

Optimal Selection of Capacitors for Radial Distribution Systems Using Plant Growth Simulation Algorithm

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Abstract

This paper presents a new and efficient approach for capacitor placement in radial distribution systems that determine the optimal locations and size of capacitor with an objective of improving the voltage profile and reduction of power loss. The solution methodology has two parts: in part one the loss sensitivity factors are used to select the candidate locations for the capacitor placement and in part two a new algorithm that employs Plant growth Simulation Algorithm (PGSA) is used to estimate the optimal size of capacitors at the optimal buses determined in part one. The main advantage of the proposed method is that it does not require any external control parameters. The other advantage is that it handles the objective function and the constraints separately, avoiding the trouble to determine the barrier factors. The proposed method is applied to 33, 34 and 69-bus radial distribution systems. The solutions obtained by the proposed method are compared with other methods. The proposed method has outperformed the other methods in terms of the quality of solution.

Keywords: *Distribution Systems; Capacitor Placement; Loss Reduction; Loss sensitivity Factors; PGSA.*

1. Introduction

The loss minimization in distribution systems has assumed greater significance recently since the trend towards distribution automation will require the most efficient operating scenario for economic viability variations. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level [1]. To reduce these losses, shunt capacitor banks are installed on distribution primary feeders. The advantages with the addition of shunt capacitors banks are to improve the power factor, feeder voltage profile, Power loss reduction and increases available capacity of feeders. Therefore it is important to find optimal location and sizes of capacitors in the system to achieve the above mentioned objectives.

Since, the optimal capacitor placement is a complicated combinatorial optimization problem, many different optimization techniques and algorithms have been proposed in the past. Schmill [2] developed a basic theory of optimal capacitor placement. He presented his well-known 2/3 rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder. Duran et al [3] considered the capacitor sizes as discrete variables and employed dynamic programming to solve the problem. Grainger

and Lee [4] developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables. Grainger et al [5] formulated the capacitor placement and voltage regulators problem and proposed decoupled solution methodology for general distribution system. Baran and Wu [6, 7] presented a method with mixed integer programming. Sundharajan and Pahwa [8] proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. In most of the methods mentioned above, the capacitors are often assumed as continuous variables.

In this paper, Capacitor Placement and Sizing is done by Loss Sensitivity Factors and Plant Growth Simulation Algorithm (PGSA) respectively. The loss sensitivity factor is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore, these sensitive buses can serve as candidate locations for the capacitor placement. PGSA is used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system. The proposed method is tested on 33,34 and 69 bus radial distribution systems and results are very promising.

The advantages with the Plant Growth Simulation algorithm (PGSA) is that it treats the objective function and constraints separately, which averts the trouble to determine the barrier factors and makes the increase/decrease of constraints convenient, and that it does not need any external parameters such as crossover rate, mutation rate, etc. It adopts a guiding search direction that changes dynamically as the change of the objective function.

The remaining part of the paper is organized as follows: Section II gives the problem formulation; Section III sensitivity analysis and loss factors; Sections IV gives brief description of the plant growth simulation algorithm; Section V develops the test results and Section VI gives conclusions.

2. Problem Formulation

The objective of capacitor placement in the distribution system is to minimize the annual cost of the system, subjected to certain operating constraints and load pattern. For simplicity, the operation and maintenance cost of the capacitor placed in the distribution system is not taken into consideration. The three-phase system is considered as balanced and loads are assumed as time invariant. Mathematically, the objective function of the problem is described as:

$$\min f = \min (\text{COST}) \text{ or } \min f = \min (P_{\text{Loss}}) \quad (1)$$

where COST is the objective function which includes the cost of power loss and the capacitor placement.

The voltage magnitude at each bus must be maintained within its limits and is expressed as:

$$V_{\min} \leq |V_i| \leq V_{\max} \quad (2)$$

where $|V_i|$ is the voltage magnitude of bus i , V_{\min} and V_{\max} are bus minimum and

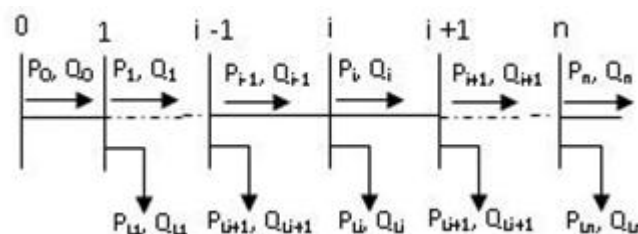


Fig. 1. Single Line Diagram of Main Feeder.

maximum voltage limits, respectively.

The power flows are computed by the following set of simplified recursive equations derived from the single-line diagram depicted in Fig. 1.

$$P_{i+1} = P_i - P_{Li+1} - R_{i,j+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (3)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,j+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (4)$$

$$|V_i|^2 = |V_{i+1}|^2 - 2(R_{i,j+1} P_i + X_{i,j+1} Q_i) + (R_{i,j+1}^2 + X_{i,j+1}^2) \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (5)$$

where P_i and Q_i are the real and reactive powers flowing out of bus i , and P_{Li} and Q_{Li} are the real and reactive load powers at bus i . The resistance and reactance of the line section between buses i and $i+1$ are denoted by $R_{i,i+1}$ and $X_{i,i+1}$ respectively.

The power loss of the line section connecting buses i and $i+1$ may be computed as

$$P_{Loss}(i,i+1) = R_{i,j+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (6)$$

The total power loss of the feeder, $P_{T, Loss}$, may then be determined by summing up the losses of all line sections of the feeder, which is given as

$$P_{F, Loss} = \sum_{i=0}^{N-1} P_{Loss}(i, i+1) \quad (7)$$

Considering the practical capacitors, there exists a finite number of standard sizes which are integer multiples of the smallest size Q_0^c . Besides, the cost per kVAR varies from one size to another.

In general, capacitors of larger size have lower unit prices. The available capacitor size is usually limited to

$$Q_{max}^c = LQ_0^c \quad (8)$$

where L is an integer. Therefore, for each installation location, there are L capacitor sizes $\{Q_0^c, 2Q_0^c, \dots, LQ_0^c\}$ available. Given the annual installation cost for each compensated bus, the total cost due to capacitor placement and power loss change is written as

$$COST = K_p P_{T, Loss} + \sum_{i=1}^n (k_{cf} + K_i^c Q_i^c) \quad (9)$$

where n is number of candidate locations for capacitor placement, K_p is the equivalent annual cost per unit of power loss in $\$/(\text{kW}\cdot\text{year})$; K_{cf} is the fixed cost for the capacitor placement. The constant k_c^i is the annual capacitor installation cost, and, $i = 1, 2, \dots, n$ are the indices of the buses selected for compensation. The bus reactive compensation power is limited to

$$Q_c^i \leq \sum_{i=1}^n Q_{Li} \quad (10)$$

where Q_c^i and Q_{Li} are the reactive power compensated at bus i and the reactive load power at bus i , respectively.

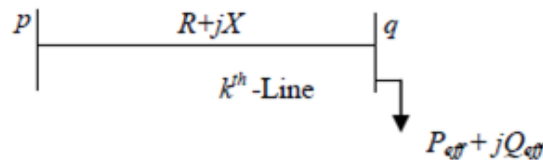


Fig. 2 Feeder

3. Sensitivity Analysis and Loss Sensitivity Factors

The candidate nodes for the placement of capacitors are determined using the loss sensitivity factors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure.

Consider a distribution line with an impedance $R+jX$ and a load of $P_{\text{eff}} + jQ_{\text{eff}}$ connected between 'p' and 'q' buses as given below.

Active power loss in the k^{th} line is given by, $[I_k^2] * R[k]$ which can be expressed as,

$$P_{\text{line loss}}[q] = \frac{(P_{\text{eff}}^2[q] + Q_{\text{eff}}^2[q]) R[k]}{(V[q])^2} \quad (11)$$

Similarly the reactive power loss in the k^{th} line is given by

$$Q_{\text{line loss}}[q] = \frac{(P_{\text{eff}}^2[q] + Q_{\text{eff}}^2[q]) X[k]}{(V[q])^2} \quad (12)$$

Where, $P_{\text{eff}}[q]$ = Total effective active power supplied beyond the node 'q'.

$Q_{\text{eff}}[q]$ = Total effective reactive power supplied beyond the node 'q'.

Now both the loss sensitivity factors can be obtained as shown below:

$$\frac{\partial P_{\text{line loss}}}{\partial Q_{\text{eff}}} = \frac{(2 * Q_{\text{eff}}[q] * R[k])}{(V[q])^2} \quad (13)$$

$$\frac{\partial Q_{\text{line loss}}}{\partial Q_{\text{eff}}} = \frac{(2 * Q_{\text{eff}}[q] * X[k])}{(V[q])^2} \quad (14)$$

3.1. Candidate Node Selection Using Loss Sensitivity Factors

The Loss Sensitivity Factors ($\partial P_{\text{line loss}} / \partial Q_{\text{eff}}$) are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system. A vector bus position 'bpos[i]' is used to store the respective 'end' buses of the lines arranged in descending order of the values ($\partial P_{\text{line loss}} / \partial Q_{\text{eff}}$). The descending order of elements of "bpos[i]" vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the ($\partial P_{\text{line loss}} / \partial Q_{\text{eff}}$) and hence the proposed 'Loss Sensitive Coefficient' factors become very powerful and useful in capacitor allocation or Placement. At these buses of 'bpos[i]' vector, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by ($\text{norm}[i]=V[i]/0.95$). Now for the buses whose norm[i] value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in 'rank bus' vector. It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for compensation placement and the 'norm[i]' decides whether the buses needs Q-Compensation or not. If the voltage at a bus in the sequence list is healthy (i.e., $\text{norm}[i]>1.01$) such bus needs no compensation and that bus will not be listed in the 'rank bus' vector. The 'rank bus' vector offers the information about the possible potential or candidate buses for capacitor placement. The sizing of Capacitors at buses listed in the 'rank bus' vector is done by using Plant Growth Simulation Algorithm.

4. Plant Growth Simulation Algorithm

The plant growth simulation algorithm [15] is based on the plant growth process, where a plant grows a trunk from its root; some branches will grow from the nodes on the trunk; and then some new branches will grow from the nodes on the branches. Such process is repeated, until a plant is formed. Based on an analogy with the plant growth process, an algorithm can be specified where the system to be optimized first "grows" beginning at the root of a plant and then "grows" branches continually until the optimal solution is found.

By simulating the growth process of plant phototropism, a probability model is established. In the model, a function $g(Y)$ is introduced for describing the environment of the node Y on a plant. The smaller the value of $g(Y)$, the better the environment of the

node for growing a new branch. The outline of the model is as follows: A plant grows a trunk M, from its root B₀. Assuming there are k nodes B_{M1}, B_{M2}, B_{M3}, ..., B_{Mk} that have better environment than the root on the trunk M, which means the function g(Y) of the nodes and satisfy g(B_{Mi}) < g(B₀) then morphactin concentrations C_{M1}, C_{M2}, ..., C_{Mk} of nodes B_{M1}, B_{M2}, B_{M3}, ..., B_{Mk} are calculated using

$$\begin{cases} C_{Mi} = \frac{g(B_0) - g(B_{Mi})}{\Delta_i} & (i = 1, 2, \dots, k) \\ \Delta_i = \sum_{i=1}^k (g(B_0) - g(B_{Mi})) \end{cases} \quad (15)$$

The significance of equation (15) is that the morphactin concentration of a node is not only dependent on its environmental information but also depends on the environmental information of the other nodes in the plant, which really describes the relationship between the morphactin concentration and the environment. From (15), we can derivate $\sum_{i=1}^k C_{Mi} = 1$, which means that the morphactin concentrations C_{M1}, C_{M2}, ..., C_{Mk} of nodes B_{M1}, B_{M2}, B_{M3}, ..., B_{Mk} form a state space shown in Fig. 3. Selecting a random number β in the interval [0, 1], β is like ball thrown to the interval [0, 1] and will drop into one of C_{M1}, C_{M2}, ..., C_{Mk} in Fig. 3, then the corresponding node that is called the preferential growth node will take priority of growing a new branch in the next step. In other words, B_{MT} will take priority of growing a new branch if the selected β satisfies $0 \leq \beta \leq \sum_{i=1}^T C_{Mi} (T = 1)$ or $\sum_{i=1}^{T-1} C_{Mi} (T = 1) \leq \beta \leq \sum_{i=1}^T C_{Mi} (T = 2, 3 \dots k)$.

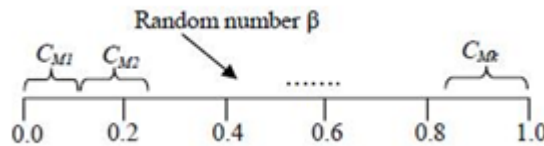


Fig. 3. Morphactin Concentration State Space.

For example, if random number β drops into C_{M2}, which means $\sum_{i=1}^1 C_{Mi} \leq \beta \leq \sum_{i=1}^2 C_{Mi}$, then the node B_{M2} will grow a new branch m. Assuming there are q nodes B_{M1}, B_{M2}, B_{M3}, ..., B_{Mq} which have a better environment than the root B₀, on the branch m, and their corresponding morphactin concentrations are C_{M1}, C_{M2}, ..., C_{Mq}. Now, not only the morphactin concentrations of the nodes on branch m need to be calculated, but also the morphactin concentrations of the nodes except B_{M2} (the morphactin concentration of the node B_{M2} becomes zero after growing the branch m) on trunk M need to be recalculated after growing the branch m. The calculation can be done using (16), which is gained from (15) by adding the related terms of the nodes on branch m and abandoning the related terms of the node B_{M2}

$$\begin{cases} C_{Mi} = \frac{g(B_0) - g(B_{Mi})}{\Delta_1 + \Delta_2} & (i = 1, 2, \dots, k) \\ C_{Mj} = \frac{g(B_0) - g(B_{Mj})}{\Delta_1 + \Delta_2} & (j = 1, 2, \dots, q) \end{cases} \quad (16)$$

Where $\Delta_1 = \sum_{i=1, j \neq 2}^k (g(B_0) - g(B_{Mi}))$

$$\Delta_2 = \sum_{j=1}^q (g(B_0) - g(B_{Mj}))$$

We can also derivate $\sum_{i=1}^k C_{Mi} (i \neq 2) + \sum_{j=1}^q C_{Mj} = 1$ from (16). Now, the morphactin concentrations of the nodes (except B_{M2}) on trunk M and branch m will form a new state space (The shape is the same as Fig.3, only the nodes are more than that in Fig.3). A new preferential growth node, on which a new branch will grow in the next step, can be gained in a similar way as B_{M2}. Such process is repeated until there is no new branch to grow, and then a plant is formed. From the viewpoint of optimal mathematics,

the nodes on a plant can express the possible solutions; $g(Y)$ can express the objective function; the length of the trunk and the branch can express the search domain of possible solutions; the root of a plant can express the initial solution. The preferential growth node corresponds to the basic point of the next searching process. In this way, the growth process of plant phototropism can be applied to solve the problem of integer programming.

A complete algorithm for the proposed method of capacitor placement is given below:

- 1) Input the system data such as line and load details of the distribution system, constraints limits etc.;
- 2) Form the search domain by giving the range of capacitor ratings (kVAr ratings) available which corresponds to the length of the trunk and the branch of a plant;
- 3) Give the initial solution X_0 (X_0 is vector) which corresponds to the root of a plant, and calculate the initial value objective function (power loss)
- 4) Let the initial value of the basic point X^b , which corresponds to the initial preferential growth node of a plant, and the initial value of optimization X^{best} equal to X_0 , and let F^{best} that is used to save the objective function value of the best solution X^{best} be equal to $f(X_0)$, namely $X_b = X_{\text{best}} = X_0$ and $F_{\text{best}} = f(X_0)$
- 5) Identify the candidate buses for capacitor placement using Loss Sensitivity Factors;
- 6) Initialize iteration count, $i=1$;
- 7) For $j=n$ to m (with step size 1), where m is the minimum available size and n is maximum available size;
- 8) Search for new feasible solutions: place kVAr at sensitive nodes in a sequence starting from basic point $X^b = [X_1^b, X_2^b, \dots, X_i^b, \dots, X_n^b]$, where X^b corresponds to the initial kVAr;
- 9) For each solution X^b in step 8, calculate the nodes voltages of the buses;
- 10) If the node voltage constraints are satisfied go to step 10; otherwise abandon the possible solution X^b and go to step 12;
- 11) Calculate powerloss $f(X^b)$ for each solution of X^b in step 8 and compare with $f(X_0)$. Save the feasible solutions if $f(X^b)$ less than $f(X_0)$; Otherwise goto step 12;
- 12) If $i \geq N_{\text{max}}$ go to step 16; otherwise goto step 14;
- 13) Calculate the probabilities $C1, C2, \dots, Ck$ of feasible solutions $X1, X2, \dots, Xk$, by using equation (15), which corresponds to determining the morphactin concentration of the nodes of a plant;
- 14) Calculate the accumulating probabilities $\sum C1, \sum C2, \dots, \sum Ck$ of the solutions $X1, X2, \dots, Xk$. Select a random number β from the interval $[0, 1]$, β must belong to one of the intervals $[0, \sum C1], (\sum C1, \sum C2], \dots, (\sum Ck-1, \sum Ck]$, the accumulating probability of which is equal to the upper limit of the corresponding interval, and it will be the new basic point X^b for the next iteration, which corresponds to the new preferential growth node of a plant for next step;
- 15) Increment i by $i+1$ and return to step 6; item two
- 16) Output the results and stop.

5. Test Results

The proposed method has been programmed using MATLAB and run on a Pentium IV, 3-GHz personal computer with 0.99 GB RAM. The effectiveness of the proposed method for loss reduction by capacitor placement is tested on 33, 34 bus and 69 bus radial distribution systems. The results obtained in these methods are explained in the following sections.

5.1.33 Bus System

The first test case for the proposed method is a 33-bus radial distribution system [20]. The single line diagram is shown in Fig. 4. The line and load data of the feeders are taken from the reference [20]. The base values of the system are taken as 12.66 kV and 100MVA.

The sensitive analysis method is used to select the candidate installation locations of the capacitor to reduce the search space. The buses are ordered according to their sensitivity values as {6, 28, 29, 30, 9,13,10,8,27,31 and 26}. In this case capacitor value has been taken as a continuous variable. The capacitor allowable range is from 200 kVAr to 1200 kVAr with step of 2kVAr. Top three buses are selected as optimal candidate locations and the amount of kVAr injected are 1200, 760 and 200 kVAr respectively.

The power loss before and after capacitor placement are 202.66 and 139.9 kW. The minimum and maximum voltages before capacitor placement are 0.9131 p.u (bus 18) and 0.997 p.u (bus 2) and are improved to 0.9463 p. and 0.9976 p.u after capacitor placement respectively at the buses 6,28 and 29. The N_{max} value is tried from 2 to 80. All of the results converge to the same optimal solution with N_{max} greater than 8. The results of the proposed method are compared with the result of GA method [22] and are shown in Table 1. From the Table 1, it is observed that the optimal candidate installation locations are three for the proposed method but it is eight for the Heuristic method [20] which decreases the complexity. The voltage profile of the 33 bus system before and after compensation is shown in fig.5. The CPU time needed by the proposed method is 5.13 sec.

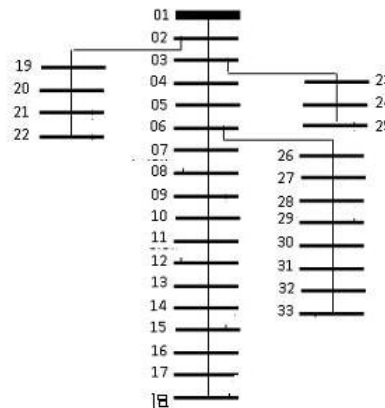


Fig.4. Diagram of 33 Bus Distribution System

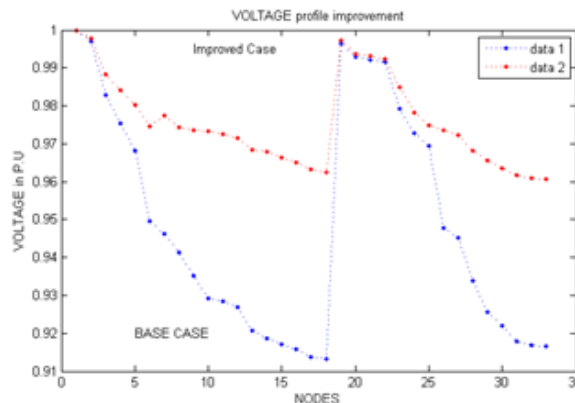


Fig. 5. Voltage Profile of 33 Bus System Before and After Compensation

Table 1. Summary of Results for 33 Bus System

Items	Uncompensated	Compensated	
		GA[22]	Proposed
Total Losses(kw)	202.67	135.5	135.4
Optimal Locations and Sizes(kvar)	--	300 at {8,15,20,21,24,26,28} 600 at 27	6 1200 28 760 29 200
Total kvar	--	2700	2160

5.2.34 Bus System

The sensitive analysis method is used to select the candidate installation locations of the capacitor to reduce the search space. The buses are ordered according to their sensitivity values as {19, 22,20,21,23,24,25,26 and 27}. In this case capacitor value has been taken as a continuous variable. The capacitor allowable range is from 200 kVAr to 1200 kVAr with step of 2kVAr. Top three buses are selected as optimal candidate locations and the amount of kVAr injected are 1200, 739 and 200 kVAr respectively.

The power loss before and after capacitor placement are 221.67 and 168.5 kW. The minimum and maximum voltages before capacitor placement are 0.9417 p.u (bus 18) and 0.9941 p.u (bus 2) and are improved to 0.9505pu and 0.995 p.u after capacitor placement respectively at the buses 19, 22 and 20. The *Nmax* value is tried from 2 to 80. All of the results converge to the same optimal solution with *Nmax* greater than 8. The results of the proposed method are compared with the results of PSO method [17] and Heuristic based method [20] and are shown in Table 2. From the results shown in Table 2, it is observed that the optimal candidate installation locations are three for the proposed and PSO methods [17], but it is four for the Heuristic method [20]. The CPU time needed by the proposed method is 5.34 sec.

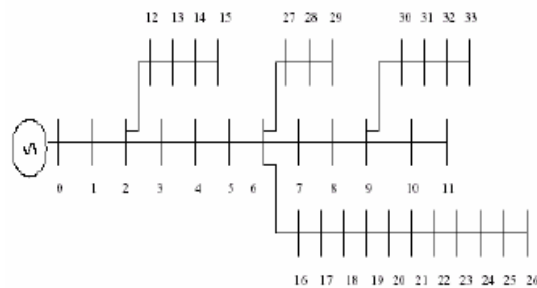


Fig. 6. 34 Bus Distribution System

Table 2. Summary of Results for 34 Bus Systems

Items	Uncompensated	Compensated			
		Heuristic based [20]	PSO [17]	GA [22]	Proposed
Total (Losses)	221.67	168.47	168.8	170	168.5
Optimal Locations and Sizes (kvar)	--	26 1400 11 750 17 300 4 250	19 781 22 803 20 479 -- ---	5 300 9 300 12 300 22 600 26 300	19 1200 22 739 20 200 -- ---
Total kvar	--	2700	2063	1800	2139

5.3. 69 Bus System

The line data and feeder characteristics are taken from reference [23]. Based on sensitivity analysis buses 57, 58 and 61 are selected as optimal candidate locations for the capacitor placement. Using proposed PGSA, the amount of kVAr injected are 1200, 274, and 200 kVAr at the above buses. The N_{max} value tried from 2 to 80 and all of the results converge to the same optimal solution with N_{max} greater than 8. The results of the proposed method are compared with the results of PSO method [17] and are shown in Table 3. The voltage profile of the 69 bus system before and after compensation is shown in fig.8. The CPU time needed by the proposed method is 15.27sec.

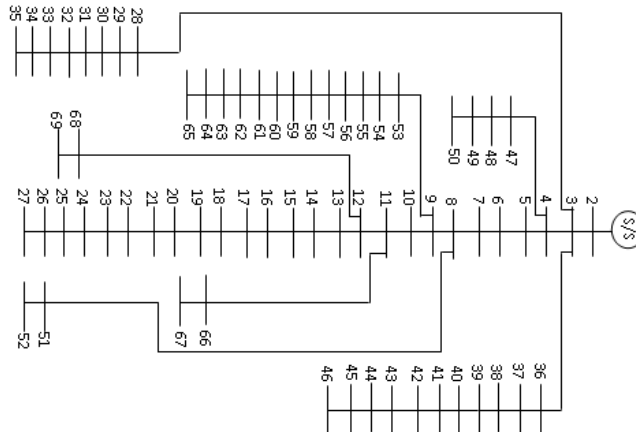


Fig.7 Diagram of 69 Bus Distribution System

Table 3. Summary of Results for 69 Bus System

Items	Uncompensated	Compensated	
		PSO [17]	Proposed
Total Losses(kw)	224.98	152.48	147.4
Optimal Locations and Sizes(kvar)	--	46 781 47 803 50 479 -- ---	57 1200 58 274 61 200 -- ---
Total kvar	--	1621	1674

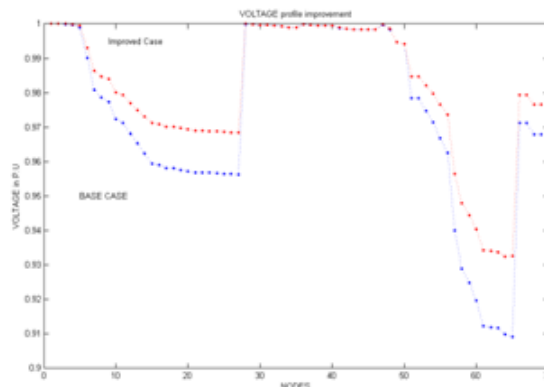


Fig. 8. Voltage Profile of 69 Bus System Before and After Compensation

6. Conclusion

A new and efficient approach that employs loss sensitivity factors and PGSA for capacitor placement in the distribution system has been proposed. The loss sensitivity factors are used to determine the candidate locations of the buses required for compensation. The PGSA is used to estimate the required level of shunt capacitive compensation at the optimal candidate locations to enhance the voltage profile the system and reduce the active power loss. The simulation results based on 33, 34 and 69-bus systems have produced the best solutions that have been found using a number of approaches available in the literature. The advantages of the proposed method are: 1) it handles the objective function and the constraints separately, avoiding the trouble to determine the barrier factors; 2) the proposed approach does not require any external parameters; 3) the proposed approach has a guiding search direction that continuously changes as the change of the objective function. This method places the capacitors at less number of locations with optimum size and offers much net annual saving in initial investment. The completion of one research project opens the avenues for work in many other related areas. The following areas are identified for future work:

1. The study has been carried out on balanced distribution system. The capacitor allocation problem can be extended to unbalanced distribution system.
2. The allocation of DSTATCOM can be considered. This will also supportive during transients.

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