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Advanced Optimization of Single Area Power Generation System Using Adaptive Fuzzy Logic and PI Control

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Abstract - *In this paper, the open loop single area power generation system is modelled using state space representation. The output response which is frequency deviation at steady state is simulated using MATLAB. Then, Proportional Integral (PI) controller combined with Adaptive Fuzzy Logic (FL) controller is added to the system to understand the effect of conventional and modern control on system steady state output response. The performance of the system steady state output response is measured in terms of undershoot percentage, settling time, and steady state error. Simulation of the controlled system shows that PI controller combined with Adaptive FL controller are considered the most efficient, reliable, and robust type of controller in addressing power generation optimization problem. The output response of the controlled system has settling time of 2.5 second, zero steady state error, and undershoot of 0.03%.*

***Key Words*: Optimization, Single Area Power Generation System, Adaptive Fuzzy Logic Control, PI Control, Steady State Output Response, Frequency Deviation**

1 INTRODUCTION

An interconnected system called Automatic Generation Control (AGC) consists of two sub-systems: Load Frequency Control (LFC) and Automatic Voltage Regulator (AVR). AVR is responsible to regulate the terminal voltage and LFC is employed to control the system frequency. In this paper, modelling and simulation of LFC is considered for careful analysis since LFC is more sensitive to load changes compared to AVR. There is only weak coupling between the two sub-systems; hence, the overlap of load frequency and excitation voltage is negligible and the two-sub-systems can be analyzed independently. Figure 1 illustrates how AVR and LFC are interconnected in AGC system [1].

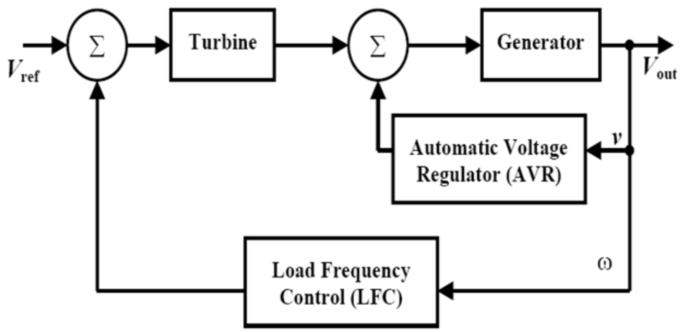

Fig- 1: Two Main Sub-Systems of Automatic Generation Control

Optimizing thermal power generation system will reduce energy or fuel consumption. Fuel reduction of even a small percentage will lead to large energy saving which results into saving the environment [2]. Hence, many researchers have been interested to solve optimization problem in thermal power generation systems. There are many papers on optimization of two and three area thermal and solar power generation systems. This paper is focused exclusively on optimization of single area thermal power generation system.

2 OPEN LOOP ANALYSIS

Figure 2 shows SIMULINK generated block diagram representation of an uncontrolled generating unit which consists of a speed governor, a turbine, and a generator [1].

In some generating units, no re-heat component is available. Re-heat or feed water re-heat is used to pre-heat the water that is delivered to the steam boiler. In this paper, the considered model does not have re-heat component.

For computational simplicity in optimization problem, the case where the thermal power generation system consists of a single boiler, a single turbine, and a single generator is considered. In many real world power generation systems, the generation unit consists of multiple boilers, steam turbines, and generators. "Network Power Loss" is referred to the loss of power from one generator to another or from one turbine to another. This loss of power is experienced in systems with multiple components of same type [3].

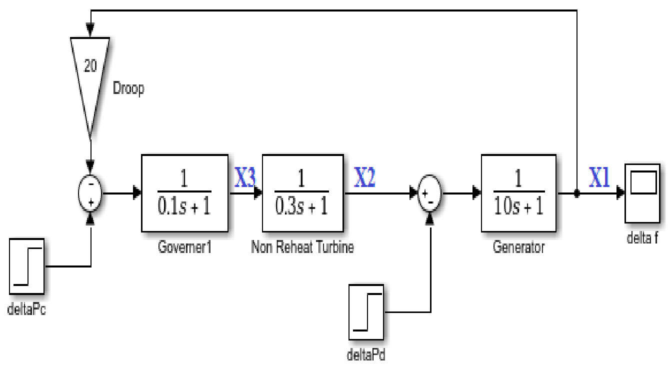

Fig-2: Block Diagram of Uncontrolled Single Area Power Generation System

The inputs of the system shown in Figure 2 are ΔP_c representing the change in speed generation by utility and 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 output of LFC is Δf which represents the change or variation in steady state frequency. The objective is to have a constant output frequency 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 2 is modelled using state space representation shown in Equation 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. .

$$\dot{x}(t) = A\,x(t) + B\,\Delta P_d \quad (1)$$
$$y(t) = C\,x(t) \quad (2)$$

The system shown in Figure 2 has 3 integral blocks which corresponds to 3 state variables. Therefore, state matrix A must be of size 3x3. Since the system has only one input which is ΔP_d, the input matrix B must be a column vector of size 3x1. The input is taken as unit step function. The output of the system is frequency deviation of the generator which corresponds to the state variable x_1 as shown in Figure 2. The output matrix C is a row vector of size 1x3.

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 Equations 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 2.

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

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

Figure 3 shows the steady state frequency deviation of the uncontrolled single area model illustrated in Figure 2. The system has settling time of 3 seconds, undershoot of 6% which corresponds to transient frequency of -0.06HZ, and steady state error of -0.048HZ. The system performance can definitely be improved especially with steady state frequency deviation. Hence, addition of a controller is required to control the system output response.

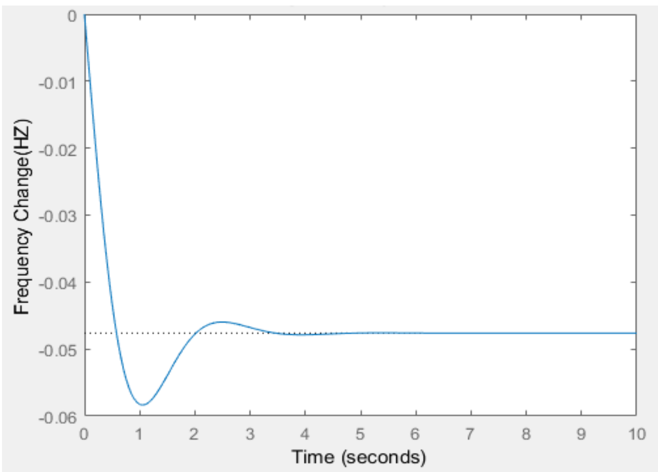

Fig-3: Output Response of Uncontrolled Power Generation System

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3 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 and optimizing a dynamic system can be addressed using Fuzzy Logic (FL). FL has been applied to power plant optimization problems in many different ways such as optimal distribution planning, generator maintenance scheduling, load forecasting, load management, and generation dispatch problem [4].

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 a stochastic system that is highly affected by non-internal factors such as weather and change of seasons. Modelling a stochastic and time varying system is a very challenging task [6]. FL control is able to enhance system performance without the need of 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 the power system. Membership rules or membership functions are fundamental part of FL. Let X be a set of objects whose elements are denoted by *x*. Membership in a subset A of X is the membership function μ_A [7].

$$A = \{(x, mA(x)), x \varepsilon X)\} \quad (9)$$

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 a membership curves.

4 DESIGN OF FUZZY LOGIC CONTROL

There exist two types of FL control:

1. Static Fuzzy Control: This controller is used when structure and parameters of the FL controller are fixed and do not change during real time operation [6].

2. Adaptive Fuzzy Logic Control: This controller is used when structure and parameters of FL controller change during real time operation. This type of controllers is more expensive to implement; however, it results in better performance and less mathematical information about the system is needed [6].

The Objective of using Adaptive FL control in optimization problem is to minimize or maximize an objective function *f(x)* in the presence of uncertainties, unknown variations, and constraints. Adaptive FL control is difficult to analyze because it is time varying; however, it ensures more desired performance in comparison to Static FL control.

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.

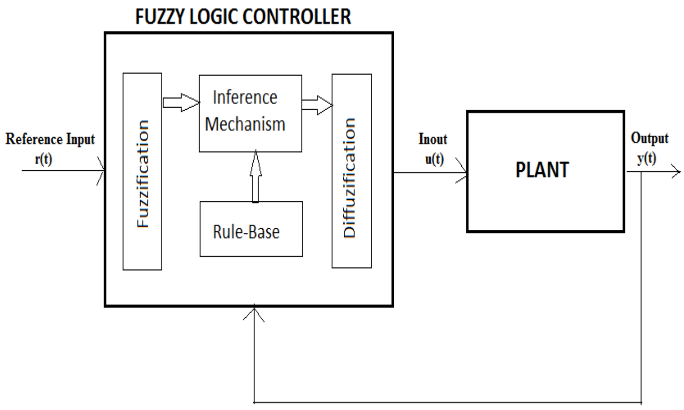

Fig- 4: Fuzzy Logic Controller Block Diagram

From Figure 4 it can be observed that FL controller has two inputs as shown below:

$$e(t) = r(t) - y(t) \quad > \quad ACE \qquad (10)$$

$$\frac{d}{dt}\, e(t) = \dot{e}(t) \quad > \quad \dot{ACE} \qquad (11)$$

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

$$e(t) = -y(t) \quad > \quad ACE \qquad (12)$$

$$\frac{d}{dt}e(t) = e\dot{(}t) = -\dot{y}(t) > A\dot{C}E \qquad (13)$$

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

1. 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.

2. 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.

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

The inputs of FL control shown in Equation 12 and 13 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 1.

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-1: Fuzzy Logic Membership Rules

		$\boldsymbol{e\dot{(}t)}$						
	AND	**NB**	**NM**	**NS**	**ZZ**	**PS**	**PM**	**PB**
e(t)	**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
	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 1. 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.

5 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 2 which has order of 3 is checked for the above conditions:

1. The system is controllable. The rank of controllability matrix is 3.
2. The system is observable. The rank of observability matrix is 3.
3. The system is stable since all the three poles lie on the left half plane. The poles are -10.8290 + 0.0000i, -1.3022 + 2.1837i, -1.3022 - 2.1837i.

FL controllers are reliable and PI controllers are robust. Combination of the two types of controllers can result in a reliable, efficient, and robust controller design. Figure 5 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 improve the system behavior. This controller is called Adaptive FL and PI controller. The system shown in Figure 5 has only one input ΔP_d and one output Δf.

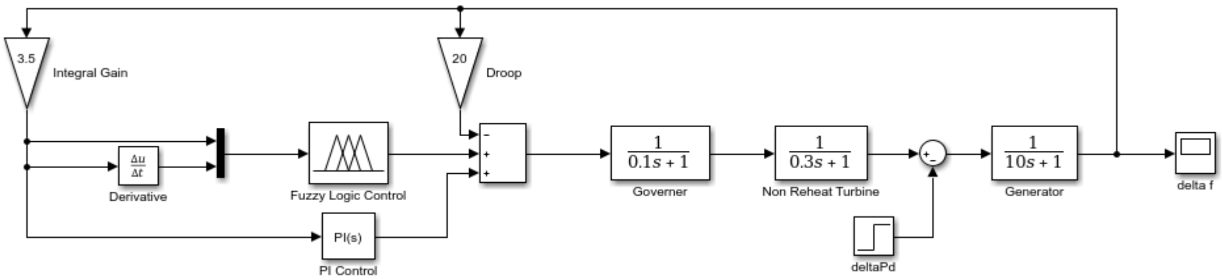

Fig-5: Block Diagram Representation of Feedback Single Area Generating Unit

Parameters of the PI controller have been tuned carefully to ensure performance improvement. Table 2 shows the parameters of the PI controller implemented in Figure 5. Equation 14 shows the transfer function of a PI controller where *U(S)* is the controller output, *E(S)* is the controller input, K_p is the controller proportional constant, and K_i is the controller integral constant.

$$\frac{U(S)}{E(S)} = K_p + \frac{K_i}{s} \quad (14)$$

Table-2: PI Controller Parameters for Feedback Single Area Generating Unit Combined with Adaptive FL Controller

Proportional Constant (K_p)	Integral Constant (K_i)	Integral Gain (K_g)
-0.25	-3.5	3.5

6 RESULT

Figure 6 shows the steady state frequency response of the controlled system after implementation of Adaptive FL controller described in Table 1 combined with PI controller described in Table 2.
Reliability of FL controller and robustness of PI controller are combined together to construct a well behaved controlled system. As shown in Figure 6, 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 0.03%. This is a well behaved system since all the parameters have been improved significantly.

The primary objective of having controller in a power generation system is to eliminate or minimize the steady state frequency deviation. In power generation system, followings are considered as standard performance specifications of a well-behaved system:

1. Steady state frequency error should not be more than $\pm$0.01HZ.
2. Settling time should be less than 3 seconds.
3. The maximum overshot/undershoot should not be more than 6% which corresponds to transient frequency of $\pm$0.06HZ.

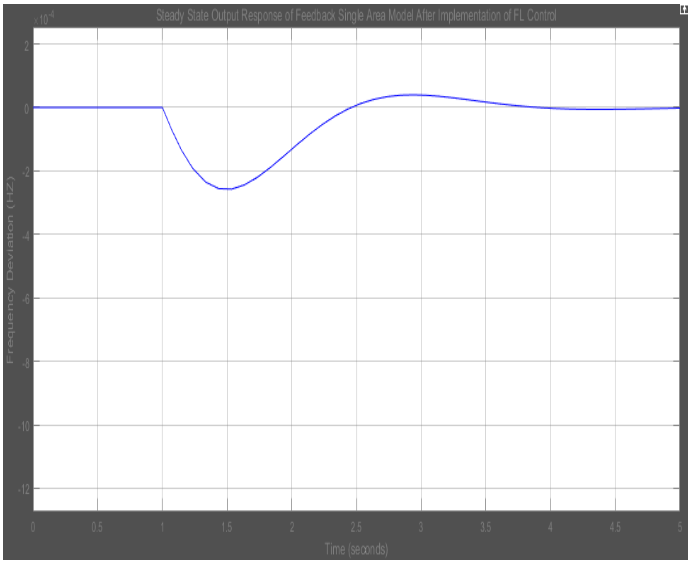

Fig-6: Steady State of Feedback Single Area Model after Implementation of FL Control

7 CONCLUSION

Adaptive FL controller and a suitable PI controller have been combined to improve the system performance of a single area power generation system. The membership functions for Adaptive FL controller and the parameters of PI controller have been tuned to ensure the specifications are met.

Adaptive FL controller is robust, reliable, and most commonly used in solving optimization problems. Table 3 compares the performance factors of uncontrolled vs controlled single area system.

Table-3: Comparison of Uncontrolled vs. Controlled Power Generation System

	Settling Time (Sec)	Steady State Error (HZ)	Undershoot (%)
Uncontrolled	3	-0.048	6
Controlled	2.5	0	0.03

REFERENCES

[1] Dr. A. Ismail, Professor of Electrical Engineering at Rochester Institute of Technology, Dubai, UAE . Advances in Power Generation System Course (2017).

[2] P. Pechtl. Integrated Thermal Power and Desalination Plant Optimization. PowerGen Middle East, Paper No.110 (2003).

[3] J. Zhu. *Optimization of Power System Operation*. Second Edition. New Jersey, USA: Wiley (2015).

[4] K. Tomsovic. Fuzzy Systems Application to Power Systems. Washington State University. Pullman, WA. USA.

[5] E. Cam, I. Kocaarslan. Load Frequency Control in Two Area Power Systems Using Fuzzy Logic Controller. Kirikkale University. Turkey (2004).

[6] K. M. Passino, S. Yurkovich. *Fuzzy Control*. California, USA: Addison Wesley Longman Inc (1998).

[7] K. Tomsovic, M.Y.Chow. Tutorial on Fuzzy Logic Applications in Power System. IEEE-PES Winter Meeting in Singapore (2000).

[8] S.N. Sivanandam, S. Sumathi, S.N. Deepa. *Introduction to Fuzzy Logic using MATLAB*. Springer (2007).

BIOGRAPHIES

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