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OPTIMAL ALLOCATION AND SIZING OF CAPACITORS EMPLOYING PATTERN SEARCH OPTIMIZATION

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ABSTRACT

Utilizing capacitors has long been recognized to improve the voltage profile and reduce the losses in power system. Many strategies have been successfully developed to determine the best allocation of capacitors in order to achieve the greatest results. In this paper, a method to find the optimal placement and sizing of capacitors in distribution system is presented. The objective function is composed of the line loss and the voltage profile of each bus. A power loss sensitivity factor is employed to identify the appropriate buses for optimal location and sizing of capacitors which is formulated and determined by using Pattern Search Optimization. This technique is used in power distribution system to select candidate locations for compensating reactive power which will enhance the system voltage and lower the power loss. To validate the proposed method, the IEEE 34 radial distribution system is used to observe the method's performance, effectiveness, and efficiency in finding solutions.

Keywords: *Capacitor Allocation, Capacitor Sizing, Loss Sensitivity Factor, Pattern Search Optimization*

1. INTRODUCTION

There is no perfect system that exists without flaws and cannot be improved. One of the main reasons for the unviability of power systems that many power companies have to deal with is the losses. The losses in the power system are related to voltage levels and line flows and it is existed not only in the transmission system but also in distribution system.

The distribution system is an essential part in power system because it is directly connected to consumers. An ideal distribution system must have a good reliability in order to maintain the power quality and power system stability. The power losses is being one of the main factors for decreasing power quality in the electricity distribution network because the R/X ratio in that system is very high [1]. According to studies, almost 10% to 13% of total electricity generated is lost as losses at the distribution level. To solve these issues, an appropriate, fast, and cost-effective solution is required, as failure to do so will compromise the system's reliability and performance, as well as increase system operating costs.

There are various methods that can be applied to minimize the power losses in distribution system such as network reconfiguration, reactive power compensation, installation of distributed geenration, regulation of transformer taps, etc. The reactive power compensation through capacitor's allocation has become an effective method that is widely and commonly used to minimize real power, maintain required voltage profile and correct the power factor.

In order to avoid abnormal conditions and instability in the system such as parallel resonance issues, undesirable power factor, and so on, an accurate analysis to define the proper capacitor selection with appropriate size and position is required. The problem of capacitor allocation has been widely discussed by many researchers using different methods to determine the best of its location and capacity. These methods have been developed based on analytical techniques, numerical programming, heuristics method and artificial intelligence applications [2]. With the advancement of computer science and information technology into the artificial intelligence sector, a number of researchers have used metaheuristic or AI optimization strategies to solve this challenge. Plant Growth Algorithm, Tabu Search, Fuzzy Logic, Genetic Algorithm and other algorithms are

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examples. These have the advantage of not requiring any function gradient input and being able to deal with many restrictions quickly, but they have the downside of taking longer in some applications and not providing proof of optimality.

Neha Goyal et al. [6] developed a genetic algorithm based population search method for optimal allocation of capacitors which is utilized to evaluate power loss in IEEE 33. Anwar S Siddiqui et al. [7] presented fuzzy logic based technique for capacitor placement which is used to reduce losses in 10 bus radial distribution system. Pravin Chopade et al. [8] presented optimal capacitor placement module for OCP simulation using genetic algorithm and ETAP software. A. A. Ahmed et al. [9] introduced a particle swarm optimization (PSO) as a tool for power loss reduction study. Khalil, T.M. et al. [10] proposed a simple modification into the binary PSO to search in selected space. The proposed technique is implemented on three feeder distribution system and Taiwan Power Distribution Company for reconfiguration and power loss minimization. A new selective particle swarm optimization (SPSO) is introduced to solve optimal capacitor placement problem. Saeid Jalilzadeh et al. [11] introduced a Shuffled frog leaping and PSO technique for optimal placement of capacitor in IEEE 45 bus radial system. Reza Sirjani et al., [10] proposed a heuristic optimization technique for optimal placement and selection of capacitor size in radial distribution network. The obtained results are compared with ant colony, fuzzy logic, genetic a lgorithm, harmony search, particle swar m optimization, tabu search, simulated annealing and hybrid methods. Meng Zhang. et.al. [13] proposed a technique in which loss sensitivity factor is used to determine the location for optimal capacitor placement. Sunday Adeleke Salimon et al [15] proposed a two-stage method of Loss Sensitivity Factor (LSF) and Cuckoo Search Algorithm (CSA) to find the optimal size and location of shunt capacitors with the objective of minimizing cost due to power loss and reactive power compensation of the distribution networks.

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2. PROBLEM FORMULATION

The objective of optimal allocation of capacitor in radial distribution system is to minimize the real power losses subjected to certain operating constraints and load pattern.

In this research, the objective function of the problem mathematically is described as:

$$min\ f\ =\ min\ (P_{Tloss}) \qquad (1)$$

where, P_{Tloss} is the total of real power loss in the system.

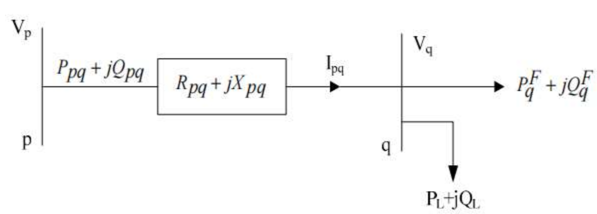

Figure 1. Power flow in distribution feeder between two nodes, p and q

Consider a distribution line between the two nodes *p* and *q* having a resistance and reactance are

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R_{pq} and X_{pq} respectively, also having a load P_L+jQ_L as shown in Figure (1). The power loss between the two nodes is calculated by the equation (2) and (3) below.

$$P_{loss} = R_{pq} \times \frac{(P_{pq}^2 + Q_{pq}^2)}{|V_p^2|} \qquad (2)$$

$$Q_{loss} = X_{pq} \times \frac{(P_{pq}^2 + Q_{pq}^2)}{|V_p^2|} \qquad (3)$$

whereas P_{pq} and Q_{pq} are the total active and reactive power flow through the branches respectively.

The total real power loss of the system is found by adding up the losses of every branch of the system.
The constraints are,

i. The voltage must be kept within the specified limits at each bus.

$$V_{min} \leq V \leq V_{max}$$

Where V_{min} and V_{max} are the lower and upper limits of bus voltage respectively.

ii. The apparent power flow through each branch must be less than the maximum apparent power admissible for the line and it may be expressed as follows.

$$S_i \leq S_{imax} \qquad i = 1,2,3,\ldots,n$$

where n is the number of branches, $S_i$is the apparent power flow of the ith branch and S_{imax} is the maximum apparent power flow limit of the ith branch.

iii. The size of the capacitor not more than the total reactive load of the system.

$$Q_i^c \leq Q_{iL}$$

where Q_i^c and Q_{iL} are size of the capacitor and total system reactive power load at bus q respectively.

3. PLOSS SENSITIVITY FACTOR TECHNIQUE

The loss sensitivity factor approach is used to analyze the sensitivity of the buses and helpful to find candidate busses to allocate the capacitor. This approach also reduces the search space during the optimization period. Based on the active power loss between the buses p and q that has been defined in Equation (2) and (3), therefore the lost sensitivity factor can calculated using Equation (4) and (5) below,

$$\frac{\partial P_{loss}}{\partial Q_{eff}} = \frac{2Q_{eff}(q) \times R_{pq}}{V_q^2} \qquad (4)$$

$$\frac{\partial Q_{loss}}{\partial P_{eff}} = \frac{2P_{eff}(q) \times X_{pq}}{V_q^2} \qquad (5)$$

where, $P_{eff}(q)$ and $Q_{eff}(q)$ is the total effective active and reactive power that flow to node q respectively. In general, the sensitivity analysis is calculated in three steps as shown below,

Step I. Calculating the value of lost sensitivity factor for all busses. Since the real power losses have become the concern in this research, therefore this value is calculated using the equation (4).

Step II. Sorting the obtained values in descending order

Step III. Those buses having high lost sensitivity factor values are selected as candidate buses for allocation of capacitors

4. PATTERN SEARCH OPTIMIZATION ALGORITHM

Pattern search optimization algorithm is part of the metaheuristic methods. Different to other metaheuristic optimization techniques the pattern search algorithm's convergence has been proven to be able to reach at least a local minima. There several terms existed in this algorithm such as patterns, meshes, polling, and expanding and contracting.

4.1. Pattern

The pattern search algorithm employs a set of vectors called a pattern to choose which points to search at each iteration. The number of independent variables in the objective function, N, determines the set d_i. The maximum basis, which has $2N$ vectors, and the minimal basis, which has $N+1$ vectors, are two often used positive basis sets in pattern search methods. For example, if the optimization problem has three independent variables, the default pattern vectors for a $2N$ positive basis are as follows,

$d_1 = [1\ 0\ 0]$, $d_2 = [0\ 1\ 0]$, $d_3 = [0\ 0\ 1]$
$d_4 = [-1\ 0\ 0]$, $d_5 = [0\ -1\ 0]$, $d_6 = [0\ 0\ -1]$

4.2. Meshes

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Pattern search looks for a point that improves the objective function in a set of points termed a mesh at each iteration. The mesh is created through pattern search by:

1. Generating a set of vectors $\{d_i\}$ by multiplying those each vector by a scalar Δm. The scalar Δm is called the mesh size.
2. Adding the $\{d_i\}$ to the current point which is the point with the best objective function value found at the previous step.

For example, using the this algorithm. suppose that:

1. The current point is [1.6 3.4].
1. Then the pattern consists of the vectors: $v_1 = [1\ 0]$; $v_2 = [0\ 1]$; $v_3 = [-1\ 0]$; $v_4 = [0\ -1]$
2. Supposed that the current mesh size Δm is 4. The algorithm multiplies the pattern vectors by 4 and adds them to the current point to obtain the following mesh.

[1.6 3.4] + 4*[1 0] = [5.6 3.4]
[1.6 3.4] + 4*[0 1] = [1.6 7.4]
[1.6 3.4] + 4*[-1 0] = [-2.4 3.4]
[1.6 3.4] + 4*[0 -1] = [1.6 -0.6]

The pattern vector that produces a mesh point is called its direction.

4.3. Polling

The algorithm polls the current mesh's points by determining their objective function values at each step. The method stops polling the mesh points as soon as it discovers a position whose objective function value is less than the current point when the complete poll option is set to *Off* (the default). If this happens, the poll is considered successful, and the point it discovers is used as the current point in the following iteration. Up until the poll is stopped, the method just computes the mesh points and their objective function values. The poll is labeled unsuccessful if the algorithm fails to identify a point that improves the objective function, and the current point remains the same in the following iteration. The algorithm computes the objective function values at all mesh locations when the complete poll option is set to *On*. The program then compares the current position to the mesh point with the least goal function value. The poll is successful if that mesh point has a lower value than the current point.

4.4. Expanding and Contracting

Following polling, the algorithm modifies the mesh size Δm. After a successful poll, the default is to multiply by 2, and after an unsuccessful poll, by 0.5. The pattern search identifies a series of points, *x0, x1, x2*,..., that are close to an ideal point. From one point in the series to the next, the objective function's value either declines or stays the same. This cycle is repeated until the specified halting requirements are met.

The Figure 2 represents the flowchart for the pattern search algorithm.

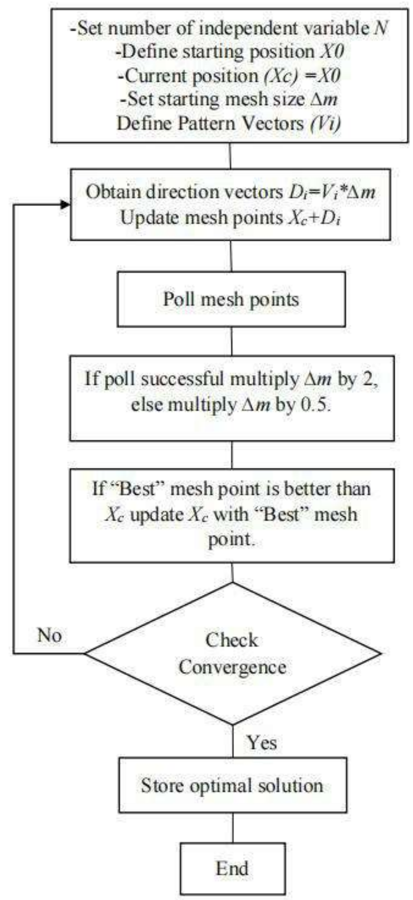

Figure 2. Pattern Search Algorithm Flow chart

4.5. The Implementation of Pattern Search Algorithm for Optimal Allocation of Capacitor

The following steps for implementation of this methods are shown in Figure 3,

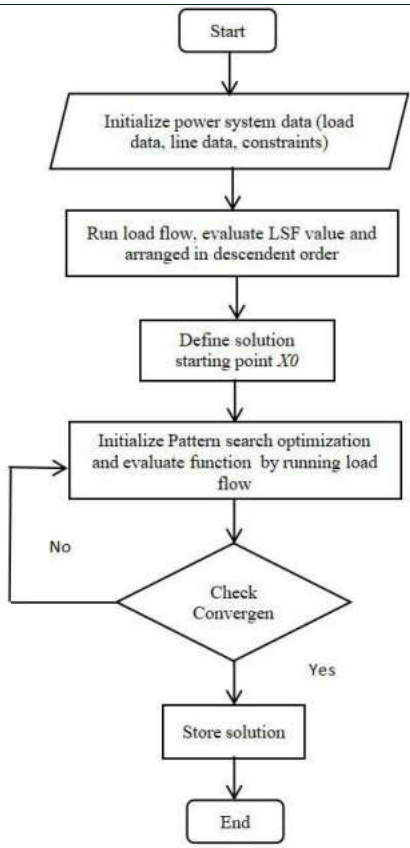

Figure 3. The Implementation of Pattern Search Algorithm for Capacitor Allocation

Step I. All data from the power system, such as line and load data, limit values, and Pattern Search Algorithm parameters, are initialized.
Step II. The position of the shunt capacitors in the search space is established after initialization based on load sensitivity values.
Step III. The capacitor's size is generated randomly in the form of vector X.
Step IV. Run the Pattern Search Algorithm and the load flow problem simultaneously using above standard values of capacitor, and use Equation (1) to calculate the objective function values.

5. SIMULATION AND RESULTS

To validate the proposed method, the IEEE 34 radial distribution system as shown in Figure 4 is used to observe the method's performance, effectiveness, and efficiency in finding solutions. This system consists of 34 bus and 4 feeders. Meanwhile, the total load taken at peak load conditions is 4.64 MW and 6.87 Mvar. The simulation is carried out using six fixed capacitors with the rating of each capacitor ranging from 50 kVar to 1 Mvar. The whole work has been programmed by MATLAB R2016b version and Intel® CORE™ i5 computer with 4 GB RAM and 64-bit operating system.

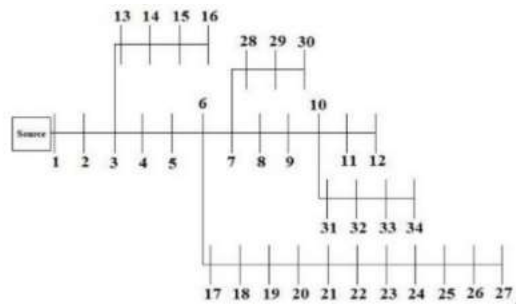

Figure 4. IEEE 34 bus radial distribution system

The calculated loss sensitivity factor values and all the buses are shown in Figure 5. The buses having high loss sensitivity factor values are selected as candidate buses for placement of capacitor; the sensitive buses are as follows {12, 22, 23, 24, 27 and 34}. The capacitors have been located at those sensitive buses with optimal size are shown in Table 1. Meanwhile the results of power losses before and after the installation of capacitors can be seen in Table 2.

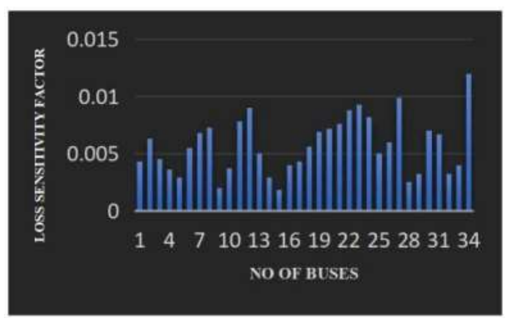

Figure 5. Load sensitivity factor values for IEEE 34 bus radial distribution system

Table 1. The optimal location and sizing of capacitor

Best Location for Capacitor Placement	Optmal Size of Capacitor
12	675 kVar
22	75 kVar
23	75 kVar
24	675 kVar
27	675 kVar
34	675 kVar

Table 2. The losses resulted from implementation of Searchh Pattern Optimization in capacitor allocation

	Total Losses
Before optimization	219 kW
After optimization	160 kW
Total losses reduction	26%
Total installed reactive power	2850 kVar

The voltage profile on each bus on the IEEE 34 bus system before and after appyling the optimization is illustrated in Figure 6. It can be seen that the voltage value on each bus is still within the specified limit range, which ranges from 0.95 pu to 1.05 pu.

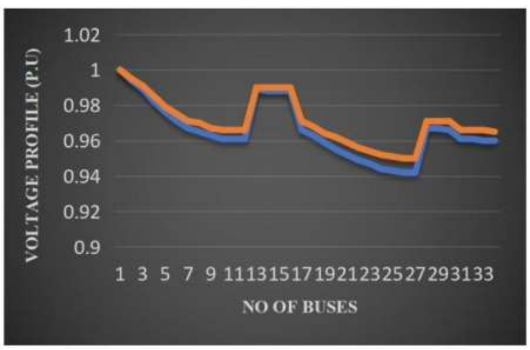

Figure 6. Voltage profile of each bus in IEEE 34 bus radial distribution system before and after capacitor allocation

6. CONCLUSION

In this study, the optimal sizing and siting of shunt capacitor in radial distribution system in order to minimize the total real power loss is introduced. The optimal allocation and size of shunt capacitor is determined using LSF approach and Search Pattern Optimization algorithm respectively. Even though gradient information is neither explicitly calculated nor approximate, this technique surprisingly produces global convergence outcomes comparable to those for line search and trust region globalization strategies.

This method is implemented on a standard test systems IEEE 34 bus radial distribution system. Simulations were carried out using MATLAB. From the experimental results, it is found that the determination of the optimal location and capacity of the capacitor can minimize the power losses in the system up to 26%, from 219 kW to 160 kW.

However, the unpredictability of the electricity network and uncertainty factors are not taken into account in this study. Further works related to capacitor allocation and sizing by accounting for uncertainty is necessary to be developed. As s result, the planning proccess in power system can be improved in the best and more realistic way possible their power systems.

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