

OPTIMAL PLACEMENT AND SIZE OF DISTRIBUTED GENERATION IN RADIAL DISTRIBUTION SYSTEM USING WHALE OPTIMIZATION ALGORITHM

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Abstract

Distributed generation (DG) is small-scale energy generation which is closely installed to a load area. It is widely preferred in distribution networks due to its potential solution for loss mitigation and voltage profile improvement. The purposes of this research paper are to find the optimal location and size of the DG in a distribution system. The Newton-Raphson power flow method is used to solve the power flow in the system. In this paper, the overall active power loss minimization in the system is the objective function. The optimal location and sizing of the DG can be obtained by using, respectively, the fast voltage stability index and whale optimization algorithm which is the most recent metaheuristic optimization algorithm based on the natural hunting behaviour of the humpback whale. Moreover, the proposed algorithm is evaluated through 15 and 33 buses of the radial distribution networks. Furthermore, 3 kinds of the DG contribution are considered to compare the efficiency and performance. The results show the effectiveness and great performance of the proposed method in determining the optimal size and location of the DG in distribution systems.

Keywords: Distribution generation, whale optimization algorithm, radial distribution network

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Introduction

An electrical power system can be divided into 3 sectors which are generation, transmission, and distribution. The distribution system has been considered as the most important part among the 3 divisions since it is connected closely to the customers. It is the part in which the voltage is stepped down from medium voltage to low voltage for the consumers' utilization. Hence, the reliability of the system is mainly ensured by an efficient distribution system (Reddy *et al.*, 2017). Increasing the demand and network expansion has been the cause of the challenge for engineers to maintain the quality and reliability of the system economically and effectively (Pandy and Bhadoriya, 2014). When a heavy load is connected to the system, the voltage magnitude drops and the system loss also increases. In the 21st century, the electrical power supply should be able to meet the customers' requirements. Based on the research, distribution has contributed approximately 70% of the loss including the primary and secondary parts; hence, distribution has been considered as the main concern at present. In this regard, the system operation design and on-site power generation have been considered in order to deal with the problems. DG, which is also defined as a dispersed generation or embedded generation, is the modernized technology of power generation in smart distribution system technology used in this century; moreover, DG is given the definition as on-site small-scale power generation which is interconnected or connected directly to the distribution network (Celli and Pilo, 2001). It can be a grid-connected or stand-alone electrical generation unit which is located near the utilization site. In addition, Dulau *et al.* (2015) wrote that DG refers to electrical power production near to a consumer's location integrating with renewable and non-renewable energy sources. Mostly, it is not required that there are transmission lines in order to connect the DG to the delivery system (Chiradeja, 2005; Wang and Xu, 2011). The integration of DG in a distribution network can reduce the system's loss and improve the voltage profile

effectively and economically (Georgilakis and Hatziahyriou, 2013).

The trend of renewable energy consumption in a smart grid distribution has been increasing due to the environmental concerns and fossil energy depletions. DG is becoming an important part of electrical power grid development for the future since the presence of DG in the distribution can improve the reliability, reduce power loss, enhance power quality, reduce transmission investment cost, and reduce greenhouse gas emissions effectively. Regarding DG applications, there are several important factors to consider such as the DG technologies, the amount and capacity of the DG, the types of DG connections, etc. In fact, the integration of DG in a distribution network has an impact on the system's voltage and power control. To avoid and solve these issues, DG should be placed in the most appropriate location. The size and amount of the DG that is accessed are also very important for consideration. Otherwise, the non-optimal location and size of the DG can cause an increase in system losses, voltage fluctuation, voltage flicker, protection failure, harmonics, system instability, and ineffective investment cost (Mishra and Bhandakkar, 2014).

Optimization is the mathematical tool used to obtain the optimal solution of the objective function. Since the optimal power flow was proposed by a French scholar in 1962 (Carpentier, 1979), it has taken several decades to develop a more efficient algorithm to solve optimization problems, which can be linear or non-linear, and many methods have been applied to solve the optimization problems. They are grouped into conventional and intelligent methods. The well-known conventional methods are the Newton method (Zhang *et al.*, 2004), gradient method (Dommel *et al.*, 1968), linear programming (Mota-Palomino *et al.*, 1986), quadratic programming (Burchett *et al.*, 1984), and interior point method (Cai *et al.*, 2007) which have been widely used. These methods are preferred for fast calculation and online computation. On the other hand, these methods are not suitable for some optimization

problems with discrete variables due to their difficulties in reaching the convergence and global solution. Due to the continuously developing technology in the last decade, many novel intelligent techniques have been developed for dealing with complex problems. These recent intelligent methods include the genetic algorithm (GA) (Konaket *et al.*, 2006), particle swarm optimization (PSO) (Hazra and Sinha, 2011), artificial bee colony (ABC) (Karaboga, 2005), and whale optimization algorithm (WOA) (Mirjalili and Lewis, 2016). A heuristic search algorithm like the GA was considered as the most suitable for solving simultaneous multi-dimensional problems for a global optimum solution. Furthermore, the GA can reach convergence easily and it has a complex encoding and decoding operation. The PSO is a heuristic method which is based on the behaviour of swarms of flies, schools of fish, flocks of birds, etc. (swarms), and it has better convergence than the GA due to its combination of social psychology principle and better calculation to enhance the behaviour of the swarms. The ABC which was proposed by Karaboga in 2005 has been recognized as the most efficient and novel swarm intelligence technique. It is based on the intelligent behaviour of the honey bee to find nectar sources. Also, the ABC has been successfully applied to solve all kinds of optimization problems, so it has better performance for numerical optimization than the GA and PSO. The most recent heuristic algorithm, the WOA, was proposed in 2016 by Mirjalili and Lewis and is an algorithm based on the behaviour of the foraging of the humpback whale.

This paper illustrates the application and performance of the WOA in solving the optimal location and size of the DG in radial distribution networks. Three radial distribution networks of 15 and 33 buses were tested with the proposed algorithm. This paper is organized into 6 sections. A more detailed description of the DG will be in the next section and the problem formulation, of which the objective function involves minimization of active power loss minimization including system constraints, will be described in section 3. Section 4 will provide a brief description of the

WOA applied to solve the problems. The algorithm procedure of working step-by-step is described. The simulation results and discussion are placed in Section 5. Finally, the conclusion of the paper is set out in Section 6.

Distributed Generation Overview

Dondi *et al.* (2002) have defined DG as a small source of electric power generation or storage which is not considered as any part of a central power system and is relatively close to the load areas. Furthermore, DG has also been considered as a small power generation which has a capacity of less than 30MW; it is likely installed near or at customers' sites in order to fulfill specific customers' needs and improve power quality (Chambers, 2001). According to the IEEE, it was defined as the generation of electricity by facilities that are sufficiently smaller than central power plants and it is designed to interconnect or connect directly to any point in a power system. Furthermore, it is also known as a small-scale power generating unit which injects power directly to a customer's site or within the local distribution network. The scope and limitation of DG contribution have been studied over the years by many researchers. Based on its technology, DG is categorized into 3 divisions: (1) renewable generation; (2) modular distributed generation; and (3) production of combined heat and power distributed generation. Furthermore, there are two main types of DG based on energy sources. They are renewable and non-renewable energy. The renewable energy sources comprise the wind, solar, hydro, geothermal, thermal, and ocean sources. The non-renewable energy sources exist in the internal combustion engine, combined cycle combustion engine, and fuel cells. In view of the clean energy consumption trend, the energy sources of DG are mostly designed to consume non-polluted energy free of greenhouse gas emissions (Aref and Davoudi, 2012). Shaddiq *et al.* (2016) wrote that DG can be categorized based on the capacity of the DG, and it is divided into 4 types:

- Micro distributed generation: 1W to 5kW

- Small distributed generation: 5kW to 5MW
- Medium distributed generation: 5MW to 50MW
- Large distributed generation: 50MW to 300MW.

Nowadays, advanced technologies in new materials and designs for electrical power generation and storage units including solar photovoltaic (PV) panels, micro turbines, gas turbines, fuel cells, supercapacitors, and advanced digital controls have increased the efficiencies and applications for DG in electrical power production to improve the quality and stability of the systems. Changes in the electrical power market regulations in the wholesale and retail markets have opened up the chances for customers to install DG to fulfill their own energy needs. This is also a good way for the utilities to meet the power demands in the system. Regarding the power injection characteristics, DG is classified into 4 types. The first type of DG generates only active power and operates at the unity of the power factor and it includes PV, fuel cells, micro turbines, etc. The second type of DG injects only reactive power and it can be a capacitor, synchronous compensator, etc. The third type of DG can generate both active and reactive power and it includes a synchronous machine, gas turbine, etc. The last type of DG consumes reactive power but it injects active power back into the system, such as an induction generator at a wind farm.

Problem Formulation

The main objectives of this research paper are to find the optimal size and location of the DG in the radial distribution system in order to minimize active power loss in the distribution network and improve the voltage profile. The problem formulation of the objective function and system constraints are mentioned:

$$\text{Minimize } f_i(x,u), i = 1,2,\dots, N, \quad (1)$$

$$\text{Subject to } g(x,u) = 0, h(x,u) \leq 0, \quad (2)$$

where,

f_i is the objective function i ,

N_{obj} is the number of objective function,

g is the equality constraints,

h is the inequality constraints,

x is the vector of dependent variables, and

u is the vector of independent variables.

Power Loss Objective Function

The power loss can be obtained by computing the power flow between 2 buses as illustrated in Figure 1, and it can be formulated in the following equations.

Where V_i and V_k are the bus voltage at bus i and k respectively, the power flow of between buses i and k at bus i is given as,

$$S_{ik} = P_{ik} + jQ_{ik}, \quad (3)$$

$$S_{ik} = V_i I_{ik}^*, \quad (4)$$

$$S_{ik} = V_i (V_i^* - V_k^*) Y_{ik} + V_i V_i^* Y_{ik0}, \quad (5)$$

Similarly, the power flow of between buses k and i at bus k is given as,

$$S_{ki} = V_k (V_k^* - V_i^*) Y_{ki} + V_k V_k^* Y_{ki0}, \quad (6)$$

Hence, the loss between these 2 buses is the sum of the power flow in Equations 5 and 6.

$$S_{Total\ loss} = S_{ik} + S_{ki}, \quad (7)$$

The total power loss in a system is obtained by summing all the power flow of the branches. The power loss in the slack bus can be obtained by summing the power flow at the terminated bus (Anumaka, 2012). In this paper,

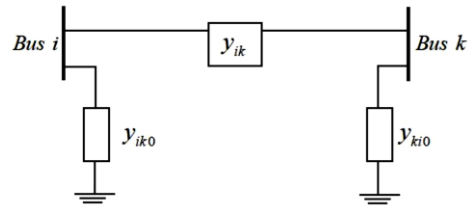


Figure 1. Diagram of power flow between 2 buses

the reactive power loss is neglected, so the objective function of total real power loss reduction is obtained as:

$$F_{Loss} = \text{real} \left(\sum_{i=1}^n S_{i \text{ Total loss}} \right). \quad (8)$$

where,

n is the number of the bus branches, and $S_{\text{total loss}}$ is the total complex power loss.

System Variable Constraints

System variable constraints are considered as inequality constraints which comprise the voltage magnitude and real power injection of the DG. These variables are optimized and they are limited to be within the constraints (upper and lower bound) in order to make sure they are in the upper and lower limits during the optimization process. The system variable constraints are expressed as,

$$0.9p.u. \leq V_i \leq 1.1p.u., \quad (9)$$

$$0.9p.u. \leq V_{DG} \leq 1.1p.u., \quad (10)$$

$$P_{\min} \leq P_{DG} < P_{\text{total load}}. \quad (11)$$

where,

V_i is the voltage magnitude at bus i ,

V_{DG} is the voltage magnitude at the bus with DG,

$P_{\min}$ is the minimum capacity of DG unit,

$P_{\text{total demand}}$ is the total power demand in the system, and

P_{DG} is the power generation from DG.

Power Flow Constraints

The power flow system is considered as the equality constraints which balance power generation, load demand, and power loss. Also, the well-known basic load flow equations can be written (Pandy and Bhadoriya, 2014):

$$S_i = P_i + jQ_i = V_i \cdot I_i^*, \quad (12)$$

$$S_i = V_i \sum_{k=1}^n V_k Y_{ik} = \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \angle (\delta_i - \delta_k + \theta_{ik}), \quad (13)$$

when the real and imaginary parts are resolved, then the power flow equation without the DG can be written as:

$$P_i = \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \cos(\delta_i - \delta_k + \theta_{ik}) = P_{G,i} - P_{D,i}, \quad (14)$$

$$Q_i = \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \sin(\delta_i - \delta_k + \theta_{ik}) = Q_{G,i} - Q_{D,i}, \quad (15)$$

The basic power balance equations are:

$$\sum_{k=1}^n P_{G,i} = \sum_{k=1}^n P_{D,i} + P_L, \quad (16)$$

$$\sum_{k=1}^n Q_{G,i} = \sum_{k=1}^n Q_{D,i} + Q_L, \quad (17)$$

The power flow equation is considered with the DG presence for a practical distribution system. Then, the power flow equation can be written as:

$$\sum_{k=1}^n P_{G,i} + \sum_{k=1}^n P_{DG,i} = \sum_{k=1}^n P_{D,i} + P_L, \quad (18)$$

$$\sum_{k=1}^n Q_{G,i} + \sum_{k=1}^n Q_{DG,i} = \sum_{k=1}^n Q_{D,i} + Q_L, \quad (19)$$

The final power flow equations for a distribution system with DG are:

$$\sum_{k=1}^n P_{G,i} + \sum_{k=1}^n P_{DG,i} - \sum_{k=1}^n P_{D,i} - P_L = 0, \quad (20)$$

$$\sum_{k=1}^n Q_{G,i} + \sum_{k=1}^n Q_{DG,i} - \sum_{k=1}^n Q_{D,i} - Q_L = 0. \quad (21)$$

where,

P_i, Q_i are the real and reactive power flow at bus i , respectively,

$P_{D,i}, Q_{D,i}$ are the real and reactive demands at bus i , respectively,

P_L, Q_L are the real and reactive power loss, respectively,

V_i, V_k are the voltage magnitudes at buses i and k , respectively,

$P_{DG,i}$ is the real power generated by the DG at bus i ,

δ_i, δ_k are the voltage angles at buses i and k , respectively,
 Y_{ik} is the magnitude of the ik th element in the bus admittance matrix,
 θ_{ik} is the angle of the ik th element in the bus admittance matrix, and
 n is the number of the total buses.

DG Location Identification

Many voltage indices have been introduced to determine the stability limit or voltage collapse prediction in the electrical power system. The fast voltage stability index (FVSI) which was proposed by Musirin and Rahman in 2002 is capable of determining critical areas in an electrical power system. Moreover, it can identify the points of voltage collapse, maximum permissible load, and sensitive bus in the system as well as the most critical line in an interconnected system (Sharma *et al.*, 2017). This index can either be applied to a bus or line identification. The FVSI formulation could be obtained from a voltage quadratic equation of the receiving bus of a 2-bus system (Figure 2),

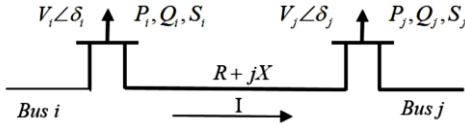


Figure 2. Modeling of 2-bus system

where,

V_i, V_j are the voltage magnitudes at the sending and receiving bus, respectively,
 P_i, Q_i are the active and reactive powers at the sending bus, respectively,
 P_j, Q_j are the active and reactive powers at the receiving bus, respectively,
 S_i, S_j are the apparent powers at the sending and receiving bus, respectively, and
 δ_i, δ_j are the angles of the sending and receiving bus, respectively.

The impedance with the current that flows in line is given as,

$$Z = R + jX, \quad (22)$$

$$I = \frac{V_i \angle \delta_i - V_j \angle \delta_j}{R + jX} \quad (23)$$

V_i is taken as the reference; hence the angle of bus i is shifted to 0. The apparent at bus j can be written as;

$$S_j = V_j I^*, \quad (24)$$

$$I = \left(\frac{S_j}{V_j} \right)^* = \left(\frac{P_j - jQ_j}{V_j \angle -\delta_j} \right), \quad (25)$$

From Equations 23 and 25, it can be expressed as:

$$\frac{V_i \angle 0 - V_j \angle \delta_j}{R + jX} = \left(\frac{P_j - jQ_j}{V_j \angle -\delta_j} \right), \quad (26)$$

$$V_i V_j \angle -\delta - V_j^2 \angle 0 = (R + jX)(P_j - jQ_j), \quad (27)$$

Separate the real and imaginary part,

$$V_i V_j \cos \delta - V_j^2 = RP_j + XQ_j, \quad (28)$$

$$-V_i V_j \sin \delta = XP_j - RQ_j, \quad (29)$$

Rearrange Equation 28 for P_j and then substituting to Equation 27 yields a quadratic equation of V_j ,

$$V_j^2 - \left(\frac{R}{X} \sin \delta + \cos \delta \right) V_i V_j + \left(X + \frac{R^2}{X} \right) Q_j = 0, \quad (30)$$

$$V_j = \frac{\left(\frac{R}{X} \sin \delta + \cos \delta \right) V_i \pm \sqrt{\left[\left(\frac{R}{X} \sin \delta + \cos \delta \right)^2 - 4 \left(X + \frac{R^2}{X} \right) Q_j}}{2}, \quad (31)$$

To obtain the real root of V_j , the discriminant is set to greater than or equal to 0,

$$\left[\left(\frac{R}{X} \sin \delta + \cos \delta \right)^2 - 4 \left(X + \frac{R^2}{X} \right) Q_j \right] \geq 0, \quad (32)$$

$$\frac{4Z^2 Q_j X}{V_i^2 (R \sin \delta + X \cos \delta)^2} \leq 1, \quad (33)$$

Since δ is normally very small ($\delta \approx 0$), then finally, the FVSI can be formulated as:

$$FVSI_{ij} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \quad (34)$$

where,

Z is the line impedance,

Q is the reactive power of the receiving bus,

V is the voltage magnitude of the sending bus, and

X is the line reactance.

The result of the FVSI could be evaluated that, if the FVSI is close to unity value = 1, it means that the line is closed to its instability point; moreover, if the FVSI goes to equal or beyond 1.0, that line may indicate that a voltage collapse may occur in the entire system. To maintain a secure condition the value of the FVSI should be maintained at well less than 1.

Whale Optimization Algorithm

Metaheuristic optimization algorithms are becoming more and more popular in engineering applications since they are easy to implement, do not require gradient information, can bypass local optima, can be utilized in a wide range of problems covering different disciplines, and, similar to the algorithms based on swarm intelligence, rely on a simple concept. The WOA is the most recent metaheuristic optimization search technique which was only proposed by Mirjalili and Lewis in 2016. It is an intelligent search method which mimics the prey hunting behaviour of the humpback whale which is considered to be an intelligent animal. It is one of the biggest mammals in the sea and it is also a predator which hunts small fish as its prey. Moreover, the whale needs to breathe from the surface of the ocean and only half of its brain sleeps (Hu *et al.*, 2016). Naturally, the humpback whale hunts small fish which are close to the ocean's surface by producing bubbles. This hunting behaviour is called bubble-net feeding (Watkins and Schevill, 1979). Mirjalili and Lewis, (2016) stated that when it encounters the prey, it produces bubbles in a circular or spiral shape around the prey and swims up toward the surface. The mathematical modelling of the WOA can be described in 3 operations (Prakash and Lakshminarayana, 2017;

Sharawi *et al.*, 2017). These are searching for prey, encircling the prey, and bubble-net feeding; the flowchart of the WOA is shown in Figure 3.

Encircling prey: the location of the prey is determined and they are encircled. In this phase, the current best position is assumed as the best candidate solution and the rest of the search agents try to update their position toward the best search agents. The process can be expressed by the following equations:

$$\vec{D} = \left| \vec{C} \cdot \vec{X}^*(t) - \vec{X}(t) \right|, \quad (35)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D}, \quad (36)$$

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a}, \quad (37)$$

$$\vec{C} = 2\vec{r}, \quad (38)$$

where,

t is the current iteration,

$\vec{A}, \vec{C}$ are the coefficient vectors,

$\vec{X}^*$ is the best solution obtained so far,

$\vec{X}$ is the vector position,

$\vec{a}$ is the linearly decrease from 2 to 0,

$\vec{r}$ is the random vector from 0 to 1, and

$\vec{D}$ refers to the distance between whale and the prey which is the best position obtained.

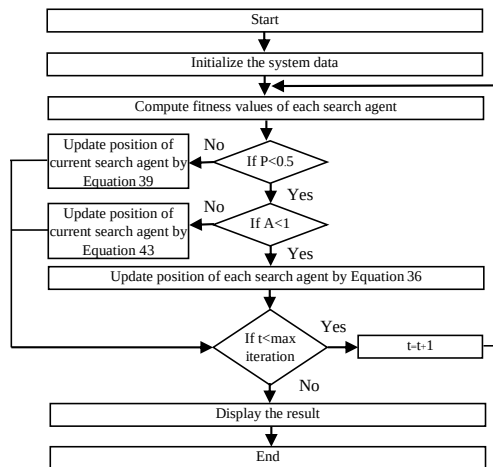


Figure 3. Flowchart of the WOA

Bubble-net hunting method (exploitation phase): there are 2 approaches to form the mathematical problem of the bubble-net feeding method.

- Shrinking encircling prey: the process is contributed by Equation 38, so it means that $\bar{A}$ is decreased when $\bar{a}$ decreases linearly. Thus, $\bar{A}$ is the random value in the interval $[-a, a]$ that a decreases from 2 to 0. The new position of a search agent can be obtained from the original position of the agent and position of the current best agent.

- Spiral updating position: the helix-shape movement of humpback whales can be formed as the spiral equation as below. It is created between the position of the whale and the prey:

$$\bar{X}(t+1) = \bar{D} \cdot e^{bl} \cdot \cos(2\pi l) + \bar{X}^*(t), \quad (39)$$

$$\bar{D} = \left| \bar{X}^*(t) - \bar{X}(t) \right|, \quad (40)$$

where,

b is the constant, and

l is the random number from -1 to 1.

During preys hunting, humpback whale swims around within shrinking circle and along spiral shape path simultaneously. During optimization, only 50% of assumption is chosen between either shrinking encircling or spiral shape to update the position of a whale. Moreover, it can be modelled as two equation system below.

$$\bar{X}(t+1) = \begin{cases} \bar{X}^*(t) - \bar{A} \cdot \bar{D} & \text{if } p < 0.5 \\ \bar{D} \cdot e^{bl} \cdot \cos(2\pi l) + \bar{X}^*(t) & \text{if } p \geq 0.5 \end{cases}, \quad (41)$$

where,

P is the random number from 0 to 1.

Search for prey (exploration phase): In this phase, the vector $\bar{A}$ is used to search randomly for prey. It means that it upgrades the position based on chosen search agents instead of the best search agents to get to the

optimum point. Furthermore, this can be expressed in mathematical form as:

$$\bar{D} = \left| \bar{C} \cdot \bar{X}_{random} - \bar{X} \right|, \quad (42)$$

$$\bar{X}(t+1) = \bar{X}_{random} - \bar{A} \bar{D}. \quad (43)$$

where,

$\bar{X}_{random}$ is the random position vector or random whale chosen from the current population.

Implementation of the Proposed Algorithm

The application of the proposed algorithm can be described as the following:

1. Read system data and compute the power flow using the Newton-Raphson method.
2. Determine the location of the DG using the FVSI.
3. Initialize the setting parameters such as maximum iteration, population, amount of DG, and parameter constraints.
4. Generate the population size of the DG size randomly.
5. Compute the power loss of the generated population and store the DG size which is the current best solution.
6. Update the position of the population.
7. Update the population and determine the power loss.
8. If the obtained power loss is less than the previous solution, store the new DG size and discard the previous solution or go back to step 7.
9. The algorithm is ended if it reaches the maximum iteration or the tolerance is satisfied.

Simulation Result and Discussion

The proposed algorithm was implemented by MATLAB 2014a and the 15 and 33 radial distribution systems were the tested cases. The objective function of loss minimization was implemented using the WOA which was set

with 50 of the population and 200 maximum iterations of the parameter setting values. The main aims of this paper were to determine the optimal location and size of the DG in the radial distribution network. The best location could be obtained using the FVSI approach and the bus whose FVSI value is close to or greater than 1 is suitable for DG installation. Moreover, 3 types of DG were studied in this research. They are type I (generates only real power and operates at the unity of power factor), type II (generates only reactive power), and type III (injects both real and reactive power, operating at lagging power factor). The obtained results of each DG type were compared to convey their performances and characteristics.

15-Bus System

Fifteen buses of the radial distribution system which was tested with the proposed algorithm are shown in Figure 4. The bus data

and line data can be obtained from Das *et al.* (1995). Bus 1 is considered as the reference bus and buses 2 to 15 are the load buses. Based on the FVSI, it was observed that bus 11 is the most suitable location for DG installation since its FVSI value was close to 1. The system power loss before minimization was 43.2kW.

Table 1 shows the obtained size of the different types of DG including the loss saving after placement of the DG at bus 11. It is observed that the loss saving of the DG type III is higher when compared to the other 2 types of DG. Furthermore, the obtained size of DG type III is a little bit higher than that of DG type I and type II which have a comparable size. The loss saving of DG type II is lower than the other DG types. The voltage profile improvement of DG type III is much better when compared to the other 2 types of DG, as illustrated in Figure 5. It can be evaluated that the reactive power required is the reason for the inductive loads in the system.

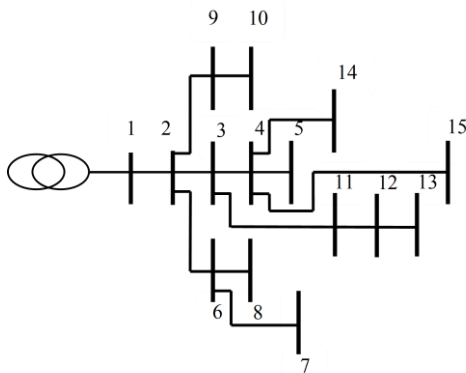


Figure 4. Fifteen buses of the radial distribution network

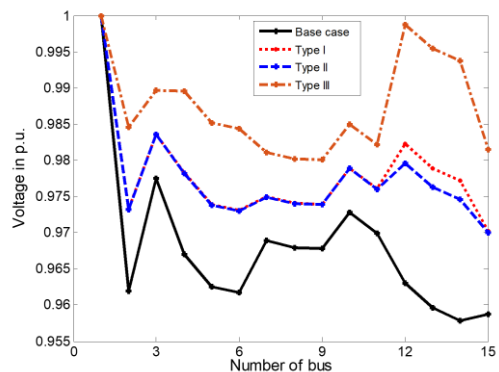


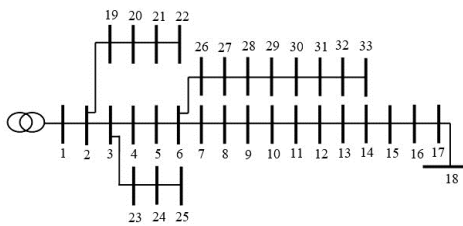
Figure 5. Voltage profile comparison of 15-bus system

Table 1. The results of 15-bus system

	Without DG	With DG		
		Type I (kW)	Type II (KVAR)	Type III (KVA)
Loss (kW)	43.2	30.8	30.4	18.3
Location	-	11	11	11
Size (kW)	-	620.84	628.0	889.30
Loss saving (kW)	-	12.4	12.8	24.9
Loss reduction (%)	-	28.70	29.62	57.63

Table 2. The results of 33-bus system

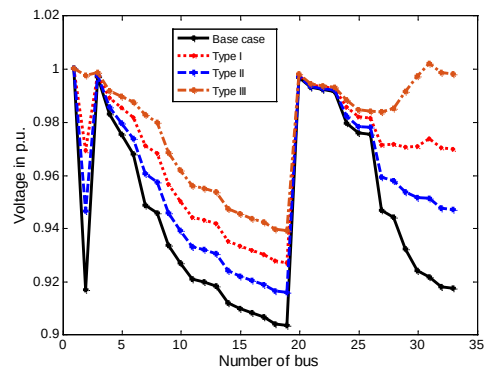
	Without DG	With DG		
		Type I (MW)	Type II (MVAR)	Type III (MVA)
Loss (kW)	206.5	119.2	150.2	67.9
Location	-	30	30	30
Size (MW)	-	1.55	1.22	1.97
Loss saving (kW)	-	87.3	56.3	138.6
Loss reduction (%)	-	42.27	27.26	67.11

**Figure 6. Thirty- three buses of the radial distribution network**

33-Bus System

The 33 buses of the radial distribution system are shown in Figure 6. It consists of a total of 33 buses and 32 lines or branches. The whole system is connected to a power transformer at 12.66kV of the secondary side while it is loaded totally at 3.175MW and 2.3Mvar. Bus 1 is considered as the reference bus and the others are load buses. The system data can be obtained in Prakash and Khatod (2016).

Based on the FVSI, bus 30 was the most appropriate location for the DG placement. The system power loss before the simulation was 206.5Kw. Table 2 shows the obtained results of each type of DG. It is shown that the size of DG type III is higher than DG type I and type II, and the loss saving of DG type III is also much higher when compared to DG type I and type II, respectively. Moreover, the voltage profile comparison of each DG type is also illustrated in Figure 7. Based on the obtained results, it can be observed that a reactive power injection is needed due to the loads which consume reactive power in the system.

**Figure 7. Voltage profile comparison of 33-bus system**

Conclusions

In this paper, a novel proposed method was introduced to determine the optimal location and size of the DG in a radial distribution network. The optimal location for the DG could be obtained using the FVSI, and the WOA was applied to compute to the optimal size of the DG. System power loss minimization was the objective function implemented in this research paper. Two radial distribution systems of 15 and 33 buses were selected as the test cases with the proposed algorithm considering 3 types of DG units. Furthermore, the proposed method can be applied with various configurations of the bus systems in determining the optimal location and size of the DG. The obtained outcome showed that the better solution was achieved with the type III of DG which generates both real and reactive power in the

system. The simulation results also indicated the effectiveness and important role of the DG contribution in power loss reduction and voltage profile improvement.

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