

Fuzzy Logic Based Load Frequency Control of a Single Area Power System

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Abstract -

Load frequency control (LFC) is a fundamental requirement for maintaining the stability and reliability of an electric power system, particularly under continuously varying load demand. Any mismatch between generation and demand manifests as a deviation in system frequency, which must be corrected quickly and with minimum oscillation in order to keep the network within its permissible operating limits. This paper investigates the load frequency control of a single area power system, consisting of a speed governor, turbine, generator and load demand, using four different controllers: a conventional Proportional Integral (PI) controller, a Proportional Integral Derivative (PID) controller, a Fuzzy Logic Controller (FLC), and a Fuzzy Tuned PI (FTPI) controller in which the fuzzy inference system dynamically supplies the proportional and integral gains. The controllers are designed and simulated in the MATLAB/SIMULINK environment. Their closed-loop frequency responses are compared based on peak frequency deviation, settling time, steady-state error (SSE), Integral Absolute Error (IAE), and Integral Time Absolute Error (ITAE). A comprehensive comparative analysis is carried out to identify the controller that provides the best overall trade-off between transient response, steady-state accuracy, and error minimization for the single-area power system.

Key Words: Load frequency control, PI controller, PID controller, Fuzzy logic controller, Fuzzy tuned PI controller, Single area power system.

1. INTRODUCTION

Modern electric power systems are subjected to constant fluctuation in load demand as a result of growing population, industrialisation and the increasing penetration of variable loads. Since power cannot be stored economically in bulk, the generation of active power must be continuously adjusted to match the demand at every instant. Any imbalance between generation and load appears as a deviation of system frequency from its nominal value, and utilities are obligated to keep this deviation within a narrow band, typically of the order of ± 0.5 Hz, which is decided largely by the speed response of the turbine-governor system [1].

The task of regulating frequency by adjusting the generator output using speed governor in response to load changes is known as load frequency control, and it forms one of the important functions of Automatic Generation Control (AGC). In an interconnected system with more than one control area, LFC is additionally responsible for regulating the tie-line power exchange between areas so that each area supplies its own load changes while the scheduled interchange with

neighbouring areas is maintained. In a single area system, which is the scope of the present work, there is no tie-line to be regulated and the entire task reduces to restoring the system frequency to its nominal value as quickly as possible following a load disturbance.

A wide variety of controllers have been proposed in the literature for LFC. The conventional PI controller remains the most widely adopted controller in industry on account of its simplicity and its ability to drive the steady state frequency error to zero [2]. The PID controller extends this idea with an additional derivative action that improves the transient response of the system [3]. Beyond these classical controllers, fuzzy logic based controllers have received considerable attention because they can incorporate expert knowledge of the system through linguistic rules and do not require an accurate mathematical model of the plant [4], and have been reported to perform well in both single area and multi-area interconnected systems [5], [6].

Several researchers have also proposed hybrid schemes in which a fuzzy system is used only to tune the gains of a conventional controller, combining the robustness of conventional controllers with the adaptability of fuzzy logic [7], [8]. Evolutionary and metaheuristic techniques have likewise been used to tune controller parameters, including electro-search optimisation [9], teaching-learning based optimisation [3] and marine predator algorithm based tuning [8], while neural network based controllers have been explored as an alternative to fuzzy logic [10]. More recent studies have examined fuzzy model predictive control [11], [12] and optimisation based strategies for renewable-rich power systems, where increasing wind and solar penetration adds further variability to the load-generation balance [13], [14].

The present work builds on this literature and focuses specifically on a single area power system. Unlike two area or multi-area studies, which must additionally model the tie-line power flow, a single area study allows the performance of individual controllers to be examined in isolation. Four controllers – PI, PID, FLC and FTPI – are designed for the single area system and compared for a step change in load demand. The gains for the PI and PID controllers are obtained using the Cohen-Coon reaction curve method, while the fuzzy controllers use a rule base derived from the frequency error and its rate of change.

The remainder of this paper is organised as follows. Section II describes the model of load frequency control for a single area system. Section III presents the design of the four controllers. Section IV outlines the Cohen-Coon tuning technique. Section V presents the simulation results and comparative analysis. Section VI concludes the paper.

2. LOAD FREQUENCY CONTROL MODEL OF SINGLE AREA SYSTEM

The physical mechanism responsible for load frequency control is the speed governing system of the turbine-generator unit. The speed governor senses the deviation of the turbine speed from its reference value and, through a linkage mechanism, adjusts the position of the governor valve that controls the flow of high pressure steam (or water, in the case of a hydro unit) into the turbine. When the load increases, the turbine tends to slow down and the governor increases the valve opening to deliver more power; when the load decreases, the governor reduces the valve opening. This closed loop action alone, however, cannot restore the frequency exactly to its nominal value, and a supplementary control loop – the load frequency controller – is required to drive the steady-state frequency error to zero.

For analysis and controller design, the single area power system is represented as a cascade of three first-order transfer function blocks: the speed governor, the turbine, and the generator-load combination, together with the feedback path corresponding to the speed regulation of the governor.

$$G_g(s) = \frac{K_g}{(1+sT_g)}, G_t(s) = \frac{K_t}{1+sT_t}, G_p(s) = \frac{K_p}{1+sT_p} \quad (1)$$

where K_g and T_g are the gain and time constant of the speed governor, K_t and T_t are the gain and time constant of the turbine, and K_p and T_p are the power system gain and time constant, representing the combined inertia of the generator and the frequency sensitivity of the load. The speed regulation R (Hz/MW) forms the feedback path around the forward path, so that an increase in frequency reduces the governor reference. The load frequency controller (PI, PID, fuzzy, or fuzzy tuned PI) is placed in the forward path, acting on the frequency error $\Delta F(s)$ to generate the control signal $\Delta P_c(s)$ in response to a load disturbance $\Delta P_D(s)$.

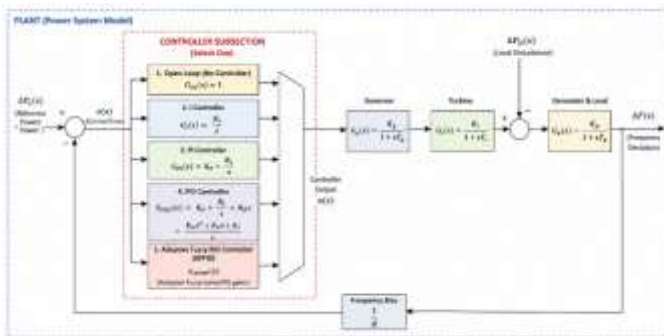


Fig -1: Proposed single-area Load Frequency Control (LFC) system with the controller subsystem.

Figure 1 illustrates the proposed single-area LFC system consisting of a reference input, error calculation unit, controller subsystem, governor, turbine, generator-load model, load disturbance input, droop feedback, and frequency deviation output. The controller subsystem incorporates the four control strategies compared in this paper – PI, PID, Fuzzy Logic, and Fuzzy Tuned PI – to generate the control signal (ΔP_c) applied to the governor. The governor and turbine regulate the mechanical power supplied to the generator, while the generator-load model produces the system frequency deviation (ΔF). A load disturbance (ΔP_D) is introduced to evaluate the dynamic performance of each controller, and the droop

feedback ($1/R$) provides primary frequency regulation by feeding the measured frequency deviation back to the governor input. The parameters used for the single area system considered in this work, namely K_p, T_p, T_g, T_t and R , are summarised in Table I.

TABLE I. SINGLE AREA SYSTEM PARAMETERS

Parameter	Value
K_p	120
T_p	20
T_g	0.08
T_t	0.3
R	2.4

3. CONTROLLERS USED FOR LOAD FREQUENCY CONTROL

A. PI Controller

The Proportional Integral controller is the controller most commonly employed for LFC in industry because of its simple structure and its ability to eliminate steady-state frequency error. The integral action accumulates the error over time until it is driven to zero, while the proportional term provides a fast initial correction. Its transfer function is

$$G_{PI}(s) = K_p + \frac{K_i}{s} \quad (2)$$

where K_p is the proportional gain and K_i is the integral gain. While the PI controller removes steady-state error effectively, it can produce a comparatively larger settling time and overshoot for large load disturbances.

B. PID Controller

The PID controller adds a derivative term to the PI structure so that it also reacts to the rate of change of the error:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d s \quad (3)$$

The derivative action anticipates the trend of the error and improves the transient response, reducing overshoot and settling time compared with a pure PI controller, though it also makes the controller more sensitive to measurement noise.

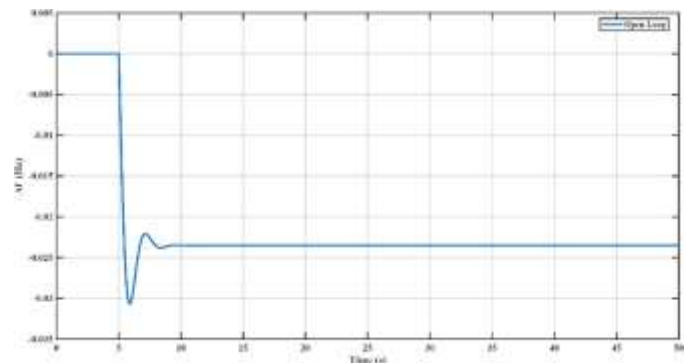


Fig -2: Open loop response of the single area system.

C. Fuzzy Logic Controller

The fuzzy logic controller (FLC) does not rely on an explicit mathematical model of the plant and instead encodes the control action as linguistic if-then rules. It has three stages:

fuzzification, where the crisp inputs frequency error e and change in error Δe are converted to linguistic variables using membership functions; rule evaluation, where the rule base combines the fuzzified inputs; and defuzzification, which converts the fuzzy output back to a crisp control signal. Triangular membership functions are used for both inputs and the output, which is the change in the governor reference power.

D. Fuzzy Tuned PI Controller

The Fuzzy Tuned PI (FTPI) controller retains the structure of a PI controller but replaces its fixed gains with gains computed on-line by a fuzzy inference system, based on the instantaneous error and its rate of change. When the error is large the fuzzy system selects a larger proportional gain to speed up correction, and as the error reduces it lowers the gains to avoid overshoot. This combines the zero steady-state error property of the PI controller with fuzzy adaptability, and has been reported to reduce settling time relative to a fixed-gain PI controller [7].

4. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

The closed loop performance of the single area system is evaluated in the MATLAB/SIMULINK environment for a step change in load demand, using each of the four controllers described in Section III in turn. For every case, the frequency deviation ΔF is recorded as a function of time, and the resulting transient response is used to extract the settling time, peak frequency deviation, steady-state error, peak frequency deviation, steady-state error (SSE), Integral Absolute Error (IAE), and Integral Time Absolute Error (ITAE) for that controller.

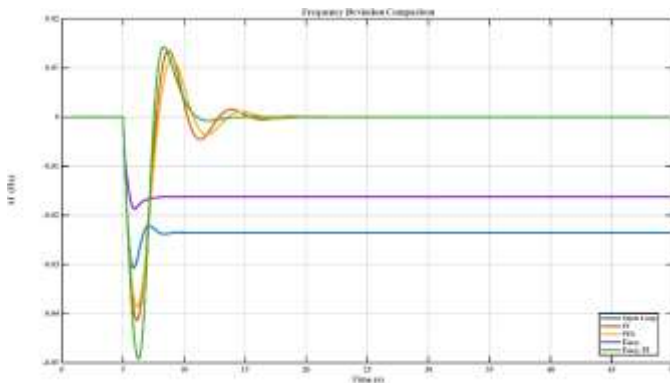


Fig -3: Frequency deviation (ΔF) with change in load demand for the four controllers.

Fig. 2 shows the open-loop frequency response of the single-area power system under a change in load demand, resulting in a noticeable frequency deviation. Fig. 3 compares the frequency responses obtained using the four controllers, namely PI, PID, Fuzzy, and Fuzzy-PI. The controlled responses significantly reduce the frequency deviation compared with the open-loop response.

The membership functions used for the fuzzy tuned PI controller are shown in Fig. 4. The Fuzzy-Tuned PI controller employs two input variables, namely Error (e) and Change of Error (Δe), and two output variables, namely change in proportional gain (ΔK_p) and change in integral gain (ΔK_i). Each variable is represented using five linguistic membership functions: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The membership

functions are defined according to the operating ranges specified in the MATLAB Fuzzy Inference System (FIS) design. The corresponding fuzzy rule base is summarised in Table II.

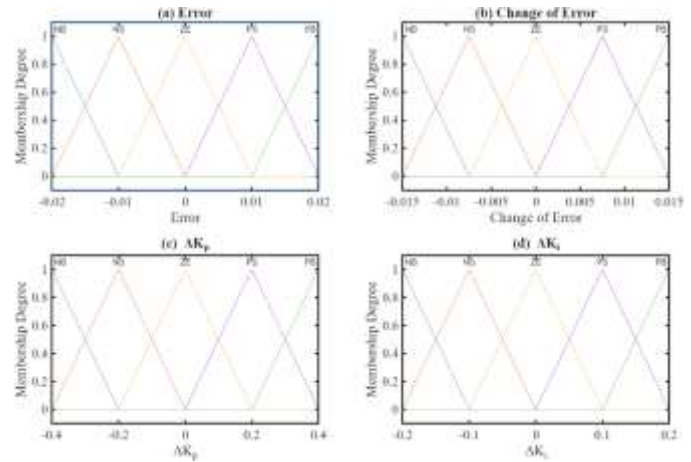


Fig -4: Membership functions of the input and output variables used in the fuzzy-tuned PI controller: (a) Error, (b) Change of Error, (c) ΔK_p , and (d) ΔK_i

TABLE II. FUZZY RULE BASE FOR THE FUZZY TUNED PI CONTROLLER

Linguistic Variable	Error	Change of Error	ΔK_p	ΔK_i
NB	$[-0.025, 0]$	$[-0.02, 0]$	$[-0.4, -0.2]$	$[-0.2, -0.1]$
NS	$[-0.025, 0]$	$[-0.02, 0]$	$[-0.4, 0]$	$[-0.2, 0]$
ZE	$[-0.0125, 0.0125]$	$[-0.01, 0.01]$	$[-0.2, 0.2]$	$[-0.1, 0.1]$
PS	$[0, 0.025]$	$[0, 0.02]$	$[0, 0.4]$	$[0, 0.2]$
PB	$[0, 0.025]$	$[0, 0.02]$	$[0.2, 0.4]$	$[0.1, 0.2]$

Settling time, peak frequency deviation, steady-state error, Integral Absolute Error, and Integral Time Absolute Error obtained for each of the four controllers are summarised in Table III.

TABLE III. COMPARISON OF PI, PID, FUZZY AND FUZZY TUNED PI CONTROLLERS

Controller	Peak	Settling	SSE	IAE	ITAE
Open Loop	0.0307	7.6219	0.023506	1.0574	29.0893
PI	0.0413	14.7238	0.000024	0.1020	0.7830
PID	0.0386	15.4428	0.000024	0.0990	0.7645
Fuzzy	0.0187	7.2260	0.016181	0.7274	20.0226
FTPI	0.0492	10.6084	0.000024	0.1041	0.7432

From the results, it can be seen that the conventional PI controller, while simple, tends to give a comparatively longer settling time. The PID controller improves the transient response through its derivative action but can be more sensitive to noise. The fuzzy logic controller adapts to the instantaneous operating condition of the system and is generally found to

reduce the settling time in comparison with the fixed-gain controllers, while the fuzzy tuned PI controller, by continuously adjusting the PI gains according to the fuzzy rule base, offers a further improvement, achieving a favourable balance between fast transient recovery and low steady-state frequency deviation. These trends for the single area system are broadly consistent with the improvements reported for fuzzy and fuzzy-tuned controllers in multi-area studies [1], [7].

Table III compares the performance of different controllers using peak response, settling time, SSE, IAE, and ITAE. The Open-Loop system has a peak of 0.0307, settling time of 7.6219 s, and relatively high SSE (0.023506), IAE (1.0574), and ITAE (29.0893), indicating poor steady-state regulation.

The PI controller significantly reduces the SSE to 0.000024, with IAE and ITAE of 0.1020 and 0.7830, respectively. The PID controller further improves the error performance, achieving an IAE of 0.0990 and the lowest ITAE among the conventional controllers (0.7645).

The Fuzzy controller provides the best transient response, with the lowest peak (0.0187) and shortest settling time (7.2260 s). However, its SSE (0.016181) remains higher than that of PI, PID, and Fuzzy-PI controllers.

The Fuzzy-PI controller achieves a low SSE of 0.000024, a settling time of 10.6084 s, and the lowest overall ITAE of 0.7432. Although its peak response (0.0492) is comparatively higher, it provides a good balance between transient and steady-state performance. Hence, the Fuzzy-PI controller demonstrates improved overall error performance and effective steady-state regulation, making it a suitable choice for the proposed system.

5. CONCLUSION

This paper has presented the design and comparative evaluation of PI, PID, fuzzy logic, and fuzzy tuned PI controllers for the load frequency control of a single area power system. The gains of the conventional PI and PID controllers were obtained using the Cohen–Coon reaction curve tuning method, while the fuzzy logic and fuzzy tuned PI controllers were designed using a two-input, one-output for fuzzy logic case and two-output for the FTPI case. fuzzy inference system based on the frequency error and its rate of change. Simulation results for a step change in load demand show that, while the conventional PI controller is effective at removing steady-state frequency error, the fuzzy-based controllers and in particular the fuzzy tuned PI controller offer a noticeably faster transient response for the single area system. Future work may extend this single area study to a two-area or multi-area interconnected system, and may also explore metaheuristic optimisation of the fuzzy rule base and membership functions to further improve the dynamic performance of the controller.

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