

## Optimal Sizing And Placement Of Capacitor In A Radial Distribution System Using Loss Sensitivity Factor And Firefly Algorithm.

Priyanka Das<sup>1</sup>, S Banerjee<sup>2</sup>

(Department of Electrical Engineering, Dr. B.C Roy Engineering College, Durgapur West Bengal, India, Email:  
<sup>1</sup>bcet.priyanka1989@gmail.com, <sup>2</sup>sumit\_9999@rediffmail.com)

### ABSTRACT

In distribution systems minimization of active power loss is very essential to raise the overall efficiency of power system. This article presents a method of reducing the loss by placing shunt capacitors. In this paper a two stage methods have been proposed for optimal allocation of capacitor in a radial distribution system. In first stage loss sensitivity factor is used to calculate the location and secondly the firefly algorithm is used for cost minimization including capacitor cost and cost due to power loss. The proposed method is tested on 33-bus and 69-bus system and results are given below.

**Keywords:** Firefly algorithm, Loss sensitivity factor, Radial distribution system, Shunt capacitors.

### 1. INTRODUCTION

Day to day the load demand is increasing and thus making distribution system more complex and due to increase in loads it tends to increase the systems losses and due to that reason the voltage profile is decreasing badly. At heavy loaded conditions the reactive power flow causes significant losses and also causes reduction in voltage level. So in the distribution company every electrical engineer should perform his/her duty to minimize the power loss and to increase the voltage profile. So to increase the voltage profile and to reduce the power loss the use of shunt capacitor is the best and reliable option as it provides reactive compensation. The shunt capacitor should be optimally sized and placed that it should be able to reduce the power loss and can enhance the voltage profile of the system. Minimization of loss will increase the life span of the distribution network and reliability of the system. Optimal allocation of capacitor deals with the appropriate location where the capacitor to be placed, type of the capacitor, size of the capacitor and the total number of the capacitor that should be placed so that the total cost should be minimized without violating the operational

constraints. With the development in optimization many research work has been done on this topic. Numerous optimization techniques have been used by researchers to optimally allocate the capacitor in a radial distribution system. They are classified into four groups, analytical methods, numerical programming methods, heuristic methods and meta-heuristic methods. The early proposed approaches are the analytical numerical programming techniques like local variation methods [1] and mixed integer linear programming techniques [2,3] have been introduced for solving the problem of capacitor sizing and allocation. In recent years, the most popular meta-heuristic approaches have been introduced for the VAR planning problem study. The authors who used meta-heuristics methods we find, Huang et al. [4] They have solved the capacitors optimal placement using an immune multi-objective algorithm. They have modeled the objective functions by fuzzy logic (FL). The method provides us a set of feasible solutions. Bhattacharya and coauthors [5] have introduced a FL-based simulated annealing (SA) method to find the optimal sizes of capacitor. Using FL the suitable locations are identified and their sizes are obtained using SA by Prakash et al. [6] have also

used a hybrid method where the capacitor suitable places are determined by means of loss sensitivity factors. The optimal sizes, considered as continuous variables, are determined using particle swarm optimization (PSO) algorithm. To determine the fixed and switched capacitor sizes, Das [7] has suggested a genetic algorithm (GA) based FL approach to maximize the net savings and minimize node voltage deviations. The two objectives are first fuzzified and integrated into a fuzzy global objective function through appropriate weighting factors. The weighting factors are optimized by GA. On the other hand, Seifi et al. [8] in their FL–GA hybrid technique have used the fuzzy reasoning to find the best capacitor locations and GA, for finding the optimal weighting factors of the voltage and the power losses exponential membership functions. The capacitor optimal size is that, among the available standard capacitors, giving the best objective function. Abdelaziz et al. [9] have proposed a method based on fuzzy expert systems to select the best candidate nodes for receiving capacitors in order to maximize the power loss reduction and total net savings. For the total power loss minimization they have determined the optimal locations and tapping ratio for voltage regulator. Banerjee et al [16] have presented a unique method to determine the weakest branch in a distribution network. Chattopadhyay et al [17] proposed voltage stability analysis of RDN under critical loading condition without and with DG for composite loads.

## 2. PROBLEM FORMULATION

Here the main objective is to minimize the total cost due to real power loss and capacitor installation. To solve the capacitor placement and sizing problem the following objective function has been taken.

$$\text{Min } f = \text{min (COST)}$$

(1) where COST is the objective function which includes the cost of power loss and capacitor placement. The voltage magnitude at each bus must be maintained within its limit and can be expressed as

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

Where  $|V_i|$  is the voltage magnitude at bus  $i$  and  $V_{\min}$  and  $V_{\max}$  are the minimum and maximum

voltage limits respectively. For the calculation of power flows the following sets of simplified recursive equations which are derived from single line diagram are shown in fig 1.

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

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

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

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

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

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

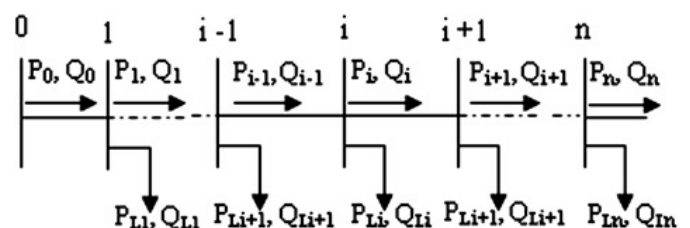


Fig1. Single line diagram of main feeder.

The total power loss of the feeder  $P_{T, \text{LOSS}}$  can be computed by summing up the losses of all the line sections of the feeder, and given as

$$P_{T, \text{LOSS}} = \sum_{i=1}^n P_{\text{loss}}(i, i+1) \quad (7)$$

The total cost due to capacitor placement and power loss change is given by:

$$\text{COST} = K_p \cdot P_{T, \text{LOSS}} + \sum_{i=1}^n (K_{cf} + K_i^c Q_i^c) \quad (8)$$

Where n is the number of candidate locations for capacitor placement  $K_p$  is the equivalent annual cost per unit of power loss in  $\$/(\text{kW year})$ ;  $K_{cf}$  is the fixed cost for the capacitor placement. The constant  $K_i^c$  is the annual capacitor installation cost, and,  $i = 1, 2, \dots, n$  are the indices of the buses selected for compensation.  $K_p = 168\$/(\text{kW year})$  and  $K_{cf} = 1000\%$  are taken.

## 2.1 Constraints

Each capacitor size minimizing the objective function, must verify the equality and inequality constraints. Two inequality constraints are considered here for capacitor placement that must be satisfied are as such:

$$(I) \quad V_{\min} \leq |V_i| \leq V_{\max} \quad (9)$$

(II) Capacitors are available in discrete sizes. So, shunt capacitors are to be dealt with multiple integers of the smallest capacitor size available and it may mathematically be expressed as:

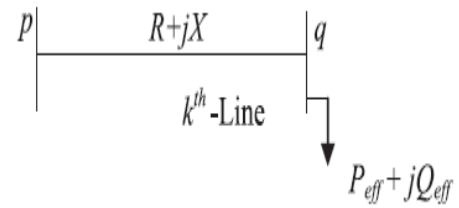
$$Q_{c_i} \leq L Q_s \quad L = 1, 2, 3, \dots, n_c \quad (10)$$

where  $n_c$  is number of shunt capacitors,  $Q_{c_i}$  is the kVAr rating of capacitor installed at the  $i^{\text{th}}$  bus and  $Q_s$  smallest capacitor size available.

## 2.2 Sensitivity Analysis and Loss Sensitivity Factors

By using loss sensitivity factors the candidate nodes for the capacitor placement is determined. By estimation of these candidate nodes it helps in the reduction of search space for optimization problem. Considering a distribution line with an

impedance  $R + jX$  and a load  $P_{\text{eff}}$  and  $Q_{\text{eff}}$  connected between buses p and q is given by.



Active power loss can be given by in (3) is rewritten for  $k^{\text{th}}$  line between buses p and q as

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

(11)

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

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

(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'.

Both the loss sensitivity factor can be given as:

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

(13)

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

(14)

## 2.3. Candidate node selection using loss sensitivity factors

The Loss Sensitivity Factors ( $\frac{\partial P_{\text{line loss}}}{\partial Q_{\text{eff}}}$ ) 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 ( $\frac{\partial P_{\text{line loss}}}{\partial Q_{\text{eff}}}$ ). The

descending order of  $\left(\frac{\partial P_{line\ loss}}{\partial Q_{eff}}\right)$  elements of ‘bpos[i]’ vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely

#### Firefly Algorithm

governed by the  $\left(\frac{\partial P_{line\ loss}}{\partial Q_{eff}}\right)$  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  $(norm[i] = V[i]/0.95)$ . 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.,  $norm[i] > 1.01$ ) 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.

### 3. FIREFLY ALGORITHM

The Firefly algorithm (FA) is a recently developed heuristic optimization algorithm by Yang [15] and the flashing behavior of fireflies has inspired it. According to Yang [15], the three idealized rules of FA optimization are as follows.

(a) All fireflies are unisex, so that one firefly is attracted to other fireflies regardless of their sex.

(b) Attractiveness is proportional to brightness, so for any two flashing fireflies, the less bright firefly will move towards the brighter firefly. Both attractiveness and brightness decrease as the distance between fireflies increases. If there is no firefly brighter than a particular firefly, that firefly will move randomly.

(c) The brightness of a firefly is affected or determined by the landscape of the objective function. Based on these three rules, the basic

steps of the FA can be summarized as the pseudo-code shown in Fig. 1 [15]. There are two essential components to FA: the variation of light intensity and the formulation of attractiveness. The latter is assumed to be determined by the brightness of the firefly, which in turn is related to the objective function of the problem

1. Initializing all the parameters of FA.
2. Generate initial population of fireflies  $X_i=(i = 1,2,\dots,n)$
3. Assume that  $f(X)$  is the objective function of  $X(x_1,x_2,\dots,x_n)$
4. Light intensity  $L_i$  is defined by  $f(X_i)$
5. while( $g < \max\ gen$ )
6.     for  $i = 1:n$  where  $n$  is all fireflies
7.         for  $j = 1:n$  where  $n$  is all fireflies
8.             If( $L_j > L_i$ )
9.                 move fireflies  $i$  towards  $j$  in all  $d$  dimensions.
10.     end if
11. Attractiveness varies with the distance  $r$  via  $e^{-r^2}$
12. Evaluate new solution and update new light intensity  $L_i$ .
13. end for
14. end for
15. Rank the fireflies and find the current best and update the global best if required
16. end while
17. Results and visualization.

Fig 1. Pseudo code for firefly algorithm.

With decrease in light intensity and attractiveness, the distance from the source increases, and the variation of light intensity and attractiveness should be a monotonically decreasing function. For example, the light intensity can be:

$$I(r_{ij})=I_0 e^{-\gamma r_{ij}^2}$$

(15)

where the light absorption coefficient  $\gamma$  is a parameter of the FA and  $r_{ij}$ , is the distance between fireflies  $i$  and  $j$  at  $x_i$  and  $x_j$ , respectively, and hence can be defined as the Cartesian distance  $r_{ij} = \left| \left| x_i - x_j \right| \right|$ . Because a firefly’s attractiveness is proportional to the light intensity seen by other fireflies, it can be defined by:

$$\beta_{ij}=\beta_0 e^{-\gamma r_{ij}^2}$$

(16)

in which  $\beta_0$  is the attractiveness at  $r = 0$ . Finally, the probability of a firefly  $i$  being attracted to

another, more attractive (brighter) firefly  $j$  is determined

$$\Delta x_i = \beta_0 e^{-\gamma r_{ij}^2} (x_j^t - x_i^t) + \alpha \epsilon_i, \quad x_i^{t+1} = x_i^t + \Delta x_i \quad (17)$$

Where  $t$  is the generation number,  $\epsilon$  is a random vector (e.g., the standard Gaussian random vector in which the mean is 0 and the standard deviation is 1) and  $\alpha$  is the randomization parameter. The first term on the right-hand side of Eq. (17) represents the attraction between the fireflies and the second term is the random movement. In other words, Eq. (17) shows that a firefly will be attracted to brighter or more attractive fireflies and also move randomly. Eq. (17) indicates that  $\beta$ ,  $\gamma$ ,  $\alpha$  must be set by user and the distribution of  $\epsilon_i$  to apply the FA, and also when  $\gamma$  is too small or large there are two limit cases as shown in Eq. (17)

(a) If  $\gamma$  approaches zero, the attractive and brightness are constants, and consequently, a firefly can be seen by all other fireflies. In this case, the FA reverts to the PSO.

(b) If  $\gamma$  approaches infinity, the attractiveness and brightness approach zero, and all fireflies are short-sighted or fly in a foggy environment, moving randomly. In this case, the FA reverts to the pure random search algorithm.

Hence, the FA generally corresponds to the situation falling between these two limit cases.

#### 4. PROPOSED OPTIMAL CAPACITOR PLACEMENT METHODOLOGY

Here in this proposed method the Firefly algorithm is applied as an optimization technique to determine the optimal size of the capacitor at the buses. Power flow is used for the computation of power loss. The procedures for implementation of the proposed optimal capacitor placement method has been described in two stages as follows:

##### Determination of candidate location

**Step1:** Input all the parameters like line data and load data.

**Step2:** Run the load flow as explained above by using set of simplified recursive equation.

**Step3:** Calculate the loss sensitivity factor.

**Step4:** Select the buses whose norm[ $i$ ] value is less than 1.01 as candidate location.

##### Optimization using Firefly Algorithm

**Step1:** Initialize all the parameters and constants of Firefly Algorithm. They are  $Q_{cmin}$ ,  $Q_{cmax}$ , (minimum and maximum limit of capacitor)  $noff$ ,  $noQc$ ,  $\alpha_{min}$ ,  $\alpha_{max}$ ,  $\beta_0$ ,  $\gamma$  and  $itermax$  (maximum number of iterations).

**Step2:** Run the load flow program and find the total power loss  $Ploss1$  of the original system (before capacitor placement)

**Step3:** Generate  $noff * noQc$  number of fireflies randomly between the limits  $Q_{cmin}$  and  $Q_{cmax}$ .  $noff$  is the number of fireflies and  $noQc$  is the number of capacitor. Each row represents one possible solution to the optimal capacitor sizing problem. For example  $noQc=1$  for one capacitor,  $noQc=2$  for two capacitors and  $noQc=3$  for three capacitors. Similarly  $noff=10$  for ten fireflies,  $noff=20$  for twenty fireflies and  $noff=50$  for fifty fireflies.

**Step4:** Compute the capacitor cost.

**Step5:** Compute the total cost (fitness function) using equation (8)

**Step6:** By placing all the  $noQc$  number of capacitors of each firefly at the respective optimal capacitor locations, and run the load flow program to find total power losses  $Ploss2$  after placement.

**Step7:** Obtain the best fitness function  $GbestFF$  by comparing all the fitness function and also obtain the best firefly values  $GbestFV$  corresponding to the best fitness function  $GbestFF$ .

**Step8:** Determine alpha ( $\alpha$ ) value of the current iteration  $\alpha(ite)$  using the equation:  $\alpha(ite) = \alpha_{max} - ((\alpha_{max} - \alpha_{min}) / (ite / itermax))$

**Step9:** Determine  $r_{ij}$  values of each firefly using the following equation:  $r_{ij} = GbestFF - FF$   $r_{ij}$  is obtained by finding the difference between the best fitness function  $GbestFF$  ( $GbestFF$  is the best fitness function i.e.,  $j$ th firefly) and fitness function  $FF$  of the  $i$ th firefly.

**Step10:** New  $X_i$  values are calculated for all the fireflies using the following equation:  $X_i(new) = X_i(old) + \beta_0 * \exp(-\gamma r_{ij}^2) * (X_j - X_i) + \alpha(ite) * (rand - \frac{1}{2})$

where,  $\beta_0$  is the initial attractiveness  $\gamma$ , is the absorption co-efficient,  $r_{ij}$  is the difference between the best fitness function  $GbestFF$  and fitness function  $FF$  of the  $i$ th firefly.

$\alpha(ite)$  is the randomization parameter varies between 20 to 0.0001 and is the random number between 0 and 1.  $X_i(new)$  is the  $Q_{cnew}$ .

**Step11:** Increase the iteration count. Go to step 5, if iteration count is not reached maximum.

**Step12:** GbestFV gives the optimal capacitor in 'n' optimal locations and the results are printed.

## 5. RESULTS

Loss sensitivity factor is used to calculate the candidate location for the capacitor placement and Firefly algorithm is used to find the optimal capacitor size. In this work,  $\alpha=0.25$ ,  $\beta=0.2$ ,  $y=1$  Number of iterations 70, number of fireflies=20,  $Q_{c_{min}}=150$ ,  $Q_{c_{max}}=2200$ .

### 5.1. Results of 33-bus system

The proposed algorithm is applied to 33-bus system [13]. Optimal capacitor locations are identified based on the Loss sensitivity factor values. For this 33-bus system, one optimal location is identified. Capacitor size in that optimal location, total real power losses before and after compensation, voltage profile before and after compensation and total annual cost before and after compensation are shown below.

Table 1.

BUS NO;	6
CAPACITOR SIZE in (KVAR)	1800
TOTAL REAL POWER LOSS in (kW) before compensation.	201.8588
TOTAL REAL POWER LOSS in (kW) after compensation.	121.9513
VOLTAGE IN P.U at bus number 6 before compensation.	0.9499
VOLTAGE IN P.U at bus number 6 after compensation	0.9676
TOTAL ANNUAL COST before compensation	40573.62\$
TOTAL ANNUAL COST after compensation	21207.80\$
LOSS REDUCTION	79.90
LOSS REDUCTION %	39.585%

### 5.2. Results of 69-bus system

The proposed algorithm is applied to 69-bus system [14]. Optimal capacitor location is identified based on the Loss sensitivity factor values. For this 69-bus system, one optimal location is identified. Capacitor sizes in that

optimal location, total real power losses before and after compensation, voltage profile before and after compensation, total annual cost before and after compensation are shown below.

Table 2.

BUS NO;	61
CAPACITOR SIZE in (KVAR)	1350
TOTAL REAL POWER LOSS in(kW) before compensation	224.5407
TOTAL REAL POWER LOSS in (kW) after compensation	150
VOLTAGE IN P.U at bus number 6 before compensation	0.9133
VOLTAGE IN P.U at bus number 6 after compensation	0.9364
TOTAL ANNUAL COST before compensation	37722.83\$
TOTAL ANNUAL COST after compensation	25740\$
LOSS REDUCTION	74.5407
LOSS REDUCTION %	33.1969%

## 6. CONCLUSION

Here the paper is providing a two- stage method Loss Sensitivity Factor and Firefly algorithm which is successfully applied for capacitor placement. By the installation of shunt capacitor at the optimal position there is a significant decrease in power loss, decrease in total annual cost and increase in voltage profile. So the combination of both Loss sensitivity factor and Firefly algorithm yields good results.

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