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A fuzzy-based approach for optimal allocation and sizing of capacitor banks

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ABSTRACT

This paper proposes a fuzzy set optimization approach for capacitor allocation in radial distribution system. In this approach, a membership function for voltage profile constraint has been used. Moreover, another membership function incorporating feeder section active power losses and total power losses constraints has been proposed. This membership function indirectly imposes thermal capability of the feeder on the optimization process. The proposed approach has been applied to 9-bus and 34-bus radial distribution systems. The results have been compared with those of two fuzzy approaches in literature. The comparison showed the effectiveness of the proposed approach for optimizing the sizes and locations of the capacitor with running and total cost reduction.

1. Introduction

Electric power system networks are typically composed of four major parts: generation, transmission, distribution and loads. Distribution networks are crucial elements in electric power systems since they link the generated power to the end user. Transmission and distribution networks share similar functionality; i.e. both transfer electric energy at different levels from one point to another; however, their network topologies and characteristics are quite different.

Distribution networks are well-known for their high *R*/*X* ratio and significant voltage drop that could cause substantial power losses along the feeders. It is estimated that as much as 13% of the total power generation is lost in the distribution networks [1]. Portion of this loss is caused by the reactive current flowing in the network. Voltage profiles throughout the network have to be kept at acceptable levels to ensure service reliability among other issues. Capacitor banks are commonly used in various parts of the electric grid to maintain voltage levels within appropriate limits, minimize the power losses and release the line capacity. With regard to the power losses in the feeders, capacitor installations have demonstrated their effectiveness in reducing the overall current by canceling part of the reactive current supplied by the substation.

Capacitor installations have proven their economical impact by significantly reducing the power losses and releasing line capacity. Published literature describing capacitor allocation algorithms are abundant. Grainger et al. pioneered the analytical methods [2].

In Ref. [2], fixed and switched capacitors are placed for optimizing the net monetary savings associated with the reduction of power and energy losses. Both the capacitor locations and sizes are treated as continuous variables. A new voltage dependent methodology for shunt capacitor compensation of primary distribution feeders is presented in Ref. [3]. Ponnavaikko et al. [4] used a numerical method called the method of local variations and further expanded the problem to include the effects of load growth, and switched capacitors for varying load.

Similarly, Baran et al. [5] formulated the capacitor placement problem using mixed integer programming. The optimal selection and placement of capacitor banks using binary particle swarm optimization (PSO) is integrated with the estimation of harmonic levels in Ref. [6]. Methods based on heuristic search techniques are introduced for distribution system loss reduction by reconfiguration [7,8]. Abdel-Salam et al. [9] proposed a heuristic technique based on the ideas from [7,8] to identify a section in the distribution system, with the highest losses due to reactive load currents, then pinpoint the sensitive node in that section having the greatest effect on the system loss reduction. Sizes of capacitors placed on the sensitive nodes are determined by maximizing the power loss reduction from capacitor compensation. Chis et al. [10] improved the work of [9] by determining the sensitive nodes that have the greatest impact on loss reduction for the entire distribution system directly, by optimizing the capacitor sizes based on maximizing the net economic savings from both energy and peak power loss reductions.

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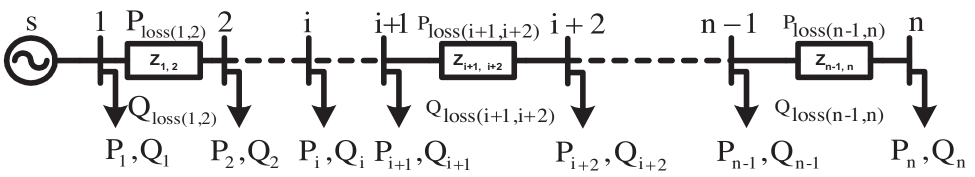

Fig. 1. A single line diagram of a radial distribution (*i*) feeder.

In addition, the method in [10] also accounts for varying loads of the distribution system considered. Hamada et al. [11] introduced a new strategy for capacitor allocation handling the reduction in the section losses by adding a new constraint to the well-known constraint (allowed voltage violation constraint). The new constraint is the sectional ohmic losses in each branch of the feeder. Ref. [12] presents a fuzzy-based approach for capacitor placement for the 9-bus feeder. Two membership functions for total real power losses and voltage sensitivity have been defined to reduce the effort of finding the optimal locations. The whole problem has been presented as a fuzzy-set optimization problem to minimize the total real losses and capacitor cost with voltage limit constraints. They used the intersection principle in fuzzy as the fuzzy decision to find the capacitor location, then a variational method has been used to find capacitor sizes to attain minimum cost without violating the voltage constraints.

In Ref. [13], exactly the same procedures using the same feeder have been implemented, but with two different membership functions. In fact, their membership functions for real power losses and voltage are the fundamental part of the membership functions that have been used in [12]. However, they have relatively achieved better results by introducing a certain constant in the real losses membership function depending on their experiences. In [14], the authors used membership functions forms of [12], but replaced the real losses by reactive losses and the intersection decision (using min operator) by product decision. They used the product fuzzy decision to determine the location of the capacitors. To find the capacitor sizes, they used their analytical method that has been explained in [15]. This analytical method is based on differentiating a well-defined net saving function of power and energy losses with respect to capacitor size, thus obtaining the optimum capacitor size. Their method has been applied on the 34-bus feeder [15].

Ref. [16] presented fast power loss computation using supervisory control and data acquisition system (SCADA), which a fuzzy-based decision maker used to compute the suitable shunt capacitor required to improve the power factor according to the measured parameters. Most of these studies consider the loss reduction for the capacitor allocation problem, but these studies take in consideration the reduction of total losses not the reduction in the individual sectional losses. The general capacitor placement problem in distribution feeders consists of determining the optimal location, type (fixed or switched), and size of capacitors; such that power and energy losses are minimized while taking the cost of the capacitor into account. For simplifying the problem fixed capacitors are only considered in this paper.

This paper presents a fuzzy-based approach for capacitor allocation in radial distribution systems. Two membership functions are defined in this paper, one for the voltage sensitivity and another proposed one for the real sectional ohmic loss constraint. This constraint has been initially introduced by the authors in a previous published paper, Ref. [11]. The problem is formulated as a fuzzy-set optimization problem to minimize the real power loss and capacitor cost with sectional loss and voltage limit constraints. Moreover, this paper presents a comparison between the proposed approach and previous works to show the validity of the proposed approach.

2. Problem formulation

The purpose of placing compensating capacitors along the distribution feeders is to lower the total power loss and bring the bus voltages within specified limits while minimizing the total power cost. The total power loss P_{Tloss} is given by

$$P_{Tloss} = \sum_{i=1}^{n-1} P_{loss(i,i+1)} \quad i = 1, 2, \ldots, n \tag{1}$$

where, i is the bus number and n is the total number of buses as shown in Fig. 1. Considering investment cost, there is a finite number of standard capacitor sizes that are integer multiples of Q_0^c. The cost per kVAr varies from one size to another. Generally, large capacitor sizes are cheaper than smaller ones. The available capacitor size is usually limited to [13]:

$$Q_{\max}^c = L \times Q_0^c \tag{2}$$

where Q_0^c is the smallest capacitor size in Table A1 and L is an integer. Therefore for each installation location, there are L capacitor sizes $\left\{Q_0^c, 2Q_0^c, \ldots, LQ_0c\right\}$ to choose from. Let $\left\{K_1^c, K_2^c, \ldots, K_L^c\right\}$ be their corresponding equivalent annual cost per kVAr. The objective (*Cost*) function can be expressed as

$$Cost = C_p \times P_{Tloss} + \sum_{j=1}^{J} K_j^c Q_j^c \tag{3}$$

where C_p is the cost per power loss ($/kW) [13] and j = 1,2,...,j represents the selected buses for compensation. The objective function Eq. (3) is to be minimized subjected to two constraints:

The *first constraint* is the bus voltage constraint.

$$V_{\min} \le V_i \le V_{\max}, \quad i = 1, 2, \ldots, n \tag{4}$$

The *second constraint* is the sectional ohmic loss constraint (proposed in the author's previously published paper).

$$P_{Sec,loss}^{(K+1)} \le P_{Sec.loss}^{(K)} \tag{5}$$

where (K + 1) is the case after the capacitor placement and (K) is the case before the capacitor placement.

3. Application of fuzzy set theory

In the conventional methods, the large number of combinations in the solution space makes the solution searching process time consuming. The problem is formulated as a fuzzy reasoning optimization model to minimize the cost and power loss subjected to voltage limit and sectional losses constraints. Minimum operation of fuzzy sets is employed to find the optimal locations and sizes of capacitors.

3.1. The proposed method

Two membership functions are defined in this method, one for the voltage sensitivity and another for the active sectional ohmic loss. This method suggests a new membership function for the