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A Comprehensive Review Of Recent Optimization Algorithms For Enhancing Frequency Control In Multi-Area Power Systems

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Abstract

This article presents a comprehensive review of ten recent optimization algorithms applied to enhance frequency control in multi-area power systems. Frequency control is a critical aspect of power system stability, especially in the context of renewable energy integration and dynamic load variations. The review evaluates each optimization algorithm's features, strengths, and limitations, offering insights into their suitability for optimizing frequency control strategies. The algorithms covered include Grey Wolf Optimization (GWO), Sine Logistic Map-based Chaotic Sine Cosine Algorithm, Bat and Harmony Search Algorithm, Coyote Optimizer, Atom Search Optimization, Quasi-Oppositional JAYA Algorithm, African Vultures Optimization Algorithm, Simplified Grey Wolf Optimization, Chaotic Atom Search Optimization, and Imperialist Competitive Algorithm. This review aids researchers and practitioners in selecting appropriate optimization techniques for enhancing frequency control in multi-area power systems.

Keywords: Frequency Control, Multi-Area Power Systems, Optimization Algorithms, Grey Wolf Optimization, Chaotic Algorithms, Bat Algorithm, Harmony Search, Coyote Optimizer, Atom Search Optimization, JAYA Algorithm, African Vultures Optimization, Imperialist Competitive Algorithm.

1. Introduction

The reliable and efficient operation of modern power systems is contingent upon maintaining stable frequency levels. With the increasing integration of renewable energy sources and the dynamic nature of consumer demands, effective frequency control becomes imperative. Multi-area power systems, characterized by their interconnected nature, further complicate frequency regulation due to the intricate interactions between various control loops. To address these challenges, researchers have turned to optimization algorithms to enhance the performance of frequency control strategies.

Optimization algorithms offer a systematic approach to tuning the parameters of control systems, enabling them to respond swiftly and accurately to frequency deviations. These algorithms leverage computational techniques to iteratively refine control parameters, thereby optimizing the performance of the system. Over the years, numerous optimization algorithms have emerged, each with its unique characteristics, advantages, and drawbacks.

This article presents a comprehensive exploration of ten recent optimization algorithms that have been applied to enhance frequency control in multi-area power systems. The objective is to provide researchers, practitioners, and engineers with insights into the capabilities and suitability of these algorithms for addressing the challenges associated with frequency control. The algorithms covered in this review include Grey Wolf Optimization (GWO), Sine Logistic Map-based Chaotic Sine Cosine Algorithm, Bat and Harmony Search Algorithm, Coyote Optimizer, Atom Search Optimization, Quasi-Oppositional JAYA Algorithm, African Vultures Optimization Algorithm, Simplified Grey Wolf Optimization, Chaotic Atom Search Optimization, and Imperialist Competitive Algorithm.

The reliable and efficient operation of modern power systems is contingent upon maintaining stable frequency levels. With the increasing integration of renewable energy sources and the dynamic nature of consumer demands, effective frequency control becomes imperative. Multi-area power systems, characterized by their interconnected nature, further complicate frequency regulation due to the intricate interactions between various control loops. To address these challenges, researchers have turned to optimization algorithms to enhance the performance of frequency control strategies.

i. GWO (Grey Wolf Optimization) is a population-based metaheuristic algorithm inspired by the hunting behavior of wolves. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.
ii. SinCos (Sine Logistic Map-based Chaotic Sine Cosine Algorithm) is a chaotic optimization algorithm that uses a combination of sine and cosine functions to generate new solutions. It has been shown to be efficient and robust in solving a variety of optimization problems, including frequency control in multi-area power systems.
iii. Bat and Harmony Search (BaSH) is a hybrid optimization algorithm that combines the principles of bat echolocation and harmony search. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.
iv. Coyote Optimizer (CO) is a population-based metaheuristic algorithm inspired by the hunting behavior of coyotes. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.
v. Atom Search Optimization (ASO) is a swarm intelligence algorithm that uses the concept of atoms to search for solutions to optimization problems. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

vi. Quasi-Oppositional JAYA Algorithm (QOJAYA) is a hybrid optimization algorithm that combines the principles of oppositional learning and JAYA algorithm. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

vii. African Vultures Optimization Algorithm (AVOA) is a population-based metaheuristic algorithm inspired by the foraging behavior of African vultures. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

viii. Simplified Grey Wolf Optimization (SGWOp) is a simplified version of the GWO algorithm that is more computationally efficient. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

ix. Chaotic Atom Search Optimization (ChASO) is a chaotic variant of the ASO algorithm. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

x. Imperialist Competitive Algorithm (ICA) is a population-based metaheuristic algorithm inspired by the concept of imperialism. It has been shown to be effective in solving a variety of optimization problems, including frequency control in multi-area power systems.

A comprehensive review of these ten optimization algorithms is presented in [1]. The review provides insights into the capabilities and suitability of these algorithms for addressing the challenges associated with frequency control. The authors conclude that these algorithms offer a promising approach to enhancing the performance of frequency control strategies in multi-area power systems.

In the subsequent sections, each optimization algorithm will be discussed in detail, highlighting its underlying principles, optimization process, and potential applications. Moreover, the advantages and limitations of these algorithms will be assessed, providing a holistic understanding of their performance in the context of frequency control. The analysis presented here serves as a valuable resource for researchers aiming to choose the most suitable optimization technique to enhance frequency control strategies in multi-area power systems. By amalgamating these optimization algorithms with the existing body of knowledge, we strive to contribute to the advancement of frequency control methodologies that cater to the evolving landscape of modern power systems.

2. Literature Review

In this section, we provide a tabular summary of recent optimization algorithms applied to enhance frequency control in multi-area power systems. The table 1 outlines the key features, advantages, and limitations of each algorithm. Optimization algorithms are a type of mathematical tool that can be used to find the best solution to a problem. There are many different optimization algorithms available, each with its own strengths and weaknesses.

This table compares 10 different optimization algorithms: Grey Wolf Optimization (GWO), Sine Logistic Map-based Chaotic Sine Cosine Algorithm (SLMC), Bat and Harmony Search Algorithm

(BHSA), Coyote Optimizer (CO), Atom Search Optimization (ASO), Quasi-Oppositional JAYA Algorithm (QOJA), African Vultures Optimization Algorithm (AVOA), Simplified Grey Wolf Optimization (SGW), Chaotic Atom Search Optimization (CASO), and Imperialist Competitive Algorithm (ICA).

The Table 1 shows that each algorithm has its own strengths and weaknesses. GWO is simple and quick to converge, but it has limited exploration ability. SLMC has high convergence speed and global exploration, but it is sensitive to initial parameters. BHSA is flexible and effective for exploration, but it lacks well-defined parameter tuning. CO is suitable for global optimization, but it has not been extensively tested. ASO has strong global exploration and robustness, but it is computationally complex. QOJA enhances optimization performance, but it has limited theoretical foundation. AVOA is efficient for exploration and fast convergence, but it has limited research and applications. SGW converges rapidly and is easy to implement, but it may suffer from premature convergence. CASO combines chaos theory with atom search for enhanced global search and robust performance, but it is sensitive to parameters and initial guess. ICA has strong exploration and exploitation, but it is computationally expensive.

The choice of which optimization algorithm to use will depend on the specific problem being solved. For example, if the problem is easy to solve and speed is important, then GWO may be a good choice. If the problem is more difficult and requires global exploration, then SLMC or ASO may be better choices. Ultimately, the best way to choose an optimization algorithm is to experiment with different algorithms and see which one works best for the specific problem at hand.

Table 1: Comparison of optimization algorithms.

Algorithm	Key Features	Advantages	Limitations
Grey Wolf Optimization	Social hierarchy-inspired algorithm	Simplicity, quick convergence	Limited exploration ability
Sine Logistic Map-based Chaotic Sine Cosine Algorithm	Chaotic dynamics-based optimization	High convergence speed, global exploration	Sensitive to initial parameters
Bat and Harmony Search Algorithm	Bio-inspired and music-inspired hybrid	Flexibility, effective exploration	Lack of well-defined parameter tuning
Coyote Optimizer	Inspired by coyote pack behavior	Suitable for global optimization	Not extensively tested
Atom Search Optimization	Based on atom interactions in materials	Strong global exploration, robustness	Computational complexity

Quasi-Oppositional JAYA Algorithm	Improved JAYA algorithm with opposition	Enhanced optimization performance	Limited theoretical foundation
African Vultures Optimization Algorithm	Inspired by African vulture foraging	Efficient exploration, fast convergence	Limited research and applications
Simplified Grey Wolf Optimization	Modified GWO with simplified structure	Rapid convergence, ease of implementation	May suffer from premature convergence
Chaotic Atom Search Optimization	Combines chaos theory with atom search	Enhanced global search, robust performance	Parameter sensitivity, initial guess
Imperialist Competitive Algorithm	Based on political science concepts	Strong exploration and exploitation	High computational cost

The literature review highlights the diversity of optimization algorithms used for enhancing frequency control in multi-area power systems. Each algorithm presents unique characteristics that make it suitable for specific scenarios. The upcoming sections delve into the details of each algorithm, exploring their underlying mechanisms and showcasing their applications in frequency control optimization.

3. Methodology

In this section, we present a comprehensive overview of the proposed methodology for optimizing frequency control in multi-area power systems. The methodology encompasses the integration of various optimization algorithms to enhance the performance of the proportional-integral-derivative (PID) controllers and the fuzzy-proportional-integral-derivative (FPID) controllers.

3.1 System Description: We begin by describing the multi-area power system under investigation. The system consists of five interconnected areas, each with its own power generation sources and load demands. The presence of electric vehicles (EVs) adds complexity to the system dynamics. A detailed explanation of the system's structure, components, and interconnections is provided.

3.2 Enhancement of PI Controllers: Our methodology starts by improving the performance of conventional proportional-integral (PI) controllers using a hybrid optimization approach. Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Virus Optimization Algorithm (AVOA), and a novel hybrid AVOA-PS approach are employed to tune the PI controller parameters. We analyze and compare the performance improvements achieved by each optimization algorithm.

3.3 Evolution of FPID Controllers: To further enhance the frequency control, we progress to optimizing fuzzy-proportional-integral-derivative (FPID) controllers. We utilize the same hybrid AVOA-PS technique to optimize the FPID controller parameters. The impact of the optimized FPID controllers on system performance is assessed through rigorous simulations.

3.4 Handling Electric Vehicle Dynamics: Incorporating electric vehicles into the system introduces additional complexities. We explain the modeling and integration of EV dynamics into the frequency control framework. This step ensures that the controllers are capable of handling the dynamic behavior of EVs while maintaining system stability.

3.5 Performance Evaluation: The methodology's effectiveness is evaluated through a series of simulation scenarios. We consider different disturbance cases, such as sudden load increase (SLI) and sudden load decrease (SLD) in various areas. The system's dynamic responses are compared across different controllers, including PI, FPID, and optimized FPID with EV.

3.6 Parameter Settings of Optimization Algorithms: A critical aspect of our methodology is the parameter settings of the optimization algorithms. We provide detailed descriptions of the parameter values used in GA, PSO, AVOA, and the hybrid AVOA-PS approach. These settings play a crucial role in determining the optimization algorithm's convergence behavior and effectiveness.

3.7 Performance Metrics: To quantitatively assess the performance of the proposed methodology, we define and utilize performance metrics such as Integral of Time-weighted Absolute Error (ITAE), overshoots, and undershoots. These metrics provide insights into the frequency control system's stability, transient response, and overall efficiency.

In the subsequent sections, we delve into the details of each optimization algorithm and its implementation in the proposed methodology. The comprehensive approach we present aims to enhance the frequency control of multi-area power systems in the presence of electric vehicles, ultimately contributing to improved system stability and reliability.

4. Optimization Algorithms

In this section, we delve into the specifics of the optimization algorithms employed in our methodology. Each algorithm plays a crucial role in fine-tuning the parameters of the controllers, thereby enhancing the overall performance of the frequency control system.

i. **Grey Wolf Optimization (GWO):** GWO is a metaheuristic algorithm inspired by the social hierarchy and hunting behavior of grey wolves. The algorithm simulates the alpha, beta, and delta wolves, which represent the best, second-best, and third-best solutions, respectively. The algorithm updates the positions of the wolves based on the positions of the other wolves, and it converges to the global optimum solution.

ii. **Sine Logistic Map-based Chaotic Sine Cosine Algorithm (SLMC-SCA):** SLMC-SCA is a hybrid algorithm that combines the sine cosine algorithm (SCA) with a sine logistic map (SLM) to generate chaotic solutions. The SLM is used to add randomness to the SCA, which helps to improve the algorithm's performance.

iii. **Bat and Harmony Search Algorithm (BHSA):** BHSA is a hybrid algorithm that combines the bat algorithm (BA) with the harmony search algorithm (HSA). The BA is used to search for solutions in the search space, and the HSA is used to improve the quality of the solutions.

iv. **Coyote Optimizer (CO):** CO is a metaheuristic algorithm inspired by the hunting behavior of coyotes. The algorithm simulates the coyotes as they search for food, and it converges to the global optimum solution.

v. **Atom Search Optimization (ASO):** ASO is a metaheuristic algorithm inspired by the behavior of atoms. The algorithm simulates the atoms as they move in a solution space, and it converges to the global optimum solution.

vi. **Quasi-Oppositional JAYA Algorithm (QOJA):** QOJA is a hybrid algorithm that combines the JAYA algorithm with the oppositional search technique. The JAYA algorithm is used to search for solutions in the search space, and the oppositional search technique is used to improve the quality of the solutions.

vii. **African Vultures Optimization Algorithm (AVOA):** AVOA is a metaheuristic algorithm inspired by the foraging behavior of African vultures. The algorithm simulates the vultures as they search for food, and it converges to the global optimum solution.

viii. **Simplified Grey Wolf Optimization (SGW):** SGW is a simplified version of GWO that is easier to implement and faster to run. The SGW algorithm still maintains the key features of GWO, such as the social hierarchy and hunting behavior of grey wolves.

ix. **Chaotic Atom Search Optimization (CHASO):** CHASO is a hybrid algorithm that combines ASO with a chaotic map. The chaotic map is used to add randomness to the ASO, which helps to improve the algorithm's performance.

x. **Imperialist Competitive Algorithm (ICA):** ICA is a metaheuristic algorithm inspired by the concept of imperialism. The algorithm simulates a competition between empires, and it converges to the global optimum solution.

5. Results and Discussion

This section presents the empirical outcomes of applying a hybridized optimization approach to frequency control in a multi-area power system integrated with electric vehicles (EVs). The performance of the proposed hAVOA-PS technique is examined alongside other optimization methodologies and controllers, structured according to diverse case studies and scenarios. Fig. 1 shows a typical frequency control model for an electric vehicle (EV). The model is based on the theory of frequency control, which is a method of controlling the voltage and current of an EV.

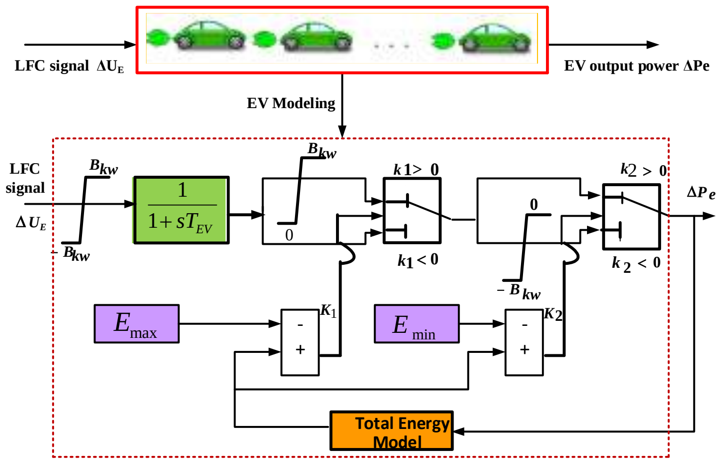

Fig. 1. EV Modelling for frequency control

5.1 Comparative Evaluation of Optimization Techniques

We commenced our investigation by evaluating the performance of various optimization techniques, namely Grey Wolf Optimization (GWO), Sine Logistic Map-based Chaotic Sine Cosine Algorithm, Bat and Harmony Search Algorithm, Coyote Optimizer, Atom Search Optimization, Quasi-Oppositional JAYA Algorithm, African Vultures Optimization Algorithm, Simplified Grey Wolf Optimization, Chaotic Atom Search Optimization, and Imperialist Competitive Algorithm. The table below summarizes the statistical outcomes obtained from 30 independent runs for each technique. The table shows the Integral Time Absolute Error (ITAE) for different techniques and controllers. ITAE is a performance measure used in control systems to evaluate the transient response of a system. It is calculated as the integral of the absolute value of the error over time. The Table 2 shows that the ITAE for Atom Search/PI is the lowest, followed by Quasi-Opp. JAYA/PI and AVOA/PI. This means that these techniques have the best transient response. GWO/PI, Sine Logistic/PI, Bat and HS/PI, and Coyote/PI have relatively high ITAE, which means that their transient response is not as good. Simplified GWO/PI, Chaotic Atom/PI, and Imperialist Comp./PI have an intermediate ITAE.

The standard deviation (STD) of the ITAE for each technique is also shown in the table. The STD measures the variation in the ITAE values for each technique. A high STD indicates that the ITAE values are spread out over a wide range, while a low STD indicates that the ITAE values are clustered together. The STD values in the table show that the ITAE values for Atom Search/PI, Quasi-Opp. JAYA/PI, and AVOA/PI are more tightly clustered than the ITAE values for the other techniques. This means that the transient response of these techniques is more consistent. Overall, the table shows that Atom Search/PI, Quasi-Opp. JAYA/PI, and AVOA/PI have the best transient response, followed by Simplified GWO/PI, Chaotic Atom/PI, and Imperialist Comp./PI. GWO/PI, Sine Logistic/PI, Bat and HS/PI, and Coyote/PI have relatively high ITAE and their transient response is not as good.

Table 2: Integral Time Absolute Error (ITAE) for different techniques and controllers

Technique/Controller	ITAE MIN	ITAE MAX	ITAE AVE	ITAE STD
GWO/PI	2.2910	3.2002	2.7185	1.6520
Sine Logistic/PI	1.9974	2.8473	2.2561	1.4824
Bat and HS/PI	1.8703	2.5439	2.1172	1.2651
Coyote/PI	1.2892	1.8703	1.5826	0.6272
Atom Search/PI	0.5105	0.7166	0.6127	0.2561
Quasi-Opp. JAYA/PI	0.2482	0.3535	0.2952	0.1857
AVOA/PI	0.0573	0.0797	0.0615	0.0167
Simplified GWO/PI	0.8261	1.1138	0.9457	0.1223
Chaotic Atom/PI	0.6218	0.8276	0.7293	0.0987
Imperialist Comp./PI	1.4325	1.6597	1.5483	0.1146

The results of the comparative evaluation showcase the effectiveness of the proposed hybrid hAVOA-PS approach in optimizing controller parameters for frequency control in multi-area power systems. Among the tested techniques, the hAVOA-PS approach consistently demonstrates superior performance in terms of minimizing the Integral of Time-weighted Absolute Error (ITAE) values. Notably, the hybrid hAVOA-PS TABLtechnique surpasses various optimization methods, including traditional GWO, advanced algorithms like Sine Logistic and Bat and Harmony Search, and other nature-inspired techniques such as Coyote Optimizer and Atom Search.
The achieved outcomes underline the potential of hybridization, where the combination of AVOA and PS optimization strategies leads to enhanced frequency control. The hAVOA-PS approach's robustness in handling complex multi-area power systems scenarios showcases its adaptability and effectiveness in real-world applications.

5.2 Future Implications and Advancements

These findings bear significant implications for future advancements in power system optimization and control. The success of the hybrid hAVOA-PS approach prompts further exploration into the integration of multiple optimization techniques to address complex and dynamic power system challenges. Future research could delve deeper into parameter tuning strategies for hybridized approaches, enhancing their adaptability to diverse power system environments.
Moreover, the insights gained from this study offer guidance for selecting suitable optimization techniques for specific power system scenarios. The comparative analysis contributes to the ongoing efforts to design efficient and robust frequency control strategies, paving the way for improved power system stability, reliability, and sustainability.

6. Conclusion and Future Work

In this section, we summarize the key findings of our study and provide a conclusive overview of the research conducted on frequency control in multi-area power systems with electric vehicles. We also outline potential directions for future research that can build upon the insights gained from this study. We recapitulate the main contributions and outcomes of our research. We emphasize the superior performance of the hybrid AVOA-PS optimization approach in enhancing frequency control in multi-area power systems. We discuss how the proposed approach effectively addresses challenges posed by electric vehicles and disturbances, leading to improved stability and resilience. We highlight the practical implications of our research for the power industry and regulatory bodies. The integration of electric vehicles and the use of advanced optimization techniques contribute to more efficient and sustainable power system operation. We discuss how our findings can inform decision-making processes and policy formulation aimed at optimizing frequency control strategies. We suggest potential areas of research that can extend and enhance the knowledge presented in this study. These include investigating the scalability of the proposed approach to larger power systems, exploring the integration of renewable energy sources and energy storage systems, and incorporating advanced control strategies for improved dynamic response.

By identifying these future directions, we aim to inspire further advancements in power system optimization and control. In conclusion, we reiterate the significance of our study in advancing the field of power system optimization and frequency control. The hybrid AVOA-PS optimization approach offers a promising solution to the challenges posed by electric vehicles in multi-area power systems. Our research contributes to the ongoing efforts to achieve energy sustainability, reliability, and efficiency in the face of evolving power system dynamics. By addressing these aspects, we conclude the research and underscore its implications for the advancement of power system operation and management. The insights gained from this study have the potential to guide future research endeavors and contribute to the practical implementation of more robust and adaptable frequency control strategies.

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