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Recent Advancements in Load Frequency Control Techniques: A Comparative Review and Future Research Recommendations

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***Abstract**: Load Frequency Control (LFC) plays a crucial role in maintaining the stability and reliability of interconnected power systems. This review explores the development and effectiveness of LFC techniques, covering both traditional approaches like Proportional-Integral-Derivative (PID) and Proportional-Integral (PI) controllers, as well as advanced optimization methods such as Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and heuristic algorithms including Cuckoo Search Algorithm (CSA) and Firefly Algorithm (FA). The review highlights that while PID controllers are effective in managing load dynamics, optimization techniques offer significant improvements in mitigating frequency deviations and enhancing system response. Recent advancements are discussed, including a comparative analysis of Smell Agent Optimization (SAO) and Grey Wolf Optimization (GWO), with SAO showing superior performance. Industrial applications and simulation studies underscore the practical benefits of these optimized controllers in real-world scenarios. This review provides valuable insights into enhancing power system efficiency and reliability, offering guidance for future research in advancing LFC techniques.*

***Keywords**: Power Generation, Load Demand, Optimization, Power Systems, Load Frequency Control.*

Introduction

In power generation systems, fluctuating power demand necessitates adjustments in generated power to maintain a balance between supply and demand. These adjustments affect generator speed and power frequency, which must remain within acceptable limits. Automatic Generation Control (AGC) manages these changes by adjusting power generation in response to load variations, ensuring stable frequency across interconnected systems by distributing the load among available generators.

A key component of AGC is Load Frequency Control (LFC), which manages frequency through feedback loops across interconnected systems via tie-lines. Effective LFC relies on well-tuned controllers to ensure system stability and responsiveness. Proportional-Integral-Derivative (PID) controllers are commonly used due to their simplicity and cost-effectiveness. However, manually tuning PID controllers can be challenging and time-consuming. Optimization algorithms offer a solution by automatically adjusting controller parameters to achieve optimal performance under specified constraints.

In addition to LFC, Automatic Voltage Regulation (AVR) is crucial for maintaining system stability and reliability. Effective management of LFC and AVR is essential for continuous operation. Various control strategies have been explored, including PID and Proportional-Integral (PI) controllers. Advanced optimization techniques such as Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO) have also been investigated for their potential to enhance control performance. This review evaluates these strategies to assess their effectiveness in maintaining system stability and improving response to fluctuations in power demand.

I. Comparative Analysis and Applications of PID and PI Controllers

The effectiveness of PID and PI controllers for load frequency management in a two-area interconnected power system has been examined due to a 0.01 p.u. load increase in region 1. The PID controller outperforms the PI controller in terms of overshoot and settling time [1]. Optimal tuning of the PID controller for both LFC and AVR is discussed in [2], with a step disturbance of 0.18 p.u. applied in Area 1. The PID controller results in a smaller peak overshoot and shorter settling time compared to conventional Integral and PI controllers.

A control system aimed at improving the transient response time of speed/load-frequency for a gas turbine in a Nigerian refinery using a PID controller is detailed in [3]. Here, the PID controller and Integral controller are applied to a single-area hydro-turbine power system, with the PID controller demonstrating superior performance compared to both the uncontrolled and Integral controllers. Further, the load frequency control for a two-area power system using PI and PID controllers, as presented in [4], shows that the PID controller has better dynamic performance in terms of overshoot, rise time, and settling time when a load change of 0.2 p.u. occurs in control area one.

II. Advanced Optimization and Intelligent Control Techniques

Several studies have employed optimization techniques to enhance PID controller performance. The Cuckoo Search Algorithm (CSA) is used to tune a two-degree freedom PID controller (2DOF-PID) for LFC, showing superiority over conventional PID controllers in terms of minimum undershoot, settling time, and peak overshoot [5]. Particle Swarm Optimization (PSO) has been applied to optimize PID parameters in the presence of load disturbance, resulting in improved damping of oscillations, reduced settling time, and minimized overshoots/undershoots [6], [7]. The superiority of PSO-PID over conventional PID controllers is further demonstrated in [8], [9], and [10], highlighting high performance, stable convergence, and good computational efficiency.

Fuzzy logic controllers have also been explored for LFC. Studies such as [11] and [12] demonstrate that fuzzy logic controllers outperform conventional PID controllers in reducing fluctuations and improving stability, with faster response times. The adaptive neuro-fuzzy technique is used to address AGC problems, proving more efficient than traditional methods [13].

Grey Wolf Optimization (GWO) has been proposed for LFC problems in two-area thermal power systems, demonstrating better performance compared to PSO, Genetic Algorithm (GA), and other algorithms [14]. The use of GWO for tuning PI and PID parameters has shown improved stability and dynamic response [15], [16]. Studies like [17] and [18] compare the performance of GWO, GA, and PSO, concluding that GWO provides faster responses and better performance indices.

The Firefly Algorithm (FA) has been used to optimize hybrid fuzzy PID controllers, showing superior performance compared to GA-tuned controllers [19], [20]. Other techniques, such as the Enhanced Gradient-Based Optimizer (EGBO) and the Seeker Optimization Algorithm (SOA), have also shown promise in improving LFC stability and response [21], [22].

III. Recent Comparative Study on Nigerian Power Systems

A recent study [24] addresses Nigeria's frequent grid collapses due to mismatches between power generation and demand, which destabilize the frequency of the interconnected power system. This study evaluates Load Frequency Control (LFC) methods to stabilize frequency, particularly using Smell Agent Optimization (SAO) compared to traditional methods like PID, PSO, and GWO. Nigeria's power network is divided into Area 1 (hydro plants) with 1,967 MW capacity and Area 2 (thermal plants) with 9,532 MW capacity. Simulation results show that SAO outperforms PID, PSO, and GWO by reducing oscillations and settling time in frequency deviation and tie-line power changes. This underscores SAO's effectiveness in enhancing frequency stability and mitigating grid collapses [24].

IV. Conclusion

This review provides a comprehensive examination of advancements in Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) within interconnected power systems. It highlights that Proportional-Integral-Derivative (PID) controllers, particularly when optimized using heuristic algorithms, consistently outperform traditional Proportional-Integral (PI) controllers and other conventional methods. Advanced optimization techniques, such as Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and heuristic algorithms like Cuckoo Search Algorithm (CSA), Firefly Algorithm (FA), and recently applied Smell Agent Optimization (SAO), have shown significant improvements in managing load dynamics and minimizing frequency deviations.

The review also accentuates the practical benefits of these optimized controllers, as demonstrated through case studies and simulations in Nigerian power networks. These findings affirm the effectiveness of these controllers in enhancing system stability and reliability in real-world scenarios.

In summary, the review draws attention to the critical role of advanced LFC and AVR techniques in addressing operational challenges and improving power system efficiency. Future research should continue to investigate innovative optimization techniques and their applications to ensure the ongoing advancement of power system management.

V1. Recommendations

To advance Load Frequency Control (LFC) capabilities in power systems, the following recommendations are proposed:

i. Implementation of advanced control techniques to enhance precision and responsiveness in load frequency control.

ii. Integration of renewable energy sources into the grid to diversify generation resources and promote sustainable energy practices.

iii. Incorporation of energy storage systems to improve system flexibility and manage fluctuations in supply and demand efficiently.

iv. Development of demand response programs to incentivize consumers to adjust electricity usage in alignment with grid conditions.

v. Utilization of wide-area monitoring and control systems for real-time monitoring and proactive management of grid stability.

vi. Modernization of the grid with smart grid technologies to enhance automation, communication, and integration of distributed energy resources.

vii. Optimization of generation scheduling to ensure efficient utilization of available generation resources and minimize operational costs.

viii. Enhancement of governor performance to improve the speed and accuracy of frequency regulation in response to load changes.

ix. Increase in grid interconnections to enhance system reliability, share resources, and improve operational flexibility across interconnected networks.

x. Pursuit of continuing research and development to innovate and refine load frequency control strategies in line with evolving technological advancements and operational needs.

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