Special Issue Published in International Journal of Trend in Research and Development (IJTRD),
ISSN: 2394-9333, www.ijtrd.com

Control of Thermal Power System Using Adaptive Fuzzy Logic Control

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Abstract **-** In this paper, the uncontrolled single area Load Frequency Control system is modelled using state space representation. Output response of the system which is frequency deviation is simulated in MATLAB. Adaptive Fuzzy Logic (FL) controller combined with Proportional Integral (PI) controlleris added to the uncontrolled system using SIMULINK and MATLAB Fuzzy Inference System. The effect of the combined control on the system output response is measured in terms of undershoot percentage, settling time, and frequency error. By comparing the simulations of uncontrolled and controlled system, it can be concluded that Adaptive FL controller combined with conventional PI controller is the most efficient, reliable, and robust control to solve power system control problem. The proposed control improves transient and steady state behavior of the system.

Key Words*-Power system control, Single area power system, Adaptive fuzzy logic control, PI control, Steady state output response, frequency deviation*

I. INTRODUCTION

Control of thermal power generation system reduces energy or fuel consumption. Fuel reduction of even a small percentage will lead to large energy saving which results into saving the environment [1].

Figure 1 illustrates structure of a thermal power system. Automatic Generation Control (AGC) consists of two main control loops: Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR). AVR system is responsible to regulate the terminal voltage and LFC system is employed to control the system frequency. Frequency and terminal voltage change continuously as power consumption changes. Any variation in power consumption leads to change in power generation. The objective in any high quality power system is to ensure generation matches load at high reliability and minimum cost. Voltage and frequency variations due to load changes must be maintained within an acceptable range. Frequency deviation due to load changes is an indicator to measure how accurately generation follows demand.

In this paper, modelling and simulation of LFC system is considered for careful analysis since frequency is more sensitive to load variations compared to voltage. There is only weak coupling between the two control loops; hence, the overlap of load frequency and excitation voltage is negligible and the control loops can be analyzed independently. Figure 2 illustrates how AVR and LFCare interconnected in AGC system [2].

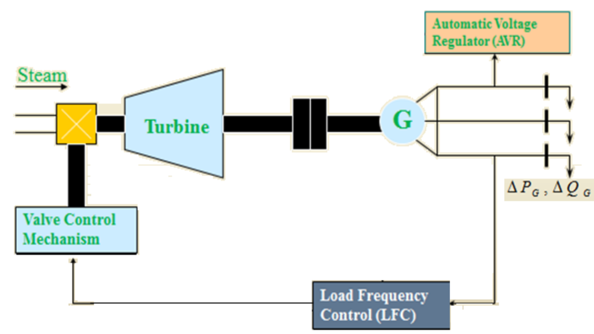

Fig. 1. Block Diagram of Power System

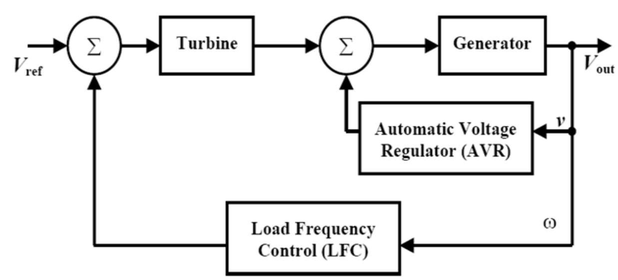

Fig. 2. Two Main Control Loops of Automatic Generation Control

Many researchers have been interested in solving optimization or control problem in thermal power systems. There are many papers on control of two and three area thermal power systems. This paper is focused exclusively on control of single area thermal power system.

II. PERFROMANCE OBJECTIVE

The primary objective of using controller in LFC system is to eliminate or minimize system frequency deviation. In power systems, following performance specifications are recommended:

- Steady state error should not be more than 0.01HZ.
- Settling time should not be more than 3 seconds.
- The maximum overshot/undershoot should not be more than 6% (0.06HZ).
- Change in power exchange ΔP_{tie} is upon mutual agreement of the areas. This is only applicable for interconnected systems.

Figure 3 illustrates block diagram of uncontrolled LFC system.The selected state variables used to develop state space representation of the system are x_1, x_2, x_3, andx_4. x_1 is the output that is considered for analysis in this paper.

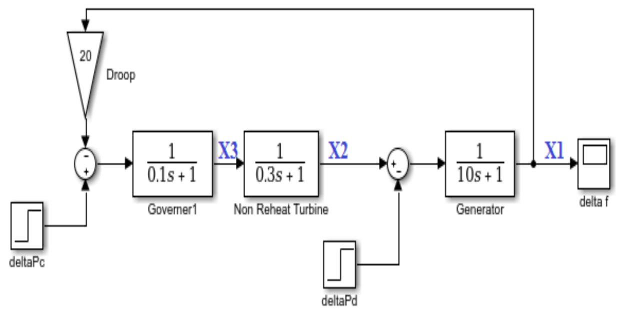

Fig. 3. Block Diagram of Uncontrolled System

The system illustrated in Figure 3 has two inputs. One input is ΔP_c representing the speed changer. The other input is ΔP_d representing the change in load by consumer also known as disturbance. Since user has no control over load changes, ΔP_d is considered as the only input of the system. Effect of ΔP_c diminishes once a controller is added to the system.

The disturbance is chosen as unit step function.The output of LFC system is Δf which represents the change or variation in frequency. The objective is to have a constant output frequency operated at 50HZ which corresponds to Δf being zero or very small. The value of Speed Regulation *R* also known as Droop is the ratio of frequency deviation (Δf) to change in power output of the generator.

The uncontrolled system shown in Figure 3 is modelled using state space representation illustrated in(1) and (2) where A is the state matrix, B is the input matrix, and C is the output matrix. *X(t)* is a column vector representing the state variables used in system modelling.

$$\dot{x}(t) = A\,x(t) + B\,\Delta P_d \quad (1)$$

$$y(t) = C\,x(t) \quad (2)$$

To obtain state space representation of the system, following transfer functions are developed:

Generator: $$\frac{X_1}{X_2 - \Delta P_d} = \frac{1}{10S+1} \quad (3)$$

Turbine: $$\frac{X_2}{X_3} = \frac{1}{0.3S+1} \quad (4)$$

Governor: $$\frac{X_3}{\Delta P_c - 20X_1} = \frac{1}{0.1S+1} \quad (5)$$

Inverse Laplace Transform of (3) – (5) is taken in order to derive the differential equations (6) – (8).

Generator: $$\dot{x}_1 = -0.1\,x_1 + 0.1\,x_2 - 0.1\,\Delta P_d \quad (6)$$

Turbine: $$\dot{x}_2 = -{}^{1}/_{0.3}\,x_2 + {}^{1}/_{0.3}\,x_3 \quad (7)$$

Governor: $$\dot{x}_3 = -200\,x_1 - 10\,x_3 \quad (8)$$

Following is the state space representation of the uncontrolled system shown in Figure 3.

$$A = \begin{bmatrix} -0.1 & 0.1 & 0 \\ 0 & \frac{-1}{0.3} & \frac{1}{0.3} \\ -200 & 0 & -10 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.1 \\ 0 \\ 0 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

Figure 4 shows the corresponding frequencyvariation response due to load changes. The system has a settling time of 3.5 seconds, undershoot of 6% which corresponds to transient frequency of -0.06HZ, and steady state error of -0.048HZ. Based on Figure 4, the system performance does not meet the specifications. Hence, addition of a controller is required to improve the system output response.

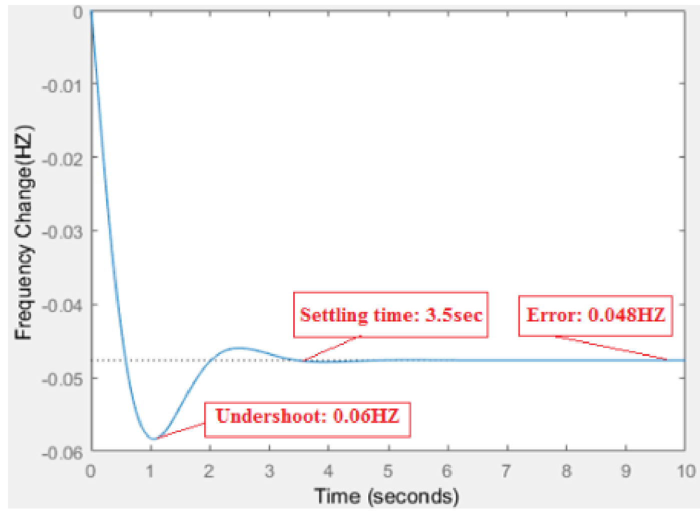

Fig. 4. Output Response of Uncontrolled System

III. INTRODUCTION TO FUZZY LOGIC

Many industrial systems such as power generation system are time-variant and are influenced significantly by external disturbances. These disturbances cause changes in system performance. The issue of controlling a dynamic system can be addressed using Fuzzy Logic (FL).

Fuzzy Logic (FL) by Dr. Zadeh is able to provide a systematic way for the application of uncertain and indefinite models when precise definition or mathematical representation of the system is unavailable [5]. Power system is highly affected by non-internal factors such as weather and change of seasons. Modelling a time varying system is a very challenging task [6]. FL controller is able to enhance system performance without the need of precise mathematical modeling of the system. It is enough to have only some knowledge about the system and its behavior. This is considered as the most important advantage of FL.

FL is strongly based on linguistic interpretation of the system. It establishes linguistic rules called membership rules to determine a systematic way of modelling power system. Membership rules or membership functions are fundamental part of FL. Fuzzy sets are functions that map a value that might be a member of a set to a number between zero and one indicating its actual degree of membership. Fuzzy sets produce membership curves.

IV. DESIGN OF FUZZY LOGIC CONTROLLER

The Objective of using Adaptive FL controller in control problem is to minimize or maximize an objective function *f(x)* in the presence of uncertainties, unknown variations, and constraints.

Figure 4 shows block diagram of a FL controller which consists of the following 4 components [6]:

1. Rule-Base: It holds knowledge in terms of set of linguistic rules called fuzzy rules defined by the user. Fuzzy rules are built using membership functions.

2. Inference Mechanism: It selects relevant rules at the current time and decides what the output of the controller should be. Output of the controller *u(t)* is input of the plant. In power system, the plant is the uncontrolled/open loop system.

3. Fuzzification: It converts controller's input into information that can be used in inference mechanism.

4. Defuzzification: It converts the output of the controller into values that can be used by the plant. Fuzzification and defuzzification are inverse processes.

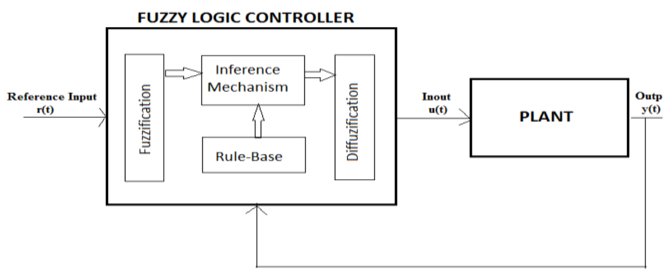

Fig. 5. Fuzzy Logic Controller Block Diagram

Based on Figure 5 it can be observed that FL controller has two inputs as shown below where ACE is Area Control Error:

$$e(t) = r(t) - y(t) > ACE \quad (9)$$

$$\frac{d}{dt}\, e(t) = \dot{e}(t) > A\dot{C}E \quad (10)$$

If reference input *r(t)* is zero, then inputs of FL controller are:

$$e(t) = -\, y(t) > ACE \quad (11)$$

$$\frac{d}{dt}\, e(t) = \dot{e}(t) = -\dot{y}(t) > A\dot{C}E \quad (12)$$

To create a FL controller, following steps must to be taken [7]:

1. Define the controller inputs:
   Error = set point – process output

   Error change = current error – last error

2. Define the controller output:

Output = controller output – plant input

3. Create membership functions:
   Membership functions are developed based on designer's knowledge and experience about the system. Membership functions are used to define fuzzy rules.

4. Create fuzzy rules:
   Fuzzy rules are defined using IF-THEN relationships. They need to be manually tuned or adjusted in order to obtain the desired system response.

5. Simulate the results:
   SIMULINK can be used to simulate the steady state output response.

The inputs of FL controller shown in (11) and (12) can be classified into membership functions. In this paper, the inputs are classified into 7 membership functions:

NB: Negative Big, NM: Negative Medium, NS: Negative Small, ZZ: Zero, PS: Positive Small, MP: Positive Medium, PB: Positive Big. These 7 membership functions lead to 49 fuzzy rules as shown in Table I.

Membership functions must be symmetrical and each membership function overlaps with the adjacent functions by 50%. Membership functions are normalized in the interval [-L, L] which is symmetric around zero [6].

The two inputs are combined together using AND operation. Table 1 is constructed based on experience and knowledge known about power generation systems.

TABLE I. Fuzzy Logic Base Rules

		e(t)						
	AND	**NB**	**NM**	**NS**	**ZZ**	**PS**	**PM**	**PB**
	NB	NB	NB	NB	NB	NM	NS	ZZ
	NM	NB	NM	NM	NM	NS	ZZ	PS
	NS	NM	NS	NS	NS	ZZ	PS	PM
	Z	NB	NM	NS	ZZ	PS	PM	PB
e(t)	**PS**	NM	NS	ZZ	PS	PS	PS	PM
	PM	NS	ZZ	PS	PM	PM	PM	PS
	PB	ZZ	PS	PM	PB	PB	PB	PB

Fuzzy Inference System (FIS) in MATLAB is used to design a FL controller based on the fuzzy rules defined in Table I. The controller output is the input of the plant. Centeroid method is used to defuzzificate the values. The range of each membership function is defined based on human's experience and knowledge about power generation system. There are various types of membership functions used in FIS such as triangular, trapezoidal, PI-curve, bell-shaped, and S-curved [8]. In this paper, triangular membership functions are used.

V. FEEDBACK ANALYSIS

To have a stable system after implementation of FL controller, controllability and observability are very important factors. Implementation of FL controller guarantees a closed loop globally stable system if the corresponding open loop system is controllable, observable, and stable [6]. Hence, the system shown in Figure 3 is checked for the above conditions:

1. The system is controllable and observable.
2. The system is stable since all the three poles lie in the left half plane.

FL controlleris reliable and PI controlleris robust. Combination of the two types of controllers can result in a reliable, efficient, and robust controller design. Figure 6 is the block diagram representation of the feedback single area system generated in SIMULINK.The Adaptive FL and PI controller are combined together in parallel to improvethe system behavior. The system shown in Figure 6 has only one input ΔP_d and one output Δf.

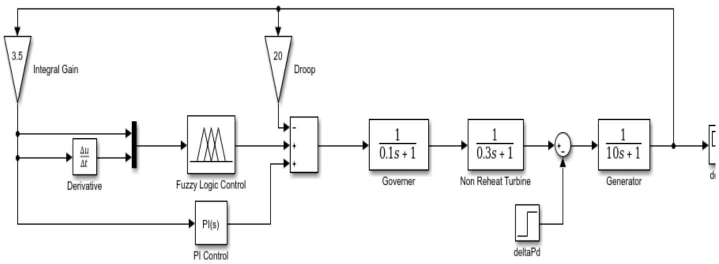

Fig. 6. Block Diagram of Controlled System

Parameters of the PI controller have been tuned carefully to ensure performance improvement. Table II shows parameters of the PI controller implemented in Figure 6. Equation 13 shows the transfer function of a PI controller where *U(S)* is the controlleroutput, *E(S)* is the controller input, K_p is the controller proportional gain coefficient, and K_i is the controller integral gain coefficient.

$$\frac{U(S)}{E(S)} = K_p + \frac{K_i}{S} \quad (13)$$

TABLE II. PI ControllerParameters Combined with Adaptive FL Controller

Proportional gainCoefficient (K_p)	Integral gainCoefficient (K_i)
-0.25	-3.5

Figure 7 shows frequency response of the controlled system after implementation of Adaptive FL controller described in Table I combined with PI controller described in Table II.

Reliability of FL controller and robustness of PI controller are combined together to construct a well behaved controlled system. As shown in Figure 7, the system settling time is reduced to 2.5 seconds and the steady state error is completely removed; this is the effect of integral controller. The undershoot percentage is about 0.025%. This is a well behaved system since all the parameters have been improved significantly.

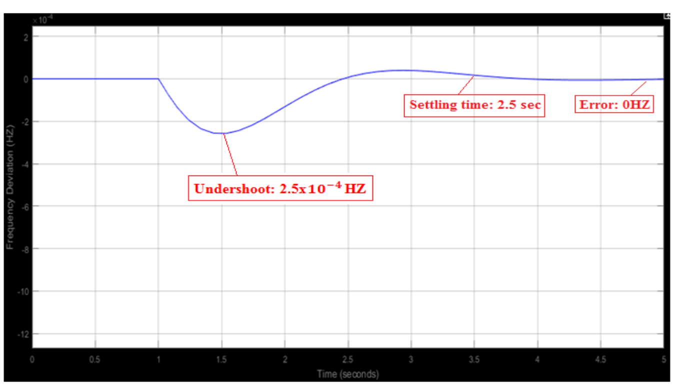

Fig. 7.Output Response of Controlled System after Implementation of Adaptive FL ControlCombined with PI Control

CONCLUSION

Combined Adaptive FL and PI controllerhave been proposed to improve the system performance of a single area power system. The fuzzy base rules for Adaptive FL controllerhave been selected wisely and the parameters of PI controller have been tuned adequately to ensure that the required specifications are met.

Adaptive FL controller is robust, reliable, and most commonly used in solving control problems. Table III compares the performance specifications of uncontrolled vs controlled single area LFC system. By studying Table III, it can be concluded that controlled/closed loop LFC system performance is superior compared to uncontrolled/open loop LFC system.

TABLE III. Comparison of Uncontrolled vs. Controlled Power System

	Settling Time (Sec)	Steady State Error (HZ)	Undershoot (%)
Uncontrolled	3.5	-0.048	6
Controlled	2.5	0	0.025

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