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Research Review on Automated Dispatch Strategies and Optimization Algorithms for Energy Storage Systems in Microgrids

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Abstract. Against the backdrop of the global energy crisis and environmental pollution, researchers are increasingly prioritizing the investigation and utilization of clean and green renewable energy sources. Wind power and photovoltaic (PV) power generation, as the most widely applied and mature renewable energy generation technologies, occupy a significant position within power systems. However, the intermittent and stochastic nature of wind and PV power generation can pose challenges to the stability and power quality of traditional power grids. Microgrids, serving as a key solution to this challenge, have become a major research focus in recent years. This paper synthesizes recent research achievements in microgrid energy storage, systematically organizing dispatch strategies and optimization algorithms. It reviews current advancements in these areas within microgrid research. The study demonstrates that energy storage dispatch strategies and optimization algorithms play a crucial role in enhancing renewable energy utilization efficiency and grid stability.

Keywords: Microgrid, Energy Storage System (ESS), Environmental Performance, Dispatch Strategy, Optimization Algorithm

1. Introduction

Based on the vision of achieving China's carbon peak and carbon neutrality goals, coupled with the strategic objective of transitioning towards high-quality development, China is placing increasing emphasis on the development of renewable energy. Microgrids, serving as a bridge between distributed energy resources and the main grid, represent one of the most effective pathways for integrating renewable energy into the power system.

As a current focal point of research, microgrids have been the subject of extensive and in-depth investigation by researchers in recent years. This review focuses specifically on research progress concerning dispatch strategies and optimization algorithms within the domain of microgrid energy storage systems. It provides an in-depth analysis and summary of current relevant research achievements, highlighting representative or breakthrough developments. These include, for instance, the practical "Grid-User Bilateral Energy Storage Microgrid Optimal Dispatch Model" and the theoretically innovative "Active Energy Optimization Management Algorithm for Microgrids Considering Generalized Energy Storage".

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This paper focuses on scheduling strategies and optimization algorithms in microgrid energy storage systems, with particular emphasis on enhancing renewable energy integration efficiency and grid stability. The study not only provides a systematic review of microgrid technology applications and development, but also offers crucial theoretical foundations and practical guidance for policymakers and researchers in achieving carbon peaking and carbon neutrality goals.

2. Overview

A microgrid is a small-scale generation, distribution, and consumption system comprising distributed generation sources, energy storage systems (ESS), power conversion devices, monitoring and protection devices, and loads [1]. To address environmental pollution and the energy crisis, increasing attention is being directed towards the utilization of clean energy generation sources such as wind power and photovoltaic (PV) power generation. However, the stochastic nature of such energy generation can adversely impact grid integration and post-integration grid stability. As an effective network structure to address this challenge, microgrids have garnered significant research interest in recent years.

Microgrids operate in two distinct modes: grid-connected and islanded. They can connect to the main grid via the Point of Common Coupling (PCC) for grid-connected operation or disconnect and operate autonomously. This dual functionality allows a microgrid to act either as a controllable unit within the larger grid or as an independent, self-sufficient system. Consequently, the complex challenge of integrating numerous distributed energy resources is transformed into the more manageable task of integrating a single controllable microgrid [2]. This significantly mitigates the negative effects of the inherent randomness and intermittency of clean energy sources on grid stability and power quality during grid-connected operation.

The Energy Storage System (ESS) is a crucial component for the reliable operation of a microgrid. By storing and releasing electrical energy, the ESS enhances the overall flexibility and stability of the microgrid. Therefore, optimizing the energy dispatch within the microgrid ESS to maximize economic benefits represents a major current research focus [3].

Economic and environmental performance are defining characteristics of microgrid technology. Consequently, dispatch strategies and optimization algorithms must be thoroughly considered during the design phase to optimally achieve these two key objectives. Through persistent research efforts, studies have demonstrated that employing enhanced whale optimization algorithms can reduce daily operating costs under wind and PV power uncertainty by up to 68%, subject to constraints including ESS capacity configuration [4].

3. Research on automated dispatch strategies for microgrids

To better achieve the economic and environmental performance objectives of microgrids, numerous researchers have conducted extensive studies on dispatch strategies and optimization algorithms.

3.1. Optimal dispatch model for grid-customer bilateral energy storage microgrids

The Grid-Customer Bilateral Energy Storage Microgrid comprises a gas turbine, fuel cell, photovoltaic (PV) units, wind turbines, energy storage equipment, and loads. The energy storage equipment includes both grid-side storage and customer-side storage, with the customer-side storage utilizing battery energy storage systems (BESS).

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Through systematic analysis, the objective function of the dispatch model is formulated as follows:

$$\min f_{cost} = \sum_{t=1}^{T} \left[f_{cost}^{mt}(t) + f_{cost}^{fc}(t) + f_{cost}^{pv}(t) + f_{cost}^{wt}(t) + f_{cost}^{pv}(t) + f_{cost}^{v}(t) \right] \quad (1)$$

Where f_{cost} denotes the total dispatch cost of the microgrid;T represents the dispatch period.

The controllable decision variables in this objective function are the power generation outputs at each time step for the following four components:Gas turbine;Fuel cell;Grid-side energy storage. Battery energy storage system (BESS) [3]. This dispatch model specifically addresses the critical challenge of balancing supply-demand relationships between the grid and loads, as well as coordinating storage utilization dynamics during practical microgrid implementation. It proposes a tailored scheduling framework to resolve these operational interdependencies.

3.2. Hierarchical coordinated power control strategy for AC/DC interconnected microgrids based on hybrid Energy Storage Systems

This dispatch strategy specifically addresses challenges in islanded microgrid operation: ineffective mitigation of inter-subgrid voltage/frequency fluctuations and the inability of single-battery storage to satisfy multi-scenario power demands. Building on this analysis, it proposes a coordinated power control strategy for AC/DC microgrids utilizing hybrid energy storage systems (HESS) comprising supercapacitors and batteries.

Regarding energy storage control, conventional HESS control strategies suffer from incomplete utilization of supercapacitor capacity and excessive charge/discharge cycles. To resolve these limitations, researchers developed an improved HESS control strategy. This strategy defines five operational modes based on supercapacitor voltage and state-of-charge (SOC) thresholds, implemented through controlled power reference values for both supercapacitors and batteries. The five operational modes are detailed below:

Mode 1: Supercapacitor Charge/Discharge Mode prioritizes supercapacitors for power fluctuation suppression between subgrids. In this mode, batteries remain in standby with suspended operation

Mode 2: Supercapacitor Discharge & Battery Charge Mode involves supercapacitors primarily supporting power deficits between subgrids, while batteries absorb surplus power. This mode ensures that excess power is stored in the batteries for later use.

Mode 3: Overcharge Protection State is activated when subgrids require power output from storage. Supercapacitors respond first to meet the power demand. Conversely, when subgrids require power absorption by storage, the HESS halts operation to prevent overcharging of the batteries.

Mode 4: Supercapacitor Charge & Battery Discharge Mode sees supercapacitors primarily absorbing surplus power between subgrids, while batteries support power deficits. This mode optimizes the use of both energy storage components to balance power flow.

Mode 5: Over-discharge Protection State prioritizes supercapacitors for power absorption when subgrids require storage to absorb power. However, when subgrids require power output from storage, the HESS halts operation to prevent over-discharge of the batteries. These modes collectively ensure the efficient and safe operation of the HESS in various power demand scenarios [5].

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3.3. Node source-sink current-differential based control strategy for energy storage power converters in DC microgrids

In DC microgrids, variations in sources and loads, as well as potential short-circuit or open-circuit faults, can adversely impact overall voltage stability. Consequently, the rapid response capability of energy storage systems responsible for charge/discharge regulation becomes critically important.

This control strategy targets energy storage power converters in DC microgrids, proposing a novel approach based on node source-sink differential current. Researchers introduce a method where the power exchange requirement for energy storage is determined by calculating the real-time power imbalance between sources and sinks within the DC microgrid. This power reference is then converted into a corresponding current adjustment signal, which directly modulates the duty cycle of the storage power converters [6].

Compared to Finite Control Set Model Predictive Control (FCS-MPC), this strategy significantly reduces computational burden during operation and remains unaffected by inductance parameter variations. These attributes collectively enhance both response speed and control accuracy.

4. Research on optimization algorithms for microgrids

Optimization algorithms constitute a critical component in microgrid design and operational optimization. During microgrid operation optimization, the most frequently employed objectives are economic and environmental performance metrics [7]. Compared to traditional algorithms characterized by high computational complexity and slow convergence, emerging artificial intelligence-based algorithms have gained significant popularity due to their high efficiency and enhanced robustness. When selecting optimization algorithms, appropriate solvers should be judiciously chosen based on three key factors: the number of optimization objectives, the complexity of the optimization model, and client priorities (whether emphasizing computational efficiency or solution accuracy in dispatch decision-making).

4.1. Multi-pivot-guided adaptive-dimension crossover artificial bee colony algorithm

Multi-Stage Optimization Algorithms represent an effective approach for addressing energy storage configuration problems in microgrids. However, as a type of multi-stage algorithm, the conventional Artificial Bee Colony (ABC) algorithm demonstrates suboptimal optimization precision and speed when confronted with highly complex requirements. The proposed algorithm addresses these limitations through targeted enhancements to ABC, resulting in a methodology better adapted to microgrid energy storage applications.

Compared to standard ABC, this algorithm introduces two major improvements. First, Multi-Pivot Guidance Strategy employs double stochastic pivots to direct employed bees' global exploration bees, while utilizing Pareto-dominant elite pivots to guide the localized search of scout bees. This approach significantly mitigates the traditional ABC's issues of excessive resource consumption during wide-area exploration. As a result, the algorithm enhances final convergence precision by 19-37% in benchmark tests. In addition, the Adaptive Crossover Mechanism is integrated into both the employed and onlooker bee phases. This mechanism improves the standard ABC's capability to tackle high-dimensional complex problems, leading to an optimization speed increase of 42% and a solution accuracy improvement of 28%. The mathematical formulation for this mechanism is detailed in Equation 2:

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$$u_{i,j}/U_{bcat_j}/u_{e,j} = \begin{cases} v_{i,j}/O_{bcat_j}/v_{e,j} & , rand_j\,(0,1) \le c_x, or\ j = j_{rand} \\ x_{i,j}/G_{bcat_j}/x_{e,j}, otherwise \end{cases} \quad (2)$$

Where $u_{i,j}/U_{bcat_j}/u_{e,j}$ refers to Candidate food source during the employed or onlooker bee phase; $v_{i,j}/O_{bcat_j}/v_{e,j}$ denotes new food source generated in the employed or onlooker bee phase; $x_{i,j}/G_{bcat_j}/x_{e,j}$ is Original food source in the employed or onlooker bee phase; c_x : Crossover probability is calculated as specified in Equation 3.

$$c_x = \left(1 - \frac{f_{cs}}{mf_{cs}}\right) \bullet c_{r0} \quad (3)$$

Where f_{cs} denotes computational resources; m is quantity of computational resource; c_{r0} is initial crossover probability [3].

4.2. Synergistic Co-optimization methodology for economic and environmental performance in microgrids based on the HSMOPSO algorithm

The objective of microgrid optimization dispatch is to achieve synergistic coordination between economic and environmental performance. Traditional Multi-Objective Particle Swarm Optimization (MOPSO) algorithms exhibit stronger local exploitation capabilities but suffer from insufficient global exploration. To enhance global search performance, researchers introduced Fuzzy MOPSO (FMOPSO). By integrating the advantages of both approaches, the Hierarchical-Structured Modified PSO (HSMOPSO) algorithm achieves balanced local-global optimization capabilities.

Under uniform particle distribution conditions,global exploration strength correlates with particle dispersion magnitude(wider spatial distribution indicates enhanced global exploration);local exploitation strength correlates with proximity to the true Pareto front (closer convergence signifies superior local optimization). The inter-particle distance is defined by Equation 4:

$$d_i = \min\left(\sum_{k=1}^{2} |f_{i,k} - f_{j,k}|\right), i, j = 1,2,\cdots,N; i \ne j \quad (4)$$

The uniformity of particle distribution is characterized by Equation 5:

$$\sigma_{SP} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(d_{av} - d_i)^2} \quad (5)$$

Where d_{av} represents mean value of all inter-particle distances, d_i is standard deviation of inter-particle distances, smaller σ_{SP} indicates superior distribution uniformity. The population's global exploration capability is quantified by Equation 6:

$$\sigma_{global} = d_{av}/\sigma_{SP} \quad (6)$$

In Equation 6, a larger value of σ_{global} indicates superior global exploration capability of the population.

The population's local exploitation capability is quantified by Equation 7:

$$\sigma_{local} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{1}{2}\sum_{k=1}^{2} f_{i,k}\right) \quad (7)$$

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In Equation 7, a smaller value of σ_{loacl} indicates superior local exploitation capability of the population.

This algorithm proposes that researchers may dynamically select between MOPSO and FMOPSO based on the relative magnitudes of population locality (σ_{loacl}) and globality (σ_{global}) during iterations. To facilitate comparative analysis, both metrics are converted into membership degrees via Equation 8:

$$f_{g,1} = \frac{\sigma_{g,1} - \sigma_{g,1min}}{\sigma_{g,1max} - \sigma_{g,1min}} \tag{8}$$

Where $\sigma_{g,1}$ denotes current population's globality (σ_{loacl}) or locality (σ_{global}) metric, $f_{g,1}$ indicates corresponding membership degree of $\sigma_{g,1}$, $\sigma_{g,1min}$ and $\sigma_{g,1max}$ suggest Minimum and maximum values observed during iterations

Based on these metrics, specific algorithm selection rules are applied. If the condition $\sigma_{global} > \sigma_{loacl}$,it indicates dominant global exploration capability. In this case, people should adopt MOPSO to enhance local exploitation precision. Conversely, if $\sigma_{loacl} > \sigma_{global}$, it suggests dominant local exploitation capability, people should adopt FMOPSO to strengthen global exploration [8].

4.3. Proactive energy management optimization algorithm for microgrids accounting for generalized energy storage

This algorithm conceptualizes renewable energy sources, diesel generators, and generalized energy storage (GES) as players in a potential game, establishing an exact potential game model for the microgrid energy management system. Concurrently, it incorporates a Conditional Value-at-Risk (CVaR) decision model on the renewable energy side, ultimately formulating a proactive energy management optimization framework for GES-integrated microgrids under CVaR constraints. The CVaR risk decision model is formally defined as follows.

The cost function is defined as shown in Equation 9:

$$f\left(P_{RE}, \Delta\delta_{RE}\right) = \sum_{t=1}^{T} r \left| P_{RE,pre}^{t} + \Delta\delta_{RE,pre}^{t} - P_{RE}^{t} \right| \tag{9}$$

The corresponding $\beta-$ CVaR is defined as shown in Equation 10:

$$\min \widetilde{F}_{\beta}\left(x, \alpha\right) = \alpha + \frac{1}{N(1-\beta)} \sum_{k=1}^{N} \left[f\left(P_{RE,}, \Delta\delta_{RE,k}\right) - \alpha \right]^{+} \tag{10}$$

Where decision variables vector is $x = \left[P_{RE}^{1}, P_{RE}^{2}, P_{RE}^{3}, \cdots P_{RE}^{T}\right]$, random variables vector (renewable forecast errors) is $y = \left[\Delta\delta_{RE,pre,1}^{t}, \Delta\delta_{RE,pre,2}^{t}, \Delta\delta_{RE,pre,3}^{t}, \cdots \Delta\delta_{RE,pre,k}^{t}\right]$. here N signifies total number of forecast error scenarios. Based on the potential game model and the integrated CVaR risk decision framework, this optimization model achieves significant outcomes. Within the potential game framework, optimized self-dispatch enables diesel generators to track renewable output, ensuring priority dispatch of renewable energy. This approach consequently reduces diesel generation, lowering carbon emissions to enhance environmental performance. Furthermore, the model incorporates Conditional Value-at-Risk (CVaR) to quantify risks from renewable uncertainty and intermittency. This integration allows for a balanced assessment of operational risk against economic return [9].

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5. Conclusion

This study focuses on dispatch strategies and optimization algorithms in the field of microgrid energy storage, aiming to enhance renewable energy integration efficiency and grid stability while contributing to carbon peaking and carbon neutrality goals. As a critical interface between distributed energy resources and the main grid, microgrid dispatch strategies and optimization algorithms are of paramount importance. This research not only provides a systematic review of microgrid technology applications and development but also offers significant theoretical foundations and practical guidance for policymakers and researchers.

However, several limitations remain in this work. First, the study primarily concentrates on theoretical analysis and model construction, with insufficient exploration of complex scenarios in practical engineering applications and implementation details. Second, although multiple optimization algorithms are discussed, the analysis of their applicability and limitations across microgrids of varying scales and types lacks depth. Finally, the examination of dynamic characteristics in microgrid-external grid interactions and market mechanism impacts is relatively limited. Future research should further explore these directions. In subsequent scientific work, addressing renewable energy uncertainty and intermittency to improve microgrid stability will remain a crucial research focus. Concurrently, as microgrids participate in electricity markets, demand-side technologies and their optimal integration into grid-wide distribution dispatch systems will continue to be key research priorities.

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