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Comprehensive framework for capacitor placement in distribution networks from the perspective of distribution system management in a restructured environment

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ABSTRACT

This paper presents a new and comprehensive Objective Function (OF) for capacitor placement in distribution networks. In this study, distribution network management's viewpoint toward identifying comprehensive OF to maximize the benefit of a distribution company is considered. In addition to considering active power loss cost and capacitor cost, two other important terms, i.e. cost of buying reactive power and voltage drop penalty for maximizing the benefit of distribution companies are considered in the OF. All actual conditions including time varying nature of load, annual load growth, time varying price of active and reactive power, and switchable and fixed capacitor are taken into account based on the reality. The profit derived from the proposed OF is compared with two other common OFs, and it is shown that the benefit achieved from the proposed OF is more than the two other OFs. The proposed OF is validated and tested on radial distribution systems with differing topologies and varying sizes and complexities.

Introduction

Capacitor banks are widely used in power systems to reduce power losses, compensate reactive power, improve voltage profile, increase system capacity, and correct power factor. Capacitor placement can be beneficial only when it correctly applied. Correct application means choosing the correct position and size of the reactive power support.

It is generally accepted that most of the power losses occur on the distribution systems [1]. The reactive power is responsible for large portion of these losses. A part of these losses can be reduced by application of shunt capacitors on distribution systems.

The first capacitor placement studies were carried out to minimize the active loss, and after which the famous two-thirds rule was defined for uniform loads [2]. Many studies have been done to solve capacitor placement with different simplified assumption. For example, the time varying nature of the loads was ignored in [3,4] and future network extension was not considered in [5,6].

Several formulations have been suggested for this problem, and they have been solved by different computational techniques. Ref. [7] included system capacity release, peak load reduction, and reduction of annual energy loss in their formulation and solved by genetic algorithm. Genetic algorithm is also used in [8] with two-stage method to discuss the problem of determining the optimal location by means of loss sensitivity technique and size of capacitors. Particle Swarm Optimization (PSO) is applied in [9] to solve discrete size of capacitor banks and variation of load during the year.

Ref. [10] adapted an objective function to maximize net yearly savings and to enhance the overall system static voltage stability index with weighting and magnifying factors. In [11], the objective function is determined to minify the system operating cost at different loading conditions and to enhance the system voltage profile by identifying higher potential buses for capacitor placement using power loss index. A combination of fuzzy multi-objective and genetic algorithm approach is proposed in [12] for optimal shunt capacitor placement to improve the substation power factor, reduce the real power loss, and reduce the burden on the substations.

Many researchers have focused on various types of heuristic optimization techniques to solve the optimal capacitor allocation problem such as tabu search [13], big bang–big crunch optimization [14], and backtracking search optimization algorithm [15]. In [16], bio-inspired optimization technique is applied to optimize

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the distribution network operation over a planning horizon by minimizing the system losses with minimum cost of investment in capacitors. Artificial bee colony is applied to allocate static capacitors along radial distribution systems [17]. Uncertainty in the variation of load is considered in [18]. Ref. [19] used sensitivity analysis to reduce search space and then used gravitational search algorithm to solve capacitor placement problems.

Different capacitor placement OFs are identified and suggested so far, and various kind of computational techniques are used to solve the problem, but optimal OF for capacitor placement from perspective of distribution company manager has not yet been proposed. Since distribution networks are under supervision of distribution company managers, they are responsible for design and implementation of any plan in networks, and intend to accomplish capacitor placement in a way that gives the maximum profit. In this study, this issue is viewed by manager of distribution networks. Distribution company relationships with other systems for obtaining an optimal OF, which gives maximum benefit, is identified. OFs which are currently used in the literature mostly consists of almost two terms i.e. active power cost and capacitor cost. In this study, new OF is identified and two terms i.e. reactive power cost and penalty of voltage drop are added to the common OFs of previous works.

Distribution networks should provide consumers with active and reactive power. If distribution systems satisfy reactive power by capacitor placement, they can save the money of reactive power that buy from power plants. Another important factor is that distribution network companies will be fined if they provide consumer with bad quality and low voltage electricity; therefor, two new terms are needed to be added to the previous OFs. This OF is proven in the following section.

The paper is organized as follows; Section ‘‘Problem definition” gives the distribution company relationships and proposed OF, Section ‘‘Power flow formulations and constraints” gives power flow formulations and its constrains. PSO algorithm and the proposed flowchart are presented in Section ‘‘Optimization method and flow chart”. Simulation results and discussion are given in Section ‘‘Test cases and numerical results”, and finally Section ‘‘Conclision” conclude the paper.

Problem definition

Capacitor placement objective function from the perspective of distribution system management

Governments implement some policies to increase the efficiency of the energy systems and improve quality of public service. One of these policies is related to distribution networks. The government obliges distribution companies to:

1. Enhance efficiency of the distribution systems.
2. Improve quality of distributed electricity to consumers.

There is an interconnection between distribution company, government, power plants, and consumers. Distribution companies purchase active and reactive power with price of K_p and K_q and sell it to consumers with price of K'_p and K'_q. To maximize distribution networks profit, managers of the distribution companies carried out capacitor placement studies on the distribution networks. Capacitor placement decreases network losses, which is in line with the government policy for enhancing the efficiency of distribution systems. In addition to the reduction of energy loss, capacitor placement reduces the input reactive power to the distribution networks. Governments consider some penalties for distribution company in case of any voltage drop or bad quality of power delivery to meet the second policy.

According to the Fig. 1, Benefit of Distribution Company (BDC) is the difference between buy and sale of energy, cost of capacitor placement ($Cost_{Cap.}$) and penalties caused by the voltage drop ($Cost_{Pen.}$), and defined as follows:

$$BDC = F_{Sale} - F_{Buy} - Cost_{Cap.} - Cost_{Pen.} \tag{1}$$

Fig. 1 shows the relationship between a distribution company, government, power plants and consumers.

In Fig. 1, K_p/K_q are purchase price of active/reactive power and K'_p/K'_q are sale price of active/reactive power. F_{Buy} is buy function and F_{Sale} is sale function of active and reactive power, and are defined as follow:

$$F_{Buy} = K_pP_{in} + K_qQ_{in} \tag{2}$$

$$F_{Sale} = K'_pP_{out} + K'_qQ_{out} \tag{3}$$

P_{in} and Q_{in} are as follow:

$$P_{in} = P_{out} + P_{loss} \tag{4}$$

$$Q_{in} = Q_{out} + Q_{loss} + Q_{compensation} \tag{5}$$

P_{out} and Q_{out} are consumed by consumers. To reduce purchase cost of distribution company, the values of P_{in} and Q_{in} should be decreased. But the values of P_{out} and Q_{out} are demanded by consumers, and depend on consumption management policies and government incentive policies, and distribution network managers consider it as constant value. But the reduction of P_{loss} and optimized value of $Q_{loss} + Q_{compensation}$ can be fulfilled by capacitor placement.

Benefit derived from capacitor placement

The benefit of distribution company before and after capacitor placement is as follows:

$$BDC_{Before} = F_{Sale,1} - F_{Buy,1} - Cost_{Pen.,1} \tag{6}$$

$$BDC_{After} = F_{Sale,2} - F_{Buy,2} - Cost_{Cap.} - Cost_{Pen.,2} \tag{7}$$

Before capacitor placement there is no capacitor placement cost; therefor, $Cost_{Cap.}$ is ignored in BDC_{Before}. Output power of distribution system depends on consumer, and considered as constant value; therefore, the sale of power does not change with capacitor placement.

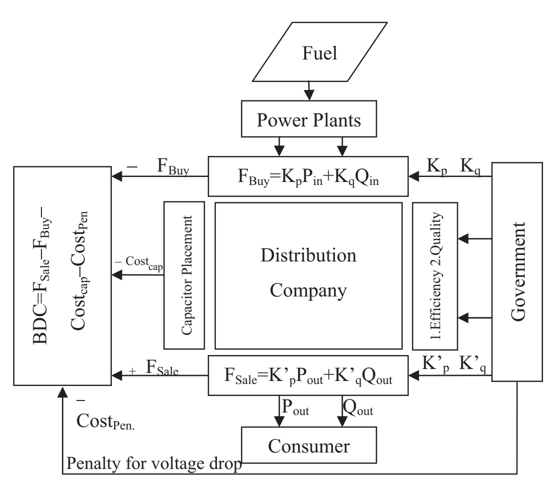

Fig. 1. The relationships of distribution company.