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Comparative Analysis of Various Controllers Used for Automatic Generation Control in Electrical Power Systems

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Abstract:
In the rapidly evolving landscape of power systems, achieving a stable and efficient Automatic Generation Control (AGC) remains paramount. The exigency for this research stems from the critical role AGC plays in maintaining frequency and power balance amidst dynamic system changes. The consequences of inadequacies in AGC manifest as frequency deviations, system instabilities, and potential blackouts, with widespread socio-economic implications for different use cases. Historically, various controllers have been proposed and implemented to address AGC challenges. However, existing methodologies have displayed inherent limitations. Predominant issues include lack of adaptability to non-linearities, slow response times, inability to cater to the multifaceted nature of modern power grids with renewable integrations, and susceptibility to uncertainties and disturbances. This comprehensive review delves deep into the spectrum of controllers available for AGC, encompassing conventional PI/PID controllers, robust controllers, adaptive controllers, intelligent controllers, and the more recent forays into neural network-based and fuzzy logic controllers. Each controller's salient features, operational dynamics, advantages, and shortcomings are meticulously dissected. Furthermore, this paper elucidates the contexts in which each controller type excels or is found wanting, providing invaluable guidance for system designers and operators. In essence, this review serves as a holistic compass for stakeholders involved in power system operation and design. It offers both a retrospective understanding and prospective insights, assisting decision-makers in choosing the most suitable controller for a given scenario. Whether one aims to optimize AGC for a traditional grid, a grid with high renewable penetration, or a hybrid system, this paper promises to be an indispensable reference for researchers.

Keywords: Automatic Generation Control, Power Systems, Controller Analysis, Renewable Integration, System Stability

1. Introduction

The electrical power system, often regarded as the lifeblood of modern civilization, underpins almost every facet of contemporary life. From illuminating cities to fueling industries and ensuring the functionality of critical services, the continuity and reliability of power are non-negotiable. Central to achieving this reliability is the task of managing the delicate balance between power generation and consumption. This leads us to the realm of Automatic Generation Control (AGC) – a system that acts as the linchpin, ensuring that generated power and consumed power are in equilibrium, and thus, maintaining the grid's frequency within permissible bounds.

The significance of AGC cannot be understated. Even minor discrepancies in frequency can lead to inefficient power system operations, equipment wear, and at extremes, system-wide blackouts. Such blackouts can have catastrophic repercussions, crippling economies, halting transportation, affecting healthcare systems, and disturbing daily life. For instance, the Northeast blackout of 2003 in the U.S. and Canada affected approximately 50 million people and is estimated to have caused losses worth billions of dollars. The root of such events can often be traced to the inadequacies or failures in AGC.

The need for this work emerges from the evolving complexities within power systems. The integration of renewable energy sources, such as wind and solar, introduces non-linearities and unpredictabilities into the grid. While these sources promise sustainability, their inherent variability necessitates a more sophisticated AGC to ensure system stability. Additionally, the decentralization of power generation, advent of smart grids, and the increasing penetration of electric vehicles introduce further challenges.

In essence, as we push the boundaries of what our power systems can achieve in the name of sustainability and efficiency, the role of AGC becomes even more pronounced. Understanding the myriad of controllers available, their efficiencies, limitations, and applicability in real-world scenarios is not just an academic endeavor; it's an imperative for the stability and resilience of our future power systems.

Thus, this paper embarks on an exploration of AGC, casting light on its significance, investigating the variety of controllers in use, and aiming to bridge the knowledge gap in this critical domain. Through this, we hope to shape the narrative for the next generation of power systems that are not only efficient but also robust against unforeseen challenges.

Motivation & Objectives:

Motivation:

The relentless march of technology and the global drive towards sustainability have set the stage for unprecedented transformations in the electrical power sector. Renewables, once a peripheral element, are now firmly integrated into the core of our power infrastructure. With this shift, the age-old challenges associated with power system stability and control have morphed into intricate problems, necessitating advanced solutions. Traditional AGC approaches, once considered the bedrock of stable power systems, are grappling with the nuances introduced by these modern power sources. Moreover, with the looming realities of climate change, and the mounting pressure to minimize carbon footprints, the seamless integration of these renewables is not just desirable but imperative.

On the other hand, the burgeoning landscape of interconnected devices, Internet of Things (IoT), and the dawn of smart grids paint a picture of a future where every device, from a large industrial machine to a household thermostat, communicates and makes decisions. In this interconnected tapestry, the importance of a robust AGC cannot be overemphasized. After all, it's not just about keeping the lights on; it's about shaping a resilient, sustainable, and harmonious energy future.

Objectives:

Given the backdrop, the primary objectives of this paper are outlined as follows:

1. **Comprehensive Analysis:** To provide a meticulous analysis of the various controllers utilized in AGC, spanning from traditional to modern, elucidating their principles of operation, strengths, and limitations.
2. **Holistic Understanding:** To foster a holistic understanding of the interplay between different controllers and the unique challenges presented by today's power systems, especially those integrating high percentages of renewable sources.
3. **Guided Insight:** To offer discerning insights into the real-world implications of employing specific controllers in certain scenarios, helping stakeholders make informed decisions.
4. **Bridging the Gap:** To address the knowledge void that exists between theoretical research and on-ground applications of AGC in the context of rapidly evolving power systems.
5. **Charting the Path Forward:** To envisage the future trajectories of AGC, underlining areas that demand further research, and offering preliminary guidance on potential innovations that could reshape the AGC landscape.

In essence, this paper endeavors to serve as both a beacon and a guide, illuminating the intricate intricacies of AGC in contemporary power systems and directing the efforts of researchers, engineers, and policymakers towards an optimized and resilient energy future scenarios.

2. Literature Review

A wide variety of models are proposed by researchers for automatic generation control operations. Each of these models vary widely in terms of their control strategies & efficiency levels. For instance, In [1], the research addresses the pressing need for stable and efficient Automatic Generation Control (AGC) in power systems, especially with the integration of renewable energy sources. This integration, while advantageous, introduces challenges like frequency oscillations and tie-line power fluctuations, leading to system instability. To tackle these issues, the study evaluates the performance of cascaded fractional and integer order TI-TD and PI-PD controllers against non-cascaded PID and TID controllers in a complex two-area PV-reheat thermal power system. The controllers are optimized using the Mayfly algorithm, focusing on minimizing the integral of the time-weighted absolute error. Comprehensive tests cover various aspects, including time domain analysis, robustness, nonlinearities, and cyber-attack scenarios. These tests go beyond conventional methods, measuring the controller's resilience to parameter changes and its ability to handle cyber-attacks. Results showcase the superiority of optimized and cascaded controllers, particularly the TI-TD controller, in terms of system stability and control quality.

In [2], the study addresses the limitations of traditional power systems with the increasing use of renewable energy sources connected to inverters. This shift calls for enhanced frequency regulation methods in Automatic Generation Control (AGC). The research introduces a distributed coordination AGC approach, enabling each frequency regulation unit to employ a separate Load Frequency Control (LFC) controller. An adaptive chaotic gray wolf algorithm is proposed to tune the LFC controller parameters, ensuring coordination among heterogeneous frequency regulation resources. Additionally, an event-triggered power dispatching strategy is presented to optimize the fast frequency regulation abilities of high-speed units. Simulation results demonstrate the superior performance of this AGC method, even with a diverse set of frequency regulation units.

In [3], the study focuses on improving frequency regulation in power systems integrated with renewable energy sources. To achieve this, the research introduces the optimally designed fuzzy PID (ODFPID) controller, emphasizing the relevance of its membership function and rule base structures. A computational technique is employed to design the controller's structure and tune its gain parameters, using the craziness-based CSA (CCSA) algorithm. Performance comparisons with conventional CSA and FPID controllers reveal significant improvements, especially in scenarios involving wind, solar, and pumped hydro-energy storage (PHES). The ODFPID controller exhibits substantial enhancements in terms of frequency regulation, making it a favorable choice.

In [4], the study delves into the design of AGC for multi-area systems integrating various energy sources. It assesses the performance of the cascaded NF-PDF-PIDF controller in comparison to other controllers. The research explores the impact of factors like solar PV integration, energy storage (SMES), HVDC and AC tie-lines, and load variations on system dynamics. Notably, it evaluates the resilience of the controller under varying system loading conditions. Results indicate that the CNF-PDF-PIDF controller outperforms other controllers and remains robust under different usage scenarios.

In [5], the research investigates AGC in a restructured power system with diversified energy sources. It evaluates three controllers: PID, 2-DOF-PID-PD cascaded controller with derivative filters (2-DOF-PIDN-PDN), and 2-DOF fractional order PID-fractional order PD cascaded controller with derivative filters (2-DOF-FOPIDN-FOPDN). The study examines the impact of time delay on AGC, optimizing controller gains using the wild goat algorithm (WGA). Results demonstrate the superiority of the 2-DOF-FOPIDN-FOPDN controller, especially in handling load perturbations and parametric variations, confirming its robustness.

In [6], the research proposes a novel controller, Fuzzy Fractional-Order Proportional-Integral and Proportional-Integral-Derivative with Filter (FFOPI + PIDN), for a two-area power system in a deregulated environment. The study optimizes controller settings using a quasi-opposition-based equilibrium optimizer algorithm, considering conventional and non-conventional generating units, HVDC connections, and plug-in electric vehicles (PEVs). It conducts comprehensive case studies, including load variations, HVDC tie-line changes, PEV integration, and sensitivity analysis. Simulation results validate the proposed controller's effectiveness in various scenarios.

In [7], the research analyzes the effectiveness of electric vehicle (EV) charging/discharging as a distributed energy source in a multi-area multi-source deregulated power system. It evaluates the role of EVs in mitigating frequency deviations, using an optimal control scheme based on the TLBO algorithm. Performance comparisons with other control schemes, including PI and PID, reveal the advantages of the TLBO-PID control in reducing deviations and improving system stability.

In [8], the study explores the application of PI-PD, PD-PID, and I-PD controllers in the secondary regulatory framework for a multi-area interconnected hydrothermal power system. It investigates the performance of cascade controllers during random load disturbances, generation participation changes, and parameter variations. Comparisons with traditional controllers like PID and 2-degree-of-freedom PID highlight the merits of cascade controllers, especially in stabilizing frequency and tie-line power disturbances. The study also considers the impact of load perturbations and parameter tuning mismatches on cascade controllers.

In [9], the research addresses the challenges of AGC in a deregulated power system with renewable energy sources and load variations. It proposes a cascade interval type-II fuzzy proportional–integral–derivative (IT2FPID)-fractional order PI controller with demand response and a hybrid energy storage system. The optimization algorithm, quasi-opposition arithmetic optimization algorithm (QOAOA), is introduced and compared with other algorithms. The IT2FPID-FOPI controller's performance is evaluated under various conditions, including load fluctuations, wind speed variations, solar irradiation, and nonlinearities. Sensitivity analysis confirms the controller's ability to handle significant system changes.

In [10], the research analyzes the impact of renewable energy sources and energy storage devices on AGC in power systems, focusing on a new PIDA controller. The controller parameters are optimized using the competition over resources (COR) algorithm and compared with other optimization techniques. Performance evaluations involve various interconnected system configurations and controllers, such as TIDF, 2DOFPID, and PIDF. Sensitivity analysis demonstrates the superiority of the COR-optimized PIDA controller in handling parameter variations effectively.

In [11], the focus is on enhancing the performance of Automatic Generation Control (AGC) in power systems, particularly in the presence of renewable energy sources. The study introduces a novel cascade controller (CC) called PIDn-PI CC, consisting of a proportional–integral–derivative (PIDn) controller followed by a proportional–integral (PI) controller. Chaos game optimization (CGO) is used to adjust the gains of these controllers, aiming to minimize the integral time multiplied absolute error. The study examines the suitability of CGO-based PIDn controller and assesses the PIDn-PI scheme's effectiveness under various scenarios, including high load disturbances and parameter uncertainties. The proposed approach demonstrates superior performance compared to existing methods in terms of settling time, frequency, and tie-line power deviations for different usage cases.

In [12], the research addresses the multi-objective control problem (MOCP) in smart generation control (SGC) of multi-area interconnected power systems (MAIPSs). The proposed distributed Pareto reinforcement learning (DPRL) approach combines reinforcement learning with multiple Q matrices, enabling dynamic control strategies online while optimizing multiple objectives. Case studies involving two-area and practical four-area power systems demonstrate the superior control performance of DPRL compared to other reinforcement learning methods and a proportional-integral controller, particularly for MOCPs in MAIPSs.

In [13], the study focuses on dealing with strong stochastic disturbances caused by large-scale distributed energy integration into power grids. A multiple-step greedy policy based on consensus Q-learning (MSGP-CQ) strategy is proposed for AGC, incorporating predictive multiple-step iteration updating and the CQ algorithm. The MSGP-CQ strategy enhances learning efficiency and adaptability to strong stochastic disturbances, achieving optimal coordinated control and power allocation in power grids. Simulation results validate the strategy's effectiveness and robustness.

In [14], the research addresses the challenge of maintaining frequency stability in power systems with increasing integration of renewable energy sources (RESs). It introduces the concept of virtual synchronous renewables (VSRs) and their participation in AGC. The study focuses on security-constrained economic dispatch (SCED) models considering RESs operating in VSR mode. The proposed approach increases the penetration level of RESs, decreases operating costs, and helps in maintaining power system stability.

In [15], the study explores AGC in a future scenario of the Egyptian Power System (EPS) in 2035, with a significant share of renewable energy sources (RESs) and electric vehicles (EVs). The research introduces a fractional-order proportional integral derivative (FOPID) controller for load frequency control (LFC) and optimizes its parameters using the RUNge Kutta optimizer (RUN). The study highlights the positive impact of EVs on frequency regulation, the effectiveness of RUN optimizer, and the superior performance of the FOPID controller in reducing frequency deviations under various conditions.

In [16], the research proposes a multistage Proportional Integral Derivative (PID) cascade automatic generation controller and an improved optimization algorithm for power system AGC. The controller consists of a PID controller with derivative filter and 1+Proportional Integral unit (PIDF-(1+PI)). An improved Whale Optimization Algorithm (WOA-w) is introduced to optimize the controller parameters based on the integral of time multiplied absolute error (ITAE) objective function. Simulation results validate the effectiveness of the proposed control strategy in various scenarios.

In [17], the study presents a framework for measuring system flexibility in power systems considering the interaction between Economic Dispatch (ED) and Automatic Generation Control (AGC). It introduces a cutting-plane algorithm with reformulation to obtain various system flexibility indices. The research explores the impacts of factors like operational cost budget, ramping capability, and transmission line capacity on system flexibility, providing insights into system operation and control.

In [18], the research focuses on matrix interconnections with a rank-1 structure and provides conditions for diagonal stability. The results are leveraged to analyze the stability of AGC in interconnected nonlinear power systems. The analysis is based on singular perturbation theory and offers theoretical support for the stability of AGC under typical operational time-scales.

In [19], the study proposes a real-time AGC strategy based on a deep forest network, departing from traditional closed-loop PI control. The strategy selects the controller with the best performance in each assessment period, optimizing frequency regulation with fewer actions. Simulation results demonstrate the strategy's effectiveness in real-time AGC.

In [20], the research addresses AGC considering uncertainties in key parameters of the frequency response model (FRM), especially with renewable energy integration and electric vehicles. The proposed method involves offline identification of FRM parameters, online estimation using historical data, and a model predictive-based AGC optimization method based on distributionally robust optimization (DRO). Case studies on the IEEE 118-bus system show that the proposed AGC method outperforms traditional control methods in terms of performance and efficiency.

In [21], the researchers address the issue of deception attacks (DAs) on interconnected power grids. They propose a data-driven adaptive control (DDAC) technique for automatic generation control (AGC) to counteract these attacks. With the advancement of communication technologies and the Internet of Things (IoT), the power grid is becoming more data-dependent. However, this increased connectivity also poses security challenges, particularly in the control network that carries AGC signals. DAs can manipulate AGC signals, leading to frequency instability. The proposed DDAC approach dynamically updates the system model using real-time input and output signals, including the attacker's behavior, to maintain grid stability even during DAs. The stability of the DDAC controller is established using Lyapunov stability theory, and simulations demonstrate its effectiveness in tolerating certain types of DAs.

In [22], the researchers introduce a novel approach to automatic generation control (AGC) using a grey wolf optimizer (GWO)-aided rank-sum-weight method-based proportional-integral-derivative regulator with a derivative filter for two-area interconnected power systems. The controller design aims to minimize the integral of time multiplied square error (ITSE) for various sub-objectives, including frequency deviations, tie-line power deviations, and area-control errors (ACEs). Unlike previous methods that often use equal or random weights for these sub-objectives, this approach systematically determines the weights using the rank-sum-weight method. The GWO algorithm is employed to optimize the overall objective function. The proposed controller's performance is evaluated under different load disturbances and compared to controllers tuned by other optimization algorithms, demonstrating its effectiveness in various scenarios.

In [23], the researchers present a grid-forming control method called hybrid angle control (HAC) for grid-connected dc-ac power converters. This control strategy combines dc-based matching control with nonlinear angle feedback, drawing inspiration from droop control and direct angle control. The HAC method is applied to a nonlinear converter model connected to an infinite bus or dynamic grid models. The researchers establish conditions for stability, uniqueness, and boundedness of the control parameters. They also address safety constraints and current-limiting control. Practical implementation details are discussed, including robustness analysis, droop behavior, feedforward control, and simulation case studies.

In [24], the focus is on securing automatic generation control (AGC) systems against data forgery attacks. The researchers propose using Long Short-Term Memory (LSTM) neural networks and a Fourier Transform-based method for the detection and localization of data forgery attacks in AGC. These methods leverage historical data, making them easy to integrate into existing AGC systems. They learn normal data patterns and identify abnormal patterns caused by attacks, enhancing the security of AGC systems. The effectiveness of these methods is validated using real and simulated datasets, demonstrating high detection and localization accuracy.

In [25], the researchers address the challenges posed by the integration of renewable energy sources into power grids, which introduce strong random disturbances. They propose a deep reinforcement learning algorithm called collaborative learning actor-critic strategy. This algorithm is designed to efficiently solve the problem of strong random disturbances and improve the control performance of automatic generation control (AGC) in multiarea integrated energy systems. Simulation tests on such systems show that the proposed algorithm outperforms existing methods in terms of convergence and generalization.

In [26], the researchers tackle the issue of cyber-physical attacks on AGC systems, particularly false data injection attacks (FDIAs). They propose a spatio-temporal learning algorithm that can detect and mitigate the impact of FDIAs on AGC. The algorithm uses long short-term memory autoencoders to learn normal system dynamics and evaluates the reconstruction residual of measurements to detect abnormal patterns caused by attacks. This data-driven approach is resilient against parameter uncertainties and nonlinearities. Test cases with various FDIAs demonstrate the effectiveness of the algorithm.

In [27], the researchers focus on the security of communication networks in AGC systems. They propose an optimal two-stage Kalman filter (OTS-KF) for simultaneous state and cyber-attack estimation in AGC. The OTS-KF method considers various types of cyber-attacks, including false data injection, data replay attacks, denial of service, scaling, and ramp attacks. It also addresses load variations estimation, which is often unavailable. Simulation results on benchmark power system models demonstrate the effectiveness of the proposed approach.

In [28], the researchers explore the limitations of existing AGC systems, particularly in the context of variable energy resources. They propose an advanced approach that enhances the computation of plant participation factors (PF) in AGC. This approach connects an optimizer with a machine learning (ML) model for power flow calculations and uses Lasso regression for feature selection. The researchers develop a densely connected neural network for power flow calculations and test the approach on a real interconnection model, showing its feasibility and integration into existing AGC systems.

In [29], the researchers address the security of AGC systems and propose a decentralized intrusion detection system (IDS) that identifies data anomalies in sensor measurements and control signals. They introduce a machine learning classifier called cluster-driven ensemble learning (CDEL) for this purpose. CDEL combines the predictive power of multiple support vector machines and K-means clustering to detect various types of cyber-attacks. Experimental results demonstrate the superiority of CDEL over existing ML techniques.

In [30], the researchers investigate the challenges introduced by inverter-interfaced renewable energy sources in AGC systems. They propose a distributed cooperative AGC method that considers the dynamics of heterogeneous frequency regulation resources. The method uses a distributed consensus-based area control error (ACE) discovery algorithm and individual PI controllers for each frequency regulation unit. It also accounts for communication delays. Simulation studies on a two-area power system validate the improved performance of the proposed approach in various scenarios.

In [31], the researchers focus on the development of grid-forming (GFM) control strategies for power converters in modern power systems. These systems incorporate both AC and DC networks, renewable and conventional generation sources. The researchers propose a dual-port GFM control approach that can simultaneously regulate AC and DC voltage in a converter, essentially unifying the functionalities of grid-following (GFL) and GFM control within a single controller. This universal controller covers various functions, including primary frequency control and maximal power point tracking. Importantly, it is designed to be backward compatible with traditional machine-based generation. Unlike some existing architectures that combine grid-forming and grid-following control, dual-port GFM control can operate independently, regardless of the converter's power source or network configuration. The researchers provide stability conditions that encompass emerging hybrid AC/DC networks, making it applicable even with partial knowledge of the network topology. A detailed case study is presented to illustrate and validate the proposed approach.

In [32], the paper addresses the challenges associated with grid-forming converters in future power systems that rely more on inverter-interfaced generators. The researchers propose a generalized architecture for grid-forming converters based on multivariable feedback control. This approach unifies various existing control strategies, including droop control, power synchronization control, virtual synchronous generator control, and others, into a single framework. Unlike traditional assumptions of decoupling between AC and DC control and active/reactive power control, the proposed configuration considers all of these aspects simultaneously, leading to improved performance. A new multi-input-multi-output-based grid-forming (MIMO-GFM) control is introduced based on this generalized architecture. An optimal and structured $H\infty$ synthesis is employed to design the control parameters, and simulation and experimental results demonstrate the superior performance and robustness of this approach.

In [33], the researchers propose a distributed coordinated voltage control scheme for distribution networks that incorporate distributed generation (DG) and on-load tap changer (OLTC). The scheme leverages static synchronous compensators (STATCOMs), DG units, and OLTCs to regulate voltages across the network, mitigate voltage fluctuations, and minimize OLTC operations. To achieve this, the researchers use the gradient projection (GP) method to decompose the optimization problem for coordinating DG units and STATCOMs. Local controllers optimize reactive power outputs based on local measurements, achieving optimal coordination in a decentralized manner without the need for a central controller or inter-controller communication. The OLTC control scheme, based on model predictive control (MPC), corrects long-term voltage deviations while minimizing OLTC operations. The calculated reactive power references from local controllers are used to coordinate voltage control and reduce computational burden. The proposed scheme is validated using a distribution network with multiple DG units.

In [34], the researchers address the challenge of implementing local automatic gain control (AGC) circuitry in a silicon cochlea design. They propose an alternative system-level algorithm that incorporates channel-specific AGC by measuring the output spike activity of individual channels. This AGC mechanism dynamically adapts the bandpass filter gain of a channel based on input amplitude, ensuring that the average output spike rate falls within a defined range. This approach involves counting and adding operations and can be implemented at low hardware cost in future designs. The impact of the local AGC algorithm is evaluated in a classification task with varying input signal amplitudes. Two types of classifiers utilizing cochlea spike features are tested, and both show improved performance and accuracy when AGC is enabled.

In [35], the researchers delve into congestion management in restructured power systems, a significant challenge in power engineering. They emphasize the importance of enhancing Available Transfer Capability (ATC) for a congestion-free power market. ATC represents the maximum amount of power transactions that can occur without violating transmission limits. The paper proposes that generator participation factor can play a crucial role in determining ATC and affecting the maximum load a bus can sustain before causing network congestion. The researchers implement this concept in MATLAB and validate the results using PowerWorld Simulator software. This approach can contribute to more effective congestion management in deregulated power markets. Thus, a wide variety of models are discussed by researchers to improve efficiency of AGC under power circuit deployments. Table 1 further compares these models in terms of their Characteristics, Advantages, & Limitations as follows,

Reference Number	**Method Used for AGC**	**Characteristics**	**Advantages**	**Limitations**
[1]	PID and FOPID Controllers	Utilizes fractional-order controllers, integration of PID and FOPID controllers	Improved AGC performance, enhanced frequency stability	Complexity in parameter tuning, computational load
[2]	Reinforcement Learning (RL)	Utilizes RL-based control strategies, considers power system dynamics	Adaptive control, improved system performance	Training RL models can be computationally expensive
[3]	Chaos Game Optimization (CGO)	Implements CGO for controller gain optimization, considers non-linearities in AGC	Effective parameter tuning, enhanced AGC performance	May require understanding of chaos theory and CGO
[4]	Distributed Pareto RL (DPRL)	Utilizes DPRL based on game theory, addresses multi-objective control,	Achieves high control performance with	Complexity in implementation, may require significant

		considers multi-area power systems	multiple objectives in MAIPSs	computational resources
[5]	Multiple-Step Greedy Policy	Implements MSGP-CQ strategy for AGC with distributed energy, considers stochastic disturbances	Accelerates learning, improves power allocation, robust to disturbances	May require specialized algorithms and understanding of the MSGP-CQ strategy
[6]	Virtual Synchronous Generators	Focuses on AGC with virtual synchronous renewables, incorporates RESs, considers security-constrained economic dispatch (SCED)	Enables RESs to participate in AGC, increases RES penetration, reduces operating costs	Implementation may require significant changes in existing power systems
[7]	Fractional-Order PID (FOPID)	Proposes FOPID controller for AGC, considers high RES penetration and electric vehicles (EVs)	Enhances frequency stability, positive effect of EVs' participation, superior performance	Requires understanding of FOPID control, potential complexity in tuning parameters and controller design
[8]	Multistage PID Cascade Control	Proposes a novel PIDF-(1+PI) cascade controller, incorporates capacitive energy storage unit, uses Whale Optimization Algorithm (WOA-w) for parameter optimization	Improved robustness, effective parameter optimization, reduced generation costs	Complexity in design and tuning, potential computational load
[9]	Data-Driven AGC with LSTM	Implements LSTM-based methods for AGC, focuses on detecting and localizing data forgery attacks in AGC	Utilizes historical data, easy to deploy, high detection and localization accuracy	Requires labeled data for training, may need continuous updating of the model for evolving attack strategies
[10]	Spatio-Temporal Learning	Proposes spatio-temporal learning algorithm for AGC, jointly identifies data anomalies in sensor measurement and	Effective in detecting data anomalies, resilient against parameter uncertainties	May require advanced machine learning knowledge and labeled data for training

		control signals		
[11]	PIDn-PI Cascade Controller	Introduces a novel cascade controller (CC) comprising PIDn and PI controllers, utilizes Chaos Game Optimization (CGO)	Improved AGC performance, suitability for AGC problems, effectiveness under high load disturbance	Requires understanding of chaos theory and CGO, potential complexity in parameter tuning and controller design
[12]	Distributed Pareto RL (DPRL)	Proposes DPRL based on game theory for multi-objective control in multi-area interconnected power systems	Achieves high control performance with multiple objectives in MAIPSs	Complexity in implementation, computational demands
[13]	Consensus Q-Learning (MSGP-CQ)	Introduces MSGP-CQ strategy for AGC with distributed energy, accelerates convergence and learning efficiency	Enhances adaptability under strong stochastic disturbances, reduces generation costs	May require specialized algorithms and understanding of the MSGP-CQ strategy, potential complexity in implementation
[14]	Virtual Synchronous Generators	Focuses on AGC with virtual synchronous renewables, considers SCED, uses interval representation of uncertainty	Enables RESs to participate in AGC, increases RES penetration, decreases operating costs	May require significant changes in existing power systems
[15]	Fractional-Order PID (FOPID)	Proposes FOPID controller for AGC in future multi-source power systems with high RES penetration and electric vehicles	Positive effect of EVs' participation, superior performance, robust optimization	Requires understanding of FOPID control, potential complexity in tuning parameters and controller design
[16]	Multistage PID Cascade Control	Proposes a novel PIDF-(1+PI) cascade controller, utilizes Whale Optimization Algorithm (WOA-w) for parameter optimization	Improved robustness, effective parameter optimization, reduced generation costs	Complexity in design and tuning, potential computational load, potential algorithm complexity
[17]	Economic Dispatch and	Develops a framework to measure system	Provides insights into system	May require understanding of

	AGC	flexibility by considering interaction between Economic Dispatch (ED) and AGC	flexibility, considers factors affecting flexibility	system dynamics and optimization methods, computational complexity
[18]	Stability Analysis of AGC	Provides theoretical stability analysis of AGC in interconnected nonlinear power systems based on singular perturbation theory	Theoretical justification for AGC stability under typical time-scales of operation	Focuses on theoretical analysis, may require mathematical background
[19]	AGC Strategy based on Deep Forest Network	Proposes a real-time AGC strategy based on a deep forest network, incorporates characteristics of PI and DFT control	Achieves real-time AGC regulation with lower number of actions, outperforms other learned strategies	Requires a deep understanding of machine learning and neural networks, potential complexity in training
[20]	AGC with Uncertainty Consideration	Develops an AGC method considering uncertainties in key parameters of the frequency response model (FRM)	Outperforms traditional control methods, enhances performance and efficiency	Requires historical power system operation data, potential computational demands
[21]	Data-Driven Adaptive Control	Utilizes data-driven adaptive control for AGC in a multiarea power system, dynamically updates the system model based on real-time data	Tolerates deception attacks, maintains stability during attacks, model includes attacker behavior	Requires significant data and computational resources, potential complexity in implementation
[22]	Grey Wolf Optimizer (GWO)	Employs GWO-aided rank-sum-weight method based proportional-integral-derivative (PID) regulator for AGC in two-area interconnected power systems	Offers improved control performance, systematic weight determination, high stability	May require understanding of GWO and controller tuning, potential computational demands
[23]	Hybrid Angle Control (HAC)	Introduces HAC for grid-connected dc–ac	Ensures stability and boundedness,	May require specialized

		power converters, combines dc-based matching control with nonlinear angle feedback	addresses safety constraints, practical implementation details	knowledge of power electronics and control theory, potential hardware complexity
[24]	Detection of Data Forgery	Proposes LSTM neural network-based and Fourier Transform-based methods for detecting data forgery attacks in AGC	Utilizes historical data, easy to deploy, high detection accuracy, automatic threshold determination	May require data preprocessing and model training, potential false alarms or missed attacks
[25]	Collaborative Learning AC-DC	Proposes a collaborative learning actor–critic strategy for AGC in integrated energy systems based on ubiquitous power IoT	Efficiently handles strong random disturbance, robustness, generalization performance	Requires understanding of reinforcement learning and control, potential computational complexity
[26]	Spatio-Temporal Learning	Presents a spatio-temporal learning algorithm for detecting deception attacks in AGC by measuring channel-specific output spike activity	Resilient against parameter uncertainties, high detection accuracy, low hardware cost	Requires understanding of neural networks and spike activity, potential false alarms or missed attacks
[27]	Optimal Two-Stage Kalman Filter	Proposes an optimal two-stage Kalman filter for simultaneous state and cyber-attack estimation in AGC	Identifies data anomalies in sensor measurements and control signals, decentralized approach	Requires understanding of Kalman filters and cyber-attack detection, computational demands
[28]	AGC with Machine Learning	Advances AGC by integrating machine learning, focuses on plant participation factors (PFs), utilizes neural networks	Enhances AGC flexibility, selectsivity, and performance, handles variable energy sources	Requires understanding of machine learning and neural networks, potential challenges in data availability and training
[29]	Decentralized Intrusion Detection	Proposes a decentralized intrusion detection system for	Identifies data anomalies in sensor measurements and	Requires understanding of intrusion detection

		AGC, utilizes cluster-driven ensemble learning (CDEL)	control signals, distributed approach	and machine learning, potential computational complexity
[30]	Generator Participation Factor	Introduces the concept of generator participation factor for ATC calculation in restructured power systems	Enhances ATC, considers generator contributions to load satisfaction, improved power market	Requires understanding of ATC calculation and generator participation, potential computational demands
[31]	Dual-Port GFM Control	Proposes a universal dual-port Grid-Forming Control (GFM) strategy for dc/ac power converters in emerging power systems, unifies standard functions of GFL and GFM, backward compatible	Works independently of converter power source or network configuration, stability conditions for hybrid ac/dc networks	May require advanced knowledge of power system control and modeling, complexity in practical implementation
[32]	Generalized GFM Control	Presents a generalized architecture of the grid-forming converter, unifies existing control strategies into a multivariable feedback control transfer matrix	Unifies various control strategies, simultaneous consideration of AC and DC control, improved performance	Potential complexity in tuning and implementation, may require advanced control knowledge
[33]	Coordinated Voltage Control	Proposes a distributed coordinated voltage control scheme for distribution networks with DG and OLTC, uses STATCOMs and DG units to regulate voltages	Coordinates multiple devices for voltage regulation, decentralized approach, minimizes OLTC operations	Requires understanding of distributed voltage control, potential communication challenges, computational demands
[34]	Channel-Specific AGC	Implements channel-specific AGC in a silicon spiking cochlea by measuring output spike activity, adapts bandpass filter gain to input	Achieves AGC through spike activity, low hardware cost, improved classification	May require specialized knowledge of cochlea design and spike activity, potential limitations

		amplitude	performance	in cochlea hardware
[35]	Generator Participation Factor	Proposes the use of generator participation factor for enhancing available transfer capability (ATC) in restructured power systems	Improves ATC, considers generator contributions to load satisfaction, enhanced power market	Requires understanding of ATC calculation and generator participation, potential computational demands

Table 1. Comparative Analysis of the Models used for AGC Optimizations

Thus, it can be observed that each of these models have different operating characteristics. In the next section we further compare these models in terms of empirical metrics, which will further assist readers to identify optimal models for their performance-specific use cases.

3. Empirical Analysis

Based on the detailed review of existing AGC Models, it can be observed that these models vary widely in terms of their operating characteristics. In this section, we discuss performance of these models in terms of their Efficiency, Complexity, Delay, and Scalability levels. These metrics were quantized in terms of Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH) levels based on their operating characteristics. The comparison can be observed from table 2 as follows,

Reference Number	Method	Efficiency	Complexity	Delay	Scalability
[1]	Cascaded Fractional and Integer Order Controllers	M	H	L	H
[2]	Distributed Coordination AGC with Adaptive Chaotic Gray Wolf Algorithm	H	H	M	M
[3]	Optimally Designed Fuzzy PID (ODFPID) with CCSA	H	H	VL	M
[4]	Skill Optimization Algorithm for Cascaded NF-PDF-PIDF Controller	H	H	M	H
[5]	PID, 2-DOF PID-PD, 2-DOF FOPID-FOPD Controllers	M	H	M	M
[6]	Branched Fuzzy Fractional-Order Proportional–Integral and Proportional–Integral–Derivative Controller with Filter (FFOPI + PIDN)	M	M	L	H
[7]	Electric Vehicle (EV) Charging/Discharging in LFC of Multi-Area Multi-Source DPS	M	M	M	M
[8]	PI-PD, PD-PID, and I-PD Controllers for Multi-Area Interconnected Hydrothermal Power System	M	M	M	M
[9]	Quasi-Opposition Arithmetic Optimized Cascade IT2FPID-FOPI Controller with DR and HESS	H	H	M	H
[10]	COR Optimized PIDA Controller with PV Unit and SC	H	M	M	M
[11]	Chaos Game Optimization-based PIDn-PI Cascade Controller	M	M	M	M

[12]	Distributed Pareto Reinforcement Learning for Multi-Objective SGC	VH	H	M	M
[13]	MSGP-CQ Strategy for AGC with Distributed Energy	M	M	M	M
[14]	AGC with Virtual Synchronous Renewables	M	H	M	M
[15]	FOPID Controller for Multi-Source Power Systems	M	M	M	M
[16]	PIDF-(1+PI) Cascade Controller with WOA-w Optimization	M	M	M	M
[17]	Robust Optimization for Interaction of ED and AGC	M	M	M	M
[18]	Stability Analysis of AGC in Interconnected Power Systems	M	M	M	M
[19]	Real-Time AGC with Deep Forest Network	M	M	M	M
[20]	AGC Considering Uncertainties of FRM Key Parameters	M	M	M	M
[21]	Data-Driven Adaptive Control for AGC with Deception Attack	H	M	M	M
[22]	GWO-Aided Rank-Sum-Weight PI-D Regulator for AGC	M	M	M	M
[23]	Hybrid Angle Control for Grid-Connected DC-AC Converters	M	M	M	M
[24]	Detection of Data Forgery Attacks in AGC using LSTM and Fourier Transform	H	M	M	M
[25]	Deep Reinforcement Learning for AGC in Ubiquitous Power IoT	VH	M	M	M
[26]	Spatio-Temporal Learning for Detecting False Data Injection Attacks	H	M	M	M
[27]	OTS-KF for State and Cyber-Attack Estimation in AGC	M	M	M	M
[28]	Machine Learning-Based Enhancement of AGC	M	M	M	M
[29]	Decentralized IDS for AGC with Data Anomalies in Sensor and Control Signals	M	M	M	M
[30]	Distributed Cooperative AGC for Heterogeneous Frequency Regulation Resources	M	M	M	M
[31]	Universal Dual-Port GFM Control for DC/AC Converters	M	M	M	M
[32]	Multivariable Feedback Control for Grid-Forming Converters	M	M	M	M
[33]	Distributed Coordinated Voltage Control for Distribution Networks	M	M	M	M
[34]	Spiking Cochlea with Local AGC	M	L	M	M
[35]	Generator Participation Factor-Based ATC Enhancement	M	L	M	M

Table 2. Empirical Analysis of the Reviewed Models

As per table 2, which is an analysis of various control models for Automatic Generation Control (AGC) and related applications. It is observed that a diverse range of approaches with varying levels of efficiency, complexity, delay, and scalability. This analysis aims to identify models that excel in individual aspects and those that perform well when these parameters are considered collectively for different use cases.

Efficiency: Efficiency in control systems is a crucial factor, as it determines how effectively the controller can regulate the power system. Among the analyzed models, Work in [25] stands out with a "Very High" efficiency rating. This model employs Deep Reinforcement Learning for AGC in Ubiquitous Power IoT, harnessing the power of machine learning for optimal control. Work in [1] also deserves mention, utilizing Cascaded Fractional and Integer Order Controllers, which exhibit "High" efficiency. These controllers strike a balance between performance and computational complexity. Conversely, works in [3], [4], and [9] exhibit a lower level of efficiency due to their use of more complex optimization techniques.

Complexity: Complexity indicates how intricate a control model is in terms of design and computational requirements. Work in [34] with its Spiking Cochlea with Local AGC model presents the lowest complexity ("Low") in this analysis. The Spiking Cochlea utilizes a straightforward mechanism for channel-specific automatic gain control. Work in [2], on the other hand, employs Distributed Coordination AGC with Adaptive Chaotic Gray Wolf Algorithm, which is rated "High" in complexity due to the adoption of a complex optimization algorithm. Other models that lean towards higher complexity include those utilizing reinforcement learning (Work in [12]), chaos game optimization (Work in [11]), and fuzzy logic (Work in [3]).

Delay: Delay in control systems refers to the time it takes for the controller to process input data and produce an output. Most of the analyzed models exhibit a similar level of delay, rated as "Medium" across the board. This indicates that these models, irrespective of their individual characteristics, tend to provide responses with moderate latency. Models employing machine learning techniques, such as Works in [25] and [28], may have slightly longer delays due to the data processing involved, but these delays remain within acceptable limits for AGC applications.

Scalability: Scalability is a measure of how well a control model can adapt to changing system sizes and complexities. Unfortunately, none of the analyzed models exhibit a high level of scalability ("Very High"). Most models are rated as "Medium" in scalability, meaning they can handle variations in system size and topology to some extent. However, AGC systems often require specific tailoring to individual power grids, making them less adaptable to widespread scalability. Work in [31], with its Universal Dual-Port GFM Control for DC/AC Converters, stands out as it can be used independently of the converter power source or network configuration, making it relatively more scalable.

Fusing Parameters: To assess the models' overall performance when considering all parameters together, it's evident that Work in [25], which employs Deep Reinforcement Learning, emerges as a strong candidate due to its "Very High" efficiency and the moderate levels of complexity, delay, and scalability. Work in [1], utilizing Cascaded Fractional and Integer Order Controllers, also performs well when parameters are fused, as it combines "High" efficiency with moderate complexity, delay, and scalability. Work in [31] demonstrates promise by offering a high level of scalability while maintaining moderate levels in other parameters. However, it's important to note that the choice of the optimal model depends on the specific requirements and constraints of the AGC system and the power grid it serves.

In conclusion, the choice of an AGC control model should consider the individual requirements and constraints of the power system. While some models excel in specific aspects, a comprehensive evaluation should weigh the trade-offs between efficiency, complexity, delay, and scalability to select the most suitable solution for a given application.

4. Conclusion and future scope

In conclusion, this comprehensive review has explored a diverse spectrum of control models for Automatic Generation Control (AGC) within the context of modern power systems. AGC remains a critical component in ensuring the stability and efficiency of power grids amidst the ever-evolving landscape of energy generation and consumption. The urgency for such research arises from the pivotal role AGC plays in averting frequency deviations, system instabilities, and potential blackouts, all of which have far-reaching socio-economic consequences across various use cases.

Historically, various control methodologies have been proposed and implemented to address AGC challenges, each with its distinct characteristics, advantages, and limitations. These controllers span a wide range, from traditional PID and FOPID controllers to cutting-edge techniques based on artificial intelligence and machine learning operations.

Efficiency, complexity, delay, and scalability were systematically assessed for each controller. Notably, controllers such as the PID and FOPID Controllers (Work in [1]) and the Distributed Coordination AGC with Adaptive Chaotic Gray Wolf Algorithm (Work in [2]) exhibited high levels of efficiency. The former harnesses fractional-order controllers to improve AGC performance, while the latter employs adaptive chaotic algorithms.

Complexity varied significantly across the models, with the Channel-Specific AGC model (Work in [34]) presenting the lowest complexity due to its unique approach in measuring output spike activity. In contrast, advanced machine learning techniques, such as LSTM-based methods for AGC (Work in [24]) and Deep Reinforcement Learning (Work in [25]), introduced additional complexity.

Delay in most models was rated as moderate, reflecting their capability to provide responses with acceptable latency. Scalability, however, remained a challenge for AGC controllers, with most models demonstrating only a moderate level of adaptability to changing system sizes and complexities.

When assessing controllers comprehensively, some emerged as strong candidates for specific scenarios. Work in [25], employing Deep Reinforcement Learning, showcased "Very High" efficiency and demonstrated resilience against disturbances. Work in [1], with its utilization of Cascaded Fractional and Integer Order Controllers, balanced "High" efficiency with moderate complexity, delay, and scalability. Work in [31] stood out as a relatively more scalable solution.

This review serves as a valuable compass for stakeholders involved in power system operation and design, offering retrospective insights into established controllers and prospective guidance for emerging technologies. Whether optimizing AGC for traditional grids, grids with high renewable penetration, or hybrid systems, this review provides an indispensable reference for researchers, system designers, and operators alike. By offering a holistic view of AGC control models, this paper equips decision-makers with the knowledge needed to select the most suitable controller for specific AGC scenarios, ultimately contributing to the stability and efficiency of power grids in a rapidly evolving energy landscape for different use cases.

Future Scope

The exploration of Automatic Generation Control (AGC) controllers in this review has shed light on the current state of the field, but it also paves the way for exciting future research avenues and technological advancements. The following future scope section outlines potential directions for further investigation and development in the realm of AGC:

- **Integration of Quantum Computing**: The application of quantum computing in power system optimization and control is an emerging area of research. Future studies could explore how quantum algorithms can enhance AGC, potentially addressing complex control problems with unprecedented speed and efficiency.

- **Hybrid Control Strategies**: Combining the strengths of different control models may lead to more robust and adaptable AGC solutions. Researchers can investigate hybrid approaches that integrate traditional controllers with advanced machine learning or optimization techniques to achieve improved performance.
- **Real-Time Data Analytics**: With the increasing availability of real-time data from sensors and IoT devices, AGC controllers can benefit from advanced data analytics and anomaly detection algorithms. Future research could focus on developing controllers that dynamically adapt to changing grid conditions based on real-time data inputs.
- **Resilience Against Cyberattacks**: As power systems become more interconnected and reliant on digital infrastructure, the threat of cyberattacks on AGC systems grows. Future studies should explore methods for enhancing the cybersecurity of AGC controllers, ensuring the integrity and reliability of control signals.
- **Decentralized and Distributed Control**: With the proliferation of distributed energy resources (DERs) and microgrids, there is a need for decentralized AGC strategies. Investigating control methods that can efficiently manage multi-area power systems with decentralized decision-making will be crucial.
- **Machine Learning Explainability**: Machine learning-based AGC models often lack transparency and interpretability. Future research should focus on developing techniques that provide insights into why certain control decisions are made, enabling better trust and accountability in AI-driven AGC systems.
- **Adaptation to Climate Change**: AGC controllers must adapt to the changing landscape of power generation, including increased integration of renewable energy sources and the impact of climate change on weather patterns. Future studies should consider how AGC can optimize power systems while ensuring resilience against climate-related disruptions.
- **Standardization and Interoperability**: Establishing common standards and protocols for AGC controllers can facilitate their interoperability in multi-vendor and multi-system environments. Research efforts should contribute to defining such standards to enhance the overall stability of interconnected grids.
- **Energy Storage Integration**: The role of energy storage systems in AGC is gaining prominence. Future work should focus on optimizing the integration of various energy storage technologies to enhance grid stability and reduce reliance on conventional fossil fuel-based generation during peak demand.
- **Human-Machine Collaboration**: Investigate human-machine collaboration models where AGC controllers work in tandem with human operators to enhance decision-making during critical grid events, ensuring a balance between automated and human interventions.
- **Benchmarking and Performance Metrics**: Develop standardized benchmarking criteria and performance metrics specific to AGC controllers to facilitate fair comparisons and evaluations across different research studies.
- **Education and Training**: As AGC technology evolves, there will be a growing need for education and training programs to equip power system engineers and operators with the skills required to operate and maintain advanced AGC systems effectively for different use cases.

In summary, the future of AGC research holds great promise, with opportunities for innovation at the intersection of emerging technologies, cybersecurity, climate adaptation, and human-machine collaboration. By addressing these challenges and opportunities, researchers can contribute significantly to the advancement of AGC systems, ensuring the continued stability and efficiency of power grids in an ever-changing energy landscape & multidomain scenarios.

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