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

**U. RAMESH BABU**
PG Scholar, Sri Kottam Tulasi Reddy Memorial College of Engineering, AP-INDIA, Email: rameshbabu211@gmail.com.

**K. MAHESH**
Asst Prof & HOD, Sri Kottam Tulasi Reddy Memorial College of Engineering, AP-INDIA.

**S.V. SRINIVASA RAJU**
Asst Prof, P.N.C & Vijay Institute of Engineering & Technology, AP-INDIA, Email: vit.ieeeliveprojects@gmail.com.

**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.

**Keywords:** 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 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. Masoum 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 non convex 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. OPTIMAL CAPACITOR PLACEMENT AND SIZING FORMULATION

Capacitors are used to provide reactive power compensation in distribution networks to reduce power losses and to maintain a voltage profile within acceptable limits. The ultimate goal in radial distribution systems is to determine the optimal location and size of the shunt capacitors to maximize loss reduction and to minimize the total cost. The problem is determining the best shunt capacitor size and location in a radial distribution system by minimizing the costs incurred due to power loss and capacitor installation. To solve this problem, the following objective function, F, is considered.

\[
F = \text{Minimize } (\text{Yearly Power Loss Cost} + \text{Yearly Capacitor Cost})
\]

Subject to:

\[
\text{Cost of Yearly Power Loss} = K_p P_{\text{loss}}
\]

\[
\text{Cost of Yearly Capacitor Cost} = \sum_{i=1}^{n} K_i Q_i
\]

The total real power loss in Eq. (1) is defined by

\[
P_{\text{loss}} = P_{\text{loss}}^{(\text{Fund.})} + P_{\text{loss}}^{(\text{harmonics})}
\]

in which,
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\[ P_{loss}^{\text{harmonics}} = \sum_{h=0}^{H} P_{loss}^{(h)} \]  

(5)

Where, \( P_{loss}^{\text{fund}} \) and \( P_{loss}^{\text{harmonics}} \) are the total power losses of the fundamental and harmonic components, respectively. \( n \) is the number of candidate locations for capacitor placement, \( K_{P} \) is the equivalent annual cost per unit of power loss ($/ (kW-year)\), \( K_{ic} \) is the annual capacitor installation cost, and \( i = 1, 2, \ldots, n \) are the indices of the buses selected for compensation. \( h_0 \) and \( H \) are the lower and upper limits of the harmonic order, respectively.

In addition to the objective function, the constraints of the optimization model must be defined. In real applications, limits are placed on the choice of control variables [2]. The constraints are associated with the bus voltages, the total harmonic distortion levels, and the shunt capacitors to be installed.

1. Bus Voltage Limits: The bus voltage magnitudes must be kept within acceptable operating limits throughout the optimization process,

\[ V_{\text{min}} \leq V_i \leq V_{\text{max}} \]  

(6)

Where, \( V_{\text{min}} \) is the lower bound of the bus voltage limits, \( V_{\text{max}} \) is the upper bound of the bus voltage limits, and \( V_i \) is the rms value of the bus voltage.

2. Total Harmonic Distortion Limits: The total harmonic distortion at each bus must be maintained less than or equal to the maximum allowable harmonic distortion level:

\[ \text{THD}^{(\%)} \leq \text{THD}_{\text{max}}^{(\%)} \]  

(7)

Where, \( \text{THD}_{\text{max}} \) is the maximum allowable harmonic distortion level at each bus.

3. Number and Sizes of Shunt Capacitors: Shunt capacitors have constraints. Commercially available capacitors come in discrete sizes, i.e., the shunt capacitors are multiple integers of the smallest capacitor size available:

\[ Q^e \leq L Q_0 \quad L = 1, 2, \ldots, n_c \]  

(8)

Where \( Q_0 \) is the smallest capacitor size available.

A. Formulation of Capacitor Placement Problem

Because capacitor sizes and locations for allocation are discrete variables, this makes the capacitor placement problem as a combinatorial nature. The problem is a zero-one decision with discrete steps of standard bank size of capacitor. In some cases, each step of the capacitor bank size has a different installation cost. Such zero-one decision and discrete steps make the capacitor placement problem as a nonlinear and non differentiable mixed integer optimization problem. The objective function of the capacitor placement problem is usually formulated as follows:

\[ \text{Min } F = \sum_{j=1}^{S} T^j P_L^j \]  

(9)  

\[ \text{Min } F = \sum_{j=1}^{S} k^j T^j P_L^j \]  

(10)  

\[ \text{Min } F = \sum_{j=1}^{S} (k_v^j T^j P_L^j) + C_c \]  

(11)  

\[ \text{Min } F = \sum_{j=1}^{S} (k_v^j T^j P_L^j) + C_c + k_p^p P_L^p \]  

(12)

Where, \( F \) is the value of the desired objective function  
\( S \) = number of load levels  
\( T^j \) = time duration for the \( j \)-th load level  
\( P_L^j \) = power loss at the \( j \)-th load level  
\( k_v^j \) = per unit cost of energy loss at the \( j \)-th load level  
\( C_c \) = investment cost of capacitor  
\( k_p \) = per unit cost of peak power loss  
\( P_L^p \) = power loss at peak load level

The aim of (9) is to minimize the total energy losses in a day whereas the target of (10) is to keep the cost of energy losses as minimum. The objective function in (11) minimizes the sum of energy loss cost and the investment cost required for capacitors allocation. Finally, the desired objective function in (12) is to minimize the total cost due to energy loss cost, peak power loss cost, and the investment cost of capacitors. In addition, the study of Sallam et al. [3] defines two new objective functions. The first one considers the cost of reliability (ECOST) and investment cost while the second, ECOST, cost of losses and the investment cost are included in the objective function. For the technical and functional constraints of the capacitor placement problem, the optimal solution should be satisfied power flow equations, bus voltage limits (to maintain the voltage profile within the upper and lower), limitation of capacitor kVAr to be installed at each bus (because there are limited space for placement).

As more and more nonlinear devices and loads appear in distribution systems, the harmonics constraint (to keep the voltage distortion in term of THD value under the maximum limit) should be added as discussed in [4] to prevent undesired occurrence of harmonic parallel resonance from nonlinear devices and loads. It should be noted that early studies on capacitor placement problem...
Applications as efficient tools in mathematical modeling at the nodes. The proposed advantages: i) considering the requirements and constraints of the systems are balanced distribution feeders under balanced loads. Three-phase unbalanced distribution systems containing feeders with missing phases, unevenly loaded feeders were shunt capacitors on single or double phase feeders are later studied in [7]-[8].

III. APPLICATION OF HEURISTIC OPTIMIZATION TECHNIQUES FOR SOLVING THE OPTIMAL CAPACITOR PLACEMENT AND SIZING PROBLEM

Several heuristic tools that facilitate solving optimization problems that were previously difficult or impossible to solve have been developed in the last decade. Reports on the applications of these tools have been widely published. To solve extremely challenging problems, these new heuristic tools have been combined. Additionally, knowledge elements and more traditional approaches, such as statistical analysis, have been added. Developing solutions with these tools offers two major advantages: i) the development time is much shorter than when using more traditional approaches and ii) the systems are very robust, i.e., relatively insensitive to noisy and/or missing data. The purpose of this section is to provide participants with a basic knowledge of evolutionary computation and other heuristic optimization techniques as well as how they are combined with knowledge elements in computational intelligence systems. Applications to optimal capacitor placement and sizing in radial distribution networks are stressed, and recent research is presented and discussed.

Heuristic optimization techniques, which promise a near global optimum, such as fuzzy logic (FL) and evolutionary computation (EC), have appeared in recent years in power system applications as efficient tools in mathematical approaches. Recently, many researchers have focused on various types of heuristic optimization techniques to solve the optimal capacitor placement problem. Fig. 1 shows the number of published research papers that have addressed the optimal capacitor problem during the last 10 years. This section surveys the heuristic optimization techniques that are used in optimal capacitor placement problems.

A. Fuzzy Logic

Fuzzy set theory can be considered a generalization of classical set theory. In classical set theory, an element of the universe either belongs to or does not belong to the set. Therefore, the degree of association of an element is crisp. A membership function measures the degree of similarity of any element in the universe of discourse to a fuzzy subset [5]. Triangular, trapezoidal, piecewise-linear, and Gaussian functions are the most commonly used membership functions. In a fuzzy set, an infinite number of memberships are allowed. The degree of membership for each element is indicated by a number between 0 and 1 [6]. The membership function is usually designed by considering the requirements and constraints of the problem. FL implements human experiences and preferences via membership functions and fuzzy rules. Due to the use of fuzzy variables, the system can be made understandable to a non-expert operator. Thus, FL can be used as a general methodology to incorporate knowledge, heuristics, or theory into controllers and decision makers. The following benefits are provided: (i) an accurate representation of the operational constraints of the power systems and (ii) fuzzified constraints that are softer than the traditional constraints [7]. FL was first introduced in 1979 to solve power system problems [5].

Power and energy losses due to installed capacitors and the cost of the fixed capacitors are used as the objective function. A fuzzy expert system (FES) method to determine suitable candidate nodes and two methods for determining the sizes of the capacitors in distribution systems for capacitor installation have been previously discussed.

Fig. 1. The number of papers published each year on the subject of optimal capacitor placement

A FES can be used to determine the nodes for capacitor allocation by finding a compromise between the loss reduction from the capacitor installation and the voltage level improvement. In addition, the FES is adapted for capacitor allocation in distribution system planning, expansion, and operation. Bhattacharya proposed new fuzzy membership functions to identify probable capacitor locations of radial distribution systems [11]. A new algorithm for selecting capacitor nodes was presented, and a simulated annealing technique was employed for final sizing of the capacitors at the nodes. The proposed membership functions were less dependent on the weighting factors. Therefore, the proposed method was more general than other fuzzy capacitor placement methods. A comparison with other fuzzy- and heuristic-based methods showed that the proposed method produced better solutions.
B. Evolutionary Computation Methods

Different types of evolutionary computation (EC) optimization techniques are used to search for optimal or near optimal solutions for many power system problems, especially for optimal capacitor placement in radial distribution networks. These techniques include tabu search (TS), simulated annealing (SA), ant colony optimization (ACO), harmony search (HS), genetic algorithm (GA), and particle swarm optimization (PSO). This survey included most of the papers that have been published during the past decade.

i) Tabu Search

Tabu search (TS) which is a met heuristic method was developed by Glover to solve combinatorial optimization problems [11, 12]. Met heuristics is defined as an optimization algorithm that iteratively uses simple rules or heuristics to evaluate better solutions [11]. TS is based on the hill-climbing method, which evaluates the final solution by repeating the process of creating solution candidates in the neighborhood around the initial solution and selecting the best solution among the candidates. The hill-climbing method stops if the solution is not improved. This method can be easily trapped in a local minimum [10]. Optimal capacitor placement has been achieved with a hybrid method that utilizes TS [12]. The TS approach has been extended with features from practical heuristic approaches and from other combinatorial approaches, such as genetic algorithms and simulated annealing. The approach has been extensively tested in a practical 135-bus network and in a range of networks available in the literature with superior results in terms of both quality and solution cost. A variable neighborhood TS method for capacitor placement in distribution systems has been proposed [11]. The method considers switching the structure of the neighborhood of the TS. The structure is changed by examining whether the obtained solution is better than the best current solution. In this paper, two kinds of neighborhoods were used to evaluate better solutions.

ii) Simulated Annealing

SA is a powerful optimization technique that exploits the resemblance between a minimization process and crystallization in a physical system. SA depends on three important parameters: initial temperature ($T$), cooling rate ($\beta$), and final temperature ($T_{\text{min}}$). The SA technique starts with a feasible solution point. The solution is then perturbed to obtain new feasible solutions that are either accepted or discarded, depending on a probabilistic acceptance criterion [1]. A modified simulated annealing (MSA) technique has been developed for simultaneous improvement of power quality and optimal placement and sizing of fixed capacitor banks in a modern distribution network [11]. The latter supplies a mix of linear and nonlinear loads and imposes voltage and current harmonics. These networks include integrated variable-speed wind turbines as a dominant form of distributed generation (DG). The stochastic power output of the wind DG is modeled by Monte-Carlo simulations of the distribution power flow.

iii) Ant Colony Optimization

Another popular evolutionary computing technique is the ant colony which initially searches among a population in parallel, and it measures the competence of each individual population based on a cost function until convergence. The ant algorithm was inspired by the behavior of ants in nature such that the ants can find the shortest path from their home to food. Biologists found that ants leave pheromone trails that communicate with other ants and transfer information about their path. Initially, a group of ants performs random searches and makes constant density trails during their movement. As a result, the density of trails for the shorter paths gradually increases, which is helpful for the subsequent searches. These trails lead ants toward shorter routes. A powerful ant colony optimization-based algorithm for the feeder reconfiguration and capacitor placement of distribution systems has been reported [10]. The objective of this study was to present new algorithms for solving the optimal capacitor placement problem, the optimal feeder reconfiguration problem, and a combination of the two.

iv) Harmony search

The harmony search (HS) algorithm is a met heuristic optimization method that was inspired by musicians improvising the pitch of their instruments to find better harmony. HS has several advantages: i) initial value settings are not required for the decision variables and ii) discrete and continuous variables can be used. Because algorithms already used in the field of optimization are based on naturally occurring processes, HS can be conceptualized as a musical performance process searching for better harmony. A HS algorithm for optimal capacitor placement in the presence of nonlinear loads has also been presented [11]. The test results for the 7 load levels showed that the HS algorithm gives greater power loss reduction and net energy-saving improvement compared to the GA. An improved HS (IHS) algorithm for optimal placement and rating of shunt capacitors in a three-phase distribution network has been reported [4]. IHS employs a method for generating new solution vectors that enhances the accuracy and convergence of the harmony search algorithm [5]. Mutual coupling, load unbalancing, and harmonic sources are considered for solving the capacitor placement problem. The proposed algorithm has been validated on a 3-phase, 9-bus radial network.

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distribution system, and the results indicated that the IHS optimization technique gives greater reduction in power loss and total cost compared to PSO. Moreover, the results of the IHS optimization technique showed that the bus voltages improved more than that using the PSO.

v) Genetic Algorithm

The genetic algorithm (GA) searches for an optimal solution using the principles of evolution based on certain string which is judged and propagated to form the next generation. The algorithm is designed such that the “fitter” strings survive and propagate into later generations. The major advantage of the GA is that the solution is globally optimal. Moreover, a GA is capable of obtaining the global solution to a wide variety of functions, such as differentiable or non-differentiable, linear or nonlinear, continuous or discrete, and analytical or procedural functions [6]. GAs belong to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover [7].

The placement of a capacitor on a printed circuit board (PCB) to reduce the effect of simultaneous switching noise has been formulated as a GA search problem [8]. The objective was to determine the minimum number of added capacitors, the minimum cost, and their position on the PCB while keeping the maximum voltage deviation within some specified noise margin. The presence of capacitors at the selected positions is represented by a stream of zeros and ones, which is interpreted as a genotype and is manipulated systematically using GA operators to approach an optimal solution. A GA-based method that incorporates nonlinear load models for the problem of finding optimal shunt capacitors on distribution systems has been reported [9]. The problem is formulated such that the optimal solution did not result in severe resonant conditions at harmonic frequencies. Here, power and energy losses due to installed capacitors and the cost of fixed capacitors were used to define the objective function. Compared with previous methods, the proposed algorithm defined a proper combination of the objective function and the constraints as the fitness function to improve the chromosomes and to select the most suitable buses for the placement of the capacitors.

Another method using index and GA algorithm to determine suitable candidate nodes in distribution systems for capacitor installation has been reported in [11]. A power loss index approach was used to determine the suitability of capacitor placement at each node. The buses with the highest suitability were identified for capacitor placement. An efficient method for determining the optimal number, location, and sizing of fixed and switched shunt capacitors in radial distribution systems using GA has been presented [12]. Unlike One technique is based on micro-GA while the other two techniques are based on the inherent structure theory of networks and the sensitivity analysis, which are used to determine a set of feasible candidate nodes to which the GA is applied. The three techniques have been compared with a simple GA method using the IEEE 34-node unbalanced test system. The problem of simultaneous placement and sizing of both voltage regulators and capacitor banks in unbalanced distribution system in the presence of linear and nonlinear loads, using GA is discussed in [10]. The problem is formulated as a mixed integer program that accounts for imbalance and incorporates network losses, cost of the capacitors/ voltage regulators, and cost of harmonic distortions.

vi) Particle Swarm Optimization

Particle swarm optimization (PSO) was originally introduced. The technique involves simulating social behavior among individuals (particles) “flying” through a multidimensional search space, in which each particle represents a single intersection of all of the search dimensions. The particles evaluate their positions relative to a goal (fitness) and the particles in a local neighborhood share memories of their “best” positions and use those memories to adjust their own velocities and subsequent positions. PSO has the advantages of parallel computation and robustness, and it can find the global optimal solution with a higher probability and efficiency than traditional methods. The main advantages of PSO are that it is easy to realize, fast converging, and intelligent. PSO can be applied in both scientific research and engineering fields. An approach based on a PSO algorithm to solve the capacitor placement problem in radial distribution systems was proposed in [7]. With full consideration of the potential harmonic effects, different load levels, and practical aspects of fixed or switched capacitor banks, the target problem was reformulated by a comprehensive objective function and a set of equality and inequality constraints. The proposed solution method employed PSO to search for the optimal location, type, and size of capacitors to be placed and the optimal numbers of switched capacitor banks at different load levels.

This study investigated the optimal solution of two subproblems simultaneously with both variables considered to be discrete while imposing some practical constraints. The results demonstrated the impact of proper capacitor placement and sizing in reducing the total real power losses in the network by canceling part of the reactive current flowing in the network. Binary PSO (BPSO) has been used for solving the discrete optimization problem of optimal capacitor placement in the presence of nonlinear loads [10]. The objective function maximizes the net savings from peak power and energy reduction while taking capacitor cost into account. A BPSO was used to
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optimize capacitor placement and the results indicated that ignoring supply harmonics, load unbalance, and mutual coupling could cause power quality degradation. The combined a discrete version of PSO with a radial distribution power flow (RDPF) algorithm to form a hybrid PSO (HPSO) algorithm [2]. PSO was employed as a global optimizer to find the global optimal solution, while the RDPF algorithm was used to calculate the objective function and to verify the bus voltage limits. To include the presence of harmonics, the developed HPSO algorithm was integrated with a harmonic power flow (HPF) algorithm.

Here, the expression of harmonic distortion of voltage sources is considered in the problem formulation. Harmonic distortion of voltage sources in the network can cause double harmonic current injection, which increases network losses and the number of incidences of resonance. The selected BPSO method considers the discrete nature of the placement problem, whereas most articles have considered this problem to be continuous. Although PSO techniques are widely used for solving the optimal capacitor placement problem, it still has disadvantages, such as difficulty in finding the optimal design parameters and properly selecting the initial conditions and parameters for an accurate solution.

C. Hybrid Artificial Intelligent Techniques

To create a hybrid intelligent system, two or more AI techniques are applied. Through cooperative interactions, such methods are used in series or are integrated to obtain successful results. During the last decade, hybrid systems have been applied in engineering applications. A GA-based fuzzy multi-objective approach for optimal capacitor placement while improving voltage profile and maximizing net savings in a radial distribution system has been presented [5]. This study attempted to maximize the fuzzy satisfaction of maximizing net savings and minimizing node voltage deviations. A combined fuzzy-GA method for multi-objective programming to solve the capacitor placement problem in distribution systems has been proposed [6]. Three distinct objectives were considered: i) minimize the total cost of the energy loss and the capacitors, ii) increase the margin loading of the feeders, and iii) improve the voltage profile. The GA was used to derive the optimal solution because it can search many paths to solve the problem with nonlinear and non-differentiable objective functions.

A two-stage methodology to find the optimal locations and sizes of the shunt capacitors for reactive power compensation of radial distribution systems is presented in [9]. A fuzzy approach was applied to find the optimal capacitor locations, and the PSO technique was applied to find the optimal capacitor sizes. A fuzzy decision function with the assistance of bacterial foraging algorithm creates a powerful optimization tool, in which both loss minimization and node voltage improvement in capacitor allocation problem are considered [10]. The objective function is formulated to reduce the cost of peak power and energy loss. Implementing the capacitor allocation problem with this new integer-code algorithm in addition to a fuzzy decision led to better results than previous attempts that focused on reducing peak power in a power system or decreasing network energy loss.

D. Other Optimization Techniques

An artificial neural network (ANN)-based method for optimally switching the switchable capacitors installed in a power distribution system has been developed [3]. This method is much faster than the traditional, optimization technique-based approaches, even for a realistic number of capacitors in the system. In this paper, the standard multilayer perceptron neural network with error-back propagation training algorithm was used. The bacteria foraging algorithm is based on the fact that natural selection tends to eliminate animals with poor foraging strategies and to favor those with successful foraging strategies. After many generations, poor foraging strategies are either eliminated or reshaped into productive ones. The algorithm is based on the foraging behavior of the bacteria Escherichia coli, which exist in human intestines. Escherichia coli have a foraging strategy governed by four processes: is, swarming, reproduction, and elimination and dispersal [10]. A two stage immune algorithm which embeds compromised programming to solve the multi-objective capacitor placement problem was proposed in [5]. The concept of the non-inferior set was applied to obtain a set of optimal compromise solutions from which the decision maker can choose one.
 Capacitor placement and sizing was performed by using loss sensitivity factors and plant growth simulation algorithm in [7]. The loss sensitivity factor was used to predict which bus has the largest loss reduction when a capacitor is placed. These sensitive buses can serve as candidate locations for capacitor placement. The plant growth simulation algorithm PGSA was used to estimate the required level of shunt capacitive compensation to improve the voltage profile of the system.

IV. RESULTS AND DISCUSSION

The three algorithms adopted in this work, namely, RDPF, HPF, and PSO, were implemented in MATLAB computing environment on a Dell Laptop with Intel Pentium M processor of 1.86 GHz and RAM of 1 GB. The developed algorithms were tested on an unbalanced-13-bus radial distribution system (unbalanced-13-bus-RDS). The unbalanced-13-bus-RDS consists of single, double, and three phase lines and loads. The total real and reactive power demand are 3464.1 kW and 1568.9 kVAR respectively. The system loads are of two types, distributed loads and spot loads. The only supply source in the system is the substation at bus 1. Bus 1 is treated as a slack bus with a constant voltage on each phase of its three phases. The other buses (2–13) are modeled as PQ constant buses. A complete description of the system can be found in [7]. The MVA base value is 10 and the line to line base voltage is the same as the feeder nominal voltage 4.16 kV. The bus voltages are to be kept within 10% of the nominal voltage throughout the optimization process. The cost of real power losses is 168 U.S.$/kW/year, while the cost of the capacitor installation without harmonics consideration after capacitor installation.

The number of shunt capacitors to be installed is not to exceed 10 banks of a discrete size of 150 kVAR each. That is to say, the total reactive power injection of these capacitors is not to exceed the total reactive power demand (1568.9 kVAR). 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 the same test system (13-Bus-RDS). For the distorted voltage-13- Bus-RDS, harmonic-producing loads, namely fluorescent lighting, adjustable speed drives (ASD), and nonspecific sources such as PCs, TVs, and etc, are considered. The typical harmonic spectrum of these nonlinear loads is provided in [8]. All loads are treated as constant PQ spot loads for harmonic studies. Load composition in terms of harmonic sources is given in [8].

The developed HPSO-HPF-based approach is applied to find the optimal locations and sizes of shunt capacitors in an unbalanced- IEEE-13-bus radial distribution system (13-Bus-RDS) while taking harmonics into account. The total harmonic distortion levels are to be maintained within 5% of the voltage value as recommended by the IEEE standard 519-1992. In the presence of harmonics, three different cases are considered to investigate the impact of shunt capacitor installation on the voltage profiles, total harmonic distortions, total real power loss, and net savings.

Case1. Represents the system with harmonics consideration before capacitor installation.

Case2. Represents the system without harmonics consideration after capacitor installation.

Case3. Represents the system with harmonics consideration after capacitor installation.

The PSO parameters were tuned to enhance the performance of the proposed algorithm. For one shunt capacitor to be installed, 20 independent runs were carried out for each PSO parameter. The maximum number of iterations was taken as 50 for the tuning process of each parameter. It was found that the PSO algorithm was less sensitive to its parameters for small problem dimension (the problem dimension was the shunt capacitor location and size). However, the larger the problem dimension is, the more sensitive the PSO algorithm becomes. A swarm size of 20 particles, acceleration constants of 2, and a particle’s maximum velocity of 4 were selected. As for the inertia weight (w), it was reduced linearly from 0.9 to 0.4 as recommended in [9]. From the results shown in Table II, installing a shunt capacitor of 600 kVAR at phase c of bus 6 in case 2 will reduce the total real power losses from 192.7494 kW to 179.1373 kW and profit the utility 2,099,694 U.S.$/year. The capacitor size required to bring the violated bus voltages back within the maximum and minimum bus voltage limits are the same for cases 2 and 3, while the PSO-based algorithm selected phase c of bus 5 to be the optimal location of the shunt capacitor in case 3. Before capacitor installation (case 1), the cost of real power losses is 32,326,694 U.S.$/year. In case 2 (after capacitor installation without harmonics consideration), the cost of real power.

### TABLE I

<table>
<thead>
<tr>
<th>Qc (kVAR)</th>
<th>150</th>
<th>300</th>
<th>450</th>
<th>600</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kc ($/kVAR)</td>
<td>0.500</td>
<td>0.350</td>
<td>0.255</td>
<td>0.220</td>
<td>0.276</td>
</tr>
<tr>
<td>Qc (kVAR)</td>
<td>960</td>
<td>1050</td>
<td>1050</td>
<td>1350</td>
<td>1500</td>
</tr>
<tr>
<td>Kc ($/kVAR)</td>
<td>0.185</td>
<td>0.228</td>
<td>0.170</td>
<td>0.207</td>
<td>0.201</td>
</tr>
</tbody>
</table>
TABLE II
RESULTS OF THE OPTIMAL PLACEMENT AND SIZING OF ONE SHUNT CAPACITOR IN A 13-BUS-RDS

<table>
<thead>
<tr>
<th>Case</th>
<th>Minimum Bus Voltage (p.u.)</th>
<th>Maximum Bus Voltage (p.u.)</th>
<th>THDmax (%), Reactive Power Injection (kVAR)</th>
<th>Real Power Losses (kW)</th>
<th>Cost Function ($/year)</th>
<th>Net Savings ($/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8954</td>
<td>0.9339</td>
<td>4.4590</td>
<td>192.749</td>
<td>32,326.694</td>
<td>2,096.694</td>
</tr>
<tr>
<td>2</td>
<td>0.9963</td>
<td>0.9993</td>
<td>-</td>
<td>179.137</td>
<td>30,227</td>
<td>30,271</td>
</tr>
<tr>
<td>3</td>
<td>0.9343</td>
<td>0.9343</td>
<td>4.1986</td>
<td>179.401</td>
<td>30,227</td>
<td>30,271</td>
</tr>
</tbody>
</table>

The total harmonic distortion reduction in case 3 with respect to case 1 is

$$THD_{\text{reduction in case 3 with respect to case 1}} = \frac{THD_{\text{max,case 1}} - THD_{\text{max,case 3}}}{THD_{\text{max,case 1}}} \times 100$$

$$= \frac{4.4590 - 3.1986}{4.4590} \times 100 = 30.587\%$$

The total harmonic distortion reduction in case 3 with respect to case 2 is

$$THD_{\text{reduction in case 3 with respect to case 2}} = \frac{THD_{\text{max,case 2}} - THD_{\text{max,case 3}}}{THD_{\text{max,case 2}}} \times 100$$

$$= \frac{3.1986 - 3.1986}{3.1986} \times 100 = 90.833\%$$

The reduction in the maximum total harmonic distortion level in case 3 with respect to cases 1 and 2 justifies the inclusion of harmonics in the optimal capacitor placement and sizing problem.

In Table III, the optimal solution of the HPSO-HPF-based algorithm for the optimal placement and sizing of one shunt capacitor yields voltage profile improvement in both cases (2&3), (see columns 5 and 7 in Table III). However, installing a shunt capacitor without taking harmonics into account (case2) caused a severe harmonic distortion problem (i.e., harmonic distortion levels at all load buses violate the maximum allowable distortion level (5%), (see column 6 in Table III). In contrast, recognizing the fact that harmonics are propagated throughout distribution systems and including their presence will keep the harmonic distortion levels within the limits (see column 8 in Table III). The convergence characteristics of the proposed HPSO-HPF based approach for cases 2 and 3 in the optimal placement and sizing of one shunt capacitor problem with the total cost being the objective are illustrated in Figs. 3 and 4 respectively. Both Figures indicate the convergence speed of the proposed HPSOHPF-based solution methodology in finding the global optimal solution of the capacitor allocation and sizing problem.
In order to do more testing on the proposed HPSO-HPF based algorithm, the capacitor placement and sizing problem is extended to multiple capacitors. Three single phase capacitors are considered instead of one capacitor. The maximum reactive power injection of these capacitors is not to exceed the total reactive demand of the system. As in the case of one shunt capacitor, the PSO parameters have to be properly adjusted. Taking the total real power loss without harmonic components as an objective, 20 independent runs were conducted to find the best settings of the PSO parameters. 100 iterations were taken as the maximum number of iterations to adjust each of these parameters. A swarm size of 25 particles, acceleration factors of 2 each, and a maximum particle’s velocity of 3 were selected. The developed PSO-based algorithm was able to find the optimal locations and ratings of three shunt capacitors such that the overall cost was minimized. The simulation results are reported in Table IV. Without harmonics consideration (case 2)

**Fig. 3.** Convergence characteristics of the HPSO-HPF-based algorithm for case 2 in the optimal placement and sizing of one shunt capacitors.

**Fig. 4.** Convergence characteristics of the HPSO-HPF-based algorithm for case 3 in the optimal placement and sizing of one shunt capacitors.

**TABLE IV**

RESULTS OF THE OPTIMAL PLACEMENT AND SIZING OF THREE SHUNT CAPACITORS IN A 13-BUS-RDS

<table>
<thead>
<tr>
<th>Bus</th>
<th>Case1</th>
<th>Case2</th>
<th>Case3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Bus Voltage (pu)</td>
<td>0.9594</td>
<td>0.9555</td>
<td>0.9556</td>
</tr>
<tr>
<td>Maximum Bus Voltage (pu)</td>
<td>0.9863</td>
<td>0.9945</td>
<td>0.9947</td>
</tr>
<tr>
<td>THD max (%)</td>
<td>4.4590</td>
<td>19.0355</td>
<td>1.7770</td>
</tr>
<tr>
<td>Reactive Power Injection (kVAR)</td>
<td>Q</td>
<td>Q</td>
<td>Q</td>
</tr>
<tr>
<td>Q</td>
<td>-450</td>
<td>-450</td>
<td>-450</td>
</tr>
<tr>
<td>Q</td>
<td>-400</td>
<td>-400</td>
<td>-400</td>
</tr>
<tr>
<td>Real Power Losses (kW)</td>
<td>192.7494</td>
<td>164.9870</td>
<td>165.2160</td>
</tr>
<tr>
<td>Cost Function ($/yr$)</td>
<td>32,326.694</td>
<td>28,069</td>
<td>28,107</td>
</tr>
<tr>
<td>Net Savings ($/year$)</td>
<td>-</td>
<td>4,257.694</td>
<td>4,219.694</td>
</tr>
</tbody>
</table>

**TABLE V**

VOLTAGE PROFILES AND TOTAL HARMONIC DISTORTIONS OF A 13-BUS-RDS FOR CASES 1, 2, AND 3 OF THE OPTIMAL PLACEMENT AND SIZING OF THREE SHUNT CAPACITORS

<table>
<thead>
<tr>
<th>Bus</th>
<th>Case1</th>
<th>Case2</th>
<th>Case3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>(pu)</td>
<td>$</td>
<td>(pu)</td>
</tr>
<tr>
<td>1</td>
<td>a</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>a</td>
<td>0.9876</td>
<td>2.3076</td>
</tr>
<tr>
<td>5</td>
<td>b</td>
<td>0.9715</td>
<td>2.1319</td>
</tr>
<tr>
<td>6</td>
<td>c</td>
<td>0.9507</td>
<td>2.3329</td>
</tr>
<tr>
<td>7</td>
<td>a</td>
<td>0.9647</td>
<td>2.3202</td>
</tr>
<tr>
<td>8</td>
<td>b</td>
<td>0.9795</td>
<td>2.1410</td>
</tr>
<tr>
<td>9</td>
<td>c</td>
<td>0.9480</td>
<td>2.3384</td>
</tr>
<tr>
<td>10</td>
<td>a</td>
<td>0.9414</td>
<td>2.4064</td>
</tr>
<tr>
<td>11</td>
<td>b</td>
<td>0.9614</td>
<td>2.1355</td>
</tr>
<tr>
<td>12</td>
<td>c</td>
<td>0.9291</td>
<td>2.4063</td>
</tr>
<tr>
<td>13</td>
<td>a</td>
<td>0.9509</td>
<td>4.4214</td>
</tr>
<tr>
<td>14</td>
<td>b</td>
<td>0.9852</td>
<td>3.6674</td>
</tr>
<tr>
<td>15</td>
<td>c</td>
<td>0.9909</td>
<td>4.0023</td>
</tr>
<tr>
<td>16</td>
<td>a</td>
<td>0.9509</td>
<td>4.4214</td>
</tr>
<tr>
<td>17</td>
<td>b</td>
<td>0.9852</td>
<td>3.6674</td>
</tr>
<tr>
<td>18</td>
<td>c</td>
<td>0.9909</td>
<td>4.0023</td>
</tr>
<tr>
<td>19</td>
<td>a</td>
<td>0.9436</td>
<td>4.4940</td>
</tr>
<tr>
<td>20</td>
<td>b</td>
<td>0.9863</td>
<td>3.6541</td>
</tr>
<tr>
<td>21</td>
<td>c</td>
<td>0.8974</td>
<td>4.7189</td>
</tr>
<tr>
<td>22</td>
<td>a</td>
<td>0.9509</td>
<td>4.4214</td>
</tr>
<tr>
<td>23</td>
<td>b</td>
<td>0.9852</td>
<td>3.6674</td>
</tr>
<tr>
<td>24</td>
<td>c</td>
<td>0.9909</td>
<td>4.0023</td>
</tr>
<tr>
<td>25</td>
<td>a</td>
<td>0.9702</td>
<td>2.3847</td>
</tr>
<tr>
<td>26</td>
<td>b</td>
<td>0.9542</td>
<td>2.3787</td>
</tr>
<tr>
<td>27</td>
<td>c</td>
<td>0.9663</td>
<td>2.3581</td>
</tr>
<tr>
<td>28</td>
<td>a</td>
<td>0.9641</td>
<td>4.5042</td>
</tr>
<tr>
<td>29</td>
<td>b</td>
<td>0.8981</td>
<td>4.7835</td>
</tr>
<tr>
<td>30</td>
<td>c</td>
<td>0.8942</td>
<td>4.5718</td>
</tr>
<tr>
<td>31</td>
<td>a</td>
<td>0.8954</td>
<td>4.8590</td>
</tr>
</tbody>
</table>

the developed PSO-based algorithm selected bus 6 as the optimal location for three single-phase capacitors with optimal ratings of 450, 300, and 600 kVAR as shown in Table IV. In case 2, the real power losses were reduced to 164.9870 kW, while in case 3 (with harmonics
Optimal Capacitor Placement and Sizing in Unbalanced Distribution Systems with Harmonics Consideration Using Particle Swarm Optimization

consideration), the proposed PSO-algorithm selected phase a of bus 5 and phases b and c of bus 6 to be the optimal locations of the three shunt capacitors with the same ratings. It can be observed that the reactive power injections required to minimize the total cost in case 2 (when harmonics are neglected) are equal to the reactive power injections in case 3 (when harmonics are considered). Moreover, the total real power loss in case 3 is higher than that in case 2. As a result, the net savings obtained in case 2 is better than that in case 3. However, the optimal solution in case 3 yields a 61.27% reduction in total harmonic distortion with respect to case 1 and 90.927% reduction in total harmonic distortion with respect to case 2. Consequently, the net savings obtained in case 2 can be justifiably sacrificed to avoid any possible damage to the electric equipment of both the utility and the customers.

Table V demonstrates that the proper installation of three shunt capacitors in the 13-Bus-RDS leads to voltage profile improvement (see columns 5 and 7 in Table V). The harmonic distortion levels at load buses within the allowable limits \( (THD_{inst} \% \leq 5) \), (column 8 in Table V). The convergence characteristics of the developed HPSO-HPF-based approach for cases 2 and 3 in the optimal placement and sizing of three shunt capacitors problem with the total cost being the objective are depicted in Figs. 5 and 6.

V. CONCLUSION

In this paper, the developed HPSO-HPF-based algorithm was tested on an unbalanced 13-bus test system to find the optimal locations and sizes of shunt capacitors taking harmonics into account. The objective was to minimize the total cost of the system real power loss and the shunt capacitors to be installed. The objective function was subject to some operating constraints and power quality constraints. The outcome of this research is that neglecting the presence of harmonics in the system may lead to undesirable harmonic distortion levels causing more damage to the electric equipment of both the electric utility and customers.

VI. REFERENCES


