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Effect of Non-linearities in Fuzzy Based Load Frequency Control

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Abstract

This paper presents an approach for designing fuzzy logic based load frequency controller with the presence of non-linearity and obtaining better dynamic response as compared to conventional controllers. Automatic generation control is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. Load frequency control (LFC) has gained importance with the growth of interconnected systems and has made the operation of interconnected system with more reliability. Any mismatch between generation and demand causes the system frequency to deviate from scheduled value. This necessitates designing of an accurate and fast controller to maintain the system frequency at nominal value. The conventional LFC controllers are slow and lack in efficiency. The Intelligent controller designed using fuzzy logic provides a satisfactory performance with balance between frequency overshoot and transient oscillations with zero stead- state error. This paper also develops an extended control to LFC scheme with the presence of generation rate constraint (GRC) non-linearity to a typical three area power system model proposed by Hadi Sadaat[1]. The simulation has been conducted in MATLAB Simulink package for the three area interconnected power system with various load changes. The simulation result shows that the proposed method of fuzzy logic controller for load frequency control is giving 40% reduction in settling time and 20% reduction in peak overshoot when compared to conventional controller.

Keywords: Load Frequency Control (LFC), Fuzzy Logic Control (FLC) and Generation Rate Constraint (GRC).

Subject Classification Numbers: 03E72, 93C10, 93C42, 93C80.

Introduction

In power system, both active and reactive power demands are never steady they continuously change with the rising or falling trend. Steam input to turbo generators(or water input to hydro generators) must therefore, be continuously regulated to match the active power demand, failing which the machine speed will vary with consequent change in frequency, which may be highly undesirable. In brief, the changes in real power affect the system frequency, while reactive power is less sensitive to changes in frequency and is mainly dependent on changes in voltage magnitude. The LFC loop controls the real power and frequency, and automatic voltage controller loop regulates the reactive power and voltage magnitude [1].

Automatic Generation Control (AGC) is the name given to a control system having three major objectives namely; to hold the system frequency at specified nominal value, to maintain area interchange at the scheduled level and to maintain each unit's generation at the most economic value. AGC tracks the load and generation level of each committed unit. Interconnections of power systems are made so that operating areas can share generation and load. To maintain a net interchange of power with its neighboring areas, an AGC uses real power flow measurements of all tie lines emanating from the area and subtracts the scheduled interchange to calculate an error value. The net power interchanges together with a gain B (called the frequency bias) as a multiplier on the frequency deviation is called the Area Control Error (ACE) and is given as input to the AGC. AGC sensing only ACE does not control the flow on the individual tie lines but is concerned with area net generation.[2]

The main reason to consider GRC is that the rapid power increase would draw out excessive steam form the boiler system to cause steam condensation due to adiabatic expansion. Wang et al [3] proposed a robust load frequency controller in the presence of GRC. Since the power system is assumed to be exposed to small changes in load, the controller is difficult to guarantee the stability for the wide range of disturbances. Moreover in deregulated environments, frequent on-off controls of large capacity units may bring about large amount of power disturbances, Hence Moon et al [4] have suggested a LFC scheme adopting a modified PID control based on optimal tracking approach. However, the conventional controller with fixed gains has been designed at nominal operating conditions fails to provide best control performance. Hence, in order to overcome this drawback Young-Hyun Moon et al proposed an extended integral control to LFC scheme with the presence of GRC in order to limit overshoot of the conventional controller[5].But, the optimal decaying factor is very difficult to set because of its time varying characteristics,. Therefore, Young et al [6] have suggested fuzzy logic based method to determine the optimal parameters for the extended integral controller. This technique has been extended by modifying and optimizing the membership function.

A three area interconnected power system including GRC is considered for implementing the proposed FLC. The proposed controller yields adequate control performance even with large load variations. Model of the plant has been developed using MATLAB package and simulated for various load conditions. The two inputs to fuzzy controller is the change in frequency (ΔF) and change in tie line power (ΔPtie). The output signal (ΔPc) controls the steam inputs to governor for increasing or decreasing the area generation for maintaining the system frequency.

This paper is organized as follows. Section 2 describes the linearized model of an LFC system. Interconnection of three area power system is demonstrated in section 3. Section 4 describes the fuzzy system design. Simulation results are presented in section 5. Conclusion is drawn in section 6.

Linearized model of an LFC system

The model of Generator, Load, pime mover and governor is obtained by transfer function method and combined to form a complete block diagram of an isolated power system,

(a) Generator Model

Applying swing equation of a synchronous machine to small perturbation, we have

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta Pm - \Delta Pe \qquad (1)$$

or in terms of small deviation in speed

$$\frac{d\Delta\frac{\omega}{\omega_s}}{dt} = \frac{1}{H}(\Delta Pm - \Delta Pe) \qquad (2)$$

where

$\Delta P_m - \Delta P_e$ = increment in power input to the generator

H = Inertia constant

ΔP_m = mechanical power output or in terms of small deviation in speed

With speed expressed in per unit, without explicit per unit notation, we have

$$\frac{d\Delta\omega}{dt} = \frac{1}{H}(\Delta Pm - \Delta Pe) \qquad (3)$$

Taking laplace of transform of equation(3), we obtain,

$$\Delta\Omega(s) = \frac{1}{2Hs}[\Delta Pm(s) - \Delta Pe(s)] \qquad (4)$$

The generator block diagram in Fig.1 is obtained from the equation (4).

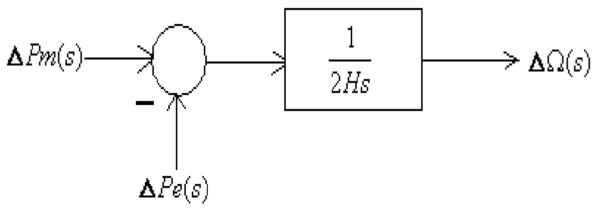

Figure 1: Generator Block diagram.

(a) Prime mover model

The model for the turbine relates changes in mechanical power output ΔP_m to changes in steam valve position ΔP_V. The simplest prime mover model for the non-reheat steam turbine can be approximated with a single time constant τ_T, resulting in the transfer function under equation(5).

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{1+\tau_T s} \tag{5}$$

The block diagram of a steam turbine in Fig.2 is obtained from equation (5).

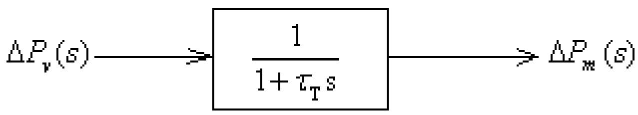

Figure 2: Block diagram of a steam turbine.

(b) Governor Model

When the generator electrical load is suddenly increased, the electrical power exceeds the mechanical power input. This power deficiency is supplied by the kinetic energy stored in the rotating system. The reduction in kinetic energy causes the turbine speed and consequently, the generator frequency to fall. The change in speed is sensed by the turbine governor, which acts to adjust the turbine input valve to change the mechanical power output to bring the speed to a new steady state. The earliest governors were the Watt governors which sense the speed by means of rotating flyballs and provide mechanical motion in response to speed changes. However, most modern governors use electronic means to sense speed changes.

Speed Changer

The speed changer consists of a servomotor which can be operated manually or automatically for scheduling load at nominal frequency. By adjusting this set point, a desired load dispatch can be scheduled at nominal frequency. For stable operation, the governors are designed to permit the speed to drop as the load is increased. The speed governor mechanism acts as a comparator whose output ΔP_g is the difference between the reference set power ΔP_{ref} and the power $\frac{1}{R}\Delta$

$$\Delta P_g = \Delta P_{ref} - \frac{1}{R}\Delta\omega \tag{6}$$

$$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta\Omega(s) \tag{7}$$

The command ΔPg is transformed through the hydraulic amplifier to the steam valve position command ΔP_v. Assuming a linear relationship and considering a simple time constant τ_g, s-domain relation is

$$\Delta P_v(s) = \frac{1}{1+\tau_g s}\Delta P_g(s) \tag{8}$$

Equations (7) and (8) are represented as speed governing system block diagram in Fig. 3.

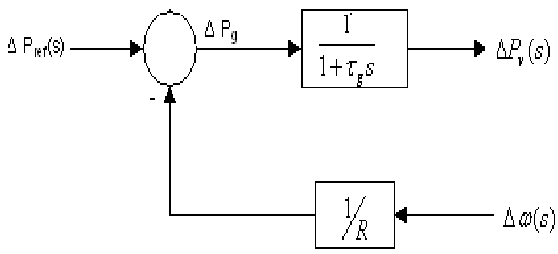

Figure 3: Block diagram for Speed Governing System of steam turbine.

(c) Load Model

The load model on a power system consists of variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. Motor loads are sensitive to changes in frequency. The speed-load characteristic of a composite load is approximated by

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{9}$$

where ΔP_L is the non-frequency sensitive load change, and DΔω is the frequency sensitive load change, D is expressed as percent change in load divided by percent change in frequency. The load model and the generator model is combined as shown in Fig.4

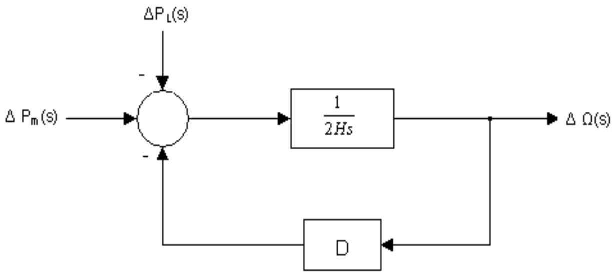

Figure 4: Generator and Load block diagram.

Eliminating the simple feedback loop in Fig. 4. resultant simplified block diagram is shown in Fig.5

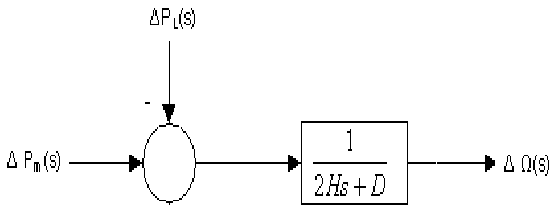

Figure 5: Simplified Block Diagram.

Combining the block diagrams of Fig 2,3 and 5 results in the complete block diagram of the load frequency control of an isolated power station as shown in Fig.6

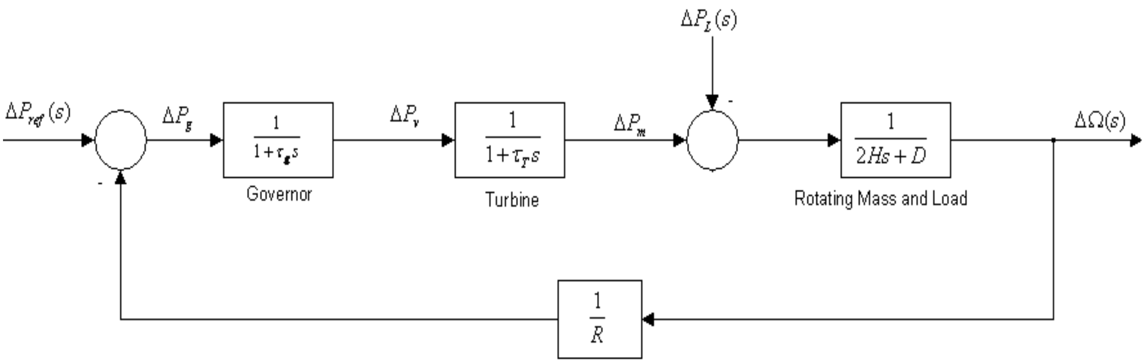

Figure 6: LFC block diagram of an isolated power system.

Redrawing the block diagram of Fig. 6 with the load change $\Delta P_L(s)$ as the input and the frequency deviation $\Delta\Omega(s)$ as the output results in the block diagram in Fig.7

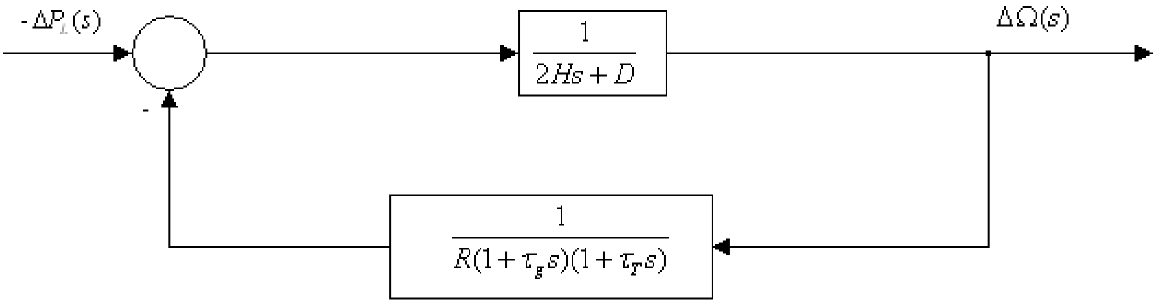

Figure 7: LFC block diagram with input $\Delta P_L(s)$ and output $\Delta\Omega(s)$.

A Three Area LFC Model

An interconnected power system is considered as being divided into control areas, which are connected by tie-lines. In each control area, all generators are assumed to form a coherent group. The power system investigated in this study contains three areas as shown in fig.8. The detailed block diagram of the system with all the parameters are shown in fig.9. Each area supplies its user pool, and tie-lines allow electric power to flow between areas. Therefore load distribution in one of the areas affects the frequencies of the other areas as well as power flows on tie-lines. Due to this, the control system of each area needs information about the transient situation in all areas to bring the local frequency to its steady state value [7].

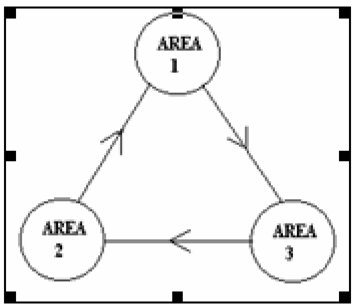

Figure 8: Schematic diagram of three area power system.

In multiarea power system, a group of generators are closely coupled internally and swing in unison. The LFC loop represents the whole system called as control area. The AGC of multiarea is realized by studying first the AGC of a three area system. Consider the three areas represented by an equivalent generating unit interconnected by a lossless tie line with reactance Xtie. During normal operation, the real power transferred over the tie line is given by

$$P_{12} = \frac{|E_1||E_2|}{X_{12}} \sin \delta_{12} \tag{10}$$

Where, $X_{12} = X_1 + X_{tie} + X_2$, and $\delta_{12} = \delta_1 - \delta_2$

The tie-line power ΔP_{12} is expressed as

$$\Delta P_{12} = P_s (\Delta\delta_1 - \Delta\delta_2) \tag{11}$$

The tie-line power flow appears as a load increase in one area and a load decrease in the other area, depending on the direction of flow. The direction of flow is dictated by the phase angle difference; if $\Delta\delta_1 > \Delta\delta_2$, the power flows from area1 to area2. A block diagram representing the single area system with LFC including GRC is shown in figure 9. Similar block diagrams can be used for area-2 and area-3. The values for various system parameters like Tg, Tt, R, H,and D are indicated inside the blocks. The gain is adjusted according to changes in the system parameters for the changes in load conditions for the steady state response[8].

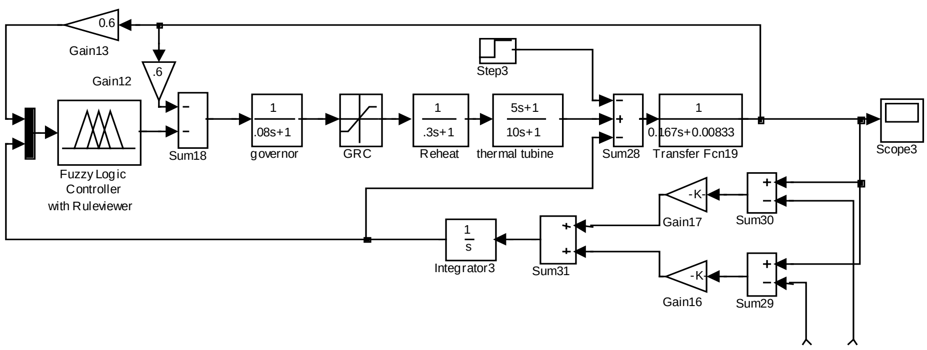

Figure 9: Area –1 of the three area power system using FLC.

Tie Line Bias Control

In figure.9, the LFC were equipped with only the primary control loop, a change of power in area 1 was met by the increase in generation in all the areas associated with a change in the tie-line power, and a reduction in frequency. In normal operating state, the power system is operated so that the demands of areas are satisfied at the normal frequency. The conventional LFC is based on tie line bias control, where each area tends to reduce the area control error (ACE) to zero. The control error for each area consists of a linear combination of frequency and tie line error [8].

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + K_i \Delta_{\omega}$$

The area bias Ki determines the amount of interaction during a disturbance in the neighboring areas. An overall satisfactory performance is achieved when Ki is selected equal to the frequency bias factor of that area, i.e, $B_i = \frac{1}{R_i} + D_i$. ACE's are used as actuating signals to activate changes in the reference set points and when changes in tie-line power, ΔP_{12} is zero. The integer gain constant must be chosen small enough so as not to cause the area to go into a chase mode. In power system having steam plants, power generation can change only at a specified maximum rate. The generation rate (from safety considerations of the equipment) for reheat units is around 3%/min. The GRCs result in larger deviations in ACEs is the rate at which generation can change in the area is constrained by the limits imposed. Therefore, the duration for which the power needs to be imported increases considerably as compared to the case where generation rate is not considered.

Design of Fuzzy Logic Controller

In power systems, because of the inherent characteristics of the changing loads and the system non-linearities such as GRC, there is no analytical method to determine optimal parameters quickly for real time application. Artificial intelligence based gain scheduling is an alternative technique commonly used in designing controllers for non-linear systems. AI based systems have many advantages to control nonlinear system since they have an approximation ability using non-linear mappings. Fuzzy systems can be successfully applied to LFC problem for promising results [9]. Fuzzy set theory has found application in many fields especially in fuzzy knowledge base systems such as fuzzy logic control and approximate reasoning. Fuzzy system transforms a human knowledge into mathematical formula. Therefore, fuzzy set theory based approach, in recent years has emerged as a complement tool to mathematical approaches for solving power system problems. Mathur and Manjunath [10] have proposed fuzzy controllers for linear LFC system and found to have better dynamic response when compared to conventional PI controllers. An attempt is made in this paper to design a fuzzy controller for LFC problem by considering the non-linear parameter GRC.

The fuzzy controller has two inputs (ΔF and ΔPtie) and one output (y) as shown in Fig.10. Kp and Ki are the proportional and integral gains respectively.

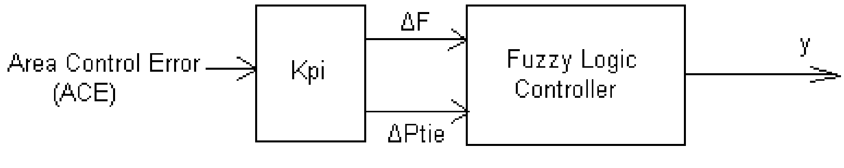

Figure 10: Fuzzy Logic Controller.

Fuzzy logic controller comprises of four principal components, a fuzzification interface, a knowledge base, a fuzzy inference system and de-fuzzification interface.

(a) Fuzzification

Fuzzification is the process of transforming real-valued variable into a fuzzy set variable. Fuzzy variables depend on nature of the system where it is implemented. The real value input here is change in frequency (ΔF) and change in tie line power (ΔPtie) which is related to their corresponding fuzzy variables by matching membership values [9]. The triangular membership function with seven linguistic variable is used in this study. The natural language representation of a variable is called as linguistic variable. The linguistic variables used here is NV(Negative Large), NM(Negative medium), NS(Negative small), ZE(Zero error), PS(Positive small), PM(Positive medium), PS(Positive small). Each linguistic variable has a membership value as shown fig.11.

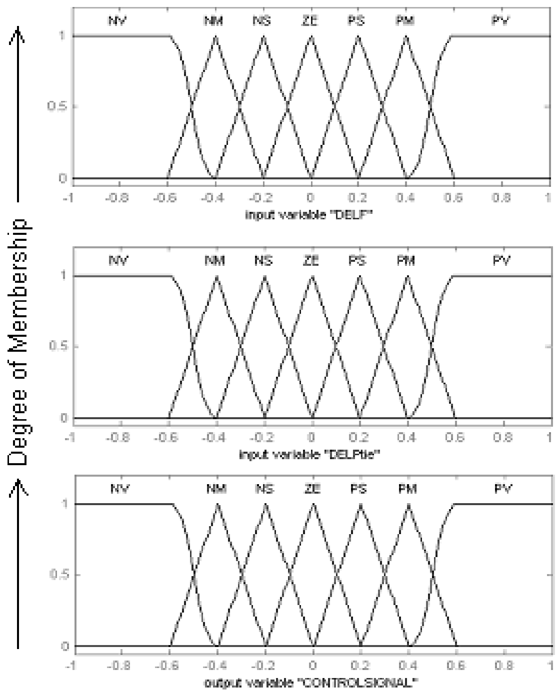

Figure 11: Input and output Membership Functions.

(b) Knowledge Base

The heart of the fuzzy system is a knowledge base consisting of fuzzy IF-THEN rules. The rule base consists of a set of fuzzy rules. The data base contains the membership function of fuzzy subsets. A fuzzy rule may contain fuzzy variables and fuzzy subsets characterized by membership function. For ex. **IF** change in frequency (ΔF) is NV and change in tie line power (ΔPtie) NV, **THEN** control signal (ΔPc) is NV. Fuzzy mathematical tools and the calculus of fuzzy IF-THEN rules provide a most useful paradigm for the automation and implementation of an extensive body of human knowledge heretofore not embodied in the quantitative modeling process [11].

Fuzzy rule base is formed using the decision table as shown in table.1, the number of rules, is based on the number of variables selected for each input membership function. The system has been simulated for different membership values 3, 5, & 7 and different shape. The process of determining the exact value and shape of membership is by experience and by trial & error method. These rules relate input signals to the output control signal. The control signal in the fuzzy form is obtained by applying mamdani product implication inference because of its computational simplicity. The heuristic rules of the knowledge base are used to determine the fuzzy controller action.

Table 1: Rule base for three area system.

	Change in frequency							
Change in Ptie		**NV**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PV**
	NV	NV	NV	NV	NV	NM	NS	ZE
	NM	NV	NM	NM	NM	NS	ZE	PS
	NS	NM	NS	NS	NS	ZE	PS	PM
	ZE	NV	NM	NS	ZE	PS	PM	PV
	PS	NM	NS	ZE	PS	PS	PS	PM
	PM	NS	ZE	PS	PM	PM	PM	PS
	PV	ZE	PS	PM	PV	PV	PV	PV

C. De-Fuzzification

The purpose of De-fuzzification is to convert the output fuzzy variable to a crisp value, So that it can be used for control purpose. It is employed because crisp control action is required in practical applications. Since the fuzzy logic controller action corresponds to an increment ΔPc, this type of controller will give zero steady-state error for an input step change in the reference to any step disturbance. The centroid method of de-fuzzification is employed here.

The membership functions, knowledge base and method of de-fuzzification essentially determine the controller performance.

Simulation Results

The fuzzy logic controller has been applied to a three area power sytem. The simulation has been conducted in Fuzzy Logic Toolbox and simulink in MATLAB. Typical parameters for the proposed sytem are as follows,

Tg = 0.08sec Tt = 0.3sec H= 0.167 D= 0.00833 B= 0.6 R = 1.66

The performance of Fuzzy Controller is compared with Conventional controller and the simulation results are presented in this section. Frequency response is obtained by applying a step load of 0.35p.u to 0.55p.u for area1, area2 and area3 respectively and their effects on nearby areas are also studied.

(i) Area-1 Loaded by 35%

The step load demand of 35% is applied to area-1 and the change in frequency in all the three areas are shown in Fig.11. The conventional controller settles nearly at 25 seconds, whereas the FLC settles at 12 seconds. The frequency error varies from -0.7Hz to +0.4 Hz and oscillates around this range during initial 10 seconds. The frequency oscillation is between -0.7 to +0.1Hz for the fuzzy controller.

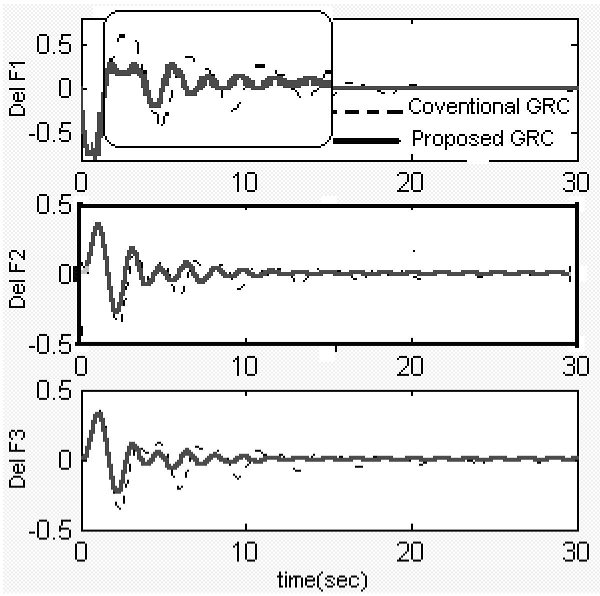

Figure 11: Response of Frequency deviation in each area following a step load of 0.35 P.U in area 1.

(ii) Area-2 Loaded by 45%

The simulation is repeated by applying a step load of 45% to area-2 and its frequency response is shown in Fig.12. The sudden increase in load records an overshoot of -0.8Hz and the FLC reacts immediately and settles down near to zero. The conventional control settles at 22seconds and with fuzzy the settling time is only 12 seconds

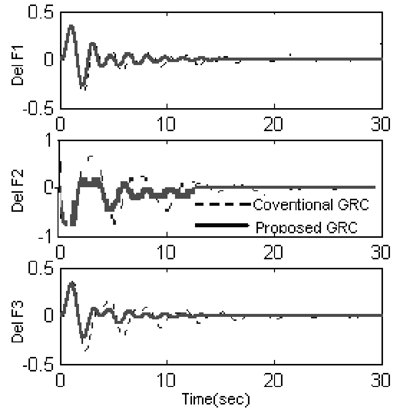

Figure 12: Response of Frequency deviation in each area following a step load of 0.35 P.U in area 2.

(iii) Area-3 Loaded by 55%

The simulation is repeated by applying a step load of 55% to area-3 and its frequency response is shown in fig.13. The frequency error varies from -0.8Hz to +0.2Hz for FLC in area-3. For conventional controller the error ranges from -0.8Hz to +0.7Hz when compared FLC which ranges from -0.8 to +0.2. The FLC settles at 15 seconds, which is less by 10 seconds when compared to conventional controller.

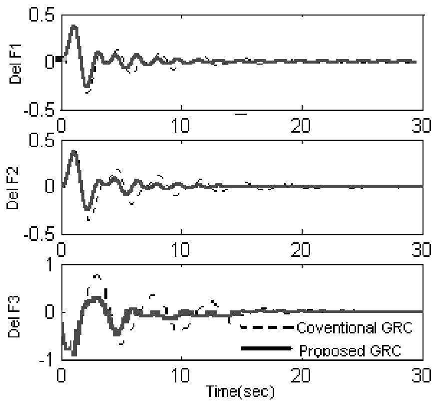

Figure13: Response of Frequency deviation in each area following a step load of 0.35 P.U in area 3.

Performance Comparison

A dynamic performance comparison of various controllers (Viz., Integral, Extended Integral, PI and Fuzzy Control) employed for LFC is represented in Table.2. In order to demonstrate the effectiveness of fuzzy controller, simulations were carried out with seven membership functions for each input and with 49 rules. The simulation was repeated for various loads and the results are found to be better for all loading conditions. The integral and extended integral controller proposed by Young et al is failed to provide best control because of fixed gains and optimal decaying factor [4][5]. Hence an intelligent controller is proposed in this study with new rules and membership functions when compared to moon et al.[6]. The simulation results shows that the proposed fuzzy controller yields 40% reduction in settling time and 20% reduction in peak overshoot when compared with recent Young et al study.[6]

Table 2: Comparison of dynamic performance of Controllers.

Parameter Considered Tg = 0.08sec Tt = 0.3sec H= 0.167 D= 0.00833 B= 0.6 R = 1.66				
Change in Frequency (Δf)	**Settling time (Ts)**	**Peak overshoot**	**Fuzzy Rules**	**Membership Funtions**
Integral controller – No GRC(Young-Hyen et al)[5]	50s	1.5	-	-
Extended Integral controller (Young-Hyen et al study)[5]	40s	0.45	-	-
Fuzzy Logic based Extended Integral Control (Moon et al) [6]	40	0.25	15	I/p 1 – 5 I/p 2 - 3
Conventional PI controller [9]	25	0.4		
Proposed Fuzzy controller	14s	0.3	49	I/p 1 &2 - 7

Conclusion

The quality of the power supply is determined by the constancy of frequency and voltage. Minimum frequency deviation and good terminal voltage response are the characteristics of a reliable power supply. LFC is vital for any interconnected power system in order to maintain constant frequency and tie line power flow between areas at prescheduled limits [13]. The conventional controllers used for this problem have large settling time, overshoot and oscillations. The proposed FLC provides a satisfactory stability between frequency overshoot and transient oscillations with zero steady state error. The simulation results demonstrate the effectiveness of the proposed method for LFC in a multi-area non-linear system. The following are the significant conclusions drawn from the proposed study,

- The Proposed method could reduce the oscillations of frequency deviation and the tie line power flow.
- The controller could respond to large load disturbances.
- Fuzzy systems often achieve tractability, robustness and overall cost effectiveness.
- Reduces the settling time by 40% and peak overshoot by 20%.
- Rules are simple and easier, hence system execution is faster.

It is concluded that the fuzzy logic based controller provides good performance even in the presence of GRC for any size of load change as compared to conventional controllers.[14]

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