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A Review On Frequency Stability Control In Multi-Source Interconnected Power Systems

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Abstract- The increasing integration of renewable energy sources (RES) in modern power systems has introduced new challenges in maintaining frequency stability due to their intermittent and uncertain nature. Multi-source interconnected power systems (MSIPS) consist of a mix of conventional and renewable generation, requiring advanced control strategies for effective frequency regulation. This paper reviews various frequency stability control techniques, focusing on Automatic Generation Control (AGC) strategies, optimization-based controllers, and artificial intelligence (AI)-driven approaches. The effectiveness of Particle Swarm Optimization (PSO)-tuned Proportional-Integral-Derivative (PID) controllers, Fuzzy Logic Controllers (FLCs), and Neural Network-based controllers is analyzed in mitigating frequency deviations. Furthermore, the impact of energy storage systems (ESS), demand-side management (DSM), and hybrid optimization methods on frequency stability is explored. The review also highlights multi-area system considerations, robustness testing, and sensitivity analysis of various control methods. Finally, a comparative assessment of recent advancements is presented to provide insights into the future of frequency stability control in multi-source power networks.

***Index terms*- Load frequency control, renewable energy systems, multi-area power system, optimization algorithms, artificial neural networks.**

I. INTRODUCTION

Modern, linked power systems' main area of concern is power system stability. It is referred to as a power system's capacity to stabilise itself following the elimination of disruptions. While an unstable system loses control through desynchronizing, this event could have a disastrous effect on how well the power system functions. Maintaining synchronism between various components of the power system is a significant task for power system engineers as stability considerations have become an inherent aspect of the design of a dependable system [1]. Electricity must be produced in accordance with load side demand while also taking losses into account. A stable power system runs within a defined region, and various external factors may cause the power system's nominal frequency to diverge to an unstable region [2].

Two control loops—one primary and the other secondary—are used in contemporary power systems to regulate frequency [3]. The first one is in charge of stopping the frequency transients caused by governor droop that can cause steady state error [4]. The second approach, sometimes referred to as automatic gain control or load frequency control, has the potential to maintain a consistent level of system frequency regulation. In the beginning, load frequency management was achieved using traditional PID controllers; however, as research progressed, intelligent controllers, fuzzy controllers, sliding mode controllers, and tilt integral derivative controllers were created. A more effective real-time control of the power system is provided by a modern controller architecture based on sliding mode control and adaptive control pattern. To enhance performance, more study is being done on support vector machine-based controllers and brain emotional learning-based intelligent controllers.

Modern power systems are evolving into complex, multi-source interconnected networks integrating conventional power generation (such as thermal, hydro, and nuclear) with renewable energy sources (such as solar, wind, and biomass). While this diversification enhances sustainability and energy security, it also introduces significant challenges in maintaining frequency stability due to the inherent variability and intermittency of renewable sources. Frequency stability is a crucial aspect of power system operation, ensuring the continuous balance between power generation and demand. Any deviation from the nominal frequency can lead to cascading failures, reduced system reliability, and even large-scale blackouts.

In multi-source interconnected power systems, frequency stability is influenced by several factors, including load variations, generator inertia, control system response, and disturbances such as sudden load changes or generation losses. Traditional frequency regulation methods, such as governor control and automatic generation control (AGC), are often insufficient in handling modern grid complexities. This necessitates advanced frequency control strategies that leverage optimization techniques, intelligent control methods, and fast response mechanisms.

The integration of renewable energy sources further complicates frequency stability due to their low inertia characteristics and unpredictable fluctuations. To address these challenges, various control approaches, such as adaptive control, predictive control, fuzzy logic-based controllers, artificial intelligence (AI)-driven techniques, and robust optimization methods, have been explored in recent research. Additionally, energy storage systems, demand response programs, and flexible AC transmission systems (FACTS) play a vital role in enhancing frequency stability in interconnected grids.

This review paper aims to provide a comprehensive analysis of frequency stability control strategies in multi-source interconnected power systems. It explores conventional and modern control approaches, their effectiveness, and their applicability in real-world scenarios. The paper also discusses the role of optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Machine Learning-based approaches in improving frequency stability. Moreover, emerging trends and future research directions are highlighted to address the growing complexity of frequency regulation in evolving power networks.

By synthesizing recent advancements and identifying key challenges, this review contributes to the ongoing efforts to develop resilient and efficient frequency control mechanisms, ensuring the stability and reliability of future power systems.

II. Literature Review

2.1 Challenges in Frequency Stability of Multi-Source Power Systems

Traditional power systems relied on synchronous generators with high inertia, which naturally helped in frequency stabilization. However, with the integration of RES such as wind and solar photovoltaic (PV) systems, the overall system inertia has decreased, leading to more frequent and severe frequency deviations [1]. Other challenges include:

- Uncertainty and variability in RES output [2].

- Delayed response in primary and secondary frequency control loops [3].

- Limited participation of RES in frequency regulation due to their power electronic interfaces [4].

- Cyber-physical security concerns in smart grids affecting frequency stability [5].

3.1 Frequency Control Strategies

Various techniques have been proposed in the literature to enhance frequency stability in interconnected power systems with multiple energy sources.

3.1.1 Primary Frequency Control

Primary frequency control is the first line of defense against frequency deviations, traditionally handled by synchronous generators through governor control. In RES-dominated systems, synthetic inertia from power electronic converters and energy storage systems (ESS) has been explored as an alternative [6].

- Virtual inertia-based control methods allow RES to emulate the inertial response of conventional generators [7].

- Droop control strategies for inverter-based resources (IBRs) help distribute frequency regulation responsibilities among different sources [8].

3.1.2 Secondary Frequency Control

Secondary control, or automatic generation control (AGC), restores the frequency to its nominal value after primary control stabilizes it. Advanced techniques for secondary control include:

- Model Predictive Control (MPC) to optimize frequency response dynamically [9].

- Adaptive and intelligent controllers such as Fuzzy Logic and Artificial Neural Networks (ANN) for enhanced AGC performance [10].

- Optimization-based AGC methods using Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) to improve response time and reduce frequency deviations [11].

3.1.3 Tertiary Frequency Control

Tertiary control optimizes power system operation by managing the economic dispatch of generators while ensuring system stability. Methods in this domain include:

- Demand Response (DR) techniques for frequency regulation through controllable loads [12].

- Hybrid energy management systems integrating storage with RES for coordinated frequency support [13].

- Decentralized and distributed control strategies leveraging multi-agent systems (MAS) for enhanced resilience and scalability [14].

4.1 Role of Energy Storage Systems in Frequency Stability

Energy storage systems, such as batteries, flywheels, and supercapacitors, play a vital role in frequency stability by providing fast-acting frequency support.

- Lithium-ion battery storage has been widely studied for its rapid response and high efficiency in frequency regulation [15].

- Supercapacitors and flywheels offer high-power density solutions for short-term frequency fluctuations [16].

- Hybrid storage systems combining batteries and supercapacitors provide a balance between power and energy density for optimal frequency control [17].

Due to the incorporation of numerous renewable energy sources and the introduction of novel systems like autonomous grids, micro-grids, nano-grids, and smart grid technologies, modern power networks are undergoing a rapid transformation [5]. The production of active electricity is uncertain due to the interconnection of renewable energy sources, such as wind turbines, tidal turbines, geothermal plants, biomass plants, hydro power plants, and solar cells, etc. Figure 1 [6] illustrates this. The use of solar energy resources has been the subject of extensive investigation. Solar energy is viewed as an easier alternative to hydro energy systems because of its cheaper construction costs and portability. Hydro energy systems are traditionally thought of as the best environmentally friendly source of energy, but their initial cost and time of development are high [7]. Thus, frequency fluctuations lead to the unreliable operation of the power system. Nowadays, a power system must be unbundled into its horizontal and vertical components because it is not vertically integrated but rather a deregulated entity. In such cases, it is crucial to analyse the situation and build improved frequency controller units. Numerous studies have been conducted to create and enhance the design of load frequency controllers [8]. A PID controller was used by Krishan et al. in [9] to work on the autonomous generation regulation of multi-area power plants. In [10], effective generation rate-constrained robust multivariable predictive-based load frequency control was accomplished. The developed controllers, however, do not offer particularly impressive settling time, peak overshoot, or peak undershoot values. A load frequency controller's primary responsibility is to immediately stabilise by adjusting its parameters in response to its surroundings [11,12]. There has been extensive study done to develop the perfect load frequency controller, but the majority of these controllers have poor settling time concerns. More recently, the intelligent design technique has become popular in LFC design. An LFC design based on an artificial neural network was aimed at the deregulated power market in [13,14]. It is an illustration of an intelligent controller with a system for learning from external events and situations. Smaller settling periods and lower transient values are required to quickly approach the steady state response [15,16].

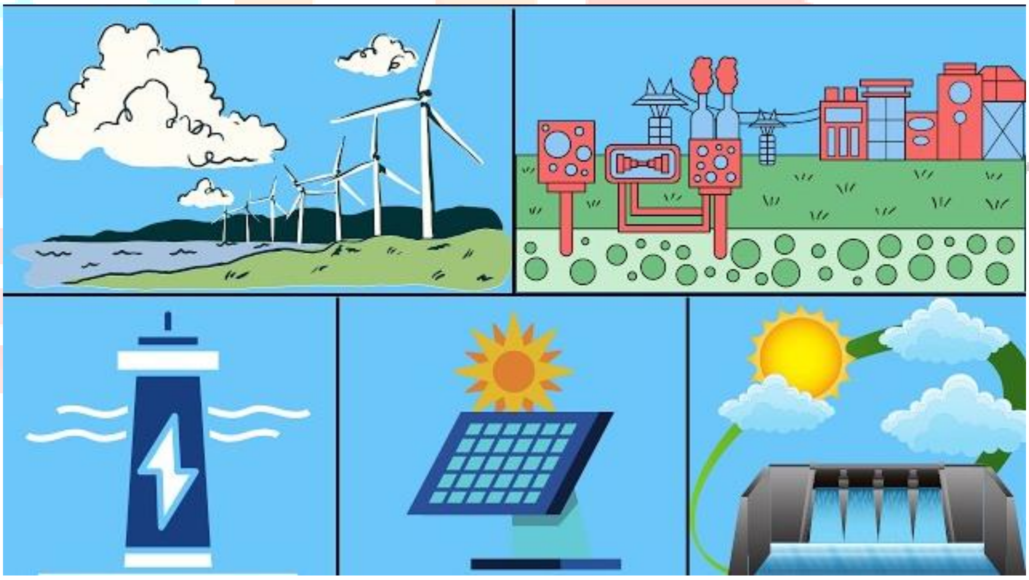

Figure 1. Renewable Energy Systems.

When applied for attack detection on LFC in [17], the stochastic process with unknown input estimators serves as an illustration of the cyber security technique used in LFC applications. The best firefly algorithm was employed in [18] to control load frequency in unregulated situations.

III. Research Motivation

The focus of this research is on understanding various LFC control techniques in hybrid power systems based on renewable energy sources. Numerous LFC control techniques for connected hybrid power systems are presented in the literature review. These methods concentrate on giving hybrid power systems the best possible control for increased power system responsiveness. Most researches focused on the conventional, integrated power networks that are ageing [19]. The development of renewable energy sources is currently a global priority due to their environmental friendliness and low operating costs. Power quality problems result from the integration of renewable energy sources with a conventional power grid. Maintaining load frequency control while supplying the necessary quantity of power is not always simple. Issues with frequency deterioration are brought on by the inertia of the power system and intermittent generation [20]. A greater number of interconnected systems could result in problems such voltage instability, frequency skew, and poor power quality. To overcome these difficulties and improve the level of integration of renewable energy sources in current power system networks, some inventive work and fresh ideas are required. Reviewing prior study, it was found that scientists tended to concentrate on conventional LFC development, but that load frequency control research has been stimulated by the ongoing integration of renewable energy sources into existing power grids [21]. The present review, which describes the integration of renewable energy sources with existing power system networks, was motivated by this.

IV. Review on Load Frequency Control with Renewable Energy Sources

systems. In contrast to the latter, which is often a tied power system, the former is an isolated power system. The integration of renewable energy sources creates transients and frequency deviations, and environmental non-linearity affects the power system's regular operation [22]. The introduction of contemporary methods for power generation, transmission, and distribution has complicated how the power system functions. In the area of load frequency controllers, research and development is being done to address power quality issues in complicated power systems. For the improvement of power quality and the system's responsiveness to irregularities, a variety of control schemes and optimization algorithms have been proposed [23]. Figure 2 displays the application of LFC in several fields along with optimization methods. For LFC optimization, many algorithms are applied to enhance the transient response and settling time.

Classical control, optimum control, adaptive control, variable structure control, and robust control are some of the several control techniques used in LFC development. The deregulation of the power system was brought about by the government's reform of laws and regulations. Nowadays, transmission congestion is a problem since power is traded like any other commodity. The difficulties of transmission congestion brought on by multi-area deregulated networks centre on the requirement for complex LFC structures. Distributed generation is gaining popularity as more people install renewable energy systems in their homes. A better-designed LFC can handle the power quality problems brought on by the power generated at several isolated places. The power system can be divided into single-area and multi-area power systems depending on how it is configured.

In contemporary power systems, LFC controllers are intelligently tuned using a variety of soft computing techniques [24]. A FOFPID controller has been created for islanded microgrids utilising the multi-objective extremal optimization method [25]. The PI-PD cascade controller's AGC regulation in multi-area power systems was optimised using the Flower Pollination algorithm [26]. To iteratively stabilise the power system transients in a hybrid context, the iterative proportional-integral-derivative H controller was created [27]. The load frequency control of a hydrothermal system in a deregulated environment has been established using the biogeography-based optimised three-degrees-of-freedom integral-derivative controller [28]. A framework for cost-effective load frequency regulation in hybrid power systems was developed using the modified multi-objective genetic algorithm [41]. In this instance, the power system quality is kept up to par economically and to satisfy consumer demands.

V. Multi-Area Power System

Renewable energy sources like wind and solar can be used with traditional power plants in today's flexible power networks. The connectivity of several generation sources increases instability, making load frequency regulation a challenging issue in multi-area power systems. The amount of frequency deviation in each area of control is used to determine the LFC design for a multi-area power system. The tie line power deviation is a severe problem in systems that are coupled because it can cause transients and power system instability. A sudden change in the demand and power produced by renewable energy sources might result in extremely unstable output power.

Figure 2 depicts the tie line power exchange between various locations. Each area is made up of conventional units with distributed generation and is connected by different sub-systems. Transients and harmonics are two examples of issues brought on by the interaction of various locations. Power flow on the connected lines becomes a problem due to power imbalances, hence frequency control entails measuring power flow on the connected lines. The entire power system is characterised by frequency management, and reliable functioning depends on this control. The entire quantity of active power generation must match the active power consumption at any given moment in order to keep the power system frequency constant.

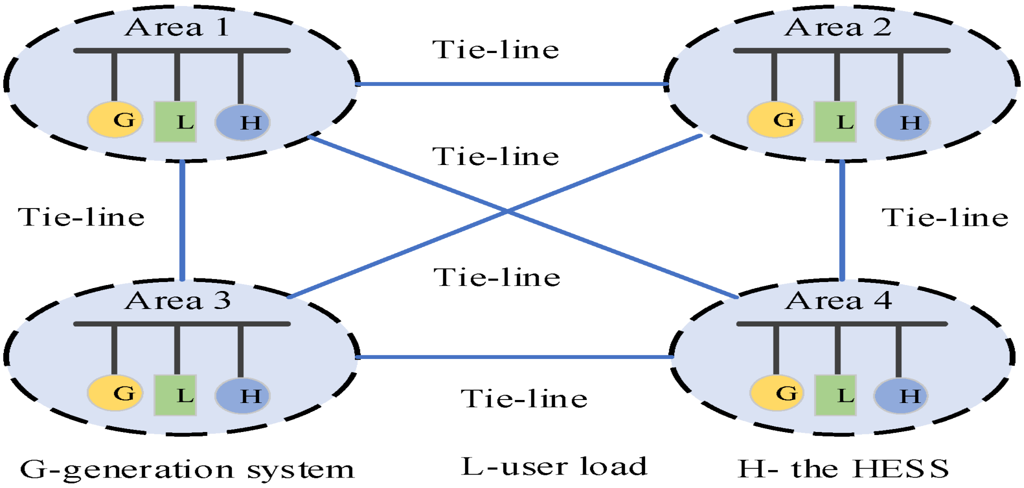

Figure 2. Power between areas

VI. Controllers based on Different Control Techniques

As research has been done to address one of the shortcomings in the current controllers, various controllers have been produced over time. Artificial Neural Network (ANN) controllers were created as a result of the advancement of intelligent computing techniques, simplifying the decision-making process in control structures. Multi-level control schemes between two extreme values were produced as a result of the development of fuzzy logic; these controllers increased the amount of control and accuracy of output signals.

Every control system experiences non-linearity, hence non-linear control systems have been created to address irregularities. The statistical analysis and approaches for creating better control systems were proved by the work in probability. While the swarm intelligence incorporated the principles of colonial intelligence for the development of ant colony optimization and particle swarm optimization, numerous algorithms, such as Genetic and Differential Evolution, were developed to address various inadequacies in power systems. Figure 3 illustrates many soft computing techniques. As various fields grow over time, better control algorithms are produced. Swarm intelligence and evolutionary tactics are developed as a result of metaheuristic methods. Ant colony optimization and particle swarm optimization are subfields of swarm intelligence, while the genetic algorithm and differential evolution are some of the fundamental evolutionary techniques.

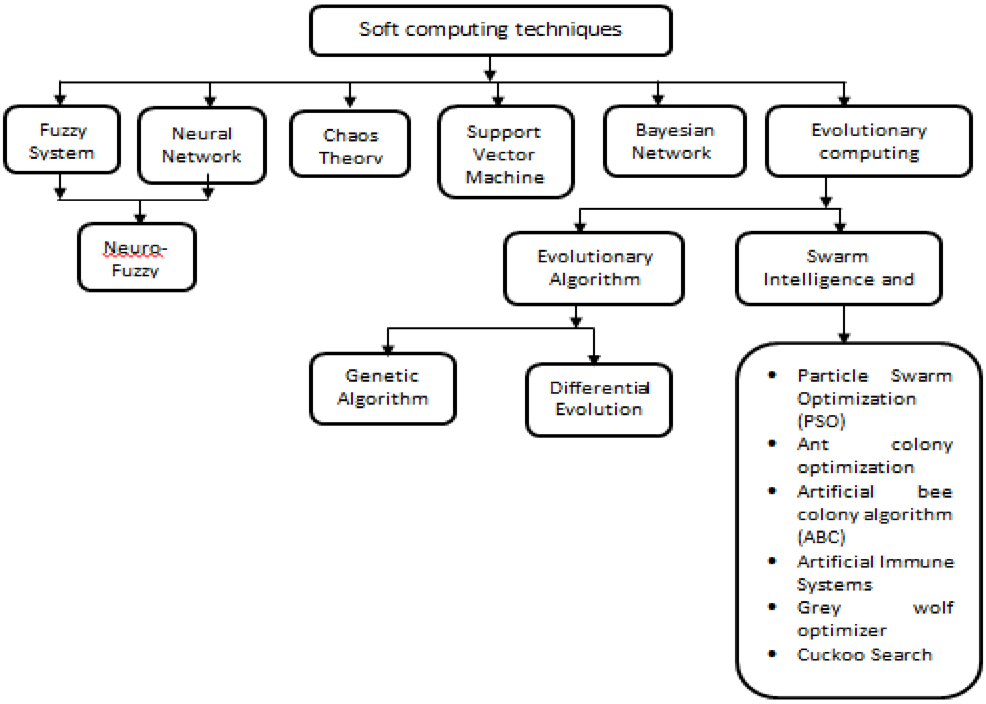

Figure 3 Soft computing techniques

VII. CONCLUSIONS

Modern power systems depend on LFC to supply power consistently, effectively, and reliably. Both single-area and multiple-area power system types are covered. Under conditions of various uncertainties, non-linear output, and multi-variable power system conditions, the primary goal of LFC is to provide frequency regulation in power systems while continuously monitoring the load demand. This article examines numerous LFC power system topologies that have been algorithmically improved. The most recent developments in LFC structure used in different types of renewable energy systems are succinctly addressed. The conclusion of this work emphasises the necessity for further research and development in the field of load frequency controllers. This work is anticipated to be a valuable resource for knowledge in the area of load frequency control for renewable energy systems.

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