Placement and optimal size of DG in the distribution network based on nodal pricing reduction with nonlinear load model using the IABC algorithm

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Abstract. The growing use of distributed generation (DG) at the distribution level has led to a change in the status of distribution networks from a passive network to an active network such as transmission systems. Therefore, transmission network pricing method such as nodal pricing could be used in the distribution network. DG connection to the distribution network affects bus nodal pricing. If the DG presence reduces losses and congestion in the distribution network, nodal pricing will also decrease. This paper presents a method for calculating the optimal size and place of DG in the distribution network based on nodal pricing. This planning is done to maximize the profits of distribution companies that have used DG in their network to meet several advantages. The simulation was performed using the improved artificial bee colony algorithm (IABC). In the IABC algorithm, by exchanging the received information between bees according to Newton and gravity laws, it uses all this algorithm capacity to find the ideal answer by considering the constraints applied to the system. In most DG placement articles, network loads are assumed to be constant. Because loads are often sensitive to voltage and frequency, constant load analysis leads to inaccurate results. Therefore, in this paper, the proposed method is implemented on a 38-bus radial distribution system with a model of real loads sensitive to the voltage and frequency of the system, including residential, commercial, and industrial loads.

Keywords. Distribution network; IABC algorithm; DG optimal placement; nodal pricing; nonlinear load model.

1. Introduction

Today, the structure of the electricity industry in most countries is changing and moving towards creating competition in the purchase and sale of electric power. This issue, along with technological advances, environmental and economic issues, and the construction of small power generation units, has led to the expansion of the use of distributed generation [1]. Distributed generation sources can be defined as sources of electric power generation that are connecting to distribution networks and local consumers. The production capacity of these sources is smaller than other conventional sources of electric power production and the technology used to generate power in them is also very different and very diverse [2, 3]. Due to the growing demand for energy in the power system, the use of DGs has many advantages, which include reducing power losses and system costs, improving voltage and power quality profiles, preventing system upgrades, delaying investment in distribution and transmission networks, greenhouse gases reduction, improve the integration, reliability, and efficiency of the system [4].

On one hand, the distribution networks location between production and transmission, and on the other hand, the load centers existence, have made the distribution network relatively passive, but the growing use of distributed generation resources in the distribution network in recent years has to change the status of these networks from a passive network to an active network such as a transmission network. Therefore, transmission pricing mechanisms such as Nodal Pricing could be used in the distribution network. Nodal pricing or locational marginal pricing (LMP) is an economically effective pricing method that shows the marginal price of electricity in network nodes or buses. DG connection to the distribution network effects at the nodal pricing of the bus. If the DG presence reduces losses and
congestion in the distribution network, nodal pricing will also decrease [5].

Distribution networks are traditional passive networks that are not designed to install generators. Therefore, when connecting a production program in the distribution network, technical issues such as the phenomenon of steady-state voltage increase have to be considered, which results from the connection of generators at low voltage levels. The allowable voltage limit for these systems is assumed to be between 1000 V and 132 kV (±6%) of the rated voltage [6, 7]. Installation of DGs in non-optimal locations leads to increasing losses, the phenomenon of increasing voltage, and increasing distribution costs for network users [8]. Therefore, distributed generation sources should be optimally installed in the distribution network to maximize their benefits.

There are many optimal DG placement methods, most of which consider the system power loss as an objective function [9]. In [10], the optimal placement of DG has been performed to reduce losses in the 33-bus IEEE system with the PSO algorithm, assuming linear load changes. The place and optimal size of DG are using loss sensitivity factor (LSF) and simulated annealing algorithm (SA) in [11]. In Reference [12] Optimal DG allocation has been implemented to reduce losses by the Monte Carlo method. In Reference [13] the analytical method for multiple DG placement is proposed to reduce losses by genetic algorithm (GA). Minimizing power losses is an acceptable goal. However, this goal is not always economic, as it does not include the total cost of operation. References [14, 15] suggest optimal DG placement based on LMP. In which single DG allocation has been performing, but it is obvious that multiple placements of small capacity DGs are more beneficial than the single installation of large capacity DG. This paper considers only the allowable voltage limit of the buses as a constraint on the formulation of the problem, while the phenomenon of voltage rise, which is an important obstacle when installing DG in the distribution network, is not taken into account. Optimal DG allocation based on nodal pricing using the genetic algorithm is suggested in [16].

Most research articles have considered the constant loads in the problem of optimal DG placement [17–19] while the system loads are uncontrollable and depend on the voltage and frequency of the system [20]. Therefore, optimal DG allocation, assuming a constant load, will lead to contradictory and misleading results. Therefore, the assumption of a constant load must be reconsidered. A combined method based on the imperialist competitive algorithm (ICA) and the GA algorithm for simultaneous placement of DG and the capacitor bank is proposed in [21].

This paper presents an effective method based on nodal pricing using the IABC algorithm with terms of load model for optimal location and size of multiple DG. This planning has been implemented to maximize the profits of distribution companies that have used DG in their network to achieve several advantages. IABC is an intelligent method that has a high convergence rate and is less to get stuck at local minimum points and find the best solution. Here the profit is calculated based on the reduced cost of power losses in the presence of DG, the cost of electricity without DG installation, and by combining DG including the cost of electricity provided by DG. The proposed method is testing on the 38-bus radial distribution network according to the load model. To confirm the proposed method, the simulation results are compared with other references and at the end, by introducing the system operation indicators, the result of implementing the proposed method in single DG and multiple DG placement modes is evaluated. The structure of the article is as follows: in section 2 modeling and problem formulation is presented, in section 3 the proposed algorithm and problem-solving method are introduced, in section 4 the simulation results are shown, and finally in section 5 the conclusions are presented.

2. Modeling and formulation of Problem

This paper defines the objective function of the problem based on nodal pricing reduction. This optimization is performed by assuming nonlinear loads that are sensitive to the voltage and frequency of the network so that the practical frequency of the system is assuming to be 98% of the nominal frequency of the network. The PQ model is used for DG modeling; In other words, DGs are considered as negative loads and the production cost of DGs is assuming to be 45 $/MWh while the cost of electricity received from the network (price in a slack bus) is assuming to be 44.5 $/MWh.

2.1 Nodal pricing

The node price represents the final or marginal price of electricity in the network nodes [22] or, in other words, the node price reflects the marginal cost of delivering one more MWh to each bus in the system. This marginal cost takes into account the effect of power injection and delivery on marginal losses (incremental changes in losses on power). In line loading, this cost increases due to consumption and increased distance from Power Supply Point (PSP) to load. Thus, nodal prices are lower for buses close to the PSP and higher for buses far from the PSP, until they show an increase in marginal losses due to distance from the PSP [23]. Thus, in the distribution network, nodal pricing for active and reactive power is obtained from Equations (4) and (5), respectively:

\[
L = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} G_{ij} \left[ V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i - \theta_j) \right]
\] (1)
characteristics of different types of loads through exponential load models are shown in Equations (6) and (7):

\[
P_{Di} = P_{0i} V_i^2 [1 + \alpha (f - f_0)]
\]

\[
Q_{Di} = Q_{0i} V_i^2 [1 + \beta (f - f_0)]
\]

Where \( P_{Di} \) and \( Q_{Di} \) are active and reactive power in nodes \( i \), \( P_{0i} \) and \( Q_{0i} \) are the amounts of active and reactive power at nominal voltage in each node \( i \), \( V_i \) is the amount of voltage in bus \( i \), \( \gamma \) and \( \tau \) Voltage indicators for active and reactive powers, \( f \) and \( f_0 \) real and nominal frequency of the network, \( \alpha \) and \( \beta \) are frequency coefficients for active and reactive powers. If it is \( \tau = \gamma = \alpha = \beta = 0 \) in Equation (6) and Equation (7), the proposed load model will be a constant load model used in traditional power flow. The values of \( \tau \), \( \gamma \), \( \alpha \), and \( \beta \) for different types of loads are showing in Table 1 [27]. These load coefficients can be extracted by studying the network over a specified period schedule. Of course, it should be noted that these coefficients may vary in different networks.

### 2.4 Problem formulation

Assume that \( C_{i}^{a}(\text{no-DG}) \) and \( C_{i}^{r}(\text{no-DG}) \) are the prices of the active and reactive power nodes in terms of $/MWh and $/MVAr in each node \( i \) without DG. \( P_{0i}(\text{no-DG}) \) is the active power loss in MW without a DG connection. \( P_{Di} \) and \( Q_{Di} \) demand active and reactive power in each node \( i \) in terms of MW and MVAr. \( \lambda \). The price of grid-supplied electricity or power supplied to the PSP is in $/MWh. The \( \pi_{(\text{no-DG})}^{\text{no-DG}} \) electricity bill price without DG for each period \( \Delta t \) is obtained according to Equation (8) [28]:

\[
\pi_{(\text{no-DG})}^{\text{no-DG}} = \sum_{i=1}^{n} \left\{ \left( C_{i}^{a}(\text{no - DG}) \times P_{Di} \times \Delta t \right) + \left( C_{i}^{r}(\text{no - DG}) \times Q_{Di} \times \Delta t \right) + \left( \lambda \times P_{L}(\text{no - DG}) \times \Delta t \right) \right\}
\]

Where \( n \) is the number of buses and \( \Delta t \) is the period in hours. Since the losses are not dependent on any particular node, the cost of losses is calculated based on the power price in the PSP (ie \( \lambda \)) from Equation (3).

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### 2.3 Modeling of load

In traditional power flow analysis, the active and reactive loads in the nodes are usually assumed constant, regardless of the voltage and frequency of the system, while in the practical operation of the power system the real load models (i.e. residential, industrial and commercial loads) depend on voltage and frequency of the systems. The

| Load type    | \( \alpha \) | \( \beta \) | \( \gamma \) | \( \tau \) |
|--------------|-------------|-------------|-------------|-------------|
| Constant     | 0           | 0           | 0           | 0           |
| Residential  | 1           | -1.7        | 1.7         | 2.6         |
| Commercial   | 1.5         | -1.1        | 0.6         | 2.5         |
| Industrial   | 2.6         | 1.6         | 0.1         | 0.6         |
MVAr in each node i with DG. \( P_{L} \) is the active power loss in MW with a DG connection. \( P_{D_{i}} \) and \( Q_{D_{i}} \) are the active and reactive power provided by DG in each node i in terms of MW and MVAr. \( C(DG) \) is the electricity prices supplied by DG in $/MWh. The \( \pi^{DG} \) electricity bill price with DG for each period \( \Delta t \) is obtained according to Equation (9):

\[
\pi^{DG} = \sum_{i=1}^{n} \left\{ (C_{i}^{P}(DG) \times (P_{D_{i}} - P_{D_{Gi}}) \times \Delta t) + (C_{i}^{Q}(DG) \times (Q_{D_{i}} - Q_{D_{Gi}}) \times \Delta t) + (C(DG) \times P_{D_{Gi}} \times \Delta t) + (\lambda \times P_{L}(DG) \times \Delta t) \right\}
\]

DG is considered a negative load. In other words, the PQ model is used. \( P_{D_{Gi}} \) and \( Q_{D_{Gi}} \) are zero in all buses except DG buses. So:

\[
P_{D_{Gi}} = 0, \quad Q_{D_{Gi}} = 0 \quad \forall \text{ buses without DG}
\]

Profit is calculated based on savings on electricity bills in the presence of DG, including the price of electricity supplied by DG. Therefore, the problem formulation could be expressed as Equation (11):

\[
\max (\pi^{no-DG} - \pi^{DG})
\]

The following constraints are also included in the placement issue:

\[
V_{0,j} \leq V_{max} \quad \forall \text{ secondary side of LTC transformers}
\]

\[
V_{end,i/\text{max load, no DG}} \geq V_{min} \quad \forall \text{ nodes at feeders ends}
\]

\[
V_{D_{Gj}/\text{min load, max DG}} \leq V_{max}
\]

\[
V_{D_{Gj}/\text{min load, max DG}} \leq V_{0,i}
\]

\[
V_{min} \leq V_{i} \leq V_{max}
\]

\[
S_{(i,j)} \leq S_{(i,j)/\text{max}}
\]

\[
P_{D_{Gj}/\text{min load}} \leq P_{D_{Gi}} \leq P_{D_{Gj}/\text{max}}
\]

\[
Q_{D_{Gj}/\text{min load}} \leq Q_{D_{Gi}} \leq Q_{D_{Gj}/\text{max}}
\]

Where \( V_{0,i} \) is the voltage per PSP and \( V_{max} \) is the maximum allowable voltage range. \( V_{end, i/\text{max load, no DG}} \) the voltage at the end of the feeders at maximum load and without DG and \( V_{min} \) indicates the minimum allowable voltage range. \( V_{D_{Gj}/\text{min load, max DG}} \) indicates the voltage at the DG place with the minimum load and maximum DG penetration, and
the voltage of each bus \( i \) is denoted by \( V_i \). Equations (12) to (16) are about voltage constraints that state the problem of voltage rise in each feeder set with Load tap-changer (LTC). \( S_{(i,j)} \) is the apparent power passing, and \( S_{(i,j)_{\text{max}}} \) is the power flow capacity between nodes \( i \) and \( j \) in terms of MVA. Equations (18) and (19) also express the limit of DG production capacity.

### 3. Methodology

The first step in solving the problem is awareness of the status of the distribution network and find the weaknesses of the network in terms of voltage stability. By solving the power flow problem, the required parameters of the problem could be included: voltage amplitude and angle in all buses, the passing current of each line, losses of each line, total feeder input power, total feeder losses, active and reactive power of each load, the apparent power of the feeders obtained.

Therefore, according to previous mentions, for power flow analysis, the following items are important. (1) Determining a bus as a reference bus along with specifying its voltage. (2) Determining the injection power of PQ buses. (3) Determining the injection active power of PV buses along with determining their voltage magnitude. (4) Specifying the load model. (5) Topology and network parameters (static information) are requiring. After obtaining the results of power flow and identifying the weaknesses of the network in terms of voltage stability and losses, the best place to install DG in the network could be identified.

#### 3.1 Optimal power flow

In terms of structure and topology of transmission and distribution networks, some differences have caused the method of solving the problem of optimal power flow (OPF) in these two networks to be different. The structure of the transmission network rings, but the structure of the distribution network is radial. In this paper, to find the weakest bus of the network in terms of voltage stability and network losses, a voltage stability index (VSI) is introduced. By equating the \( n \)-bus distribution network of figure 1a in the form equal to two buses of figure 1b, the voltage stability index of the bus \( i \) is extracted by Equation (20).

\[
VSI_i = |V_1|^4 - 4|V_1|^2 \left( R_{eq} P_{Di} + X_{eq} Q_{Di} \right) - 4 \left( X_{eq} P_{Di} - R_{eq} Q_{Di} \right)^2
\]  

(20)

Where \( |V_1| \) is the magnitude of the busbar voltage and \( R_{eq} \) and \( X_{eq} \) are equivalent line resistances and reactances, respectively, calculated by Equation (21).

\[
R_{eq} + jX_{eq} = \sum_{i=2}^{n} \left( R_{i-1,i} + jX_{i-1,i} \right) \frac{I_{i-1,i}}{I_{i-1,i}}
\]  

(21)

\[
P_{Di} + jQ_{Di} = |V_i| |I_{i-1,i}| (cos\phi_i + jsin\phi_i)
\]  

(22)
Where $\Sigma$ is the sum of the path from a substation to bus $i$, $I_{i-1,i}$ represents the current from bus $i-1$ to bus $i$, $|V_i|$ voltage magnitude bus $i$, and $\phi_i$ the angle difference between the voltage and the load demand current in the bus $i$. It is assumed that bus 1 is the substation as the reference bus and $d_1=0$. The voltage vector relations of figure 1c will be Equations (23) and (24).

\[
|V_1|\cos\delta_i - |V_i| = R_{eq}|I_{i-1,i}|\cos\phi_i + X_{eq}|I_{i-1,i}|\sin\phi_i \quad (23)
\]

\[
|V_1|\sin\delta_i = X_{eq}|I_{i-1,i}|\cos\phi_i - R_{eq}|I_{i-1,i}|\sin\phi_i \quad (24)
\]

\[
\Delta V = |V_1|\cos\delta_i - |V_i| \quad (25)
\]

Where $\delta_i$ is the angle of the bus $i$ voltage. Equation (23) and Equation (24) could be rewritten by multiplying their sides in $|V_i|$ by Equation (26) and Equation (27), respectively.

\[
R_{eq}P_{Di} + X_{eq}Q_{Di} = |V_i|\Delta V \quad (26)
\]

\[
X_{eq}P_{Di} - R_{eq}Q_{Di} = |V_1||V_i|\sin\delta_i \quad (27)
\]

Therefore, Equation (20) can be rewritten as Equation (28).

\[
VSI_i = |V_1|^4 - 4|V_1|^2(|V_i|\Delta V) - 4(|V_1||V_i|\sin\delta_i)^2 \quad (28)
\]

The VSI index in Equation (28) depends only on the voltage of substation and bus $i$ also on the bus $i$ voltage angle. In this method, it is no longer necessary to calculate the bus admittance matrix, bus impedance matrix, and equivalent impedance to node $i$ to substation (i.e., Equation (21)). The above advantages will make this index suitable for real-time calculations and the calculation of this index requires only one power flow. Also, the stability limit of the bus $i$ voltage is when $VSI_i = 0$. Therefore, by solving the problem of power flow without DG, the weaknesses of the network could be identified with the help of the VSI index and considered as candidate points for installing DG in the network, and then the problem of power flow with DG could be solved.

Figure 2 shows the flowchart of the problem-solving method. As you can see, the optimal solution to the problem is obtained in two steps. In the first stage, the candidate places for installing DG in the network have been extracted and in the second stage, the problem has been solved with the presence of DG in the network. Finally, the output of the problem will include the maximum profit, the optimal place and size of the DG, the node price of the active and reactive power of the network, the reduction of losses, and the improvement of the network voltage profile.

3.2 Improved artificial bee colony algorithm

In this paper, the IABC algorithm is used for the optimal placement of DG in the distribution network. The ABC algorithm is a technique for solving optimization problems based on the behavior of bees. In this method, each of the bees, by direct cooperation and sharing information, tries to get the best answer according to the rules of probability. Bees of a complex system to find out the place and quality of food sources outside their hive. First, a set of food sources is selected randomly (initial answers), then the worker bees refer to the sources and check the amount of honey and their quality and return to the hive and give their information to the spectator bees. Then each bee moves to the place and, based on the information, selects a source in its neighborhood, that is, the bee decides whether to stay in the new place or to go to the previous place based on the type of flower and the amount of honey. When the resource is depleting, they move to a new source found by the bees.
and this process is repeated until the needs are meting. The algorithm encoding is as follows.

 Initialization: The value of $X_{ij}$ is selected as the initial answer in the search space of the algorithm and the value of their competence is examined based on the objective function studied, each of which is introduced as a source of honey used. The choice of these answers was random in the search space and represents worker bees.

 Movement of explorer bees: The probability for the selected sources is based on Equation (29) and the selection of a food source using the choice of the roulette wheel for each explorer bee and determining the honey amount for each of them with the model developed based on the reciprocal gravity force between the explorer bees is obtaining in Equation (30) to Equation (34).

$$p_i = \frac{f_{it_i}}{\sum_{n=1}^{N} f_{it_n}} \tag{29}$$

The mutual force between two masses in $m_2$, $m_1$ is in the form of Equation (30). Which is shown in figure 3 of the interaction of these forces.

$$F_{12} = G \frac{m_1 m_2}{r_{21}^2} \tag{30}$$

$$\vec{r}_{21} = \frac{r_2 - r_1}{|r_2 - r_1|} \tag{31}$$

Where $F_{12}$, $r_{21}$, and $G$ are mutual forces, unit vector, and constant gravity. In the same way for bees, we express the following equations based on their suitability.

$$F_{ij} = G \frac{F(\theta_i) \times F(\theta_j)}{|\theta_{ij} - \theta_{ij}|}$$

$$X_{ij}(t + 1) = \theta_{ij}(t) + F_{ij} \cdot [\theta_{ij}(t) - \theta_{ij}(t)] \tag{33}$$

In Equation (32) $F(\theta_i)$ and $F(\theta_j)$ are the amount of competency introduced for worker bees, respectively, which results in its effect on the new feed source in the form of Equation (33). Also, considering the interaction of all bees, Equation (33) is expressed by expanding as Equation (34) [15].

$$X_{ij}(t + 1) = \theta_{ij}(t) + \sum_{k=1}^{N} F_{ij} \cdot [\theta_{ij}(t) - \theta_{ij}(t)] \tag{34}$$

In fact, in the IABC algorithm, the criterion used is instead of the random value, which increases the efficiency of this algorithm.

The motion of Pioneer Bees: If the Fitness value of the function is not corrected in the next iterations of the algorithm, it is called Limit and those resources are called abandoned, which is used by the movement of pioneer bees to retrieve and replace new resources. The movement of these bees is in the form of Equation (35).

$$\theta_{ij} = \theta_{ijmin} + r \cdot (\theta_{ijmax} - \theta_{ijmin}) \tag{35}$$

Placement: If the food source found in later stages is better than before, this amount will enter the bees’ memory. And finally, this program continues to meet the optimal answer. Figure 4 shows the flowchart of the IABC algorithm.
Finally, the method presented in figure 2 is implemented by the IABC algorithm as follows:

Step 1: Create the initial population randomly. Each member of the initial population is the network bus voltage.
Step 2: Check the voltage and other constraints for each member of the population at all network nodes.
Step 3: Extract the network node voltages and DG installation candidate places.
Step 4: Create new members. Each member of the new population includes the size of the DG and the candidate places for DG installation on the network.
Step 5: Apply each member of the new population to the distribution network, i.e. the size of DG produced in each member at the relevant bus place to the network.
Step 6: Calculate the value of the objective function for each member of the population. The member that yields the value of the optimal objective function will be the optimal member.

Figure 5. 38-bus radial distribution network.
Step 7: If the convergence criterion is fulfilled, stop the operation and show the results, otherwise repeat with the new members until the optimal answer is reached.

4. Simulation results

In this paper, the proposed method is implemented on a 38-bus radial distribution network. The single-line diagram of the network is shown in figure 5. Network information is available at [29]. The price of electricity on the PSP is assumed to be 44.5 $/MWh. The proposed method is performed in two modes of simulation of optimal single DG allocation and multiple DG in terms of load model. Similar to reference [30–33] is assuming that the distribution company (DISCO) owns the DG and the DISCOs profit is calculated based on the savings in the electricity bill, which includes the cost of electricity supplied by the DG. The cost of electricity supplied by DG is equal to 45 $/MWh.

Table 2. Results of single DG placement with voltage and frequency sensitive load model.

| Load type     | Optimal place (bus) | Optimal size (MW) | Losses (kW) | Minimum voltage (p.u.) | Maximum nodal pricing ($/MWh) | Profit ($) |
|---------------|---------------------|-------------------|-------------|-------------------------|--------------------------------|------------|
|               |                     |                   | No DG       | With DG                 | No DG                          | With DG    | No DG | With DG | No DG | With DG |
| Constant      | 6                   | 2.5072            | 210.1735    | 110.3946                | 0.9041                         | 0.9415     | 51.6983| 47.7230| 115570 |
| Residential   | 9                   | 1.0461            | 159.7881    | 106.2504                | 0.9178                         | 0.9400     | 50.5293| 47.9254| 39571  |
| Industrial    | 9                   | 1.2742            | 182.7798    | 108.9232                | 0.9108                         | 0.9400     | 51.1406| 47.8277| 57938  |
| Commercial    | 10                  | 1.1701            | 172.1548    | 106.7024                | 0.9139                         | 0.9400     | 50.9795| 47.9276| 42475  |
| Mixed         | 6                   | 2.0509            | 174.8570    | 98.2646                 | 0.9125                         | 0.9400     | 51.1270| 48.0976| 65156  |
| HGDA [29]     | 19                  | 1.17              | –           | 110.3734                | –                              | 0.93       | 48.38  | 46856  |
| PDLMP [30]    | 25                  | 0.91              | –           | 109                     | –                              | 0.93       | 50.30  | 45107  |

Figure 6. Nodal pricing of the active power with and without DG for mixed loads.

4.1 Single DG placement

The proposed method is implemented by a single DG placement for different types of loads in the 38-bus network. The simulation is first implemented with the same type of total loads (such as, the total loads are industrial) and then in the mixed load mode. The results are also compared with the constant load’s assumption, which is shown in table 2 of the single DG placement results. As could be seen, the simulation results differ in the presence of voltage and frequency sensitive loads with a constant load mode. The results should be reviewed assuming a constant load. In figures 6 and 7 the price of each unit of active and reactive power in the reference bus (power supplied by the network) in each node without the DG presence and with the optimal placement of DG is calculated. These results are shown in the case of mixed loads. The nodal pricing of the active and reactive power of each node has decreased significantly with the presence of DG.
Multiple DG placement

The proposed method could be extended to more DG placements. Implemented the simulation to placements 2 and 3 DG units on the test system. Tables 3 and 4 show the optimal place and size of the respective DG and total power losses by installing 2 and 3 DG units with the nonlinear load’s presence (mixed loads). It is observed that multiple DG placement is more beneficial because the profit increases by 25.3% in two-DG placements and 33.2% in three-DG placements compared to single-DG placements.

On the other hand, active and reactive losses, as seen in tables 3 and 4, are further reduced compared to single-DG placement (losses compared to single-DG placement, in the placement of two-DG units 16.1% and the placement of the three-DG units decreased by 28.2%).

The amount of reduction in the active power node price in the buses with the connection of one DG, two DG, and three DG compared to without DG in figure 8. It could be seen that the reduction in the nodal pricing in the buses is better in the case of multiple DG placement than in the single DG placement.

Figure 9 shows the total network line losses for the mixed load mode and figure 10 shows the network voltage profile. As you can see, with the help of the stability index introduced in section 3 and the network weaknesses identification and with the DG installation, the results of voltage profile improvement from method [29] are also better.

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Figure 8. Results of reduction in active power nodal pricing per number of DGs.

Figure 9. Active and reactive losses of network lines.

Figure 10. Network voltage profile for mixed load.
According to figure 10, the lowest VSI of the system belongs to bus 18-33-37, which is equal to 0.67912, and the voltage amplitude of this bus is 0.9110 p.u. Now, to improve the voltage profile and reduce losses, and then reduce nodal pricing, the tangible effect of DG installation in the network on the voltage stabilization index of bus 18 is obtained according to figure 11. Figure 11 shows that the installation of three-DG in the network was able to increase the VSI of the network buses, especially buses 18-33-37.

4.3 Assessment of the proposed method

The following performance indicators are introduced to verify the proposed method and to investigate the effect of the load model on distributed generation planning.

Active power loss indices are defined according to Equation (36) [31]:

$$LPI = \frac{P_{LDG}}{P_{L}}$$  \hspace{1cm} (36)

$P_{LDG}$ is active power loss with DG, $P_{L}$ is an active loss without DG. A decrease in the value of this index indicates a reduction in system losses. The penetration level of the DG affects the network voltage profile. Optimal DG installation leads to an improved grid voltage profile. VPI is calculating according to Equation (37) [31]:

$$VPI = \max_{i=2}^{n} \left( \frac{|V_{1} - |V_{i}||}{|V_{1}|} \right) \times 100$$  \hspace{1cm} (37)

If $V_{DDG}$ and $V_{D}$ are the mean system voltage deviations from the reference with and without DG installation, the voltage deviation index (VDI) is obtained from Equation (40) [32]:

$$V_{D} = \frac{1}{n-1} \sum_{i=2}^{n} |V_{i} - V_{1}|$$  \hspace{1cm} (38)

$$V_{DDG} = \frac{1}{n-1} \sum_{i=2}^{n} |V_{DGi} - V_{1}|$$  \hspace{1cm} (39)
Reducing the VDI value indicates improved voltage regulation in the bus. A value of 1 indicates a state without DG. To present the effect of DG on the nodal price of network buses, the NPI index according to Equation (41) is introduced:

\[
NPI = \max_{i=2}^{n} \left( \frac{C_i^p - \lambda}{\lambda} \right) \times 100
\]  

(41)

The simulation results for all modes (without DG, one, two, and three DG) for the mixed load model are shown in figures 13 and 14. It could be seen that all evaluation indicators have improved with DG. This change is more noticeable in the multiple placements of DG so that compared to the case without DG in the network, in the placement positions of one, two, and three DG units with LPI index, 43.8%, 52.7% and 59.6%, respectively, VDI index 38.6% and 50%, 57.1%, VPI index, 31.5% and 46.4%, 48.4% and NPI index 45.7% and 68.2%, 70.9% decreased. The percentage change of indices between two and three DG units is insignificant. Therefore, the placement of more than three DG units in the sample distribution network is not recommended.

Table 5 shows a comparison between some of the methods presented so far in the power network considering several criteria and the percentage of LMP reduction in each method. As you can see from the results, the percentage of LMP reduction of the proposed method is higher than other methods. However, it should be noted that the type of network studied, network size, load model, and type
| Method provider | Methods | With | OPF type | Load model | Dependent on | Calculating losses and voltage profile | Network type | Network size | Percentage of reduction (%) |
|-----------------|---------|------|----------|------------|--------------|----------------------------------------|--------------|-------------|-----------------------------|
| Abu-Mouti et al (2011) [41] | ABC algorithm | Yes | – | Constant | Active and reactive power | Losses and voltage profile | Distribution | IEEE 33-bus | 30.27 |
| Shaloudegi et al (2012) [33] | ANN tool | Yes | – | Constant | Market price and demand predict | Losses | Distribution | IEEE 37-bus | 8 |
| Sahriatzadeh et al (2012) [34] | DLMP | Yes | AC | Constant | Demand response | Losses | Distribution | 12-bus | 25 |
| Wei et al (2015) [35] | GARCH | Yes | TCIM | Constant | Three-phase current injection | – | Distribution | IEEE 13-bus | 10.61 |
| Hao et al (2016) [36] | DC-LMP | – | DC, AC | Constant | Generation Shift Factor | Losses | Distribution | 60-bus | 19.30 |
| Retnamony et al (2016) [37] | NCP | Yes | AC | Constant | Active and reactive power | Losses | Transmission | IEEE 14-bus | 26.58 |
| Alsaleh et al (2018) | SDP | [40] | Yes | AC | Constant | Active and reactive power | Losses | Distribution | IEEE 37-bus | 20 |
| Tolba et al (2018) | PSOGSA-MFO | Yes | Backward/Forward Sweep | Constant | Loss Sensitivity Factors | Losses and voltage profile | Distribution | IEEE 33-bus | 32.60 |
| Brooks et al (2020) | CC-DCOPF | Yes | DC | Constant | The marginal cost of injected real power variability | Losses | Transmission | IEEE 14-bus | 47.15 |
| Sharifinia et al (2020) [8] | EKF | Yes | AC | Constant | Power supply point prices (PSP) | Losses | Distribution | 17-bus radial | 16.5 |
| Li et al (2021) [38] | Game theory | Yes | linearized AC | Constant | Loss price caused by nodal reactive and active power | Losses | Distribution | IEEE 33-bus | 30.88 |
| Dashtdar et al (2021) | GA algorithm | Yes | DC-AC | Constant | Generation Shift Factor | Losses and voltage profile | Transmission | IEEE 14-bus | 57 |
| Presented | IABC Algorithm | Yes | AC | Real | The network voltage stability index | Losses and voltage profile | Distribution | 38-bus radial | 26.51 |
of power flow have a direct effect on the percentage of LMP reduction. For example, in references [3, 6, 37–39], a higher reduction was obtained, and this is in the case that the largest network of choice in these methods is the IEEE 33-bus network, and sometimes for the transmission network, this percentage is reduced. This percentage will certainly decrease as the network gets bigger. Therefore, the proposed method has a good performance in reducing LMP. Table 5 shows the dependence of each method on quantities, indices, parameters in reducing LMP. The proposed method uses the network voltage stability index to the DG placement and combines loads (including residential, industrial, and commercial) to make the results real.

Finally, the features of the proposed method can be listed as follows:

• Nodal Pricing Reduction in the Distribution Network using the IABC Algorithm.
• Consider different load models.
• Calculate the price of active and reactive power in the whole network node with optimal DG placement.
• Provide voltage stability index (VSI) to solve the OPF problem.
• Extraction of optimal DG installation place in the network, based on VSI.
• Calculation of the maximum profit of DG based on OPF with Nodal Pricing criterion under the supervision of DISCO.
• Reduce network losses and improve voltage profile, calculate maximum profit per number of different DGs.
• Consider LPI, VDI and NPI criteria.

5. Conclusion

In this paper, an effective method based on nodal pricing for optimal place and size of multiple DGs in the distribution network by considering nonlinear loads using the IABC algorithm is proposed. The efficiency of the proposed method has been tested on a 38-bus radial distribution network. As observed, the simulation results are different from the assumed constant load by considering the nonlinear load model. It has been observed that an optimized small-capacity DG produces more profit than a non-optimized large-capacity DG. Therefore, placement DG is essential to meet maximum profit and minimum loss. It is also clear that multiple DG placement with small sizes is both technically and economically more profitable than single placement DG with large capacity, as nodal prices, losses, and voltage profiles have been much improved. On the other hand, according to the proposed method evaluation, the indices of losses, voltage profiles, nodal pricing, and voltage deviation in the case of multiple DG placement have changed much compared to the single placement of DG and without DG.

Declaration

Conflict of interest: The authors declare that they have no conflict of interest.

References

[1] Dashtdar, Masoud, Najafi, Mojtaba and Mostafa Esmaeilbeig 2021 Calculating the locational marginal price and solving of optimal power flow problem based on congestion management using WPSO-GSF algorithm. Journal of Nonlinear Systems in Electrical Engineering 7(1): 81–107
[2] Lakum, Ashokkumar and Vasundhara Mahajan 2019 Optimal placement and sizing of multiple active power filters in radial distribution system using grey wolf optimizer in presence of nonlinear distributed generation. Electric Power Systems Research 173: 281–290
[3] Dashtdar, Masoud, Mojtaba Najafi and Mostafa Esmaeilbeig 2020 Calculating the locational marginal price and solving optimal power flow problem based on congestion management using GA-GSF algorithm. Electrical Engineering 1–18
[4] Dashtdar, Masoud, Olena Rubanenko, Vladislav Kuchansky, Seyed Mohammad Sadegh Hosseinimoghadam, Irfan Sami and Mohit Bajaj 2021 Simultaneous Competition Modeling of Generations and Consumers in the New Market Structure based on the Supply Function Equilibrium Model Systems. In: 2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON), pp. 321–326
[5] Najafi, Mojtaba, Samaneh Ahmadi and Masoud Dashtdar 2019 Simultaneous energy and reserve market clearing with consideration of interruptible loads as one of demand response resources and different reliability requirements of consumers. International Journal of Emerging Electric Power Systems 20(5)
[6] Dashtdar, Masoud, Mojtaba Najafi and Mostafa Esmaeilbeig 2021 Reducing LMP and resolving the congestion of the lines based on placement and optimal size of DG in the power network using the GA-GSF algorithm. Electrical Engineering 103(2): 1279–1306
[7] Dashtdar, Majid and Masoud Dashtdar 2019 Voltage Control in Distribution Networks in Presence of Distributed Generators Based on Local and Coordinated Control Structures. The Scientific Bulletin of Electrical Engineering Faculty 19(2): 21–27
[8] Sharifinia, Sajjad, Mehdi Allahbakshsi, Mohammad Mehdi Arefi, Mohsen Tadjidian, Midezra Shafie-khah, Taher Niknam, and João P S Catalão 2020 Extended Kalman Filter-Based Approach for Nodal Pricing in Active Distribution Networks. IEEE Systems Journal 15(1): 487–496
[9] Poornazaryan, Bahram, Peyman Karimyan G B and Gharehpetian and Mehrdad Abedi 2016 Optimal allocation and sizing of DG units considering voltage stability, losses, and load variations. International Journal of Electrical Power & Energy Systems 79: 42–52
[10] Kashyap, Mohan, Satish Kansal and Bhanu Partap Singh 2018 Optimal installation of multiple type DGs considering constant, ZIP load and load growth. *International Journal of Ambient Energy*, 1–9

[11] Sultana U, Azhar B Khairuddin, Mokhtar A S, Zareen N and Beenish Sultana 2016 Grey wolf optimizer based placement and sizing of multiple distributed generation in the distribution system. *Energy* 111: 525–536

[12] Das, Choton K, Octavian Bass, Ganesh Kothapalli, Thair S Mahmoud and Daryoush Habibi 2018 Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm. *Applied energy* 232: 212–228

[13] Seet, Chin Chia, Jagadeesh Pasupuleti and M. Reayasudin Basir Khan 2019 Optimal placement and sizing of distributed generation in distribution system using analytical method. *International Journal of Recent Technology and Engineering* 8(4): 6357–6363

[14] Singh A K and Parida S K 2018 A review on distributed generation allocation and planning in deregulated electricity market. *Renewable and Sustainable Energy Reviews* 82: 4132–4141

[15] Dashtdar, Masoud, Mojtaba Najaﬁ and Mostafa Esmaeilbeig 2020 Probabilistic planning for participation of virtual power plants in the presence of the thermal power plants in energy and reserve markets. *Sadhana* 45(1)

[16] Tolba, Mohamed A, Hegazy Rezk, Vladimir Tulskey, Ahmed A Zaki Diab, Almoatayz Y Abdelaziz and Artem Vanin 2018 Impact of optimum allocation of renewable distributed generations on distribution networks based on different optimization algorithms. *Energies* 11(1): 245

[17] Balu, Korra and Vivekananda Mukherjee 2020 Siting and Sizing of Distributed Generation and Shunt Capacitor Banks in Radial Distribution System Using Constriction Factor Particle Swarm Optimization. *Electric Power Components and Systems* 48(6–7): 697–710

[18] Milovanović, Miloš, Dragan Tasić, Jordan Radosavljević and Bojan Perović 2020 Optimal Placement and Sizing of Inverter-Based Distributed Generation Units and Shunt Capacitors in Distorted Distribution Systems Using a Hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm. *Electric Power Components and Systems* 48(6–7): 543–557

[19] Deb, Gagari, Kabir Chakraborty and Sumita Deb 2020 Modified Spider Monkey Optimization-Based Optimal Placement of Distributed Generators in Radial Distribution System for Voltage Security Improvement. *Electric Power Components and Systems* 48(9–10): 1006–1020

[20] Saha, Subhodip and Mukherjee V 2020 A Novel Meta-heuristic for Optimal Allocation of Distributed Generation in Balanced Distribution Network Considering Hourly Load Variation. In: *IEEE 9th Power India International Conference (PIICON)*, pp. 1–6

[21] Malik, Muhammad Zeeshan, Mahesh Kumar, Amir Mahmood Soomro, Mazhar Hussain Baloch, Mehr Gul, Muhammad Farhan and Ghulam Sarwar Kaloi. 2020 Strategic planning of renewable distributed generation in radial distribution system using advanced MOPSO method. *Energy Reports* 6: 2872–2886

[22] Georgilakis, Pavlos S and Nikos D Hatzigianni 2013 Optimal distributed generation placement in power distribution networks: models, methods, and future research. *IEEE transactions on power systems* 28(3): 3420–3428

[23] Sotkiewicz, Paul M and Jesus M Vignolo 2006 Nodal pricing for distribution networks: efficient pricing for efficiency-enhancing DG. *IEEE Transactions on Power Systems* 21(2): 1013–1014

[24] Moghaddas-Tafreshi S M and Elahe Mashhour 2009 Distributed generation modeling for power flow studies and a three-phase unbalanced power flow solution for radial distribution systems considering distributed generation. *Electric Power Systems Research* 79(4): 680–686

[25] Hosseimoghadam, Seyed Mohammad Sadegh, Masoud Dashtdar, Majid Dashtdar and Hamzeh Roghanian 2020 Security control of islanded micro-grid based on adaptive neuro-fuzzy inference system. *Scientific Bulletin*: *Series C Electrical Engineering and Computer Science* 1: 189–204

[26] Hosseimoghadam, Seyed Mohammad Sadegh, Hamzeh Roghanian, Masoud Dashtdar and Seyed Mohammad Razavi 2020 Size optimization of distributed generation resources in microgrid based on scenario tree. In: *IEEE 8th International Conference on Smart Grid (iSmartGrid)*, pp. 67–72

[27] Hosseimoghadam S M, Masoud Dashtdar M E N Bushehri and Majid Dashtdar 2021 Size Optimization of Distributed Generation Resources in Microgrids with Considering Uncertainty Units Based on Scenario Tree. *Automatic Control and Computer Sciences* 55(1): 92–101

[28] Singh, Rajesh Kumar and Goswami S K 2010 Optimum allocation of distributed generations based on nodal pricing for profit, loss reduction, and voltage improvement including voltage rise issue. *International Journal of Electrical Power & Energy Systems* 32(6): 637–644

[29] Veeramsetty, Venkataramana, Chintham Venkaiah and Vinod Kumar D M 2018 Hybrid genetic dragonfly algorithm based optimal power flow for computing LMP at DG buses for reliability improvement. *Energy Systems* 9(3): 709–757

[30] Rezvanfar, Razi, Mehrdad Tarafdar Hagh and Kazem Zare 2020 Power-based distribution locational marginal pricing under high-penetration of distributed energy resources. *International Journal of Electrical Power & Energy Systems* 123: 106303

[31] Kalantari, Meysam, Ahad Kazemi and Mohammad Saleh Zakerinia 2012 Optimization of Distributed Generation Placement for Minimizing Power Losses and Voltage Profile Improvement Using Genetic Algorithm. *International Journal of Advanced Computer Science* 2(10): 376–381

[32] Singh, Raj Kumar and Goswami S K 2011 Multi-objective optimization of distributed generation planning using impact indices and trade-off technique. *Electric Power Components and Systems* 39(11): 1175–1190

[33] Shaloudegi, Kiarash, Nazli Madinehi, Hosseinian S H and Hossein Askarian Abyaneh 2012 A novel policy for locational marginal price calculation in distribution systems based on loss reduction allocation using game theory. *IEEE Transactions on Power Systems* 27(2): 811–820

[34] Sahraizadeh, Farshid, Pramila Nirbhavane and Anurag K Srivastava 2012 Locational marginal price for distribution system considering demand response. In: *IEEE 2012 North American Power Symposium (NAPS)*, pp. 1–5

[35] Wei, Jie, Leslie Corson and Anurag K Srivastava 2015 Three-phase optimal power flow based distribution...
loational marginal pricing and associated price stability. In: *IEEE Power & Energy Society General Meeting*, pp. 1–5

[36] Hao, Jun, Yi Gu, Yingchen Zhang, Jun Jason Zhang and David Wenzhong Gao 2016 Locational marginal pricing in the campus power system at the power distribution level. In: *2016 IEEE Power and Energy Society General Meeting (PESGM)*, pp. 1–5

[37] Retnamony, Rajesh and Jacob Raglend I 2016 Determine the locational marginal price and social welfare maximization in a deregulated power system. In: *IEEE International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, pp. 1–7

[38] Li, Zhenhao, Chun Sing Lai, Xu Xu, Zhuoli Zhao and Loi Lei Lai 2021 Electricity trading based on distribution locational marginal price. *International Journal of Electrical Power & Energy Systems* 124: 106322

[39] Brooks, Adria E and Bernard C Lesieutre 2020 The validity of a locational marginal price on variable power injections in energy and regulation markets. *International Journal of Electrical Power & Energy Systems* 121: 106092

[40] Alsaleh, Ibrahim, and Lingling Fan 2018 Distribution locational marginal pricing (dlmp) for multiphase systems. In: *IEEE 2018 North American Power Symposium (NAPS)*, pp. 1–6

[41] Abu-Mouti, Fahad S and El-Hawary M E 2011 Optimal distributed generation allocation and sizing in distribution systems via artificial bee colony algorithm. *IEEE Transactions on Power Delivery* 26(4): 2090–2101