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RESEARCH ARTICLE

A COMPARATIVE STUDY OF OPTIMIZATION TECHNIQUES FOR CAPACITOR LOCATION IN ELECTRICAL DISTRIBUTION SYSTEMS

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ABSTRACT

The location of capacitors to be installed in electrical distribution system is an optimization problem that needs immediate attention. In this paper, an overview of various approaches for solving problems of optimal location of capacitors in electrical distribution system is carried out. The objective functions and constraints of the problem are formulated. The total energy losses are minimized; the cost of energy losses are kept at minimum, the sum of energy loss cost and the investment cost required for the capacitor location are minimized. The cost due to energy loss cost, peak power loss and the investment cost of the capacitors are also minimized. The optimal solution for the power flow equation and bus voltage limits are obtained to limit the capacitor KVAr to be located. The various approaches for solving capacitor location problems are discussed and compared.
The Particle Swarm Optimization technique is the most popular of all the techniques due to its simple implementation and relatively smaller computation with a faster convergence even though; premature convergence of algorithm is the draw-back.
The accuracy of the results can be improved upon by combining two or more of the optimization techniques to locate capacitors in electrical distribution system.

INTRODUCTION

In electrical distribution system, a portion of power loss can be reduced by adding shunt capacitors in order to supply a part of the reactive power demand (Kannan *et al*, 2007, Chin and Lin 1994).There is also the need to decrease the losses associated with the reactive power flow through the branches in the distribution systems. Location of capacitors in electrical distribution systems is accompanied with benefits such as bus voltage regulation, power quality improvement, feeders and system capacity release, energy loss reduction and power factor correction (Schmil 2005, Song *et al* 1997, Kaplan 1994, Neg *et al* 2000). The location and control of capacitors under different loading conditions depict the extent of the advantages of the capacitor placement in distribution systems. In this case, the optimization problem needs to be formulated as well as the objective functions after which the solution approaches will be applied to determine optimal position to install the capacitors on electrical distribution systems(Wang *et al* 2010, Mekhamer *et al* 2002, Salama *et al* 1995, Baran and Wu 2009).

The power loss in a distribution system is significantly high because of lower voltage and hence high current compared to that in a high voltage transmission system. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level (Grainger and Lee 2011).

Reconfiguring the network can reduce the power loss in a distribution system. The reconfiguration process changes the path of power flow from the source to the loads. The loss can also be reduced by adding shunt capacitors to supply a part of the reactive power demands. Shunt capacitors not only reduce the loss but also improve the voltage profile, power factor and stability of the system (Salama *et al* 1995, Neg *et al* 2000).

The active power demands at all nodes and losses must be supplied by the source at the root node, as distribution system is mainly radial. However, addition of shunt capacitors can generate the reactive power and therefore it is not necessary to supply all reactive power demands and losses by the source. Thus, there is a possibility to minimize the loss associated with the reactive power flow through the branches (Schmil 2005).

Distribution system accounts for a major portion of power system losses. The power loss in a distribution system is significantly high because of lower voltage and hence high current, compared to that in a high voltage transmission system. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss,

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especially at the distribution level. The same technique can be applied to other types of feeders (Masoum *et al* 2004).

Capacitors are used widely to reduce the distribution system loss. In addition, shunt capacitors could also accommodate voltage regulation and VAR supply. For capacitor optimal location, general considerations include (Song *et al* 1997):

1. The number and location;
2. Type (fixed or switched);
3. The size;

When capacitors are placed, power loss is reduced and also energy loss is reduced. These factors contribute to increasing the profit. Cost of capacitors decreases this profit. So profit is weighted against the cost of capacitor installation. The whole saving can be given as follow:

$$S=K_p\Delta P+K_e\Delta E-K_C C \quad (1)$$

Where,

K_{P} = Per unit cost of peak power loss reduction($/KW)
K_E= Per unit cost of energy loss reduction ($/KWh)
K_C= Per unit cost of capacitor ($/KVAr)
Δ_p= Peak power loss reduction (KW)
ΔE= Energy loss reduction (KWh)
C= Capacitor size (KVAr
S= Saving in money per year ($/year)

The voltage constraint must be satisfied i.e voltage (pu) should be between min (0.9) to max (1.1).i.e.

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

Real Power Loss formulation (RPL)

If vi….. is the ith bus voltage and vj is jth bus voltage, then, the line current between ith and jth buses is given by (Sallam *et al* 1994):

$$I_{ij} = \frac{V_i - V_j}{Z_{ij}} \quad (3)$$

Where, Z_{ij} is the impedance between ith and jth buses, the transmission power between the ith and jth buses and vice versa can be expressed as (Kaplan 1994):

$$S_{ij} = V_i I^* V_{ij} \quad (4)$$

$$S_{ij} = V_i I^* V_{ji} \quad (5)$$

The real active loss between ith and jth buses is defined as:

$$S_{ij} = V_i I^* V_{ji} \quad (6)$$

Total loss power in power system is defined by (Eajal and El-Hawary 2010, Masoum *et al* 2004):

$$P_{Loss}^{Total} = \sum_{i=j}^{N} \sum_{j=i}^{N} P_{loss}^{i,j} \quad (7)$$

Where, N is the number buses of power system and the real power loss| is given by:

$$\text{RPL}= \frac{P_{Loss}^{Total}}{P_{Loss}^{nominal}} \quad (8)$$

Where, $P_{Loss}^{nominal}$ is the real power loss .

Voltage Profile Improvement (VPI)

One of the components of optimal location of capacitor banks is the improvement in voltage profile. This index penalizes the size-location pair which gives higher voltage deviations from the nominal value (Vnom). In this way, closer the index to zero better is the network performance (Santoso and Tan 2013, Grainger and Lee 2011).

MATERIALS AND METHOD

i. Formulation of the objective functions for the capacitor location problem.

This is given as:

$$\text{MinF}= \sum_{j=1}^{s} T^j P_L^j \quad (9)$$

$$\text{MinF}= \sum_{j=1}^{s} K_e^j T^j P_L^j \quad (10)$$

$$\text{MinF}= \sum_{j=1}^{s} (K_e^j T^j P_L^j) + C_c \quad (11)$$

$$\text{MinF}= \sum_{j=1}^{s} (K_e^j T^j P_L^j) + C_c + K_p P_L^p \quad (12)$$

Where F = the value of the desired objective function

S = number of load levels
Tj = time duration for the j-th load level
P_L^j= power loss at the j-th level
k_e^j = per unit cost of energy loss at the j-th load level
C_C = investment cost of capacitor
K_P = per unit cost peak power loss
P_L^p = power loss at peak load level

From equations (9) to (12) above, the following sub-tasks were performed:

1. Minimization of the total energy losses.
2. Keeping the cost of energy losses at minimum.
3. Minimizing the sum of energy loss cost and the investment cost required for capacitor location.
4. Minimizing the total cost due to energy loss cost, peak power loss cost and the investment cost of the capacitors.

ii. Obtaining the optimal solution for the power flow equations and bus voltage limits.

Review of the capacitor location approaches

The capacitor location problems have been solved with a variety of techniques. Conventional analytical method is one of the methods recently used with some heuristics.

Algorithms based on heuristic programming have been emphasized ln recent times. The features of heuristics algorithms include robustness and lesser computational effects. Some of the approaches for optimal location of capacitor on distribution feeders are as fellows:

1. Ant colony optimization; The behaviours of real ants are imitated in this approach. Without using visual cues, real ants can take the shortest path from two sources to the nest. They are capable of adapting to changes in the environment. The ants establish the “Pheromone”. The pheromone is the material deposited by the ants, which serves as critical communication information among ants, thus guiding the determination of the nest movement.
2. Harmony search algorithm: This is a meta-heuristic optimization algorithm inspired by playing music. This algorithm deals with meta- heuristic analysis which combines races and randomness to imitate natural phenomena. The best harmony between components that are involved in the operation process for optimal solution is motivated by the operation of orchestra music. I n this case, optimization design variables can be assumed to be discrete in nature as a result of computational intelligence and random processes involved. Musical instruments can be played with some discrete musical notes determined by player experience and random processes in improvisation. Based on aesthetics standards, music players improve their experience while improvement in the design variables of computer memory is determined by the objective function.
3. Graph: A set of nodes connected by arcs is called a graph. A possible combination of capacitor sizes and locations determine each node for a given number of capacitors to be placed. A separate graph is used for each possible number of capacitors to be installed. The nodes of a graph is usually found by the search process to determine the optimal solution. The minimum value of the objective function is determined by a search process to locate the node in the graph with some minimum number of capacitors to be placed. The next graph is searched if the maximum number of capacitors to be installed is not reached and in this case, the number of capacitors to be placed is incremented. The process is then terminated with the addition of another capacitor which will increase the objective function.
4. Simulated Annealing: This approach has to do with annealing of metals or crystals, temperature that is controlled by cooling schedule at each iteration is employed by simulated annealing. The state converges to solution when the temperature cools down. The state moves freely to other state when the temperature increases and stops moving to other state at low temperature
5. Fuzzy Logic: A computational representation of heuristic knowledge about a particular problem is illustrated here. Solutions of control and optimization problems are some of the few application areas. Solving the problem using fuzzy logic involves identification of the main variables that have influence on the decision to be taken and quantify their values. The profile of this variable is established by a relationship function to express the degree of compatibility of each of them with information that is previously known. In this case, necessary actions are determined after the establishment of the rules. Rules are set up to find out the advantage of installing a capacitor bank in a particular bus. The fuzzy variables in this case are the bus voltages and the objective function values. They are a function of the bus that is accessed to verify the practicability of installing capacitor.
6. Genetic Algorithm: This is an optimization statistical method. The robustness feature of genetic algorithm makes it to have a flexible balance between efficiency and necessary features to survive in different environment. Coding is a main concept in genetic algorithm. It encodes problem parameters of variables and uses the code. The solution accuracy, range of parameter changes and the relation between variables determine the number of bits used for encoding procedure. String of bits in the encoded form of possible solutions of the problem constitutes chromosomes. Each set of genetic algorithm deals with the sets of chromosomes in the search spaces. To solve the problem of capacitor location, the chromosome is made up of n+1 bit of binary numbers where n is the number of probable capacitor location. The capacitor is usually located by the first bit and it is called location selector. The length of location selector bit is equal to the number of probable locations of capacitor and each location is represented by bit of the string. In the bit position, a 1(one) is used to select a location and a 0(zero) bit implies non selection of the locations. The KVAr bit for a particular location may have a non zero value when the selection bit for that location in the location selector bit is zero. The KVAr bit in this case is ignored and determines the fitness function value of the chromosome.
7. Particle Swarm Optimization: This is a meta-heuristic parallel search approach. The iteration of particles in swarm, using common evolutionary computation algorithm guide the direction of swarm towards the optimal region of several space. Some of the advantages of particle swarm optimization are: computational efficiency, simplicity in concept and implementation, less computation time and inexpensive memory for computer resources.
8. Tabu Search: This is used for solving a combinatorial optimization problem and it is a meta- heuristic method. It is a hill- climbing method that evaluates the final solution through repeating the process of creating solution in the neighbourhood around the initial solution and selecting the best solution in them. Tabu search is an extension of the hill- climbing method since it has the adaptive memory called the tabu lists which are just some attributes in order not to change. A new attribute that enters into the tabu list stays in the tabu list for a while. There after, the oldest attribute is released from the tabu list as soon as a new attribute enters into the tabu list. A new attributes is also assigned to the tabu list each time the iteration count is updated. Tabu search

employs intensification and diversification methods to obtain optimal solution. The solution structure has a frequency counter which is used in the intensification or diversification approach. Whenever the frequency counter is less than three times the frequency counter threshold, then there is possibility of intensifying the search in the neighbourhood of the sub – optimal region. Tabu search in this case now finds an optimal solution to the combinatorial optimization problem.

9. Analytical optimization technique: This technique involves computation of minimum losses and cost savings with the assumption that the distribution feeders do not have any sub-branch. The 2/3 rule is a peculiar feature of this method.
10. Plant Growth Simulation Algorithm: Plant growth process is the oasis upon which this technique rests. In this method, the trunk of a plant grows from its root, some branches will grow from the nodes and some new branches will grow from the nodes on the branches. The process continues until a plant is formed.
11. Body immune algorithm: This technique imitates the behaviour of human body against the external invasions. It is a computational tool in pattern recognition. It considers the objective function while satisfying the constraints.

(Hybrid Artificial Intelligence Technique: This is a four-stage approach involving the simulated annealing, genetic algorithm, Tabu-search and the hybrid genetic algorithm-fuzzy logic algorithm for solving a combinatorial optimization problem with a non-differential function.

Comparative study of the optimization techniques

The most popular method is Particle Swarm Optimization technique. This technique is simple to implement, the computation load is relatively smaller with a faster convergence. Most difficult problems are easily solved with this method. Premature convergence of algorithm is found to be a draw-back to this approach

The genetic algorithm optimization technique is next to particle swarm optimization technique in term of popularity even though its divergence nature makes it a disadvantage during application. Fuzzy approach is employed in Hybrid optimization technique to find capacitor location while appropriate sizes of capacitors are found using genetic algorithm, Tabu search, Harmony search algorithm and Simulated annealing.

CONCLUSION

A comparative study of optimization techniques for capacitor location on electrical distribution system has been presented.
The optimal location of capacitors on electrical distribution systems is a challenging task as a result of its combinatorial nature. Technical and functional objective functions were formulated for an optimal location of capacitors. The total energy losses, cost of energy losses, sum of energy loss cost and the investment cost required for capacitor location were minimized to obtain the optimal solution for the power flow equation and bus voltage limits.

The analytical optimization technique is very simple to implement, even though, its convergence is relatively poor with a slow computation. The convergence of Heuristic technique is fast. Large and complex networks are easily solved using these optimization techniques. A high level of result accuracy can be achieved by combining two or more of the aforementioned techniques.

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