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COMPARATIVE PERFORMANCE OF PID, FUZZY AND ANFIS CONTROLLERS FOR AGC IN POWER SYSTEMS

Saiful Islam Tuhin[1]
Md Al Araf
Md. Sahadat Hossain Sani
Tahrim Fatiha
Avijit Kundu

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A B S T R A C T

This research explores the optimization of Automatic Voltage Regulator (AVR) systems to improve stability and response time, which are essential factors for ensuring dependable power delivery also examines the effectiveness of PID, ANFIS, and fuzzy logic controllers in strategic controller selection. This is done through comprehensive MATLAB/SIMULINK simulations and comparative comparison with contemporary metaheuristic optimization-based AVR designs. Performance benchmarks encompass the evaluation of dynamic reaction and stability under different operating situations. Moreover, the study investigates the incorporation of Area Control Error (ACE) into LFC strategies to enhance frequency regulation. This research provides vital insights for enhancing the performance of AVR systems by selecting controllers that are specifically designed for the system. This has a significant impact on the reliability and efficiency of power systems. The utilization of ANFIS controllers with ACE in LFC introduces a new method to improve frequency regulation, providing practical benefits for power system operators and researchers aiming to better system performance and reliability.

1. INTRODUCTION

The reliable delivery of electricity is a cornerstone of modern society. As power demands surge globally, the need for resilient and responsive electrical grids becomes ever more critical (Mehta & Mehta, 2005). At the heart of this challenge lies the optimization of Automatic Voltage Regulators (AVRs), essential components that maintain stable voltage levels within power systems (Gupta, 2009). AVRs play a vital role in ensuring the smooth operation of generators, industrial machinery, and even everyday electronics by mitigating voltage fluctuations caused by load variations and external disturbances.

Traditionally, AVR systems have relied on Proportional-Integral-Derivative (PID) controllers due to their simplicity and effectiveness in various applications (Veinović et al., 2022). However, the increasing complexity of power systems, coupled with the integration of renewable energy sources, demands more sophisticated control strategies to achieve higher levels of stability and faster response times (Fang et al., 2011; Gharavi & Ghafurian, 2011; Glover, 2012). This need has spurred extensive research into advanced control methodologies, including fuzzy logic, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) (Jang, 1993; Sivanandam et al., 2007). These intelligent techniques offer the potential to

[1] Corresponding author: Saiful Islam Tuhin
Email: saifulislamtuhin15@gmail.com

enhance AVR performance by capturing system nonlinearities and adapting to dynamic operating conditions (Kundu et al., 2023; Sivanandam et al., 2007). This work delves into the optimization of AVR systems, specifically focusing on strategic controller selection to achieve superior stability and responsiveness. The research evaluates and compares the performance of PID, fuzzy logic, and ANFIS controllers through comprehensive modeling and simulation studies using MATLAB/SIMULINK software. These simulations are benchmarked against recent metaheuristic optimization-based AVR designs reported in the literature (Bayram et al., 2013). Also recognizing the interconnected nature of modern power grids, this work explores the integration of Area Control Error (ACE) signals into Load Frequency Control (LFC) techniques (Abdeltawab & Radwan, 2022). ACE, a key metric reflecting the real-time balance between power generation and demand, can provide valuable feedback for enhancing frequency regulation in multi-area power systems (Abdillah & Setiadi, 2023). The effectiveness of ANFIS controllers, coupled with ACE signals, is investigated to determine their potential in achieving robust frequency control and ensuring overall system stability under various operating scenarios.

This research provides crucial insights for optimizing AVR systems by selecting tailored controllers, impacting the reliability and efficiency of power delivery within electrical networks. Additionally, the exploration of ANFIS controllers with ACE in LFC offers a novel approach to enhance frequency regulation, carrying significant practical implications for power system operators and researchers pursuing improved grid performance and dependability.

2. LITERATURE REVIEW

Ensuring voltage and frequency stability within acceptable parameters is crucial for dependable functioning of the power system (Gupta, 2009). This analysis digs into current improvements in AVR and LFC systems, highlighting the expanding role of intelligent control strategies.

2.1 AVR Optimization Through Advanced Control

Recent research has explored various control techniques for AVR system enhancement, with a notable focus on intelligent methods:

Abdillah and Setiadi, (2023) examined the use of hybrid intelligence optimal controllers, incorporating parts of fuzzy logic and optimization algorithms, for boosting Area Control Error (ACE) performance in a two-area power system. Their findings showed the potential of such approaches in enhancing frequency regulation and stability. Abdeltawab and Radwan (2022) proposed a deep learning-based approach for ACE predictions, enabling more proactive and adaptive control actions for enhanced frequency management. Their study highlights the rising applicability of machine learning techniques within the field of power system control. Tanwani et al., (2014) gave a detailed assessment of simulation methodologies for power system stability examines using MATLAB/Simulink, highlighting its relevance in testing AVR and LFC designs. Their study underlined the significance of proper modeling and simulation for credible performance assessment. Ekinci and Hekimoğlu (2019) employed an Improved Kidney-Inspired Algorithm for maximizing PID controller gains in an AVR system. This nature-inspired optimization strategy proved its capacity to provide faster response times and lower overshoots compared to standard tuning methods. Sambariya and Nath (2015) examined the application of Particle Swarm Optimization (PSO) for adjusting PID controller gains in AVR systems with Automatic Generation Control (AGC). Their work demonstrated the efficacy of PSO in determining optimal controller parameters for increased system performance.

2.2 Load Frequency Control (LFC) Strategies Control

Research in LFC has focused on tackling the issues provided by linked power systems and the integration of varied generation sources:

Sudha and Santhi (2012) studied the usage of type-2 fuzzy logic systems for LFC in a two-area interconnected power system containing Superconducting Magnetic Energy Storage (SMES) units. Their findings proved the higher performance of fuzzy controllers in handling uncertainties and nonlinearities related with SMES integration. Parmar et al. (2012) explored LFC in a multi-source power system, addressing the difficulties created by merging multiple generation technologies. Their findings underlined the necessity for adaptive and resilient control mechanisms to ensure frequency stability in such hybrid systems. Jiang et al. (2011) investigated the impact of time delays, inherent in communication and control infrastructure, on LFC performance. They introduced delay-dependent stability analysis and control design methodologies to limit the harmful impacts of delays and assure system stability. Doolla and Bhatti (2006) explored LFC in an isolated small-hydro power plant with lower dump load, addressing the special issues involved with controlling smaller-scale hydroelectric generation. Rerkpreedapong et al. (2003) employed evolutionary algorithms in conjunction with linear matrix inequalities for robust LFC design. Their approach highlighted the capacity of evolutionary algorithms to successfully handle system uncertainties and adjust controller parameters for enhanced performance. Arif et al. (2017) created a complete model for LFC in a single-area power system with diverse generation sources, including both thermal and hydroelectric plants. Their work set the framework for assessing and managing frequency in systems with various generating combinations. Pan and Liaw (1989) proposed an adaptive controller for LFC, enabling the controller to alter its settings live based on the system's dynamic behavior. This adaptive technique solved the constraints of fixed-gain controllers in effectively handling changing operating conditions.

This study highlights the expanding landscape of AVR and LFC research, driven by the need for enhanced grid stability, responsiveness, and adaptability in the face of growing complexity and renewable energy integration. Intelligent control strategies are developing as potential alternatives, giving better performance and resilience compared to traditional systems. As electricity systems continue to improve, future research will definitely focus on further refining these intelligent control algorithms for practical implementation and smooth integration into next-generation smart grids.

3. METHODOLOGY

This work applies a comprehensive methodology encompassing mathematical modelling, simulation, and comparative analysis to evaluate the optimization of AVR systems through strategic controller selection.

3.1. System Modelling

AVR System: A thorough mathematical model of a typical AVR system will be created utilizing transfer function representations for each component, including the generator, exciter, amplifier, sensor, and feedback loops (Bayram et al., 2013). The model will be built and simulated within the MATLAB/Simulink environment, a widely recognized platform for power system analysis (Tanwani et al., 2014) .

LFC System: Similarly, a multi-area LFC system will be studied, incorporating the dynamics of interconnected regions, tie-line power flows, and governor reactions (Saadat, 1999). This model would contain ACE signals as a feedback mechanism for frequency adjustment (Abdillah & Setiadi, 2023; Tuhin et al., 2024).

3.2. Controller Design and Implementation

Three distinct controllers will be devised, implemented, and integrated with the AVR and LFC models:

PID Controller: A standard PID controller will be constructed and tuned using established approaches, potentially utilizing optimization algorithms for fine-tuning (Gupta, 2009; Sambariya & Nath, 2015).

Fuzzy Logic Controller: A fuzzy logic controller will be constructed, utilizing expert knowledge and language rules to handle system nonlinearities and uncertainties (Sivanandam et al., 2007; Zadeh, 1965). Membership functions and rule bases will be established based on the specific characteristics of the AVR/LFC system.

ANFIS Controller: An ANFIS controller will be created, integrating the learning capabilities of neural networks with the interpretability of fuzzy logic (Jang, 1993). The ANFIS structure will be trained utilizing input-output data from the AVR/LFC system to learn and adapt its fuzzy rules for maximum performance.

3.3. Simulation and Performance Evaluation

The performance of each controller will be extensively assessed by comprehensive simulations under various operational conditions:

AVR Performance Metrics: Step response analysis will be undertaken to analyse settling time, overshoot, and steady-state inaccuracy of the AVR system with each controller (Bayram et al., 2013).

LFC Performance Metrics: Frequency deviations, tie-line power flow fluctuations, and ACE response will be examined to evaluate the performance of each controller in preserving frequency stability within the multi-area LFC system (Abdeltawab & Radwan, 2022; Parmar et al., 2012).

3.4. Comparative Analysis and Validation

The overall performance of the proposed controllers will be tested against each other and benchmarked against recent metaheuristic optimization-based AVR designs reported in the literature (Ekinci & Hekimoğlu, 2019). The simulation findings will be evaluated against theoretical predictions and known performance requirements for AVR and LFC systems (Glover, 2012).

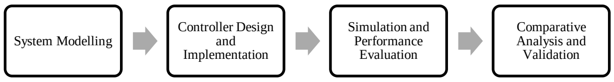

Figure 1. Comparative Analysis and Validation

This rigorous technique will give a full evaluation of several control strategies for AVR and LFC systems, guiding the selection of the most effective controller for better power system stability, responsiveness, and dependability (Figure 1).

4. RESULTS AND DISCUSSION

This chapter presents and analyzes the results obtained from the simulation studies conducted using the methodology described previously. The performance of the PID, fuzzy logic, and ANFIS controllers for both AVR and LFC systems is assessed and compared.

4.1. Reactive Power and Voltage Control (AVR)

PID Controller Performance:

The PID controller, when applied to the AVR system, demonstrated its capability to enhance the system's dynamic response and reduce steady-state error. Figure 2 illustrates the terminal voltage response of the uncompensated AVR system, exhibiting a large overshoot and extended settling time, indicative of poor stability.

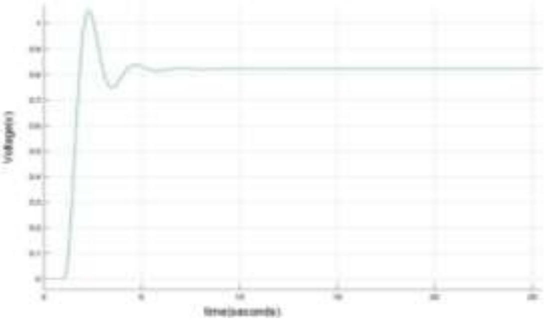

Figure 2. Terminal Voltage Response for an AVR System

The introduction of the PID controller, as depicted in Figure 3, significantly improved the system response. Through careful tuning of the controller gains (Kp, Ki, Kd), a more desirable response was achieved, characterized by minimal overshoot and a reduced settling time in Figure 4. Table 1 lists the optimized PID controller gains used in this study.

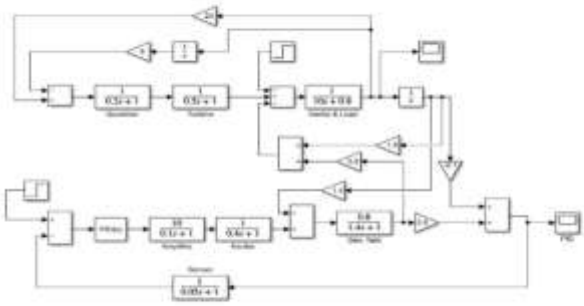

Figure 3. AVR System with PID Controller

The substantial improvement observed in Figure 4 compared to the uncompensated response in Figure 5 highlights the effectiveness of the PID controller in enhancing AVR system stability and responsiveness.

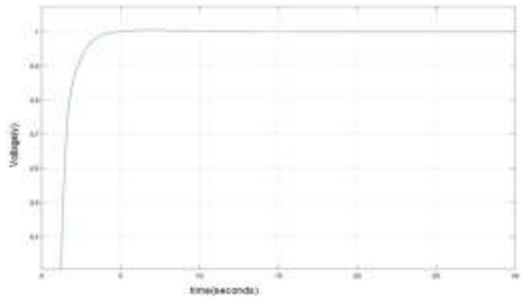

Figure 4. Terminal Voltage Step Response with PID Controller

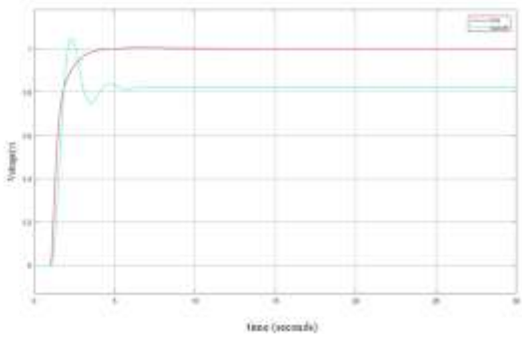

Figure 5. Terminal Voltage Step Response PID Controller Vs Without AVR

Table 1. Parameters of the PID Controller

PID controller gains	Value
Proportional gain, KP	0.770575
Integral gain, KI	0.371320
Derivative gain, KD	0.315085

Fuzzy Logic Controller Performance:

The fuzzy logic controller, incorporating expert knowledge through linguistic rules, demonstrated comparable performance to the PID controller. Figure 6 depicts the AVR system with the implemented fuzzy controller. The system's response, illustrated in Figure 7, exhibited a rapid settling time and negligible overshoot, confirming its capability in handling the AVR system's nonlinearities.

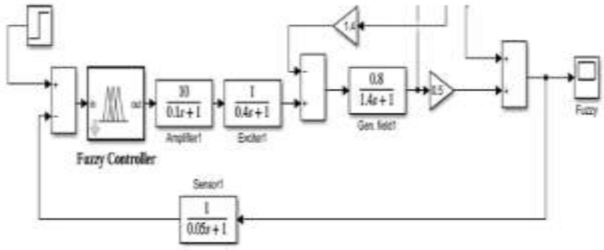

Figure 6. AVR System with Fuzzy Controller

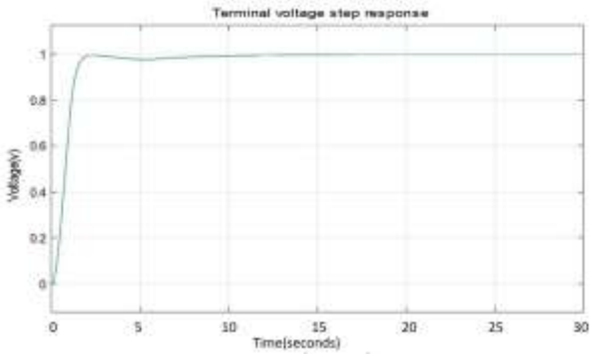

Figure 7. Response of AVR system with Fuzzy Controller

A comparison between the fuzzy-controlled response and the uncompensated system in Figure 8 further underscores the fuzzy controller's effectiveness in enhancing the AVR system's dynamic performance.

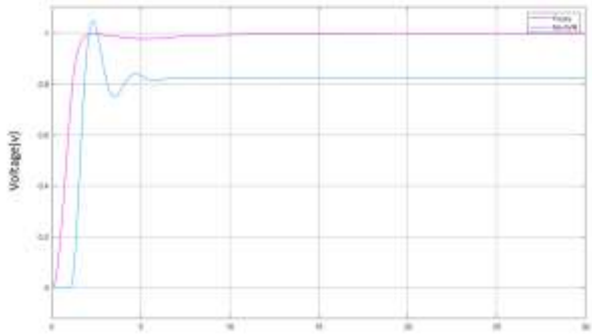

Figure 8. Terminal Voltage Step Response Fuzzy Logic VS Without Fuzzy Logic in AVR

ANFIS Controller Performance:

The ANFIS controller, combining the strengths of fuzzy logic and neural networks, demonstrated remarkable adaptability and performance in regulating the AVR system. Figure 9 illustrates the AVR system integrated with the ANFIS controller. As depicted in Figure 10, the ANFIS controller achieved a swift settling time with minimal overshoot, showcasing its ability to learn and adapt to the system's dynamics effectively.

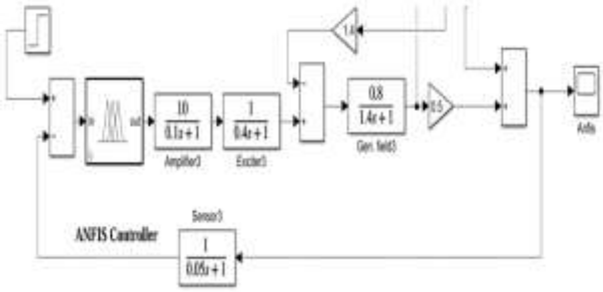

Figure 9. AVR system with ANFIS Controller

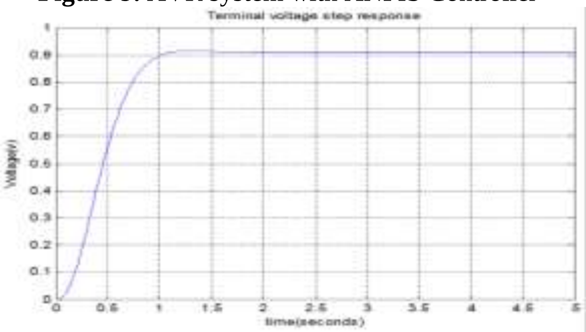

Figure 10. Response of AVR System with ANFIS Controller

The significant improvement compared to the uncontrolled system in Figure 11 emphasizes the ANFIS controller's superior capability in enhancing AVR system performance.

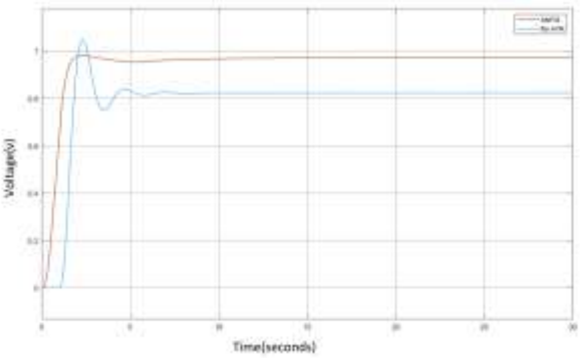

Figure 11. Terminal Voltage Step Response ANFIS Controller Vs Without AMFIS in AVR

Comparative Analysis of AVR Controllers:

A comprehensive comparison of the terminal voltage step responses for all three controllers, along with the uncompensated AVR system, is presented in Figure 12. The PID, fuzzy, and ANFIS controllers all significantly outperform the uncompensated system, showcasing the importance of implementing a control strategy.

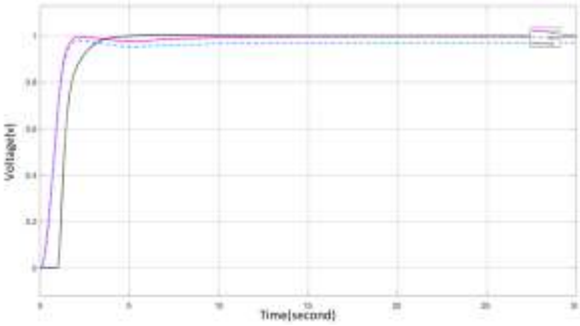

Figure 12. Response of AVR, with PID, Fuzzy Logic and ANFIS Controllers'

Table 2 summarizes the key performance metrics – settling time, overshoot, and rise time – for each controller. This quantitative comparison reveals that while all three controllers improve the system, the ANFIS controller achieves marginally faster response times and minimal overshoot, suggesting its suitability for applications demanding high performance and adaptability.

Table 2. Performance Parameters of Different Control Techniques.

Controller	Settling time (%)	Overshoot (%)	Rise Time (%)
PID	1.0052	0. 5213	1.1816
Fuzzy Logic	0.9993	0.658	1.0091
ANFIS	0.9816	0.9794	0. 9632

4.2. Reactive Power and Voltage Control (AVR)

Frequency Response Analysis

Initial simulations focused on analyzing the frequency response of a two-machine LFC system without any control intervention in Figure 13. The introduction of a step load change revealed a significant frequency deviation, highlighting the system's inherent instability under disturbances in Figure 14.

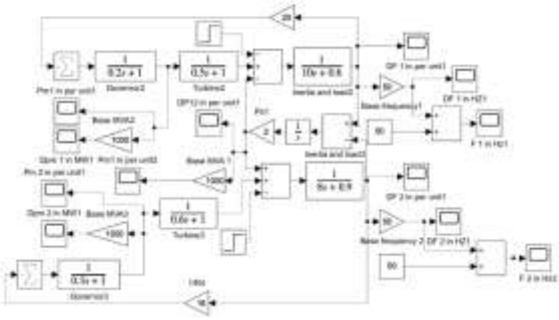

Figure 13. Frequency Response for Two Two-Machine LFC System

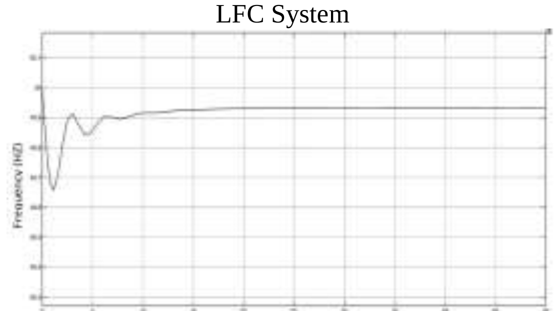

Figure 14. Response of Frequency without Controller

ACE-Based Control Performance:

To address the observed frequency instability, an ACE-based controller was incorporated into the LFC system in Figure 15. This strategy led to a drastically improved frequency response, effectively minimizing deviations and maintaining the desired frequency level in Figure 16. The ACE controller successfully adjusted generation dispatch, ensuring a stable power system operation even under load disturbances.

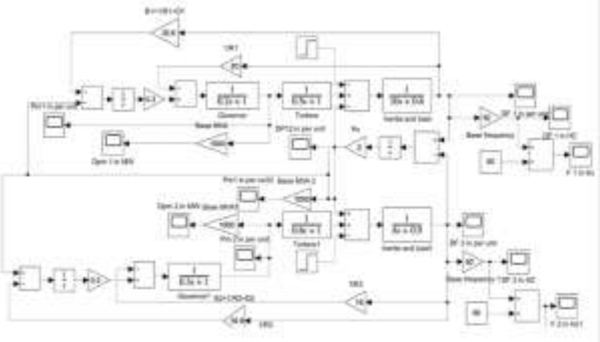

Figure 15. Frequency Response for Two-Machine LFC System using a Controller ACE.

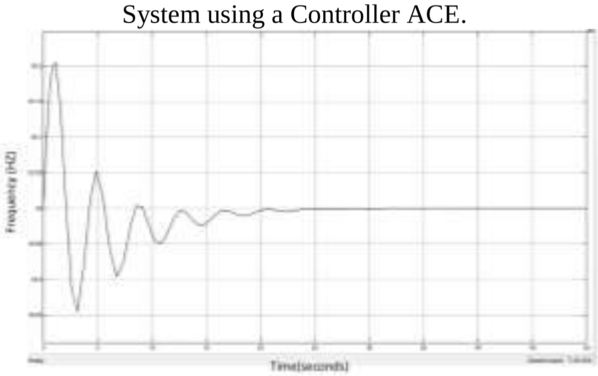

Figure 16. Response of Frequency with Controller ACE

Comparative LFC Performance:

Figure 17 provides a clear visual comparison between the LFC system's behavior with and without the ACE controller. The uncontrolled system exhibits significant frequency drops upon load changes, leading to potential instability and blackouts due to imbalances between generation and demand.

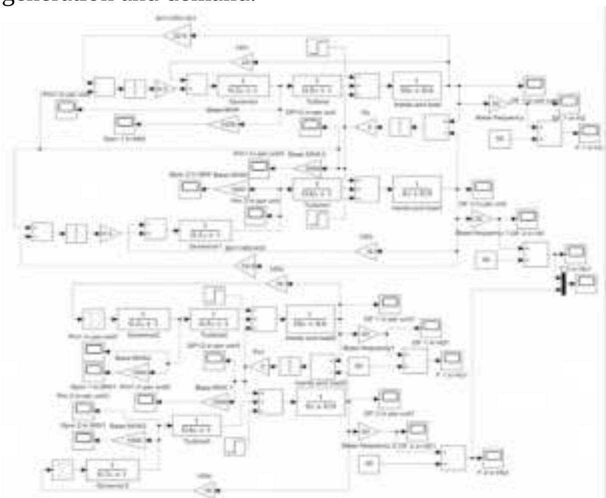

Figure 17. LFC System without a Controller and with Controller ACE.

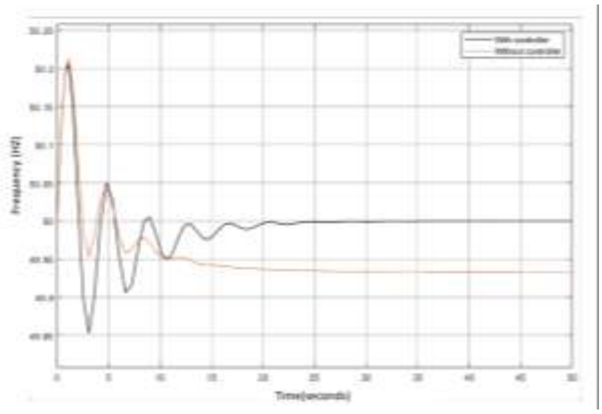

Figure 18. Response of Frequency without Controller and with Controller ACE

In contrast, the ACE-controlled system maintains a near-constant frequency in Figure 18, highlighting the controller's efficacy in regulating generation and ensuring a stable power supply. The improved response translates to enhanced reliability and prevents potential disruptions caused by frequency deviations.

This research demonstrates the crucial role of advanced control strategies in enhancing the performance and stability of AVR and LFC systems. While the PID controller proves to be an effective solution for AVR systems, the ANFIS controller demonstrates superior adaptability and response times, making it a compelling option for applications requiring high performance. In the context of LFC, incorporating ACE signals as a feedback mechanism drastically improves frequency regulation, ensuring a more stable and reliable power system operation. The insights gleaned from this study provide valuable guidance for selecting and implementing appropriate control strategies to meet the evolving challenges of modern power systems.

5. CONCLUTION

This research has examined the crucial significance of advanced control strategies in improving the stability and responsiveness of Automatic Voltage Regulator (AVR) and Load Frequency Control (LFC) systems, which are vital elements for ensuring dependable power system operation. This research has obtained useful insights into the effectiveness of various control approaches by thorough modeling, simulation, and comparison analysis. The inquiry on AVR optimization emphasized the substantial performance improvements that may be achieved by carefully choosing the controller. Although the standard PID controller has shown its potential to enhance system stability and response time, intelligent control techniques such as fuzzy logic and ANFIS have showed higher performance. The ANFIS controller, which combines fuzzy logic and neural networks, demonstrated exceptional adaptability and achieved the quickest response times with low overshoot. This makes it an excellent option for high-performance AVR applications, the incorporation of Area Control Error (ACE) signals as a feedback mechanism in LFC systems proved particularly successful in controlling frequency variations induced by load disturbances. The ACE-based controller effectively managed generator dispatch, providing consistent frequency levels and mitigating the risk of blackouts caused by power imbalances. This discovery emphasizes the significance of integrating up-to-date system data into control algorithms to improve the stability and dependability of the power grid.

The findings obtained from this research have substantial practical ramifications for power system engineers and operators. This study offers significant information for designing and executing control strategies to optimize Automatic Voltage Regulation (AVR) and Load Frequency Control (LFC) systems. It carefully considers aspects such as system dynamics, performance requirements, and controller complexity. As power grids continue to evolve with the increasing penetration of renewable energy sources and the growing demand for reliable electricity, the development and implementation of advanced, adaptive control techniques will become even more critical in ensuring a robust and sustainable power infrastructure.

Future research possibilities include studying the performance of hybrid control methods, exploring the potential of more advanced optimization techniques for controller tuning, and validating the proposed strategies through hardware-in-the-loop testing on real-world AVR and LFC systems.

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Saiful Islam Tuhin
Bangladesh University of Business and Technology (BUBT),
Dhaka 1216, Bangladesh
saifulislamtuhin15@gmail.com
ORCID: 0009-0002-4351-9374

Md. Al Araf
Bangladesh University of Business and Technology (BUBT),
Dhaka 1216, Bangladesh
md.al.araf.2001@gmail.com
ORCID: 0009-0000-7058-8784

Md. Sahadat Hossain Sani
Bangladesh University of Business and Technology (BUBT),
Dhaka 1216, Bangladesh
sahadathossainsani@gmail.com
ORCID: 0009-0003-4215-6249

Tahrim Fatiha
Central Queensland University,
Norman Gardens QLD 4701,
Australia
tahrim.fatiha@gmail.com

Avijit Kundu
Bangladesh University of Business an Technology (BUBT),
Dhaka 1216, Bangladesh
avijitkundu1280@gmail.com
ORCID: 0009-0003-2214-8823