



A Review of the Application of Swarm Intelligence-Based Algorithms for Optimization in Microgrids

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Abstract

The unique features of swarm intelligence algorithms have led to their use in solving complex and diverse problems in various fields. These algorithms are widely used as a powerful tool in artificial intelligence and computational science. In this review, the capabilities of swarm intelligence-based algorithms such as ant colony optimization (ACO), particle swarm optimization (PSO), artificial bee colony (ABC), and fish swarm algorithm (FSA) for optimizing the performance of microgrids are examined. First, the concepts of microgrids and the introduction of each swarm intelligence-based algorithm are presented. Then, the advantages and disadvantages of the application of the algorithms are stated. The application of the algorithms in various topics such as energy management, protection, loss reduction, and virtual impedance in microgrids is stated. A comparison between the expression features of the algorithms is also mentioned. Finally, the existing challenges and future research directions are mentioned. This study can be a foundation for future research that uses the capabilities of swarm intelligence to solve real-world challenges in various fields of energy systems and optimizing the performance of microgrids.

Keywords: artificial intelligence, microgrid, optimization, swarm intelligence algorithm

Article history: Received 2025/08/15; Revised 2025/08/26; Accepted 2025/08/31, Article Type: Research paper

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<https://doi.org/10.82234/IJSEE.2025.1218129>

1. Introduction

Concerns about climate change, caused by greenhouse gas emissions, have driven a global shift towards renewable energy sources (RES). This transition aims to reduce the effects of global warming and transition to more sustainable energy systems. Energy is crucial to modern life, underpinning everything from basic human needs to economic development and technological advancements. Essential services such as communication and transportation are made possible by energy, and it is vital for industrial production, agriculture, and household consumption and energy-generating businesses [1-10]. The growing demand for electrical energy and the increasing penetration of non-renewable energy, coupled with environmental problems and constraints on energy production, are among the greatest energy challenges. Renewable energy sources such as solar, wind, hydroelectric, and geothermal offer a path to reducing greenhouse gas emissions. They harness natural resources that are renewed by nature and emit little or no

pollutants, making them a key component in climate change mitigation strategies. Microgrids (MGs) play an important role in reducing environmental problems and promoting energy sustainability by integrating RESs and minimizing transmission losses. The use of local generation reduces dependence on centralized power plants. Microgrids, with their ability to integrate distributed generation and renewable energy, face challenges in maintaining stable performance due to fluctuations in electricity resources and demand. Microgrids provide control over energy sources, and enable strategic management based on demand fluctuations and pricing. Microgrids also contribute to the overall stability of the grid by providing ancillary services to the main grid, such as frequency regulation and voltage support. Microgrid performance is a measure of how effectively a microgrid provides reliable, flexible, and efficient energy supply, especially in the event of a disruption to the main power grid [11-20].

Artificial intelligence is a discipline in computer science that is developing and investigating

frameworks that operate logically. Common AI algorithms include bio-inspired computing, metaheuristics, and computational intelligence [21-26]. Computational intelligence emphasizes strategy and outcome and is divided into five dominant areas: evolutionary computing, swarm intelligence, artificial immune systems, artificial neural networks, and fuzzy systems. Since the emergence of swarm intelligence algorithms in the field of optimization, the use of these methods has expanded as an effective tool for dealing with complex problems [27-32].

Various review papers have been presented in various fields of application for microgrids [33]. A review of the control structure and objectives of hierarchical microgrid control is presented in [34], and an analysis of the interrelationships between different control layers is presented. Hierarchical control, a multi-layered approach, is an effective strategy to address these issues by coordinating control actions at different time scales and levels of complexity.

The droop control strategies in AC microgrids are reviewed in [35] with a focus on hierarchical control, power sharing, optimization, and technical aspects. Different control techniques are considered, their strengths and weaknesses are analyzed, and optimization methods for microgrid performance are presented. Various optimization techniques, such as metaheuristic-based techniques or mathematical models, are proposed to enhance the reliability and performance of the network.

So far, various reviews have been presented on the application of metaheuristic algorithms [36,37]. The use of metaheuristic optimization algorithms, such as genetic algorithm (GA), firefly algorithm, particle swarm optimization and artificial ant optimization, to solve the problem of optimal reactive power distribution in a power system with integrated solar and wind energy generation has been investigated in [38], which aims to minimize power losses, voltage deviation and improve the voltage stability index while considering the uncertainties introduced by renewable energy sources. This research provides a comprehensive analysis of the use of metaheuristic algorithms for optimal reactive power distribution in a power system with integrated renewable energy sources and shows the potential of these techniques in managing uncertainties and maintaining stability in the system.

The basic concepts of metaheuristic optimization algorithms, inspired by natural phenomena, have been reviewed in [39], and they have been applied to various power system challenges, and their effectiveness has been demonstrated in load dispatch optimization, reactive power distribution, economic and emission-based hybrid distribution,

volt/var control, and distributed generation placement and sizing. The review shows that these algorithms are effective in dealing with sparse data or limited computational resources. They are also powerful tools for solving complex power system problems, especially in the field of environmental sustainability and renewable energy integration.

The use of metaheuristic optimization algorithms (MHOAs) in microgrids to address the challenges posed by the intermittent nature of renewable energy sources and poor power quality has been reviewed in [40], and their potential to improve operational performance in various aspects such as energy management, cost optimization, reliability, and balancing of renewable resources has been demonstrated. Various MHOAs, such as PSO, GA, and GWO, have been successfully applied in various microgrid scenarios. MHOAs can be used to optimize energy management, load forecasting, improve resilience, control operations, fault detection, and overall system performance. Research shows that there is a significant trend towards the use of PSO in microgrid optimization, with approximately 25% of studies using this method.

The optimization of the size of hydrogen storage-based microgrids with high renewable energy penetration, especially using metaheuristic algorithms, is investigated in [41], which aims to minimize the cost of the microgrid and ensure a stable energy flow. The results show that the PSO algorithm outperforms other methods and achieves 25.3% lower annual system cost compared to the worst performing algorithm. The PSO algorithm has emerged as the most effective algorithm, outperforming the other algorithms in terms of cost savings.

This paper presents a review of the use of swarm intelligence algorithms in microgrids to improve their operational performance in various aspects such as stability, energy management, load modelling, and reliability. Swarm intelligence algorithms with specific search mechanisms such as bacterial foraging optimization (BFO), artificial bee colony (ABC), fish swarm search (FSS), cuckoo search (CS), fireworks algorithm (FWA), and brainstorming optimization (BSO) can be used for optimization in microgrids.

The highlights of this research include the following:

- An overview of the application of swarm intelligence algorithms in microgrids
- Categorizing numerous studies based on their application in microgrids
- Suggesting future research directions in the field of microgrid optimization

The structure of the paper is as follows. In section 2, the basic framework of microgrids and

their classification along with key indicators for optimization are mentioned. In section 3, an overview of swarm intelligence algorithms is mentioned along with the advantages and disadvantages of each algorithm. In section 4, an overview of studies in the field of microgrids based on swarm intelligence algorithms is presented. Among the topics discussed in this section, energy management, virtual synchronous generator, loss and energy optimization can be mentioned. Various statistical parameters are considered to evaluate the comparative performance and stability of optimization techniques, some of which are mentioned in section 5. Finally, the conclusion and suggestions are stated in section 6.

2. Microgrid

A microgrid is composed of distributed loads and energy sources and operates as a decentralized energy system. The microgrid is an essential part of the modern grid, and acts as a controllable entity relative to the main grid, and can help manage electricity supply and demand. Energy in a microgrid is generated by multiple sources and stored in batteries and controlled locally. Microgrids help improve resilience to grid disturbances and increase energy efficiency by efficiently managing energy production and consumption at the local level. The microgrid is connected to the main grid at a common connection point, and can improve the performance of the microgrid by providing a local and controllable energy system that operates independently or in conjunction with the main grid. Microgrids can operate independently of the main grid during power outages, ensuring continuous power supply, especially for critical infrastructure or in remote areas [42-45].

Key performance indicators of microgrids include reliability, resilience, efficiency, cost-effectiveness and environmental impact. Factors affecting microgrid performance include: control and management systems, renewable energy integration, energy storage, grid interconnection and islanding.

Microgrids can be classified based on various factors, including their connection to the main grid, voltage characteristics, and the types of energy sources they use. Based on voltage characteristics, they are divided into alternating current microgrids [46-48], direct current microgrids [49-51], and hybrid microgrids [52,53]. DC microgrids primarily focus on voltage and current control, while AC microgrids deal with frequency and reactive power, which are crucial for maintaining system stability and power quality. Based on the grid connection, they are divided into three categories: grid-connected microgrids, islanded microgrids, and grid-connected microgrids (multiple microgrids

connected together) [54-56]. In the grid-connected mode, the microgrid controller primarily manages the energy flow, while the power grid stabilizes the microgrid. In the islanded mode, the controller focuses on voltage and frequency regulation, load sharing, and energy management [57-59].

Advantages of microgrids include increased reliability, reduced energy costs, reduced environmental problems, increased flexibility and grid support. Disadvantages of microgrids include high initial costs, technical complexity, regulatory barriers, maintenance and operation, data management and security, intermittent nature of energy sources, electricity cost and resynchronization challenges.

3. Swarm Intelligence Algorithms

In recent years, the need for researchers to use optimization methods to solve complex theoretical and practical problems in various fields has increased. Metaheuristic algorithms are designed as optimization techniques to find solutions to complex problems due to their ease of implementation and effective capabilities combined with simplicity. These algorithms are usually inspired by natural phenomena, social behaviours, or physical processes [60,61]. Figure (1) shows the classification of types of metaheuristic algorithms [62,63].

Swarm intelligence is an adaptive strategy that evaluates the collective behaviour of decentralized and self-organizing systems. Swarm intelligence algorithms are metaheuristic optimization methods, which are inspired by the collective behaviour of living organisms, and are used to solve complex problems. These algorithms consist of multiple artificial agents, and are used in various fields such as optimization, control, machine learning, clustering, image processing, and routing [64,65]. Key features of swarm intelligence algorithms include decentralization, self-organization, learning, and flexibility. As metaheuristic algorithms, swarm intelligence algorithms do not guarantee the determination of an optimal solution, but they usually show rapid convergence to a near-optimal solution if the solution is not optimal. A number of swarm-based algorithms that are more widely used are listed in Table (1).

A) Ant Colony Optimization

Ant Colony Optimization (ACO) is a multi-agent probabilistic search algorithm, inspired by the foraging behaviour of ant colonies. This metaheuristic algorithm is used to solve complex computational problems, especially those involving finding the best path in a graph. The algorithm relies on the actions of multiple ants, making it a distributed approach. The ACO algorithm simulates

the shortest path from the ant nest to the food source by leaving a pheromone trail. The pheromone update mechanism provides positive feedback and guides the algorithm towards better solutions. The advantages of this algorithm include good performance on complex optimization problems, robustness and ability to handle noisy data, and suitability for distributed computing. The potential for long execution times, the possibility of getting stuck in local optima, and the tediousness of parameter tuning are some of the disadvantages of this algorithm [66,67]. Figure (2) shows the general flowchart of the ant colony optimization algorithm, which operates based on initialization, path selection, pheromone update, and iteration [68,69].

Table.1.
examples of swarm-based algorithms

Method	Abbreviation	Characteristic
Artificial bee colony	ABC	Inspired by the foraging behaviour of honeybees
Ant colony optimization	ACO	Inspired by the foraging behaviour of ants
Artificial immune system	AIS	Based on modelling immune cells and antibodies
Cuckoo search	CS	Inspired by the parasitic behaviour of cuckoo chicks
Firefly algorithm	FFA	Inspired by the blinking behaviour of fireflies
Fish swarm algorithm	FSA	Inspired by the natural feeding behavior of fish
Gravitational search algorithm	GSA	Imitating the law of gravity and mass heterogeneity
Gray wolf optimization	GWO	Simulating the leadership hierarchy and hunting behaviour of gray wolves
Particle swarm optimization	PSO	Mimicking the social behaviour of birds in groups
Salp swarm algorithm	SSA	Inspired by the group behaviour of salps
Whale optimization algorithm	WOA	Imitating the hunting strategy of humpback whales using bubble nets

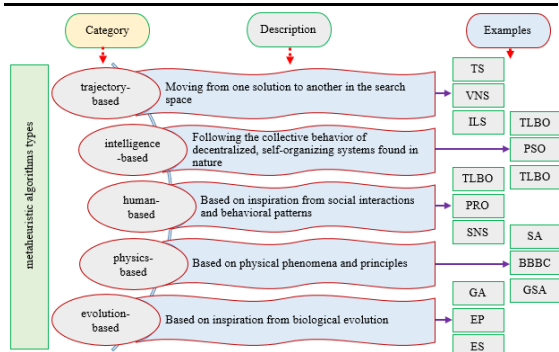


Fig. 1. Classification of metaheuristic algorithms

B) Particle Swarm Optimization

Particle swarm optimization (PSO) is a metaheuristic optimization algorithm inspired by the

social behaviour of flocks of birds or schools of fish, which is commonly used to optimize the performance and design of complex microgrid systems. The PSO algorithm is a powerful tool for microgrid operators to adjust the parameters of systems with renewable resources to achieve various objectives such as reliability. Each particle adjusts its position based on its best known position and the best known position of the entire swarm. This iterative process allows the particles to converge towards the optimal solution. The disadvantages of the PSO algorithm include early convergence and the propensity for local search [70-74]. The common steps in the PSO flowchart are shown in Figure (3). The particle swarm optimization (PSO) flowchart generally involves initializing a group of particles with random positions and velocities, and then iteratively updating their velocities and positions based on their own best-found positions and the best position of the entire swarm. Each iteration requires calculating the fitness for each particle, updating the individual best positions (Pbest) and the global best positions (Gbest), and repeating this process until a termination condition is met.

C) Artificial Bee Colony Algorithm

The Artificial Bee Colony (ABC) algorithm is inspired by the foraging behaviour of honey bees and is used to optimize the performance of microgrids [75,76]. The algorithm is based on three types of bees: worker bees, observer bees, and sentinel bees. Worker bees exploit known food sources (solutions), while observer bees select a food source based on information provided by worker bees, and sentinel bees explore new areas. Simplicity, fast convergence, and flexibility in handling complex optimization challenges in microgrid systems are the salient points of this algorithm. Also, less need for control parameters and good adaptability are other advantages of this algorithm [77,78].

The flowchart of the artificial bee colony algorithm is shown in Figure (4), which includes initialization, employed bee phase, onlooker bee phase, scout bee phase, and termination condition.

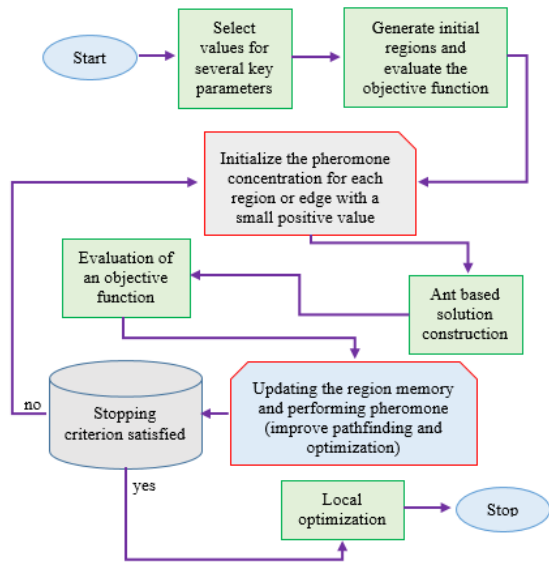


Fig. 2. Flowchart of the ant colony optimization algorithm

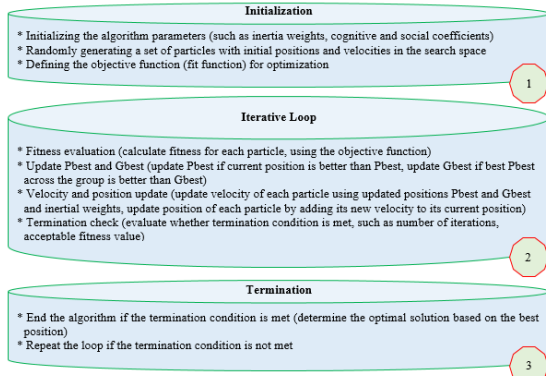


Fig. 3. Typical steps in the particle swarm optimization flowchart

D) Fish Swarm Algorithm

The fish swarm algorithm (FSA) is a swarm intelligence optimization algorithm, inspired by the foraging behaviour of fish. This algorithm simulates the swarming, clustering, and following behaviours of fish to find optimal solutions to various optimization problems. The algorithm iteratively adjusts the “positions” of artificial fish (which represent potential solutions) based on these behaviours, and aims to converge to the best solution. The advantages of this algorithm include robustness, global search capability, flexibility, and high convergence speed, while its disadvantages include low optimization accuracy, slow convergence speed in later stages, and the potential for getting stuck in local optima [79,80].

E) Whale Optimization Algorithm

The whale optimization algorithm (WOA) is a metaheuristic optimization algorithm inspired by nature, inspired by the hunting behaviour of humpback whales. Due to its relatively simple structure, ease of implementation, and effectiveness in solving

optimization problems, this algorithm has found applications in various fields such as load frequency control [81], distribution network reconfiguration [82], and power system stabilizer design [83]. Compared to some other optimization algorithms, it requires fewer parameters, and can achieve fast convergence in certain scenarios. It also balances exploration (searching the solution space) and exploitation (focusing on promising areas). The limitations of this algorithm include the potential for premature convergence, slow convergence in some cases, and the challenge of maintaining an optimal balance between exploration and exploitation. Key features of this algorithm include: inspiration from humpback whales, bait encirclement, bubble net attack, and bait search [84].

F) Bacterial Foraging Optimization

Bacterial foraging optimization (BFO) is a nature-inspired optimization algorithm that mimics the social foraging behaviour of E. coli bacteria. By simulating how bacteria move, reproduce, and disperse in search of nutrients, it is used to find approximate solutions to complex optimization problems. Global optimization, robustness, and simplicity are advantages of this technique. BFO algorithms can be used to optimize various aspects of microgrid performance, including energy management, power transfer, and controller design [85,86].

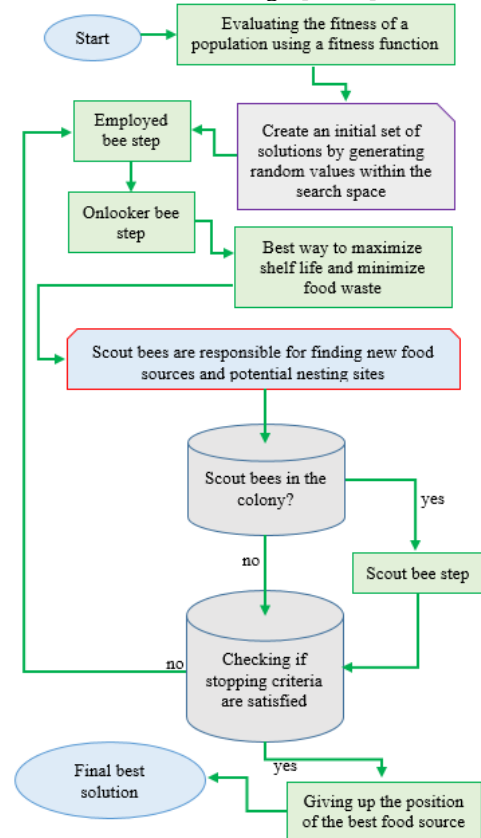


Fig. 4. Flowchart of the artificial bee colony algorithm

G) Salp Swarm Algorithm

The salp swarm algorithm (SSA) is a biology-inspired optimization algorithm that simulates the swarming behaviour of salps (marine animals that form chains for navigation and foraging). It is a population-based metaheuristic algorithm that uses a leader-follower strategy to explore and exploit the search space, and aims to find optimal solutions to various problems. The algorithm structure includes the population (starting with a population of salps), leaders and followers (dividing the population into leaders and followers), position updating (updating the position of leaders based on a goal and random exploration, and updating the position of followers based on the leader and salp in front of them), exploration and exploitation (balancing exploration and exploitation to find the best solution), and fitness function (evaluating the fitness function, the quality of each solution to guide the search). Simplicity, few parameters, balance, and effectiveness are the advantages of this algorithm. The convergence rate (slow convergence in complex problems) and premature convergence (convergence to a local optimum instead of the global optimum) are its limitations [87,88].

H) Gravity Search Algorithm

The gravity search algorithm (GSA) is a metaheuristic optimization algorithm inspired by Newton's law of universal gravitation. It models the search space as a system of masses (agents), where each agent represents a potential solution to an optimization problem. Like other metaheuristic algorithms, premature convergence or getting stuck in local optima are among its drawbacks. Due to its ability to handle complex and nonlinear systems, this algorithm is increasingly used in microgrids to solve various optimization problems [89-93].

I) Artificial Immune System

Artificial immune system (AIS) is a type of computational intelligence and machine learning system that models the principles of the biological immune system to solve complex problems. These systems use concepts such as pattern recognition and immune memory to identify and respond to problems, similar to how the biological immune system recognizes and fights antigens. Key AIS algorithms include negative selection, clonal selection, and artificial immune networks, which allow the system to learn from past problems and improve its solutions over time through evolutionary processes such as mutation and selection. While AIS was initially investigated for computer security and detecting viruses and intrusions, its applications have now expanded to other areas of computational intelligence [94,95].

4. Review and Discussion of Research

This section reviews a number of studies conducted in the field of microgrid optimization using swarm intelligence algorithms.

A) Microgrid Management

Effective control and management strategies are important and essential for optimizing microgrid performance. Strategies include complex algorithms and communication systems, are responsible for balancing energy supply and demand, and manage energy storage, ensuring stable performance in both grid-connected and islanded modes. The inherent variability and periodicity of renewable energy sources pose significant challenges in microgrid performance. Microgrid management involves optimizing various components, and ensures the sustainability and economic performance of the microgrid by minimizing production costs and maximizing the use of renewable energy [96].

An energy management strategy for microgrids is proposed in [97], where chaotic local search is used to reduce local search constraints and early convergence of the particle swarm optimization algorithm.

Following the increasing consumption demand, the need for energy management systems to optimize energy transfer while ensuring stability and efficiency is very important. The development and validation of a comprehensive multi-objective optimization strategy for energy management and trading in microgrids is proposed in [98], which considers the integration of distributed energy resources (DERs) and electric vehicles. The improved particle swarm optimization method is used to solve the existing complexities such as optimal energy scheduling and electric vehicle user satisfaction. The study results show a reduction in net costs compared to the baseline scenario while optimizing the use of renewable energy and increasing the satisfaction of electric vehicle users.

B) Power Sharing

Microgrids use a local power distribution network that allows for the integration of distributed energy resources, while also allowing for grid-connected and islanded operation. Power distribution in a microgrid involves managing the flow of power from different sources to local loads, optimizing efficiency and reliability, and potentially sharing power with the main grid [99,100]. Effective power control in the two main operating states of the microgrid, especially during transitions, is crucial to maintain stability and prevent inverter shutdown due to high voltage. Key areas for study include power sharing (active and reactive) between parallel inverters, matching the power sharing percentage,

and minimizing the overshoot in active and reactive power during mode transitions [101]. Power distribution strategies in microgrids include: voltage drop control, intelligent control systems, active and reactive power management, optimal resource allocation and load shedding [102,103].

In order to minimize the cost for the entire system and each microgrid, in [104], optimization of power transfer between microgrids using artificial bee colony algorithm is proposed. A model for a hybrid renewable energy system including photovoltaic systems, wind turbines, battery storage and gas turbines using smart grid is presented.

C) Power Quality

Power quality in microgrids is related to the stability and reliability of the electrical power delivered to the loads, compliance with specific standards and ensuring the correct operation of the equipment [105]. Microgrids, especially those incorporating renewable energy sources, can face power quality problems such as voltage fluctuations, harmonic distortion, and voltage imbalance, which require careful management and mitigation strategies [106,107]. Short-term voltage increases or decreases can potentially damage sensitive electronic devices. Although frequency deviations from the nominal value are less common in microgrids compared to larger grids, they can affect the performance of some equipment [108,109].

A power control technique for inverter-based distributed generation (DG) in an islanded microgrid is presented in [110] to improve the dynamic and steady-state response. An inner current control loop, an outer power control loop, and a conventional PI controller constitute the control scheme. The design is based on voltage-frequency control for the power controller. Intelligent search techniques including PSO and GA are used to find the optimal parameters of PI controllers in the power control loop, which leads to the improvement of power quality.

A method for minimizing the harmonic distortion at a critical point and minimizing the total harmonic distortion in the entire islanded microgrid using a population-based optimization approach is presented in [111]. The central controller optimizes the voltage harmonics of the grid, while ensuring the appropriate sharing of active power among the distributed generation units. The controller improves the droop controller by adding the optimized harmonic components generated by the PSO algorithm to the voltage reference.

The use of an AI-based optimization strategy to enhance power quality and efficiency in a maximum power point tracking system for hybrid renewable energy sources is investigated in [112]. This study focuses on fuzzy logic and artificial bee

colony (FLABC) technique to optimize the maximum power point tracking controller and the overall power flow of the microgrid, with the aim of improving economic load dispatch and reducing greenhouse gas emissions. The results show that the proposed controller outperforms other methods in terms of solar energy absorption and overall power quality improvement.

A control strategy for an islanded microgrid with multiple photovoltaic arrays is proposed in [113], which demonstrates the enhancement of power quality by optimizing power extraction and voltage regulation. The core of this strategy includes an ACO-based maximum power point tracking technique to address the challenges of partial shading in PV arrays and minimize voltage fluctuations caused by power electronic inverters. The proposed control strategy is simulated using MATLAB/Simulink, to demonstrate its effectiveness in improving power quality in an islanded microgrid.

D) Energy System Management

The increase in renewable energy generation significantly increases the intermittent and stochastic nature of the energy management problem. Therefore, an optimal energy management technique is needed to achieve a high level of system reliability and operational efficiency [114].

Energy management in microgrids involves optimizing the use of diverse energy sources to ensure reliable and cost-effective power supply, especially in situations where the grid is intermittent or unreliable. This is achieved through an energy management system that monitors, controls, and optimizes the performance of various components such as distributed energy sources, energy storage systems, and loads [115,116].

A smart agent-based approach to energy management in islanded hybrid microgrids is presented in [117], which aims to improve the performance, efficiency, and reliability of the system. The system has three operational agents: an AC microgrid agent, a DC microgrid agent, and a system operator agent. The system optimization is performed using a multi-objective particle swarm optimization engine, and the proposed method is tested on a 33-node islanded AC-DC microgrid with diverse resources and loads.

The optimization of electrical system performance through demand response and energy management systems is investigated in [118], where the goal is to increase the efficiency and reliability of the microgrid by minimizing the generation costs and market settlement prices and making better use of renewable energies. A multi-period ABC optimization algorithm is implemented to manage

generation, storage, and responsive loads, which shows significant cost reduction and improved convergence speed compared to the modified energy management system, especially under uncertainty conditions. An artificial neural network approach combined with a Markov chain is also used to predict uncertainties in power generation and load demand.

Optimizing fuel costs using a microgrid management system with a differential evolution algorithm is investigated in [119], where power generation from solar, wind, and fuel cell plants is balanced with variable loads. Potential transactions with the main grid or energy storage systems are also considered. The results show that the system's ability to regulate electricity supply and demand is improved, and the microgrid is able to sell excess electricity or purchase the required electricity when needed. Improving real-time energy management in microgrids by optimizing battery storage operations using a modified PSO algorithm is investigated in [120], where the main idea is to modify the cost function in PSO to better reflect the battery charging and discharging dynamics, which leads to reduced operating costs. The proposed cost function includes a dynamic penalty for charging based on the electricity price, which optimizes the energy exchange with the grid. Simulation results show a 12% cost reduction compared to the original cost function over a 96-hour period, demonstrating the effectiveness of this approach.

A comprehensive power control and optimization strategy for microgrids is presented in [121], and the limitations of existing approaches that often separate these functions are pointed out. The strategy integrates model-based predictive control (MPC) with droop control at the device level for flexible power distribution and load sharing, and an evolutionary particle swarm optimization algorithm at the system level to generate optimal power set-points. The MPC and droop control methods are used to control inverters, which are critical components for converting DC power from distributed energy sources to AC power for the grid or loads. This integrated approach aims to improve voltage regulation and minimize operating costs in the microgrid, applicable in both islanded and grid-connected modes.

An integrated energy management system model including spatial marginal pricing and BFO is proposed to address energy losses and stability issues in smart grids with distributed generation in [122]. By integrating renewable energy sources and DG uncertainty management, the model aims to reduce losses, optimize DG contribution, and enhance the overall stability of the distributed energy system. The estimated power resources, obtained through the BFO algorithm, serve as

critical input parameters for a developed predictive control strategy. This strategy is specifically designed to control a three-phase inverter in a power system. The effectiveness and performance of both the BFO algorithm and the predictive control strategy are rigorously evaluated using MATLAB/Simulink simulations under varying load conditions.

E) Virtual Synchronous Generator

The increasing use of distributed generation (DG) and renewable energy sources, which often lack the inertia provided by traditional synchronous generators, poses challenges for grid stability. To address this problem, virtual synchronous generators have been proposed, which, implemented using power electronics and short-term energy storage, can simulate the dynamic behaviour of synchronous generators and provide the necessary inertia and damping to maintain grid stability [123,124]. This approach is particularly important for inverter-based DG/RES units where synchronization and stability during disturbances are critical [125,126].

Increasing the stability of islanded microgrids is presented in [127], where the microgrid uses virtual synchronous generators and feeds different types of loads. A small-signal stability analysis framework and an optimization platform using PSO are presented to determine the optimal values of virtual impedances, virtual inertia, virtual damping, and current-mode feedback coefficient. The optimization aims to improve the stability of the microgrid by minimizing voltage drop, reducing reactive power mismatch, and minimizing frequency drop.

F) Stability Analysis and Improvement

Microgrid stability is related to the ability of a microgrid to maintain a stable operating state, even when faced with disturbances. Instability in a microgrid may manifest itself as voltage or frequency deviations and sometimes as system collapse. Key factors affecting stability include the microgrid operating state, types of distributed generation sources, control strategies, and load characteristics [128].

Enhancing stability in islanded microgrids with multiple converter-based distributed generation units is reviewed in [129], where attention is paid to power sharing and voltage regulation, especially after load changes or outage events. Small-signal stability analysis for islanded microgrids is performed to investigate the dynamic behaviour of the microgrid under different operating conditions. PSO is used to design virtual impedances for microgrid converters with the aim of improving stability and minimizing reactive power mismatch.

A fractional objective function is used to simultaneously optimize stability and minimize reactive power mismatch. Also, all possible operating points of the microgrid are considered to maximize the stability index in the optimization process.

In [130], a method using the chaotic artificial bee colony (CABC) algorithm is proposed to optimize the placement and size of DG units in radial distribution systems to enhance voltage stability. The CABC algorithm, which combines chaos theory with the ABC algorithm, is used to identify optimal DG locations and capacities. The impact of DG on the system voltage stability is evaluated using various indices, and PV curves are prepared to analyse its impact on the weakest bus. The effectiveness of the CABC method is demonstrated on 38-node and 69-node radial distribution systems.

A modified self-organizing hierarchical PSO with variable acceleration coefficients with jump time based on fuzzy PI controller for enhancing frequency stability in islanded intermittent microgrids, especially with high renewable energy penetration and fluctuating loads, is presented in [131]. This controller optimizes its parameters using a PSO algorithm, and shows superior performance in reducing frequency deviations caused by load variations, renewable resource uncertainty, and white noise compared to traditional methods such as classical PI controller, fuzzy logic PI, and fuzzy logic PI optimized with the propeller optimization algorithm.

A method for finding the optimal location and size of distributed generation units in power distribution systems to minimize power losses, reduce operating costs, and increase voltage stability is presented in [132], which uses the loss sensitivity factor to determine the appropriate locations for DG installation, and uses the BFO algorithm to determine the optimal size of each DG unit. This approach considers technical constraints such as voltage limits and branch current carrying capacity. The effectiveness of this method is tested on 33-bus and 69-bus IEEE radial distribution systems with different models and load levels.

G) Component and Load Modelling

Accurately modelling the inherent uncertainty (stochastic nature) of renewable energy sources, loads, and battery storage is crucial for effective planning and operational efficiency, and choosing the appropriate modelling technique from among the available options is crucial. This complexity arises from the intermittent availability of renewable energy, the unpredictable behaviour of loads, and

the dynamic performance of storage systems, which can vary significantly [133].

Load modelling in a microgrid is important and essential to investigate the impact of different types of loads on system stability and performance, especially when integrating renewable energy sources and distributed generation. Accurate load models are needed for various studies such as voltage and frequency stability analysis, and optimal scheduling.

In order to improve dynamic load modelling in electrical microgrids, a two-stage adaptive approach using machine learning is presented in [134]. The proposed approach uses a database of microgrid disturbances and machine learning tools and optimization algorithms. In the offline phase, load models are created using the parametric ACO technique and classified based on disturbance characteristics, but in the online phase, the selection of the appropriate load model is performed using these classifications.

The Improved Artificial Bee Colony (IABC) algorithm is proposed in [135] for modelling and managing a microgrid-connected system. This algorithm improves the standard ABC algorithm by integrating the GSA into the scout bee phase. This integration improves the search accuracy due to the gravitational constant of GSA, and overcomes the limitations of the memoryless ABC search in the scout bee phase. The IABC method optimizes microgrid configurations by minimizing fuel costs, greenhouse gas emissions, and operating costs, using inputs such as wind turbines, solar panels, fuel cells, and other components.

H) Energy Storage System

The ability to integrate different renewable energy sources, such as solar and wind, is crucial for reliability and environmental impact. However, the intermittent nature of some renewable energies requires careful management and energy storage solutions. Energy storage systems, such as batteries and super-capacitors, are crucial for managing the variability of renewable energy sources and ensuring reliable power supply during power outages [136].

The design of a hybrid renewable energy-based energy storage system with optimal component size and cost reduction is presented in [137] using two meta-heuristic methods, PSO and genetic algorithm. Simulation results show that PSO outperforms GA due to simultaneous global and local searches.

In order to reduce costs and improve reliability in photovoltaic microgrids, an optimal operation model is developed in [138]. The model considers hybrid energy storage systems (ESSs) with energy

cost levelled as a control criterion and incorporates construction, maintenance, and energy trading costs. It combines an improved ACO algorithm with dynamic programming to improve search accuracy and convergence speed. The improvements to the ACO algorithm include attenuation parameters, a Boltzmann selection strategy, a deviation angle coefficient, and turning point parameters. The ultimate goal is to find an optimal system allocation strategy for energy storage over a full load time period.

The use of metaheuristic algorithms to improve the reliability and efficiency of a residential microgrid powered by solar and wind energy with battery storage is reviewed in [139]. Genetic algorithms and ACO are used to evaluate the system performance using Python-based simulations to evaluate the reliability of different optimization strategies. The results show that the load loss probability criterion is reduced from 22.7% to 11% and the supply loss probability criterion is reduced from 26.6% to 16.4%. There is also a better balance between generation and consumption, especially during low demand, and the distribution of wind and photovoltaic generation is more efficient using ACO.

The use of ABC algorithm to optimize the design of a photovoltaic system to meet isolated load demand is investigated in [140]. The advantages of the proposed method over traditional genetic algorithm methods are demonstrated by minimizing the life cycle cost while maximizing the output power of the PV module. The results show that ABC outperforms GA in terms of finding optimal PV system configurations, and ABC is better for designing solar power systems in rural areas.

Optimal microgrid design is crucial for economic efficiency. The establishment of low-carbon rural microgrids is essential for transforming rural energy networks into more sustainable networks, especially with the decarbonization of agricultural production. The optimization of the configuration of this microgrid example using an improved ant colony optimization algorithm to minimize annual costs is investigated in [141]. The results demonstrate the effectiveness of the algorithm in finding optimal solutions quickly and efficiently.

The optimization of the placement and capacity of renewable energy sources, especially wind turbines and solar panels, in distribution systems is investigated in [142], where the multi-objective Salp swarm algorithm (MSSA) is used to minimize losses, improve voltage profiles, and reduce RES costs, considering different load models, load levels, and weather data. The MSSA algorithm is tested on a 33-bus IEEE system, and compared with particle swarm optimization and

genetic algorithm. The results show that the MSSA algorithm performs better in reducing losses and improving voltage profiles compared to PSO and GA.

A hybrid MPPT controller combining genetic algorithm and ACO is proposed in [143] to improve the performance of photovoltaic systems under partial shade conditions. The results are compared with traditional perturb and observe and conventional ACO MPPT controllers. The GA-ACO hybrid MPPT controller shows improved robustness and speed in tracking the overall maximum power point under partial shade, where multiple maximum power points can exist.

1) Energy and Loss Optimization

Energy and loss optimization of microgrids involves managing generation, storage, and consumption to minimize costs, maximize efficiency, and increase reliability. This is usually achieved through advanced control strategies and optimization techniques that consider factors such as renewable energy integration, demand response, and energy storage.

The integration of renewable energy sources into a hybrid microgrid and the importance of realistic battery degradation modelling are reviewed in [144]. A hybrid method of firefly algorithm and PSO (FA-PSO) is proposed to minimize the net active cost and the probability of load loss considering battery degradation, which shows better performance compared to traditional algorithms.

A multi-strategy multi-objective micro ABC algorithm, named MMABC, is proposed to solve the microgrid energy optimization problem (MEOP) in [145], which is suitable for resource-constrained microcontrollers. The proposed algorithm uses a multi-strategy ABC optimizer to maintain diversity, and incorporates an adaptive update mechanism for better exploration and exploitation. It also includes a reference point reconstruction strategy for irregular Pareto fronts.

An improved multi-strategy ABC algorithm (MSIABC) is proposed to overcome the limitations of traditional ABC algorithms for power grid loss optimization, especially on convergence accuracy and local optimum trapping, in [146]. The proposed algorithm includes a distinct search mechanism with dual elite individuals, a safety adaptive state switch model for dynamic equilibrium, and a variable-scale neighbourhood search strategy based on the Levy flight to enhance the overall optimization capabilities. In benchmark experiments, the algorithm shows significant improvements over traditional algorithms, especially in higher-dimensional scenarios, and achieves better cost optimization when applied to a multi-constraint

model for power grid operation. Battery energy management in a DC microgrid is presented in [147]. In this microgrid, distributed photovoltaic generators are located at the highest power point, and a multi-objective approach is chosen to reduce energy losses and operating costs. Using the master-slave approach, two multi-objective algorithms, the multi-objective particle swarm optimizer and the multi-objective ant-lion optimizer, are applied in the master stage. The implementation of the proposed method has been done in MATLAB environment, and to evaluate the standard deviation, maximum reduction, average reduction and processing time, and each algorithm has been run 100 times. The simulation results show that, based on minimizing the operating costs and reducing energy losses, the multi-objective particle swarm optimization method has the best performance.

Memory-based gravity search algorithm (MBSGA) is proposed to optimize power generation in microgrids with PV, combined heat and power (CHP) and diesel systems to minimize costs in [148]. MBGSA improves upon the conventional gravity search algorithm (GSA) by addressing the slow convergence and poor memory of finding optimal solutions by combining the best solutions from previous iterations, based on Newton's laws of gravity. MBGSA shows superior performance in solving the economic load dispatch problem compared to classical methods such as quadratic programming and other metaheuristics such as GSA, ABC, GA and PSO.

A hybrid optimization algorithm combining Spider Monkey Optimization (SMO) and Firefly algorithm is proposed to minimize microgrid operating costs by strategically placing and sizing distributed generators and power support devices in [149]. The hybrid approach improves the solution finding process in the complex microgrid operating environment, resulting in a 7.5% reduction in operating costs, a 36.5% reduction in real power losses, and a 17% reduction in voltage deviation in a 33-bus IEEE test system. The hybrid method also shows superior ability in determining the optimal location and size of real and reactive power support devices in microgrids.

J) Control System Design

Hierarchical control in microgrids, which is usually composed of three layers, is a control strategy that manages power distribution and quality. The primary control layer focuses on power sharing between DERs using a decentralized and unconnected approach. Secondary control aims to regulate voltage deviations and enhance power quality. Finally, the tertiary control layer manages

transactions and long-term electricity market planning [150,151].

A predictive control strategy based on the BFO technique for power management in an autonomous microgrid is investigated in [152]. The microgrid, consisting of a diesel generator and a battery storage system, uses BFO to determine the optimal power reference for non-renewable energy sources and loads. A two-stage control system maintains the DC link voltage, regulates the AC voltage and frequency, and improves power quality. The predictive control manages the power exchange on the AC side using the system parameters and the estimated BFO power references, while a DC-DC buck-boost converter regulates the DC link voltage on the DC side using the forward Euler method. The effectiveness of these strategies has been verified through simulation and experimental results. In an islanded microgrid with multiple distributed generators (DGs), differences in line impedance can lead to uneven power sharing and voltage deviations. To address this problem, an improved droop control strategy using fuzzy inference system (FIS) and improved particle swarm optimization (IPSO) is proposed in [153]. This method optimizes the droop control parameters, and improves the power allocation accuracy, voltage stability, and dynamic performance of the microgrid.

An approach to optimize the control of a doubly fed induction generator (DFIG)-based wind turbine is presented in [154]. This approach uses sensitivity analysis to accurately determine the important control parameters, called unified dominant control parameters (UDCPs), and reduces the optimization complexity. These UDCPs are then optimized using PSO, which leads to optimal control of the DFIG. The effectiveness of this method is verified through simulations.

A nature-inspired MPPT controller named ACO-new pheromone updates (ACO_NPU) is presented in [155], which is based on the ant colony optimization algorithm with a novel pheromone update strategy for photovoltaic systems. The ACO_NPU MPPT is designed to improve tracking accuracy, speed, robustness, and partial shade management under variable weather conditions, outperforming conventional MPPT methods and other nature-inspired soft computing methods. The design and implementation details of the ACO_NPU MPPT controller, including parameter selection, are investigated through experiments under standard conditions. The results show that the ACO_NPU MPPT achieves superior performance, especially in global maximum power point (GMPP) tracking under partial shade conditions.

Optimization of renewable energy plant sizing due to remote transmission lines with unreliable power supply is presented in [156]. By analysing

energy demand and available resources, a multi-objective PSO algorithm (MOPSO) is used to determine the optimal plant sizes, minimizing costs and grid imports. The results, which yield a 20-year internal rate of return of 8.33%, demonstrate the feasibility of a diverse renewable energy portfolio, including solar, wind, hydro, and biomass, for this specific scenario. The MOPSO algorithm aims to produce a set of non-dominated solutions, forming a Pareto front, where no single objective can be improved without sacrificing another objective.

The application of mixed-integer distributed ant colony optimization (MIDACO) to optimize the discharge load (DL) allocation and distributed generation droop adjustments in islanded microgrids is presented in [157], where the goal is to minimize voltage and frequency deviations, along with power losses, especially during off-peak hours. The MIDACO method is combined with a specialized backward/forward sweeping load flow method, to effectively manage droop characteristics, and enhance convergence. The approach has been validated using IEEE 69 and 118 bus test systems, and demonstrates its ability to achieve acceptable voltage and frequency regulation while reducing system losses.

The shift towards RES is crucial due to the decline of conventional energies, but their inherent uncertainty poses operational challenges. The performance of the artificial fish swarm algorithm in optimizing generation in a microgrid with RES is investigated in [158], and compared with the adaptive interference mitigation (AIMD) algorithm. The AFS algorithm showed superior cost-effectiveness both in a scenario where the costliest resource is used simultaneously with other resources, and in a more realistic scenario where it is accessed only after the cheaper resources are exhausted.

An improved droop control strategy for islanded low-voltage microgrids with parallel inverters is presented in [159], which aims to enhance reactive power sharing and voltage stability. This strategy combines virtual impedance control with the adaptive weighted particle swarm optimization (APSO) algorithm to optimize the PID controller parameters. The APSO algorithm is used to optimize the PID controller parameters in the voltage outer loop control module, which further enhances voltage stability and reduces fluctuations. Simulation results demonstrate the effectiveness of this approach in achieving balanced reactive power distribution and improving voltage regulation.

A stochastic optimal power allocation strategy for a droop-controlled islanded microgrid with moderate X/R ratio is presented in [160]. Power distribution optimization in a microgrid with plug-in hybrid electric vehicle (PHEV) charging and

discharging is performed using a multi-objective optimization approach, which aims to balance economic, environmental, and grid sustainability objectives while managing uncertainties associated with PHEV load and renewable energy sources. The proposed method uses a modified particle swarm optimization and gray wolf hybrid optimizer in a fuzzy framework to solve the complex problem and is validated on a 33-node test system.

A frequency controller based on model predictive control (MPC) for microgrids with renewable energy sources is proposed in [161]. For the controller in the secondary frequency control loop, MPC is used to optimize the controller coefficients and PSO algorithm is used to optimize the MPC weight parameters. Simulation results show that the proposed controller effectively reduces frequency deviations and oscillations, is more robust to parameter uncertainties, and outperforms traditional controllers such as PI, fuzzy logic PI, fractional order PID (FOPID), and PID controllers. The proposed controller exhibits better performance than traditional controllers, including lower frequency deviations, less oscillations, and more robust to parameter uncertainties.

The development and validation of a hybrid optimization algorithm called SSIA-PSO for the optimal design of microgrid droop controllers is proposed in [162]. SSIA-PSO is a combination of the Salp swarm-inspired algorithm and the PSO algorithm. This hybridization incorporates the position and velocity updating features of PSO into SSIA and enhances its search capabilities. The hybrid SSIA-PSO is specifically applied to address various uncertainties in real microgrid droop control, including inaccuracy in controller gains, system parameter degradation, multi-source energy sharing challenges, and system dynamics. Experimental results confirm the effectiveness of the hybrid SSIA-PSO algorithm in addressing these real-world microgrid control challenges.

A hybrid PID and PI-PD controller based on PSO and GWO is reported in [163] to investigate the frequency and power flow deviations of interconnected microgrids. The importance of maintaining these parameters due to continuous load changes and increasing renewable energy integration is shown. The performance of a PID controller based on the hybrid PSO-GWO algorithm is also investigated, and it is compared with the PID controllers based on single PSO and GWO. Then, the performance of the hybrid algorithm is investigated in a cascade PI-PD controller, and it is compared with the PID controller using the integral time multiplied by the absolute error as the objective function. The simulation results show the superiority of the hybrid PSO-GWO based PI-PD controller in

terms of settling and overshoot times compared to other techniques.

K) Fault Location and Fault Recovery

Fault location and fault recovery in microgrids is a self-healing process, in which an automated system, known as fault location, isolation and service recovery, detects a fault, isolates the affected section, and then restores power to the remaining healthy sections of the network by reconfiguring the network topology. This process relies on communication-based techniques, which use data from different points in the network to accurately locate the fault. The goal is to restore service quickly and minimize the duration of the outage for customers [164-168].

The challenge of coordinating overcurrent relays in modern distribution systems including distributed generators is reviewed in [169], which change the short-circuit levels, and can cause relay disoperation. A comparative study of PSO and GSA is presented to find the optimal relay settings, aiming to avoid unwanted outages. A 4-bus radial system is simulated in PSCAD/Simulink and programmed using MATLAB, and practical cases with different DG penetration levels and fault types are analysed.

A two-part PSO-based approach for fault location and recovery in microgrids is reviewed in [170]. The fault location algorithm uses modified network connectivity matrices for pre-fault analysis, a backward/forward scan, and an impedance matrix modification algorithm and PSO are used to find the fault location. The recovery section uses PSO to solve a multi-objective function for optimal recovery under constraints. These methods have been validated on the IEEE 37-bus test system, and show their effectiveness in solving fault location and recovery problems in microgrids.

As seen, the application of swarm intelligence algorithms in microgrids is widespread, taking advantage of their decentralized, adaptive, and self-organizing nature to address complex optimization challenges. Table (3) summarizes the applications along with their descriptions.

5. Performance Evaluation Parameters

Various statistical parameters have been defined to evaluate the comparative performance and robustness of optimization techniques [171-176].

The mean absolute error (MAE) metric quantifies the average error of a model's predictions. It is calculated by considering the mean absolute difference between the predicted and actual values, and is defined as:

$$MAE = \frac{\sum_{r=1}^N (x_r - x_{\min})}{N} \quad (1)$$

where x_r is the value of the objective function at the r^{th} run; x_{\min} is the minimum value obtained from the objective function; and N is the total number of data points.

The relative linear error (RLE) is a measure of the accuracy of an approximation or measurement, expressing the error as a ratio of the true or true value. This metric provides a standard way to understand the magnitude of the error, especially when comparing errors on different scales. Essentially, it is the absolute error (the difference between the actual and measured value) divided by the actual value:

$$RLE = \frac{\sum_{r=1}^N (x_r - x_{\min})}{x_{\min}} \quad (2)$$

The root mean square error (RMSE) is a measure, often used to measure the difference between the values predicted by a model and the actual observed values of the environment it models. It is essentially the root mean square of the differences between the predicted and actual values.

Table.2.
Different advantages of applying algorithms based on collective intelligence in microgrids

Optimization Area in Microgrids	Objectives/Benefits in Microgrids	Swarm Intelligence Algorithms Applied
Demand-Side Management (DSM)	Shifting or eliminating non-critical loads to optimize load profiles to reduce peak demand, adjusting energy consumption patterns in response to grid conditions, improving grid efficiency by further integrating renewable energy	PSO, ABC, GWO
Security and Resilience Enhancement	Increase the anti-interference ability of the microgrid, improve the ability of the microgrid to withstand and recover from disturbances	Various SI algorithms (often hybridized)
Energy Management Systems	Minimizing operating costs, maximizing the use of renewable energy, optimally scheduling distributed energy resources, managing energy storage systems, increasing the satisfaction of electric	PSO, ACO, ABC, GWO, SSA

	vehicle users, balancing production with demand.	
Fault Detection and Diagnosis	Rapid identification and location of errors, increasing system reliability and resilience, rapid error detection with the development of intelligent systems	PSO, ACO, ABC, FFA, AIS
Optimal Power Flow	Minimizing real and reactive power losses, improving voltage profiles, increasing system stability, optimizing load distribution in the system	PSO, SSA, GWO
Resource Allocation and Sizing	Determining the optimal location and size of distributed energy resources, planning the operation of distributed generation units, reducing losses, and minimizing investment costs.	PSO, ABC, ACO
Load Forecasting	Improve planning and operational efficiency using future energy demand forecasting	PSO, ABC
Protection System Coordination	Optimize relay settings and protection schemes to ensure selective and rapid fault clearance and prevent cascading faults	PSO, ACO

RMSE is a good general error measure for assessing the accuracy of predictions:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{r=1}^N (x_r - x_{\min})^2} \quad (3)$$

The average efficiency of an optimization technique is defined as:

$$\eta_{\text{mean}} = \frac{\sum_{r=1}^N \frac{x_{\min}}{x_r}}{N} \times 100 \quad (4)$$

Mean percentage error (MPE) is a statistical measure that averages the percentage difference between predicted and actual values over a set of observations. It is used to evaluate forecasts and indicate forecast bias, revealing whether a model tends to over-predict or under-predict, though it can be misleading due to the cancellation of positive and negative errors.

$$\text{MPE}_{\text{mean}} = \frac{\sum_{r=1}^N \frac{(x_{\min} - x_r)^2}{x_{\min}}}{N} \times 100 \quad (5)$$

6. Conclusion

Metaheuristic optimization algorithms are increasingly gaining attention in engineering applications due to several key advantages. These advantages include: simplicity and ease of implementation, independence from gradient information, ability to bypass local optima, and broad applicability in various disciplines. Swarm intelligence is a natural metaheuristic algorithm that describes the emergent behaviour of decentralized and self-organizing systems and is used in artificial intelligence. Swarm intelligence, also known as collective intelligence or group intelligence, is a group of computational methods that are inspired by the collective behaviour of insects and social animals. These algorithms are usually used in optimization and search problems and work based on the interaction between simple agents.

Microgrids are emerging as a solution to integrate renewable energy sources and address challenges related to reliability, environmental impact and economic efficiency. One of the essential parts of modern networks in order to improve network stability and reliability is microgrids. In essence, microgrids represent a shift towards more localized, flexible and resilient power systems, and offer a promising approach to modernize the electricity grid and integrate more renewable energy sources.

This paper provides a brief overview of the application of crowd intelligence algorithms for microgrid optimization. The application of crowd intelligence algorithms such as PSO, ACO, and FA, which mimic the collective behavior of animal groups to find optimal solutions, to microgrid optimization is described. Crowd intelligence refers to intelligent behavior that arises from the interactions of a large number of simple agents. In the context of microgrids, these algorithms are designed to address various optimization challenges, such as economic dispatch (minimizing operating costs by optimally allocating power generation between DERs and ESSs in the microgrid), energy management (optimizing the scheduling and dispatch of DERs and ESSs to meet demand, maximize renewable energy utilization, and ensure grid stability), reliability enhancement (optimizing component sizing, redundancy, and fault management strategies), and power quality improvement (minimizing voltage deviations, frequency fluctuations, and harmonic distortions in the microgrid).

Compared with GA, PSO, and refrigeration simulation, the ACO algorithm shows that ACO often outperforms these algorithms in terms of cost, renewable energy utilization, and grid stability. In essence, ACO provides a powerful and versatile tool for optimizing various aspects of microgrid

performance, helping to develop more efficient, reliable, and sustainable energy systems.

The Whale Optimization algorithm helps find optimal configurations and operating strategies for microgrids, especially those that incorporate renewable energy sources.

These algorithms offer advantages such as handling complex and nonlinear problems, robustness to uncertainties, and the ability to find near-optimal solutions in large-scale microgrid systems.

Some of the challenges facing microgrids include uncertainty in load forecasting and renewable energy generation, technical complexities in microgrid design and implementation, and high initial investment in microgrid infrastructure.

Topics for further research include combining swarm intelligence with other techniques to improve microgrid performance and overcome limitations, developing adaptive and self-tuning swarm intelligence algorithms to automatically adjust parameters based on microgrid conditions, applying swarm intelligence to emerging microgrid technologies to optimize the integration of new technologies, validating swarm intelligence algorithms in the real world to conduct further studies to validate the performance of swarm intelligence algorithms in real-world microgrid environments, and developing standard criteria for evaluating artificial intelligence algorithms in microgrid applications.

Abbreviations

ABC	Artificial bee colony
ACO	Ant colony optimization
AIMD	Additive increase multiplicative decrease
AIS	Artificial immune system
BFO	Bacterial foraging optimization
BSO	Brain-Storming optimization
CABC	Chaotic artificial bee colony
CHP	Combined heat power
CS	Cuckoo search
DER	Distributed energy resource
DFIG	Doubly-fed induction generator
ESS	Energy storage system
FA	Firefly algorithm
FIS	Fuzzy inference system
FOPID	Fractional-order PID
FSA	Fish swarm algorithm
FWA	Fire-works algorithm
GA	Genetic algorithm
GMPP	Global maximum power point
GSA	Gravitational search algorithm
GWO	Gray wolf optimization
MG	Microgrid
MHOA	Meta-heuristic optimization algorithm
MPC	Model predictive control

MPE	Mean percentage error
NPU	New pheromone updating
PSO	Particle swarm optimization
SMO	Spider monkey optimization
SSA	Salp swarm algorithm
SSIA	Salp swarm inspired algorithm
USCP	Unified dominate control parameters
WOA	Whale optimization algorithm

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