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Optimal Capacitor Placement in Distribution System for Loss Minimization Using SA

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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 $R.I^2$ loss which depends on the current and resistance.*
In this paper, the optimal location and size of the capacitor is found using a new computational intelligent algorithm called Sorting algorithm (SA). To calculate the power flow and losses in the system, novel data structure load flow is introduced. The proposed approach is examined and tested on 69 bus power network simulation results are presented and discussed.

Key words: *Radial Distribution System, Voltage Profile, Loss Minimization, Sorting algorithm*

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 function of a distribution system is to deliver electrical power from the transmission network to end users. The distribution systems are usually unbalanced and have a high R/X ratio compared to transmission systems, which results with the effect of high voltage drops and power losses in the distribution feeders. The vital tasks in the distribution system are reduction of power losses and improvement of the system voltage profile. Many research works have been carried out in this direction since the supporting of analytical and software approach. Power loss reduction and voltage profile improvement are goals for electricity utilities. Distribution system reconfiguration and optimal capacitor placement are two of the low Cost available tools for Power loss reduction and voltage profile improvement. Reconfiguring the network means altering its topology by changing the status of normally opened and normally closed switches. By minimizing the power losses, the system may acquire longer life span and has greater reliability. Feeder reconfiguration is a very important tool to operate the distribution system at minimum cost and improve the system reliability and security. The reconfiguration of a distribution system is a process, which alters the feeder topological structure by changing the open/close status of the switches in the distribution system. Two types of switches, normally closed switches (sectionalizing switches) and normally open switches (tie switches), are used in primary distribution systems for protection and configuration management. Distribution network reconfiguration for loss reduction is a complicated combinatorial, non-differentiable, constrained optimization problem since the reconfiguration involves many candidate switching combinations. Several papers have considered the problem of optimal network reconfiguration using different optimization techniques.

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.

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 optimal location and size of the capacitor is found using a new computational intelligent algorithm called *Sorting algorithm* (SA). The proposed approach is examined and tested on 69 bus power network simulation results are presented and discussed.

II. Formulation

In this paper, the objective is to minimize the system power loss under a certain load pattern through network optimization while electrical and operational constraints are met, that is the process of altering the topological structures of distribution network by changing the open/closed status of switches so as to minimize total system real power loss. The objective function of the problem is,

$$\text{Minimiz } P_{loss} = \sum_{i=1}^{nl} R_j \frac{P_j^2+Q_j^2}{V_j^2} \qquad (1)$$

The branch's capacity and voltage magnitude at each branch and each bus must be maintained within limits. These constraints are expressed as follows:

For any branch

$$s_j \leq s_{j,max}$$

For any bus

$$|V_{i,min}| \leq |V_i| \leq |V_{i,max}|$$

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

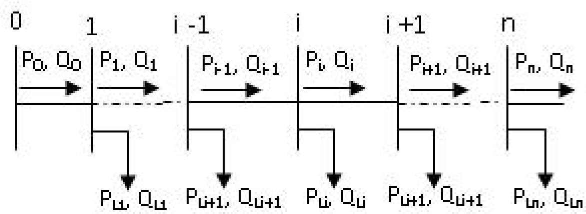

Figure 1: Single line diagram of main feeder

$$P_{i+1} = P_i - P_{Li+1} - R_{ij+1} \frac{P_i^2 + Q_i^2}{|V_i|^2}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{ij+1} \frac{P_i^2 + Q_i^2}{|V_i|^2}$$

$$|V_i|^2 = |V_i|^2 - 2\left(R_{ij+1}\ P_i + X_{ij+}\ Q_i\right) + \left(R_{ij+1}^2 + X_{ij+1}^2\right)\times\frac{P_i^2 + Q_i^2}{|V_i|^2}$$

Where Pi and Qi 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

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

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

$$P_T^{LOSS} = \sum_{i=0}^{n-1} P_{LOSS}(i, i+1)$$

Considering the practical capacitors, there exists a finite number of standard sizes which are integer multiples of the smallest size Q0 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

$$Q_c^{max} = LQ_c$$

Therefore, for each installation location, there are L capacitor sizes {$1Q_C$, $2Q_c$, $3Q_c$, … ,LQc} available. Given the annual installation cost for each compensated bus, the total cost due to capacitor placement and power loss change is written as

$$COST = K_p \times P_T^{LOSS} + \sum_i^c \left(K_{cf} + K_i^c Q_i^c\right)$$

Where n is number of candidate locations for capacitor placement, Kp is the equivalent annual cost per unit of power loss in \$/(kW-year); K_{cf} is the fixed cost for the capacitor placement. Constant K_i^c is the annual capacitor installation cost, and, i = 1, 2, ... , n are the indices of the buses selected for compensation. The bus reactive compensation power is limited to

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

Where $1Q_c$ and LQ_c are the reactive power compensated at bus i and the reactive load power at bus i, respectively. THD index presents the impact of the harmonics on network and is considered in the objective function according to the following equation

V. Power 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 Backward Sweep calculates the current injected into each branch as a function of the end node voltages. It performs a current summation while updating voltages. Bus voltages at the end nodes are initialized for the first iteration. Starting at the end buses, each branch is traversed toward the source bus updating the voltage and calculating the current injected into each bus. These calculated currents are stored and used in the subsequent Forward Sweep calculations. The calculated source voltage is used for mismatch calculation as the termination criteria by comparing it to the specified source voltage. The Forward Sweep calculates node voltages as a function of the currents injected into each bus. The Forward Sweep is a voltage drop calculation with the constraint that the source voltage used is the specified nominal voltage at the beginning of each forward sweep. The voltage is calculated at each bus, beginning at the source bus and traversing out to the end buses using the currents calculated in previous the Backward Sweep [12]. Single line diagram of main feeder depicted in Fig 2.

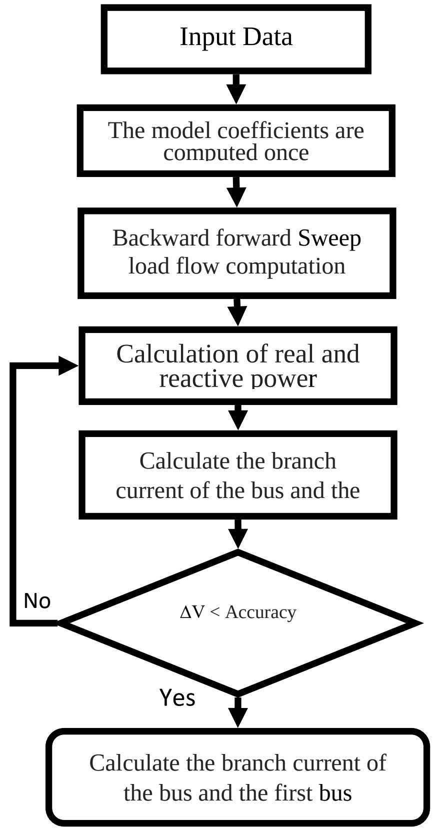

Fig 2. Single line diagram of main feeder

III. Sorting Algorithm (SA)

Sorting algorithm is an algorithm that puts elements of a list in a certain order. The most-used orders are numerical order and lexicographical order. Efficient sorting is important for optimizing the use of other algorithms (such as search and merge algorithms) which require input data to be in sorted lists; it is also often useful for canonicalizing data and for producing human-readable output. More formally, the output must satisfy two conditions:

- The output is in nondecreasing order (each element is no smaller than the previous element according to the desired total order);
- The output is a permutation (reordering) of the input.

Further, the data is often taken to be in an array, which allows random access, rather than a list, which only allows sequential access, though often algorithms can be applied with suitable modification to either type of data. Since the dawn of computing, the sorting problem has attracted a great deal of research, perhaps due to the complexity of solving it efficiently despite its simple, familiar statement. For example, bubble sort was analyzed as early as 1956.[1] Comparison sorting algorithms have a fundamental requirement of O(n log n) comparisons (some input sequences will require a multiple of n log n comparisons); algorithms not based on comparisons, such as counting sort, can have better performance. Although many[who?] consider sorting a solved problem—asymptotically optimal algorithms have been known since the mid-20th century—useful new algorithms are still being invented, with the now widely used Timsort dating to 2002, and the library sort being first published in 2006.

Sorting algorithms are prevalent in introductory computer science classes, where the abundance of algorithms for the problem provides a gentle introduction to a variety of core algorithm concepts, such as big O notation, divide and conquer algorithms, data structures such as heaps and binary trees, randomized algorithms, best, worst and average case analysis, time-space tradeoffs, and upper and lower bounds. More formally, the data being sorted can be represented as a record or tuple of values, and the part of the data that is used for sorting is called the key. In the card example, cards are represented as a record (rank, suit), and the key is the rank. A sorting algorithm is stable if whenever there are two records R and S with the same key, and R appears before S in the original list, then R will always appear before S in the sorted list.

When equal elements are indistinguishable, such as with integers, or more generally, any data where the entire element is the key, stability is not an issue. Stability is also not an issue if all keys are different. Unstable sorting algorithms can be specially implemented to be stable. One way of doing this is to artificially extend the key comparison, so that comparisons between two objects with otherwise equal keys are decided using the order of the entries in the original input list as a tie-breaker. Remembering this order, however, may require additional time and space. One application for stable sorting algorithms is sorting a list using a primary and secondary key. For example, suppose we wish to sort a hand of cards such that the suits are in the order clubs (♣), diamonds (♦), hearts (♥), spades (♠), and within each suit, the cards are sorted by rank. This can be done by first sorting the cards by rank (using any sort), and then doing a stable sort by suit:

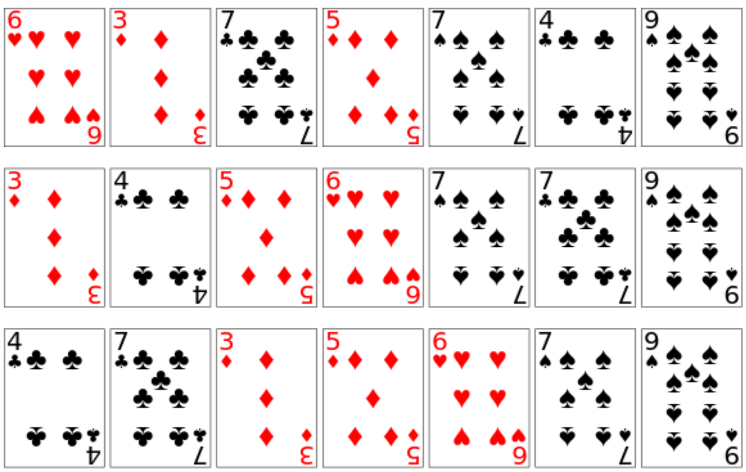

Fig 3. SA method

In the real world, modern science and industry are indeed rich in the problems of optimization. Since the HS has been originally proposed by Geem and applied to solve the optimization problem of water distribution networks in 2000, the applications of the HS have covered numerous areas including industry, optimization benchmarks, power systems, medical science, control systems, construction design, and information technology [24]. There is a lot of work focused on the optimization issues concerning power systems, such as cost minimization. A modified HS algorithm is proposed to handle nonconvex economic load dispatch of real-world power systems. The economic load dispatch and combined economic and emission load dispatch problems can be converted into the minimization of the cost function [19]. Sinsuphan et al. combine the HS with sequential quadratic programming and GA to solve the optimal power flow problems. The objective function to be optimized is the total generator fuel costs in the entire system [20]. The chaotic self-adaptive differential HS algorithm, proposed by Arul et al., is employed to deal with the dynamic economic dispatch problem [21].

IV. Test Results

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. 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. To study the proposed method, 69 bus power network is simulated. Figure 4 illustrates the single-line diagram of this network.

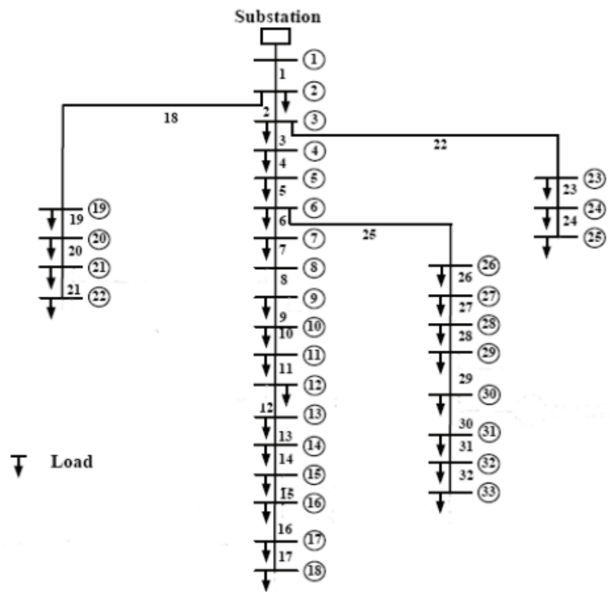

Fig 4. Single-line diagram of 69 bus power network

Initially, a load flow was run for the case study in both fundamental frequency and harmonics frequencies without installation of capacitor. 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 1. This given size of capacitor is used to install in 33 and 69 bus to optimize the given multi objective. As it is clear, all the obtained values confines with all the considered constraints. The obtained penetration lever is 0.27, which is less than the assumed allowable value.

Table 1: Optimal place and capacity of DGs

Location [#bus]	Capacity [KVA]
5	5.5
11	1.25
48	3.5
60	4.05

Multi objective SA for solving the minimization of loss and the voltage deviation for the 69 bus system is given in the following Table 2. Optimization variables are the capacitor size ranges from 150 to 2100 kvar and the location ranges from 2 to 60. The result of SA.

Table 2: voltage deviation for the 69 bus system

Description	**Base case**	**SA (proposed)**
Total Loss (kW)		
$C_{Location}$	-	5, 11, 48, 60
% Savings	0.0 %	41.05 %

Fig. 5 shows voltage profile of the base case and the optimized SA. From the figure it is clear that the SA finds best location and size of capacitor for 69 bus and improves the voltage. The minimum voltage at this case is 0.96 for the objective of the voltage deviation minimization. Fig. 6 gives voltage magnitude of all the 69 buses as bar.

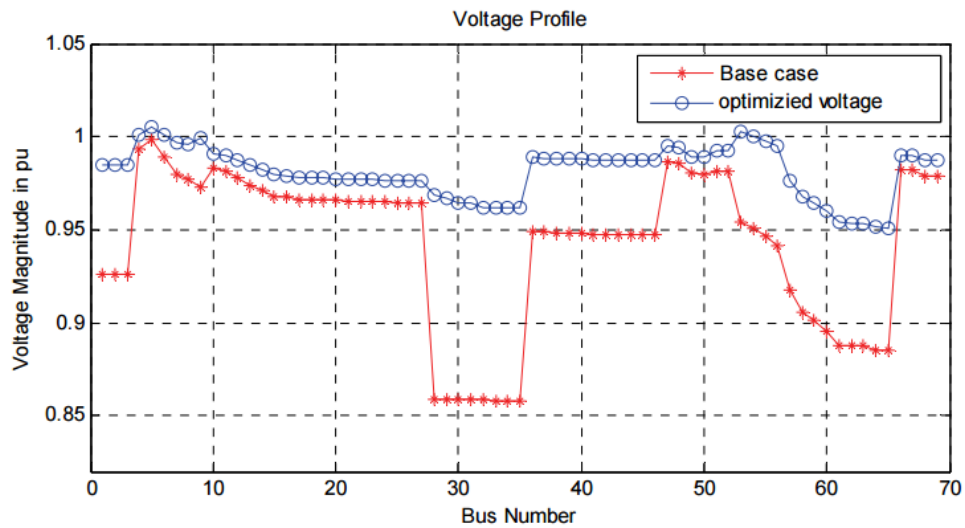

Fig 5: Voltage profile of 69 bus system before and after capacitor placement

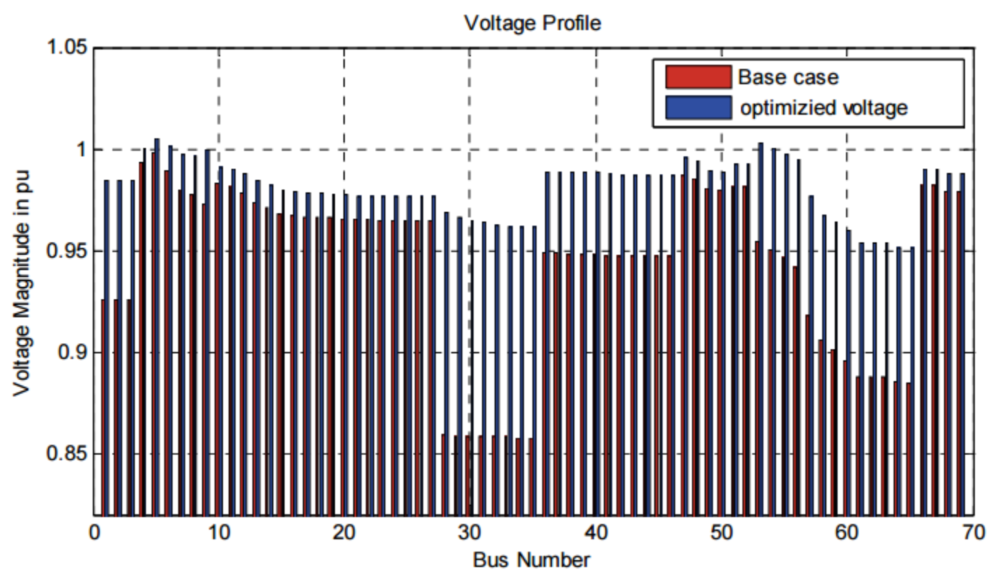

Fig 6: Voltage profile of 69 bus system before and after capacitor placement using line bar chart

VIII. Conclusion

In the present paper, a chaotic sorting algorithm (SA) for optimal placement and sizing of capacitor on distribution systems with an aim of reducing the power losses and improving voltage stability. Simulations are carried on 69 bus power network. 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 69 bus system proves that the proposed sorting algorithm gives the best multi objective problem solution.

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