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Review Article

Evolution of Load Frequency Control: From Classical Approaches to Intelligent & Resilient Frameworks

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Abstract - *Load Frequency Control (LFC) plays a vital role in keeping the frequency stable and maintaining the tie line power in interconnected power systems. With the addition of a large number of Renewable Energy Resources (RES), reduced system inertia, communication delay and cybersecurity issues, the conventional controllers fail to deliver optimal performance. This research presents a systematic and comprehensive review of various LFC methodologies from classical to intelligent control frameworks. This work provides a structured analysis based on quantitative and qualitative performance parameters, which include settling time, overshoot, robustness, scalability and computational complexity. An in-depth classification of various control techniques from conventional controllers to advanced controllers, which include model predictive control, robust control, AI-based controllers and optimisation methods, is presented. Further, the impact of emerging technologies, which include HVDC links, energy storage systems and decentralised architectures, on load frequency control is examined. The main challenges include cyber threats, high computational burden and lack of real-time validation. The study highlights that intelligent controllers and optimisation-based controllers offer superior performance, but the practical application is limited by complexity and stability concerns. Finally, future research is focused on real-time execution of LFC strategies for next-generation smart grids.*

Keywords - *Load Frequency Control (LFC), Automatic Generation Control (AGC), and Proportional Integral Derivative (PID).*

1. Introduction

The rapid expansion of interconnected modern power systems, driven by rising electricity demand, integration of renewable energy sources, and growth of interconnected networks, has increased the complexity of system operation and control. Maintaining power system stability is really important. One of the things to do is to keep the system frequency within a definite limit.

Stability is fundamental to dependable operation of interconnected power systems, and it is the ability of the system to remain synchronised and return to an acceptable operating condition following disturbances such as load changes, faults, or parameter variations. Loss of stability can cause generator desynchronization, frequency collapse, or cascading outages. The growth of recent power systems to satisfy global demands and increased interconnection among control regions make maintaining stable operation more difficult.

Maintaining the balance between total generation and load demand is essential to keep the system frequency within permissible bounds [18]. Persistent imbalances degrade power quality, system reliability, and equipment safety if frequency deviates from nominal for extended durations.

Maintaining the system frequency within the permissible limit is the fundamental requirement for dependable and safe operation of an interconnected power system. LFC, also known as AGC, is responsible for maintaining balance between power generation demands while keeping the tie line power exchanges among various control zones [5]. Conventional controllers such as PI and PID regulators have been widely used in applications due to their simplicity [1]. However, modern power systems have changed significantly due to the addition of RES such as wind, solar, energy storage systems and smart grid technologies [4, 12].

These changes in the system introduce uncertainty, reduced system inertia and communication delay, which complicate the load frequency control problems [7, 8]. As a result, conventional controllers struggle to maintain the proper performance under various conditions. Recent research has therefore focused on advanced control strategies including optimal control, Robust Control (RC), Model Predictive Control (MPC), Intelligent Controllers (IC) and Artificial Intelligence (AI) based approaches such as fuzzy logic, neural networks, etc [6, 30]. Various types of fractional order controllers, such as TID [50, 51] and FOPID, are also introduced for LFC. Although several review studies have summarised various LFC methods, many surveys provide only descriptive overviews of control strategies without offering comparison, clear research gap identification and integration of emerging intelligent control frameworks [14]. The purpose of the review is to provide a comprehensive and systematic evolution of the LFC strategies from classical approaches to modern intelligent approaches. Unlike the existing surveys, this study presents a structured comparison of load frequency control techniques based on performance matrices such as settling time, overshoots, robustness, complexity and scalability for interconnected systems.

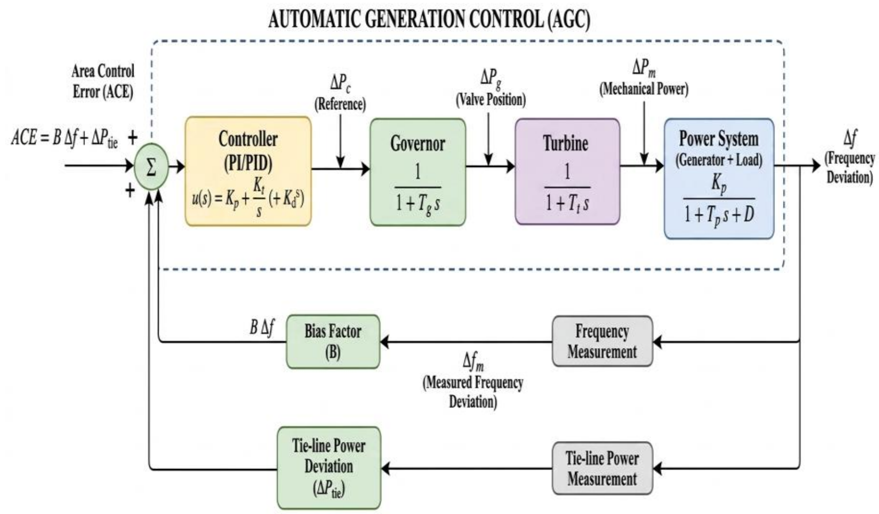

Fig. 1 Frequency regulation block diagram

Frequency-dependent performance is a serious aspect of stability for interconnected networks. LFC is the principal regulatory appliance that preserves frequency and scheduled power exchanges among areas under both routine and disturbed conditions. LFC continuously manages the output of generators as auxiliary control to manage the variations in the load. The governors are used to provide speed control, which is handled by AGC to maintain the deviation in the frequency and tie line powers. LFC is evaluated using the ACE, which is a weighted combination of frequency deviation and tie line variations. The studies over several decades have focused on refining the performance of the interconnected system. The classical control methods and tie line schemes have served as the basis for LFC architectures [10].

Various traditional methods failed due to the system nonlinearities, the uncertainty in the parameters, and the increase in the size and complexity of the modern system. A large number of techniques, including artificial neural networks, fuzzy logic, adaptive and various intelligent methods, were developed to overcome the drawbacks that the traditional controller suffered [52, 53]. These methods improved the transient state response and the steady state responses, which improved the frequency disturbances and increased the robustness of the system. Further, with the implementation of growing renewable integration, FACTS devices, microgrids, etc., the LFC implementation becomes complex. Also, due to the increased use of digital control and communication, cybersecurity has also become a critical issue.

Many studies have focused on particular aspects of load frequency control, such as soft computing and intelligent approaches, research gaps are still present. The main objective of this research is to present a thorough analysis of load frequency control strategies. They are as follows:

- A comprehensive and systematic review of LFC methodologies published between 2000 and 2025.
- Classification of LFC techniques into classical, modern, and intelligent control frameworks.
- Comparative evaluation of different control approaches using quantitative and qualitative metrics.
- Identification of key research gaps and emerging challenges in frequency regulation.
- Presentation of future research directions for next-generation smart grid control.

2. Literature Review

Early studies from 2006 to 2010 were totally focused on good decentralized control, sampling data, optimal control and conventional PID control in the context of power systems, in which frequency stability and tie-line power play a vital role. However, the studies are based on deterministic control, and the integration of other sources was not taken into consideration. Further communication delays and nonlinearity were also not considered, which led to poor system performance. From 2011 to 2015, the focus was on decentralized LFC control [13, 32], hierarchical optimal control [31], and model predictive control in a multi-area power system. These methods improved the transient response and the stability of the system. During the period 2016 to 2020, there was a strong transition towards the use of intelligent controllers, which included MPC's [41]. Predictive control, deep reinforcement learning, and renewable energy integration were developed to address the uncertainties associated with it. The methods proved to be more robust and adaptable than standard controllers, but the issues of load burden, data dependency and real-time implementation were present. From 2021 to 2025, have centered on artificial intelligence, neural networks and optimisation algorithms to control the frequency deviation in multi-area connected power systems. Despite this excellent progress, there are still a number of research barriers. The obtained results suggest there is a need for a thorough and systematic review to critically evaluate the development of LFC methods [46], identify research gaps, and suggest ways for the development of intelligent, resilient and sustainable frequency control systems. Table 1 shows a summary of some research that has been done in the field of load frequency control.

Table 1. Summary of some of the research that has been done in the field of Load Frequency Control

Year, Authors (Reference)	Control Technique	Major Contribution	Research Limitation
2007 – Ramakrishna and Bhatti [10]	Sampled-Data AGC	Developed sampled-data AGC for multi-source generation	Limited to conventional power systems
2012 – Tarek Hassan Mohamed et al. [56]	Decentralised MPC	A decentralized MPC-based LFC strategy for an interconnected multi-area power system, considering wind turbine integration, was developed.	Investigation is required for more diverse multi-source systems and advanced optimization-based MPC tuning.
2011 – Wen Tan [13]	Decentralised PI Controller	Improved decentralised LFC in multi-area systems	Ignored renewable intermittency
2012 – Bevrani et al. [37]	Intelligent Fuzzy Control	Proposed intelligent adaptive frequency control using online PSO-based fuzzy tuning	Mainly validated for microgrids and limited interconnected systems
2015 – Pourmousavi and Nehrir [55]	Demand Response-based LFC	Integrated demand response for frequency support	Mainly applicable to microgrids
2013 – Rahmani and Sadati [31]	Two-Level Optimal Control	Hierarchical optimal frequency regulation	Increased computational complexity
2013 – Padhan and Majhi [36]	PID-based LFC	Improved transient performance	Sensitive to nonlinear operating conditions
2014 – Raheel Ali et al. [25]	Coefficient Diagram Method	Improved frequency stability	Limited robustness analysis
2016 – A.M. Ersdal et al.[57]	Model Predictive Control	Developed model predictive LFC for interconnected systems while considering operational constraints	Optimization-based MPC may involve increased computational requirements.
2015 – Yi Zhang et al. [54]	Model Predictive Control	Applied MPC to LFC with wind power integration and constraint handling capability	High computational burden for real-time implementation
2017 – Ojaghi and Rahmani [41]	Predictive LFC	Addressed communication delays using predictive control	Model dependent
2018 – Alhelou et al. [14]	Comprehensive Review	Reviewed challenges and opportunities of modern LFC	Limited discussion of AI developments after 2018
2018 – Kunya and Argin [24]	MPC	Demonstrated superior dynamic response	Real-time implementation complexity
2019 – Tungadio and Sun [7]	Renewable-based LFC	Addressed renewable integration challenges	Limited AI-based comparative analysis
2019 – Kumar and Anwar [23]	Decentralized Control	Improved frequency regulation under varying operating conditions	Limited renewable penetration studies
2022 – Vafamand et al. [22]	Disturbance Observer	Enhanced disturbance rejection capability	Cybersecurity not investigated
2021 – Bagheri et al. [49]	Terminal Sliding Mode Control	Improved robustness in islanded microgrids	The chattering phenomenon remained

2022 – Gulzar et al. [12]	Review of Hybrid LFC	Comprehensive review of renewable hybrid systems	Limited implementation-oriented comparison
2022 – Shakibjoo et al.[15]	Type-2 Fuzzy Intelligent Controller	Improved transient response and robustness using intelligent fuzzy-based frequency control	Offline tuning and computational complexity
2022 – Peddakapu et al. [44]	State-of-the-Art Review	Summarised recent AGC/LFC developments	Limited critical analysis and taxonomy
2023 – Sobhanam et al. [17]	Artificial Electric Field Optimisation	Improved controller tuning using metaheuristic optimisation	Increased computational effort
2025 – Dao Huy Tuan et al. [2]	Grey Wolf Optimisation-based LFC	Demonstrated improved controller tuning and dynamic performance for modern interconnected systems	Practical large-scale implementation and real-time validation remain limited.

3. Research Gap

Based on the literature review, it is clear that the LFC strategies have been developed in the last two decades. The early work focused on PI and PID, decentralised and optimal control strategies to maintain system stability in a connected power system under various operating conditions. Despite the significant improvements, there are some important research gaps. Firstly, most of the present work focuses on controller design or optimisation, and only a few analyses are done on the whole range of LFC approaches, such as classical, robust, optimal, adaptive and hybrid controllers. Secondly, although the integration of renewable energy is a major topic of research, mostly the studies evaluate the performance of the controller under specific operating conditions and fail to consider low-inertia characteristics and large-scale interconnected power systems at the same time. Also, the communication delays, cybersecurity threats, data uncertainty and complexity have received less attention at present despite their significance in modern cyber-physical power systems. In order to address some of these issues, this review presents a comprehensive and systematic assessment of the evolution of the LFC controllers from classical to intelligent methods. This review provides a single taxonomy of LFC methodologies, comparing it with other new methods, discussing their advantages and disadvantages.

4. Key Contribution of this Work

This paper reports a detailed analysis that presents a framework that looks at the evolution of Load Frequency Control strategies. This paper put forth a which is in the form of a continuum that includes traditional PI/PID controllers through to very advanced robust, optimal and intelligent control models in the setting of very complex and renewable-rich power systems.

Also, a structured taxonomy of LFC methods, which were put into classical, adaptive, robust, optimisation-based, artificial intelligence-oriented, and hybrid categories, which at the same time allows for performance, scale, and implementation issues to be put into perspective. This study puts forth a multi-criteria decision-making framework that looks at control strategies through a quantitative as well as a qualitative lens, which includes dynamic response features, performance in variable uncertain environments, computational efficiency, and communication issues and how improved performance translates to practical field application. At present, issues like high penetration of renewables, low system inertia, nonlinear elements, communication delays, and cybersecurity issues were integrated into our analysis for a real-world look at control performance in today's environment [62]. The advanced technologies, such as HVDC systems, virtual inertia, energy storage integration, and demand side participation and what they do to improve frequency stability in the next generation grids. A note on the fact that there is a gap in high-performance control measures between theory and practice. This study focuses on central, local, and network-wide LFC systems in terms of scale and communication tradeoffs in large-scale interconnected systems.

5. Materials and Methods: Systematic Methodology

In order to guarantee transparent and repeatable selection of research papers referring to load frequency control, this study employs a systematic literature review process. The basic criteria that have been considered for inclusion of the review paper are: It is a peer-reviewed article from a journal or conference, the publication is between 2000– 2025, paper evaluates load frequency control tactics. Power system stability denotes the capability of the network to return to a steady working condition after disturbances.

The system variables are within a reasonable range in a stable system, which maintains the stability and reliability of the system. Many disturbances, such as faults, load variations, voltage collapse, etc., can make the assessment of stability quite difficult. Short-term and long-term stability are categorised by the magnitude of the disturbance over a particular time. The property of the system to uphold the synchronism among all the generators after a disturbance is caused is known as rotor angle stability. The rotor angle of the generator represents the equilibrium between the electrical and mechanical system. When the system is balanced, a sudden disturbance can cause the system to oscillate and can cause a rotor angle disturbance. The capacity to maintain the voltage within the permissible limit under disturbance is called voltage stability. Various switching events, overloads, etc. can lead to voltage variation. While long-term instability may take minutes to develop, short-term instability may appear in a fraction of a second. The capacity of the system to keep frequency within the nominal value by maintaining the generation load balance is known as frequency stability. Various protective equipment are used to separate the system if the frequency is not maintained.

6. Evolution

The various advancements in LFC for interconnected power systems have followed the control theory, which includes Root locus, Bode plots, Nyquist diagrams, etc. These methods were used in the early 1950s. These were totally based on time and frequency domain transfer function analysis on graphical methods. These methods were limited when applied to multivariable systems. However, these are best for single-input, single-output systems. Early work by Van Ness and Barcelona examined the multi-area load frequency control dynamics under disturbances using root locus and related methods.

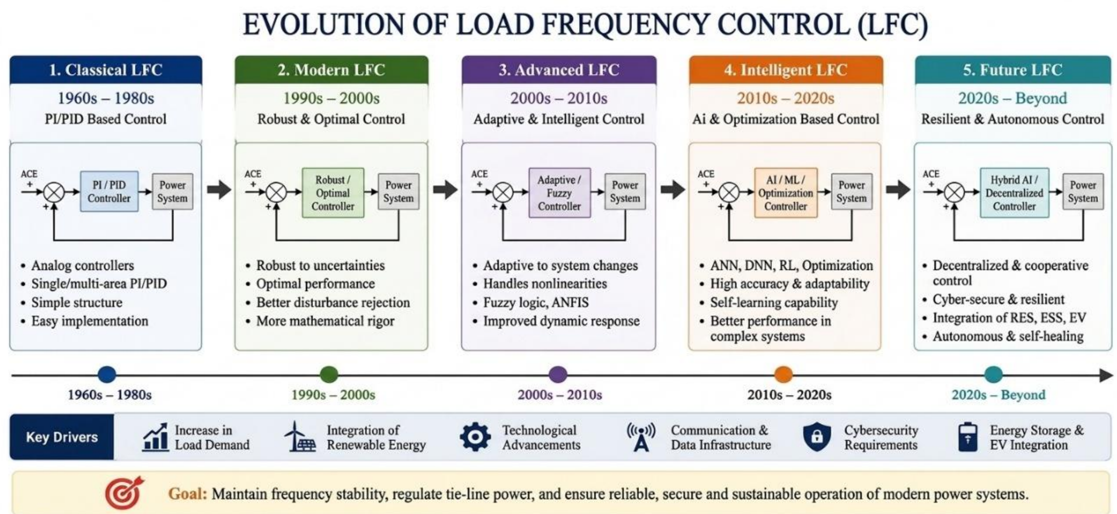

Fig. 1 Evolution and methods of LFC

The state space framework was used in the 1960s, which allows the time domain analysis of the multi-input and multi-output systems. More efficient AGC implementation and the development of linear controllers that can manage the generation rate. These methods were developed to ensure stability in large-scale linked power systems. Modern systems, which include RES, communication delays and nonlinear behaviour of the system, present various difficulties in implementing the LFC. To improve this, hybrid intelligent controllers such as sliding mode control have been presented [43, 67].

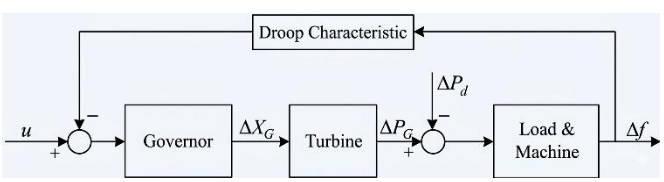

Fig. 2 Single area LFC control

The flexibility and the resilience of the system are enhanced by using energy storage technologies, including distributed battery energy storage systems [74]. Considering the complexity of the modern grids, the need for an innovative control strategy guarantees the steady operation of the system under disturbances. The evolution of the LFC is shown in Figure 2.

7. Deregulation and LFC

Power system operations have been greatly affected by the deregulation of the electricity market. Under this scheme, electricity is purchased in competitive markets where many producers compete to meet the demand of the user. The prices and service delivery are determined by the market, though the utilities frequently retain the physical assets. Due to market regulations, the independent system operators and generating firms also participate in frequency control, which presents a new challenge for load frequency control. Oscillatory responses have been linked to various nonlinear effects. In order to handle these systems working under deregulation and non-linearity, various intelligent controllers such as hybrid fuzzy PID controllers adjusted with the firefly algorithm is implemented [63, 64]. LFC formulations respect the market commitments while maintaining the frequency of system power with the help of area participation matrix, an augmented generation matrix to model between market arrangements. Hybrid systems generally include hydro, gas. Solar and energy storage elements are also now included in load frequency control.

The growing use of electrical vehicles and microgrids has also increased the operational uncertainty, making their design quite difficult [61]. In order to deal with the nonlinear interactions, communication delays, and demand fluctuations advanced control strategy including H infinity controllers, bio-inspired algorithms and model predictive control. Centralized load frequency control schemes gather a lot of information at one place, which can require a large amount of data transfer and strong computational capabilities. As a result, distributed techniques have become popular. In conclusion, to maintain the frequency regulation, load frequency control favours strong intelligent and adaptive controllers that can function under various different conditions, such as multi-source generation and renewable power integration.

8. Performance Analysis of Previous Control Strategies

8.1. LFC of Single and Multi-Area Systems

Single-area system models are generally represented by thermal plants, which are the focus of early load frequency control research. Various evaluations and investigations were conducted to provide a clear LFC structure. Time delays, GRC and GDB rates were all added in the models. To check the performance in real time, adaptive controllers were developed. For example, Riccati equation-based controllers address parameter uncertainty to improve the accuracy and performance in single-area situations. A single area system is shown in Figure 3.

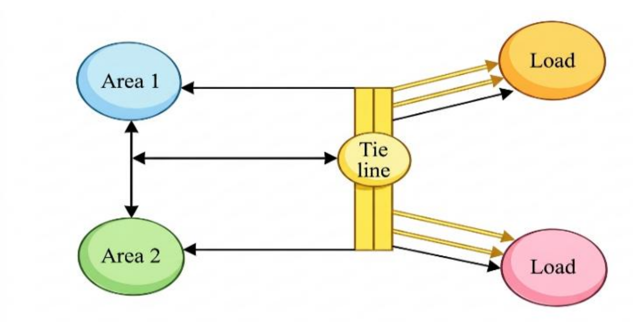

Fig. 3 Multi area interconnected system

Lyapunov theory and linear matrix inequalities have been used to study delay-dependent stability, which allows the evaluation of performance under communication delays [34]. Single-area systems evolved with the addition of RES. In order to surge the disturbance rejection of more modern techniques such as Routh and Pade approximations, two degrees of freedom IMC filters were used. The goals of predictive LFC methods are to reduce time varying conditions, parameter uncertainty and delays [41, 71].

To handle the power system interactions, LFC research expanded from the single area to a multi-area model. These multi-area models, combined with optimal linear controllers, with the stability analysis, which shows nonlinear behavior. Various research shows more detail about the turbines, plants, and GRC. When the GRC parameters are ignored, which affects the performance when compared to the optimal performance. The selection of frequency and integrator gains was developed by Lyapunov-based techniques, which shows the integrator deadbands can cause long-time oscillations in the frequency and tie line power. A multi-area linked power system is shown in the Figure 4.

To function under various conditions, sophisticated controllers were created. Optimal linear control and variable structure systems were applied to the discrete model LFC. Tie line deviations and frequency errors were considered to ACE formulations. Integral, washout and PID controllers were used in renewable integration to control the variations in active power. With multi-area hybrid power systems integrating conventional and renewable plants, they attracted a lot of attention. By managing the nonlinear evaporation and pheromone update behaviors, intelligent controllers such as fuzzy PID tuned by Ant colony optimization improved the dynamic response [45]. Coordinated control was improved by artificial intelligence and reinforced learning. Cooperative strategies for smart generation control were derived by using multi-agent reinforcement learning, which facilitated information sharing and long-term performance optimization [40].

Differential game-based controllers reduced wear on conventional units by addressing the higher regulatory requirements brought by intermittent renewal energy sources. Lyapunov Krasovski functional and LMI methods applied to PI type schemes with time varying delays, that provides an advanced stability analysis for interconnected systems. In systems where there are significant delays, robust H infinity sliding mode solutions provide frequency stabilization [42, 43]. In order to combat the denial of service attack, the researchers recognized sampled data where control commands are updated on a regular basis [58, 69]. They proposed adaptive and resilient load frequency control approaches that combine various events to secure operation while reducing communication requirements. The majority of the literature focuses on two area systems, although work on three or four areas examines the complexity and optimizes to maintain the stability and proper power sharing.

8.2. Decentralized Control

Due to the geographical distribution of large-scale power systems, centralized LFC approaches, which collect all system states in one place, are difficult because they require good connectivity and complicated data capture. Control performance can be hampered by delays in communication and redundancy, which increases the cost and complexity of the system. Observability and controllability properties of the state space have informed state space models that decouple area loops. Reduced-order observers paired with local PI regulators allow decentralized control that preserves the global performance [29]. Distributed realizations of centralized rules, model reduction, and inter-area behavior modeling support local controller synthesis. MIMO architectures and structured singular value approaches support local controller design when diagonal dominance is absent. Variable-structure methods have been applied to manage GRC and GDB nonlinearities [28, 68]. Mixed H2/H∞ decentralized controllers and μ-synthesis approaches treat inter-area interactions and contractual effects as disturbances, supporting stable independent operation.

Adaptive and model-reference decentralized controllers using only local input-output data have been effective for systems with uncertain parameters. Recent decentralized LFC extensions include demand-side resources, controllable appliances [16], PHEVs, and combined heat-and-power units often orchestrated via aggregators and MPC techniques. Decentralized SMC improves dynamics in multi-area systems with matched/unmatched uncertainties, and PI-switching surfaces enhance convergence. Aggregated V2G systems act as distributed battery storage for frequency control under variable renewables. Advances in data-driven and intelligent control have propelled decentralized LFC into Multi-Agent Deep Reinforcement Learning (MADRL), enabling decentralized deployment after centralized training [41].

8.3. Robust Control

Interconnected power systems have continuously varying parameters because of various factors such as load swings, modeling approximations and environmental changes. Each of the areas can face different uncertainties and disturbances, which cause operating points to move significantly over time. Consequently, controllers designed solely on nominal parameters may underperform or destabilize the system. Two central challenges emerged in LFC research during the 1970s: computing optimal controllers for high-order, multi-area systems, and the lack of full state measurements for optimal controller synthesis.

Early contributions tackled these issues via observer-based methods and optimal control formulations by researchers like Glover and Schweppe, and Kwatny et al., enabling observer-based compensation to attain closed-loop performance similar to fully observed designs. Given pervasive uncertainty, robust control design became a research priority. Lyapunov-based methods produced stabilizing controllers for less predictable interconnections, often using matching conditions to improve security.

Decentralized Riccati-equation-based robust controllers relying solely on local measurements were proposed to guarantee asymptotic stability despite parameter variations. FACTS devices have been recommended to enhance the damping of inter-area modes. LMI-based robust decentralized LFC techniques have been developed to offer strong disturbance rejection and uncertainty tolerance [33, 35]. Simplified, design-friendly tuning algorithms have also been proposed to reduce complexity while delivering comparable performance.

Adaptive control schemes such as Fuzzy PI adjust PI gains in real time, which is based on ACE signals to track the various system changes [72]. The intelligent and adaptive architectures use reinforcement learning to refine control actions under stochastic operating conditions [9]. Data driven reinforcement learning approaches also have been investigated for automatic generation control [9, 40]. Robust derivative action controllers, including $PIDD^2$ types, handle time-delayed interconnected systems and parametric uncertainty. Recent studies focus on high renewable and restructured systems with adaptive LFCs combining Unknown Input Observers (UIOs) and interval type 2 fuzzy controllers, which reduces frequency deviations and handles unknown disturbances in a very good manner [70].

8.4. Optimization Controllers

The large-scale use of RES and distributed techs has seen a transformation in LFC in interconnected systems [12]. The variable and unpredictable output from RES changes the generation-load balance, which in turn requires better LFC which can handle dynamic changes. Fuzzy-based LFC schemes are very much into research. Fuzzy PI controllers are favored for their easy implementation and do a great job at reducing steady state errors, although they may be on the slow side in terms of transient response; out of which have come fuzzy gain scheduling and self-tuning fuzzy PID variants. Also, these controllers are designed to take into account ACE, GRC and dead band non linearity's in to which zero steady state error and minimum tie line deviations are secured.

Distributed fuzzy control systems break down multi-area issues into local fuzzy controllers for scale [73]. Hybrid controllers, which put fuzzy logic together with genetic algorithms or neural networks, improve performance by tuning rule bases and inference mechanisms [48]. Indirect/direct adaptive fuzzy controllers change parameters to reduce approximation errors and external disturbances, which in turn gives closed-loop stability at high RES penetration. Particle Swarm Optimization (PSO) is very much into tuning membership functions, which in turn improves frequency regulation. In LFC research, ANNs and hybrid fuzzy-neural networks are popular for modeling strong nonlinearity and to adapt to operating modes [75, 76]. ANNs use parallelism and learning to do out of the best job in uncertain dynamics; also, they perform better in transient robustness when compared to classical controllers [77].

For adjusting the controller parameters, various optimization algorithms [2, 3, 26, 60, 65, 66] and hybrid optimization methods with fuzzy PID are used [21, 27]. To determine the best performance of single and multi-area systems, proper tuning of the controller parameters is required. PSO-based optimization has also been applied to tune controllers and improve frequency regulation problems [11, 17]. Classical controllers struggle with the nonlinearity and varying behavior, which requires intelligent and adaptive methods for the controller.

Combining the latest AI-based controllers with the optimization techniques moderates classical limitations, delivering robust, adaptable regulation under renewable integration, deregulation, and nonlinear dynamics for hydro governor control to improve performance [20]. Contemporary load frequency control frameworks use fuzzy logic, neural networks, hybrid controllers, and optimizers to maintain frequency deviations, stabilize tie-line flows, and improve stability in multi-area grids.

8.5. DC Links

Long-distance power transfer has been made possible by use of HVDC transmission since the late 1960s that provides both technical and financial benefits that complement the AC system. Early research examined the automated frequency control in the system, which uses DC power implementation to help stabilize the frequency response variations found in AC systems. For proper coordination of AC and DC, automatic generation control uses tie line bias control. According to a number of studies, parallel DC links can speed up transient response, especially in systems that use multi-area systems.

Intelligent resources like smart energy systems and electric vehicles are also now incorporated in the modern load frequency control models, which show better stability [19, 60]. Improved frequency restoration has been demonstrated. Thermal, hydro and gas plants are combined and used in the realistic model. To reduce the frequency deviations, higher-order and fractional-order controllers are tuned by PSO. They show better performance against the non-linearity of the system.

Voltage-source converters provide virtual inertia to a connected network [38] and supports inertia emulation control, allowing HVDC links to emulate synchronous generator dynamics and stabilize frequency under disturbances [47]. Various algorithms realize the frequency modulation without real-time synchronous signals, using generator emulation to adjust HVDC power in response to disturbances. Various significant research gaps are:

- Not enough study is done on cyber security
- Optimization control approaches have a high computational demand
- Lacks a scalable distributed LFC framework
- Limited hardware used to validate the efficacy of controller

9. Comparative Analysis

The performance, robustness, scalability, and implementation of various LFC parameters are compared in Table 2. Since classical PI and PID controllers are simple and easy, they are used in industries. They have limited robustness and are affected by parameter uncertainty. Model predictive controllers are better as they manage the parameter uncertainty and handle the disturbances. The practical application is limited, and more hybrid AI controllers can offer the best dynamic performance. The ability of LFC technologies is shown in Table 3. Classical controllers face difficulties under high RES penetration, low inertia, communication delays, and nonlinearities, while robust, intelligent, and HVDC-based controllers cope with them effectively. Communication delays are also being considered in the LFC studies for hybrid distributed generation systems [38].

High-performance optimization-based and AI controllers are useful in renewable-rich and multi-area systems, and HVDC integration offers excellent frequency regulation for low-inertia and AC/DC hybrid systems. This trade-off between performance and complexity is described in Table 4. PI/PID controllers possess low computational burden and minimal communication requirements, but are suitable for conservative and practical applications. On the contrary, MPC, ANN, and hybrid AI + optimization controllers achieve remarkable performance and learning power, but also require high computational and communication resources. HVDC and virtual inertia methods exhibit good practical performance with moderate complexity, which are both feasible solutions for contemporary grids to be considered. Table 5 relates LFC methods to system scale and architecture. Single-area traditional systems prefer simple PI or adaptive PI because of low system uncertainty, but multi-area interconnected systems have to handle inter-area dynamics by robust or decentralized H∞ methods. Deregulated markets and renewable-based grids use decentralized, intelligent, or optimization-based controllers for dealing with stochastic generation and market limitations. For the given controller complexity, the high-performance approaches are impractical. The importance of adaptive learning is highlighted that AI-based controllers depend on offline training.

To connect simulation-heavy studies to practical application, validation and field testing are critical. Similar performance measures were reported by Table 7 across various controllers. Classical PI and PID controllers show moderate settling times and frequency overshoot with acceptable steady-state error at low RES conditions. In contrast, robust, MPC, ANN, and hybrid AI controllers exhibit minimal settling time, very low overshoot, and near-zero steady-state error, resulting in superior dynamic performance. HVDC and virtual inertia schemes both produce excellent frequency response and better system stability in low-inertia grid systems. Table 8 reviews the literature on LFC methods in different system configurations. Single-area LFC is concerned with providing frequency stability in isolated systems with low complexity, while multi-area and decentralized control concern inter-area coordination and local autonomy. Robust and optimization-based controllers improve performance under uncertainty and RES variability, while HVDC and AC/DC hybrid LFC strategies achieve fast power modulation, superior transient response, and improved inertia support.

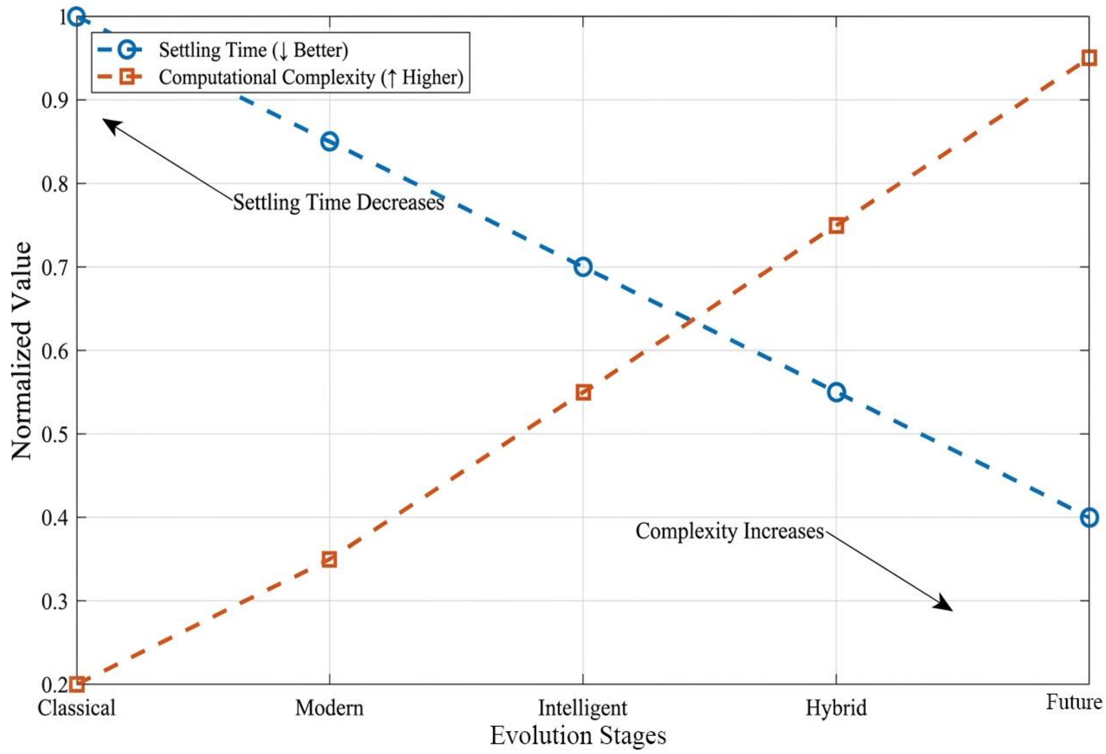

Fig. 4 Performance trend in evolution of LFC

Table 2. The comparison of LFC control paradigm based on performance and practicality

Control Paradigm	Dynamic Performance	Robustness to Uncertainty	Scalability	Implementation Complexity	Practical Deployment Readiness
Classical PI / PID	Moderate; slow settling under high RES	Low (parameter-sensitive)	Low–Moderate	Very Low	High (widely used in industry)
Adaptive PI / Gain Scheduling	Improved transient response	Moderate	Moderate	Low–Moderate	High
Robust Control (H∞, LMI-based)	Good disturbance rejection	High	Moderate	High	Medium
Sliding Mode Control (SMC)	Fast response, minimal overshoot	High (matched uncertainty)	Moderate	High (chattering issue)	Low–Medium
Model Predictive Control (MPC)	Excellent constraint handling	High	Low–Moderate	Very High	Low
Fuzzy Logic Controllers	Good nonlinear handling	Moderate	Moderate	Moderate	Medium
ANN-based Controllers	Strong nonlinear adaptability	High (after training)	Moderate	High (training burden)	Low
Hybrid AI Controllers (Fuzzy–ANN)	Very High	High	Moderate	Very High	Low
Optimization-Based Controllers	High (depends on optimizer)	Moderate–High	High	High	Medium

Table 3. Analytical strategies of LFC under modern power system

Power System Challenge	Classical Controllers	Robust Control	Intelligent Control	Optimization-Based	HVDC-Based LFC
High RES Penetration	Poor	Moderate	Excellent	High	Excellent
Reduced System Inertia	Ineffective	Moderate	High	High	Very High
Communication Delays	Poor	Good	Moderate	Moderate	Good
Parameter Uncertainty	Poor	Excellent	High	High	Moderate
Nonlinearities (GRC, GDB)	Poor	Good	Excellent	High	Moderate
Cyber Attacks (FDI, DoS)	Vulnerable	Moderate	High (with detection)	Moderate	High
Multi-area Coordination	Limited	Good	High	Excellent	High

Table 4. Performance and complexity LFC analysis

LFC Technique	Performance Gain	Computational Burden	Communication Requirement	Overall Trade-Off
PI / PID	Low	Very Low	Minimal	Balanced, conservative
Robust H∞ / LMI	Medium–High	High	Moderate	Performance-oriented
MPC	Very High	Very High	High	Performance at high cost
Fuzzy Control	Medium–High	Moderate	Moderate	Practical nonlinear solution
ANN / Deep RL	Very High	Extreme	High	Research-focused
Hybrid AI + Optimization	Maximum	Extreme	High	Not yet industry-ready
HVDC / Virtual Inertia	High	Moderate	Moderate	Promising practical solution

Table 5. Analytical correlation of LFC methods to system scale and architecture

System Type	Most Suitable LFC Methods	Analytical Justification
Single-Area Conventional	PI, Adaptive PI	Simple dynamics, low uncertainty
Multi-Area Interconnected	Robust PI, Decentralized H∞	Inter-area coupling and uncertainty
Deregulated Power Systems	Decentralized MPC, Optimization-Based	Market constraints and autonomy
Renewable-Dominated Grids	Intelligent + Optimization	Stochastic generation
Low-Inertia Microgrids	Virtual Inertia, ANN, MPC	Fast dynamics, weak frequency response
AC/DC Hybrid Systems	HVDC-based LFC, Fractional Controllers	Fast power modulation capability

Table 6. Research gaps and future directions

Research Aspect	Current Limitation	Analytical Research Need
Controller Complexity	High-performance methods impractical	Reduced-order intelligent control
Cyber-Resilient LFC	Mostly attack detection only	Integrated control + defense design
AI-Based LFC	Offline training dependency	Online learning with stability proof
Optimization Methods	High tuning time	Real-time adaptive optimization
HVDC-Based LFC	High infrastructure cost	Coordinated AC–DC decentralized LFC
Validation	Simulation-heavy studies	Hardware-in-the-loop & field tests

Table 7. Comparative performance metrics of LFC controllers (analytical perspective)

Controller Type	Settling Time	Frequency Overshoot	Frequency Nadir / ROCOF	Steady-State Error	Overall Dynamic Quality
Classical PI	High	Moderate–High	Poor (large nadir)	Zero	Acceptable only for low RES

Classical PID	Moderate	Moderate	Poor–Moderate	Zero	Improved over PI
Adaptive PI	Moderate–Low	Reduced	Moderate	Zero	Better adaptability
Robust H∞ / LMI	Low	Low	Good	Zero	Strong robustness
Sliding Mode Control	Very Low	Very Low	Excellent	Zero	Fast but chattering risk
MPC	Very Low	Very Low	Excellent	Zero	Best constraint handling
Fuzzy PI / PID	Moderate	Low	Moderate–Good	Near zero	Nonlinearity tolerant
ANN-Based	Low	Very Low	Excellent	Near zero	Learning dependent
Hybrid AI (Fuzzy-ANN)	Very Low	Minimal	Excellent	Zero	Superior but complex
HVDC / Virtual Inertia	Very Low	Very Low	Best	Zero	Ideal for low inertia

Table 8. Comparative analysis in detail from literature

Aspect	Single-Area LFC	Multi-Area LFC	Decentralized Control	Robust Control	Optimization & Intelligent Control	DC Link / HVDC-Based LFC
Primary Objective	Maintain frequency stability in isolated systems	Regulate the frequency and power between interconnected systems	Achieve local control with minimal inter-area communication	Ensure stability under uncertainties and disturbances	Enhance dynamic performance under RES variability	Improve frequency response and power sharing using DC links
System Complexity	Low to moderate	Moderate to high	High (distributed & large-scale systems)	High (uncertainty-driven design)	Very high (AI + optimization)	Very high (AC/DC hybrid systems)
Early Models	Thermal units with simple PI control	Two-area nonlinear stochastic models	Decoupled state-space models	Optimal control & observer-based methods	Classical PI/PID tuning	AFC and Tie-Line Bias Control (TBC)
Key Dynamics Considered	GRC, delays, multi-source (thermal, hydro, gas)	GRC, reheat turbines, tie-line power, ACE	GRC, Governor Dead Band (GDB), inter-area effects	Parametric uncertainty, delays, and nonlinearities	RES intermittency, nonlinear load-generation balance	PLL dynamics, DC converter delays, inertia emulation
Control Strategies	PI/PID, adaptive PI, IMC, prediction-based	PI/PID, variable structure, cooperative control	Local PI, reduced-order observers, MIMO	H∞, sliding mode, Riccati-based	Fuzzy, ANN, hybrid AI controllers	Differential feedback, fractional-order controllers
Advanced Control Methods	IMC with Padé & Routh, DR integration	MARL, differential games, cooperative control	µ-synthesis, MPC, decentralized SMC	Lyapunov–Krasovski, LMI-based design	PSO, GA, ACO, hybrid PSO–GA	INEC, virtual inertia, VSC-HVDC control
Handling of Delays	Stability boundary locus, LMIs	L-K functionals, delay-dependent LMIs	Event-triggered communication	Delay-robust observers & controllers	Adaptive optimization under delay	Modeled PLL and communication delays
Renewable Integration	Limited (mostly	Extensive (wind, solar,	Demand-side resources,	Robust design for	Core focus of optimization-	HVDC supports RES via fast

	modeling extensions)	hybrid systems)	V2G, EVs	high-RES uncertainty	based schemes	power modulation
Cybersecurity Considerations	Resonance attacks studied	DoS attacks and resilient LFC	Reduced vulnerability due to locality	Secure observer-based architectures	Learning-based controllers with resilience	Local AFC reduces cyber-attack exposure
Performance Strengths	Simple, intuitive, foundational	Accurate real-world modeling	High reliability, scalability	Guaranteed stability under uncertainty	Fast response, minimal overshoot	Superior transient response & inertia support
Performance Limitations	Not scalable to large systems	High computational & communication demand	Possible suboptimal global coordination	Design complexity	High computational cost, tuning burden	High cost, modeling complexity
Optimization Role	Limited (PI tuning)	Moderate (controller gain tuning)	Moderate (local optimization)	Low (stability-focused)	Core component (PSO, GA, ACO)	PSO-tuned fractional controllers
Typical Applications	Educational models, initial studies	Regional interconnected grids	Deregulated, large-scale systems	Uncertain and time-varying systems	High-RES penetration grids	Long-distance, hybrid AC/DC networks
Scalability	Low	Moderate	High	Moderate	High (with decentralized learning)	High (multi-terminal HVDC)
Future Trends	Benchmarking & validation	Multi-agent & resilient control	Data-driven decentralized AI	Adaptive robust observers	Hybrid AI–optimization frameworks	Virtual inertia & grid-forming HVDC

10. Conclusion

This study presented a broad review of the evolution of the LFC strategies in modern interconnected systems. This study examined the progression of control approaches from classical controllers to advanced optimal, robust and intelligent control methods. Classical controllers are extensively used due to their simplicity and ease of application. However, their performance is often limited under highly nonlinear and uncertain operating conditions. Advanced strategies such as MPC, FOC and adaptive control methods have shown improved dynamic response. Robust performance to parameter variations and improved disturbance rejection is reported. The intelligent control methods, which include fuzzy logic, artificial neural networks and optimization algorithms, have very great promise in weeding out the issues presented by today's power systems. In regard to the reduction of frequency fluctuations in low inertia systems, technologies like energy storage, virtual inertia and HVDC interconnections are at very forefront. Furthermore, new cyber security flaws in automatic generation control systems are brought by the increasing reliance on the communication networks. The computational complexity of sophisticated algorithms, model dependency, stability guarantee for learning-based controllers are some of the issues that still need to be resolved despite significant advancements. Thus, the future work will concentrate on creating scalable, effective and cyber secure load frequency control that are verified by real world testing.

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