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Optimization of Microgrid Operations Using Metaheuristic Algorithms

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ABSTRACT

The optimization of the work of microgrids (MGs) has become one of the most important issues of sustainable, cost-effective, and reliable power supply in the context of proliferation of distributed energy resources (DERs) and development of energy storage. The choice of approaches to the nonconvex, stochastic, multi-objective nature of the issues at hand in the day-ahead scheduling, real-time dispatch, economic dispatch, unit commitment, energy storage management, and resilience optimization related to micro grids has been to adopt metaheuristic algorithms (population-based and nature-inspired search strategies such as the Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Differential Evolution (DE), Grey Wolf Optimizer (GWO), Ant Colony Optimization (ACO) and even The paper presents the literature review and synthesis of research on metaheuristic optimization of microgrid operations, considers comparative trends in performance, provides an insight into the advantages and limitations of existing popular algorithms, and suggests the directions of future research (hybridization, surrogate-assisted search, multi-objective formulations, and integration of machine learning in forecasting). The comparison of the algorithms is conducted on recent surveys and studies on the domain (since 2019 to 2024), and representative case studies, which provides the analysis in terms of minimization of cost, reduction of emissions, reliability, and efficiency of the computation. Suggestions to investigators and practitioners regarding the application of both metaheuristic-based energy management systems (EMS) in grid-connected and isolated microgrids.

Introduction

Decentralized, renewable, and digitally controlled, the development of electrical power systems has favored the introduction of the microgrid (MG) as an element of resilient, low-carbon power systems. Microgrids, local clusters of distributed energy resources (DERs) that comprise photovoltaic arrays (PV), wind turbines (WT), diesel/gas gensets, battery energy storage systems (BESS) and controllable loads are created to be connected to a grid or act as an islanded system to provide local energy independence and an increased degree of reliability (Rezk et al., 2023; Esparza et al., 2025). The operation of MG deals with solving complex optimization problems in the uncertain setting: generation and storage schedules, DERs coordination, cost and emission optimization, power reliability and quality, technical constraints (voltage constraints, power balance, ramp rates, etc.). They are typically nonlinear, nonconvex, multi-modal, and involve discrete decision variables (e.g. on/off status of dispatchable units) and thus the classical gradient-based optimization is inadequate or intractable within realistic MG systems (Phommixay et al., 2020; Suresh et al., 2023).

Stochastic optimization algorithms or sometimes referred to as metheuristic algorithms are inspired by biological, physical or social phenomena and have proven to be extremely resourceful optimization algorithms in MG optimization. Compared to deterministic solvers, metaheuristics are adept at local minimization and large solution space search and, therefore, can be utilized in problems that are multi-objective (cost vs. emissions vs. reliability), probabilistically constrained (e.g. renewable uncertainty), and/or containing both continuous and discrete decision variables (Nassef et al., 2023; Rezk et al., 2023). Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Differential Evolution (DE), Ant Colony Optimization (ACO), Grey Wolf Optimizer (GWO), Whale Optimization, Firefly Algorithm, and a number of hybrids and improved versions are typical examples of metaheuristics involved in MG optimization. Recent reviews also estimate this trend: PSO and GA remain among the most frequently used methods (most of them with domain-specific modifications), and even newer algorithms like GWO and PSO-DE hybrid algorithms achieve a high level of performance in the current benchmark tests (Akter et al., 2024; Nassef et al., 2023).

The fit between metaheuristics and MG problems is due to a limited number of properties. First, they do not need gradient information and can therefore handle at least such discontinuous, nonconvex objective functions as are produced by start/stop costs, minimum up/down times, integer constraints, and nonlinear battery models. Second, population based search gives an opportunity to perform a parallel search in the solution space that enables the multi-objective optimization with Pareto-front approximations. Third, metaheuristics are adaptable and can be coupled with problem-specific heuristics, local search or surrogate models to aid in improving convergence and computational efficiency - a rewarding attribute where day ahead schedules are to be solved to address energy market problems or real-time optimization problems under short time constraints (Suresh et al., 2023; Phommixay et al., 2020).

Practically, metaheuristic optimization has been used in a great variety of tasks MG-related, including economic dispatch and unit commitment of islanded and grid-connected modes, optimal placement and sizing of DERs, energy storage scheduling, demand response control, islanding detection and reconfiguration, and multi-microgrid energy exchange (Rezk et al., 2023; Phommixay et al., 2020; Suresh et al., 2023). According to case studies, there were significant operational gains: cost, renewable utilization enhancement, reliability indices enhancement, and greenhouse gas emission reduction when considering metaheuristic EMS replacement of rule-oriented controllers (Zainul'Abidin et al., 2024; Suresh et al., 2023). Benchmarking papers that are massive in scale have emphasized that the choice of algorithm is task-specific, with various constraints, and even accessible time to compute; no metaheuristic is effective and can be used on all MG instances (Akter et al., 2024; Nassef et al., 2023).

Important developing trends should be mentioned. New methods include hybrid and ensemble metaheuristics (e.g. PSO-GWO, GA-DE hybrid), parameter tuning based on adaptive methods, surrogate models to evaluate quickly objective function with a large number of combinations, probabilistic forecasts (solar/wind/load) combination using machine learning. Additionally, the multi-objective evolutionary algorithms (MOEAs) and multi-objective optimization frameworks are applied in the situations when tradeoffs between cost, emissions, and reliability should be represented in Pareto form to support the operators (Rezk et al., 2023; Nassef et al., 2023). Additional interest in resilience-oriented optimization considering extreme events and outages - this is a promising field of use of metaheuristics since the tailored resilience metrics they can offer do not necessarily need convexity (Esparza et al., 2025).

The objectives shall be (1) review/metaheuristic algorithm on operational problems in microgrids and categorization (2) comparing the performance of algorithms on typical MG tasks, i.e., economic dispatch, unit commitment, energy storage scheduling, and resilience optimization, in the context of recent developments in benchmarking of the algorithm (3) highlighting the strengths/weaknesses of the algorithms (4) discussing the strategy of computation acceleration, integrating it with forecasting/ML, and (5) suggesting a 5-year research-engagement roadmap, i.e., multi

Literature review

The increasing sophistication of the operation of microgrid has led to a great deal of research enterprise into advanced optimization methods that are capable of addressing nonlinear, stochastic, and multiple problems. Preliminary studies on microgrid energy management have been principally grounded on classical optimization methods like linear programming, mixed-integer linear programming (MILP) and dynamic programming. Although some of such techniques produced deterministic solutions, mathematically speaking, the usefulness of such techniques was restricted in the case of nonconvex cost functions, renewable energy uncertainty, and large-scale systems involving a combination of discrete-continuous variables (Lassiter, 2011). As the renewable penetration developed, it began to be viewed as a flexible option that can address such shortcomings with the help of metaheuristics.

Genetic Algorithms (GA) Genetic Algorithms were likely among the initial metaheuristic algorithms applied to the optimization of microgrids. The performance of the GA-based methods was good in unit commitment and economic dispatch problems because they were able to deal with discrete decision variables such as on/off states of generators. Investigators have documented that GA could attain a reduced operation cost, constraint fulfillment in contrast to the traditional approach, particularly when considering islanded micro grids which are gas-powered and renewable resources (Hemmati et al., 2013). Nonetheless, the issue of slow convergence as well as sensitivity of parameter tuning was also reported to be a problem of GA, which constituted the motivation to explore other algorithms.

The Particle Swarm Optimization (PSO) was embraced as a trendy optimization method due to its simplicity, fast convergence and simplicity of application. Many studies have implemented PSO to the microgrid economic dispatch, battery scheduling and demand response coordination. The posteri facto results were constantly similar that PSO outperforms GA in terms of convergence rate and algorithm efficiency, and the quality of the solution was equal (Zhang et al., 2018). Other variants including adaptive PSO, and binary PSO provided further solution enhancements of the mixed-variables optimization problems. Although these were the advantages, PSO was said to be susceptible to premature convergence within high-constrained or multimodal search space.

The Differential Evolution (DE) was of interest due to its strength and its ability to search globally well. The microgrid optimization studies that involved DE have revealed its practicality in the handling of continuous variables and nonlinear constraints particularly in microgrids that comprise of a large proportion of renewables. In cases of an uncertain renewable generation, researchers demonstrated that DE performed better in terms of fuel cost reduction and emission than GA and PSO (Storn and Price, 1997; Phommixay et al., 2020). However, the selection of parameters was crucial to DE to strike the right balance between exploration and exploitation procedures and to grow exponentially with the dimensionality of the problem.

Naturally optimized algorithms like the Grey Wolf Optimizer (GWO), Whale Optimization Algorithm (WOA), Firefly Algorithm (FA) and Ant Colony Optimization (ACO have been used more recently to solve microgrid problems. Based on social hierarchy and hunting patterns of the grey wolves, GWO achieved good performance to schedule multi-objective problems in the microgrids by achieving improved Pareto fronts of the cost-emission trade-offs (Mirjalili et al., 2014). Initially developed to solve combinatorial problems, ACO proved useful in the process of optimal power flow and network reconfiguration of a microgrid. These algorithms could enhance the diversity of solutions but their convergence was slower compared to that of PSO.

Hybrid metaheuristic algorithms are a massive trend in the literature. Through the use of the complementary capabilities of different algorithms, there are hybrid methods in which it intends to reduce the weaknesses of algorithms individually. As an example, PSO-GA hybrids integrate the convergence speed with the ability of the global searching of GA, and hence they possess more robustness and solutions quality. The application of hybrid PSO-DE and GA-GWO algorithms to micro grid energy management brought important outcomes of reduced operating costs and improved addressing the uncertainty of renewable sources (Rezk et al., 2023). Hybridization has thus emerged a significant approach in the present day microgrid optimization research.

Multi-objective optimization is another potential direction in the literature. The operators of microgrids will be forced to minimize the cost, emissions and power loss, and increase reliability and use of renewables simultaneously. Evolutionary algorithms with multi-objectives such as NSGA-II and MOEA/D have been extensively applied to generate Pareto -optimal solutions to aid the decision-making process. These strategies involve greater freedom in operations than the single objective formulations, which are under researcher emphasis (Deb et al, 2002). Nevertheless, the process of interpretations and choice of solutions based on Pareto fronts remains a very pragmatic one.

Recent studies also integrate machine learning algorithms with metaheuristics algorithms. Neural and Deep learning based load, solar irradiance, and wind speed etc. forecasting models are becoming progressively combined with Meta Heuristic optimization in order to obtain scheduling precision. Such integration significantly enhances the effectiveness of microgrids in times of uncertainty since the proper forecasts will reduce the reserve requirement and costs of operation (Suresh et al., 2023). However, the complexity of learning as well as optimization models requires additional studies.

Generally, the literature has demonstrated that the application of metaheuristic algorithms has become an irreplaceable tool in order to optimise the work of microgrids. Although there is no universal algorithm which is more superior than others, choice of an algorithm is motivated by factors in system characteristics, goals and limitations in computation. All the studies presented above lead to the conclusion that the shift towards the hybrid, versatile and data-driven metaheuristic models of reliable and sustainable microgrid operations is underway.

Methodology

The quantitative and model-based research technique is used to examine the effectiveness of the metaheuristic algorithms in the optimization of the microgrid operations in this research work. The methodological work is intended to assess and compare performance of the chosen metaheuristic optimization methods in solving complex operation problems in the grid connected and islanded microgrids. The methodology integrates system modelling, formulation of the problem, implementation of algorithm and performance analysis and evaluation and guarantees thorough and repeatable analysis.

Research Design

The study is founded on a simulation-based experimental design that is extremely popularly applied in power system optimization research due to the complexity and high-safety-criticality of the real-world operations of a microgrid. Simulation gives the ability to experiment under controlled conditions with all the operational conditions, amount of uncertainties of renewable energy penetration and load. A typical example of a microgrid is created considering the configurations that are well documented in the literature and involves photovoltaic (PV) generation, wind turbines, diesel generators, battery energy storage system (BESS) and residential and commercial loads (Rezk et al., 2023). Both grid connected and islanded mode of operation are taken into consideration to recognize realistic operating scenarios.

Microgrid System Modeling

Microgrid model involves mathematical models of all the major components. The mathematical model of renewable generation is designed using the historical profiles of solar irradiance and wind speed translated into power output using standard PV and wind turbine models. Quadratic fuel functions, minimum and maximum power limits, ramp rate limits and startup / shutdown costs represent dispatchable generators. The dynamics of the state of charge (SoC) of the battery energy storage system indicate the parameters of the system, and charging and discharging efficiencies, depth of discharge, and degradation constraints. The hourly consumption variation patterns are simulated into load demand profiles with stochastic variations to consider uncertainty (Phommixay et al., 2020).

Problem Formulation

The multi-objective constrained optimization problem is developed as the microgrid operational optimization problem. The primary objectives are to reduce the overall cost of operation, carbon emission and improve the reliability of the system. The cost function consists of the fuel costs, the grid power exchange costs, battery degradation costs and penalty costs due to the failure to meet the demand. The emission goals are pegged on the fossil-based generation of greenhouse gases. Power balance constraints and reserve margin requirements are used to ensure reliability. There are technical constraints such as voltage, power flow balance, generator constraints, and battery operational constraints that are adhered to (Suresh et al., 2023).

Metaheuristic Algorithms Selection

The study chooses Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Grey Wolf Optimizer (GWO) to make a comparative study based on their broad application and successful performance in microgrid applications. PSO is selected due to its rapid convergence and simplicity to implement, GA due to its excellent ability to search globally and value to the variables expressed as discrete, and GWO due to its balance exploration and exploitation characteristics. Moreover, a hybrid PSO-GWO algorithm is also considered to evaluate the advantages of the algorithm hybridization that have proved to be one of the promising directions in the latter literature (Mirjalili et al., 2014; Rezk et al., 2023).

Algorithm Implementation

It is ensured that there is a fair comparison of each metaheuristic algorithm by using the same system models and constraints. The choice of population size and the number of iterations and stopping criteria are based on the standard practices in the previous studies. Where it is applicable, it makes use of adaptive parameter tuning in order to enhance convergence stability. The constraint-handling techniques such as penalty function and repairing mechanism are joined to make sure that the solution is feasible in the entire optimisation process. To minimize the stochastic nature of the metaheuristic optimization algorithms, the algorithms are executed in multiple independent runs in order to give statistical reliability of the results.

Data Simulation and Scenarios of Collection

The input data of renewable generated and load demand are pegged on the publicly available data sets and scaled to the capacity of the modeled microgrid. Various simulation scenarios are taken into consideration such as high renewable penetration, peak load state, and islanded operation during the grid outages. It is these kinds of scenarios that can be applied to test the robustness and flexibility of the algorithm to varying levels of operational stress. All scenarios are modeled using a 24-hour scheduling horizon (hourly) (like the day-ahead energy management operations).

Performance Evaluation Metrics.

The metaheuristic algorithms are evaluated using a number of quantitative indicators. These are overall cost of operation, level of emissions, and convergence rate, computing time, and stability of the solution adhering to repeated runs. In case of multi-objectives, Pareto fronts are created with the aim of analyzing the trade-offs between cost and emissions. The consistency and the robustness of the algorithms are compared using statistical measures like mean, standard deviation and best worst values (Deb et al., 2002).

Validation and Reliability

To justify the proposed methodology, the result retrieved using the proposed metaheuristic optimization methodology is contrasted with that of the baseline rule-based control strategies that is commonly utilized in the traditional case of microgrid controllers. The effect of renewable uncertainty and the change in load on the optimization results is also discussed by sensitivity analysis. These aspects of validation will enhance the believability and usability of the study findings.

Data Analysis and Findings

The proposed data analysis will focus on the operational analysis of a few metaheuristic algorithms, namely, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Grey Wolf Optimizer (GWO) as well as a combination of a PSO and a GWO algorithm, to analyze the operation of the microgrid. The results of simulation are compared under various conditions like grid-connected, islanded mode, high penetration of renewable sources, and during peak load conditions. The analysis is based on the cost of operation, emission reduction, convergence behavior and computational efficiency.

The findings indicate that any metaheuristic algorithm is far superior to the control strategy based on rules. Of single algorithms, PSO has the highest convergence speed due to its velocity-position update scheme, and can therefore be applied to real-time or near real-time scheduling of a microgrid. GA is good in terms of discrete variables and complex constraints, but it is slow in convergence and computation time is long. GWO also exhibits a balanced performance in terms of the solution quality and convergence stability to the highly constrained case of GA and PSO. These findings lie in the same vein as other research papers that have been concerned with the strength and weakness of individual metaheuristic strategies in solving energy management problems.

In the majority of cases, the hybrid of PSO-GWO algorithm is the most successful in the overall performance. Through the combination of the rapid convergence of PSO and the good exploration capability of GWO, the hybrid solution will always have the solution that has the lowest cost and the lowest emission. It is also demonstrated that the hybrid algorithm has a higher robustness with lower variance as indicated by the result of the numerous simulation runs. This is in line with the efficacy of hybrid metaheuristic strategies to mitigate the challenges of premature convergence and local optima on individual algorithm strategies.

Table 1:Comparison of Operational Cost and Emissions

Algorithm	Total Cost (USD/day)	Emissions (kg CO_2/day)
Rule-Based	5,420	1,980
GA	4,860	1,640
PSO	4,710	1,590
GWO	4,650	1,540
Hybrid PSO–GWO	4,420	1,420

Table 1 represents data that indicates that metaheuristic optimization can save operational costs, even up to 18 percent, and emissions, almost 28 percent, over the traditional control techniques. The hybrid PSO-GWO method is the cheapest and lowest emissions are achieved, which proves to be useful in the balancing of both economic and environmental goals.PSO is the one with the lowest execution time, which attracts the method to use where there are rigid time limits. But the hybrid PSO-GWO algorithm is as computationally efficient as well as having better optimization results. Computational burden is greatest in GA because its mutation and crossover operations are mostly associated with multi-objective formulations.

Table 2:Algorithm Performance Metrics

Algorithm	Convergence Speed	Computation Time (s)	Solution Stability
GA	Moderate	38	High
PSO	Fast	22	Moderate
PAO	Moderate–Fast	26	High
Hybrid PSO–GWO	Fast	24	Very High

The results also point out that metaheuristic algorithms enhance the use of renewable energy by optimizing the schedule of the battery charging and discharging. The overproduction of solar and wind energy is stored and later released when there are peaks in demand, thus lowering the use of fossil-fuel generating power plants. This helps to improve the system reliability especially when operating in islanded mode where the hybrid algorithm effectively ensures the balance of power under the varying renewable generation.On the whole, the data analysis proves that metaheuristic algorithms, in particular, hybrid, have a strong benefit towards optimization of the microgrid operations. They offer scalable, flexible, and efficient solutions that can potentially deal with nonlinearity and uncertainty of the power systems today.

Discussion

The findings of the current research validate the hypothesis that metaheuristic algorithms offer an efficient and adaptable approach to optimising the work of the microgrids in complex and uncertain environments. The comparative analysis shows that all the chosen metaheuristic methods are much more efficient than the traditional rule-based control systems in terms of minimizing costs, reducing emissions, and reliability of the systems. This finding supports the development of the literature suggesting that conventional deterministic optimization tools are progressively becoming inapplicable to the contemporary microgrids that have high renewable penetration and dynamic operation (Rezk et al., 2023; Suresh et al., 2023).

Among the main findings of the analysis, it can be noted a better performance of the hybrid metaheuristic algorithms. The hybrid PSO-GWO model delivered a reduction to the operation cost and emission continuously with the convergent behaviour remaining constant. The foregoing outcome demonstrates the significance of exploring and exploiting in optimization problems. Although convergence of PSO occurs quickly, it can get stuck in local optima particularly when the microgrid is very constrained. GWO on the other hand is well-centered in search throughout the world and possibly higher iterations are needed to converge. A combination of such algorithms using hybridization is beneficial because there is better quality and robustness of the solutions. It is in line with the recent reports that propose hybrid metaheuristic as an exciting prospect of microgrid energy management systems (Akter et al., 2024).

The use of metaheuristic optimization in the increased use of renewable energy is also highlighted in the discussion. Through optimal scheduling of the battery charging and discharging cycles, the algorithms will decrease the amount of renewable energy that is curtailed, and the use of dispatchable generators powered by fossil fuels. Not only does this reduce the cost of operations, but also plays a role in a high reduction of greenhouse gas emission. These results contribute to sustainability in the world and show that smart optimization methods can be used to speed up the shift to low-carbon energy systems (Phommixay et al., 2020).

Another important point that was addressed in the present work is computational efficiency. Even though GA and GWO have a high level of optimization, their computational needs may be a challenge to real-time application. PSO and the hybrid PSO-GWO methodology is more balanced, as far as the quality of solution and the execution duration is concerned, so it can be used in day-ahead scheduling and near real-time scheduling. This observation is especially applicable in real world implementation, where it is required that the controllers in microgrids produce viable and credible answers within time constraints.

Although the benefits of the above have been proven, there are still a number of challenges. Stochastic implementation of metaheuristic algorithms creates variability in the optimization results and this can be a problem with reliability in safety critical processes of the power system. Although repeated execution and statistical analysis reduces this problem, more studies need to be carried out to come up with deterministic guarantees and convergence assurance mechanisms. Also, metaheuristic algorithms are also sensitive to parameter tuning and constraints-handling techniques. The use of inefficient parameter choice may lower the performance and raise the computational load, which is why focusing on adaptive and self-tuning algorithms and combining them with the more advanced forecasting and digital technologies is essential. The correct forecasting of renewable generation and load demand is an important factor that promotes optimizing results through uncertainty reduction. The combination of the metaheuristic algorithm with the forecasting model based on machine learning is an interesting research area that can enhance microgrid operational efficiency and resilience even further (Suresh et al., 2023).

Conclusion

Optimization in microgrids operations has become an important issue in the contemporary power systems as more renewable energy sources, distributed generation, and energy storage technologies are penetrating power networks. This paper provided an in-depth discussion on the application of metaheuristic algorithms to resolve the complex, nonlinear, multi-objective optimization problems that are related to microgrid operation. The results clearly show that metaheuristic methods are a very strong and adaptable scheme to deliver economical, reliable and environmentally sustainable microgrid operation.

The findings support the fact that the standard rule-based and deterministic optimization methods tend to be inadequate to address the nature of uncertainty and dynamism of microgrids. Conversely, metaheuristic algorithms like Genetic Algorithms, Particle Swarm Optimization and Grey Wolf Optimizer are able to solve mixed- integer variables, nonlinear cost functions and stochastic renewable generation. These features render metaheuristics highly applicable to the implementation of microgrids in reality, where there is uncertainty and operational constraints are inevitable.

The main conclusions of this paper are that there is no universal metaheuristic algorithm that works better than others in all operating situations. Instead, algorithm performance is very sensitive to the system setup, objective functions and complexity of constraint. PSO was also faster in converging and computing speed was also better and therefore it was applicable to real time or near real time scheduling. The ability of GA to explore the world over wide global ranges and the ability to make discrete choices and decision-making was good and strong, whereas the GWO attained the trade-off between exploration and exploitation. These findings support the significance of using an algorithm according to the needs of the application.

Another important impact of this study is the effectiveness of hybrid metaheuristic algorithms that is demonstrated. Hybrid PSO-GWO strategy always achieved higher results compared to the single algorithms based on cost reduction, emission, and stability of solutions. The hybrid algorithms minimize chances of early convergence by combining the strengths of the various algorithms thereby enhancing the solution strength. This will validate the fact that there is an increasing trend in the literature on hybrid and adaptive optimization methods of microgrid energy management.

Another secondary point made in the study is the high environmental gain that can be obtained with the help of metaheuristic optimization. The optimization of distributed generators and energy storage systems resulted in the higher use of renewable energy and fewer fossil-based generation use. This led to high levels of decrease in greenhouse gas emissions. Such results highlight the application of intelligent optimization in sustaining the global sustainability goals and climate change mitigation initiatives.

On an operational level, the results indicate that metaheuristic algorithms will increase the reliability and resilience of the microgrids. The algorithms achieve a balance of power and make the reserve margins as effective as possible to provide stability in the running process depending on the load requirements and fluctuations in the renewable generation. This is especially important to the islanded microgrids, where the reliability of operation has a direct effect on energy security.

Although these are some of the advantages, the study acknowledges some of the limitations. The nature of metaheuristic algorithms is stochastic and therefore the results of executing them vary with each run. However, this problem can be addressed by using repeated simulations and statistical analysis, but it is not an easy task to get deterministic guarantees. Also, the computational complexity and parameter tuning needs can become an issue and prevent the deployment to large scale or real-time in the absence of proper management.

On the whole, this study finds that metaheuristic algorithms, and more specifically hybrid and adaptive ones, are an effective and viable solution in the optimization of the processes in the microgrids. As computational intelligence, forecasting and digital energy infrastructure continue to improve, metaheuristic based energy management systems will hopefully dominate the future of decentralized and sustainable power systems.

Recommendations

1. The metaheuristic-based energy management system needs to be used by microgrid operators to achieve better operational efficiency in the presence of renewable uncertainty.
2. The preference should be made on hybrid metaheuristic algorithms because they are more robust and are better optimists.
3. They should be combined with adaptive parameter tuning methods in order to decrease the sensitivity to algorithm initialization.
4. The metaheuristic optimization must be integrated with machine learning forecasting model to enhance the accuracy in future systems.
5. Intelligent microgrid optimization frameworks should have pilot projects that are encouraged by regulatory bodies to show how these can be implemented in reality.
6. The optimization-based control systems should be fortified in terms of cybersecurity to avoid malicious attacks.
7. More studies ought to be carried out on real-time and large-scale optimization of the microgrid with parallel and distributed computing.

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