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Optimal capacitor placement in distorted distribution networks with different load models using Penalty Free Genetic Algorithm

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ABSTRACT

Genetic Algorithm with special constraint handling procedure is proposed for the discrete optimization problem of capacitor placement and sizing in distribution system for cost reduction and power quality improvement. We use gene encoding that enables simple integer representation of possible different number of capacitors of various standard sizes to be placed on a bus. A pair-wise comparison in tournament selection operator is used so that it does not require any penalty parameter tuning, thus avoiding the most difficult aspect of the selection of appropriate penalty parameters.

Proposed Penalty Free Genetic Algorithm (PFGA) is tested on 18-bus, 69-bus and 141-bus systems and the obtained results are better than the results from other methods. Simulations with different load models are also performed. It is shown that load models where active and reactive loads are voltage dependent, such as residential, commercial and industrial, constant *Z* and constant *I* model lead to completely different solutions. Therefore, careful load modeling should be put in place in order to obtain more realistic picture of the total savings.

Introduction

Optimal capacitor placement has been a challenge for power system planners and researchers for many years. The procedure aims towards finding a minimum of certain objective function by solving a combinatorial problem in which the location and sizes of capacitors are to be determined. There are plenty of published papers where different formulations of the problem along with solution methods have been proposed. In general, the goal is to find optimal locations and sizes of shunt capacitors such that the cost of total real power/energy loss and that of shunt capacitors is minimized. At the same time, acceptable voltage levels have to be maintained throughout the whole network. In recent years, more pronounced presence of harmonic sources in distribution systems complicate the problem even more.

The problem of optimal capacitor placement has been treated in a various different ways in the past. Approaches ranged from master–slave problem [1], non-linear programming [2], simulated annealing [3] and heuristic methods (immune system algorithm [4], genetic algorithms [5,6] and particle swarm [7]). Load level variation during the optimization procedure was introduced in [1]. In the recent years, heuristic optimization methods for optimal capacitor placement under distorted conditions are heavily used [8,9,5,10].

In all of the aforementioned references, power flow calculations are performed with loads modeled as constant active and reactive power that are voltage independent (constant *PQ* model). However, as the system gets more loaded, the voltage dependency of the actual loads becomes more important in the representation [11]. In the framework of power losses or voltage optimization, which is of interest in this paper, the load voltage dependency plays an important role, therefore the performance of the algorithm and the results are highly dependent on the load modeling. In this paper, we use different load models (constant *PQ* and constant *ZI*) and investigate their influence on the voltage levels and active power losses which are crucial parameters in the decision process of optimal capacitor placement.

An excellent overview on the use of search oriented methods is presented in [12], genetic algorithms (GA) included. Table 1 presents a chronological overview on the use of GA's and the definition of fitness function.

When solving constrained optimization problems using genetic algorithms, one can see from Table 1 that nearly always, the penalty function methods are the usual approach mainly because of their simplicity and ease of implementation. However, most

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Table 1
Chronological overview on the use of Genetic Algorithms and the definition of fitness function.

Reference	Solution method	Fitness function	Publication
[5]	GA	Penalty terms	2004
[6]	Fuzzy-GA	Penalty terms	2008
[10]	Fuzzy-GA	Penalty terms	2008
[13]	PSO[a]-GA	Penalty terms	2012
[14]	GA	Penalty terms	2012
[15]	ICA[b]-GA	Penalty terms	2014
[16]	GA	Penalty terms	2014
[17]	GA	Weight coefficients	2014
[18]	GA	Penalty terms	2015

[a] Particle Swarm Optimisation.
[b] Imperialist Competitive Algorithm.

difficult aspect of the penalty function approach is finding the appropriate penalty factors needed to guide the search towards the constrained optimum. If the penalty factors are high, the GA will get trapped in a local optimum, while if the penalty factors are low, the GA may not be able to detect a feasible solution. When using weighting coefficients, one always bears the risk of over/underestimating certain aspects in the objective function.

Selecting the proper penalty factors is highly reliant on the problem's nature and their fine tuning is practically based on a case-by-case basis. The process of moving from an infeasible solution to a feasible one can be as challenging as solving the original problem. To overcome this difficulty as suggested in [19], we use selection operator based on pair-wise comparison in tournament selection thus avoiding the penalty function approach, meaning that there are no penalty parameters to tune and the fitness function is equal to the objective function. Comparisons between feasible and infeasible solutions are made in such a way as to provide a search direction towards the feasible region (Section 'Penalty Free Genetic Algorithm').

Problem formulation

Objective function

The non-linear integer problem of capacitor placement in distribution system is solved with discrete values of capacitor sizes and selection of their locations. The objective function, as in [10], comprise of yearly system operation costs including costs for capacitor installation, power and energy losses and it is given with

$$\min F = F_{\text{loss}} + F_{\text{cap.}} + F_{\text{pow.}} = C_e \Delta W + p \sum_{k \in \mathbf{C}} (C_f + C_v Q_{c,k}) + C_p \Delta P^{\max} \quad (1)$$

where F_{loss} energy loss cost; $F_{\text{cap.}}$ cost of capacitors; $F_{\text{pow.}}$ cost corresponding to power losses (e.g., used capacity of the system); C_e electricity cost per kilowatt-hour ($/kW h); ΔW yearly electricity losses (kW h); p fixed annuity payment rate expressed in relative units; C_f fixed costs for capacitors installation ($/location); C_v capacitors costs per unit size ($/kvar); $Q_{c,k}$ capacitor size at location k (discrete values in kvar), $\mathbf{C}$ set of locations where capacitors are installed; C_p saving per kilowatt for reduction in losses which is price for peak power ($/kW) and $\Delta P^{\max}$ power losses at peak power (kW).

Since we are interested in energy losses for a given period of time (one year), load variation has to be taken into account [1]. The assumption is that the load variation can be approximated with discrete levels that can be different among the loads, that is, the loads may have different pattern of variations. Let L_t be Load Duration Curve (LDC) as shown in Fig. 1. A complex load at bus i at time interval t can be represented as:

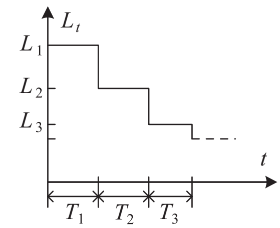

Fig. 1. Load duration curve.

$$\underline{S}_i(t) = L_t \cdot \underline{S}_i^{\max} \quad (2)$$

where $\underline{S}_i^{\max}$ is the peak value of the load. Choosing complex values for L_t, enables for modeling of load power factor as well. If we denote the number of intervals in the LDC as N_{LDC} then for the total energy loss we may write:

$$\Delta W = \sum_{i=1}^{N_{\text{LDC}}} \Delta P_i \cdot T_i \quad (3)$$

where ΔP_i is the active power loss in time interval i whose duration is T_i. Note that in this paper all complex variables are underlined, otherwise they are either real variables or magnitudes of corresponding complex variables.

Constraints

We impose two sets of constraints on bus voltages for their root mean square values (RMS) and total harmonic distortion (THD). Constraints on RMS values are defined with the lower and upper bounds, $V^{\min}$ and $V^{\max}$ respectively, as follows:

$$V^{\min} \leqslant \sqrt{\sum\nolimits_h \left[V_i^{(h)}\right]^2} \leqslant V^{\max}, \quad \text{for } i = 1, \ldots, N \quad (4)$$

where $V_i^{(h)}$ is the RMS value of voltage at bus i for harmonic h and N is the number of buses in the network.

The voltage distortion constraint is considered by specifying the maximum THD of voltages denoted with $\text{THD}^{\max}$

$$\text{THD}_i = \frac{100}{V_i^{(1)}} \cdot \sqrt{\sum\nolimits_{h \neq 1} \left[V_i^{(h)}\right]^2} \leqslant \text{THD}^{\max}, \quad \text{for } i = 1, \ldots, N \quad (5)$$

The bounds for (4) and (5) are specified by the IEEE-519 standard [20], and they are $V^{\min} = 0.9$ pu, $V^{\max} = 1.1$ pu and $\text{THD}^{\max} = 5\%$.

One major concern arising from the use of capacitors in a power system is the possibility of a system resonance, which imposes voltages and currents that are considerably higher than in the case without resonance. The reactance of a capacitor bank decreases with frequency and the capacitor bank therefore acts as a sink for higher harmonic currents. This effect increases the heating and dielectric stresses which yields shortened capacitor life. The IEEE-18 standard sets limitations on voltage, current, and reactive power of capacitor banks. According to this standard, the following limitations should not be exceeded: (1) 110% of rated RMS voltage $V^{\text{cap,RMS}}$; (2) 120% of rated peak voltage $V^{\text{cap,max}}$, including harmonics; (3) 135% of nominal RMS current $I^{\text{cap,rat}}$ and (4) 135% of rated kvar $Q^{\text{cap,rat}}$.

If we assume that the capacitor rated RMS voltage is at least equal to the bus nominal voltage, which is usually the case, then