Optimal Capacitor Placement and Sizing in Unbalanced Distribution Systems With Harmonics Consideration Using Particle Swarm Optimization

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***Abstract*—Shunt capacitors installation in distribution systems requires optimal placement and sizing. More harmonics are being injected into distribution systems. Adding shunt capacitors may lead to high distortion levels. The capacitor placement and sizing problem is a nonlinear integer optimization problem, with locations and ratings of shunt capacitors being discrete values. The goal is to minimize the overall cost of the total real power loss and that of shunt capacitors while satisfying operating and power quality constraints. This paper proposes to solve the problem using particle swarm optimization (PSO). A discrete version of PSO is combined with a radial distribution power flow algorithm (RDPF) to form a hybrid PSO algorithm (HPSO). The former is employed as a global optimizer to find the global optimal solution, while the latter is used to calculate the objective function and to verify bus voltage limits. To include the presence of harmonics, the developed HPSO was integrated with a harmonic power flow algorithm (HPF). The proposed (HPSO-HPF)-based approach is tested on an IEEE 13-bus radial distribution system (13-Bus-RDS). The findings clearly demonstrate the necessity of including harmonics in optimal capacitor placement and sizing to avoid any possible problems associated with harmonics.**

***Index Terms*—Harmonics, particle swarm, shunt capacitors.**

I. Introduction

Shunt capacitors are commonly used in distribution systems to reduce power losses, improve voltage profile, and release system capacity. The achievement of such benefits among other benefits depends greatly on how optimally these shunt capacitors are installed. Studies have indicated that approximately 13% of generated power is consumed as loss at the distribution level. In addition, with the application of loads, the voltage profile tends to drop along distribution feeders below acceptable operating limits. Along with power losses and voltage drops, the increasing growth in electricity demand requires upgrading the infrastructure of distribution systems. Shunt capacitors can be of great help in enhancing the performance of distribution systems. Distribution systems are inherently unbalanced for several reasons. First, distribution systems supply single and three-phase loads through distribution transformers. Second, the phases of transmission lines are unequally loaded. Third, unlike those in transmission systems overhead lines in distribution systems are not transposed.

Due to the widespread use of harmonic-producing equipment in distribution systems, harmonics are propagated throughout those systems. Harmonics are undesirable and cause equipment overheating due to the excessive losses and potential malfunctioning of electric equipment. Inclusion of shunt capacitors without considering the presence of harmonic sources in the system may lead to an increase in harmonic distortion levels due to resonance between capacitors and the various inductive elements in the system.

Baghzouz developed a local variations-based heuristic approach to find the global optimal ratings of shunt capacitors such that the cost of total real power loss and that of shunt capacitors were minimized [1]. The optimal capacitor sizing problem was formulated as a nonlinear integer programming problem with inequality constraints. The constraints considered were the rms values of bus voltages and total harmonic distortions. The only harmonic source assumed was the utility substation. A heuristic algorithm based on local variations was proposed to overcome the prohibitive computational time associated with considering every single potential capacitor size at a given iteration. Yan accounted for the presence of harmonic-producing loads in distribution systems [2]. A hybrid differential evolution algorithm was developed to optimally locate and rate shunt capacitors in distorted distribution systems. A sensitivity test was done prior to the optimization process to determine the candidate buses for reactive power compensation. The objective was to minimize the cost of real power losses and that of shunt capacitors while satisfying some practical constraints. The results indicated that neglecting the presence of harmonic sources could cause a severe harmonic distortion problem. Carpinelli *et al.* solved the capacitor placement and sizing problem in a way that the overall cost was minimized [3]. The cost function involved the cost of real power losses, shunt capacitors, and harmonic distortions. An approximate power flow method and a linear harmonic power flow method were used to calculate the cost function at the fundamental and various harmonic frequencies.

Another optimization technique used to solve the optimal capacitor placement and sizing problem is genetic algorithms (GA). Abou-Ghazala proposed a GA to find the best combination of locations and ratings of shunt capacitors such that the total net savings were maximized [4]. Loss reduction was achieved through the proper installation of shunt capacitors

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while rms values of bus voltages and total harmonic distortions being kept within allowable limits. Nikham *et al.* also used a genetic algorithm to solve the optimal capacitor allocation and sizing problem taking the presence of harmonic sources into account [5]. The objective function consisted of the cost of real power losses and that of shunt capacitors to be installed. The cost associated with the reactive power injection was fixed for all possible capacitor sizes. In other words, the cost of the reactive power injected was assumed to be constant independent of the capacitor size. Masoum *et al.* developed a hybrid tool based on maximum sensitivity selection (MSS) and local variations (LV) to solve the optimal capacitor placement and sizing problem [6]. The former was used to enhance the convergence speed by narrowing down the search space, while the latter was employed to find the global optimal solution. Three harmonic distortion levels were considered for the system investigated. The system under investigation involved only one harmonic source and that was a six-plus converter. The results of the hybrid MSS-LV algorithm were compared with those of the MSS-based algorithm. In later work, Masoum *et al.* applied a fuzzy logic-based algorithm to solve the same problem [7]. Both the objective function and the constraints were fuzzified. Alpha cuts were used to direct the search process and to ensure that the objective function improved each time. The candidate buses were determined according to the objective function, constraints and reactive power compensation sensitivities. Two harmonic distortion levels were considered this time to compare the results obtained with those obtained by the MSS-based algorithm. A conclusion was drawn that the appropriate locations and ratings of shunt capacitors would not only improve voltage profiles but also would reduce harmonic distortion levels. Masousm *et al.* took advantage of the capability of genetic algorithms (GAs) to escape local optima [8]. Improvements in voltage profiles and power quality were achieved through the proper installation of fixed shunt capacitors in distorted distribution systems. The applicability of GA-based approach was proven to yield to better results compared to the previous work done by the same authors.

Another method based on particle swarm optimization (PSO) was offered in [9] to solve the capacitor placement and sizing problem considering harmonics. The problem was mathematically modeled as a nonconvex optimization problem. The objective function was augmented by quadratic penalty functions to account for inequality constraints. That is, the objective function was penalized whenever the inequality constraints were violated. The proposed PSO algorithm did not account for unbalanced operating conditions. Khalil *et al.* [10] proposed a binary PSO algorithm to find the best locations and ratings of fixed shunt capacitors in balanced distribution systems. The only harmonic source considered was the substation voltage. Their objective was to properly place and size shunt capacitors while keeping the cost of real power losses and that of shunt capacitors at a minimum. The objective function was subject to equality and inequality constraints.

II. Problem Formulation

The optimal capacitor placement and sizing problem is formulated as a constrained nonlinear integer optimization problem with both locations and sizes of shunt capacitors being discrete. The objective function encompasses the total cost of the total real power loss and that of shunt capacitors. The objective function is restricted by equality and inequality constraints.

Objective Function: The goal is to minimize the cost of the total real power loss and that of the shunt capacitor installation. The cost function is given by

$$F = K_p Ploss + \sum_{i=1}^{nc} K_{ci} Q_{ci} \qquad (\$) \tag{1}$$

where

K_p	annual cost per unit of the real power loss ($/kW/year);
K_{ci}	annual cost per unit of the reactive power injection at bus i ($/kVAR/year);
Q_{ci}	reactive power injection at bus i (kVAR);
nc	total number of shunt capacitors to be installed;
$Ploss$	total real power loss (kW).

The total real power loss is defined by

$$Ploss = \underbrace{\sum_{i=1}^{nb} Ploss_i^{(1)}}_{Fund.component} + \underbrace{\sum_{i=1}^{nb}\sum_{h=h_o}^{h_{\max}} Ploss_i^{(h)}}_{Harmonic\ \text{component}} \qquad (\text{kW}). \tag{2}$$

where

nb	number of branches;
h_0	smallest harmonic order of interest;
$h_{\max}$	highest harmonic order of interest.

The fundamental component of the total real power loss is calculated using a three phase power flow algorithm (RDPF) [11].

The harmonic component of the total real power loss is computed by a harmonic power flow algorithm (HPF) [12].

Note that the harmonic component of the total real power loss is small compared with the fundamental one. However, this portion of the total real power loss increases as harmonic-producing loads continue to increase in RDS. Consequently, the undesirable presence of harmonics will cause more equipment overheating, stress on equipment insulation, and equipment failure. Not to mention of course the interference with communication networks. It should be pointed out that the cost of the real power loss per unit is fixed. However, the cost of the reactive power injection per unit varies from one capacitor size to another [1]. Generally, the larger the capacitor size is, the cheaper it becomes.

Constraints: Along with the objective function, there is another significant part of the optimization model that needs to be defined and that is the constraints. In real applications, there are always limits on the choices of control variables. The constraints considered in this research are of two types: equality and inequality.