Optimal Capacitor Placement in Radial Distribution System using Group Search Optimization Algorithm

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Abstract— Power generated in generating station is transmitted through transmission lines and fed to the consumers through distribution substation. The power distributed in to the network has losses, which is greater in distribution system than the transmission system. This problem could be addressed by placing capacitor at strategic location due to which the kW loss can be minimized by improving the voltage profile. This paper involves two methods where the first method being the Sensitivity Analysis and the second method is the Group Search Optimization Algorithm (GSO). Sensitivity Analysis is a methodical technique which is used in order to reduce the search space and to arrive at an accurate solution for recognizing the locality of capacitors. Capacitor values are allocated for the respective locations using GSO. The proposed approach is demonstrated by employing the IEEE 33 bus test system. Computational results show that by taking capacitor settings, one can minimize kW losses more efficiently.

Key Words — Group Search Optimization (GSO), Capacitor Placement (CP), Radial Distribution System (RDS), Loss Sensitivity Factor (LSF), Sensitivity Analysis, Kw Loss.

NOMENCLATURE

V_j	=	Voltage magnitude of the jth bus
P_j	=	Real power injection at the jth bus
Q_j	=	Reactive power injection at the j^{th} bus
δ_j	=	Phase angle at the j^{th} bus
P_{acc}	=	Real power accumulated
Q_{acc}	=	Reactive power accumulated
$P_{ij(loss)}$	=	Real power loss in the line connecting i^{th} and j^{th} bus
NVB	=	Number of buses that violate the recommended voltage limits
V_L	=	Upper limit of the i^{th} load bus
V_i	=	Voltage magnitude of bus i
V_{min}	=	Minimum Voltage Limit
V_{max}	=	Maximum Voltage Limit
P_i	=	Real power load demand in the bus i
Q_i	=	Reactive power load demand in the bus i
R_{ij}	=	Resistance in the line connecting the i^{th} and j^{th} bus
VDI	=	Voltage Deviation Index

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I. INTRODUCTION

In distribution network, if the distance of the buses from the distribution substation increases, the voltage at buses reduces. This result in the power losses in the distribution system which are normally high compared to the transmission network. The decrease in the voltage at the buses and the power losses are due to the deficient amount of reactive power. For this purpose reactive power compensation is employed to reduce power loss and improve the voltage profile. Capacitors are very commonly employed to provide reactive power compensation in distribution systems. The benefit of reactive power compensation greatly depends on the size of the capacitors added. The size of the capacitors installed in the buses can be varied by using switched capacitors. Here in this paper we are choosing fixed capacitors so that optimized solution for the Radial Distribution System (RDS) can be found.

Capacitor placement has been commonly employed to provide reactive power compensation in distribution system. The placement of capacitor banks involves determination of size (KVAr ratings), location of capacitors. Selecting the best location for the capacitor will reduce the requirement of the reactive power, which consequently minimizes the cost for power loss and also used to maintain voltage profile within permissible limits. To find out the potential locations for compensation, Loss sensitivity factors (LSF) are used. These factors are computed using Sensitive analysis. Using the Loss sensitivity factors (LSF), the candidate number of buses is recognized. Group Search Optimization Algorithm (GSO) employed here allows us to choose the optimized capacitor settings to be installed in the respective buses which are obtained through the Loss sensitivity factors (LSF).

Ahmed R. Abul'Wafa [1] suggested a method for capacitor placement problem in RDS. This paper has presented a method to find the candidate location of capacitor through loss sensitivity technique and the sizing of the capacitor is determined through a loss saving equation with respect to capacitor currents. H. Mohkami et al., [2] presented the use of Bacteria Foraging (BF) oriented by Particle Swarm Optimization (PSO) algorithm (BF-PSO) for loss reduction in radial and meshed networks in the presence of unbalanced and nonlinear loads. Apart from minimizing power loss and energy loss, this method also addresses the problem of total harmonic distortion (THD), and deviation of voltage fundamental component from the permitted value. R.A. Jabr [3] used a two phase solution. In this paper, the Phase I approaches the problem with a conic program where all nodes are considered as a candidate for placing the capacitor banks to arrive at a global result with the aid of interior-point based conic programming solver. In phase II, the problem is approached by mixed integer linear program to lessen the L1 norm of deviations from Phase I state variable values. Phase II utilizes mixed integer linear programming solver. T. Ghose and S.K. Goswami [4] used heuristic search technique to support the simulated annealing (SA) to study the effect of network and load unbalances, supply harmonics and load non-linearity. SA technique starts with a feasible solution and perturbed to reach new feasible solution, which may be accepted or discarded. Silivo segura et al., [5] propose the use heuristic algorithm wherein the solution is obtained through a relaxed mathematical model solved through specialized interior point method to arrive at the most sensitive bus to add capacitors at each step of algorithm. In this method Sensitivity indicator incorporated into optimization strategy to find the optimal solution. S.K. Bhattacharya and S.K. Goswami [6] formulated two fuzzy membership functions – active power membership and voltage membership which are less or even not dependent on weighing factors. The fuzzy method plays a main role in choosing the candidate location for capacitors. Simulated annealing technique is used for identifying final selection of capacitor sizes. Ying-Tung Hsiao et al., [7] worked on a fuzzy-GA method where objective functions are formulated as fuzzy sets. Then it is formulated as fuzzy satisfying objective function through appropriate weighing factors by incorporating GA into the fuzzy method to optimize the capacitor size. D. Das [8] fuzzified the maximization of net savings and minimization of nodes voltage deviation and then integrating the objectives into a fuzzy satisfaction objective function through appropriate weighting factor followed by the optimization of capacitor through GA technique.

Gary Boone and Hsiao-Dong Chiang [9] examined several implementation issues such as selection pressure, fitness scaling and ranking, unity crossover probability and selection of generalized control parameters in GA. Seyed Abbas Taher et al., [10] described the computation of a near global solution with lesser possibility of getting stuck at a local optimum and weak dependency on initial conditions using genetic algorithm which can be effectively used in distorted distribution system. S.K. Goswami et al., [11] developed a GA based capacitor placement solution using basic search technique as an additional operator of genetic search technique. Tsong-Liang Huang et al., [12] employed compromise programming with a model involving fuzzy sets to indicate the imprecise nature of objectives and integrate multiple planning requirements. Their approach obviates the need for user defined weight factor. Cheng-Chien Kuo [13] proposed the use of interactive bi-objective programming with value trade-off (IBVT) approach for scheduling problems and simulated annealing-like modified particle swarming optimization for better solution quality where in cost and quality are two factors considered for optimization. H.M. Khodr et al., [14] proposed a computationally efficient method which is tested in a 15 bus system and 33 bus systems delivers promising solutions resulting in higher loss savings with a lower amount of capacitive compensation. This method implemented in a real life radial distribution system served by AES – Venezuela resulted with a convergence time of 4s after 22,298 iterations. John F. Francoet al., [15] presented a mixed linear programming method to model a steady state operation of a radial distribution system through linear expressions. This paper presents a multi objective function with cost and voltage deviation as objectives.

R. Srinivasas Rao et al., [16] approached the capacitor placement problem using LSF to identify the candidate location and the optimal capacitor size is determined through Plant Growth Simulation Algorithm (PGSO). José Federico Vizcaino González et al., [17] used Extended Dynamic Programming (EDP) method capable of providing a global optimal solution with pseudo-polynomial complexity in worst case and with linear complexity for practical applications. Xin-mei Yu et al., [18] employed Particle Swarm Optimization (PSO) for identifying locations, type and size of capacitor to be placed taking into account of Harmonic distortion effect, discrete nature of capacitors and different load levels. Kalyuzhny.A et al., [19] approached a solution for placing shunt capacitors which is found to be good for system of feeders fed through their transformers and not for any individual feeders. Genetic algorithm is used to optimize the sizing of capacitor which is now implemented in Isreal Electric Corporation (IECo). Ji-Pyng Chiou et al., [20] identified an effective method namely Variable Scaling Hybrid Differential Evolution (VSHDE) where the drawback of Hybrid Differential Evolution (HDE) is suppressed by variable scaling factor in VSHDE. S.M. Tabatabaei and B. Vahidi [21] proposed a fresh method for placing shunt capacitors in a distribution system where the node for installation is identified by fuzzy reasoning based on fuzzy set theory. The determination of optimal node for capacitor is achieved by Bacterial Foraging Algorithm (BFA). This method results as an economic solution for reducing energy loss, power loss and total capacitive compensation.

In the light of the above progresses, this paper presents an optimization technique called Group Search Optimization (GSO) algorithm, which has been developed as the solution technique for feeder reconfiguration. The application of GSO for minimization of I^2R losses due to network reconfiguration is formulated as an objective problem subject to operational and electric constraints. The objectives considered are I^2R loss reduction, voltage at buses to be kept within a specified range and the radial structure of the network must persist even after reconfiguration in which all loads must be served. A load flow program was developed and the algorithm based on [13] is used to compute the power flow. Then it is integrated into GSO for determining the minimum loss RDS configuration. The distribution network presented by Baran and Wu [14] is used to demonstrate the reliability and efficacy of the proposed algorithm.

This paper is organized as follows: Section 2 describes the Problem formulation. Section 3 delivers the mathematical model of the load flow. Section 4 explains the sensitivity analysis. Group Search Optimization Algorithm and its ability to solve the optimization problem are discussed in Section 5. Test system and the result analysis are done in the sections 6 and section 7 respectively. And finally this paper is concluded in Section 8.

II. LOAD FLOW

To meet the present emerging domestic, industrial and commercial load day by day, effective forecasting of the RDS is essential. To ensure the effective planning with load transferring, the load flow study of RDS becomes utmost significant. Load flow analysis is concerned with describing the operating state of an entire power system. Newton Raphson and Fast decoupled load flow solution techniques are used to solve well- behaved power system. However these are in general unsuitable for solving load flow for RDS because of their low X/R ratios of branches.

A section of RDS has a sending end bus (i^{th} bus) and receiving end bus (j^{th} bus). The line in connection with these two sections has an impedance $(Z = r + jx)$. The power flow through this line can be in both directions. The power flow at the sending end bus $(S_i = P_i + jQ_i)$ is different from the power flow at the receiving end bus $(S_j = P_j + jQ_j)$.

A load flow algorithm [13] solves the power balance equations at all buses and finds the corresponding voltage solution. At load buses, the load flow algorithm will solve for the bus voltage magnitude and phase angle. The known parameters at a load bus are the received real and reactive powers. Hence a load flow must solve for the bus voltage magnitude in equation (1) and phase angle, equation (2).

$$V_j^2 = -\left[rP_j + xQ_j - \frac{V_i^2}{2}\right] + \sqrt{\left(rP_j + xQ_j - \frac{V_i^2}{2}\right)^2 - [r^2 + x^2][P_j^2 + Q_j^2]} \quad (1)$$

$$\delta_j = \delta_i - \sin^{-1}\left(\frac{xP_j - rQ_j}{V_i V_j}\right) \quad (2)$$

If the voltage magnitude and phase angle values are to be computed for the receiving end bus, the only variables needed are the receiving end bus real and reactive power values, the sending end bus voltage magnitude and phase angle value, and the value of the line impedance connecting the two buses. All the values needed for the load bus calculations are easily attainable in practice.

2.1 Load Flow Algorithmic steps

Step 1 : Read System data structure. $Q_{T,loss} = \sum_{i=1}^{n} Q_{ij(loss)}$

Step 2 : Goto Slack bus.

Step 3 : Initialize $P_{acc} = 0$ and $Q_{acc} = 0$

Step 4 : Calculate P and Q for all buses

Step 5 : Calculate V_j and δ_j for all buses using equations (1) and (2)

Step 6 : Determine P_{loss} and Q_{loss} for all lines

Step 7 : Update P_{acc} and Q_{acc} using the formula $P_{acc} = P_{loss} + P_j$; $Q_{acc} = Q_{loss} + Q_j$

Step 8 : Goto Next bus and reprise the step from 4 to 8 up until Last bus is reached.

Step 9 : Check for convergence, equation (3) and print the result, else goto step 2.

2.1.1 Convergence Criteria

In this Load Flow [13], it is checked whether the sum of powers flowing out of the lines connected to each bus equals (or equals within a tolerable limit) the net power injected into that bus. Mathematically, convergence criteria for the presented load flow is given in equation (3)

$$(PG_i - PD_i) - \left|\sum_j \left(V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij})\right)\right| \le \varepsilon$$

$$(QG_i - QD_i) - \left[\sum_j \left(V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij})\right)\right] \le \varepsilon \quad (3)$$

III. MATHEMATICAL PROBLEM STATEMENT

The goal of capacitor placement problem in RDS is the improvement of economic aspects of power system.

The proposed approach is formulated as capacitor placement problem with a mathematical programming model which has two objectives, viz., i) reduce power losses and ii) reduce total cost of real power losses and capacitor cost. Power loss and cost reductions are considered in objective function and voltage limit along with reactive power capacity as its

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constraint.

The objective function, C which will be minimized by the capacitor allocation algorithm, is:

$$\text{Minimise } C = C_1 P_l + \sum_{i=1}^{n} C_{2,i} Q_{c,i} \quad (4)$$

Subject to the constraint,

$$V_{min} \leq V_i \leq V_{\max} \quad (5)$$

$$Q_c^{total} < Q_L \quad (6)$$

Where P_l is the real power loss in kW, $C_1$and C_2 are the cost coefficients of power loss and capacitors expressed as \$/kW and \$/kVAr respectively and Q_c^{total} Q_c is the size of capacitor in kVAr. Vi is voltage at bus i, is total connected kVAr of capacitor banks and Q_L is total kVAr of load available in distribution network.

This objective function is minimized by selecting optimal node using sensitivity analysis and then choosing the size of the capacitor by GSO.

IV. SENSITIVITY ANALYSIS

Sensitivity analysis [21] has been considered to reduce the search space and accurate solution for recognizing the locality. The sensitivity analysis is a methodical technique to find out those locations with maximum influence on the system real power losses with respect to the node reactive power. Sensitivity analysis is carried out also to find the Loss Sensitivity Factor. The Loss Sensitivity Factor is so important that the candidate number of buses is recognized.

4.1. Loss sensitivity factor (LSF)

To identify the location for capacitor placement in distribution system Loss Sensitivity Factors have been used. 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 buses for the capacitor placement. The estimation of these candidate buses basically helps in reduction of the search space for the optimization problem. As only few buses can be candidate buses for compensation, the installation cost on capacitors can also be reduced.

Consider a distribution line with an impedance R + jX and a load of Peff + jQeff connected between 'i' and 'i+1' buses. Peff and Qeff are the Real and Reactive power supplied beyond the receiving end bus. Real power loss in the kth line connecting 'i' and 'i+1' bus is given by, $I_k^2 * R_k$ which can also be expressed as,

$$P_{lineloss}(i+1) = \frac{\left(P_{eff}^2(i+1) + Q_{eff}^2(i+1)\right) * R(k)}{(V(i+1))^2} \quad (7)$$

Similarly the reactive power loss in the kth line is given by

$$Q_{lineloss}(i+1) = \frac{\left(P_{eff}^2(i+1) + Q_{eff}^2(i+1)\right) * X(k)}{(V(i+1))^2} \quad (8)$$

Where,

P_{eff} = Total effective real power supplied beyond the bus 'i+1'

Q_{eff} =Total effective reactive power supplied beyond the bus 'i+1'

Now, the Loss Sensitivity Factors can be calculated as

$$\frac{\partial P_{lineloss}(i+1)}{\partial Q_{eff}(i+1)} = \frac{2 * Q_{eff}(i+1) * R(k)}{(V(i+1))^2} \quad (9)$$

$$\frac{\partial Q_{lineloss}(i+1)}{\partial Q_{eff}(i+1)} = \frac{2 * Q_{eff}(i+1) * X(k)}{(V(i+1))^2} \quad (10)$$

4.2. Algorithm for Sensitivity Analysis

Normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given as below:

norm [i] = |V (i)|/0.95 (11)

The 'norm[i]' decides whether the buses need reactive compensation or not. The buses whose norm[i] value is less than 1.01 can be selected as the candidate buses for capacitor placement.

STEP 1: Calculate the Loss Sensitivity Factor, $S = \frac{\partial P_{LOSS}}{\partial Q}$ at all the buses.

STEP 2: Arrange the value of Loss Sensitivity Factor in descending order. Also store the respective buses into bus position vector

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STEP 3: Calculate the normalized voltage magnitude $\mathrm{norm(i)} = \frac{\mathrm{v[i]}}{0.95}$ of the buses

STEP 4: The buses whose $\mathrm{norm(i)} = \frac{\mathrm{v[i]}}{0.95}$ is less than 1.01 are selected as candidate buses for capacitor placement.

V. GROUP SEARCH OPTIMIZATION (GSO)

This paper adopts a new search algorithm called Group Search Optimization (GSO) algorithm as the solution technique for feeder reconfiguration. This algorithm was developed by S.He et al., [15] to address various high-dimensional multimodal problems. When tested against benchmark functions, in low and high dimensions, the GSO algorithm has competitive performance to other evolutionary algorithms in terms of accuracy and convergence speed.

In this paper, GSO is applied to minimize the feeder losses by reconfiguring RDS. It is formulated as real power loss minimization problem subject to operational and electric constraints. GSO is inspired by animal behavior, especially animal searching behavior. The framework is mainly based on the producer–scrounger model, which assumes that group members search either for “finding” (producer) or for “joining” (scrounger) opportunities. Based on this framework, concepts from animal searching behavior, e.g., animal scanning mechanisms, are employed metaphorically to design optimum searching strategies for solving continuous optimization problems.

5.1 GSO Algorithmic steps

Step 1: Initialization:
Set iteration = 0; randomly initialize positions Xi (parameters given in (12)) and head angles of all members.

$$d_{i_j}^{k} = \sin\left(\varphi_{i_{j-1}}^{k}\right) \cdot \prod_{q=j}^{n-1} \cos\left(\varphi_{i_q}^{k}\right) \quad (12)$$

$$(j = 2, \ldots, n-1)$$

Step 2: Fitness evolution and fitness computation:
Calculate the fitness values of initial members: f (Xi); using (12).

Step 3: Compute Producer Xp:
For each members i in the group and find the producer Xp of the group; the producer will scan at zero degree and then scan laterally by randomly sampling three points in the scanning field using (13-15),

$$X_z = X_p^k + r_1 l_{\max} D_p^k\left(\varphi^k\right) \lim_{x\to\infty} \quad (13)$$

$$\varphi^{k+1} = \varphi^k + r_2 \alpha_{\max} \quad (14)$$

$$\varphi^{k+a} = \varphi^k \quad (15)$$

Step 4: Calculate the Best Resource:
Find the best resource (fitness value). If the best point has a better resource than its current position, then it will fly to this point. Or it will stay in its current position and turn its head to a new angle using (14),

Step *5: Zero Degree:*
If the producer cannot find a better area after specified iterations, it will turn its head back to zero degree using (15),

Step *6: Scrounging & Ranging:*
Randomly select 80% from the rest members to perform scrounging; for the rest members, they will be dispersed from their current position to perform ranging:

1). Generate a random head angle using (14);

2). Choose a random distance li from the Gauss distribution using (16) and move to the new point using (17)

$$l_i = a \cdot r_1 l_{\max} \quad (16)$$

$$X_i^{k+1} = X_i^k + l_i D_i^k\left(\varphi^{k+1}\right) \quad (17)$$

Step 7: Calculate the fitness value of current member: f (Xi).

Step 8: If the convergence criterion is satisfied then go to next step else update Iteration=iteration+1 then go to step 3.

Step 9: Print the optimal parameters and its fitness value.

VI. TEST SYSTEM

6.1. 33 Bus Test System

The real power loss minimization is done by placing capacitor and is executed in a 33 bus RDS. The load data, transmission line data are taken from [25]. The test system consists of 33 bus and 32 lines. The first bus is considered as

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the substation bus and the loads are connected to all buses except the first bus. The total real power load of this test system is totaled to 3715 kW and the reactive power load is summed to 2300 kW. The substation voltage is 12.66 kV.

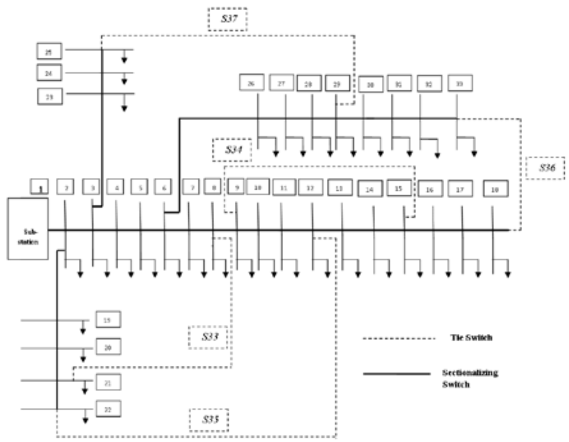

Figure 1. Line diagram of 33 bus RDS

VII. RESULT ANALYSIS

The results of 33 bus test system are given in case A. Load flow is executed using MATLAB software which is installed in an Intel® Core™ i5-2410M CPU @ 2.30GHz with an installed memory of 4.00 GB & 64-bit Operating System. The Load flow Program first runs for the base case which gives a real power loss of 210.89kW.The minimum voltage is found to be 0.9036V at 18th bus. In order to reduce the losses in the system, the capacitor allocation has to be done. From the result of sensitivity analysis, the candidate buses are chosen as 8, 30 and 31. The optimal capacitor values obtained from GSO are 900, 760, 250 kVAr and are placed in the respective buses. After placing the capacitors, the power loss is reduced to 143.76kW. The percentage of loss reduction is 31.83%. A comparison is done with other algorithm and is tabulated in table 1.

Table 1. Comaprative Analysis of 33 bus system

Algorithm	Base Case	GA	Loss saving equation	GSO (proposed)
Power Loss (kw)	210.89	145.4	144.04	143.76
Loss Reduction (%)	---	31.05	31.7	31.83
Candidate Buses	---	6, 28, 29	7, 29 30	8,30,31
Capacitor values (kVAr)	---	1200, 760, 200	850, 250 900	900, 760, 250

VIII. CONCLUSION

In this paper, a new strategy for capacitor placement problem has been presented, and GSO has been proposed as a solution algorithm. The capacitor placement problem is defined as optimal allocation of the reactive resources along the feeder, which would enable it to enter deeper voltage enhancement modes as well as to function as a loss-reduction mechanism during normal operation. The results obtained justify the above statement. The optimal solution in GSO is obtained by movement of agents in search space and its direction is based on the overall force of all other agents. Therefore, the search direction towards the optimal solution is effective in this algorithm. The proposed method is tested on established 33-bus RDS. The results obtained demonstrate that the GSO method optimally places the capacitor in the RDS minimizing the kW losses and obtains the best voltage profile.

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