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A Comprehensive Study of Optimal Capacitor Placement in Radial Distribution System

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Abstract: This paper presents a novel approach that determines the optimal location and size of capacitors on radial distribution systems to improve voltage profile and reduce the active power loss. Capacitor placement & sizing are done by Loss Sensitivity Factors and Differential Evolution respectively. Loss Sensitivity Factors offer the important information about the sequence of potential nodes for capacitor placement. These factors are determined using single base case load flow study. Differential Evolution is well applied and found to be very effective in Radial Distribution Systems for capacitor placement.

Keywords: optimal, placement, radial, distribution system, approach.

I. INTRODUCTION

Shunt capacitors are used extensively for reactive power compensation to maintain voltage profile in a distribution system. The reactive power supplied by capacitor provides several benefits i.e. power loss reduction, voltage-profile improvement and power factor correction. The term reactive power compensation corresponds to compensate the lagging reactive current of the power system by supplying leading reactive current to the power system. This leading reactive power is supplied by shunt capacitors to the power system. The pioneers of optimal capacitor placement, Neagle and Samson [1] used analytical approaches for capacitor placement. They gave two-third rule for capacitor placement. The two-third rule says that for maximum loss reduction capacitor should be installed at a position two thirds of the distance along the total feeder length. The method was based on assumption of a feeder with a uniformly distributed load. Thats the reason why Loss Sensitivity Factor method is used for capacitor placement in this paper as the model taken in the paper is not having a uniformly distributed load.

The radial type system is the most commonly used one for power distribution [1-6], yet when something does go wrong in the system, an instantaneous blackout may occur. In order to satisfy the high expectations of the high-tech industry for a reliable power supply system, we pay greater attention to the use of a loop distribution system. This system not only improves reliability and service quality of the power supply, but also entails less power loss than occurs with the radial type. At present, Taiwan Power Company has been actively promoting the use of the loop type distribution system to satisfy the demand of users in general, and those in high-tech industry, in particular, for reliable power supply, and to prevent the occurrence of instantaneous blackouts caused by maintenance, switching operation, and single incidents of the distribution system.

The loss minimization in distribution systems has assumed greater significance recently since the trend towards distribution automation will require the most efficient operating scenario for economic viability variations. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level. To reduce these losses, shunt capacitor banks are installed on distribution primary feeders. The advantages with the addition of shunt capacitors banks are to improve the power factor, feeder voltage profile, Power loss reduction and increases available capacity of feeders. Therefore it is important to find optimal location and sizes of capacitors in the system to achieve the above mentioned objectives. Since, the optimal capacitor placement is a complicated combinatorial optimization problem, many different optimization techniques and algorithms have been proposed in the past. Schmill [2] developed a basic theory of optimal capacitor placement. He presented his well-known 2/3 rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder.

The capacitor placement problem is a well-researched topic. Earlier approaches differ in problem formulation and the solution methods. In some approaches, the objective function is considered as an unconstrained problem. Some have formulated the problem as constrained optimization and included voltage constraints into consideration.

The objectives for determination of capacitor sizing consist of two important terms, which are reduction of power losses and reduction of capacitor purchasing cost. These objectives conflict with each other in the sense that any improvement in one objective results into the decrement of the other objective. The aim of this problem is to find a compromise between the objectives for the satisfying solution of the problem. Optimization problem is solved by the goal-attainment method in this paper. Two types of capacitors are usually considered: fixed and switched capacitor banks. Fixed banks are operating on the feeder all the time. In this paper, fixed capacitor banks are taken into account, optimal placement is determined using Loss Sensitivity Factors method, sizing is determined using Goal Attainment method with the help of MatLab and load flow is carried out in MiPower [3] software.

LOAD FLOW ALGORITHM

Comparing with transmission systems, distribution systems usually have two characteristics: radial construction and high ratio of (r/x) [4]. Above characteristics attribute the incomplete network to distribution systems. This problem causes not to use usual transmission systems load flow algorithm for distribution systems. If these algorithms are used for distribution systems, load flow will be diverged. So, it's necessary to use another load flow algorithm like forward-backward that is appropriate for this study.

Forward-Backward Algorithm

The forward-backward algorithm uses Kirchhoff's Laws. Figure 1 shows a distribution systems consist of n nodes with n-1 branches and one voltage source in root node. In this tree construction, for proposed branch of L, L1 and L2 are named for nodes that is near and far from root node respectively. Branches in every layer are numbered with respect to getting far from root node.

Forward-Backward Algorithm

Solution With the given voltage magnitude and phase angle at the root and known system load information, voltage of all buses is considered equal to voltage of root node. The power flow algorithm needs to determine the voltages at all other buses and currents in each branch.

II. LITERATURE REVIEW

Some of the recent publications have taken into account the presence of distorted voltages for solving the capacitor sizing problem. These investigations include: exhaustive search, local variations, mixed integer-nonlinear programming heuristic methods for simultaneous capacitor and filter placement maximum sensitivities selection and fuzzy set theory genetic Algorithm [5], partial swarm optimization. All above publications have discussed on radial networks, the present paper GA employed to determine the optimal sizing of fixed capacitor banks in an interconnected distribution network with non sinusoidal substation voltages, Commercial package ETAP Power Station program is used for harmonic load flow analysis.

H. Ng et al (2000) proposed the capacitor placement problem by using fuzzy approximate reasoning. Sundharajan and Pahwa (1994) proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. Ji-Pyng Chiou et al (2006) proposed the variable scale hybrid differential evolution algorithm for the capacitor placement in distribution system. Both Grainger et al (1981) and Baghzouz and Ertem (1990) proposed the concept that the size of capacitor banks was considered as a continuous variable. Bala et al (1995) presented a sensitivity-based method to solve the optimal capacitor placement problem.

In this paper a new method is proposed to find the optimal and simultaneous place and capacity of these resources to reduce losses, improve voltage profile. The artificial bee colony algorithm is a new meta heuristic approach, proposed by Karaboga [6]. It is inspired by the intelligent foraging behavior of honey bee swarm.

Schmill developed a basic theory of optimal capacitor placement. He presented his well known 2/3 rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder. Duran et al considered the capacitor sizes as discrete variables and employed dynamic programming to solve the problem. Grainger and Lee developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables. Grainger et al [7] formulated the capacitor placement and voltage regulators problem and proposed decoupled solution methodology for general distribution system. Baran and Wu [6, 7] presented a method with mixed integer programming. Sundharajan and Pahwa [8], proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. In most of the methods mentioned above, the capacitors are often assumed as continuous variables. However, the commercially available capacitors are discrete. Selecting integer capacitor sizes closest to the optimal values found by the continuous variable approach may not guarantee an optimal solution [9].

Chin uses a fuzzy dynamic programming model to express real power loss, voltage deviation, and harmonic distortion in fuzzy set notation. Sundharajan and Pahwa used genetic algorithm for capacitor placement. Simulated Annealing [10], Tabu Search [11], Ant colony optimization [12] and Particle Swarm Optimization searches are used for optimal capacitor placement problems. Salem Arif and Abdelhafid Hellal [13] have also used various meta- heuristic techniques for reactive power optimization problem.

III. METHODOLOGY FOR OPTIMAL LOCATION OF CAPACITOR

Works A methodology named Loss Sensitivity Factors (LSF) is used to determine candidate nodes for the placement of capacitors. The estimation of the potential nodes from this method reduces the search space for optimization [14]. Power losses for each node can be found by Eq. (2) and from that LSF can be determined. LSF can be obtained as shown in below Eq..

$$\frac{\partial P_{lineloss}}{\partial Q[q]} = \frac{(2 * [Q[q] * [R_k])}{V[q]^2}$$

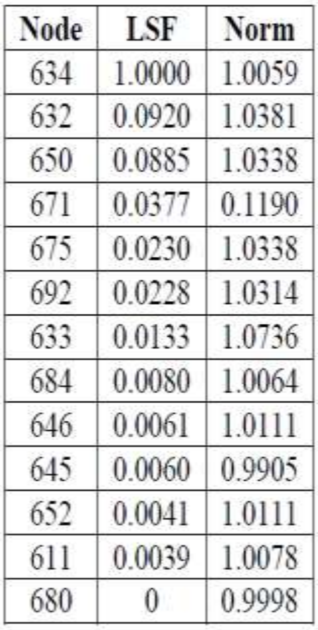
Eq. (2) represents total line loss of the particular node. LSF for all the nodes can be calculated from above Eq..The LSF *(∂Plineloss/∂Q)* are calculated for each node from load flows and they are normalized in the range of 0-1. The obtained values are arranged in descending order for all lines of the distribution system. The descending order of *(∂Plineloss/∂Q)* will decide the sequence in which the buses are to be considered for compensation. This sequence is exclusively governed by the *(∂Plineloss/∂Q)* and hence the proposed method is called as Loss Sensitivity Factors‟ method. In this way, it is useful for determining the potential locations for capacitor placement.

At these buses, normalized voltage‟ magnitudes are calculated by considering the base voltage given by (Norm‟= V(p.u.)/0.95). V(p.u.) represents per unit voltage magnitude. Buses whose Norm value is < 1.01 are considered as buses requiring the capacitor placement. If Norm value for the bus is >1.01, such bus needs no reactive power compensation. Table I represents LSF and Norm values for the IEEE 13 Node Test Feeder with standard data. Table II shows LSF and Norm values for IEEE 13 Node Test Feeder with 0.7 power factor data. Loss Sensitivity factors value helps to decide the sequence in which buses are to be considered for compensation placement and the Norm decides whether the buses needs reactive power compensation or not [15]. From Table I, it can be seen that for the IEEE 13 Node Test Feeder with standard data, node to be considered for the placement of capacitor is {675} and for IEEE 13 Node Test Feeder with 0.7 power factor data, nodes to be considered for the placement of capacitors are {634,671,684,645,611} as shown in Table II.

Table I : LSF & Norm Values for IEEE 13 Node Test Feeder with Standard Data

Node	LSF	Norm
632	1.0000	1.0439
650	0.9725	1.0736
671	0.4053	1.0216
675	0.2457	1.0046
692	0.2441	1.0122
633	0.1444	1.0401
634	0.1443	1.0385
684	0.0858	1.0189
646	0.0657	1.0382
645	0.0655	1.0402
652	0.0446	1.0177
611	0.0415	1.0175
680	0	1.1058

Table II: LSF & Norm Values for IEEE 13 Node Test Feeder with 0.7 Power Factor Data



Node	LSF	Norm
634	1.0000	1.0059
632	0.0920	1.0381
650	0.0885	1.0338
671	0.0377	0.1190
675	0.0230	1.0338
692	0.0228	1.0314
633	0.0133	1.0736
684	0.0080	1.0064
646	0.0061	1.0111
645	0.0060	0.9905
652	0.0041	1.0111
611	0.0039	1.0078
680	0	0.9998

IV. METHOD FOR OPTIMAL SIZING OF CAPACITOR

Many methods of Gembickia are used to determine capacitor sizing. It involves expressing design goals i.e. {F*= F1*, F2*} which is associated with objectives i.e. {F(x) = F1(x), F2(x)}.The problem formulation allows the objectives to be under or over achieved with respect to initial design goals. A vector of weights i.e. {w = w1, w2} where wi > 0 controls the degree of over or under achievement of the goals. The method is expressed as an optimization problem by the following formulation [16]:

minimize γ
wrt x
such that

$$F_i(x) - w_i\gamma \leq F_i^* \qquad i = 1, \ldots, m$$

The term *wi* γ introduces an element of slackness into the problem, which otherwise imposes that the goals must be solidly met. The vector of weights *w* makes designer (i.e. distribution utility) to express a measure of the relative trade-offs between the objectives. A set of goals that a designer (i.e. distribution utility) wishes to achieve for each objective function can be fixed. Eq. (7) shows that the method reduces the difference between the solution and the goal [17-22].

Node Selection using Loss Sensitivity Factors

The loss sensitivity factors PQ line loss eff ∂ are calculated using the base case load flows and Equation (5). The values are arranged in descending order for all the lines of the given system. A vector bus position is used to store the respective ‘end’ buses of the lines arranged in descending order of the values. The descending order of elements vector will decide the sequence in which the buses are to be considered for compensation. At these buses, 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 [23]. 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 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 [24-25].

CONCLUSION

Previous literature has shown that the study of reactive power compensation in the distribution system mostly focuses on radial structure and this paper takes another perspective to address the effectiveness issue based on circuit with loop-type structure. At present, power systems use capacitors to reduce feeder loss, to improve bus voltage, and to achieve the ultimate goal of safety and quality of power supply. In addition to system loss, economic factors such as the installation cost of the capacitor, are also taken into consideration and would be beneficial to future studies of the distribution system.

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