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Metaheuristic Optimization in Space Science and Engineering: A Comprehensive Literature Review

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Abstract.

Metaheuristic algorithms have become potent and flexible in solving complex problems in various contexts, including load forecasting, power outage minimization, energy dispatch, and cybersecurity. This paper conducts a literature review of the research currently being conducted in metaheuristic optimization techniques for addressing creative grid systems, trends in hybridization, algorithm performance, real-time flex- ibility, and their application fields. The review establishes the boundaries and validates the authority of the most commonly used methods, including PSO, GA, ACO, and GWO, as well as the currently used hybrid and AI-combined methods. Although successful, their flaws are found in scalability, real-world usage, benchmarking consistency, and integration with cybersecurity. It also highlights some of the recent research trends in the field, including agent-based optimization, sustainability-conscious goals, explainability, and the interactions between metaheuristics, machine learning, and edge computing.

Keywords. Metaheuristic Optimization, Smart Grid, Load Forecasting, Energy Management, Cyber-Physical Systems

1. INTRODUCTION

The historical approach to electrical power generation and distribution considered and modelled traditional power systems with linear energy flow in mind, where electricity was generated in centralized power plants and then flowed hierarchically directly to end consumers. These legacy systems, which have been highly effective over the past few decades, are now viewed as insufficient and unable to meet the emerging grid requirements, such as the realization of two-way power flow, distributed gener- ation, close-grained real-time monitoring, and distribution- based control strategies. Such a radical shift as the smart grid has turned out to be quite promising in addressing these limitations. Smart grids serve as an enabling infrastructure for a broad array of functionalities, not only facilitating the seamless integration of renewable energy sources such as solar and wind but also supporting advanced mechanisms for demand-side management (DSM), coordinated control of electric vehicle (EV) charging, and implementation of dynamic and time-sensitive pricing models [1].

The augmented complications and inadequacies of more conven- tional optimization methods have prompted a significant rise in interest among the research community in studying and creating metaheuristic optimization methods. These algorithms are inspired by natural and biological mechanisms, such as evolution, swarm behavior, and animal hunting strategies, and provide a strategic tradeoff between global exploration (search) and local refinement (exploitation). Together with the fact that they are used in the acting process with solutions of gigantic, high-dimensional, and non-congruent spaces add to the fact that only minimal structural assumptions about the region of the problem studied are made in their use and application [2]. This natural flexibility and scalability has facilitated their successful implementation in a wide scope of novel grid applications including (but not limited to) optimal power flow (OPF), unit commitment (UC), scheduling of energy storage systems, integration of renewable energy sources, and resilience of cyberspace physical systems enhancement using metaheuristic algorithms [3].

2. LITERATURE REVIEW

The marked uptake of renewable energy sources, the rapid growth of electric vehicles (EVs), and the accelerated devel- opment and decentralization of distributed energy resources (DERs) have all contributed to changing the very paradigm of how traditional electrical power systems operate. The new improvements have necessitated excessive complexity and dynamism in the activities of the grids, thereby rendering the legacy infrastructure and conventional methods of handling the grids ineffective in meeting the demands of present-day power systems [4]. On this note, smart grids are not only now an enabling infrastructure, i.e., a sophisticated mix of electrical and information technologies, but also a multi-layered and multi-functional platform to monitor, control, and optimize grid performance. Even though these developments are very encouraging, associated computational and algorithmic issues are enormous due to the characteristic features of smart grid problems (i.e., high degree of nonlinearity, large-scale uncer- tainty, and the problems are often large-scale and multidimen- sional) [5]. In the complexity and uncertainty of such a high level, traditional deterministic optimization methods, which usually assume some form of convexity, continuity, or gradient, have not performed well. This has resulted in one of the most critical areas in smart grid research circles, such as the appli- cations of metaheuristic algorithms, gaining significant popu- larity. Such algorithms have shown high potential due to their robustness, flexibility, and intrinsic ability to address NP-hard optimization problems with a wide range of applications in the smart grid [6], [7]. Metaheuristics, including well-established approaches such as Particle Swarm Optimization (PSO), Ge- netic Algorithms (GA), Ant Colony Optimization (ACO), Grey Wolf Optimizer (GWO), and Harmony Search

(HS), have showcased notable efficacy in addressing a wide range of op- timization problems within smart grids. These include, among others, duties related to energy management, fault detection, load prediction, and demand response. The fundamental power of these algorithms lies in their ability to easily search and exploit complex, multimodal, and high-dimensional solution spaces using biologically and naturally motivated algorithms of attraction, swarming, evolution, and foraging. For example, Hafeez et al. [8] proposed an improved version of the PSO algorithm tailored for optimal residential load scheduling. Their enhancement addressed critical issues, such as premature convergence and the trade-off between global exploration and local exploitation, and their results demonstrated superior performance when benchmarked against standard PSO, GA, and Wind-Driven Optimization (WDO). Similarly, many researchers introduced a novel hybrid algorithm that combined Differential Evolution with Earthworm Optimization. Their strategy became a source of significant savings in terms of energy cost and the peak-to-average ratio of load, providing. One area where metaheuristics have played a particularly prominent and transformative role is in smart home energy management systems (HEMS). These systems are designed to manage and coordinate household appliances, distributed generation sources (e.g., rooftop solar panels), and energy storage devices, particularly under real-time pricing schemes and demand response signals [4-8].

3. DISCUSSION

The reviewed literature clearly establishes metaheuristics as a central computational tool in addressing complex op- timization challenges in modern smart grids. These algo- rithms—ranging from GA, PSO, and GWO to hybridized and AI-integrated versions—have demonstrated their effectiveness in diverse applications, including load forecasting, distributed generation, and cybersecurity. Their ability to manage nonlin- earities, multi-objective formulations, and real-time constraints positions them as highly adaptable solutions. Notably, the re- search community is increasingly emphasizing hybridization, where combining complementary techniques or coupling with neural networks helps overcome weaknesses such as premature convergence or limited exploitation. This trajectory reflects a maturation of the field and signals a shift toward adaptable, problem-specific solutions rather than a reliance on universal, standalone algorithms.

At the same time, the literature highlights critical method- ological and practical gaps. Chief among them is the overre- liance on simulation-based validation, often using simplified IEEE bus systems that fail to capture the complexities of the real world. This creates uncertainty about the generalizability and robustness of proposed models. Moreover, the absence of standardized evaluation frameworks hampers fair benchmark- ing of algorithmic performance, as different studies employ varying performance metrics and assumptions. The lack of reproducible testbeds and unified criteria hinders cumulative progress and makes meaningful comparisons challenging. Addressing these limitations through open-source datasets, standardized protocols, and collaborative benchmarking in- frastructures is essential to move research from theoretical demonstration to field-ready deployment.

4. CONCLUSION

This review presents a thorough analysis of the application of metaheuristic optimization methods in the design and oper- ation of smart grids. With the growing decentralization, data intensity, and dynamicity of modern power systems, adaptive, robust, and scalable optimization tools have become central. Metaheuristics — including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Grey Wolf Optimizer (GWO), and numerous hybridized vari- ants — have emerged as highly effective candidates for solv- ing complex, nonlinear, and multi-objective problems across various smart grid domains. The literature highlights several key limitations: limited real-world deployment, a lack of standard- ized benchmarking, underdeveloped uncertainty modeling, and insufficient emphasis on real-time performance and cyber- physical resilience. Many promising algorithms have been val- idated only in simulation using simplified test systems, raising concerns about scalability and practical integration into utility- level operations. To move the field forward, future research should prioritize the development of real-time, interpretable, and secure optimization frameworks. Efforts should be made to test algorithms on large-scale and realistic datasets, incorporate probabilistic modeling for renewable uncertainty, and ensure resilience against adversarial disruptions.

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