A Review of Optimal Capacitor Location Techniques in RDS

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Abstract: - Numerous approaches have been suggested in the literature for strategically placing capacitors on transmission and distribution lines to reduce line losses and improve voltage stability within power systems. Optimal capacitor placement focuses on identifying the most effective sizes and positions for installing capacitors. This study concentrates on formulating the issue of optimal capacitor placement and sizing, utilizing analytical and heuristic artificial intelligence-based optimization techniques. The aim is to provide researchers with an overview of the various methodologies introduced so far, thereby facilitating further advancements in this area for enhanced outcomes.

Key-Words: - Optimal Capacitor Positions; Distribution Networks; Objective Function; Analytical Method; Heuristic Optimization; Evolutionary Computation Methods.

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1 Introduction

The electric transmission system serves as the intermediary stage for transferring electrical energy from central generating stations to consumers, while the distribution grid represents the final stage in delivering power to consumers through utility companies. The installation of large pithead thermal power plants and nuclear power plants has resulted in increasingly intricate transmission and distribution networks. The flow of non-active power in these networks contributes to additional power losses and heightened voltage drops, [1]. Transmission network losses were recorded approximately 13% of produced power is lost as real dissipation [2] and [3].

Parallel capacitors are widely employed in power grids to mitigate energy losses by compensating for reactive power. They are instrumental in reducing losses in transmission and distribution networks and improving overall power system efficiency, which translates to increased revenue from metering. Additionally, placing capacitors strategically can indirectly reduce the need to transport megavolt-ampere reactive (MVAR) at superior voltage ranks in the transmission system and help maintain voltage stability within permissible ranges, [4]. The effectiveness of capacitor placement depends significantly on their location and sizing in the distribution and transmission networks. This challenge has spurred power system planners and researchers to explore analytical optimization and heuristic tactics for identifying the prime placement and sizing of capacitors in electrical power networks, as discussed in recent studies.

2 Problem Formulation

To calculate the active power loss in a transmission line connected between two buses, let the buses be labeled as 'i'and 'k' buses, as shown in Figure 1. The real power loss in this line may be expressed mathematically as $I_{ik}^2 R_{ik}$ [5],

$$P_{Lineloss}[k] = \frac{(P_k^2 + Q_k^2)R_{ik}}{(V_k)^2} \tag{1}$$

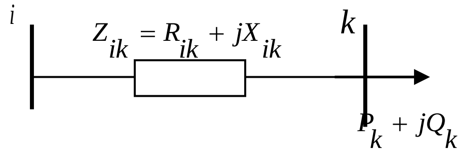

Fig. 1: Identical network for a radial distribution grid

2.1 Objective Function

The objective function used for optimal capacitor placement in Radial Distribution Systems (RDS) is the reduction of line dissipation during operation, and it could be written as

$$P_{Loss} = \sum_{m=1}^{N} I_m^2 R_m \tag{2}$$

where
m : The branch count,
N : gross branch count,
I_m : The current flowing through path m,
R_m : The resistance in path m,
P_{Loss} : The net real dissipation in kW.

The yearly price due to power dissipation may be calculated from formula 3:

$$\text{yearly price} = K_P \text{ *T* } P_{Loss} \tag{3}$$

where
K_P : The price per kWh is equal to 0.06 \$/kWh,
T : The time in hours is equal to 8760.

The cost function of the optimal capacitor location task can be more complicated to include the cost of installation and maintenance, the total cost could be written by the formula below, [6]:

$$Cost = \mathrm{K_P} . \mathrm{P_{Loss}} . \mathrm{T} + \mathrm{D}\left(\mathrm{K_I} . \mathrm{CB} + \mathrm{K_C} . \sum_{\mathrm{i}}^{\mathrm{CB}} \mathrm{Q_{Ci}}\right) + \mathrm{K_o} . \mathrm{CB} \tag{4}$$

Here the elements are obtained from [6].
D : The depreciation agent equalizes to 0.2,
CB: The size of installing capacitors,
K_C : The price for each Kvar equalizes to 25 \$/Kvar,
K_I : The price for each inauguration equalizes to 1600\$,
Q_{Ci} : The amount of inaugurated non-active power in Kvar,
K_0: The working price equalizes to 300 \$/year/position.

The previous equation is constricted whereas achieving the next limits.

2.2 Restrictions

Formula (4) is optimized to meet the following restrictions.

2.2.1 Equality Restrictions

- **Power Flow Restriction**

Conventional techniques like Newton-Raphson and Gauss-Seidel are not applicable to RDS due to their ill-conditioning. To address the load flow issue in RDS, the Forward Sweep technique has been employed, [5]. The equality restriction is represented by the next formula:

$$P_{Swing} = \sum_{i=1}^{L} P_{Lineloss}(i) + \sum_{q=1}^{N} Pd(q) \tag{5}$$

$$Q_{Swing} + \sum_{i=1}^{CB} Q_{Ci} = \sum_{i=1}^{L} Q_{Lineloss}(i) + \sum_{q=1}^{N} Qd(q) \tag{6}$$

where
P_{Swing} : The real power of slack point,
Q_{Swing} : The imaginary power of slack point,
L : The size of the transmission path,
$Pd(q)$: The need for real power at point q,
$Qd(q)$: The need for imaginary power at point q,
N : The scale of full points.

2.2.2 Inequality Limits

- **Voltage Limit**

The value of voltage at every node must be restricted by the next formula:

$$V_{\min} \le |V_i| \le V_{\max} \tag{7}$$

Here $V_{\min}, V_{\max}$ are the smallest and highest voltages at node i. These voltages in RDS range from 0.90 to 1.1 p.u as specified in [5].

- **Compensation Restriction**

The non-active power injected at every candidate point must be less than its effective non-active power.

- **Gross Non-active Power Restriction**

It is important to note that the gross injected non-active power is constrained by the next formula:

$$\sum_{i=1}^{CB} Q_{Ci} \le \sum_{q=1}^{N} Qd(q) \tag{8}$$

- **Power Factor Restriction**

The power factor of the network (PF) must be greater than the smallest value and less than the highest value, as indicated by the next formula.

$$PF_{\min} \le PF \le PF_{\max} \tag{9}$$

- **Line Capacity Restriction**

The complex power flowing through any path should not exceed its capacity limit, as shown by the next formula.

$$S_{Li} \le S_{Li(rated)} \tag{10}$$

- **Capacitor Rating Restriction**

The supplied kVAr of the combined capacitor is represented as a discrete magnitude in the step of 50 kVAr and is defined by the next formula [6].

$$Q_{c\min} \le Q_c \le Q_{c\max} \tag{11}$$

3 Analytical Optimization Methods

The analytical method was the most effective for placing capacitors in power systems. This method employed calculus to identify the optimal location for the capacitor that minimized losses and maximized cost savings. It assumed that the feeder had no sub-branches, had a uniform cross-section throughout, and was evenly distributed, [7]. This method required minimal numerical data from the power system and was straightforward to apply in practice. A widely recognized outcome of analytical methods was the (2/3) rule. According to this rule, to meet maximum reduction, a capacitor with (2/3) of the non-active power from the beginning of the feeder must be installed at a point two-thirds of the way along the feeder's range from the beginning. While this simplifying assumption could introduce errors, and increase losses as discussed in [8]. An analytical method that minimized loss by placing shunt capacitors was illustrated in [9], first identifying nodes to be compensated and then optimizing the capacitor size at those nodes. A voltage-independent non-active current pattern for loss reduction through the use of shunt capacitors was introduced in [10]. An analytical method for capacitor position on prime distribution feeders based on non-active current as outlined in [11].

4 Fuzzy Logic: A Heuristic Optimization Technique

Heuristic optimization methods enabled the resolution of optimization issues that were challenging or impractical to address using analytical techniques. These tools had been combined to tackle extremely difficult problems, offering two significant advantages: (i) They significantly reduced development time compared to traditional approaches, and (ii) they yielded robust systems. Heuristic optimization techniques, which aimed to find near-global solutions, were generally divided into three groups: fuzzy logic techniques, evolutionary approaches, and integrated artificial intelligence strategies. The fuzzy logic method was rooted in Fuzzy Set Theory (FST), presented for handling logical reasoning, [12]. FST provided a mechanism to address uncertainties in data. Moreover, fuzzy logic incorporated heuristics and integrated engineering judgments to enhance the optimization process for placement of capacitors. To apply fuzzy logic effectively, it was essential to identify key variables influencing the decisions and measure their importance levels. A correlation function defined the behavior of these parameters by indicating their alignment with known data. Based on these conditions, rules were established to determine vital actions for achieving a solution. The application of fuzzy logic has been successful in practical distribution systems for optimal capacitor planning, [13]. For instance, a fuzzy approach to identify optimal capacitor locations with dual objectives: minimizing ohmic power loss and maintaining voltage inside allowed thresholds were discussed in [14]. The capacitor setup issue addressed through fuzzy approximate reasoning was addressed in [15]. FST was employed in [16] to solve discrete optimization problems related to determining the sizing and placement of fixed shunt capacitors in the presence of harmonic conditions.

5 Evolutionary Computation Techniques

5.1 Simulated Annealing

Simulated Annealing (SA) was based on the process of annealing in metals or crystals. It relied on three key features: preliminary temperature, cooling speed, and last temperature. The cooling schedule governed the temperature at every iteration, guiding the state toward a solution as it cooled. At high temperatures, the state could move freely between other states, but at low temperatures, this movement became more restricted. SA was a robust and versatile stochastic optimization method that, in theory, can asymptotically reach the global best with certainty.

However, a major drawback was that it required significant CPU time to locate the global optimum, [17]. The importance of accounting for unbalance and harmonics in a distribution system when using a heuristic SA approach was explored in [18]. The use of SA for capacitor placement problems using general heuristic optimization techniques was discussed in [19]. The SA approach for planning optimal VAR resources in large-scope power networks was utilized in [20]. A combined simulated annealing/genetic approach to minimize the CPU time of SA while preserving its primary benefits, such as achieving near-optimal global solutions within a limited duration was introduced in [21]. A Modified SA (MSA) approach had been created to improve the siting and capacity of fixed capacitor banks while improving power quality in contemporary distribution grids, [22]. These networks, which supported a mixture of nonlinear and linear characteristics, imposed voltage and current harmonics and included changeable-speed wind turbines as Distributed Generation (DG). The uncertain power production of wind DG was simulated through Monte Carlo methods to model the distribution of power flow.

5.2 Harmony Search

The Harmony Search Approach (HSA) was a recent meta-heuristic approach stimulated by the Procedure of natural musical performance, [23]. Musicians began with certain harmonies and aimed to improve them through improvisation, iteratively creating new and better solutions based on past ones with random adjustments. Ultimately, HSA arrived at an optimal amount. The use of HSA for finding the best siting and size of parallel capacitors in 9-node RDS was discussed in [24]. Tests across 7 load levels showed that HSA achieved a greater reduction in power loss and more substantial energy savings compared to the Genetic Approach (GA). The use of HSA as a novel meta-heuristic optimization method for determining the optimal placement and size of shunt capacitors in a distribution network, employing a backward/forward sweep power flow for faster solutions was detailed in [25]. The use of the HSA as a novel meta-heuristic optimization way to identify the best site and size of connected capacitors in a RDS with nonlinear loads has been demonstrated in [26]. A novel multi-objective approach to refine the site and capacity task while meeting acceptable and sufficient standards was introduced in [27]. The optimization problem considered four objectives: Net Harmonic Distortion (THD) of voltage, High total line loss, maximum load loss factor, and net currents of Active Power Filters (APFs), which included the costs of the APFs. The new model investigated the impact of different types of APFs to upgrade flexibility in harmonic control. The best site and capacity of capacitors in order to lessen both the net ohmic power loss and the cost of installing connected capacitors, while ensuring compliance with working and power quality limitations were investigated, [28]. This was achieved using the HSA, a relatively fresh meta-heuristic approach. The net price of ohmic power loss was used as the cost function, dependent on the voltage profile and THD constraints. Power flow simulations were carried out using the Backward/Forward Sweep-based RDS power flow approach and the harmonic power flow approach. The developed HSA's performance was evaluated on the standard IEEE 13-bus unbalanced RDS. A Self-Adaptive Harmony Search Approach (SAHSA) for optimizing the capacitor site to minimize power loss was presented in [29]. The Forward/Backward Sweep power flow technique was employed to resolve the RDS. The developed approach was examined on the IEEE 33-bus and IEEE 69-bus RDS. The outcomes were in comparison to those obtained using the Particle Swarm Optimization (PSO) approach and the Plant Growth Simulation Approach (PGSA), showing that the developed method delivered superior solution quality.

5.3 Particle Swarm Optimization

PSO was a population-based, self-adaptive meta-heuristic search way initially addressed in 1995, [30]. This method used a group of particles, every serving a possible resolution to the reactive power issue. These particles explored a multidimensional search space by changing their positions until they reached a relatively stable state or ran into computational constraints. In the realm of social science, PSO combined a social-only model, where individuals adjusted their behavior based on the successful beliefs of their neighbors, and a cognition-only model, where individuals acted independently. Particles updated their positions based on these models, [31]. A binary PSO for solving binary optimization problems related to ideal capacitor positioning in systems with nonlinear loads was utilized, [32]. An approach to reduce transmission losses by installing SVCs using PSO as the optimization method was suggested in [33]. They developed PSO source code to define the best capacity of SVCs to decrease power dissipation in transmission, considering voltage profiles and installation costs, studied on the IEEE 30-point RTS. A discrete PSO with a radial distribution power flow (RDPF) approach to create a hybrid PSO (HPSO) approach was combined in [34]. PSO was used for global optimization, while the RDPF algorithm calculated the cost function and verified bus voltage boundaries. To account for harmonics, the HPSO was incorporated with a harmonic power flow (HPF) approach, and this technique was examined on an IEEE 13-point RDS. A PSO method was presented to get the best capacity and site of capacitors, [35]. The approach identified the best sites for connected capacitors based on the 24-hour load profile and determined appropriate values for both constant and dynamically switched-type capacitors. To narrow down the search space, a dynamic sensitivity analysis method was utilized to choose potential installation sites for the capacitors. Capacitor site and sizing using LSF and PSO were addressed in [36]. PSO was applied to estimate the necessary degree of connected capacitive compensation to enhance the system's voltage gradient. The developed approach was evaluated on 10, 15, and 34-point RDS, yielding very promising outcomes. The capacitor site process in RDS through a three-step approach was developed in [37]. First, candidate nodes were identified using a sensitivity analysis approach. Then, the capacity and quantity of capacitors were refined employing a PSO with Differentially Perturbed Velocity (PSODV) method. This approach minimized power losses while keeping the voltage gradient inside permissible boundaries. By combining the benefits of PSO and Differential Evolution (DE), the PSODV method achieved the best possible solution without becoming stuck in local minima. An efficient new method for capacitor placement in radial distribution systems, aiming to enhance the voltage profile and reduce power loss was suggested in [38]. The solution was divided into two parts: first, LSF was used to identify candidate locations for capacitor placement; second, a novel algorithm combining the Shuffle Frog Leaping Approach (SFLA) and PSO was employed to determine the ideal capacity of capacitors at the selected locations. Two evolutionary methods, PSO and Multi-Agent PSO (MAPSO), for more impactful capacitor positioning in RDS, aiming to lower ohmic power loss and enhance the voltage gradient under variable load cases were compared in [39]. The Fuzzy Expert System determined the capacitor locations in a 69-bus system. PSO and MAPSO were then used to optimize the costs related to capacitor placement and to maximize annual cost savings for the power systems.

5.4 Tabu Search

Tabu Search (TS) originated dating back to the 1970s and was first formally presented in [40]. TS was a meta-heuristic technique for resolving combinatorial optimization tasks [41] and [42], specified as an optimization approach that repeatedly used basic principles to assess better remedies, [43]. TS built on the hill-climbing approach, which improved solutions by generating and selecting the best candidates in the neighborhood of an initial solution. However, the hill-climbing approach could conveniently become trapped in a regional optimum, [44]. TS extended this method by incorporating an adjustable memory named the tabu outline, where attributes of solutions remain for a while before new attributes are added. Each iteration updated the tabu outline with a recent feature. TS also employed intensification and diversification techniques to find optimal solutions, using a frequency counter that tracked how often a solution had been visited. TS had been employed for an ideal capacitor site in radial feeders, [45], [46]. A hybrid method combining TS for an ideal capacitor site was introduced in [47]. TS had been enhanced with characteristics from realistic heuristic methods and other integrative methods, like GA and SA. TS-based strategy for choice support in capacitor allocation in RDS, considering conflicting objectives cost-related and working features was described in [48]. This model allowed decision-makers to explore a range of potential solutions and select a satisfactory compromise.

5.5 Ant Colony Optimization

The analogy between ant foraging behavior and combinatorial optimization problems had inspired the Ant Colony Optimization (ACO). Ants deposit an aromatic material known as a chemical signal along their route to meal, with the amount based on the length of the route and the condition of the food supply. The strength of the chemical signal trail influences the path choice of other ants. Over time, if no additional pheromone was deposited, the trail evaporated. Ants were attracted to stronger pheromone trails, which led them to follow and reinforce these paths, especially those directing to richer food supplies closer to the home. This behavior ensured that the best paths, with more intense pheromone trails, were more likely to be selected. This behavior of real ants could be simulated to resolve integrative optimization tasks. In the ant system approach, artificial ants searched the solution space, mimicking real ants. The target parameters of solutions were related to the value of food supplies. Pheromone trails in the ant system were associated with features of the solutions, serving as a responsive memory of prior solutions. Ant systems has shown excellent outcomes in various applications. ACO to the capacitor choice task in a balanced three-phase distribution network, using the Newton-Raphson technique to compute the price function was applied in [49]. The use of ACO for parallel capacitor sites within transition restrictions in distribution systems was presented in [50]. ACO for feeder reconfiguration and capacitor site in RDS was addressed in [51]. The study aimed to develop new techniques for resolving optimal capacitor sites, optimal feeder restructure, and their mixture.

5.6 Genetic Approach

The conceptual basis for GA was first addressed in [52] and elaborated on later in [53]. GA was motivated by the procedure of biological development and utilized Darwin's theory of natural selection to find optimal solutions. GA typically consisted of a fitness function, selection, and variation. Key operators in genetic variation were mutation and crossover, which enabled the reproduction of chromosomes by changing their positions or altering some of their bits. Ultimately, this process generated a chromosome with the peak fitness rate, thus identifying the global optimal resolution, [54]. Combinations of genetic methods with other techniques could be used for optimal capacitor design. A ten-step GA-based procedure for capacitor placement was presented in [55]. GA-based approach for capacitor site in a symmetrical grid that could assess fluctuations in load was introduced in [56]. In [57], an elite-based simplex GA hybrid technique, coupled with a multi-population GA, was suggested to set the site, capacity, and count of capacitors in asymmetrical RDS, though harmonic distortion was not regarded. The technique utilizing an indicator and GA to identify appropriate candidate points for capacitor installation in RDS was reported in [58]. A PLI indicator was employed to ascertain the appropriateness of the capacitor site at every point, identifying the most suitable points for placement. GA-based method for ideal capacitor site and capacitance calculation in RDS, considering multiple contributing elements in its multi-objective cost function was addressed in [59]. A Non-dominated Sorting GA-II (NSGA-II) based technique was discussed in [60] for RDS restructure. Unlike the traditional GA-based approaches, the suggested technique did not need weighting factors for the transformation of the multi-objective function into an identical single cost function. The application of GA for non-active power loss alleviation in RDS was developed in [61]. IEEE 34-point was applied simultaneously with the ERACS and MATLAB as effective tools for the analysis and simulation work. ERACS was used to carry out a power flow study while MATLAB was applied for the detection of capacitor current via GAtool, and approach for the computation of loss savings, its particular capacitor capacity, and site.

5.7 Plant Growth Simulation Approach

The Plant Growth Simulation Approach (PGSA), [62] mimicked the natural growth process of plants, where a plant's trunk expands outward from its root, segments expand outward from points on the trunk, and further segments expand outward from points on those segments. This procedure was reiterated till the plant was fully formed. Analogously, in the PGSA, the system to be optimized started "growing" from a root and continually "growing" segments till the optimal resolution was detected. An effective strategy combining LSF and PGSA for capacitor sites in RDS was presented in [63]. LSF identified candidate bus locations for compensation, and PGSA estimated the requested rank of parallel capacitive compensation at these optimal sites to improve the voltage gradient and lower ohmic power loss. This algorithm was tested on 9 and 34-bus grids. A method using PLI and PGSA to select initial voltage regulator buses and decide the best locations, count, and tap settings of voltage regulators, ensuring a soft voltage gradient across the grid was introduced in [64]. Capacitor placement was determined using LSF, while the PGSA was utilized for sizing in [65]. The LSF helped identify the bus with the greatest potential for loss reduction when a capacitor was installed. Consequently, these sensitive points could be considered potential sites for capacitor sites. PGSA estimated the requested amount of parallel capacitive compensation to enhance the grid's voltage gradient. Capacitor site and capacity were specified utilizing LSF and the PGSA, respectively in [66]. The suggested approach was tested on 33 and 34-point RDS, successfully achieving the objectives of loss reduction and voltage profile enhancement.

5.8 ABC Approach

The Artificial Bee Colony (ABC) approach, introduced by [67], mimicked the behavior and intelligent foraging patterns of honey bee swarms as they searched for food resources and communicated the quantity of these sources to other bees. ABC was discussed for the contraction of the dissipated power in the RDS. The suggested method was examined on 14, 33, and 119-point grids and the collected results were effective and encouraging [67]. ABC was presented to get the best and synchronous site and capability of these sources to lower power dissipated, and enhance voltage gradient. The introduced method was verified on a real grid of Kerman Province, Iran and the simulation outcomes were addressed in [68]. The Hybrid Honey Bee Colony (HHBC) optimization method was employed to identify the optimal sites and quantities of static and dynamic connected capacitor units in asymmetrical IEEE 25-point and IEEE 37-point deformed RDS, which included nonlinear loads and DG, [69].

5.9 Flower Pollination Approach

The Flower Pollination Approach (FPA) was stimulated by the pollination procedure of flowering plants. The primary objective of a flower was basically reproduction by way of pollination. Flower pollination was regularly correlated with the shift of pollen, which is linked with pollinators specifically birds and insects, [70]. An efficient algorithm named the FPA was introduced for the optimal placement and capacity of capacitors in different RDS. As a starting point, the PLI was used to identify the most suitable nodes for capacitor installation. Subsequently, the developed FPA decided on the appropriate capacity and precise locations of the capacitors among the selected buses, [70]. The FPA was suggested to lower net active dissipated power, lower overall costs, and elevate voltage gradient in various RDS. Initially, potential locations for shunt capacitors were identified by examining buses with higher LSFs and lower VSIs. Then, the FPA was applied to determine the optimal sites and sizes of capacitors from these identified sites. The potency of the suggested approach in improving voltage profiles and lessening dissipated power was demonstrated across three RDS of diverse ranges and configurations, [71].

5.10 Differential Evolution Algorithm

The Differential Evolutionary (DE) approach was introduced by Storn in [72]. To begin the approach, an initial population was generated. To locate the global optimum, the population was modified using mutation and crossover operators. An enhanced DE approach, labeled SaDE, was applied to resolve the OLSC process, [73]. The presented approach was acquired by self-adapting the control factor of mutation and crossover agents. Three working conditions, fixed and Fluctuating as well as effective, were examined on 10-point and 34-point RDS. Fitness was a function of yearly cost, besides charge, six other factors employed for comparison were connected capacitor units and related charge, CPU time, lower potential, active dissipated power, and related charge. DE approach was presented for the optimal site and capacity of capacitor in RDS, [74]. The decision criteria included net charge, lower potential, gross connected capacity, and dissipated power. Outcomes of emulation had been measured against others. DE method for multi-objective programming was addressed in [75] related to the capacitor site in the RDS. The identified locations had decreased dissipated power, leading to increased global funds, despite a slight increase in the net capacity of the capacitors to be installed.

5.11 Heuristic Algorithm

Heuristic Algorithm (HA) was first announced by [76] and formed later, when various heuristic was implemented for defined tasks in various areas of science, such as electrical systems. Fundamentally, a heuristic was formulated to offer better computational results as compared to traditional optimization strategies, at the expense of lower accuracy. HA was introduced to address the optimal capacitor site issue in RDS, [77]. The core concept involved solving a simplified version of the precise arithmetic model by relaxing the integrity constraint of the capacitor-related variable and approximating the cost function with a derivable function. The relaxed issue, formulated as a non-linear programming (NLP) problem, was tackled using an efficient NLP approach. From this resolution, a heuristic technique identified a set of near-optimal buses for the primary issue.

A quick heuristic method for addressing the problems of capacitor sizing and placement was presented in [78]. The method was effective for deciding both static and dynamic capacitor sizes. Initially, candidate sites for capacitors were identified using node stability indicators. The optimal capacitor sizes were then identified by solving a non-linear constrained issue. Since strict voltage constraints could make the problem unsolvable, these constraints had been replaced with constraints on the reactive branch currents. A HA that focused on selecting a few critical nodes, known as sensitive nodes, for capacitor installation to achieve significant overall loss reduction and optimal savings in the system was addressed in [79]. The approach was based on the premise that sensitive points were relatively few compared to the gross number of points, thereby significantly reducing the problem's complexity. While sensitive nodes were ideal for both fixed and switched capacitor banks, this study was limited to fixed capacitors only.

5.12 Bat Approach

The Bat approach (BA) is inspired by the echolocation mannerisms of microbats. These bats use a form of sonar, known as echolocation, to identify prey, navigate around obstacles, and find their roosting crevices in the night. They generate powerful sound pulses and hear the echoes reflected from nearby bodies, [80]. Five techniques have been applied to the IEEE-34 bus test system for optimally locating the capacitor banks for power loss reduction in RDS, [80]. Comparison between different approaches can be carried out to find the best approach for the given problem. The LSF method was employed to identify the optimal positions for capacitors, while the BA was employed to determine their optimal sizes to achieve loss decline. A modified load flow approach, known as the branch current load flow method, was applied to solve radial distribution networks, [81]. A novel approach for simultaneously allocating DG and capacitors in RDS with multiple load configurations was presented. The approach aimed to diminish power loss and improve the VSI. The BA was employed to decide the finest size and location of both DG units and capacitors. The feeder requirements were uniformly varied from 0.5 (low demand) to 1.6 (maximum demand) in increments of 0.01, [82].

5.13 Firefly Approach

The Firefly approach (FA) is a population-based, nature-inspired metaheuristic optimization method [83]. It is modeled on the behavior of fireflies, particularly their light radiation, light retention, and reciprocal attraction mechanisms. A two-stage method combining the LSF and the FA for effective capacitor placement was introduced. Installing a shunt capacitor in the optimal position leads to a notable reduction in power loss, a decrease in total annual costs, and an enhancement in the voltage configuration. Therefore, the integration of the LSF and the FA produced favorable outcomes, [83]. The optimal capacitor allocation challenge was addressed using loss sensitivity analysis combined with the FA to minimize power loss in the distribution system. The developed method was applied on IEEE 15, 34, 69, and 85-bus radial distribution systems. It strategically installs capacitors at fewer locations with optimal capability, skilfully reducing both preliminary and operational costs, [84]. The FA was designed to handle the capacitor allocation challenge and quantify the overall decline in line losses across the distribution system. Simulations were conducted on a real-world power network in Kerman Province, Iran, [85].

5.14 Bacterial Foraging

A fuzzy verdict process, combined with an evolutionary approach known as the Bacterial Foraging Algorithm (BFA), was developed into a reliable optimization tool to handle the capacitor placement challenge. This tool effectively regarded both loss decline and node voltage refinement. It was implemented as a cost-based objective function aimed at minimizing the cost of energy loss and peak power. The implementation of this integer-coded approach, alongside fuzzy decision-making, resulted in superior outcomes compared to prior algorithms that focused solely on either reducing peak power or energy loss in power systems, [86]. An Improved BFA (IBFA) was further utilized to optimally determine the location and size of capacitors in radial distribution systems, with the dual objectives of diminishing power loss and elevating potential profiles. A basic load flow procedure, built upon the Bus Injected to Branch Current (BIBC) matrix approach, was encoded in MATLAB to execute the process. The success of this approach was confirmed in the IEEE 33-bus radial distribution system and a realistic 50-bus Canteen feeder in the Zaria power system, Nigeria, [87]. A Linear Adaptive BFA (LABFA) which was an enhanced version of the conventional BFA was applied for allocation and scaling of D-STATCOM in radial distribution systems. The effectiveness of the LABFA was applied to the IEEE 33-bus. The suggested LABFA indicated the grid voltage profile was enhanced by 43.11% with the installation of D-STATCOM, [88].

5.15 Cuckoo Search Algorithm

Cuckoo Search Algorithm (CSA) was a meta-heuristic search method developed by Yang, motivated by the obligate brood parasitism behavior noticed in certain cuckoo species. The primary advantage of CSA was that it required the tuning of only one parameter. Two-level processes had been introduced for the optimal placement of capacitors in a RDS in [89]. In the initial level, the LSF was utilized to determine the optimal location, and in the final level, the CSA was employed to minimize costs, including both the charge of the capacitors and the charge related to power loss. A two-level method for identifying the optimal placement and sizing of capacitors in RDS to enhance the potential profile and decrease real power loss was presented in [90]. In the first level, capacitor locations were determined using the LSF. The second level employed the CSA to determine the optimal capacitor capabilities. The sizes that yielded maximum annual savings were calculated by considering the charge of the capacitors. A method for evaluating the optimal position and capability of capacitors was being assessed, with an objective function designed to improve the potential profile and mitigate power loss of the system, subject to equality and inequality limitations were addressed in [91]. The VSI was used to re-establish the optimal capacitor locations. The recently advanced CSA was suggested to find the optimal capacitor sizes. To validate the feasibility of the suggested approach, it was checked on IEEE 34-bus and 69-bus RDS under various load factors. The CSA was utilized to locate the optimal placement of capacitors, or capacitors combined with DG units, with the goal of improving the potential profile, reducing total power losses, and enhancing system stability, relative to the base system, [92].

5.16 Imperialist Competitive Algorithm

The Imperialist Competitive Algorithm (ICA) was motivated by the concept of imperialistic challenge. ICA began by generating a random population referred to as countries, which were divided into colonies and imperialists, forming empires. The empire with the lowest costs provided the optimal capacitor placement solution, identifying the best size and position within the RDS. The primary goal was to minimize the energy loss cost. The ICA had been tested on the IEEE 69-Bus system across various demand levels, [93]. The ideal placement of capacitors in an unbalanced network was determined, considering harmonic distortion, [94]. To accurately analyze the unbalanced network, a three-phase load flow using a backward-forward sweep method was employed, incorporating mutual inductance in the optimization process. The capacitor placement issue, a discrete nonlinear optimization problem, was addressed using the ICA. An efficient hybrid method that combined the ICA and GA to effectively address the challenges of optimal sizing and location of DG units and capacitor units synchronously was discussed in [95]. The objective was to reduce power loss, mitigate the system voltage gradient, increase the VSI, balance the load, and provide distribution and transmission to alleviation capacity for both energy systems and consumers.

6 Hybrid Artificial Intelligent Techniques

A hybrid intelligent approach combines multiple artificial intelligence methods to achieve more effective outcomes. In [96], a four-stage technique was launched, integrating SA, GA, TS, and a hybrid GA-Fuzzy Logic algorithm to address a combinative optimization challenge with a non-differentiable targeted function. The process began with a sensitivity analysis to identify potential locations for capacitor placement. In [97], a merged Fuzzy-GA approach for optimal capacitor allocation in radial distribution systems was illustrated, focusing on minimizing losses and enhancing potential profile. This procedure was tested across various systems, considering both voltage profile and loss decline simultaneously in capacitor allocation decisions. A two-level process for determining the optimal sizes and positions of parallel capacitors to compensate for reactive power in RDS was proposed in [98]. The GA was used to identify optimal capacitor allocation, while the PSO approach was applied to determine the finest capacitor capability. In [99], a hybrid algorithm combining PSO with bacterial foraging was introduced for optimal capacitor positioning, across a multi-objective function that included lessening power losses and placement charges of parallel capacitors along with DG units. The outcome was optimized for various demand requirements with different capacitor sizes. A fuzzy-ant approach was presented to determine the appropriate locations and capacitor size, offering versatility for use in planning, growth, and running analyses of distribution systems. This technique was evaluated on a 25-bus electrical distribution system, [100]. A fuzzy multi-objective method based on a GA was introduced to find the optimal values for fixed and switched shunt capacitors. This approach aimed to raise the net savings along with enhancing the potential profile in a radial distribution system. The two primary goals, maximizing net savings and minimizing voltage deviation at nodes, were first converted into fuzzy variables. These goals were then merged into a solitary fuzzy satisfaction objective function using suitable weighting factors, [101]. A novel algorithm combining fuzzy logic, Forward Update (FWD) along with the GA algorithm was proposed for capacitor placement in distribution feeders. The challenge was formulated with three divergent goals: minimizing capacitor procurement and installation charge, active losses charge, and power production charge under peak demand case. This innovative development addressed a multi-objective, non-differentiable optimization challenge. The developed method utilized an iterative optimization technique, integrating the FWD approach within the GA framework, [102]. Additionally, a new method for optimal capacitor allocation was introduced, using GA and fuzzy reasoning to enhance potential profiles and decrease power losses in main distribution systems. Fuzzy reasoning identified delicate buses, which were then considered potential positions for capacitor allocation. The GA approach solved the optimization challenge efficiently, identifying optimal or near-optimal compensations with manageable mathematical effort. This procedure was implemented on two systems, [103]. Furthermore, a refined method for placing capacitors in radial distribution feeders to enhance potential and minimize active power loss profiles was presented. The algorithm involved identifying both the position and size of the capacitors. The nominated nodes for capacitor allocation were identified using FES rules, and capacitor sizing was formulated as an optimization challenge aimed at minimizing losses, fixed using the HPSO technique, [104].

7 Other Techniques

In addition to the methods outlined in earlier sections, other techniques employed to determine the optimal location and size of capacitors in power distribution systems are discussed including the Artificial Immune Algorithm [105], Fireworks Algorithm [106], [107], and Shark Smell Optimization Algorithm [108].

8 Conclusion

This paper provides a review of various optimization algorithms employed to address the optimal capacitor allocation challenges in power distribution and transmission systems, with the target of reducing line losses and improving potential stability. Although analytical approaches are straightforward, they are often hindered by sluggish calculation speeds and limited convergence. On the other hand, heuristic optimization techniques deliver faster computations and better convergence, making them more adequate for large, complicated systems. The integration of multiple AI techniques, referred to as Hybrid AI techniques, can further enhance the quality of the results. This work serves as a comprehensive literature review that is valuable for research in optimal capacitor allocation.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

While preparing this work, the author used Grammarly to edit the language. After using this service, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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