bus system, the node 61 exhibits the highest Voltage Stability Index in the network. Thus, the node 61 is chosen as the optimal location of the DG. In addition bus 27 and 8 are also selected for the simulation, as bus 27 is the furthest away bus of the network, and bus 8 for its strategic node in the network. The Voltage Stability Index profiles are determined for both network test systems with and without DGs placement and are shown in Figs. 13 to 17.

All simulation results using the Voltage Stability Index and various algorithms for the two test systems are presented in Tables 4 and 5.

3.2.1 Results for 33-bus test system using Voltage Stability Index

In the 33-bus system, without allocating DG, the 6th bus has the maximum VSI value and is equal to 0.0111. The minimum voltage of the system is 0.882 pu at 18th bus (bus 33 is the furthest away bus in the second longest branch of the network and has low voltage value of 0.8867 pu).

The Voltage Stability Index profiles, when the optimal DG unit size at up has been connected at buses 6, 18 and 33, respectively and also when the optimal DG unit
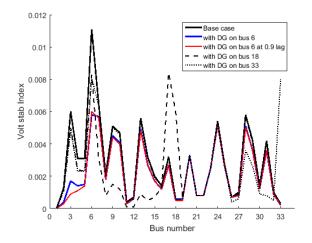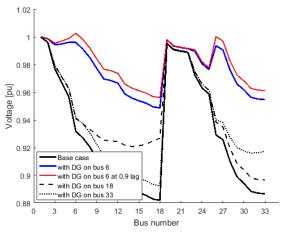

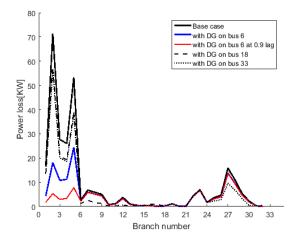**Fig. 13** The 33-bus system Voltage Stability Index

Fig. 14 Voltage profiles of 33-bus system

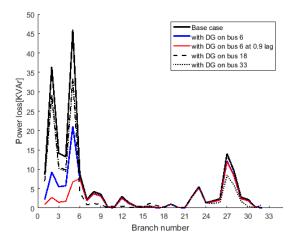**Fig. 15** Active power lines loss of the 33-bus system

Fig. 16 Reactive power lines loss of the 33-bus system

size at 0.9 pf has been connected at bus 6, are presented in Fig. 13, while Fig. 14 presents the voltage profiles of network buses for the same cases.

In the case where the decentralized production units at unit power factor are connected to buses 6, 18 and 33, the optimal sizes are respectively 3.2405 MW, 0.4163 MW and 0.452 MW. The total active power losses
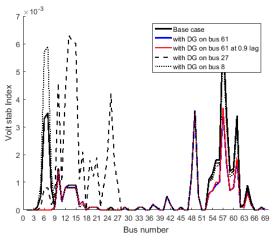
Fig. 17 The 69-bus system Voltage Stability Index

Table 4 Simulation results of 33-bus system

Methods	DG location	DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case			281.578	187.560	0.882
GWO	6	upf	3.2405	145.15 (48.45)	105.206 (44.03)	0.9487
		lag	3.0206	96.48 (65.736)	74.2516 (60.496)	0.9562
WOA	6	upf	3.2406	144.0732 (48.835)	104.4284 (44.44)	0.9476
		lag	3.0206	96.2806 (65.81)	74.0696 (60.59)	0.9555
PSO	6	upf	3.2406	145.5037 (48.327)	105.4582 (43.89)	0.949
		lag	3.0206	96.2816 (65.81)	74.0704 (60.59)	0.9555

Table 5 Simulation results of 69-bus system

Methods	DG location	DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case			337.3014	150.664	0.8697
GWO	61	upf	2.6874	139.766 (58.56)	63.613 (57.78)	0.9657
		lag	2.6995	73.5082 (78.20)	35.4285 (76.48)	0.9685
WOA	61	upf	2.6878	138.8929 (58.82)	63.2816 (57.998)	0.9656
		lag	2.6998	72.7282 (78.44)	35.1375 (76.68)	0.9683
PSO	61	upf	2.6878	140.8083 (58.25)	64.0093 (57.51)	0.9658
		lag	2.6998	65.7631 (80.503)	32.5653 (78.38)	0.9673

after installation of the DGs are 145.151 kW, 217.498 kW and 214.763 kW, representing reductions of 48.45 %, 22.76 % and 23.73 % respectively. The total reactive power losses are 105.206 kVAr, 144.349 kVAr and 143.877 kVAr wich represent reductions of 44.03 %, 23.20 % and 23.45 % respectively. The maximum VSI of this system is improved from 0.0111 to 0.0058 and also the minimum voltage is improved to 0.9487 pu after DG placed at bus 6.

The simulation results indicate that the size of the DG obtained is lower for the lagging power factor 3.0206 MW than for the unit power factor 3.2405 MW; similarly, the losses are lower for the DG at the lagging power factor than for the DG at the unit power factor. The total losses after placement at the 6th bus of DG at 0.9 power factor lag are 96.483 kW and 74.2516 KVAr respectively witch present a reductions of 33.53 % and 29.42 % compared with those obtained with DG at unit power factor and a total reductions of 65.74 % and 60.50 % compared with losses obtained without DG.

Figs. 15 and 16 show the active and reactive power losses in each of the branches of the 33-bus system for the two cases where no DG is connected and in the case where a DG at unity and lagging power factor is connected to the selected bus. For the IEEE 33-bus test system, the branches 2 and 5 have the highest losses in case of DG at unit power factor while in case of lagging power factor the highest losses are at branch 27.

It is observed from Fig. 14, that the profile voltage also improves with a DG at the lagging power factor than with a DG at the unit power factor. The minimum bus voltage increases from 0.882 pu without DG to 0.9562 pu with a DG at 0.9 pf lagging against 0.9487 pu with a DG at the unit pf.

It should be noted that adding a DG unit to bus 18 or bus 33 brings a slight improvement in the profile of the bus voltage and also a slight decrease in power losses, as shown in Figs. 14, 15 and 16.

3.2.2 Results for 69-bus test system using Voltage Stability Index

Similarly, in the 69-bus test system without allocating DG, the maximum VSI value is at bus 61 and is equal to 0.0066. The minimum voltage of the system is 0.8697 pu at 65th bus.

Fig. 17 shows the Voltage Stability Index profiles, when the optimal DG has been connected at buses 8, 27 and 61 respectively, while Fig. 18 presents the voltage profiles of network buses for the same cases.
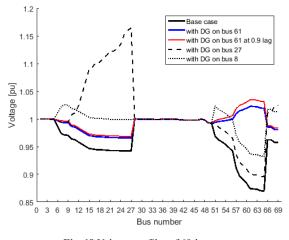
Fig. 18 Voltage profiles of 69-bus system

Fig. 19 Active power lines loss of the 69-bus system

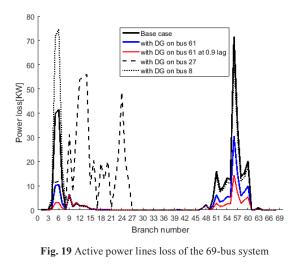**Fig. 20** Reactive power lines loss of the 69-bus system

In the case where the decentralized production units at unit power factor are connected to buses 8, 27 and 61 the optimal sizes are respectively 7.3582 MW, 3.2956 MW and 2.6874 MW. The total active power losses after installation of the DGs are 382.592kW, 673.881 kW and 139.766 kW, representing an increase of 13.42 % and 99.78 % when the DGs are connected to buses 8 and 27, whereas a reduction of 58.56 % is observed when the DG is connected to bus 61. The total reactive power losses are 178.833 kVAr, 247.465 kVAr and 63.613 kVAr, wich represent an increase of 18.69 % and 64.25 % when the DGs are connected to buses 8 and 27, while a reduction of 57.78 % is observed when the DG is connected to bus 61.

After DG placement at bus 61, the maximum VSI of this system is improved from 0.007 to 0.0036 and also the minimum voltage is improved from 0.8697 pu to 0.9657 pu.

The size of the DG obtained is higher for the lagging power factor 2.6995 MW; however, the power losses are lower. The total losses after placement at the 61th bus of DG at 0.9 power factor lag are 73.5082 kW and 35.4285 KVAr respectively witch present a reductions of 47.40 % and 44.30 % compared with those obtained with DG at unit power factor and a total reductions of 78.20 % and 76.48 % compared with losses obtained without DG.

The active and reactive power losses in each of the branches of the 69-bus system for the two cases where no DG is connected and in the case where a DG at unity and lagging power factor is connected to the selected bus are presented in Figs. 19 and 20. The highest power losses are in the branches 6 and 56.

It should be noted that the voltage improves more with a DG at the lagging power factor than with a DG at the unit power factor. The minimum voltage value increases from
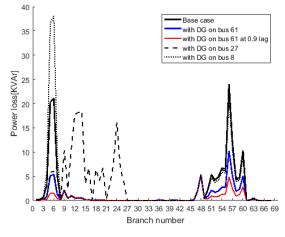
0.8697 pu without DG to 0.9685 pu with a DG at 0.9 pf lagging against 0.9657 pu with a DG at the unit pf.

It is worth note that adding a DG unit to bus 8 or bus 27 brings a slight improvement in the profile of the bus voltage, however, brings an increase in the power losses especially when the DG unit is connected to bus 27 as shown in Figs. 18, 19 and 20.

3.3 Results using Voltage Deviation Index

The buses are sorted in descending order according to the Voltage Deviation Index (the voltage deviation from the nominal voltage). For the 33-bus system, the buses selected for the DG site are bus 18 as the optimal location since it has the highest Voltage Deviation Index in the network (lowest voltage value) Figs. 21 and 22, bus 33 which has the highest Voltage Deviation Index in the second longest branch of the network and bus 6 for its strategic node in the network. Similarly for the 69-bus system, the node 65 exhibit the highest Voltage Deviation Index in the
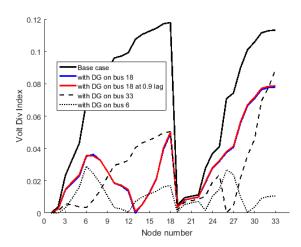
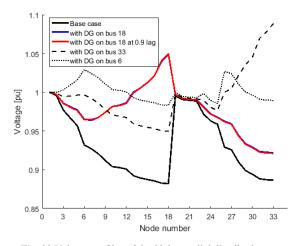**Fig. 21** The 33-bus system Voltage Deviation Index

Fig. 22 Voltage profiles of the 33-bus radial distribution system

network Fig. 23. Thus, the node 65 is chosen as the optimal location of the DG. Two other buses are also selected, bus 27 that has the highest Voltage Deviation Index in the second longest branch of the network and bus 8 for its strategic node in the network.

All simulation results using the Voltage Deviation Index and various algorithms for the two test systems are presented in Tables 6 and 7.

3.3.1 Results for 33-bus test system using Voltage Deviation Index

The total active and reactive power losses of the base case are 281.5877 kW and 187.9595 kVAr respectively. VDI for the same is obtained as 0.11798 at node 18 (i. e. voltage equal to 0.882 pu).

Fig. 21 shows the grid Voltage Deviation Index when the optimal DG unit for each case has been connected to buses 18, 33 and 6 each time, while Fig. 22 shows
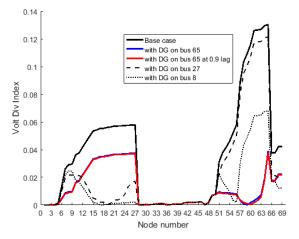

Fig. 23 The 69-bus system Voltage Deviation Index

Table 6 Simulation results of 33-bus system

Methods	DG location	DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case			281.578	187.560	0.882
GWO	18	upf 1.6407	229.224 (18.59)	176.974 (5,84)	0.922
		lag 1.4145	188.094 (33.20)	143.738 (23.52)	0.9212
WOA	18	upf 1.6408	229.063 (18.65)	176.8137 (5.93)	0.9212
		lag 1.4144	186.7024 (33.696)	142.1917 (24.35)	0.9214
PSO	18	upf 1.6408	229.0521 (18.657)	176.8029 (5.93)	0.922
		lag 1.4144	187.633 (33.366)	143.2277 (23.798)	0.9215

Table 7 Simulation results of 69-bus system

Methods	DG location	DG optimal size (MW)	P_{loss} (kW) (TLR %)	Q_{loss} (kVAr) (TLR %)	V_{min} (pu)
Base case			337.3014	150.664	0.8697
GWO	65	upf 2.3379	186.453 (44.72)	90.6358 (39.84)	0.9626
		lag 2.1689	116.0727 (65.58)	60.7789 (59.66)	0.9632
WOA	65	upf 2.3380	188.078 (44.24)	91.3711 (39.35)	0.9628
		lag 2.1689	113.7712 (66.27)	59.702 (60.37)	0.9629
PSO	65	upf 2.3380	186.2266 (44.79)	90.5329 (39.91)	0.9633
		lag 2.1689	116.7041 (65.40)	61.0729 (59.46)	0.9626

the profiles grid bus voltage for the same cases. It should be noted that the optimal size of Distributed Generation obtained for a unit power factor is 1.6407 MW, 3.2891 MW and 4.9766 MW when the Distributed Generation unit is connected to buses 18, 33 and 6, respectively.

With the installation of an optimal size DG operating at the pf unit on bus 18, the active and reactive power losses obtained are 229.224 kW and 176.974 kVAr, resulting in reductions of 18.59 % and 5.84 % respectively compared to the case without DG installation and, in the case of DG operating with 0.9 pf lag, the active and reactive power losses obtained are 188.094 kW and 143.738 kVAr, or a reduction of 33.20 % and 23.52 % respectively. It should be noted that the optimal size of Distributed Generation obtained for 0.9 pf lag is 1.4145 MW.

Figs. 24 and 25 present the network power losses in each branch of the system when DG unit is connected at buses 18, 33, and 6.

3.3.2 Results for 69-bus test system using Voltage Deviation Index

The total active and reactive power losses of the base case, without allocating DG, are 337.277 kW and 150.653 kVAR respectively. VDI for the same is obtained as 0.1303 at node 65 (i.e. the voltage equal to 0.8696 pu).

Fig. 23 shows the 69-bus es network Voltage Deviation Index when the optimal DG unit for each case was connected to buses 27, 65 and 8, respectively, while Fig. 26 shows the network bus voltage profiles when the optimal DG unit is connected to the same buses as before. The optimal size of the Distributed Generation obtained for a unit power factor is 0.9794 MW, 2.3379 MW and 7.2112 MW when the Distributed Generation unit is connected to buses 27, 65 and 8 respectively.
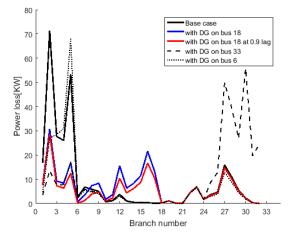

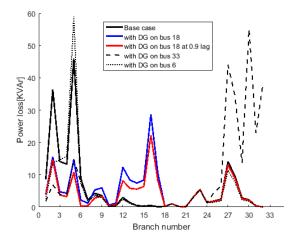**Fig. 24** Active power lines losses of the 33-bus radial distribution system

Fig. 25 Reactive power losses of the 33-bus radial distribution system
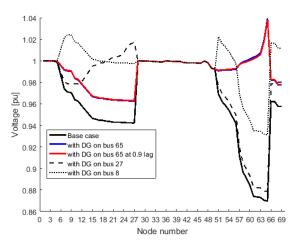

Fig. 26 Voltage profiles of the 69-bus radial distribution system

With the installation of an optimal size DG operating at the power factor unit on bus 65, the active and the reactive power losses obtained are respectively 186.453 kW and 90.6358 kVAr, resulting in reductions of 44.72 % and 39.84 % respectively compared to the case without DG installation and in the case of Distributed Generation operating with 0.9 pf lag, the active and the reactive power losses obtained are 116.0727 kW and 60.7789 kVAR, representing reductions of 65.58 % and 59.66 % respectively.

Figs. 27 and 28 show the network power losses in each branch of the system when a DG unit with an optimal size and working up is connected to buses 27, 65 and 8 respectively, and also in the case of a DG unit with an optimal size working at 0.9 pf lag is connected to bus 65.

4 Comparison of results
A summary of the results obtained for the 33 and 69-bus test systems with the approaches based on the Index Vector Method, the Voltage Stability Index and the Voltage Deviation Index is presented in Tables 8 and 9.
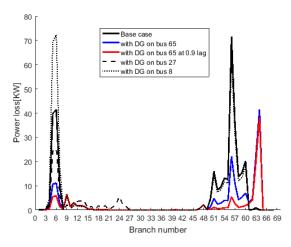
Fig. 27 Active power lines losses of the 69-bus radial distribution system
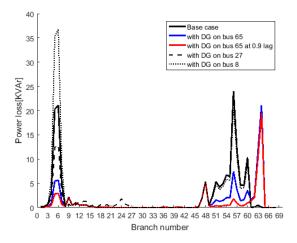

Fig. 28 Reactive power lines losses of the 69-bus radial distribution system

A comparison of the results corresponding to active and reactive power losses, minimum voltage level and DG dimensions was provided for both test systems taking into account the installation of the DG at unit and at 0.9 lagging power factor.

For both test systems, it can be concluded that the installation of an optimal size DG at the optimal location leads to a significant reduction in power losses. In addition, when the decentralized generating unit produces both active and reactive power (at a lag power factor of 0.9), network losses are lower than when only active power is fed into the grid, the voltage is also slightly improved, regardless of the index used.

The best results in terms of power losses reduction and minimum bus voltage are obtained for the VSI index with DG unit operating at 0.9 power factor. But it requires a significant DG size compared to the other two indices.

Noting that the Index Vector Method gives satisfactory results with a DG size lower than that obtained in the case of VSI.

On the other hand, the results obtained show that the three algorithms give very similar values.

5 Conclusion

In the present investigation, the DG units impact on radial power network was studied considering losses reduction and voltage profile improvement. Analyses were carried out on the IEEE 33 and 69 bus distribution systems using

Table 8 Simulation results of 33-bus system

	Without DG	With DG at unity pf			With DG at 0.9 pf lag		
		IVM	VSI	VDI	IVM	VSI	VDI
optimal DG bus location	-	30	6	18	30	6	18
DG optimal size (MW)	-	1.6319	3.240	1.6407	1.7995	3.0206	1.4146
total power loss (kW)	281.588	151.6819	145.151	229.2246	106.3945	96.483	188.0949
total reactive power loss (kVAr)	187.96	106.913	105.206	176.9749	77.0343	74.251	143.7386
V_{min} (pu)	0.882	0.9184	0.9487	0.922	0.9281	0.9562	0.9217

Table 9 Simulation results of 69-bus system

	Without DG	With DG at unity pf			With DG at 0.9 pf lag		
		IVM	VSI	VDI	IVM	VSI	VDI
optimal DG bus location	-	61	61	65	61	61	65
DG optimal size (MW)	-	1.9043	2.687	2.3379	2.0446	2.699	2.1689
total power loss (kW)	337.301	113.0785	139.766	186.453	51.7467	73.508	116.0727
total reactive power loss (kVAr)	150.664	54.3294	63.613	90.6358	280549	35.428	60.7789
V_{min} (pu)	0.8697	0.9594	0.9657	0.9626	0.9627	0.9685	0.9632

three methods (Index) for optimally allocating Distributed Generation and three methods to determine their optimal sizes. The study is carried out on DG operating at unity power factor and on DG operating at 0.9 power factor lag. From the simulation results, it is very clear that whatever method is used, the optimal allocation of Distributed Generation in the radial distribution system will greatly reduce the total power loss and improve the system voltage profile. On the other hand, a wrong allocation can lead to an increase in power losses.

Due to its contribution to the system's reactive power supply, DG at lagging power factor yields better results compared to DGs at unity power factor.

The best result in terms of losses reduction and minimum bus voltage is obtained for the VSI index with a DG unit at a power factor of 0.9 compared to the other indexes. But it requires a DG with large size compared to the other two indexes.

In this paper, the optimal DG size problem is solved with three metaheuristic algorithms, the results obtained show that the three algorithms give very similar values.

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