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Multi objective Flower Pollination Algorithm for solving capacitor placement in radial distribution system using data structure load flow analysis

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Abstract: The radial distribution system is a rugged system, it is also the most commonly used system, which suffers by loss and low voltage at the end bus. This loss can be reduced by the use of a capacitor in the system, which injects reactive current and also improves the voltage magnitude in the buses. The real power loss in the distribution line is the I^2R loss which depends on the current and resistance. The connection of the capacitor in the bus reduces the reactive current and losses. The loss reduction is equal to the increase in generation, necessary for the electric power provided by firms. For consumers, the quality of power supply depends on the voltage magnitude level, which is also considered and hence the objective of the problem becomes the multi objective of loss minimization and the minimization of voltage deviation. In this paper, the optimal location and size of the capacitor is found using a new computational intelligent algorithm called Flower Pollination Algorithm (FPA). To calculate the power flow and losses in the system, novel data structure load flow is introduced. In this, each bus is considered as a node with bus associated data. Links between the nodes are distribution lines and their own resistance and reactance. To validate the developed FPA solutions standard test cases, IEEE 33 and IEEE 69 radial distribution systems are considered.

Keywords: Flower Pollination Algorithm; data structure; loss minimization; voltage improvement; capacitor placement

1. Introduction

The modern power system has three major sections, namely generation, transmission and distribution. For economic reasons, the power is generated in bulk and then transmitted over a long distance. Finally the distribution system provides electric power to the end consumers. Among the three sections, the distribution system has more loss and this loss leads to poor voltage regulation at the end buses. The losses are increased by connecting inductive loads. If the inductive currents are supplied at the load end, then current in the system and its associated

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line loss may be reduced. The inductive current supplier is the capacitor. Hence the connecting capacitor at the load end to supply the reactive current and reactive (Q or VAR) power is essential in the distribution system. The next problem is the location and size of the capacitor for the system which depends on the load condition. In the current decade, using an intelligent algorithm for an optimization problem is common since it escapes from local optima and finds global optima. Many intelligent algorithms have been developed and implemented for engineering application.

In this paper, a novel data structure based on load flow analysis is proposed. This method is superior since the bus is considered as the node and the distribution line is considered as the link between nodes. The essential parameter associated with the bus is taken as the data for the node. The link has resistance and reactance of the distribution line. The commonly used, a forward and backward sweep algorithm is implemented in the data structure as pre order and post order traversal of the connected nodes (tree). The pre order traversal finds bus voltages and the post order traversal finds distribution line current and power losses. The combined pre order and post order traversals give distribution line losses and voltage of all buses.

Mesut E. Baran, and Felix F. Wu [1], considered the capacitor placement in the radial distribution system. Their objective of the work was to find the best capacitor location and size of the capacitor in the radial system. They used mixed integer technique for the problem solving. They decomposed the problem into master and slave, to simplify the execution. Ramon A. Gallego, Alcir Jose Monticelli, and Ruben Romero [2], introduced reactive power injection using a capacitor of a discrete size. These capacitor size and position in the radial distribution system is vital for better control and to reduce loss. Their mathematical model uses resistance for the calculation of real power and reactance for the calculation of reactive power loss. The current injection in the bus is sufficient to supply the demanded current in behind buses. M.H. Haque [3] developed a procedure to minimize copper loss due to resistance of the distribution line. For this, he considered the current as real and reactive components. His method was to introduce a capacitor into the buses which would-thereby reduce the total current in the branch. The reduction of the current leads to the reduction of the copper loss in the distribution line. He ordered the buses to be compensated by the capacitor for reactive power for location and then the size of a capacitor is decided based on requirement in the bus. Yahia Baghzouz, and S. Ertem [4] used the capacitor to compensate non sinusoidal harmonic distortion. The objective of the work was to minimize the total harmonic distortion in the radial distribution line. The connection of the capacitor in the radial distribution line improves the quality of the power and reduces the total harmonic distortion. The radial distribution line has high resistance as compared to the transmission line [5]. This distribution line cannot be solved by the Newton or fast decouple method, since it seems to be an ill conditioned system. In their approach, the voltage magnitude alone is considered for the load flow. They claimed that their approach requires less memory to achieve guaranteed convergence. The authors solved many practical Indian radial distribution system problems. A sensitivity factor gives the best location of the capacitor [6], for the reactive power compensation and to reduce the losses. The problem is divided into two parts, in the first part, the sensitive location is searched and in the second part, the optimal size is decided by the use of the intelligent

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algorithm. The new intelligent algorithm used is Plant Growth Simulation Algorithm (PGSA). This problem is solved without augmenting a constraint in the objective function. The results were compared with other published literatures and proved better quality of the solution. Apart from the distributed generator placement, their approach was used for reconfiguration to minimize the loss [7]. The reconfiguration itself reduces the loss and the constraint is that closing of the tie line doesn't form a loop in order to maintain the radial structure. Harmony Search Algorithm (HSA) is used to find the optimal size of the distribution generator and sensitive analysis is used to find the optimal location for the capacitor. HAS is used to find the reconfiguration condition along with the distributed generator placement for the loss minimization. Sneha sultana, and Provas Kumar Roy [8] used teaching learning optimization for placing and sizing of the capacitor. It uses teacher teaching technique and student learning process for the implementation of an algorithm for the location and sizing of the capacitor. They used standard test buses for the implementation and the results are compared to other intelligent algorithms. In the recent paper, Gravitational Search Algorithm (GSA) is used to find the optimal location and sizing of capacitor for the loss minimization [9]. For the location of capacitor, an earlier sensitive analysis is used and for the size optimization, GSA is used. The authors claimed that their algorithm provides better solution. Their result is compared with an analytical and other intelligent algorithm.

In all the above literature, the intelligent algorithm is used to find the size of the capacitor and they are underutilized since the location is found by analytical sensitive analysis method. This drawback is avoided in this paper. Flower Pollination Algorithm (FPA) [10] is used to find the simultaneous optimization location and size of the capacitor. FPA is best suitable for multi objective optimization. In this paper objectives of loss minimization and voltage profile improvement are considered for optimization.

Section II briefs a novel data structure based load flow based on the tree traversal. Section III states problem formulation, objective function and constraints of the problem. Section IV gives overview and step by step procedure for solving FPA for general purpose optimization. Section V provides overview of the different test cases considered for the work. Section VI provides result and discussion of the simulation. Finally section VII concludes the present work for capacitor optimization for the loss minimization and the voltage profile improvement.

2. Data structure based load flow

In computer programming, the data structure plays a vital role and improves the performance of program. Data structure provides simple way for retrieving and analyzing data. The distribution system is similar to tree in a data structure. The traversal of the tree is similar to forward and backward sweep in the radial distribution line. The tree traversal proved better retrieve and analysis of data. In this paper, a bus is considered as node and the distribution line connecting the bus is considered as link. Hence the node has all bus associated data which are voltage, real and reactive power load connected to the bus. The data associated with link are resistance and reactance. The substation of the radial distribution line is considered as the root

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node and successive buses are successive nodes connected to the root node. The branch in radial distribution line is considered as sub-tree branch. Three traversals in the tree are In-order, Preorder and Post order traversal. Post order traversal is similar to the backward sweep finding cumulative real and reactive power to the previous node. Preorder traversal is similar to forward sweep which is used to find losses in the radial distribution line. To understand pre and post order traversal a simple tree is given in Fig. 1.

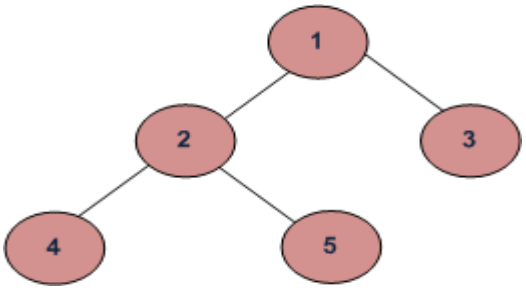


Fig. 1. Sample tree

In preorder traversal the nodes are visited in the following order. Nodes: 1, 2, 4, 5 and 3. The tree is traverse left direction to the end and then one level up and checks if there is any right branches then visit or move to the next level up. This traversal is similar to forward sweep of radial line. In post order traversal, the nodes are visited in the following order. Nodes: 4, 5, 2, 3 and 1. The tree traverses all last level nodes and next level up to traverse all nodes in that level, the tree traverse up to root node. This traversal is similar to the backward sweep in radial line.

Hence forward and backward sweep load flow is replaced by preorder and post order traversal of tree before the traversal buses are converted into nodes and distribution line is converted into links among the nodes. This traversal finds distribution line losses and all the bus voltages. As like forward and backward sweep, the convergence condition is calculated. The convergence condition is that the calculated root node (substation/first node) voltage is equal to the scheduled voltage of 1.0 per unit (pu).

3. Problem formulation

The objective of the problem is to minimize the real power loss and to minimize the voltage deviation of buses from 1.0 pu. The above two objectives of the problem is considered as multi objective problem. The problem is subjected to the power balance equality constraint and voltage level of inequality constraint. The problem formulation is given below

$$\min f = sf_1 \sum_{i=1}^{n\text{bus}-1} P_{\text{loss}(i,i+1)} + sf_2 \sum_{i=1}^{n\text{bus}} (1 - v_1), \tag{1}$$

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$$P_{\text{loss}(i,i+1)} = \frac{(P_i^2 + Q_i^2)}{V_i^2} R_{(i,i+1)} \,. \tag{2}$$

Subjected to:

Equality constraint

$$P_{\text{Root}} = P_{T,\text{ Load}} + P_{T,\text{ Loss},} \tag{3}$$

$$Q_{\text{Root}} = Q_{T,\text{ Load}} + Q_{T,\text{ Loss}.} \tag{4}$$

Inequality constraint

$$V_{\min} \le V_i \le V_{\max} \,, \tag{5}$$

$$Q_i^c \le \sum_{i=1}^{n} Q_{Li} \,, \tag{6}$$

where sf_1 and sf_2 are scaling factors to combine objectives, $P_{\text{Loss}(i,i+1)}$ is the loss between bus i and $i + 1$, P_i is the real power at bus i, Q_i is the reactive power at bus i, $Q_{C,I}$ is the capacitor compensation at bus i, Q_{Li} is the reactive power load, V_i is the voltage magnitude at bus i, $R_{(i,i+1)}$ is the resistance between bus i and $i + 1$, $X_{(i,i+1)}$ is the reactance between bus i and $i + 1$, P_{Root} is the total real power at root node, $P_{T,\text{ Load}}$ is the total real power demand or load, $P_{T,\text{ Loss}}$ is the total real power loss in the system, $V_{\min,}$ $V_{\max}$ is the minimum and maximum voltage limit.

Equation (1) is a multi-objective problem of minimizing the real power loss and the voltage deviation. Scaling factors are used to combine two objectives into the single objective problem. Equation (2) is used to find the real power loss using i^{th} bus powers and their consecutive line resistance. Equation (3) and (4) are equality constraints that supplied real and reactive power should be equal to the total demand and the losses in the system. Equation (5) gives inequality constraint of the voltage limit of the bus. Size of the capacitor has maximum limit and hence the connected capacitor should be less than that of the maximum value as given in Equation (6).

Power flow and voltage in all nodes are calculated from previous node power and voltage, to understand the simple one line diagram as given in Fig. 2. Real and reactive power of the $(i + 1)$ bus is calculated from the bus i as given in Equation (7) and (8). Equation (9) is used to find the $(i + 1)^{\text{th}}$ bus voltage from i^{th} bus voltage magnitude.

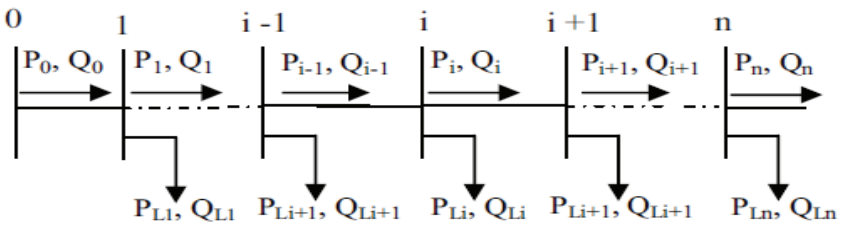


Fig. 2. One line diagram of distribution line

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$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1}\left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right), \tag{7}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1}\left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right), \tag{8}$$

$$|V_{i+1}|^2 = |V_1|^2 - 2(R_{i,i+1}P_i + X_{i,i+1}Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2)\left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right), \tag{9}$$

where P_i is the real power available at bus i, P_{i+1} is the real power available at next bus of i (i.e. $i + 1$), P_{Li+1} is the local real power load at next bus of i (i.e. $i + 1$), Q_i is the reactive power available at bus i, Q_{i+1} is the reactive power available at next bus of i, Q_{Li+1} is the local reactive power load at next bus of i.

4. Flower Pollination Algorithm

Xin-She Yang [10] introduced a nature inspired new algorithm, named a Flower Pollination Algorithm (FPA). In the universe, nature optimizes all living things for their survival. Genetic Algorithm (GA) mimics Darwin's theory of survival of fitness for the reproduction and to keep their species exist. GA improves the quality of the solution generation by generation and gives promising optimal solution. Before the evolution of animals, plants and trees are exist in the universe for the food sources of animals. Among the nature inspired algorithm, flower pollination is the longest successful survival technique. Hence this FPA might give global optimal solution for the minimization or maximization of the problem. Engineering optimization problems are multi objective in nature and needs most powerful optimization technique. The inventor of FPA proved its efficiency for solving bench mark multi objective problem and one mechanical engineering problem with the objective of designing disc brake. Flowering plants exist for more than 1.250,000 thousand years [10-12]. This is the most powerful reproduction in the universe. The reproduction of plants is due to pollination of the flowers. This pollination may be by the flower of the same plant or by the flower from some other plant. The pollination is classified into two group, one is local pollination – pollen of same flower and another one is cross pollination – pollen from the flower of any another plant of same spices. Local pollination occurs by the plant itself without the help of insects. Cross pollination sometimes called biotic pollination since it occurs by the insects. As nature evolution, cross pollination may yield good nursery. For engineering application, the control variables of the problem are considered as the flower and group of flower form the population of flowers. The cross or biotic pollination process is called global pollination featured by the insects, the insects behavior is addressed by levy flights. Levy flight (L) behavior as given in the Equation (10)

$$L = \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}. \tag{10}$$

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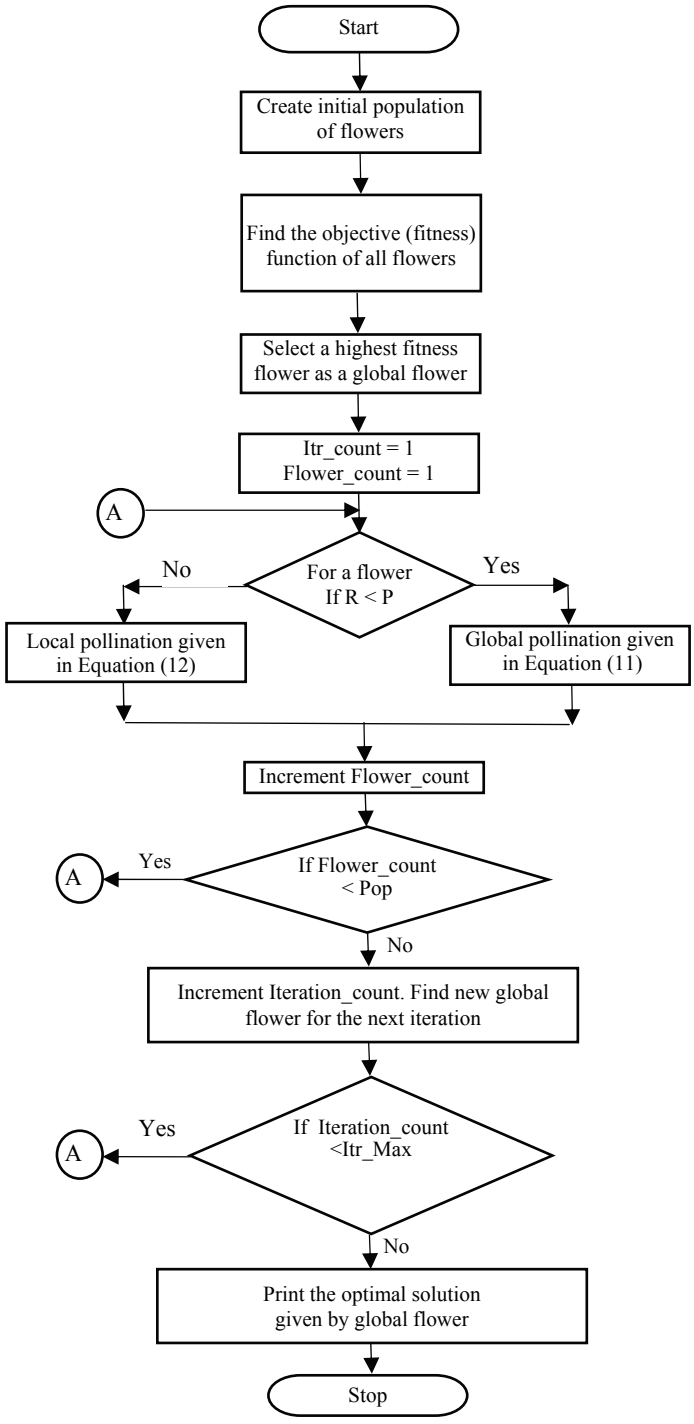


Fig. 3. Flower pollination algorithm flowchart

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In this Equation (10) where λ is a constant that characterizes the flying angle $\Gamma(\lambda)$ is the standard gamma function and *s* is another constant for step movement of the insect, and greater than zero. This Levy flight is used to find global pollination in the flower as given in the Equation (11).

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \gamma L(\lambda)(\boldsymbol{g}_* - \boldsymbol{x}_i^t), \tag{11}$$

where $\boldsymbol{x}i = \lfloor x_{1,i} \;\; x_{2,i} \;\; .....x_{d,i} \rfloor$ is the i^{th} flower that undergoes global pollination in iteration *t*, *L* is the Levy flight and $\boldsymbol{g}_*$ is the global best flower of the population. In some flowers local pollination may take place which is given as

$$x_i^{t+1} = x_i^t + \varepsilon(x_i^t - x_k^t), \tag{12}$$

where $\boldsymbol{x}$ with suffixes, *i, j* and *k* are the different flower positions in the population, and ε is a random number between zero and one.

For each flower the type of pollination is decided by the switching constant. If the random number correspond to the flower is less than the switching constant then global pollination is carried out else local pollination is carried out. The algorithm of flower pollination to solve optimization problem is given below.

Step 1: Create initial population of flowers.

Step 2: Find the fitness function of each flower.

Step 3: Find the best solution $\boldsymbol{g}_*$ in the initial population.

Step 4: For each flower generate a random number *R*.

Step 5: If *R* is less than switching probability, P Є [0, 1], go to step 7, else go to step 6.

Step 6: Implement global pollination as given in eq. (3.2) and go to step 8.

Step 7: Implement local pollination as given in eq. (3.3).

Step 8: Check stopping criterion and repeat step 2 to step 7.

Step 9: If stopping criterion is satisfied, print global solution.

Fig. 3 shows the flowchart of the Flower Pollination Algorithm. The type of pollination of the flower is decided by the switching constant P, if the random number of the corresponding flower is less than that P then global pollination takes place or else local pollination taken place. In iteration, only one flower is chosen as global flower and all flower undergone pollination. The iterations are repeated for the maximum number to get the best results.

5. FPA Implementation for distribution system

Multi objective of the problem is to minimize the loss and to minimize the voltage deviation. Hence the control variables are capacitor size and their location. These two control variables size and location form a flower. 20 flowers are considered for the population. For each flower, their control variables are used to update the radial distribution system and Data Structure (DS) based load flow is executed to find the losses and voltage in all buses. The outcome of the DS load flow is used to calculate the objective or fitness of the flower using Equation (1). The best fitness (minimum loss and minimum voltage deviation) flower is chosen as

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global flower. To carry out pollination, switching probability constant P is taken as 0.6, 's' constant is taken as 6, value of θ and φ are taken as 1.5 and 3.14, and for local pollination the constant γ is taken as 0.7. For each flower, a random number is generated if this random number is less than switching probability constant then global pollination otherwise local pollination is taken place. These steps are repeated for 200 iterations to get the global optimal value of control variables, capacitor size and its location in the radial distribution system. 30 trail runs are executed to get best solution. Key parameter for FPA implementation is given in Table 1. To evaluate FPA standard radial system IEEE 33, 69 buses are considered.

Table 1. FPA key parameter values

Parameters	Values
No. of flower	20
Max. iteration	200
Switching probability (P)	0.6
Theta (θ)	1.5
Gamma (γ)	0.7
No. of Runs	30

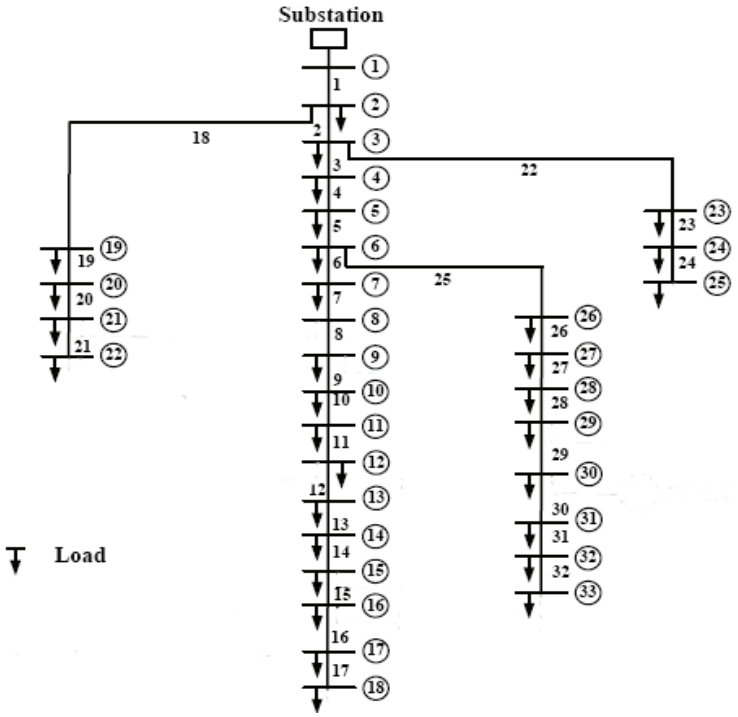


Fig. 4. IEEE 33 bus single line diagram

This 33 bus radial system has 33 buses and 32 distribution lines, the cumulative real and reactive power demands are 3715 kW and 2300 kvar respectively [9]. This radial system has

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low voltages at end buses due to heavy inductive loads. This low voltage may be improved by connecting capacitor to the buses which supplies part of reactive power demand. Further, this capacitor reduces the current flow and thereby the losses. Single line diagram of this 33 bus is given in Fig. 4.

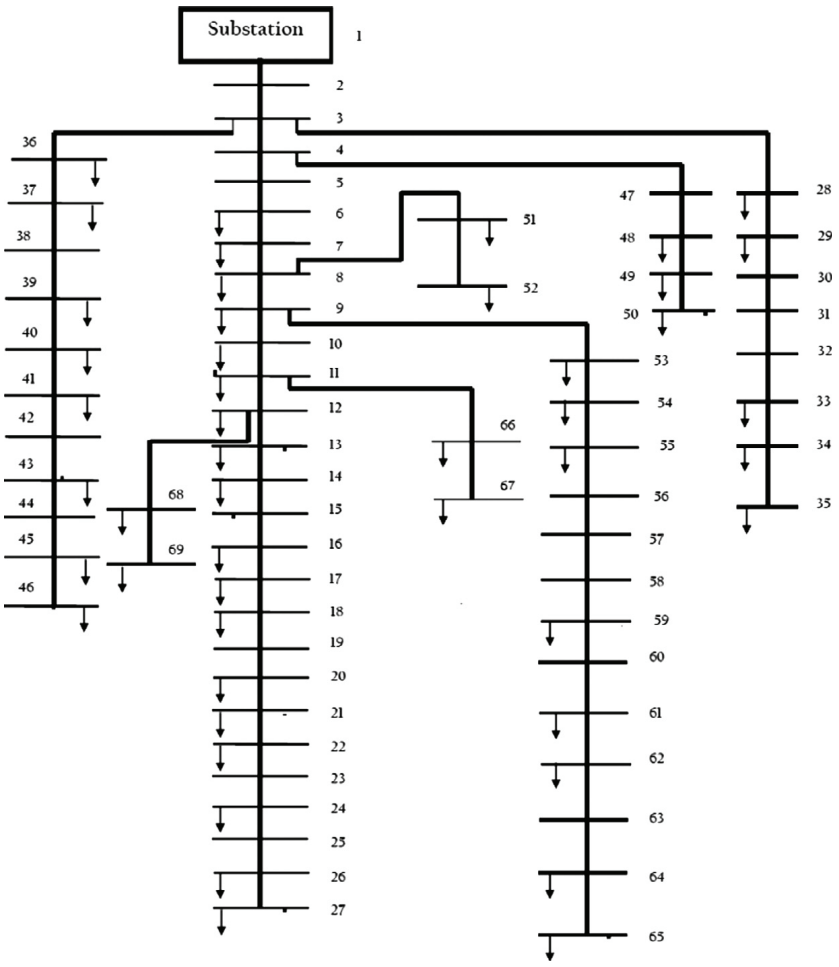


Fig. 5. IEEE 69 bus single line diagram

The 69 bus single line diagram [9] is given in Fig. 5. It has 69 buses and 68 distribution lines. Cumulative real and reactive power demand of the system is 3801.89 kW and 2694.1 kvar respectively. The first bus is the substation and has no local load and all other buses have their own local load connected to the bus. Bus 3 has three branches and bus 4, 7, 9, 11 and 12 have two branches, other buses have only one branch connected to its next bus.

The size of capacitor installed in the buses is limited to discrete size as given in the Table 2. This given size of capacitor is used to install in 33 and 69 bus to optimize the given multi objective.

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Table 2. Capacitor size

SI. No.	Capacitor	
	Size (kvar)	Cost ($/kvar)
1.	150	0.500
2.	300	0.350
3.	450	0.253
4.	600	0.220
5.	750	0.276
6.	900	0.183
7.	1050	0.228
8.	1200	0.170
9.	1350	0.207
10.	1500	0.201
11.	1650	0.193
12.	1800	0.870
13.	1950	0.211
14.	2100	0.176

6. Results and discussions

FPA and data structure load flow is implemented using MATLAB software installed in the computer having, i3 processor, 2.4 GHz, 4 GB RAM and 64 bit. The cost of capacitor is chosen from the Table 2 and the cost of real power loss is calculated as 168 $/kW [9]. The results of the two test cases are discussed below.

6.1. 33 Bus test system

Multi objective FPA for solving minimization of loss and voltage deviation is given in this section. Optimization variables are the capacitor size whose minimum range is 150 VAR and maximum range is 2100 kvar, the capacitor location ranges from 2 to 33 (excluding source node). To measure the performance of FPA, the results are compared with latest published algorithms [9] as given in Table 3. It compares the loss minimization as it is the first objective. FPA results are compared with the analytical method Interior Point (IP) method and latest intelligent algorithm Gravitational Search Algorithm (GSA).

Table 3. Loss comparison of FPA for 33 bus

Description	Base case	IP (analytical)	GSA	FPA (proposed)
Total loss (kW)	210.97	171.78	134.50	134.35
$C_{Location}$	–	9, 29, 30	26, 13, 15	13, 16, 29
C_{Size}	–	450, 800, 900	350, 450, 800	150, 150, 1050

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Description	Base case	IP (analytical)	GSA	FPA (proposed)
Total kvar	–	2150	1600	1450
Cost of kW loss (A) ($)	35442.96	28859.04	22596	22571.20
Cost of capacitor (B) ($/kvar)	–	499.35	457.15	389.40
Total cost (C = A + B) ($)	35442.96	29358.39	23053.15	22960.6
Net savings ($) (D = 35442.96 – C)	0.0	6084.57	12389.81	12482.36
% Savings (E = D/35442.96)	0.0%	17.17%	34.96%	35.22%

The second objective of minimization of voltage deviation is compared in the Table 4. For all the 33 buses, its voltage magnitude difference with nominal voltage (1.0 pu) is calculated and sum of this difference is considered as voltage deviation which is given in the second term of Equation (1). Voltage deviation is taken as the objective and is 0.91 pu, for the voltage profile obtained after compensation. Equation (13) finds sum of voltage deviation in all buses in base case is 1.7876 pu and in the FPA optimization it is reduced to 0.91 pu.

$$VD = \sum_{i=1}^{n\text{bus}} (1 - V_1) \tag{13}$$

The voltage magnitude of all the bus is improved near to the nominal value (1.0 pu) as compared to the base case. This voltage profile improvement is important parameter for the quality of power supply which is not addressed in the compared algorithms (IP and GSA).

Voltage profile of the considered test case is shown in Fig. 6 and 7. In this case, voltage magnitude is focused and the FPA improves the voltage in all buses. Fig. 6 gives line plot and Fig. 7 gives voltage magnitude of all 33 buses. It is clear from the plot that the voltage at root node is 1.0 pu and bus voltages are near to 1.0 pu. minimum value of voltage 0. 9703 pu occurs at the end node 33. Table 5 provides the result of three different objectives of FPA analysis, first the focus in given to loss at this time voltage deviation is more as given in column 3 and when focus is given to voltage deviation, loss is more as given in the 4th column and the optimization both loss and voltage deviation minimization is given in the 5th column.

Table 4. VD comparison of FPA for 33 bus

Description	Base case	IP (analytical)	GSA	FPA (proposed)
V_{min} (pu)	0.9089	0.9501	0.9672	0. 9703
VD (pu)	**1.7876**	–	–	**0.91**

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Description	**Base case**	**IP** (analytical)	**GSA**	**FPA** (proposed)
Improved VD (pu)	–	–	–	0.8776
P_{Loss} (kW)	210.97	171.78	134.50	134.35
$C_{Location}$	–	9, 29, 30	26, 13, 15	13, 16, 29
C_{Size}	–	450, 800, 900	350, 450, 800	150, 150, 1050

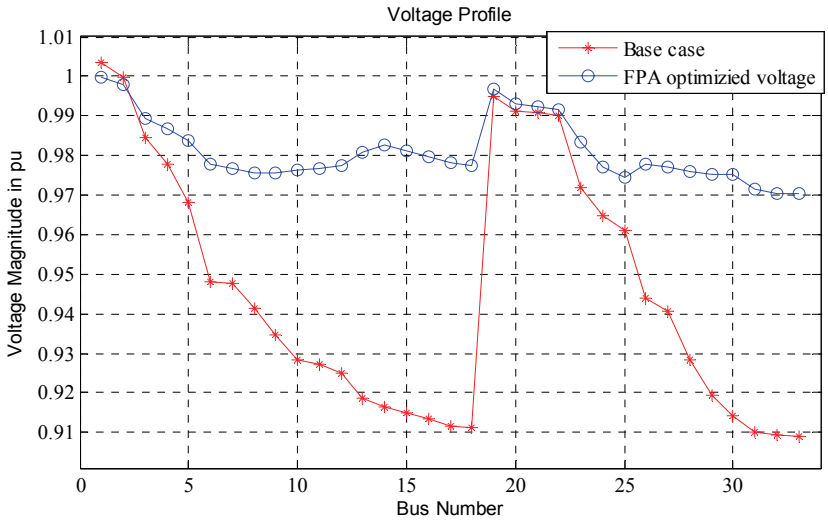


Fig. 6. IEEE 33 bus voltage profile using line plot

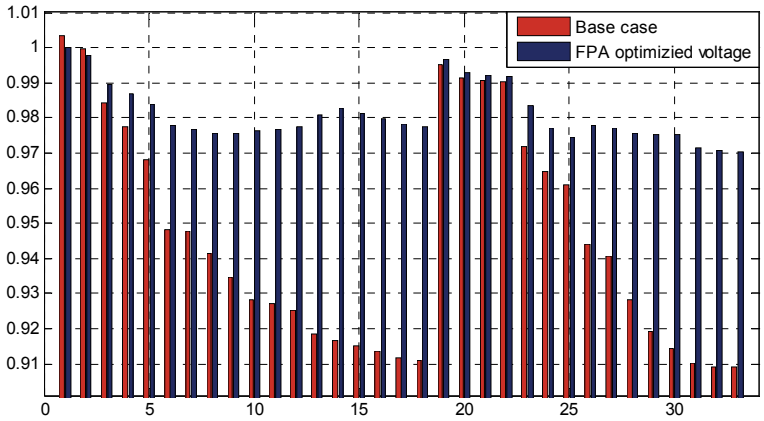


Fig. 7. IEEE 33 bus voltage profile using line bar chart

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Multi objective considered in this paper are the loss minimization and the minimization of voltage deviation. The individual minimization and combined minimization as given in Equation (1) is solved and its result is given in the Table 5.

Table 5. Multi objective result of FPA for 33 bus

Description	Base case	P_{Loss} minimization	VD minimization	P_{Loss} + VD minimization
P_{Loss} (kW)	210.97	**134.098**	168.523	**134.35**
VD (pu)	1.7876	1.1683	**0.6242**	**0.91**
V_{min} (pu)	0.9089	0.9390	0.9703	0.9602
$C_{Location}$	–	10, 15, 29	13, 24, 29	13, 16, 29
C_{Size}	–	150, 150, 1200	1050, 150, 1500	150, 150, 1050
Total kvar	–	1500	2700	1450

When loss alone minimized it leads to more VD, when VD is focused then the losses are more (168.523 kW). The compromised optimized multi objective is given in the last column. The convergence curve for the FPA is shown in Fig. 8. The FPA is iterated or pollinated for generation by generation up to 200 generations or iterations to find the best global value in the population. This convergence curve is derived for the multi objectives of the loss minimization and the minimization voltage deviation of all the 33 buses.

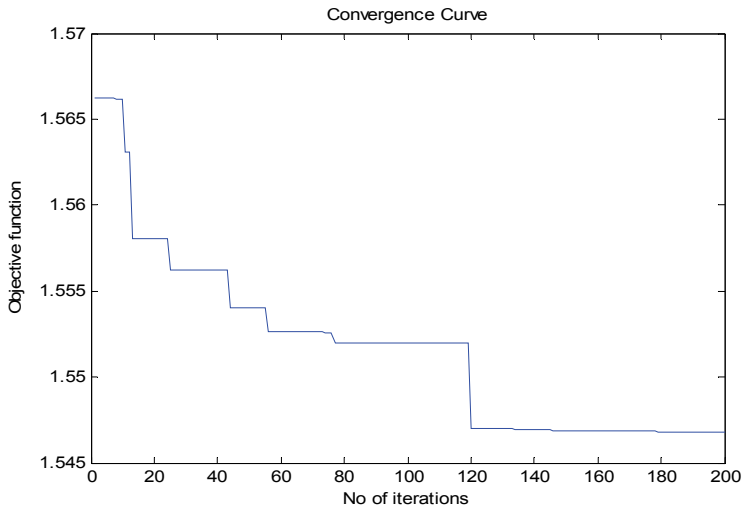


Fig. 8. Convergence curve of multi objective FPA for IEEE 33 bus

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6.2. 69 Bus test system

Multi objective FPA for solving the minimization of loss and the voltage deviation for the 69 bus system is given in the following Tables 6 to 8. Optimization variables are the capacitor size ranges from 150 to 2100 kvar and the location ranges from 2 to 60. The result of FPA is compared to the analytical IP and new intelligent algorithm GSA.

Table 6. Loss comparison of FPA for 69 bus

Description	**Base case**	**IP** (analytical)	**GSA**	**FPA** (proposed)
Total Loss (kW)	225	163.28	145.9	141.37
$C_{Location}$	–	11, 29, 60	26, 13, 15	9, 13, 60
C_{Size}	–	900, 1050, 450	150, 150, 1050	800, 450, 1050
Total kvarr	–	2400	1350	2300
Cost of kW loss (A) ($)	37800	27431.04	24511.2	23750.16
Cost of capacitor (B) ($/kvar)	–	517.95	451.5	574.05
Total Cost (C=A+B) ($)	37800	27948.99	24962.7	24324.21
Net Savings ($) (D =37800 - C)	0.0	9851.01	12837.3	13475.79
% Savings (E = D/37800)	0.0 %	26.06 %	33.96 %	35.65 %

To measure the performance of FPA, the results are compared with the latest published algorithms [9] as given in Table 6. It compares the loss minimization being the first objective. FPA result is compared with the analytical method Interior Point (IP) method and latest intelligent algorithm Gravitational Search Algorithm (GSA). The second objective of the minimization of voltage deviation is compared in Table 7. For all the 69 buses its voltage magnitude difference with the nominal voltage (1.0 pu) is calculated and sum of this difference is considered as voltage deviation is given in the second term of Equation (1).

Multi objective considered in this paper are the loss minimization and the minimization of voltage deviation. The combined form of the minimization as given in Equation (1) is solved and its result is given in the Table 8. When loss is focused, the minimum voltage is 0.9412 pu, and when the voltage deviation is focused, minimum voltage is 0.95097 pu. and when optimization of the loss and the voltage deviation is focused the minimum voltage is 0.9440 pu. Similarly the minimum loss 139.89 kW occurs when loss is focused, maximum loss 146.91 kW occurs when the voltage deviation is focused and the optimal loss 141.27 kW occurs when the optimized multi objective is considered. Multi objective considered in this paper are the loss minimization and the minimization of voltage deviation. The individual minimization and combined minimization as given in Equation (1) is solved and its result is given

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in the Table 8. When loss alone minimized it leads to more VD (0.9601), when VD is focused losses are more (146.91 kW). The optimized multi objective is given in the last column.

Table 7. VD comparison of FPA for 69 bus

Description	**Base Case**	**IP** (Analytical)	**GSA**	**FPA** (Proposed)
V_{min} (pu)	0.9399	0.9532	0.9611	0.9640
VD (pu)	**1.0301**	–	–	**0.8722**
P_{Loss} (kW)	210.97	163.28	145.9	141.37
$C_{Location}$	-	11, 29, 60	26, 13, 15	9, 13, 60
C_{Size}	–	900,1050,450	150,150,1050	800,450,1050

Table 8. Multi objective result of FPA for 69 bus

Description	**Base Case**	**P_{Loss}** ***Minimization***	**VD** ***Minimization***	**P_{Loss} + VD** ***Minimization***
P_{Loss} (kW)	225	**139.89**	146.91	**141.37**
VD (pu)	1.0301	0.9601	**0.6401**	**0.8722**
V_{min} (pu)	0.9399	0.9412	0.95097	0.9440
$C_{Location}$	–	9, 12, 63	9, 13, 60	9,13,60
C_{Size}	–	800, 350, 1050	450, 800, 1200	800, 450, 1050
Total (kvar)	–	2200	2450	2300

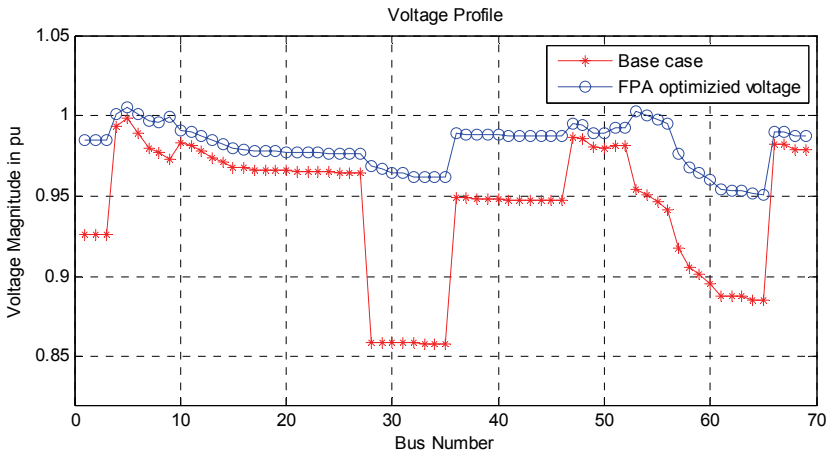


Fig. 9. IEEE 69 bus voltage profile using line plot

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Fig. 9 shows voltage profile of the base case and the optimized FPA. From the figure it is clear that the FAP finds best location and size of capacitor for 69 bus and improves the voltage. The minimum voltage at this case is 0.95097 for the objective of the voltage deviation minimization. Fig. 10 gives voltage magnitude of all the 69 buses as bar.

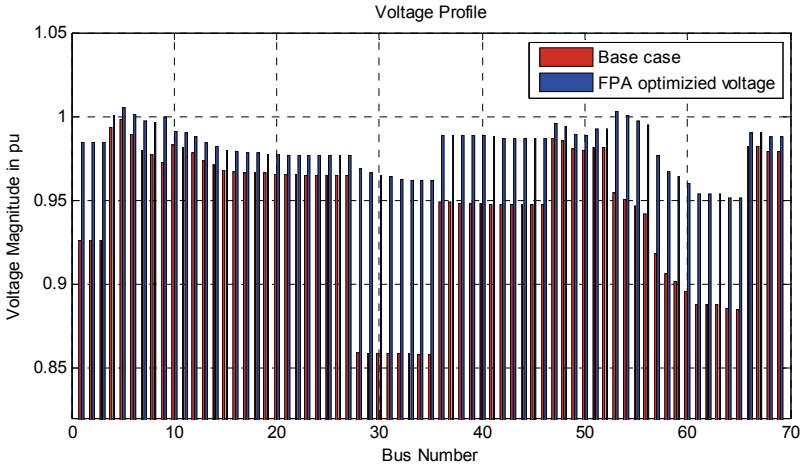


Fig. 10. IEEE 69 bus voltage profile using line bar chart

Figure 11 shows the convergence characteristic curve for the 69 bus system. To find the best global optimal multi objective value the FPA is iterated for 200 iterations or generations. In each generation of FPA individual flowers undergone either local or global pollination and in each generation a global flower is found. The final global flower gives the best global optimal value.

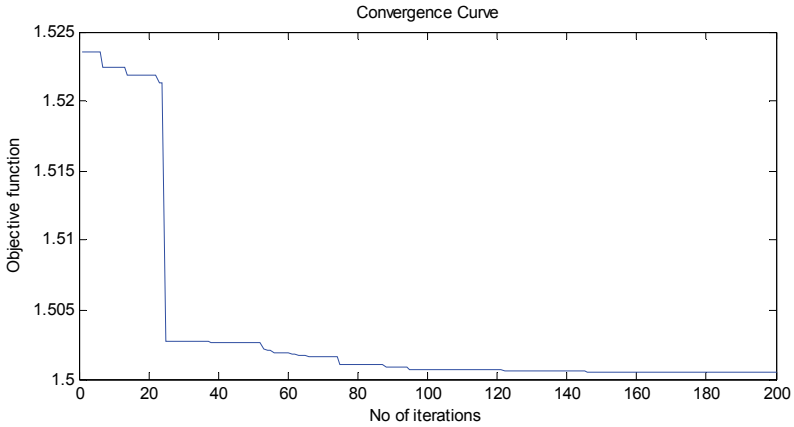


Fig. 11. Convergence curve of multi objective FPA for IEEE 69 bus

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7. Conclusion

In this paper, the Data Structure based load flow is used to solve the radial distribution system. This approach is more appropriate than another load flow method since the buses in the distribution system are considered as a node and a substation is considered as a root node. The links between the nodes are the distribution lines. The attributes of buses are considered as the data for the node. The tree traversal of pre order and post order traversal are similar to the forward and backward sweep. This makes the solution for the load flow is reliable. An efficient intelligent algorithm called the Flower Pollination Algorithm is used for multi objective optimization. Two main issues of the radial distribution system are low voltage and losses. To overcome these issues, many book recommend capacitor installation at buses. The problem of installing the capacitor in the radial distribution system focused the combined multi objective methods of loss minimization and voltage deviation minimization. In this paper, it is addressed to minimize voltage deviation and loss minimization simultaneously. The results are compared with the analytical and intelligent algorithm. The comparison for the IEEE 33 bus and IEEE 69 bus system proves that the proposed Flower Pollination Algorithm gives the best multi objective problem solution.

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