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# Stability Analysis of Multi-Source Power Systems Using Fuzzy Logic and Integral Controllers for Load Frequency Regulation

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**Abstract-** The increasing integration of diverse energy sources into modern power systems presents significant challenges in maintaining frequency stability due to their variable and nonlinear characteristics. This study investigates the stability and dynamic performance of a multi-source power system comprising thermal, hydro, and renewable energy sources under load disturbances. A comparative analysis of Fuzzy Logic Controllers (FLC) and conventional Integral Controllers (IC) is conducted for Load Frequency Regulation (LFR). The proposed FLC is designed to handle system nonlinearity and parameter uncertainties by dynamically adjusting control signals based on rule-based inference. Time-domain simulations are performed in MATLAB/Simulink to evaluate system responses in terms of frequency deviation, settling time, and overshoot. The results demonstrate that the FLC provides superior transient and steady-state performance compared to the traditional IC, effectively enhancing the stability and robustness of the multi-source power system. This work supports the adoption of intelligent control strategies for improved frequency regulation in complex, hybrid power networks.
**Keywords**: AGC, Fuzzy logic controller, I Controller, Stability Analysis, Wind power generation.

## I.INTRODUCTION

The increasing integration of diverse energy sources into modern power grids, including renewable and conventional systems, has introduced significant challenges to the stability and control of power system operations. Among these challenges, maintaining the nominal system frequency in the presence of load disturbances and fluctuating generation—commonly referred to as Load Frequency Regulation (LFR)—has become a critical area of focus. Effective LFR is essential to ensure system reliability, power quality, and seamless interconnection among multiple power sources such as thermal, hydro, solar, and wind units [1].

In multi-source power systems, dynamic interactions and uncertainties due to variable renewable generation complicate the control strategies traditionally employed for load frequency control (LFC). Classical controllers, particularly Integral Controllers, have been widely used owing to their simplicity and robust steady-state error performance. However, they often struggle to adapt to the nonlinearities and time-varying nature of multi-source systems, potentially compromising transient performance and overall stability [2-3].

To address these limitations, intelligent control methods such as Fuzzy Logic Controllers (FLCs) have emerged as promising alternatives. FLCs offer the ability to handle system nonlinearity and uncertainty without requiring an exact mathematical model, making them highly suitable for modern, complex power networks. By combining the conventional integral action with fuzzy inference mechanisms, hybrid control strategies can leverage the advantages of both approaches—achieving improved dynamic response and enhanced system robustness.

This paper presents a comprehensive stability analysis of a multi-source power system employing both Fuzzy Logic and Integral Controllers for LFR. The study investigates the frequency dynamics under various operating conditions, assesses the effectiveness of each control strategy, and provides comparative insights into their impact on system stability and performance. Simulation results validate the proposed control schemes, demonstrating the potential of fuzzy-based approaches in enhancing load frequency regulation in contemporary multi-source power systems [4-6].

In remote and rural places where installing electric lines is challenging due to price, right of way restrictions, or environmental considerations, wind power resources are the most cost-effective source of electrical energy [6]. Diesel generators are typically used to create wind resources since they are unpredictable or fluctuate in nature. High reliability is provided by the wind-diesel power generation to increase power to the isolated load. Nevertheless, because the active power requirements of the isolated community vary often, the huge and severe variation of frequency is brought on by the disparity between the generation and load. System device will be disrupted if the deviation could not be controlled and kept within the permissible range. Additionally, the system can become unstable [7].

In AVR and AGC, fuzzy logic controllers are used. Analysed are a large number of triangle-shaped membership functions (MFs) that provide a good response. Fuzzy PI controller has the following benefits: (i) it provides a better approach to copy with incorrect information; (ii) it allows for flexibility in decision-making; and (iii) it provides a good machine/human interface by adopting a human rule for extracting information and by following a logic for the explanation's conclusion [8].

In section (2) explain single area system in thermal, wind briefly with problem formulation. Optimization technique (Fuzzy logic controller) explain in section (3). Finally result analysis and conclusion briefly explain in section (4) and section (5).

## II. SINGLE AREA SYSTEM

2.1 **Thermal power system**: The steam produced in the boiler flows to the turbine blades, where it is converted into mechanical energy, in the thermal model that is being discussed here [1]. This model was chosen for ease of comparison and execution. This energy is changed into electrical energy by employing a generator. Thus, the steam turbine is the focus of the thermal power plant concept. Open loop systems are not employed because the power supply exhibits frequency variations and an erratic nature without a controller. The proper controller gains are used with closed loop systems. single area thermal system is perturbed by 1% steps. Without a controller, the thermal system's reaction is unstable, thus an integral controller value is computed ($K_i$=0.047) through trial and error. After the influence of the controller, the controller significantly increases the system's stability, and the system is approximately stable at 19s, with a pear over shoot of -0.043.

2.2 **Wind power system**: In ref, the transfer functions of wind power system operations with and without pitch controls are primarily investigated. Without the pitch controller, there will be greater variations in a typical step disruption. The fluid coupling serves as the tie line foundation in this arrangement. The change in power is the result of fluid coupling and frequency variation. This is seen as a feedback reaction that links the two systems. The thermal system receives 1% of the step disturbance for each individual reaction. The specifics of a wind system's architecture have already been covered in ref. [9]. The response of a wind system without a pitch and I controller is examined there as well [10]. Changes in wind speed create steady-state errors of 0.052 magnitudes and oscillatory responses from the wind system for both disturbance signals. In order to maintain system stability and prevent wind system components from being harmed by excessive wind speed variation, the steady state error must be under control. There are no matches between the load and generation under standard processing circumstances. The production as a whole is given by Equation (1):

$$P_G=P_{Gth}+P_{GW} \tag{1}$$

Where: $P_{Gth} = K_{th}\, P_G$, $P_{GW}= K_w\, P_G$ $K_{th}$ and $k_w$ stand for the proportions of thermal and wind power generation to total power generation, respectively. The total load dispatch affects the values of Kw and Kth. Equation (7.1), for small perturbation, can be written as:

$$\Delta P_G=\Delta P_{Gth}+\Delta P_{GW} \tag{2}$$

From equation (7.2), under normal operating condition and loading $P_G$=$P_L$=1.0 P.U, we have

$$K_{th}+K_w= 1.0 \tag{3}$$

By adjusting the speed-varying signals, the ungoverned system becomes governed. It is believed that the automatic manipulation of $P_{Cth}$ and $P_{CW}$ by thermal and wind power plants helps to control load frequency. The thermal system and the wind system were initially investigated individually in this paper, both with and without a controller. The performance of the system was also examined, even when the system loads and parameters were changed.

## III.FUZZY LOGIC CONTROLLER

The FLC architecture can be broken down into three categories: allocating inputs to certain regions, figuring out the rules associated with inputs, and defuzzing output to its original value [11]. Determining the process states and control output: The initial stage focuses on choosing the appropriate input signal for the fuzzy logic controller. The content of the rule base antecedent is represented by a selection of process state variables for this controller.

- ACE and ACE change. ACE versus ΔACE
- ACE and change in frequency (ACE Vs Δf)

ACE and change in ACE are selected for the controller created for automatic generation control.

Fuzzy rules: The guidelines used when employing fuzzy controllers are listed in the table 1. The following examples show how the rules work: if ACE is NLa and ACE is NLa, ACE-out is NLa; if ACE is NSm and ACE is NLa, ACE out is NLa; etc. The "Mid-max" rule for "and" and "or" was implemented in the formula as a result. The challenges resulting from measurements and time are reduced to a minimum with this method. Since they differ from the norms, ACE is given far more attention than ACE. As a result, the ACE location with greater influence in this region is allowed to have a dead band on a variation basis.

**TABLE 1:** Rule base for Thermal+Wind system

**ACE**

| **DEL ACE** | **NLa** | **NSm** | **ZEr** | **PSm** | **PLa** |
|---|---|---|---|---|---|
| **NLa** | **NLa** | **NLa** | **NSm** | **NSm** | **ZEr** |
| **NSm** | **NLa** | **NLa** | **NSm** | **ZEr** | **ZEr** |
| **ZEr** | **NSm** | **NSm** | **ZEr** | **PSm** | **PSm** |
| **PSm** | **ZEr** | **PSm** | **PSm** | **PLa** | **PLa** |
| **PLa** | **ZEr** | **ZEr** | **PSm** | **PLa** | **PLa** |

Fuzzy sets: It represents the meaning of the Linguistic variables of the input and output variables. A choice of five or seven classes may be satisfactory. In this case five sets are used. Physical domains: They contain their normalized counter parts and the normalization / demoralization scaling factors. This is very important step as the input and output values of the controller depend mainly on it. These ranges are critical so, a systematic method to get it may help a lot. The domain ranges may be obtained by the past experience. Decision table: A fuzzy system is characterized by a Linguistic statement. It is in the form of "IF-THEN" rules; these rules are easily implemented by fuzzy conditional statements. In fuzzy logic, the collection of fuzzy control rules that are expressed as fuzzy conditional statements forms the rule or the rule set of an FLC. The proper choice of process state variables and control variable is essential to characterize the operation of fuzzy system. Then it describes the output response of the controller at various inputs by a fuzzy logic notation as shown in table 1. The rule base can be developed by relating each value of f and change in f and fuzzy controller out to its maximum membership class.

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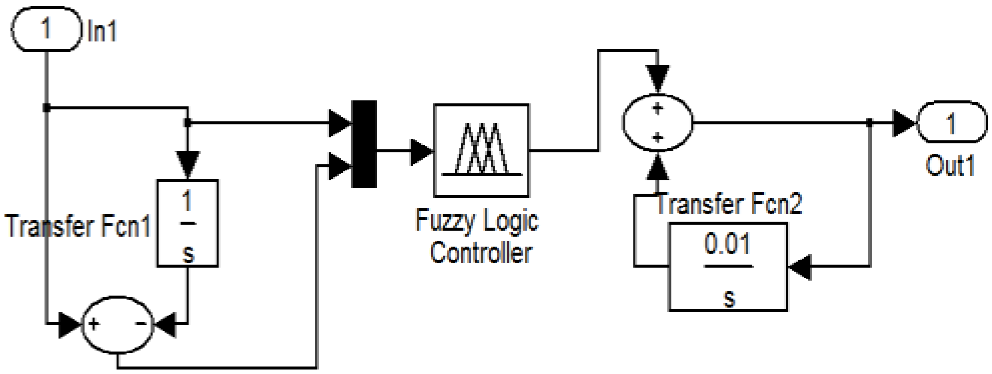


Fig. 1 Fuzzy Controller with Input, Output and Feedback Gain

The fig. 1 shows a fuzzy controller with input, output and feedback gain, Kt. Analysis of fuzzy logic controller provides the fast and better dynamic response. For the 5-member function the optimum value of feedback gain Kt for the thermal area is 0.07 and optimum value of feedback gain Kt for the hydro area is 0.01 respectively.

## IV.RESULT ANALYSIS

The effectiveness of a single area has been discussed how to use a traditional I controller, a fuzzy logic controller, and a MATLAB SIMULINK model for a thermal, wind, and steam+wind system. A controller for fuzzy logic with input, output, and feedback gain. FLC analysis demonstrates that it enables quick and effective dynamic reactions. The optimal gain $K_t$ for the thermal area of the 5-membership function is 0.07, while the optimal feedback gain $K_t$ for the wind area is 0.01, respectively. The FLC is superior, as can be seen from the comparison of the traditional I controller in the following figure 2, 3, and 4. The FLC requires less time for settling than the traditional I controller.

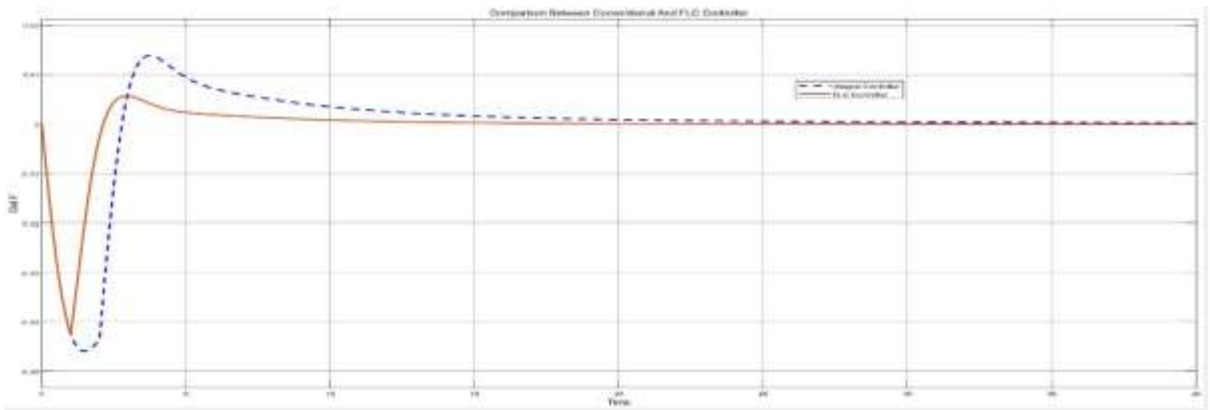

**Fig 2** Performance comparison for a single area steam system using conventional and FLC controllers

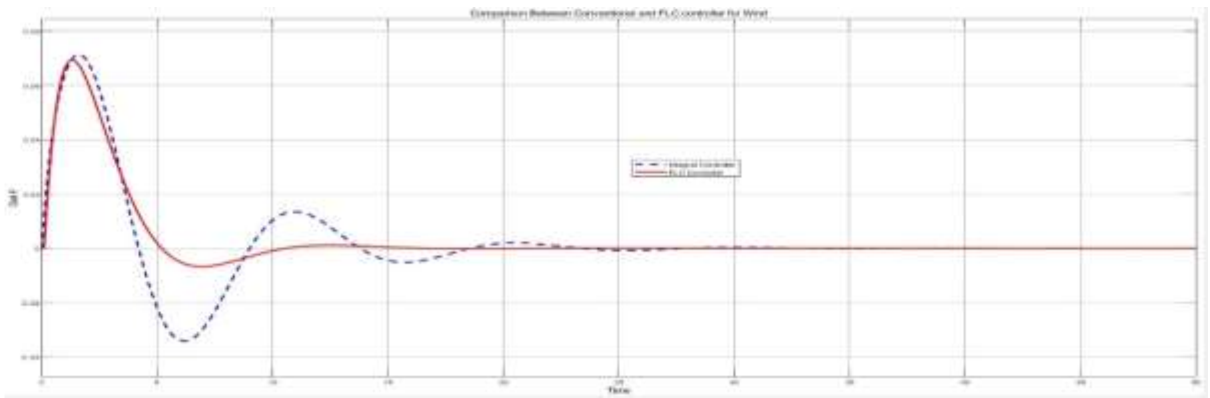

**Fig 3** Performance comparison for a single area Wind system using conventional and FLC controllers

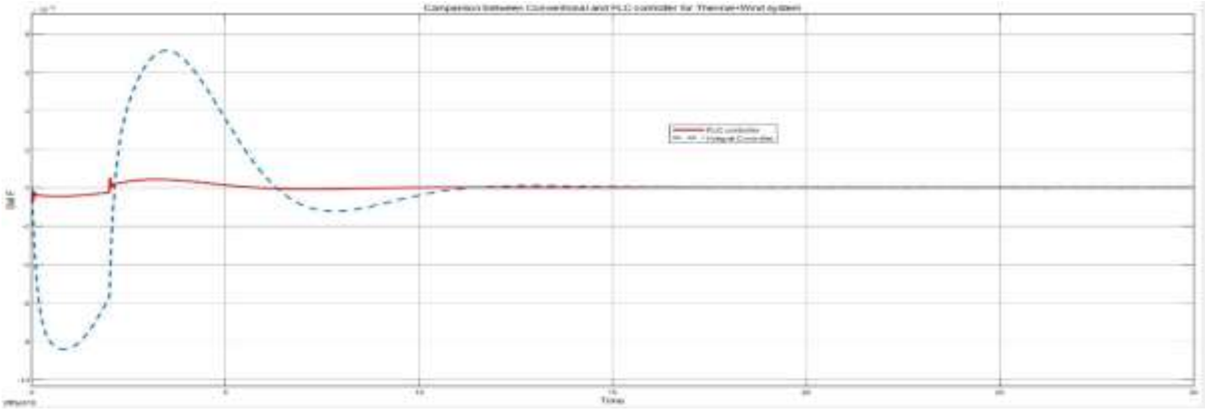

**Fig 4** Performance comparison for a single area Steam +Wind system using conventional and FLC controllers

Table 2 clearly proves that an FLC-based integral controller performs better when compared to a traditional controller by displaying the time required for peak settling and overshoot in a thermal, wind and steam+wind system located at a specific location.

**TABLE 2**: analysis between Conventional I Controller and Fuzzy logic controller

| **S. No.** | **Systems** | **Parameters** | **Conventional I Controller** | **Fuzzy logic Controller** |
|---|---|---|---|---|
| 1 | Steam power system | Settling Time (Ts) | 24 Sec | 13 Sec |
| | | Peak overshoot (Ms) | 0.044 | 0.04 |
| 2 | Wind power system | Settling Time (Ts) | 23 Sec | 11 Sec |
| | | Peak overshoot (Ms) | 0.078 | 0.064 |
| 3 | Steam+Wind power system | Settling Time (Ts) | 13 Sec | 10 Sec |
| | | Peak overshoot (Ms) | 0.009 | 0.004 |

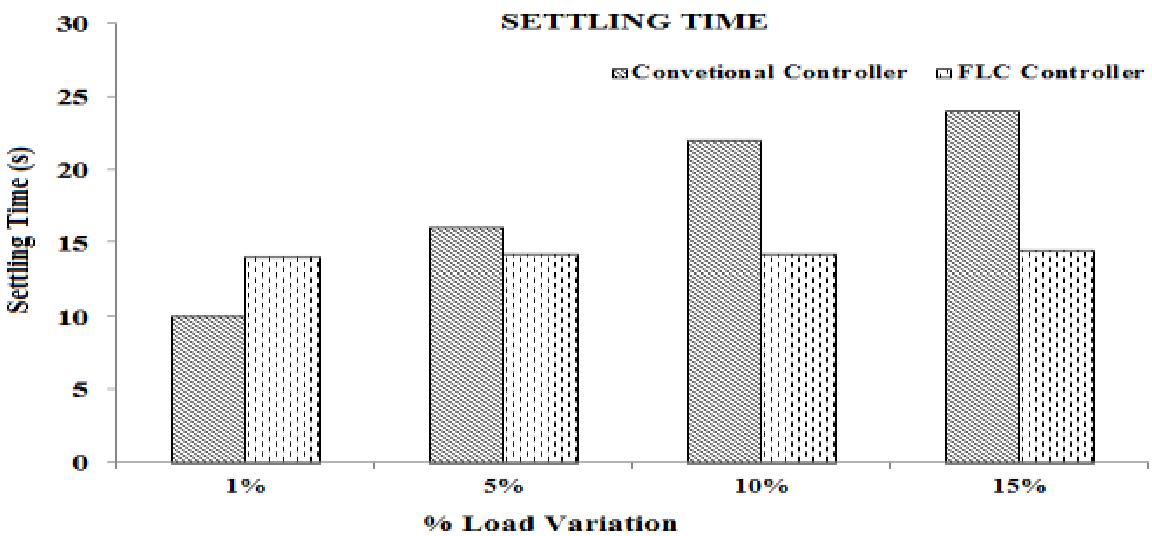

**Fig 5**: Performance comparison of a single area, multigenerational system using conventional and FLC controllers for settling time

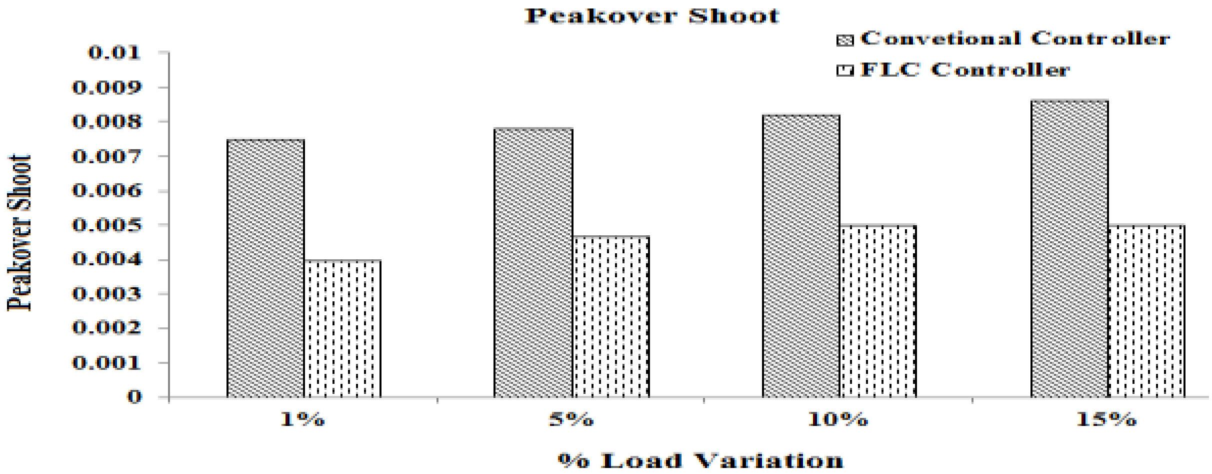


**Fig 6**: Performance comparison of a single area multigenerational system with conventional and FLC controllers for Peak Over Shoot

Simulated integral controller gains for the suggested systems are obtained from the FLC, and the outcome demonstrates the time-domain evolution gradually. It has been demonstrated that the FLC governor in use is more effective than a traditional controller controlled by a Ziegler mechanism. Furthermore, because more system tool knowledge is not required, the suggested controller is simpler and easier to build. The typical area multi-source has been processed for various future generations for a variety of loads with a difference of ±15% and ±15% from the assigned value in both locations, and the scheduled power production from Steam+Wind system are regulated to adapt with the typical operating load as shown in Fig. 5 and 6.

## V.CONCLUSION

This study presented a comprehensive stability analysis of multi-source power systems employing Fuzzy Logic Controllers (FLC) and conventional Integral Controllers for Load Frequency Regulation (LFR). The primary objective was to assess and compare the dynamic performance and robustness of these control strategies in maintaining system frequency within permissible limits under varying load disturbances and generation scenarios. Simulation results demonstrated that Fuzzy Logic Controllers outperform conventional Integral Controllers in terms of settling time, overshoot, and adaptability to system non-linearities and parameter variations. The FLC's ability to incorporate human-like reasoning and handle uncertainties without requiring an accurate mathematical model makes it a highly effective tool for real-world applications in complex power systems.

Furthermore, the integration of multiple power sources such as thermal, hydro, and renewable energy sources introduces additional challenges in maintaining frequency stability due to their differing response characteristics. The proposed fuzzy-based control framework showed strong potential in coordinating these diverse sources more effectively than traditional methods.

In conclusion, Fuzzy Logic Control offers a promising and robust alternative to classical approaches for Load Frequency Regulation in modern, multi-source power systems. Future work may involve hybrid control approaches, incorporation of intelligent optimization techniques, and real-time hardware implementation to further enhance system performance and reliability.

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