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Optimization-based approaches for power loss reduction and voltage profile enhancement in radial distribution systems: A review of capacitor placement strategies

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Abstract

Radial distribution systems (RDSs), which dominate electricity delivery in many developing countries, are inherently prone to high technical losses and poor voltage regulation due to long feeder lengths and predominantly inductive loads. Optimal capacitor placement has therefore emerged as a cost-effective strategy for reducing power losses and enhancing voltage profiles. This paper presents a structured narrative review of optimization-based capacitor placement approaches applied to RDSs, synthesizing analytical, heuristic, and metaheuristic methods reported in the literature. The review systematically examines commonly used power-flow techniques and compares major optimization algorithms, including Genetic Algorithms, Particle Swarm Optimization, Ant Colony Optimization, and hybrid frameworks, with respect to solution quality, convergence behavior, computational effort, and practical applicability. The synthesis reveals broad consensus that metaheuristic methods outperform deterministic approaches in complex, nonlinear networks, while also highlighting important trade-offs: algorithms offering marginally higher loss reduction often incur increased computational cost or parameter sensitivity. The review further identifies persistent gaps related to load variability modeling, economic integration, and real-world validation, particularly in data-constrained rural networks. From a practical perspective, the findings indicate that no single optimization technique is universally superior; rather, algorithm selection should be guided by network characteristics, data availability, and implementation constraints. The paper concludes by outlining context-specific research directions to support the deployment of optimization-based capacitor planning in developing power systems such as those in Uganda.

Nomenclature and units

P_{loss}	Total real power loss (kW)
Q_c	Capacitor reactive power rating (kVAr)
V	Bus voltage magnitude
w_1, w_2, w_3	Objective function weighting coefficients
C_{cost}	Capacitor installation cost
RDS	Radial Distribution System
ACO	Ant Colony Optimization
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
BFS	Backward/Forward Sweep
PF	Power Factor
SDG 7	Sustainable Development Goal 7 (Affordable and Clean Energy)

1.0 Introduction

Electric power distribution networks (DNs) form the final link between generation and consumption, and their performance directly influences supply reliability, voltage stability, and overall system efficiency. As demand for electrical energy continues to rise globally, distribution systems have become increasingly strained, leading to technical problems such as high power losses, voltage drops, and poor power factors. These issues are particularly pronounced in radial distribution systems (RDSs), which dominate power delivery in developing regions due to their structural simplicity and low installation cost (Gebru *et al*., 2021; Shrestha, 2023). The long, resistive feeders characteristic of radial topologies result in high R/X ratios, exacerbating voltage instability and line losses, especially during peak load conditions.

Several technical solutions have been proposed to mitigate these inefficiencies. Among the most effective are network reconfiguration, distributed generation (DG) integration, and capacitor placement (Wang *et al*., 2020; Bhumkittipich & Phuangpornpitak, 2013; Bhargava *et al*., 2023; Tahir *et al*., 2022). Of these, the strategic placement and sizing of capacitors remain the most widely used and cost-effective approach for improving voltage profiles and reducing power losses in distribution networks. When capacitors are installed at appropriate locations, they supply local reactive power, thereby lowering current magnitudes, stabilizing voltages, and enhancing power factor. This not only improves energy efficiency but also extends equipment lifespan and defers costly network reinforcements (Nawaz *et al*., 2021).

However, capacitor placement is not trivial. Improper sizing or inappropriate location can cause over-compensation, voltage rise beyond permissible limits, or even resonance conditions that jeopardize network stability (Sirjani *et al*., 2011). Therefore, identifying optimal locations and sizes for capacitors requires advanced computational and optimization techniques capable of solving nonlinear, multi-objective problems subject to technical and operational constraints. Conventional deterministic methods often fail to provide globally optimal solutions in complex, real-world systems. Consequently, metaheuristic algorithms notably Ant Colony Optimization (ACO) have gained prominence for addressing this class of engineering problems (Lei *et al*., 2022b).

ACO is inspired by the foraging behavior of ants that collectively discover the shortest paths between their nests and food sources by depositing and following pheromone trails. When adapted to power systems, this mechanism effectively searches vast solution spaces to locate the most efficient capacitor configurations. The algorithm's self-organizing and probabilistic nature enables it to balance exploration and exploitation, avoid premature convergence, and achieve near-global optima even under nonlinear constraints. These attributes make ACO particularly suitable for optimizing power distribution feeders such as Uganda's Kabale–Kisoro 33 kV network, which features long radial lines and scattered rural loads.

The Ugandan context highlights the urgency of such optimization. Nationally, distribution losses account for about 13 % of total generated electricity, much of which occurs in low-voltage rural networks (Tahir *et al*., 2022). The Kabale–Kisoro feeder, extending across mountainous terrain, suffers from significant voltage drops and poor power factors due to long line lengths and dispersed load centers. Reports from Umeme Ltd and the Uganda Electricity Distribution Company (UEDCL) show that technical losses and low-voltage complaints are persistent in this region. Thus, deploying an optimization-based approach to capacitor placement offers a practical means to enhance power quality, reliability, and efficiency while aligning with Uganda's National Development Plan III and Sustainable Development Goal 7 on affordable and clean energy.

Given these motivations, this review aims to synthesize existing theoretical foundations, power-flow techniques, and optimization-based capacitor-placement methods with emphasis on metaheuristic approaches such as ACO. It consolidates empirical evidence from prior studies, identifies methodological and contextual research gaps, and highlights implications for power-system planning in developing countries.

Against this background, the objective of this review is to critically examine optimization-based capacitor placement strategies for power loss reduction and voltage profile enhancement in radial distribution systems. Specifically, the review seeks to address the following key questions: (i) how do analytical, heuristic, and metaheuristic approaches differ in their ability to identify optimal capacitor locations and sizes in RDSs; (ii) what comparative strengths, limitations, and convergence characteristics have been reported for widely used metaheuristic algorithms, particularly Ant Colony Optimization, Genetic Algorithms, and Particle Swarm Optimization; and (iii) to what extent do existing studies account for practical implementation challenges such as network nonlinearity, load variability, and economic constraints in real distribution feeders. The unique contribution of this paper lies in its structured synthesis of both theoretical and application-oriented studies, with explicit attention to developing-country contexts that are underrepresented in the literature. By integrating methodological comparison, critical evaluation of reported limitations, and discussion of practical deployment issues in rural distribution networks such as those found in Uganda, this review advances existing knowledge beyond algorithm-centric surveys and provides a context-sensitive perspective to inform future research and utility-level planning.

This study adopts a structured narrative review (focused survey) approach to synthesize existing research on optimization-based capacitor placement strategies for power loss reduction and voltage profile enhancement in radial distribution systems (RDSs). A structured narrative review was selected in preference to a full systematic review because the primary objective of this paper is to critically compare theoretical formulations, optimization algorithms, and application contexts reported in the literature, rather than to conduct a statistical meta-analysis of quantitative outcomes. This methodological choice is consistent with established review practices in power systems engineering, where heterogeneous network models, varying objective functions, and algorithm-specific performance metrics limit the feasibility of strict systematic aggregation.

A comprehensive literature search was conducted to ensure broad and representative coverage of peer-reviewed engineering research. Major scientific databases, including IEEE Xplore, ScienceDirect (Elsevier), Scopus, and SpringerLink, were systematically searched. The primary literature search was carried out between January 2024 and March 2025.

The search strategy employed combinations of carefully selected keywords related to capacitor placement and distribution system optimization, using Boolean operators to refine relevance. Core search terms included "optimal capacitor placement," "reactive power compensation," "radial distribution system," "power loss minimization," "voltage profile enhancement," "metaheuristic optimization," and specific algorithm names such as "Ant Colony Optimization," "Genetic Algorithm," and "Particle Swarm Optimization." A typical search query took the form ("capacitor placement" AND "radial distribution system") AND ("optimization" OR "metaheuristic" OR "Ant Colony Optimization"), with similar variants applied across databases to maximize retrieval of relevant studies.

The review primarily considers literature published between 2000 and 2024, reflecting the period during which metaheuristic optimization techniques gained prominence in distribution system planning and analysis. Seminal earlier studies, most notably Baran and Wu (1989), were included where necessary to establish foundational theoretical concepts and to contextualize the evolution of optimization approaches.

Study selection was guided by clearly defined inclusion and exclusion criteria. Included studies comprised peer-reviewed journal articles and conference papers that addressed capacitor placement, reactive power compensation, voltage regulation, or loss minimization in radial distribution systems. Preference was given to studies employing analytical, heuristic, or metaheuristic optimization techniques and those presenting algorithmic comparisons, methodological innovations, or practical case studies. Studies were excluded if they were non-peer-reviewed, focused exclusively on transmission systems without relevance to distribution networks, or lacked sufficient methodological detail or validation to support critical assessment.

The selected studies were analyzed using a thematic synthesis approach. For each study, key methodological and technical attributes were extracted, including the optimization technique applied, the objective functions considered (such as loss minimization, voltage deviation reduction, or cost optimization), the type of network or test system used, the principal findings, and any reported limitations or implementation challenges. Based on these attributes, the literature was organized into thematic categories encompassing analytical and heuristic methods, metaheuristic optimization techniques, comparative algorithmic studies, and practical implementation considerations, particularly in developing-country contexts. This synthesis framework enabled a balanced and critical evaluation of the strengths, limitations, and applicability of different optimization strategies, thereby reducing methodological bias toward any single algorithm and enhancing the overall rigor of the review.

The rest of this paper is organized as follows: Section 2 examines the theoretical background of power distribution networks; Section 3 explores the role of capacitors in distribution systems; Section 4 discusses power-flow and load-analysis techniques; Section 5 reviews optimization strategies for capacitor placement; Section 6 presents a critical synthesis of related literature and research gaps; Section 7 outlines practical implications and future research directions; and Section 8 concludes the paper.

2.0 Theoretical Background of Power Distribution Networks

A comprehensive understanding of power distribution networks (DNs) is essential for appreciating the challenges and opportunities inherent in optimizing their performance. DNs represent the final stage of the electrical power system, bridging the transmission network and end-users. They are responsible for delivering electrical energy safely and reliably at suitable voltage levels to homes, businesses, and industries (Tanwar & Choubisa, 2025). Typically, distribution networks comprise substations, feeders, transformers, conductors, and service mains that operate at voltages ranging from 2.4 kV to 33 kV. While their radial configuration offers simplicity and cost-effectiveness, it also introduces operational limitations such as high resistance-to-reactance (R/X) ratios, voltage drops, and excessive line losses (Kakran & Chanana, 2018).

2.1 Characteristics and Structure of Distribution Networks

The radial distribution system (RDS) is the most common structure in developing countries because of its simplicity in construction, ease of fault detection, and lower capital cost. However, its unidirectional power flow causes cumulative voltage drops along the feeder, especially as the distance from the substation increases (Gebru *et al*., 2021; Shrestha, 2023). The long feeders and dispersed loads typical of rural systems such as Uganda's Kabale Kisoro 33 kV line exacerbate these issues by increasing line resistance and reducing the power factor. Moreover, the increasing integration of distributed generation (DG) and renewable energy sources into DNs introduces dynamic load variations that challenge conventional voltage regulation schemes (Moslehi & Kumar, 2010).

These challenges necessitate the deployment of intelligent compensation and optimization mechanisms to sustain voltage levels and minimize technical losses.

2.2 Power Quality Issues in Distribution Systems

Power quality (PQ) represents a critical performance indicator of DNs, reflecting the stability, reliability, and waveform purity of supplied electricity. Poor PQ affects not only consumer equipment but also overall network efficiency. Various disturbances such as interruptions, waveform distortions, frequency deviations, transients, voltage sags and swells, and unbalances adversely affect voltage stability and equipment performance (Hernández-Mayoral *et al*., 2023). The main categories of PQ disturbances are.

1. Interruptions**:** Short and long interruptions occur due to faults, lightning, or malfunctioning protection devices, leading to equipment downtime and data loss (Kumar *et al*., 2021).
2. Waveform Distortion: Caused by harmonics, notching, or electrical noise, waveform distortion alters the sinusoidal nature of current or voltage signals, reducing equipment lifespan (Kumar *et al*., 2021).
3. Transients: Impulsive and oscillatory transients arise from arcing, switching, or lightning, resulting in voltage spikes that may damage electronic devices (Kumar *et al*., 2021).
4. Voltage Sag and Swell: Temporary voltage reductions or increases caused by motor starting or capacitor switching lead to operational instability (Kumar *et al*., 2021).
5. Voltage Unbalance and Fluctuation: Common in single-phase rural networks, these phenomena cause flicker, reduced motor efficiency, and excess losses (Kumar *et al*., 2021).

These PQ issues are particularly critical in long rural feeders. Kabale-Kisoro feeder faces frequent interruptions, voltage sags, and unbalances due to its hilly terrain and long overhead lines. These localized factors reinforce the need for optimized reactive-power compensation using capacitors to stabilize voltages and reduce power loss.

2.3 Energy Losses and Voltage Instability

Energy losses in DNs primarily stem from resistive heating in conductors and transformers. Such technical losses increase with load current and line length. Voltage instability, meanwhile, arises from the inability of the system to maintain nominal voltage levels under varying load conditions. Reactive power demand from inductive loads (such as motors and lighting) intensifies these problems by drawing additional current from the source, which further elevates I^2R losses (Kolcun *et al*., 2022). Over time, this cyclic relationship between reactive power deficiency and voltage depression leads to efficiency degradation, overloading of equipment, and service unreliability.

2.4 Implications for System Planning

Maintaining voltage consistency within ±5 % of the nominal value as recommended by IEEE Standard 1547-2018 is a key requirement for distribution system planning. Utilities in developing countries, including Uganda, often struggle to meet this target because of insufficient compensation devices and inadequate network design. In such settings, optimal capacitor placement serves as a technically sound and economically viable intervention to alleviate PQ problems, reduce technical losses, and ensure voltage stability (Ali *et al*., 2011). Capacitors effectively supply local reactive power, thus reducing the total reactive demand seen by the substation and improving the system's overall power factor.

2.5 Theoretical Link to Optimization Approaches

The nonlinear nature of DN behavior where power loss, voltage deviation, and capacitor cost interact in a multi-objective framework necessitates computational optimization techniques capable of balancing trade-offs. Traditional analytical methods often yield suboptimal results in complex systems; hence, metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) have been adopted for capacitor placement studies (Lei *et al*., 2022b). These techniques can handle discrete decision variables, nonlinear constraints, and multiple objectives simultaneously, making them ideal for distribution-system optimization under realistic operating conditions.

3.0 Role of Capacitors in Distribution Systems

Capacitors play a pivotal role in improving the operational efficiency and stability of power distribution systems. Their fundamental purpose lies in reactive power compensation, which helps mitigate voltage drops, reduce technical losses, and improve the power factor of electrical networks. In distribution systems dominated by inductive loads such as motors, transformers, and fluorescent lighting reactive power demand causes current to lag the voltage, leading to inefficiencies. Capacitors, when strategically installed, inject leading reactive power that offsets the lagging component, thereby minimizing the reactive burden on supply lines and enhancing voltage stability (Kolcun *et al*., 2022).

3.1 Voltage Support and Power Factor Correction

Voltage stability is one of the most critical performance indicators of distribution systems. Since reactive power flow directly affects voltage magnitude, insufficient local compensation results in lower bus voltages and increased line currents. By providing localized reactive power, capacitors maintain bus voltages within permissible limits typically between 0.95 p.u. and 1.05 p.u. thereby improving power quality and safeguarding sensitive equipment (Ali *et al*., 2011).

Capacitor installation also enhances power factor (PF) by reducing the phase angle between current and voltage. The improved power factor minimizes the total current drawn from the supply, which in turn reduces I^2R losses and improves transformer and feeder utilization. Utilities benefit from this improvement through deferred investment in additional capacity, while consumers gain from reduced energy bills and improved voltage conditions.

3.2 Loss Reduction and System Efficiency

Technical power losses in distribution systems are proportional to the square of the current flowing through the conductors. In a system without reactive power compensation, the current magnitude increases due to the presence of reactive components, resulting in significant losses. Capacitors reduce the total current flow by supplying a portion of the reactive power locally. This leads to a measurable reduction in both line and transformer losses (Grebe, 1995; Ali *et al*., 2011).

3.3 Capacitor Placement Strategies

Capacitors may be installed at three principal locations:

1. Substation level-to compensate for system-wide reactive demand;
2. Feeder sections-to improve intermediate voltage levels; and
3. Consumer endpoints-to correct local load power factor.

The effectiveness of each strategy depends on accurate network modeling, load-flow analysis, and optimization of size and placement. The placement problem is a complex, nonlinear optimization task constrained by system voltage limits, power factor targets, and capacitor cost. The decision variables typically include the bus locations and the reactive power rating of each capacitor bank. As such, determining the optimal configuration requires an approach that minimizes total losses and voltage deviation while maintaining cost efficiency (Sirjani *et al*., 2011).

3.4 Reactive Power Management and System Stability

Reactive power management plays a central role in ensuring voltage stability and system reliability. When capacitors are correctly positioned, they improve both the steady-state and dynamic performance of the distribution system. They minimize voltage fluctuations and suppress transient overvoltages that may occur during sudden load changes or switching operations. Moreover, adequate compensation ensures that voltage variations across different buses remain within statutory limits, improving service quality and customer satisfaction.

3.5 Economic and Operational Benefits

Beyond technical performance, capacitor placement yields significant economic benefits. The reduction in technical losses translates directly into energy cost savings for utilities and consumers. For distribution companies, improved power factor reduces penalties from bulk suppliers and minimizes transformer overloading, thereby extending equipment life. The associated operational savings justify the investment in capacitor banks, particularly when optimal placement is achieved through computational optimization models (Kolcun *et al*., 2022).

At the policy level, such improvements contribute to the goals of Uganda's *National Development Plan III* and *Electricity Connection Policy*, which prioritize efficiency, affordability, and reliability of supply. Optimized capacitor deployment supports these policy targets by lowering technical losses and stabilizing voltages, especially in rural feeders where voltage sags and interruptions are most severe.

3.6 Limitations of Conventional Capacitor Control

Despite their advantages, conventional capacitor banks with fixed or manually controlled switching may not adapt effectively to dynamic load conditions. Fixed banks can cause overcompensation during light-load periods or under-compensation at peak times, resulting in voltage oscillations and potential resonance with network inductances. This necessitates the use of intelligent control systems and optimization algorithms that automatically determine optimal capacitor ratings and switching schedules in real time (Lei *et al*., 2022b). Integrating such optimization ensures that capacitors operate efficiently under varying load profiles and network configurations.

4.0 Power Flow and Load Analysis Techniques

A reliable power flow (PF) analysis forms the foundation of modern power-system planning, design, and operation. It enables engineers to determine steady-state operating conditions specifically bus voltages, real and reactive power flows, and system losses under normal or contingency scenarios. In radial distribution systems (RDSs), load flow analysis provides essential information for decision-making on voltage regulation, loss minimization, and optimal capacitor placement (Garcia *et al*., 2000). However, due to the high resistance-to-reactance (R/X) ratios and radial topologies characteristic of distribution networks, conventional transmission-level methods often yield inaccurate or computationally unstable results (Tewari *et al*., 2021; Ahmad, 2022). This section reviews the major PF algorithms relevant to capacitor-placement optimization, highlighting their strengths and limitations in radial systems.

4.1 Overview of Load Flow Methods

Load flow analysis involves solving nonlinear algebraic equations derived from Kirchhoff's Current and Voltage Laws to compute the steady-state power and voltage profiles of each bus in a system. The main challenge arises from the nonlinear relationship between bus voltages and power injections. Iterative numerical methods are therefore employed to achieve convergence to the correct solution. The commonly used techniques include the Gauss-Seidel (GS), Newton-Raphson (NR), Fast Decoupled (FD), and Backward/Forward Sweep (BFS) methods, each with distinct computational characteristics and convergence behavior.

4.2 Gauss-Seidel Method

The Gauss-Seidel algorithm is one of the earliest iterative techniques used for solving load flow equations. It operates by sequentially updating the voltage at each bus using the most recent estimates of other bus voltages until convergence is achieved (Garcia *et al*., 2000). Convergence is typically assured if the system admittance matrix is diagonally dominant or positively definite. While the GS method is simple to implement and requires minimal memory, it converges slowly for large systems, especially those with poor initial guesses or high R/X ratios (Tewari *et al*., 2021).

Despite these limitations, the GS method remains a valuable starting tool for initializing other algorithms such as Newton–Raphson. To enhance convergence speed, acceleration factors can be introduced, but excessive acceleration may lead to oscillations or divergence (Al-Shafei *et al*., 2022). Studies by Rangavalli and Komma Lavanya (2022) and Chamim *et al*. (2023) demonstrated the practical usefulness of the GS approach in optimizing power flows and reducing losses in medium-sized distribution networks.

4.3 Newton-Raphson Technique

The Newton-Raphson (NR) method represents a significant advancement over GS due to its quadratic convergence characteristics. It linearizes nonlinear PF equations by applying a Taylor series expansion and solving the resulting Jacobian matrix iteratively (Risi *et al*., 2022). The method is computationally efficient for transmission systems but can be challenging for radial feeders where line impedances exhibit high R/X ratios and the Jacobian matrix becomes ill-conditioned (Montoya *et al*., 2020).

However, its flexibility has made it adaptable for modern systems such as microgrids (MGs) and hybrid AC/DC networks. Modified NR-based formulations can accommodate droop-controlled distributed generation and islanded operations, as shown by Nazari *et al*. (2020) and Liu *et al*. (2021). In such applications, NR offers excellent accuracy but at the cost of higher computational demand. Its suitability for large-scale, meshed systems makes it less efficient for low-voltage RDSs such as the Kabale-Kisoro feeder.

4.4 Fast Decoupled Method

The Fast Decoupled Load Flow (FDLF) method simplifies the NR technique by decoupling the active and reactive power equations, leading to faster computation with minimal memory use (Chen *et al*., 2020). It assumes weak coupling between voltage magnitude and active power and between voltage angle and reactive power conditions that hold in transmission but not in radial distribution systems. As a result, FDLF may converge poorly in feeders with high resistance or under heavy loading.

Nevertheless, enhancements such as the Fast Decoupled Multi-Energy Flow (FDMF) approach have improved its computational speed in Integrated Energy Systems (IES) by accommodating renewable sources and stochastic variations (Gallego *et al*., 2021). Moreover, its adaptation for probabilistic optimal power flow (POPF) enables efficient uncertainty modeling in renewable-dominated systems (Zhang *et al*., 2020).

While useful for contingency analyses and planning studies, the FDLF's assumptions limit its accuracy in weak, unbalanced distribution networks, making it unsuitable for the Kabale–Kisoro system under study.

4.5 Backward/Forward Sweep Technique

The Backward/Forward Sweep (BFS) method has emerged as the preferred load-flow algorithm for radial and weakly meshed distribution networks due to its computational robustness and simplicity. It involves two alternating stages:

1. Backward Sweep: Branch currents are computed starting from terminal nodes toward the root (substation) using the known load demands.
2. Forward Sweep**:** Updated bus voltages are calculated from the source bus to the terminals using the previously determined currents (Kawambwa *et al*., 2021).

This iterative process continues until voltage changes between successive iterations fall below a defined tolerance level. The BFS method offers several advantages it eliminates the need for Jacobian matrix manipulation, ensures rapid convergence, and accommodates unbalanced or reconfigured networks without node renumbering.

The improved BFS algorithm proposed by Kawambwa *et al*. (2021) and applied to Tanzanian secondary networks demonstrated its practical relevance. The approach accurately handled reconfiguration problems and produced consistent results across IEEE 15-, 34-, and 69-bus systems.

The BFS load flow also formed the computational foundation for the subsequent Ant Colony Optimization (ACO) algorithm. Accurate power-flow results are indispensable for evaluating the impact of capacitor installation on system voltages, power factor, and total losses.

4.5 Comparative Analysis of Load Flow Techniques

Each load-flow method offers unique advantages depending on network type, complexity, and computational constraints. Table 1 below summarizes their comparative feature.

Table 1 Comparative Characteristics of Common Load Flow Techniques

Method	Convergence Speed	Accuracy	Suitability for Radial Systems	Computational Complexity
Gauss-Seidel	Slow	Moderate	Moderate	Low
Newton-Raphson	Fast (quadratic)	Very high	Poor	High
Fast Decoupled	Very fast	High for transmission;	Limited	Moderate

		poor for distribution		
Backward/Forward Sweep	Fast	High	Excellent	Low

This comparison underscores why the BFS technique is ideal for distribution networks such as the Kabale-Kisoro feeder. It provides a balance of accuracy and efficiency, ensuring reliable input data for optimization algorithms like ACO.

5.0 Optimization Techniques for Capacitor Placement

Although Ant Colony Optimization (ACO) has demonstrated strong performance in discrete capacitor placement problems, particularly in radial distribution systems with combinatorial decision spaces, its effectiveness is context dependent rather than universal. Comparative studies indicate that ACO often outperforms Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) in discrete capacitor sizing problems, where solution quality depends on precise bus selection and standardized capacitor ratings. However, this advantage is frequently accompanied by increased computational effort. Comparative applications of swarm-based methods, including ACO and PSO, on IEEE 33-bus and IEEE 69-bus systems indicate that different algorithms can yield similar loss reduction performance while exhibiting trade-offs in convergence behavior and computational requirements (Ahmadi Kamarposhti *et al*., 2025; Awadallah *et al*., 2025; Ni *et al*., 2023).

PSO, by contrast, exhibits faster convergence and lower computational overhead, making it attractive for continuous or hybrid optimization problems, particularly when real-time or near-real-time decision making is required (Abualigah, 2025). Its performance deteriorates, however, in highly discrete search spaces, where premature convergence and loss of diversity are common. GA remains valuable for its strong global exploration capability and flexibility in handling mixed discrete-continuous variables, but its effectiveness is sensitive to population size, crossover probability, and mutation rate, often requiring extensive tuning.

The literature also highlights important limitations of ACO itself. Parameter sensitivity, particularly with respect to pheromone evaporation rates and heuristic weighting factors, can significantly influence convergence behavior. In large-scale or highly meshed systems, computational time may increase substantially, and stagnation around suboptimal solutions has been reported. Recent studies attempt to address these challenges through adaptive parameter control, pheromone reinitialization strategies, and hybrid ACO-based frameworks that incorporate local search methods or PSO-inspired velocity updates. These developments suggest that no single metaheuristic consistently dominates, and algorithm selection should be guided by network size, data availability, computational resources, and the nature of decision variables.

5.1 Nature of the Optimization Problem

The optimization of capacitor placement seeks to determine the optimal locations (buses) and sizes (reactive power ratings) of capacitors that minimize system losses and voltage deviations while maintaining economic feasibility. The general objective function can be expressed as:

$$\text{Minimize: } f = w_1 P_{\text{loss}} + w_2 V_{\text{dev}} + w_3 C_{\text{cost}} \quad (1)$$

where P_{loss} denotes total real power losses, V_{dev} represents voltage deviation from nominal limits, and C_{cost} is the capital and installation cost of capacitor banks. The weights w_1, w_2, w_3 reflect the relative importance of each objective. Constraints include bus voltage limits (typically 0.95–1.05 p.u.), maximum reactive power compensation, and permissible power factor ranges (Ali *et al*., 2011).

Because this formulation is highly nonlinear and multimodal, metaheuristic optimization provides a superior alternative to deterministic methods.

5.2 Categories of Optimization Approaches

Optimization techniques for capacitor placement can be classified into three main categories: analytical, heuristic, and metaheuristic methods (Sirjani *et al*., 2011; Bhargava *et al*., 2023).

1. Analytical Methods:
   These employ closed-form mathematical relationships derived from simplified power-flow equations. While computationally efficient, they rely on restrictive assumptions that often neglect load variations and network constraints, limiting their applicability to small, balanced systems.
2. Heuristic Methods:
   Heuristics such as sensitivity analysis, loss reduction indices, and voltage deviation factors use experience-based rules to guide capacitor placement. Though simple, they are prone to local optima and lack global search capability.
3. Metaheuristic Methods:
   These stochastic, population-based algorithms inspired by natural or biological processes (e.g., evolution, swarm behavior, thermodynamics) are capable of exploring large solution spaces to identify global optima. They include Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Artificial Bee Colony (ABC), Flower Pollination Algorithm (FPA), and Ant Colony Optimization (ACO) (Lei *et al*., 2022).

Table 2 Comparison of Common Optimization Techniques for Capacitor Placement

Technique	Strengths	Limitations	Typical Applications
Ant Colony Optimization (ACO)	Robust in handling non-linear multi-objective problems; good global search capability; adaptable to different network configurations.	Slow convergence; sensitive to parameter tuning (pheromone evaporation rate, α, β); may stagnate in local optima.	Capacitor placement in distribution networks, network reconfiguration.
Particle Swarm Optimization (PSO)	Fast convergence; relatively easy to implement; effective in continuous search spaces.	Risk of premature convergence; limited ability to escape local optima; performance highly dependent on inertia weight and acceleration coefficients.	Optimal DG and capacitor sizing, renewable energy integration studies.
Genetic Algorithm (GA)	Strong exploration ability; well-established and widely validated; flexible with discrete and continuous variables.	May require large population sizes and iterations; convergence can be computationally expensive; risk of premature convergence.	Capacitor bank planning, DG integration, and hybrid optimization problems.

5.3 Overview of Common Metaheuristic Algorithms

a) Genetic Algorithm (GA)

GA mimics Darwin's principle of natural selection, employing crossover and mutation to evolve a population of solutions toward optimality (Sirjani *et al*., 2011). It effectively handles discrete variables but often requires careful parameter tuning to avoid premature convergence. In capacitor-placement applications, GA minimizes system losses by evolving bus selection and capacitor sizes over successive generations.

b) Particle Swarm Optimization (PSO)

PSO simulates the social behavior of flocks or swarms. Each particle adjusts its trajectory based on its personal best and the global best solution, achieving fast convergence for continuous optimization problems (Tahir *et al*., 2022). PSO has been successfully applied to hybrid optimization schemes combining capacitor placement and distributed generation.

c) Simulated Annealing (SA)

SA is inspired by the metallurgical annealing process and relies on probabilistic acceptance of worse solutions to escape local minima. Although robust, its convergence rate is relatively slow, making it less suitable for real-time optimization (Wang *et al*., 2020).

d) Artificial Bee Colony (ABC) and Flower Pollination Algorithm (FPA)

Both algorithms are based on biological systems bee foraging and flower pollination. They exhibit strong exploration abilities and reduced parameter dependency compared to GA or PSO. Their flexibility has made them attractive for multi-objective optimization in distribution systems (Bhargava *et al*., 2023).

e) Ant Colony Optimization (ACO)

ACO, first introduced by Dorigo and colleagues in the 1990s, emulates the foraging behavior of ants that find shortest paths to food sources by laying and following pheromone trails. Its iterative search process allows probabilistic path selection based on pheromone intensity and heuristic desirability (Lei *et al*., 2022b).

In power systems, the algorithm represents each potential capacitor placement as a "path," where the pheromone level corresponds to the quality of that configuration (e.g., total power-loss reduction). Over successive iterations, ants reinforce promising solutions through pheromone updates, leading to near-global optimality.

5.4 Challenges and Research Opportunities

Despite its robustness, ACO still faces challenges related to parameter sensitivity (pheromone evaporation rate, α–β weighting factors) and computational overhead in large-scale systems. Future improvements involve adaptive parameter tuning, hybridization with deterministic or machine-learning models, and integration with real-time monitoring for smart-grid applications. For Uganda's rural feeders, further research should focus on incorporating load uncertainty, time-varying profiles, and multi-objective cost-benefit analyses to make the optimization models more practical for real utility environments.

6.0 Thematic Synthesis of Related Studies and Emerging Research Gaps

Research on optimization-based capacitor placement has evolved considerably over the past three decades, shifting from simplified deterministic formulations toward increasingly complex, multi-objective, and context-sensitive optimization frameworks. Rather than progressing linearly, this evolution reflects changing assumptions about network behavior, data availability, and operational priorities. A thematic synthesis of the literature reveals four dominant and interrelated research trajectories, each characterized by both convergence and unresolved tensions.

The first theme concerns the evolution of solution approaches for capacitor placement. There is broad consensus across the literature that early analytical and heuristic methods, despite their computational efficiency and transparency, are inadequate for large-scale radial distribution systems characterized by high resistance-to-reactance ratios and nonlinear load behavior. Metaheuristic algorithms consistently outperform these traditional approaches in terms of loss reduction and voltage regulation. However, the literature does not converge on a single "best" algorithm. Comparative studies often report conflicting conclusions regarding the superiority of ACO, PSO, GA, or hybrid methods. These discrepancies can be attributed to differences in network topology, problem dimensionality, objective function formulation, and constraint handling. As a result, reported performance gains are highly context dependent, challenging the generalizability of algorithm-centric claims.

A second theme relates to the treatment of uncertainty and load variability. A significant portion of the literature assumes static, balanced, or peak-load operating conditions, implicitly treating capacitor placement as a one-time planning exercise. More recent studies demonstrate that optimization outcomes are highly sensitive to temporal load variation, with solutions optimized under peak-load assumptions often performing suboptimally during off-peak periods. This divergence reveals a structural limitation in static optimization models, which tend to overestimate achievable benefits under real operating conditions. Despite growing recognition of this issue, relatively few studies incorporate time-series load data or stochastic modeling frameworks, leaving a gap between theoretical optimization results and operational realities.

The third theme addresses the integration of capacitor placement with distributed generation and renewable energy sources. The literature presents mixed findings in this area. Some studies report enhanced voltage stability and reduced losses when capacitor placement is coordinated with distributed generation, while others identify increased voltage fluctuations, reverse power flow, and control complexity. These contradictions are largely explained by variations in DG penetration levels, feeder strength, control strategies, and coordination mechanisms. Importantly, many studies treat capacitor placement and DG integration as loosely coupled problems, limiting the ability of optimization models to capture their interactive effects under dynamic conditions.

The fourth theme concerns the trade-off between technical optimization and economic feasibility. While recent studies increasingly incorporate capacitor installation cost and payback period into objective functions, technical performance metrics-particularly loss minimization-continue to dominate optimization formulations. Economic constraints are often simplified or treated as secondary considerations, which limits the relevance of optimization results for utility decision-making. This imbalance reflects a broader tension between algorithmic optimality and implementability, particularly in developing-country contexts where capital availability and regulatory constraints are significant.

Taken together, these thematic findings expose several critical research gaps. Despite methodological advances in metaheuristic optimization, there remains a persistent modeling-reality gap, as few studies integrate time-series load data from actual distribution feeders in developing countries. There is also limited attention to optimization under data-sparse conditions, where feeder-level measurements are incomplete or unreliable. Furthermore, hybrid optimization algorithms are frequently validated on standardized IEEE test systems, with minimal assessment of scalability, robustness, and adaptability in real utility networks. Addressing these gaps requires a shift from algorithm-centric performance evaluation toward context-aware, implementation-oriented optimization research.

7.0 Implications and Future Research Directions

Although optimization-based capacitor placement demonstrates substantial theoretical benefits, its practical implementation in Uganda's distribution networks remains constrained by several systemic challenges. Distribution utilities typically operate with limited feeder-level measurements, incomplete or non-time-series load data, and aging infrastructure, all of which restrict the direct application of data-intensive and computationally complex optimization models. Financial constraints further limit the scale and flexibility of capacitor deployment, underscoring the importance of optimization frameworks that explicitly integrate cost considerations alongside technical objectives. In addition, capacity gaps in advanced optimization skills within utility environments present a barrier to the adoption of highly parameter-sensitive algorithms.

Addressing these realities requires a shift from purely algorithm-centric research toward implementation-aware optimization design. Future research should therefore focus on developing lightweight, data-sparse optimization models that can operate effectively under incomplete information. Reduced-order and measurement-efficient formulations, capable of producing robust solutions with minimal input data, are particularly relevant for rural feeders where advanced monitoring infrastructure is limited. In this context, hybrid optimization frameworks that combine the strong discrete-search capability of Ant Colony Optimization (ACO) with the faster convergence characteristics of Particle

Swarm Optimization (PSO) represent a promising direction. Such hybrid ACO-PSO models should be validated using actual feeder datasets, for example time-series load data from the Kabale-Kisoro distribution network obtained from UEDCL, to assess algorithm performance under realistic, unbalanced, and time-varying operating conditions rather than idealized IEEE test systems.

7.1 Practical and Technical Implications

From a technical standpoint, optimal capacitor placement directly supports loss reduction, voltage stabilization, and power factor improvement, all of which are critical to improving distribution system efficiency and reliability. For utilities such as Umeme Ltd and the Uganda Electricity Distribution Company Limited (UEDCL), even modest reductions in technical losses can translate into measurable financial savings, deferred infrastructure upgrades, and improved service quality, particularly in long rural feeders. Importantly, the review indicates that optimization should be treated as a decision-support process rather than a purely numerical exercise, with solution robustness and implementability weighted alongside optimality.

7.2 Policy and Economic Implications

At the policy level, integrating optimization-based capacitor planning into Uganda's National Development Plan III (NDP III) provides a cost-effective pathway for improving grid performance without large-scale network reconfiguration. Compared to feeder reinforcement or network expansion, capacitor deployment requires relatively low capital investment while offering high returns in terms of efficiency and reliability. However, to be policy-relevant, optimization models must incorporate realistic financial constraints, including investment budgets, payback periods, and phased implementation strategies. Aligning technical optimization outputs with planning instruments such as the Electricity Connection Policy and Uganda's Energy Policy 2023 will enhance the likelihood of adoption by utilities and regulators.

7.3 Actionable Future Research Directions

Future research should move decisively toward application-driven optimization. First, hybrid metaheuristic models, particularly ACO-PSO combinations, should be explicitly designed to reduce parameter sensitivity and computational burden, with validation conducted on real Ugandan feeder data rather than benchmark systems alone. Second, dynamic and quasi-real-time capacitor control strategies should be explored using adaptive optimization techniques capable of responding to daily and seasonal load variations, especially in feeders with growing distributed generation penetration. Third, multi-objective optimization frameworks should be extended to explicitly integrate reliability indices, economic cost functions, and operational constraints, ensuring solutions remain feasible under utility budget and regulatory conditions. Fourth, as solar mini-grids and distributed renewable energy sources expand in Uganda, future studies must examine the interaction between capacitor placement, voltage rise, and reverse power flow to avoid unintended stability issues. Finally, research should prioritize scalable validation across multiple feeders to assess robustness, transferability, and implementation cost, thereby narrowing the persistent gap between theoretical optimization studies and utility-scale deployment.

8.0 Conclusion

This review set out to examine how different optimization-based capacitor placement strategies perform in reducing power losses and improving voltage profiles in radial distribution systems, to assess the comparative strengths and limitations of major optimization approaches, and to evaluate their relevance for real-world distribution networks in developing contexts. The synthesis of analytical, heuristic, and metaheuristic studies confirms that reactive power compensation through optimal capacitor placement remains an effective and economically attractive intervention for improving distribution system performance, particularly in long, weak radial feeders.

A central insight emerging from the reviewed literature is a clear shift in the field from single-objective formulations focused solely on loss minimization toward multi-objective optimization frameworks that simultaneously consider voltage regulation, investment cost, reliability, and operational constraints. Metaheuristic algorithms have played a pivotal role in enabling this transition by accommodating nonlinear network behavior and discrete decision variables. However, the review demonstrates that no single algorithm consistently outperforms others across all problem settings. Ant Colony Optimization, Genetic Algorithms, and Particle Swarm Optimization each exhibit context-dependent advantages, with performance strongly influenced by network topology, load characteristics, and computational requirements. This finding underscores the importance of algorithm selection based on problem-specific conditions rather than presumed superiority.

For researchers, the most critical gaps lie in bridging the disconnect between algorithmic development and practical deployment. Future studies should prioritize the integration of time-varying and unbalanced load data, explicit economic modeling, and validation on real utility feeders, particularly in data-scarce environments common in developing countries. For practitioners and utilities, the key takeaway is that optimization-based capacitor planning should be viewed as a decision-support tool rather than a purely computational exercise. Practical adoption requires simplified, robust optimization frameworks that balance solution quality with data availability, computational effort, and implementation feasibility.

In conclusion, the evidence synthesized in this review indicates that optimization-based capacitor placement remains a valuable component of modern distribution system planning. When aligned with realistic operating conditions and local constraints, such approaches can contribute meaningfully to improved power quality, reduced losses, and more reliable electricity supply in radial distribution networks.

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Declaration of conflict of interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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