# A Critical and Comparative Review of Load Frequency Control Topologies and Control Techniques

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***Abstract*- The most complicated systems ever developed by mankind are power systems. There must be numerous control loops present for such systems to function in a stable state. Voltage frequency is a crucial component of power systems that must be carefully managed. In order to do this, main and secondary frequency control loops are used in power systems to regulate the frequency of the voltage. After a disturbance, secondary frequency control, also known as load frequency control (LFC), is in charge of keeping the frequency at a suitable level. The power transfers between various control zones are also governed by LFC strategies. Numerous control strategies have been proposed in recent decades for LFC in power systems. This essay provides a thorough review of the literature on LFC. In this study, the commonly utilized LFC models for various power system topologies are first explored and categorized for both current and foreseeable smart power systems. Additionally, the suggested LFC control mechanisms are examined and divided into several control groups. The research gaps and new research directions in the area of LFC are highlighted in the paper's conclusion.**

***Keywords:* Load Frequency Control, Distributed Energy Resources.**

## I. INTRODUCTION

We are aware that since consumer load and industrial load are always changing, a power system's active and reactive power needs are never constant. Therefore, input supply, such as steam input to turbogenerators or water input to hydro generators, must be carefully controlled; otherwise, machine speed might vary, leading to a change in frequency, which is extremely undesirable in the functioning of the power system. Although it is theoretically feasible to achieve zero frequency change, this is not practical. There is therefore a maximum fluctuation in frequency that is allowed. The customer will suffer as a result of larger frequency variations, which might also severely harm the industry's expensive equipment. Today, nature's systems are all interrelated. So any issue with the electricity system is really an issue with many systems. Thus, keeping frequency consistent is a very difficult problem.

Manual regulation is ineffective in a contemporary, vastly networked system, necessitating automated digital control, which has its own set of issues including communication lags. The frequency variances necessitate the creation of a controller that is reliable and, most significantly, simpler in nature. Because of its simplicity, obvious functioning, and usability, PID controllers are still used in more than 90% of sectors. However, many control specialists argued that a PID controller adjusted using traditional methods was not reliable. Advanced control methods such sliding mode control, H-infinity, quantitative feedback theory (QFT), linear matrix inequality (LMI)-based approaches, etc. were thus required. Although it first seemed like these strategies were superior than PID control designs, it has now been shown that these controllers are complicated and have difficulties with resilience in unpredictable environments. The researchers felt there was a need to integrate the ease of PID controllers with optimum tuning methods due to the widespread usage of PID and the shortcomings of optimal control techniques. It was shown that a controller of this kind produces superior results when dealing with parametric uncertainties, disturbance rejection, and nonminimum phase behavior. This article provides a succinct overview of several PID-based control systems. This paper's primary goal is to compile the numerous controller approaches for the LFC issue that have recently been put forward.

## II. MOTIVATION

Numerous media have commented on the rising frequency of power system outages seen in recent years. For instance, there were blackouts in Brazil in 1999, the Northeastern United States and Canada in 2003, and Russia in 2005. In reality, it was just in July 2012. With over 620 million affected, or 9% of the world's population, India had the greatest power outage in history. The load frequency must be consistent in order to prevent these problems. The functioning of the power system may be directly impacted by the frequency variation. Large deviations have the potential to harm equipment, degrade load performance, interfere with different power system protection plans, and even result in system failure. Therefore, it's critical to maintain the system frequency within the acceptable tolerance range. Effective robust control mechanisms are required in order to address the challenges brought on by frequency changes, as they may enhance both the system's performance and security. The PID type controller is considered to be the most significant and straightforward controller to solve these challenges. Therefore, it is necessary to investigate several PIDs and their variations, including two-degree freedom PID type controllers. PID controller with fractional order. PID controller with an IMC, etc. Making PID a robust controller that can manage parametric uncertainty, disturbance rejection, the impact of noise, and the impact of communication latency is also necessary.

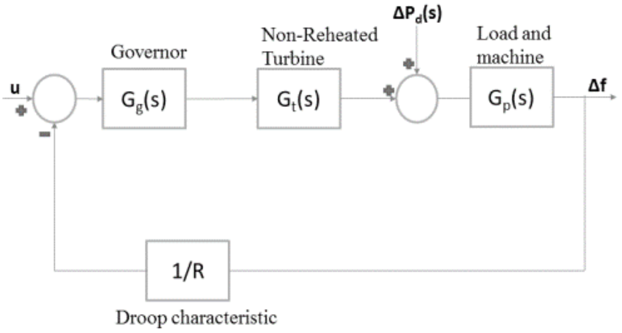

Fig. 1. Linear model of a single-area power system

## III. SURVEY ON DIFFERENT LOAD FREQUENCY CONTROL (LFC) TOPOLOGIES AND STRUCTURES

In this section, the term "conventional power systems" refers to an electric power system where the electricity is produced using fossil fuels. In fact, the most well-known power plants for these systems are thermal, hydroelectric, and nuclear generating units. Power systems are often split into single-area, two-area, three-area, and four-area power systems according to their size. A thorough assessment of the power systems models for LFC is provided in the following subsections. Several frequency response models for LFC are offered in the literature.

### 3.1. Single-Area Power Systems

The design and implementation of load frequency controllers for single-area power systems is the subject of the first research on frequency control. The literature [1,2] examines a number of single-area power system models that use LFC control techniques. Single-area power systems made up of thermal power plants are denoted in [1-3]. [4] discusses a dynamic mathematical model of frequency response for single-area power networks. For power systems with several energy sources, such as hydro, gas, and thermal sources, single-area frequency response models are described in [5]. A well-described frequency response model of electric power networks made up of hydropower plants is presented in [6]. [5] proposes an autonomous generation control system for hydro power stations that takes into account certain nonlinearities. [3] provides an illustration of the relationship between active and reactive power regulation and how it affects LFC models of single-area power systems.

### 3.2. Dual-Area Power Systems

In two-area power systems, an overview of LFC and AGC systems is provided in [7]. [7] studies tie-lines models and their impacts on the LFC of two-area power systems. The LFC models for two-area power systems that take into account the frequency response's impacts of voltage control loops are developed in [8]. [9] suggests frequency response models for two-area power systems that take into account the nonlinearities of the generation rate constraints (GRC) and the governor dead-band (GDB). [10] presents a discussion on how to simplify the frequency response model by reducing its complexity. The multi-source, two-area LFC models that take nonlinearities into account are highlighted in [11]. LFC models of two-area power systems with parametric and nonparametric uncertainties are discussed in reference [10]. In [12], an LFC method for two connected power systems that use HVDC/DC transmission lines is presented. [12] presents two-area power system frequency response models made up of reheat-thermal turbines linked by AC/DC cables. [8,13] proposes load frequency management techniques for thermal-thermal two-area power systems that take communication channel delay into consideration. [8] sketches out a frequency model for a reheat thermal turbine with a governor dead-band zone in two area power systems. For the reheat thermal turbine-governor system in two-area power systems, GRC non-linearity is taken into account in [14]. The LFC approach for hydro-hydro linked power systems taking into account the non-linearities of hydro power plants is suggested in [15]. Superconducting magnetic energy storage (SMES) system LFC models for two-area power systems are suggested in [16]. [17] describes a frequency control model for two-area power systems that takes into account the contribution of batteries and SMES. LFC model of traditional two-area power networks coupled with involvement of electric vehicles and energy storage devices is proposed in reference [18]. In [19], the stochastic nature of the electrical demand is taken into account. Uncertainties related to renewable energy sources are included for the LFC model in [20].

### 3.3. Three-Area Power Systems

[21,22] offer studies on LFC modeling for three-area linked power systems. A LFC model for a three-region linked power system is provided in [50], where steam-hydro power plants are taken into account in the first and second areas while a steam power plant is the sole source of energy in the third area. Three control areas of a thermal power system are investigated in [23]. In three-area linked power systems, radial and ring connections between the various control areas are explored in [24]. [25] presents an LFC model for a three-area power system that takes GDB and GRC nonlinearities into account. [26] investigates how communication channel latency affects LFC in three-area linked power systems. The effects of parametric uncertainty on LFC of three-area linked power systems are highlighted in references [27]. Three-area thermal power systems frequency response model is developed in [28]. The LFC for hydropower systems with three areas is shown in [25]. A three-area hydrothermal power system is constructed using load frequency controllers [21]. [29] proposes the LFC for multi-source power systems that take into account thermal, gas, and hydro energy sources.

### 3.4. Four-Area Power Systems

To keep the frequency within a permitted range, large power systems are often separated into various control regions. [30] presents LFC difficulties in four-area linked power systems. Malik et al. in [31] present an LFC for four-area linked hydro power systems as the first effort in this sector. [32] introduces frequency response models for LFC-compatible four-area linked power systems. In [33], an LFC model for linked power systems with nonlinearities like GDB and GRC is taken into account. Using a fuzzy control for an LFC model, the uncertainties of the power system characteristics are taken into account in [34]. [35] presents a four-area linked power system with various energy sources and turbines, including hydro, gas, non-reheat thermal, and reheat thermal power plants. It is suggested in [37] to link four thermal power areas together using various connection architectures, such as longitudinal and ring connections, with each area consisting of three thermal units and one hydro unit. [38] presents the LFC for a three-area system with reheat thermal units linked to a second hydro control area by a tie-line.

## IV. BRIEF REVIEW OF PID BASED CONTROL TECHNIQUES USING SOFT COMPUTING

The Computational Intelligence (CI) family, which includes a large variety of cutting-edge heuristic search strategies drawn from mostly four fields including mathematics, biology, physics, and chemistry, includes soft computing approaches. Bo Xing (2014) lists 134 such strategies in all. The Big Bang Big crunch algorithm (BBBC), Firefly algorithm (FFA), Base optimization method, and the Genetic algorithm (GA) are a few of the well-known and often used ones. They get around the issues encountered in the conventional optimization methods by combining randomization, tolerance for uncertainty, and inductive reasoning. Researchers have also used them in the adjustment of PID parameters in LFC problems due to their many benefits. Due to its greater flexibility than a traditional PID controller, Kumar et al. (2017) used the BBBC algorithm to tune the parameters of a fractional order PID controller, whereas Yesil (2014) used the same algorithm to tune the scaling factor and footprint of uncertainty (FOU) for the membership functions of an interval type-2 fuzzy PID controller. While Jagatheesan et al. (2017) utilized FFA to optimize the settings of a PID controller and compared the results with GA and PSO, Dhillon et al. (2015) used a combination of fuzzy based inferences and the PSO method to effectively tune a PID controller for a five area LFC model. In Ahuja et al. (2014), a single area non-reheated type power system is given a resilient FOPID controller using the PSO algorithm. In Zamani et al. (2016), the authors combined the benefits of fractional order and Gases Brownian Motion Optimization (GBMO) to design a FOPID controller while taking into account the governor's saturation limits, whereas in Sahu et al. (2013), differential evolution (DE) is used to design a 2-degree of freedom PID controller for a realistic power system that incorporates the effects of physical constraints like time delay and generation rate constraints. The authors used a modified objective function that is derived by using weighted integral time absolute error (ITAE), damping ratio of dominant eigenvalues, settling times of frequency, and peak overshoots. Additionally, the superiority of the proposed approach is demonstrated by comparison of the results with Craziness based PSO (CPSO) for an interconnected two area thermal system. Debbarma et al. (2015) introduce a two degree of freedom based proportional integral double derivative (PIDD) controller for a three unequal area thermal system, and it is discovered to be resilient for large changes in the location of step load perturbation (SLP). In Guha et al. (2016), an LFC problem is solved for the first time using a novel optimization technique known as the quasi-oppositional grey wolf optimization algorithm (QOGWO), and the outcomes are evaluated in comparison to those of other intelligent techniques like fuzzy logic, artificial neural networks (ANN), and adaptive neuro-fuzzy interface systems (ANFIS). To further explore the resilience in an unpredictable environment, sensitivity analysis is conducted. In addition to the methods listed above, Yesil et al. (2014), Abdelaziz and Ali (2016), Abdelaziz and Ali (2015), and El-Hameed and El-Fergany (2016) also explain other soft computing-based methods for the LFC issue.

Due to its benefits, evolutionary computing-based control system design has attracted a lot of interest from academics over the last 10 years. The well-known benefits of using soft computing techniques include their low solution costs, assurance of a solution, and their viability. They can deal with difficult, nonlinear, and unpredictable technological problems. In contrast to other approaches, several research have shown the viability of control systems based on soft computing methodology. The load frequency controllers' settings have been optimized using soft computing approaches in order to obtain excellent control and dynamic system performances. To best tune the gains of the controllers, for instance, a variety of evolutionary optimization techniques have been used. Genetic algorithm (GA) has been suggested as a potential approach for tackling the LFC issue and other power system problems as the first study on this subject in [39]. In [40], GA for AGC in hydro-thermal power systems has also been proposed. Similar to this, GA is utilized in power systems for LFC fuzzy controller gains as well as controller tweaking. In order to solve the LFC issue in linked power systems, particle swarm optimization (PSO), which is based on population and inspired by the cooperative behavior of fish schooling or bird flocking, is often utilized. In [41], PSO is used to tackle the LFC issue in single-area power systems. Similar to this, PSO has addressed the LFC issue in linked power systems with different sources, including thermal, hydro, and gas turbines, in [42]. In [43], hybrid PSO strategies including additional soft computing techniques are also suggested for LFC. Recently, various freshly suggested soft computing techniques addressing the LFC issue in both traditional and contemporary power systems have been created. For instance, LFC in connected power systems has been optimized using the differential evolution (DE) algorithm [44], firefly algorithm (FA) [45], bacterial foraging optimization (BFO) [46], artificial bee colony (ABC) [47], grey Wolf Optimizer algorithm [48], and wind driven optimization algorithm [49].

## V. OBJECTIVE FUNCTIONS AND OPTIMIZATION FORMULATION

When a disturbance occurs in an interconnected power system, load frequency controllers should accomplish two basic tasks: (i) reset the steady state frequency to zero; and (ii) keep the transferred power at the predetermined levels. Load frequency controllers should be adjusted properly to meet these objectives. To this goal, the optimization issue of LFC in linked power systems may be formulated using a variety of objective functions. The major objective of LFC is to reduce frequency and tie-lines power flow irregularities, which enhances the operation, control, and stability of the power system [49]. Area control error (ACEi) is often utilized as an index as follows to lessen the deviation:

$$\begin{aligned} &ACE_i = \Delta P_i + \beta_i \Delta f_i \\ &\text{where } \beta_i = D_i + \frac{1}{R_i} \end{aligned} \qquad (1)$$

where fi is a measure of frequency deviation in p.u., Pi is a measure of power flow deviation in p.u., i is a measure of frequency bias, Ri is a measure of governor droop, and Di is a measure of power system damping. To further help the LFC decision maker accomplish its objectives, various indices like settling time, overshoot, and oscillation damping improvement may be included into the proposed objective function. To get the optimum LFC performance, soft computing approaches must first be employed effectively with the right goal function. The frequency error and tie-lines power have been included in the objective functions using various criteria that have been proposed in the literature. The most crucial factors considered when constructing load frequency controllers are the integral of absolute error (IAE), integral of time multiplied by absolute error (ITAE), integral of squared error (ISE), and integral of time multiplied by squared error (ITSE) [50, 51, 52, and 53]. Based on the aforementioned requirements, the following are the typical objective functions used in literature to tune load frequency controllers [49]:

$$J_1 = IAE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left( \alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right) \times dt \qquad (2)$$

$$J_2 = ISE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left( \alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right)^2 \times dt \qquad (3)$$

$${}_3 = ITAE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left( \alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right) \times t \times dt \qquad (4)$$

$$J_4 = ITSE = \sum_{i=1}^{NA} \left( \alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right)^2 \times t \times dt \qquad (5)$$

The weights for transmitted power error in each tie-line (ij) and frequency error in each region (i) are taken into account. The proper weights are utilized in the object functions whenever the frequency deviation and/or transmitted power deviation in certain locations and/or tie-lines are more essential than others [49].

In order to achieve the power balance as quickly as feasible, the goal function provided in Equation (6) that takes into account the damping of frequency oscillations and the settling times of both frequency error and tie-lines error has recently been developed

$$\begin{aligned} J_5 = {} & \omega_1 \sum_{i=1}^{NA} \int_0^{t_{sim}} \left( \alpha_i \Delta f_i(t) + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \Delta P_{tie_{i-j}}(t) \right) \times t \times dt + \omega_2 \frac{1}{\min\left( \left\{ (1 - \zeta_i),\, i = 1 \ldots n \right\} \right)} \\ & + \omega_3 \left( \sum_{i=1}^{NA} \left( ST(\Delta f_i(t)) + \sum_{\substack{j=1 \\ j \neq i}}^{NA} ST(\Delta P_{tie_{i-j}}(t)) \right) \right) \end{aligned} \qquad (6)$$

for LFC [50].

The moment the final value of the signal settles to less than 0.00001 is referred to as the settling time (ST) [50]. Each term's weight () in the objective function should be chosen such that its significance is taken into account in the overall objective function [49].

## VI. CONCLUSION

The state of the art for load frequency management in power systems is discussed in this study. Frequency response mathematical models of various power system types, such as conventional and smart systems, are thoroughly evaluated due to their significance. Additionally, many smart system models are denoted, including distributed generation, micro-grids, and smart grids. Modern power systems with significant renewable energy resource penetration are also denoted. Additionally, both traditional control strategies and adaptive control techniques are thoroughly reviewed. In addition, contemporary control techniques including load frequency management in power systems are discussed, as well as optimum control theory, resilient control, and soft computing-based control technology. Finally, a few research directions and gaps are provided in the area of contemporary load frequency control systems.

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