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Optimal unbalanced capacitor placement in distribution systems for voltage control and energy losses minimization

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ABSTRACT

This paper describes an allocation methodology for capacitor placement in unbalanced distribution systems to achieve loss minimization with an adequate voltage profile. Switched capacitor banks and/or fixed banks can be allocated on a per-phase or multi-phase, discrete basis, and this allows consideration of the actual unbalanced characteristics of distribution systems. While most methods available in the literature address some specific network loading conditions, e.g. average, light-load or heavy-load, the proposed algorithm is based on the daily load variation curve. The method consists of two main steps: (*i*) reactive power demand calculation to achieve loss minimization; (*ii*) discrete capacitor placement. The method is applied on the IEEE 4-bus, IEEE 123-bus and IEEE NEV Test Feeders as well as on an 85-bus feeder. Several alternative allocations are calculated and comparisons with results available in the literature are presented.

1. Introduction

Capacitor placement in distribution systems (DS) has been a much studied subject. In spite of the progress obtained through the numerous contributions in the literature, a sufficiently general methodology that can cope with the inherent DS characteristics and multiple operational aspects has not yet been developed.

There are many well known advantages arising from the connection of capacitors to DS, voltage control being possibly the most important [1,2]. Other beneficial consequences are loss reduction [3,4], voltage security [5], operational flexibility with switched capacitors [6], mitigation of voltage unbalances [7], power factor correction [8], filters [9] and increased reliability [10]. Even though voltage control can be effectively achieved using voltage regulators, capacitor banks require less capital and operational costs.

The computational challenges of capacitor placement in DS stem from several aspects of the problem, including: (*i*) the exponential increase of the search space with the system dimension due to the combinatorial nature of the problem; (*ii*) the need to rely on discrete variables to express capacitor sizes; (*iii*) the presence of non-linear constraints and, (*iv*) the actual modeling of the DS network including the load conditions.

Several researchers have proposed different approaches to find optimal solutions. A mixed integer, nonlinear programming methodology (MINLP) was described by Nojavan et al. in Ref. [11] but convergence difficulties arise for large DS.

Heuristics and Evolutionary algorithms were proposed in Refs. [12–22]. Although global optimum solutions are not ensured due to the very large search space, good results have been reported: in Ref. [12] a two-stage method for capacitor placement is proposed; the first stage consists of a GA to find neighborhoods of high quality solutions and the second stage consists of a sensitivity-based heuristic method tailored for capacitor placement. Ref. [13] describes an approach to shunt capacitor placement on distribution systems. The optimum capacitor allocation solution is found for several feeders connected to a substation transformer and not for any individual feeder. Ref. [14] presents an approach to feeder reconfiguration and capacitor placement for power-loss reduction and voltage profile enhancement in distribution systems using simulated annealing technique. In Ref. [15] a hybrid approach to determine the location, size, and number of capacitors to improve voltage profile and minimize power losses in unbalanced distribution systems is described; the proposed method was compared with several methods using GA. In Ref. [16] operating costs were considered. In Ref. [17] a network reconfiguration and capaci-

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tor placement procedure is presented where the reconfiguration method is based on a simple branch exchange method and a discrete genetic algorithm is used to optimize the location and size of capacitors. A single-objective probabilistic method based on the use of a micro-genetic algorithm is proposed in Ref. [18] to reduce the computational effort. In Ref. [19] a direct search algorithm was applied. In Ref. [20] a teaching-learning algorithm was used. A gravitational search algorithm for capacitor placement in radial systems is proposed in Ref. [21] and in Ref. [22] both fixed and switched-capacitor banks were allocated using an ant colony algorithm.

While most of the studies above have adopted positive-sequence network models, in recent years some authors have used three-phase representations to obtain more realistic results. Losses and harmonic distortion mitigation were incorporated in the objective functions in Ref. [23]. Estimations of the distances from the monitoring location to switched-capacitor banks were examined in Ref. [24]. Evolutionary techniques were proposed to address capacitor placement in unbalanced DS [25]. The reduction of voltage unbalances using the interior point method was proposed in Ref. [7]. The daily load demand variations were considered in Refs. [26,27], particle swarm optimization was applied to allocate delta-connected switched-capacitor banks in unbalanced DS.

This paper describes a method to solve for the capacitor placement problem in unbalanced DS to achieve voltage control and loss minimization. Switched capacitor banks and/or fixed banks may be allocated on a per-phase or multi-phase, discrete basis, and this allows consideration of the actual unbalanced characteristics of distribution systems. The actual daily load curve of the DS is also considered.

The proposed method is based on a two-layer optimization approach. In the first layer, Module I, a Multiphase Optimal Power Flow (MOPF) algorithm is applied to calculate the optimal reactive power demand to ensure that all bus voltages are within the specified limits. This MOPF algorithm adopts a complete multiphase DS model as described in Refs. [7,28]. Voltage regulators are also incorporated in the model. In the second layer, Module II, a genetic algorithm is constructed to determine the discrete capacitor values, including the switched-on values when this kind of equipment is to be commissioned using the N-phase Current Injection Method (NCIM) [29] algorithm (please refer to Appendix A for a brief description of NCIM). The methodology is applied on the IEEE 4-bus, IEEE 123-bus, IEEE-NEV Test Feeders as well as on an 85-bus feeder. Several alternative allocations are calculated and comparisons with results available in the literature are presented.

It is important to highlight that unbalanced capacitor placement in DS including voltage regulator control actions [30] have not been addressed in the literature and is regarded as one of the main contributions of the present research work.

2. Proposed capacitor placement algorithm

2.1. Formulation

The optimization problem is expressed by Eqs. (1)–(5). The objective function (1) aims to minimize the DS operational cost of losses, taking into consideration loading variations, and the capital cost of the capacitors:

$$\min\ C_{cap} + \sum_{y=1}^{n} \frac{CE_y}{(1+r)^y} \tag{1}$$

s.t.

$$\begin{aligned} &\mathbf{I}_{Re}^{i}\left(\mathbf{V}_{Re}, \mathbf{V}_{Im}, \mathbf{Q}_{cap}^{fixed}, \mathbf{k}_i\mathbf{Q}_{cap}^{switch}\right) = 0 \\ &\mathbf{I}_{Im}^{i}\left(\mathbf{V}_{Re}, \mathbf{V}_{Im}, \mathbf{Q}_{cap}^{fixed}, \mathbf{k}_i\mathbf{Q}_{cap}^{switch}\right) = 0 \end{aligned} \tag{2}$$

$$\mathbf{V}_{\min}^{i} \le \mathbf{V}^{i} \le \mathbf{V}_{\max}^{i} \tag{3}$$

$$\mathbf{Q}_{cap}^{fixed}, \mathbf{Q}_{cap}^{switch} \in \left\{0, Q_1, \ldots Q_n\right\} \tag{4}$$

$$\mathbf{k}_i \in [01] \tag{5}$$

where,

C_{cap} is the capital cost of the capacitor banks in the DS;

CE_y is given by Eq. (6) which reflects the savings in the cost of the losses in the DS, as result of capacitor placement, for each year of operation. A negative value of CE_y will mean that losses have been reduced as result of capacitor placement.

$$CE_y = \sum_{i \in \Omega_s} C_{loss}\left(Loss_i - Loss_{base,i}\right)\Delta t_i \tag{6}$$

y defines the year of operation;

i identifies the load level;

Ω_s is the set of loading conditions that will be included in the optimization study;

C_{loss} is the cost of the losses (a constant value was adopted);

$Loss_i$ is the active power losses for a given load condition i;

$Loss_{base,i}$ is the active power losses of the base case for a given load condition i;

Δt_i is the time interval during which load level i applies during year y;

r is the return ratio;

n is the number of years considered in the study.

It is seen that the sum in Eq. (1) is the present value of the losses (PVL) and that the solution of the optimization problem should lead to a negative value of the objective function (1). Thus, a negative value will reflect the actual savings introduced by the capacitors. Some conditions may arise however, so that the savings in the losses will not be sufficient to cover for the capacitor capital costs. In this case the optimization will still be important to minimize the overall cost while ensuring that the operational restrictions (e.g. voltage limits) are not violated.

The power flow equations written in rectangular coordinates for each load condition i are given by Eq. (2) and will be solved using the NCIM algorithm [29].

$\mathbf{V}_{Re}$ e $\mathbf{V}_{Im}$ are the real and imaginary components of the nodal voltages.

Eq. (3) indicates that all voltages must operate within limits for each load level i.

Eq. (4) indicates that the var compensations must belong to a pre-specified set of values.

$\mathbf{Q}_{cap}^{fixed}$ are the discrete capacitor values (var) that will remain connected during all time.

$\mathbf{Q}_{cap}^{switch}$ are the discrete capacitor values (var) available but whose connection to the DS will depend on parameter $\mathbf{k}_i$.

$\mathbf{Q}_{cap}^{fixed}$ and $\mathbf{Q}_{cap}^{switch}$ are handled internally as constant impedance by algorithm.

$\mathbf{k}_i$ in Eq. (5) is a column vector that reflects the status of switched capacitor banks. For a given switched capacitor bank and load level i the value 1 indicates the status is "on", otherwise the value is 0.

2.2. Proposed algorithm, Module I

The above formulation (1)–(5) expresses an integer, non-linear and combinatorial optimization problem. The combinatorial aspect arises from the multiple allocation decisions to be determined, including the choice of buses on a per-phase basis and the switching