A Review of Strategies for Decentralized Automatic Generation Control in Restructured Electricity Framework

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Abstract: The main component in charge of making sure that the production and operation of an electric power system are both efficient and smooth is called automatic generation control (AGC). The primary objective of AGC is to maintain the generated power at the standard level suitable for electrical market while also ensuring that the operating frequency remains within the prescribed limits. There have been presentations on a variety of control strategies, including those for frequency and power regulation. These strategies take into consideration a wide diversity of decentralized power generation sources from conventional, and renewable energy sources. As a consequence of this, in order to ensure adequate supply of power is maintained, an AGC system needs to be supplemented with control strategies that are both modern and ingenious. This study's goal is to conduct a comprehensive analysis and evaluation of various Automatic Generation Control (AGC) methodologies used in various power system topologies such as optimal, classical, adaptive, predictive, robust, digital, artificial neural network-based, fuzzy logic-based and neuro-fuzzy based control. The objective is to determine the most effective approach that could be improved upon in subsequent research studies.

Keywords: *Generation Control, Electricity Market, Operating Frequency, Control Techniques, Decentralized Generation.*

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I. INTRODUCTION

In grid connected power system (PS) where manual control is not an option, efficient frequency and grid-connected power management is crucial [1], [2]. Furthermore, it is a sophisticated and challenging process to precisely match the generated power with the load in its desired state. A procedure commonly known as Automatic Generation Control (AGC) or Load Frequency Control (LFC) uses the central systems of power producing facilities as a mechanism to control power and frequency.[1], [3], [4].

The majority of the study on the AGC has been devoted to the analysis of complex power systems that have been divided into numerous control zones. An element of a power system known as a control area is characterized by the concurrent operation of numerous generators with the same frequency characteristics. The control area is in charge of monitoring the power consumption of each specific region and ensuring that the overall frequency of the system remains stable throughout regular steady-state operation. This responsibility falls under the purview of the control area.

It has been observed that each control area is able to efficiently regulate its frequency and tie-line power during load perturbations by applying a technique that entails minimizing the area control error (ACE). Even when the load is disturbed, this is still the case. This error statistic accounts for the tie-line power variations as well as frequency variations. There is currently a growing corpus of research focused on multi-area systems' automatic generation control, with a particular focus on the incorporation of several control areas. [5]. The frequency and tie-line power must be maintained at predetermined levels in order for the current systems to function properly.

The primary loop and secondary loop are the two separate loops that make up the LFC loop. The primary control

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loop responds to frequency inputs with a quicker response time [6]. In contrast, the secondary loop is characterized by a slower operational pace, as it is primarily responsible for executing precise frequency adjustments and facilitating the efficient transfer of megawatts between various control areas [6].

The secondary loop does not possess the capability to effectively address abrupt changes in frequency and variances in tie-power, in contrast to the primary loop. Once the first loop has finished executing its task, the secondary loop is subsequently triggered. Therefore, it is imperative to implement appropriate controller architecture in order to effectively manage Automatic Generation Control loops.

The presence of a proficient secondary controller is crucial in order to effectively mitigate undesired deviations and maintain the Automatic Control Error (ACE) at a steady-state value of zero [4]. The AGC system, which consists of the LFC and automatic voltage regulator loop, is depicted in Figure 1. The restructured and deregulated power system (PS) is an adaptation of the standard AGC power system, incorporating appropriate planning and operation [7].

A vertically integrated utility (VIU), which included utilities for generation, transmission, and distribution, was what made the conventional Power System unique [8]. In contrast, a deregulated power business does not have the concept of a VIU. Rather, it consists of three distinct organisations: distribution enterprises (commonly known as DISCOs), transmission companies (often known as TRANSCOs), and generation companies (also known as GENCOs). [9].

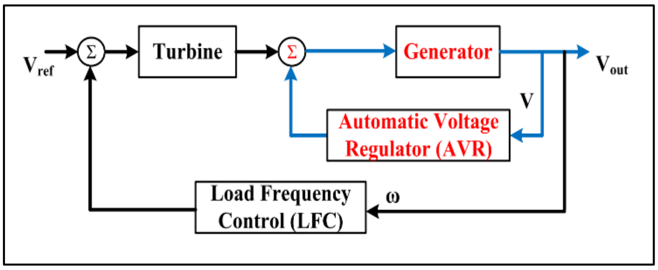

Fig 1: The AGC System, with LFC and Automatic Voltage Regulator Loop [2].

The utilization of renewable energy sources (RES) in contemporary power systems (PSs) has been driven by the depletion of conventional energy sources and their adverse environmental effects [10], [11], [6]. RES are widely prevalent in the natural environment and have a reduced environmental footprint due to their enhanced energy conversion efficiency [12]. Wind and solar energy sources are more prevalent than other renewable energy sources due to their extensive accessibility. Contemporary scholarly works discuss current advancements in solar energy technologies, albeit with a focus on stand-alone and two-area systems, thereby highlighting their existing limitations [13]–[15].

Moreover, wind energy conversion systems have been extensively employed in the field of power systems research throughout the past few decades. Limited research has been conducted on the automatic generation control of interconnected systems that integrate solar thermal and wind systems. Moreover, the research conducted on the integration of solar and wind systems by the Automatic Generation Control has only employed a first order transfer function model. In addition, there have been advancements in the development of realistic models for RES; nevertheless, it is important to note that these models are currently constrained to isolated systems alone. Therefore, the incorporation of realistic RES models in contemporary Power Systems (PSs) offers opportunities for networked AGC systems.

The growth in population is having a substantial impact on the load demand in the electrical systems. The need for improved power transmission capability in inter-area AGC Power Systems is driven by the increase in load demand. In addition to integrating flexible AC transmission system (FACTS) devices inside the control areas, high-voltage direct current (HVDC) tie-lines must be added alongside the current alternating current (AC) tie-lines in order to achieve this goal.

The introduction of HVDC tie-lines and FACTS devices has generated significant attention among academics seeking to enhance power transfer capacities through the use of flexible operation and control in studies related to Automatic Generation Control (AGC) [2], [3]. HVDC and FACTS devices are crucial in enhancing the performance of power systems. They contribute to the improvement of real power flow, reduction of real power losses, and enhancement of damping ratio. Consequently, these devices lead to a decrease in the number of oscillations, lower peak overshoot values, and faster settling time.

The careful selection and optimal placement of a FACTS controller inside a power system is a crucial decision. Moreover, contemporary scholarly works in the field of AGC have introduced a precise model for High Voltage Direct

(HVDC) tie-lines for current. It should be highlighted, nonetheless, that this approach can only be used to isolated and two-area systems [2]. Therefore, chances for the development of interconnected AGC systems are presented by the inclusion of the AHVDC tie-line model with the FACTS device in modern Power Systems (PSs).

The unpredictable, fluctuating, and variable nature of RES's power output raises the possibility of an unstable power supply. This means that energy storage devices (ESD) including battery systems, flywheels, capacitive energy systems, superconducting magnetic energy storage, ultra-capacitors (UC), and redox flow batteries (RFBs), among others, can be used to solve the problem. With this integration, a cost-effective system would be maintained and a constant supply of power would be delivered to the load.

The paper offers a thorough examination and analysis of a number of AGC tactics that work in various power system topologies. Among the strategies discussed are Neuro-fuzzy logic-based control strategy, fuzzy logic-based control strategy, artificial neural network-based control strategy, and a few more. The study examines various control viewpoints

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for power and frequency regulation inside a decentralized electrical system.

This article's remaining sections are organized as follows; section two reviews pertinent literature with regard to automatic generation control. The operation of automatic generation control is described in Section 3. Section 4 classifies a few chosen automatic generation control systems and evaluates their benefits and drawbacks. The study's concluding section makes suggestions for additional investigation.

II. REVIEW OF RELATED LITERATURE

Over the past five decades, the AGC problem has been largely resolved, and the principal solution involves linearized models. The AGC system is modelled using small-signal analysis while taking into account small perturbations in order to analyze the system reaction. The PS stability, which gained significance, is not guaranteed when a non-linear system is being controlled by an AGC model that has been linearized. Later, both continuous and discontinuous PS models incorporate nonlinearities like GRC and GDB [16], [17].

In an interconnected power system (PS), massive generating units, dense load centres, and complex dynamic structures are frequently coupled. The traditional/classic version of PS has been used for power generation, transmission, and distribution (GTD) with conventional sources like hydro, thermal, gas, and nuclear. The AGC research is built on a single-area classical PS with a linearized thermal system model. Later, studies on AGC use conventional sources like hydro, gas, nuclear, diesel generators, and electric cars.

In the twenty-first century, distributed generation is created by combining RES such wind, tidal, geothermal, and solar photovoltaic. Energy efficiency can be raised by integrating RES and using cutting-edge, advanced techniques with little negative environmental effects. For the AGC study, authors in [4] developed a solar PV system where solar energy is captured by solar panels and stored in thermal form from which steam is produced to power the turbine. In order to conduct an AGC research, a grid combining thermal and solar system was developed.

AGC investigation with geothermal and gas thermal systems into account was presented by the author in [18], adoption of this system is generally limited by certain policies. The practice of restructuring or deregulating the electricity market involves changing the rules and legislation that control the industry so that consumers can select retailers or traders as their electricity suppliers. It increases the effectiveness and economy of the production of power. Energy prices are expected to decline as a result of greater competition for the benefit of consumers. It is difficult to implement the conventional ACE-based LFC in a deregulated power market. Recently, a few control solutions have relied on the best and most reliable methods for deregulated AGC.

The GTD corporations own a monopoly in the conventional market. However, there are more market participants in a market that is unregulated. When these GTD firms are bidding, ISO gives terms for a variety of transactions, including bilateral, PoolCo, and contract violations [3], [5], [8], [19], [20]. This is necessary due to unanticipated frequency bias in PS, unscheduled generation and demand variations, and both. Any governor in the PS must act fast in response to a change in frequency caused by a change in demand, regardless of whether they are selected for AGC. Authors in [9] created the Disco Participation Matrix (DPM) relationship between GENCOs and DISCOs using Contract Participation Factor (CPF) as one of its components.

The initial conventional/deregulated AGC efforts started with two-area thermal systems and advanced to three-area thermal systems with the integration of RES, FACTS, and ESD devices [6]. Current developments in AGC in a deregulated environment include the use of meta-heuristic optimisation techniques and the development of various cascade secondary controllers using the new HPA-ISE as an objective function for reducing the ACE [21].

III. OPERATION OF AUTOMATIC GENERATION CONTROL

Automatic Generation Control (AGC) is used to achieve the primary goal of delivering effective, dependable, and stable electricity in an integrated power network. AGC is in charge of continuously tracking changes in load and modifying generator output accordingly. Tie-line interchanges and frequency variations must be continuously monitored inside the AGC service in order to achieve success. A mathematical model derived from the interaction of these two variables is presented in equation 1 [3], [18], [22].

$$P_z = \sum_{j\,i}^{z} \left(V_i V_j \left(G_{ij} \cos\left(\theta_i - \theta_j\right) + \ B_{ij} \sin\left(\theta_i - \theta_j\right) \right) \right) \qquad (1)$$

where, V_i is the voltage magnitude of bus i, G_{ij} + j B_{ij} is the (i j) entry of the system admittance matrix in area z.

The actual frequency of the area z according to authors in [3], is presented in equation 2.

$$f_z = \sum_{i\,\mathcal{E}\,G}^{z} \mathcal{r}\mathrm{i}\ (\mathrm{fn} + 1\mathrm{d}\theta_i / 2\pi\mathrm{dt}) \qquad (2)$$

Where $\mathcal{r}$i is a function of H, which is the *i-th* generator initial constant.

IV. CLASSIFICATION OF AUTOMATIC GENERATION CONTROL STRATEGIES

Various sorts of controls have been developed and implemented since the emergence of automatic generation control (AGC). This section provides an overview of classical, current, and advanced control strategies. Table 1 presents a comprehensive overview of control strategies, highlighting their merits and demerits.

Table 1: Summary of Control Strategies, Highlighting their Primary Merits and Demerits.

Control Strategies	Merits	Demerits
Optimal Control Strategy: a mathematical optimization method for deriving control policies.	The system is capable of effectively managing delays.	There is a significant need for a substantial amount of storage capacity.
Classical Control Strategy: a mathematical optimization method based on Laplace Transform.	Straightforward and readily implementable.	The dynamic performance of the system is suboptimal.
Adaptive Control Strategy: based on the variation of input parameters.	Offers rapid methodology for modifying parameters in order to adapt to variations in process dynamics.	Not suitable for implementation as a system with significant dimensions.
Predictive Control Strategy: used to control a process while satisfying a set of constraints.	Possesses the ability to efficiently manage and redistribute the highest demand of power resources.	The algorithm is complex, this resulted in a longer execution time compared to other strategies
Robust Control Strategy: an approach that explicitly deals with uncertainties.	Offers optimal functionality for a system characterized by uncertainties and external interruptions.	Not suitable for a system with significant dimensions and wide fluctuations in parameters.
Digital Control Strategy: an approach based on precise and accurate discrete parameter handling.	Offers accurate and dependable solutions with minimal noise	The selection of the digital controller may only be considered appropriate if both the programme requirements and the features of the digital controller are well stated.
Artificial Neural Network-based Control Strategy: an approach suitable for determining the unknown non-linear functions.	This system demonstrates effective performance in the presence of nonlinearities and uncertainties.	Requires a large amount of tuning parameters.
Fuzzy Logic-based Control Strategy: a mathematical system that analyzes analog input values in terms of logical variables.	The utilization of a certain model is not obligatory.	The durability of comprehensive rules is a major problem.
Neuro-fuzzy based Control Strategy: a system that has the ability to function under multiple objectives	Combines the merits of neural network and fuzzy logic, enabling the capacity to handle nonlinearities and system uncertainties perfectly.	Lacks the capability of managing weak power constraints.

V. CONCLUSION AND FUTURE SCOPES

This study provides a critical analysis of current studies within the AGC domain. Special attention has been made to categorize various AGC strategies, and its key traits, merits, and demerits are highlighted. With the advent of Neuro-fuzzy as the most promising strategy, due to its features which combines the merits of neural network and fuzzy logic, giving it capability of handling nonlinearities and system uncertainties perfectly. Though Neuro-fuzzy is not without a limitation, but adaptive systems can be looked into in future research to handle the strategy's lack of capacity to manage weak power constraints.

The structure of the modern power system is changing and it is moving towards a hybrid power system, where distributed generators from various sources including renewable energy are integrated. With the integration of RES, inertia levels of hybrid power systems decrease. This implies that the hybrid power system of the future would have problems with frequency regulation. Therefore, a modern control mechanism with adaptive optimization approaches taking into account restructured electricity framework is necessary, depending on the application, to alleviate frequency regulation concerns.

The authors of this study are currently working on developing an adaptive technique for decentralized automatic generation control in restructured electricity market.

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