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Heuristic Optimization Techniques to Determine Optimal Capacitor Placement and Sizing in Radial Distribution Networks: A Comprehensive Review

***Abstract**. Capacitors in power systems are used to supply reactive power to minimize loss and to improve the voltage profile. The appropriate placement of capacitors is also important to ensure that system power losses and total capacitor costs are minimal. The capacitor placement problem is commonly solved using heuristic optimization techniques which are diverse and have been the subject of ongoing enhancements. This paper presents a survey of the literature from the last decade that has focused on the various heuristic optimization techniques applied to determine optimal capacitor placement and size.*

***Streszczenie.** Kondensatory używane są w sieciach zasilających do poprawy jakości napięcia – zmniejszenia mocy biernej. Ważną rolę odgrywa umiejscowienie kondensatora. W artykule zaprezentowano przegląd literaturowy prac na temat metod optymalizacji umożlwiających określenia optymalnej pozycji I wielkości kondensatora. (**Heurystyczne techniki optymalizacji umiejscowienia kondensatora w promieniowych sieciach zasilających – przegląd stanu wiedzy**)*

Keywords: Capacitor Placement, Radial Distribution Network, Heuristic Optimization, Power System Harmonics.
Słowa kluczowe: sieci zasilające, kondensator, zawartość

1. Introduction

Shunt capacitors in distribution networks are used for various purposes: reducing power loss, improving the voltage profile along feeders, and increasing the maximum transmitted power in cables and transformers. To reduce power loss, shunt capacitors, which are commonly installed in power distribution networks, are used to compensate for reactive power. However, the installation of shunt capacitors in distribution networks requires consideration of their appropriate location and size. Capacitor placement is important to maximize loss reduction by properly installing shunt capacitors while minimizing shunt capacitor costs.

Distribution networks are unbalanced due to mutual coupling between phase conductors and loading on the different phases [1, 2]. Due to the widespread use of harmonic-producing equipment in distribution systems, harmonics propagate throughout the systems. Harmonics are undesirable and cause equipment to overheat because of excessive losses and may cause the potential malfunctioning of electric equipment. Installing shunt capacitors without considering the presence of harmonic sources in the system may lead to increased harmonic distortion levels due to resonance between the capacitors and the various inductive elements in the system [2].

The problem of locating and sizing shunt capacitors in distribution systems has been a challenge for power system planners and researchers. Many published papers and reports were found in the literature that addressed this issue. Different formulations of the methodologies have been utilized to solve this difficult combinatorial problem [3]. The unbalanced operating conditions and the presence of harmonic sources in the distribution systems further complicate the capacitor placement and sizing problem. These issues have been neglected in many of the studies conducted on the capacitor optimization problem.

Many techniques have been developed for solving the capacitor placement problem: analytical techniques, numerical programming, heuristic or artificial intelligence (AI)-based techniques [4]. Among these methods, heuristic or AI optimization techniques have been widely applied to solve the optimal capacitor placement problem. AI is a powerful knowledge-based approach that can address the nonlinearity of practical systems. AI can decrease the mathematical complexity and has a rapid response, which can be utilized for transient analysis.

In this work, a comprehensive analysis of the heuristic optimization techniques that solve the optimal capacitor placement problem and that have been proposed recently by various researchers is presented. This analysis includes important heuristic optimization techniques such as fuzzy logic, artificial neural network, and evolutionary computing used in solving power system optimization problems. In addition, applications of hybrid artificial intelligence techniques in optimal capacitor problems are discussed.

2. 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.

(1) *F = Minimize {Yearly Power Loss Cost + Yearly Capacitor Cost}*

Subject to:

(2) *Cost of Yearly Power Loss* = $K_P.P_{loss}$

(3) *Cost of Yearly Capacitor Cost* = $\sum_{i=1}^{n} K_i^c Q_i^c$

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

(4) $$P_{loss} = P_{loss}^{(Fund.)} + P_{loss}^{(harmonics)}$$

in which,

(5) $$P_{loss}^{(harmonics)} = \sum_{h=h_0}^{H} P_{loss}^{(h)}$$

where $P_{loss}^{(Fund.)}$ and $P_{loss}^{(harmonics)}$ 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,...,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.

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

(6) $$V_{\min} \le |V_i| \le V_{\max}$$

where V_{min} is the lower bound of the bus voltage limits, V_{max} is the upper bound of the bus voltage limits, and V_i is the rms value of the bus voltage.

ii. 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:

(7) $$THD_i(\%) \le THD_{\max}(\%)$$

where THD_{max} is the maximum allowable harmonic distortion level at each bus.

iii. 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:

(8) $$Q^{ci} \le LQ_0 \qquad L = 1,2,...,nc$$

where Q_0 is the smallest capacitor size available.

3. 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 radian 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.

3.1. 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].

Masoum used fuzzy set theory for the discrete optimization problem of fixed shunt capacitor placement and sizing under harmonic conditions [8]. Power and energy losses due to installed capacitors and the cost of the fixed capacitors are used as the objective function. The power quality limits of IEEE-519, the maximum fundamental and harmonic voltage amplitudes, and the allowed number of capacitor banks are employed as constraints. 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 [9,10].

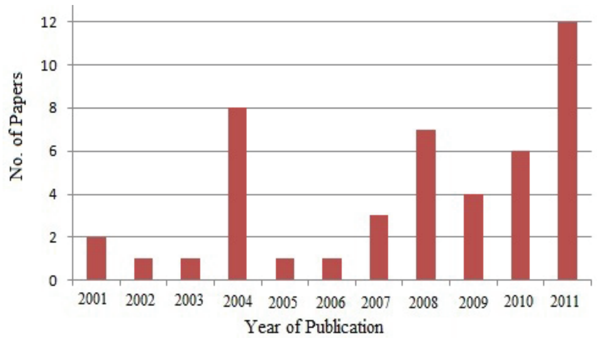

Fig. 1. The number of papers published each year on the subject of optimal capacitor placement

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.

3.2. 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.

3.2.1. Tabu Search

Tabu search (TS) which is a metaheuristic method was developed by Glover to solve combinatorial optimization problems [12, 13]. Metaheuristics is defined as an optimization algorithm that iteratively uses simple rules or heuristics to evaluate better solutions [14]. 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 [15].

Optimal capacitor placement has been achieved with a hybrid method that utilizes TS [16]. 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 [15]. 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.

3.2.2. 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 (β), and final temperature (T_{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].

Ghose investigated the necessity of considering the unbalance and the presence of harmonics in a distribution system while solving the capacitor placement problem, and proposed a method for solving the problem with a heuristic SA technique [1]. The results indicate that the obtained capacitor kVar ignores network unbalance and supply harmonics and thus give non-optimal solution. A novel heuristic search technique has also been developed to identify a feasible capacitor setting quickly. This search technique has been used to enhance the solution speed of the SA technique.

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 [17]. 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.

3.2.3. 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.

Annaluru applied the ant colony algorithm to solve the capacitor placement and sizing problem, in which the Newton-Raphson power flow method was used to calculate the cost function [18]. However, the Newton-Raphson power flow is well known as a time-consuming method. The gradient method has been combined with the ant colony optimization in [19]. Here, the gradient vector provides a measure of the impact caused by the injection of reactive power losses in the system. The metaheuristic is used to guide and accelerate the search. The result is a methodology that can determine the global optimum solution more easily.

A powerful ant colony optimization-based algorithm for the feeder reconfiguration and capacitor placement of distribution systems has been reported [20]. 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.

3.2.4. Harmony search

The harmony search (HS) algorithm is a metaheuristic 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 [21]. The application of the HS algorithm as a new metaheuristic optimization technique to determine the optimal location and size of shunt capacitors in a distribution network has been presented [22]. The backward/forward sweep power flow is also used to obtain faster power flow solutions. A HS algorithm for optimal capacitor placement in the presence of nonlinear loads has also been presented [23]. 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 [24]. IHS employs a method for generating new solution vectors that enhances the accuracy and convergence of the harmony search algorithm [25]. 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 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.

3.2.5 Genetic Algorithm

The genetic algorithm (GA) searches for an optimal solution using the principles of evolution based on a 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 [26]. 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 [27].

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 [28]. 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 [29]. The problem is formulated such that the optimal solution did not result in severe resonant conditions at harmonic frequencies. Another GA-based method was developed for solving the discrete optimization problem of fixed shunt capacitor placement and sizing in the presence of voltage and current harmonics [30]. 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 [31]. 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 [32]. Unlike the conventional objective function, a new constraint objective cost function was formulated to maximize the net annual savings by minimizing real power loss and optimizing the cost of annual investments on shunt capacitors while considering a better voltage profile of the system. The power losses at different load levels were determined after the optimal placement of capacitors which perform a cost-benefit analysis for reactive compensation.

Some rapid GA-based methods for the optimal sizing and setting of capacitors in unbalanced multi-converter distribution systems have been used and compared to obtain a good solution with tolerable computational efforts [33]. 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 [34]. 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.

3.2.6. Particle Swarm Optimization

Particle swarm optimization (PSO) was originally introduced by Kennedy and Eberhart [35]. 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) at every iteration, 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 [36]. 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 [37]. 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.

Prakash proposed a PSO-based parallel search technique to estimate the required level of shunt capacitive compensation to improve the voltage profile of the system and reduce active power loss [38]. Loss sensitivity factors were used to determine the optimal locations required for compensation. The main advantage of this PSO-based method is that it systematically decides the locations and sizes of the capacitors to realize the optimal size reduction in active power loss and to improve the voltage profile significantly. A PSO algorithm for solving the fixed capacitor placement and sizing problem has been presented [39]. This study investigated the optimal solution of two sub-problems 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 [40]. The objective function maximizes the net savings from peak power and energy reduction while taking capacitor cost into account. Zhezhelenko extended the work reported in [40] to include the effect of mutual coupling, load unbalancing, and harmonics on the capacitor placement problem in distribution systems [41]. A BPSO was used to optimize capacitor placement and the results indicated that ignoring supply harmonics, load unbalance, and mutual coupling could cause power quality degradation.

A comparison study of PSO and the two variants of evolutionary PSO (EPSO) algorithms and their application to optimal capacitor placement in radial power distribution system is reported in [42]. The results showed that the variants of EPSO perform better in terms of the number of iterations and the ability to handle more complex fitness tests. The optimal capacitor placement considering voltage stability enhancement has been presented [43]. To calculate the voltage stability margin, the interior point method (IPM) was applied. Based on the IPM result, the dual variable was applied to the velocity of the PSO for solving the optimal capacitor placement problem.

Ejal 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. The proposed (HPSO-HPF)-based approach was tested on an IEEE 13-bus radial distribution system.

Afaghzadeh also applied the BPSO for solving optimal capacitor placement problem in a radial distribution network [44]. 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.

3.3. 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 [45]. 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 [46]. 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 GA-fuzzy logic algorithm has been proposed for solving the discrete optimization problem of fixed shunt capacitor placement and sizing in the presence of voltage and current harmonics [47]. Power losses, energy losses, and the cost of fixed capacitors were used in the objective function. The power quality limits of the IEEE-519 standard, the maximum and minimum bus voltages, and the allowed numbers of capacitor banks were considered as constraints.

A combinatorial optimization problem with a non-differentiable objective function has been formulated [48]. Four solution strategies based on simulating annealing, GA, TS, and the hybrid GA-fuzzy logic algorithms are presented. The solution methodologies are preceded by a sensitivity analysis to select the candidate capacitor installation locations. The effect of nonlinear loads on the optimal solution was also studied.

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 [49]. 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 [50]. 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.

Mohkami determined the optimal placement of capacitors using the bacterial foraging with a PSO algorithm by considering a multi-objective function [51]. The considered objective function includes reduction of power losses and installation costs of shunt capacitors and DG units. The solutions for different load levels and the utilization of capacitor discrete values were determined for optimization.

The bacterial foraging-PSO algorithm was also applied to solve the optimal placement of capacitor banks to reduce the cost of energy losses and to improve the voltage profile [52]. Here, the objective function variables include the cost of energy losses and the installation costs of the fixed and switching capacitors.

3.4. 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 [53]. 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 multi-layer perceptron neural network with error-back propagation training algorithm was used.

Passino proposed the use of bacteria foraging algorithm for solving the optimal capacitor placement problem [54]. 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 has a foraging strategy governed by four processes: chemotaxis, swarming, reproduction, and elimination and dispersal [50]. A two-stage immune algorithm which embeds compromised programming to solve the multi-objective capacitor placement problem was proposed in [55]. 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.

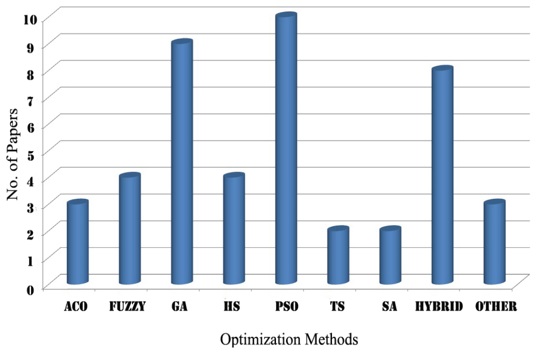

Fig. 2. Number of papers published by different heuristic optimization techniques for optimal capacitor placement

Haghdar proposed the use of a generalized pattern search method for calculating the placement and sizing of capacitor and DG in distribution networks [56]. The method was considered more precise and leads to faster results than GA-based methods.

Capacitor placement and sizing was performed by using loss sensitivity factors and plant growth simulation algorithm in [57]. 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.

4. Comparison of Various Heuristic Optimization Techniques

The number of publications and the heuristic optimization techniques applied to solve the optimal capacitor placement problem in the specified period are shown in Fig 2. PSO, GA, the hybrid methods, fuzzy and HS are the most popular optimization techniques for solving the optimal capacitor placement problem in the last decade.

From the figure, the PSO is the most popular technique applied because of its advantages which include simple implementation, small computational load, and fast convergence. PSO is efficient for solving many problems for which it is difficult to find accurate mathematical models. However, the PSO algorithm is prone to relapse into local minima and premature convergence when solving complex optimization problems. The GA which is considered as one of the first metaheuristic techniques for solving the optimal capacitor placement problem has some drawbacks, such as divergence and local optima problems. Many recent publications use hybrid techniques or multi-stage methodologies to find the optimal locations and sizes of shunt capacitors. In most of these hybrid techniques, a fuzzy approach is proposed to find the optimal capacitor locations, while other optimization techniques such as PSO, GA and bacteria foraging algorithm are used to find the optimal capacitor sizes.

5. Conclusions

This paper presents a bibliographical survey of the work published on the application of different heuristic optimization techniques to solve the optimal capacitor problem in power distribution systems. Various heuristic optimization techniques that were used to address the problem are summarized and classified, including their advantages and limitations. The paper also provides a general literature survey and a list of published references as essential guidelines for the research on optimal capacitor placement and sizing.

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