

PI and Fuzzy Logic Controller-based Analysis of Load Frequency Control for Thermal–Nuclear Hybrid Energy Systems

Yatinkumar Rajendrabhai Daraji^{1,*}, Kalpana Meena²

Abstract

In this study, a two-area system is analyzed, where area-1 contains a thermal power plant and area-2 houses a nuclear power plant. By combining these domains, two-area thermal–nuclear systems are developed in the MATLAB Simulink framework. To ensure the quality of power generated and to feed the load, generation should be raised in tandem with the growth in load demand, or the network should be connected. Using various controllers, load frequency control (LFC) is utilized to stabilize the power system's factors. We are comparing the in motion and settling time values for each scenario utilizing PI and fuzzy logic control approaches separately for 1% disturbance in either area to examine the performance of a two-area system. The simulation's outcome demonstrates that the fuzzy logic controller solves the LFC problem effectively. Hybrid energy systems have emerged from the integration of renewable and non-renewable energy sources, offering enhanced efficiency and reliability. This paper focuses on the analysis of Load Frequency Control (LFC) in thermal-nuclear hybrid energy systems using fuzzy logic controllers (FLC) and proportional-integral (PI) controllers. The study aims to compare these different control strategies to identify their respective advantages and disadvantages in maintaining system performance and stability across various load scenarios.

Keywords: Fuzzy Logic controller, PI controller, load frequency control (LFC), thermal–nuclear hybrid energy system

INTRODUCTION

Large-scale power systems are typically operated by considering that they are composed of interconnected control zones. All control areas must fulfill their scheduled exchange powers as well as their demands [1]. A variation in frequency can be used to detect any mismatch between the generation and load areas, where a failure to any load shift could occur and have an impact on other regions. The interchange of power with constant main frequency and bus voltage is one of the most significant

benefits of this system [2]. As soon as possible, the oscillation frequency and voltage values that cause power load variations must be eliminated from electric power transmission networks to maintain high quality and consistency [3]. A crucial component of the quality of electricity systems is fixed frequency. Some of the harmonics are caused by subscribers linked to the energy system at a frequency where fluctuations in energy demand occur [4]. These variations should be detected by the load frequency management system, which is not distorted. The operational goals of load frequency control (LFC) are to regulate the tie-line exchange schedules and maintain a fairly constant frequency to split the load among the generators [5].

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By decreasing the peak overshoot and bringing the steady-state error to zero, the PI and fuzzy controllers aid in the regulation of fluctuations in the load frequency [6].

REASONS FOR KEEPING FREQUENCY CONSTANT

The following justifies maintaining stringent restrictions on fluctuations in system frequency. The AC motor speed and frequency are closely correlated [7]. Although a frequency difference of 50 ± 1.5 Hz does not significantly influence most AC drives, some applications require higher-order consistency in terms of speed. Synchronous motors power electric clocks and the accuracy of these clocks depends not only on the frequency error but also on the integral of this error. Turbine blade damage is likely to occur if the turbines are operated at speeds that correspond to frequencies greater than or equal to 47.5 Hz or 52.5 Hz, given that the usual frequency is 50 Hz. Consequently, a rigorous frequency limit should be maintained. Owing to the concomitant decrease in load demand, providers experience a loss of revenue when the system operates at a frequency and voltage below normal. The network frequency must remain consistent for the power plants to operate satisfactorily in parallel. If the frequency deviation is strictly within the limits, the overall functioning of the power system can be better managed. The actual power balance of the entire network is directly correlated with frequency [8]. Variations in frequency lead to variations in the speed of a consumer plant, which impacts production operations [9]. A nuclear power plant's governor model is shown in Figure 1. The turbine model for nuclear plants circuit diagram is shown in Figure 2.

THERMAL-NUCLEAR INTERCONNECTED POWER SYSTEM

Figure 3 illustrates a two-area system composed of two single-area systems joined by a tie-line. Each area supplies its user pool, and the tie-line permits electricity to move between areas. The tie-line power fluctuations contain local area information. Consequently, both locations receive the sensed tie-line power and the consequent tie-line power signal. It is a convenient assumption that a turbine, generator,

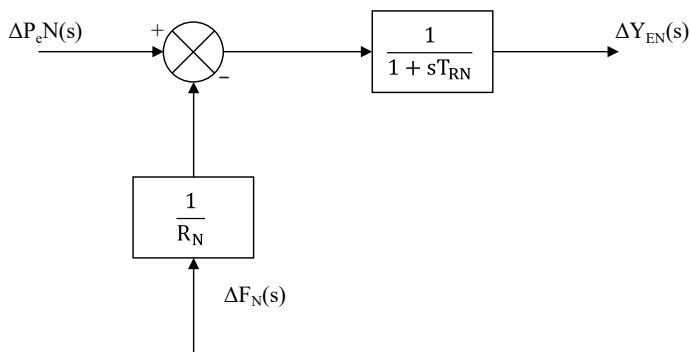


Figure 1. Governor model representation of the nuclear plant.

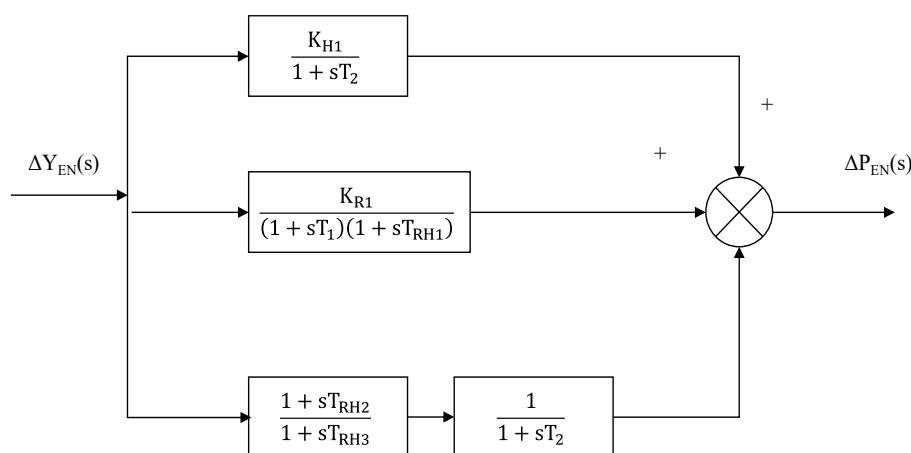


Figure 2. Turbine model for nuclear plant.

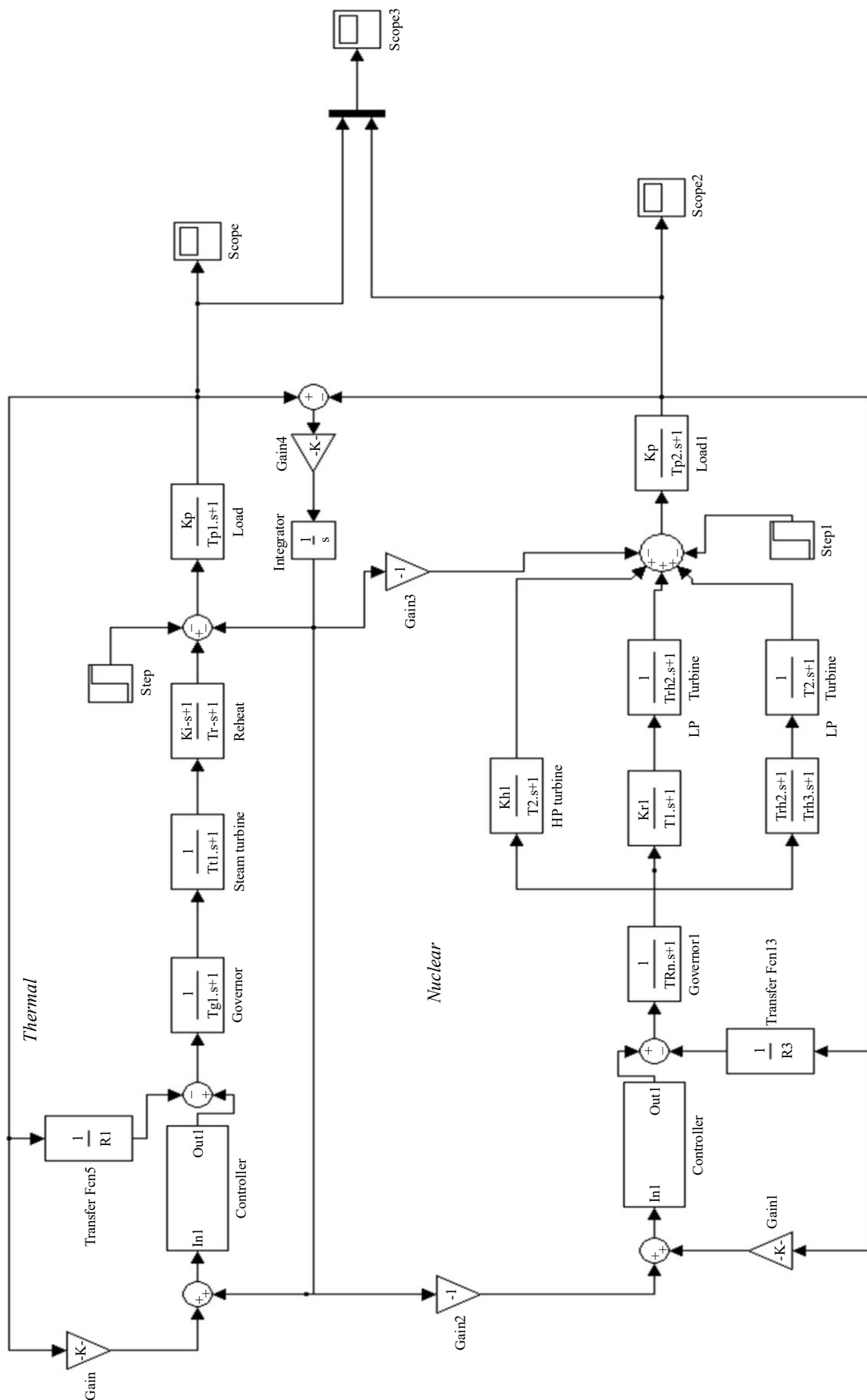


Figure 3. Model representation of controlled two-area thermal–nuclear system.

and governor system of equal sizes can be used to represent each control region. Area 1 is denoted by symbols with a suffix of 1, and area 2 is denoted by symbols with a suffix of 2. The turbines, speed governors, and generators for nuclear power systems must be simulated. In this instance, one high-pressure turbine (HP) and two low-pressure turbines (LP) were employed. The nuclear turbine's block diagram is displayed as in Figure 2.

The transfer functions of the low- and high-pressure turbines are shown in Figure 3. When high-pressure steam initially enters the primary impetus turbines, the high-pressure turbine is designed to efficiently separate the work from it. The goal of the low-pressure turbine is to efficiently extract work from the steam that the high-pressure turbine loses at low pressure [10].

In this case, the power system architecture can be divided into several load recurrence control areas connected by tie lines. Currently, the main objectives are to maintain tie-line power adjustments for each region and to regulate or modify the rate of recurrence in each region [11]. Any changes to the framework load in the primary load frequency control loop will result in a consistent state deviation in the frequency, which is dependent on the regulator's speed parameter. Therefore, we should provide a reset action or control action to manage these frequency deviations to reduce the rate of recurrence variation to zero. Here, a PI controller and fuzzy controller were employed to maintain the frequency at a steady level.

CONTROL METHODOLOGY

PI Controller

The PI-type controller is one of the most often utilized control laws in the regulating systems of thermal and hydropower plants. As proportional controllers have faster transient responses, they can attain steady-state conditions considerably more quickly. For $u(t) = K_p e(t)$, the proportional term of the controller generates a control signal proportional to the system error. Generally, low values of K_p result in reliable responses with substantial steady-state errors when there is a step shift in load demand. A better steady-state performance was achieved with higher K_p values, but the transient reaction was worse. As a result, even if increasing the gain K_p lowers the system time constant and damping, it is utilized to lower the steady-state error. It follows that the selection of the ideal K_p value is obvious [12]. The steady-state error of the system cannot be eliminated by proportional action because a limited amount of error is necessary to provide a control output, as shown in Figure 4. Integral action in the controller is a popular method for reducing the steady-state error [13]. In this case, the integral of the error signal determines the resulting control signal:

$$U(t) = K_i \int e(t) dt$$

Where, K_i represents integral gain.

The integrator prefers to increase the control action when there is an error that moves the plant output closer to the demand output. The ongoing integrator output can then be utilized to maintain the control action required for steady-state conditions once the error vanishes. However, an overshoot, which increases dramatically as a function of gain, occurs if the integrator K_i 's gain is sufficiently high. This is undesirable. A lower K_i value shortens the rise time of the system but decreases the overshoot. Following the discussion, it is necessary to appropriately design both the K_p and K_i .

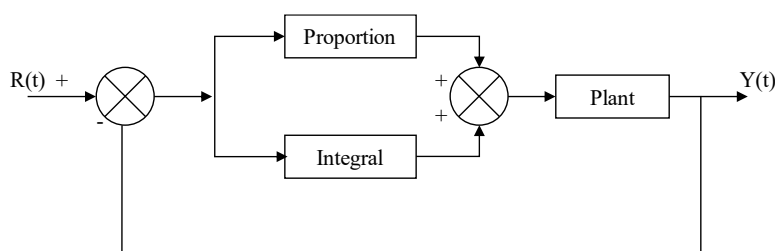


Figure 4. PI controller block diagram.

Fuzzy Logic Controller

In control system engineering, fuzzy logic is a problem-solving approach or thought process used to regulate systems in situations where inputs are either imprecise or lack mathematical models entirely. Distributed processors are likely to be simpler to design because fuzzy logic can handle a respectable number of inputs; however, as the number of inputs and outputs increases, so does the system complexity. The process of transforming a sharp quantity into a fuzzy quantity is called fuzzification. However, they are somewhat ambiguous. If imprecision, ambiguity, or vagueness are sources of uncertainty, the variable is most likely fuzzy and can be represented by a membership function. Fuzzification is the process of turning a precise quantity into a fuzzy quantity, whereas defuzzification is the process of turning a fuzzy quantity into a crisp quantity. A fuzzy inference system is created using the smallest of the maximum methods, which is one of several defuzzification techniques. The inference rules engine, defuzzification interface, and fuzzy logic interface are the three primary steps in fuzzy logic control. The processes operator is expected to react to errors in variables (e) and changes in errors (ce) for load frequency control. Figure 5 shows the fuzzy logic controller (FLC) with errors and changes in the error.

The real power system frequency variation (Δf) is equal to the variable error. The difference between the real power system frequency (f) and the nominal or scheduled power system frequency (f_N) is known as the frequency deviation, or Δf . Considering the global function of the FLC output signal with the scaling gains is as follows:

$$\Delta Pc = F [n c e(k), n c e ce(k)]$$

Where, F is a fuzzy nonlinear function and ne and nce are the error and change in error scaling gains, respectively. The FLC depends on the scaling gains of the inputs (Ha QP, 1998). With a sampling time of 0.01 seconds, a label set corresponding to the linguistic variables of the input control signals $e(k)$ and $ce(k)$ is provided. Seven different triangle membership functions (MFs) have been attempted to be examined: Positive Big (PB), Positive Medium (PM), Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Negative Big (NB). The range of input, or the universe of discourse, is $-0.25 - 0.25$ and -0.01 . This represents the error in the frequency deviation and change in the frequency deviation as shown in Table 1. There were 49 regulations in total. Figure 6 shows the membership functions (MFs) of the input variables.

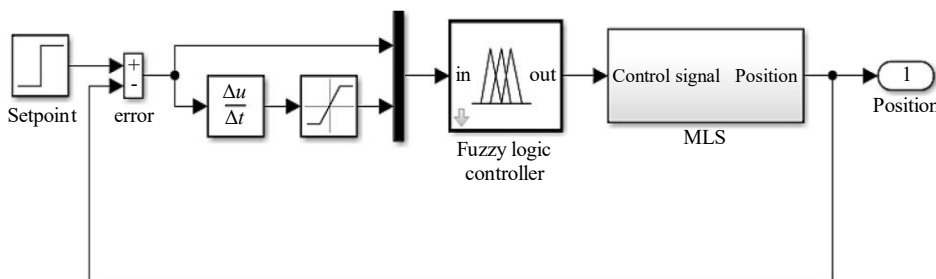


Figure 5. Fuzzy logic controller.

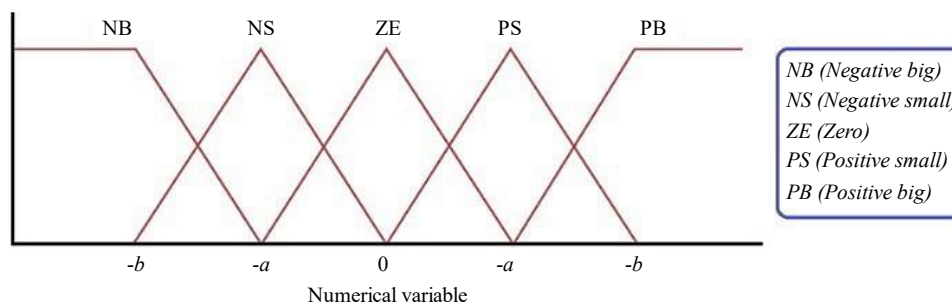


Figure 6. Membership function for the control input variables.

Table 1. Fuzzy inference rule for fuzzy logic controller.

Input	$e(k)$							
		NB	NM	NS	ZE	PS	PM	PB
$ce(k)$	NB	PB	PB	PB	PB	PM	PM	PS
	NM	PB	PM	PM	PM	PS	PS	PS
	NS	PM	PM	PS	PS	PS	PS	ZE
	ZE	NS	NS	NS	ZE	PS	PS	PS
	PS	ZE	NS	NS	NS	NS	NM	NM
	PM	NS	NS	NM	NM	NM	NB	NB
	PB	NS	NM	NB	NB	NB	NB	NB

SIMULATION RESULTS

The simulation was run using the parameters listed in the Appendix and two different types of controllers: fuzzy logic and PI controllers. The modeling of load frequency regulation using PI and FLC was finished using “MATLAB” in the Figure 7. Figures 7–14 illustrate the influence of the two region-related thermal power frameworks and nuclear power systems.

Case 1: Result parameter of the nuclear plant using PI and FLC when 1% disturbance occurs in the thermal plant.

1. *By using the PI controller*
 - i. Nuclear results (Figure 7).
 - ii. Result of both the areas of thermal–nuclear system (Figure 8).
2. *By using a FLC*
 - i. Result of nuclear area (Figure 9).
 - ii. Results of both the areas of the thermal–nuclear system (Figure 10).

The tie-line-connected result of the thermal–nuclear power system is displayed in Case 1. Once again, the frequency was kept constant using the controllers. This illustrates the impact of area 2 when disturbances occur in area 1. Area 2 settles at 60 s when using the PI controller and 19 s when using the FLC. The FLC settles faster than the PI controller and more slowly. Table 2 predicts the comparison of both the areas at different parameters for case 1.

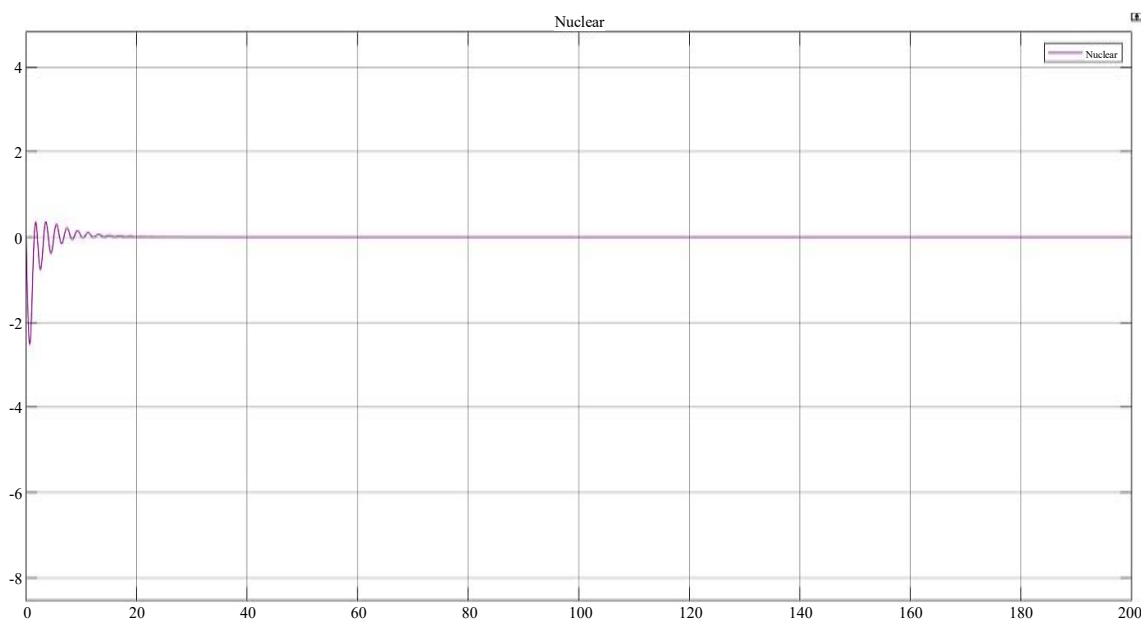


Figure 7. Result of both the areas when 1% disturbance occurs in the thermal plant by PI.

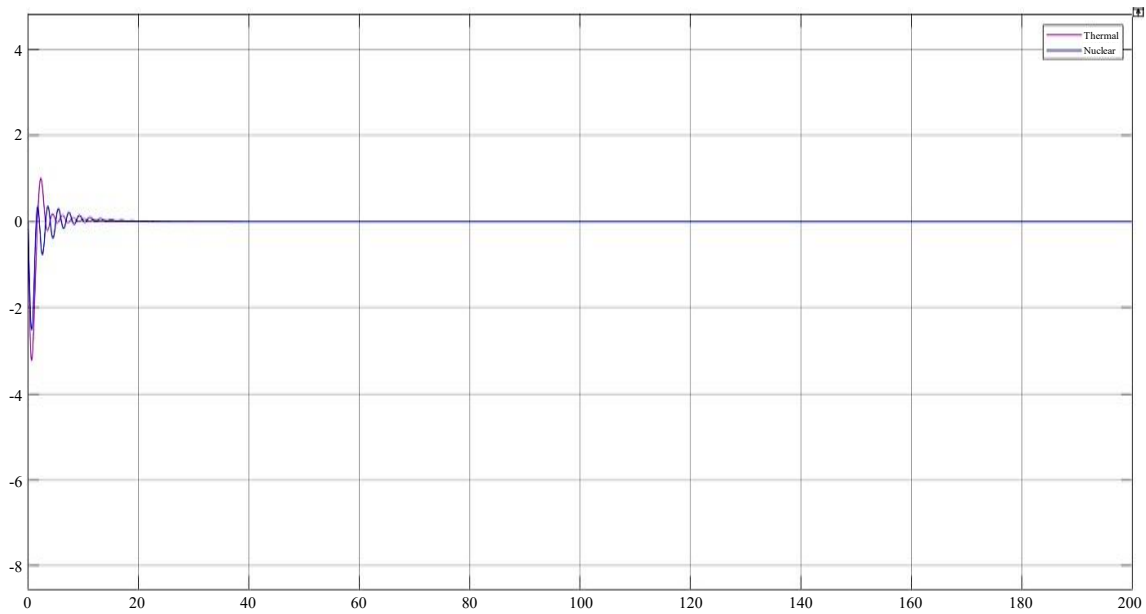


Figure 8. Result of both the areas when 1% disturbance occurs in the thermal plant by PI.

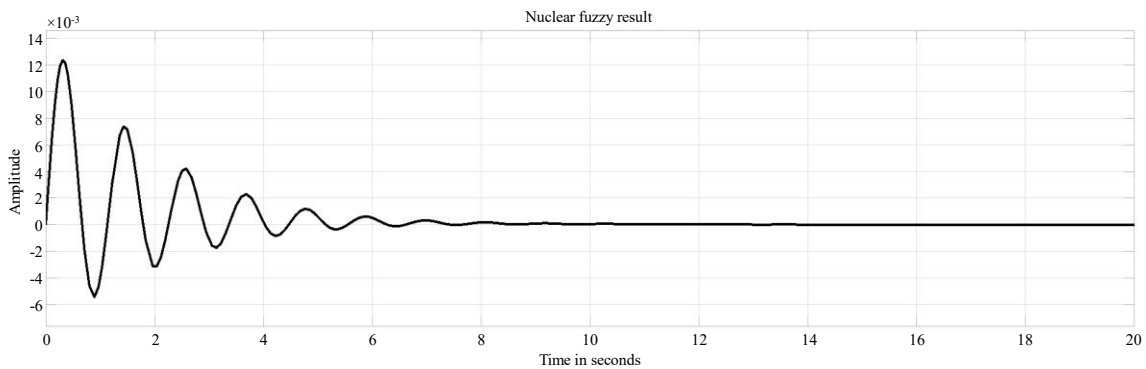


Figure 9. Result parameter nuclear plant when 1% disturbance occurs in the thermal plant by FLC.

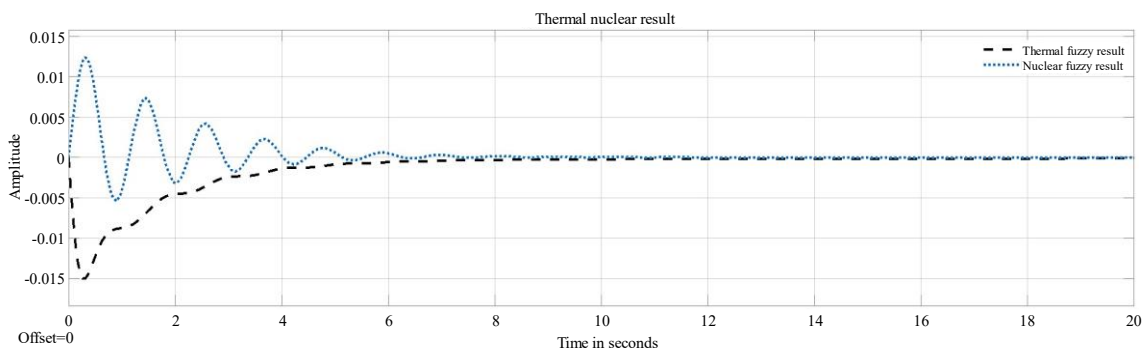


Figure 10. Result of both the areas when 1% disturbance occurs in the thermal plant by FLC.

Table 2. Result of different parameters after simulation of the nuclear plant (area 2) when a disturbance occurs in the thermal plant (area 1).

Parameters	PI controller	FLC controller
Settling time (sec)	60	7
Maximum overshoot	1.08	0.0109
Minimum overshoot	-3.178	-0.015

Case 2: Result parameter of the thermal plant using PI and FLC when 1% disturbance occurs in a nuclear plant.

1. *By using the PI controller*
 - i. The result of the thermal area (Figure 11).
 - ii. The result of both the areas (Figure 12).
2. *By using FLC*
 - i. The result of the thermal area (Figure 13).
 - ii. The result of both the areas of the thermal–nuclear system (Figure 14).

Case 2 shows the result of the thermal–nuclear interconnected power system through the tie-line. The controllers were again used to maintain the frequency at a constant level. Here, we show the effect of region 1 when an interruption occurs in region 2. The settling time of area 1 using the PI controller is 60 s, and by FLC, the settling time is 20 s. The PI controller takes more time to settle and the FLC takes less time to settle. Table 3 predicts the comparison of both the areas at different parameters for case 3.

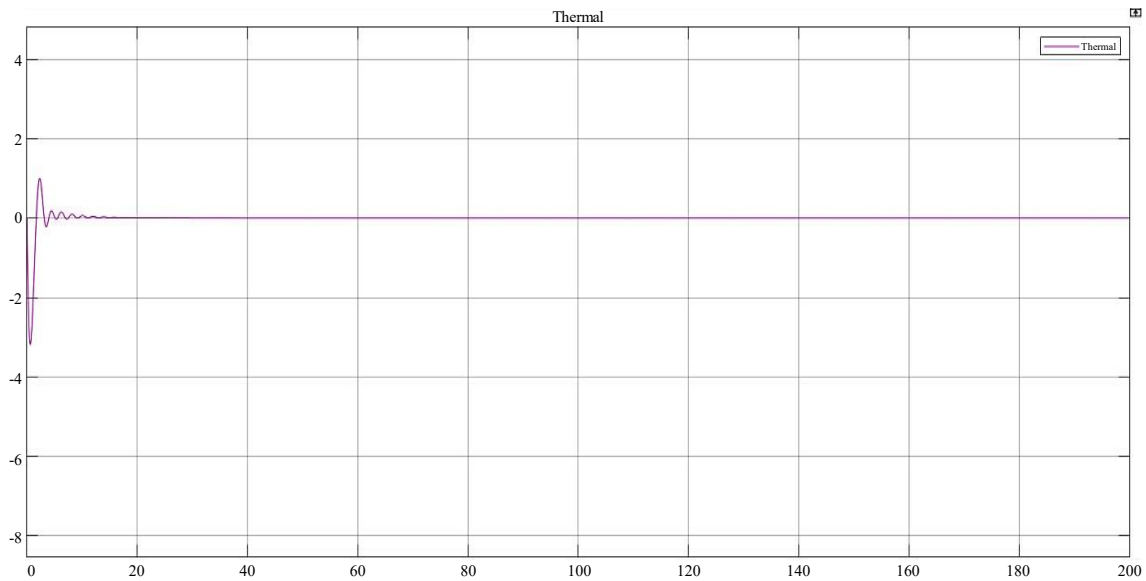


Figure 11. Result parameter thermal plant When 1% disturbance occurs in the nuclear plant by PI.

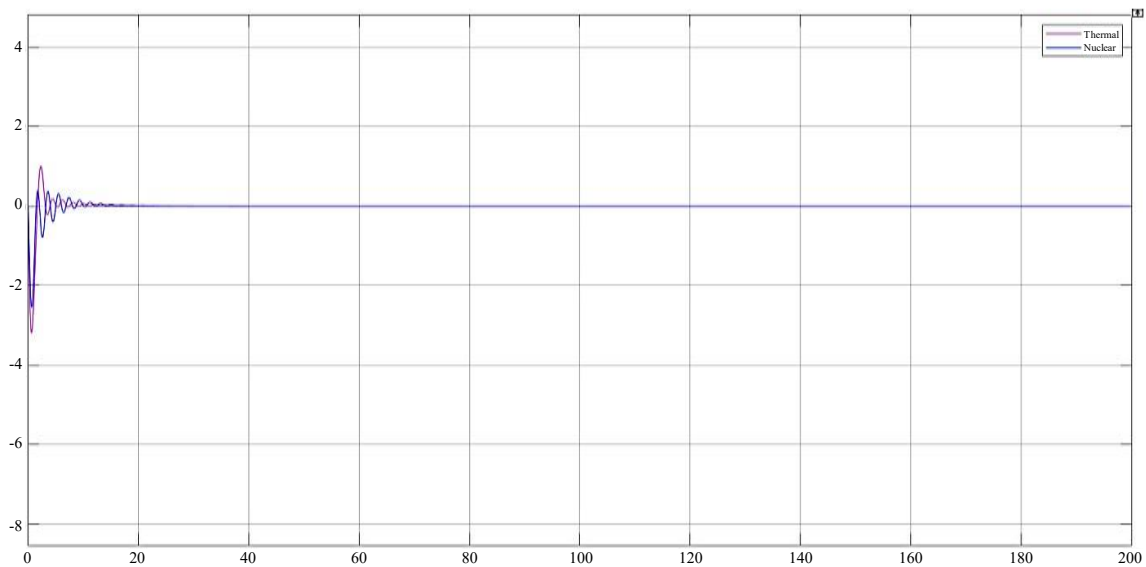


Figure 12. Result of both the areas when 1% disturbance occurs in the nuclear plant by PI.

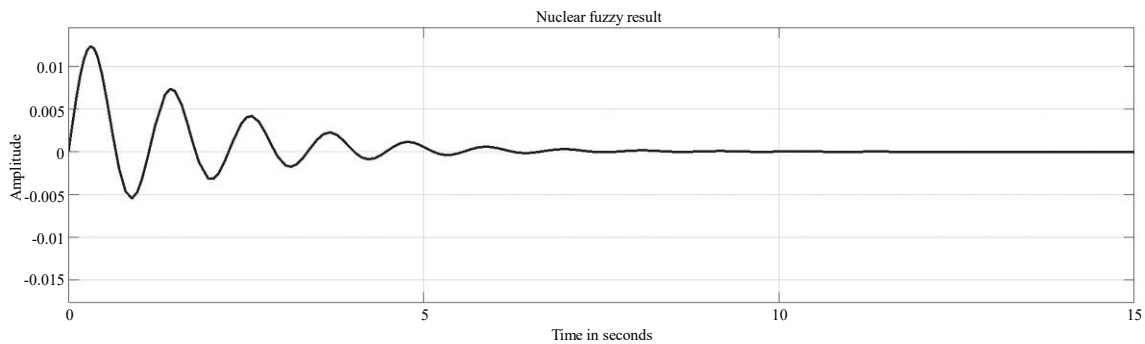


Figure 13. Result parameter thermal plant When 1% disturbance occurs in the nuclear plant by FLC.

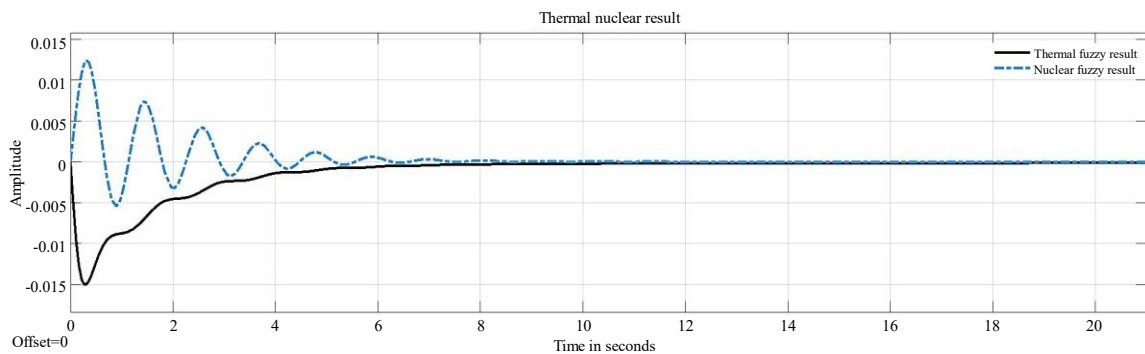


Figure 14. Result of both the areas when 1% disturbance occurs in the nuclear plant by FLC.

Table 3. Result of different parameters after simulation of the thermal plant (area 1) when a disturbance occurs in the nuclear plant.

Parameters	PI controller	Fuzzy logic controller
Settling time (sec)	60	7
Maximum overshoot	1.008	0.01
Minimum overshoot	-3.185	-0.015

CONCLUSION

The two-area systems were investigated using fuzzy logic controllers and PI. When the disturbance is set to 1%, the results for various scenarios are compared, demonstrating that fuzzy logic controllers outperform PI controllers in terms of dynamic reactions. The transients of the frequency response were minimized using a fuzzy controller.

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