ISSN 2250-3153

Load Frequency Control Using Fuzzy Logic

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Abstract- In industry or any area increasing load is a vast problem for power generation plants due to increase in demand for power. So making balance between generation and demand is the operating principle of load frequency control (LFC). The reliable operation of a large interconnected power system necessarily requires an Automatic Generation Control (AGC). The objective of AGC is to regulate the power output of Generators within a specified area in response to change in the system frequency, tie line power or relation of the two to each other, so as to maintain the scheduled system frequency and power interchange in the other are within the prescribed limits Several studies in LFC have led to the trend of applying the adaptive approach to the implementation on automatic generation control (AGC). However, the adaptive controller with self-tuning technique requires online acquisition of system parameters that was not clearly stated in the related literatures. Fuzzy controller and integral controller have been used to the models of single area power system and responses of area control error (ACE), tie line power and change in frequency are observed. The design of Fuzzy Logic Controller (FLC) involves the allocation of areas inputs and outputs , mapping of rules between inputs and outputs and defuzzification of outputs into a real value. There are some parameters (TP, M, β) which are used online for the adaptive tuning of fuzzy controller. We have solved for those parameters with model equations and used in the designing of the controller. Simulation results show that fuzzy control based estimate with an adaptive controller could enhance the performance of the LFC.

Index Terms- LFC, AGC, FLC, ACE, Tie line, acquisition, Defuzzification

I. Introduction

1.1 AUTOMATIC GENERATION CONTROL

When load in the system increases turbine speed drops before the governor can adjust the input. As the change in the value of speed decreases the error signal becomes smaller and the positions of governor valve get close to the required position, to maintain constant speed. However the constant speed will not be the set point and there will be an offset, to overcome this problem an integrator is added, which will automatically adjust the generation to restore the frequency to its nominal value. This scheme is called automatic generation control (AGC). The role of AGC is to divide the loads among the system, station and generator to achieve maximum economy and accurate control of the scheduled interchanges of tie-line power while maintaining a reasonability uniform frequency. Automatic generation control (AGC) plays a very important role in power system as its main role is to maintain the system frequency and tie line flow at their scheduled values during normal period.

Automatic generation control with primary speed control action, a change in system load will result in a steady state frequency deviation, depending upon governor droop characteristics and frequency sensitivity of the load. Restoration of the system frequency to nominal value requires supplementary control action which adjusts the load reference set point. Therefore the primary objectives of the automatic generation control are to regulate frequency to the nominal value and to maintain the interchange power between control areas at the scheduled values by adjusting the output of selected generators. This function is commonly referred to as load frequency control. A secondary objective is to distribute the required change in generation among the units to minimize the operating costs.

A control signal made up of tie line flow deviation added to frequency deviation weighted by a bias factor would accomplish the desired objective. This control signal is known as area control error (ACE).ACE serves to indicate when total generation must be raised or lowered in a control area.

In an interconnection, there are many control areas, each of which performs its AGC with the objective of maintaining the magnitude of ACE (area Control Error) "sufficiently close to 0" using various criteria. In order to maintain the frequency sufficiently close to its synchronous value over the entire interconnection, the coordination of the control areas' actions is required. Any wide deviation from the nominal value of frequency or voltage will lead the system to total collapse. Hence AGC has gained importance with the growth of interconnected systems and with rise in size of interconnected system automation of the control system have aroused. A number of control strategies exist to achieve better performance. Due to non-linearity of power system, system parameters are linearized around an operating point. PI controller is generally used. The disadvantage of PI controller is that the mathematical model of the control process may not exist or may be too expensive in terms of computer processing powers and memory.

II. Theory of Load Frequency Control

2.1 FREQUENCY RESPONSE IN PRIMARY CONTROL

When the system frequency drifts from nominal value 50Hz, some frequency sensitive components react to this change, the

ISSN 2250-3153

effective load for the power system changes. This process is called load damping and modeled with damping factor D. second, if the system frequency goes beyond the governor dead band (about 35 MHz); the governor will act to increase or decrease the output power of generating units. This can be done with the help of governed speed droop R, which is actually the feedback loop gain in the governor. The speed droop is defined as

$$R = \frac{\Delta w}{\Delta P} \text{pu}$$

Where

Δw = speed deviation

ΔP = output power

Percent speed regulation or droop R

The value of R determines the steady state speed versus load characteristics of the generating unit as shown in figure 2.1 below.

The ratio of speed deviation (ΔW_r) or frequency deviation (Δf) to change in valve/gate position (ΔY) or output power (ΔP) is equal to R. the parameter R is referred to speed regulation or droop. It can be expressed in percent as

Percent R=percent speed or frequency change/percent power output change*100

= [w (nl)-w (fl)]/w0 * 100

Where

w (nl) = steady state speed at no load

w (fl) = steady state speed at full load

w0= nominal or rated speed

For example 5% speed droop or regulation means 5% frequency deviation causes 100% change in power output.

In figure 2.1 speed droop characteristics of governor is shown. A typical value of speed droops in the governor is 5%. These governors' responses from each unit in the control area collectively to stabilize the system frequency at a new equilibrium

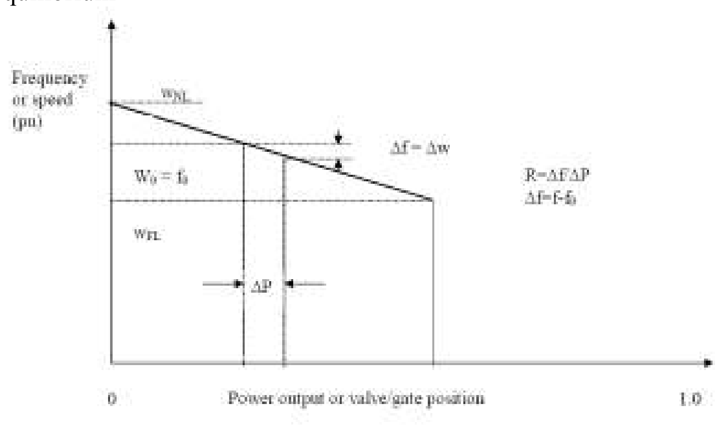

Figure 2.1: Ideal steady state characteristics of governor with speed droop

These two responses, load damping and governor response; help the system interconnection to be more stable. In short the system frequency goes up when the generation output is relatively bigger than the loads and the vice versa. This can be understood as a strong natural inertia to stay on equilibrium. The governor speed droop characteristics intentionally put to help this natural process to be more effective.

These responses are mathematically modeled as D and R respectively and are combined into one frequency response characteristic.

$$\beta = \sum \left(\frac{1}{R} + D\right)$$

2.2 AGC (Automatic Generation and Control)

The objectives of AGC are as follows:

(i) To hold system frequency at or very close to a specified/nominal value.

(ii) To maintain correct value of interchange power between control areas

(iii) To maintain each units generation at the most economic value.

To accomplish these objectives, each control area has to continually determine and monitor system deviation in measured frequency, Δf and tie line flow, ΔT, to determine the Area Control Error (ACE) as a measure for the secondary control. The raw values of ACE is first processed through filters, and then pass through a PI regulator, distributed by regulation participation factors before being dispatched as the load reference signal to the governor of units. A demand signal may also be sent to coordinate boiler turbine controllers to initiate boiler action in advance for improved overall unit response. The response time of AGC is approximately, a minute or two, mainly limited by the delays associated with the response rate of the units.

2.4 Area Control Error

Area Control Error is defined by

$ACEi = \Delta Pij + Bi * \Delta f$

Where i control area for which ACE is being measured

ΔPij power interchange in areas i and j

Bi control area frequency bias coefficient

Δf deviation in frequency

ACE is an error signal consisting of two terms. First term represents the error in the scheduled tie flows. The second term is inter area assistance in generation from control area to prevent large deviation of interconnection frequency. ACE, as defined, represents the generation versus load mismatch for the control area. The ACE signal is used in conventional AGC which has PI control logic.

ACE serves to indicate when total generation must be raised or lowered in a control area. A general criterion can be given about which AGC is considered 'good'. The ACE signal should ideally be kept from becoming too large. Since ACE is directly influenced by random load variations, this criterion can be treated statically by saying that the standard deviation of ACE should be small ACE should not be allowed to 'drift'. This means that the integral of ACE over appropriate time should be small. A 'drift' in ACE has the cumulative effect of creating system time errors or inadvertent interchange errors. The amount

ISSN 2250-3153

of control action called for by the AGC should be kept to a minimum.

2.5 Tie line bias control

Tie-line bias control is a control philosophy developed for load frequency control in a power system. It is widely used in AGC. It has been proved efficient in maintaining interconnection reliability and its simplicity in control implementation. The concept allows each control area to operate its generation and to fulfill areas control obligation, independently by monitoring and control the area's ACE. The frequency bias term in the ACE equation is important in that it assures that the objective of the AGC regulation is fulfilled while an area's responsibility to provide frequency response is not forfeited.

2.6 AGC in a single area system

In an isolated power system, maintenance of interchange power is not an issue. Therefore, the function of AGC is to restore frequency to the specified nominal value. This is accomplished by adding a reset or integral control which acts on the load reference settings of the governors of units on AGC. The integral control action ensures zero frequency error in the steady state.

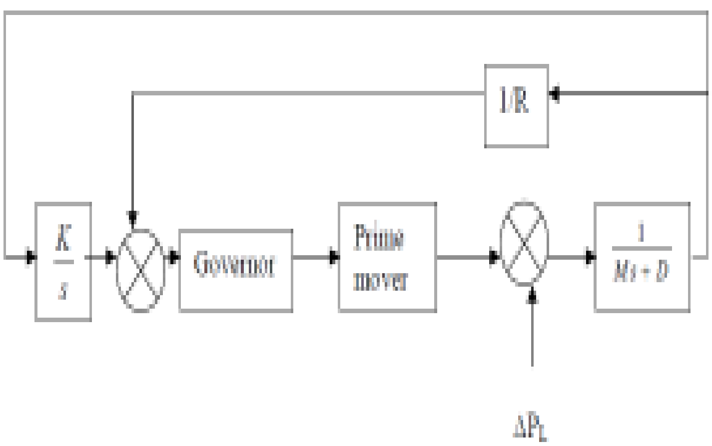

Figure 2.2: Addition of integral control on generating units selected for AGC

The supplementary generation control action is much slower than the primary speed control action. As such it takes effect after the primary speed control (which acts on all units on regulation) has stabilized the system frequency. Thus, AGC adjusts load reference settings of selected units, and hence their output power, to override then effects of composite frequency regulation characteristics of power system. In doing so, it restores the generation of all other units not on AGC to scheduled values.

2.7 AGC for a two area system

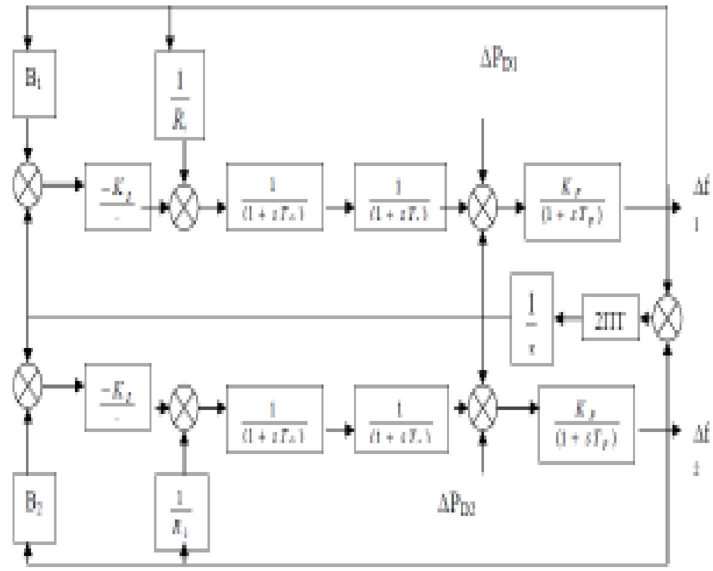

Figure 2.3: Transfer function model of a two area interconnected system

ΔPD1 Incremental load change in area 1.
ΔPD2 Incremental load change in area 2
R Governor speed regulation parameter.
T_G Mechanical governor response time (second).
T_1 turbine time constant.
B_1 Frequency bias constant for area 1.
B_2 Frequency bias constant for area 2
TP =2H/fD
K_P=1/D
D load damping constant
KI Integral gain
Δf1 Change in frequency for area 1
Δf2 Change in frequency for area 2

Figure 2.3 below shows block diagram representation of a two area interconnected system with each area represented by an equivalent inertia M, load damping constant D, turbine and governing system with a an effective speed droop R. The power flow on tie line from area 1 to area 2 is

$$P_{12} = \frac{E1E2}{Xt}\sin(\delta 1 - \delta 2) \qquad (2.1)$$

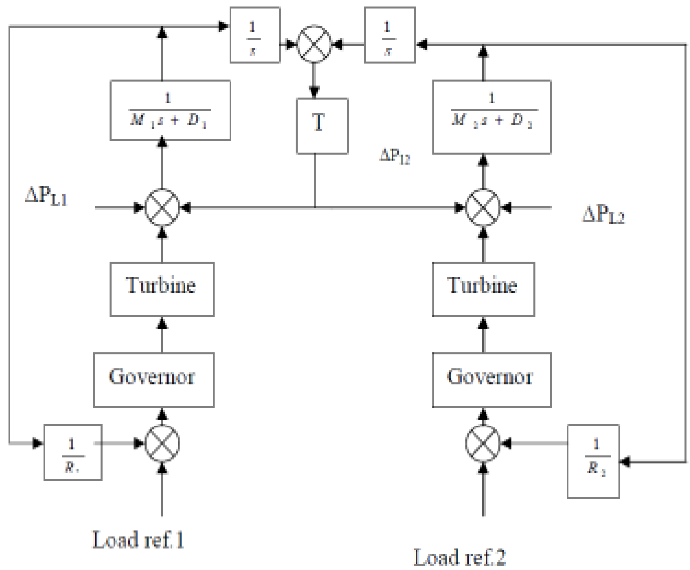

Figure 2.4: Two area system with primary speed control

Linearizing about an initial operating point represented by

$\delta_1 = \delta_{10}$ and $\delta_2 = \delta_{20}$

And $\Delta P12 = T\Delta\delta_{12}$ (2.2)

Where $\delta_{12} = \Delta\delta_1 - \Delta\delta_2$ (2.3)

The tie line is represented by the synchronizing torque coefficient T. synchronizing coefficient T is given by

$T = E_1E_2\cos(\delta 1 - \delta 2)/X_t$ (2.4)

A positive ΔP_{12} represents an increase in power transfer from area 1 to area2. The steady state frequency deviation (f-f0) will be same for two areas. For a total load change of ΔP_L

$\Delta f = \Delta w_1 = \Delta w_2 = \frac{-PL}{(1/R1+1/R2)+(D1+D2)}$ (2.5)

Consider the steady state values following an increase in area 1 load by ΔP_{L1}. for area 1

$\Delta P_{m1} - \Delta P_{12} - \Delta P_{L1} = \Delta f\, D_1$ (2.6)

And for area 2

$\Delta P_{m2} + \Delta P_{12} = \Delta f D_2$ (2.7)

The change in mechanical power depends upon regulation. Hence

$\Delta P_{m1} = -\frac{\partial f}{R1}$ (2.8)

$\Delta P_{m2} = \frac{-\partial f}{R2}$ (2.9)

Substitution of equation (2.8) in eq. (2.6) and eq. (2.9) in eq. (2.7) yields

$\partial f\,(\frac{1}{R1}+D_1) = \Delta P_{12} - \Delta P_{L1}$ (2.10)

And

$\partial f\,(\frac{1}{R1}+D_2) = \Delta P_{12}$ (2.11)

Solving equations (2.10) and (2.11)

$\Delta f = \frac{-\partial PL}{(1/R1+1/R2)+(D1+D2)} = \frac{-\partial PL}{(\beta 1+\beta 2)}$ (2.12)

Where β_1 and β_2 are the composite frequency response characteristics of area 1 and area 2 respectively. An increase in area 1 load by ΔP_{L1} results in a frequency reduction in both areas and a tie line flow of ΔP12. a negative ΔP12 is indicative of flow from area 2 to area1. The tie line flow deviation reflects the contribution of the regulation characteristic (1/R+D) of one area to another.

Similarly for a load change in area 2 by ΔP_{L2}

$\Delta f = \frac{-\Delta PL2}{\beta 1+\beta 2}$ (2.13)

And

$\Delta P_{12} = -\Delta P_{21} = \frac{-\Delta PL2 * \beta 1}{\beta 1+\beta 2}$ (2.14)

Examination of equations from (2.10) to (2.13) indicates a control signal made up of tie line flow deviation added to frequency deviation weighted by a bias factor would accomplish the desired objective. This control signal is known as area control error (ACE). From equation (2.10) and (2.11), it is apparent that a suitable bias factor for an area is its frequency response characteristic β.

Thus area control error for area 2

$ACE_2 = \Delta P_{12} + B_2\Delta f$ (2.15)

Where

$B2 = \beta 2 = \frac{1}{R2} + D_2$ (2.16)

Similarly for area 1

$B1 = \beta 1 = \frac{1}{R1} + D_1$ (2.17)

The ACE represents the required change in area generation, and its unit is MW. The unit normally used for expressing the frequency bias factor B is MW/0.1Hz

III. Fuzzy System Logic

Logic is the science of reasoning. Symbolic or mathematical logic has turned out to be powerful computational paradigm. Not only symbolic logic help in the description of events in the real world but has also turn out to be an effective tool for inferring or deducing information from a given set of facts.

3.1 FUZZY LOGIC CONTROLLER

Fuzzy logic controller is used for automatic generation control in a two area system. Basic block diagram of fuzzy logic controller is as shown under.

ISSN 2250-3153

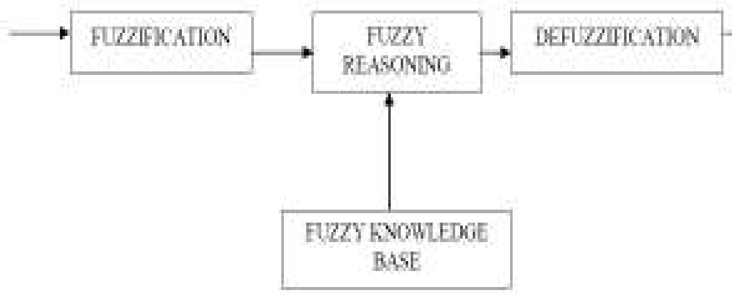

Figure 3.2: Basic structure of fuzzy logic controller.

The main building units of an FLC are a fuzzification unit, a fuzzy logic reasoning unit, a knowledge base, and a defuzzification unit. Defuzzification is the process of converting inferred fuzzy control actions into a crisp control action.

3.2 Design of FLC

In the design of an FLC system it is assumed that:

- The input and output variables can be observed and measured.
- An adequate solution (not necessarily an optimum one) is acceptable.
- A linguistic model can be created based on the knowledge of a human expert.

Fuzzy controllers are normally built with the use of fuzzy rules. The membership functions for the fuzzy sets will be derived from the information available from the domain experts and/or observed control actions.

The basic configuration of Fuzzy Logic Controller (FLC) consists of four main parts

(i) Fuzzification
(ii) Knowledge base
(iii) Decision-making logic and
(iv) Defuzzification

The functions of the above modules are described below.

(i) The Fuzzification:
(a) Measure the values of input variables
(b) Performs a scale mapping that transforms the range of values of input variables into corresponding universe of discourse.
(c) Performs the function of fuzzification that converts input into suitable linguistic values, which may be, viewed labels of fuzzy sets.

(ii) The Knowledge Base:
It consists of data base and linguistic control rule base.
(a) The database provides necessary definitions, which are used to define linguistic control rules and fuzzy data, manipulation in an, FLC.
(b) The rule base characterizes the control goals and control policy of the domain experts by means of set of linguistic control rules.

(iii) The Decision Making Logic:
It is the kernel of an FLC; it has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

(iv)The Defuzzification:
(a) A scale mapping which converts the range of values of input variables into corresponding universe of discourse.
(b) Defuzzification, which yields a non-fuzzy, control action from an inferred fuzzy control action.

IV. Case Study and Results

4.1Application of Fuzzy Logic to Automatic Generation Control

Fuzzy logic is used to calculate ACE (out) i.e. control signal in the form of area control error that will be provided to both the areas to generate according to change in total load to maintain the system frequency within permissible limits. Area control error and change in frequency of the system as input are used as inputs for FLC.

4.1.1 Algorithm for fuzzy logic application to AGC problem

The calculation of the control action in the fuzzy algorithm consists of following four steps.

1. Calculate area control error (ACE) and change of frequency (delF).
2. Convert the error and change of frequency into fuzzy variables i.e. linguistic variables such as Positive Big (PB), Positive Medium (PM) etc., as given below.
3. Evaluate the decision rules shown in rule base given below using the compositional rule of inference.
4. Calculate the deterministic input required to regulate the process. The control rules are formulated in linguistic terms using fuzzy sets to describe the magnitude of error, the frequency deviation and the magnitude of the appropriate control action.

NS = negative small
ZE = zero
PS = positive small

4.2 Online Estimation of T_P, M

The input and output relations could be approximated by Where Pin is unit's MW input commands. Pout is unit's actual MW output. Relocating the denominator and taking the inverse Laplace transform of , the

$$P_{in} \times \left(\frac{1}{T_P s + 1}\right) = P_{out} \qquad (4.1)$$

equation becomes

$$P_{in} = \dot{P}_{out} \times T_P + P_{out} \qquad (4.2)$$

4.3 Online estimation of system's inertia constant M

The electromechanical power balance equation of an isolated power system is

$$(P_{out} - P_L) \times \frac{1}{Ms + D} = \Delta F \qquad (4.3)$$

Where Pout is total MW generation, M is system's inertia constant in second, ΔF is frequency deviation in Hz, D is load damping in MW/Hz, and PL is system MW load. Relocating the denominator term in (4.3) and taking the inverse Laplace transform, (4.3) becomes

$$P_{out} = M \times \Delta\dot{F} + D \times \Delta F + P_L \qquad (4.4)$$

Once the system parameters are available, the integral gains in AGC could be scheduled corresponding to some nominal operating conditions. In general, the operating states of LFC in a control area could be categorized into three load conditions, on peak, semi-on peak, and off peak. Each state may result in different T_P and M in the system. As a result, three parameters for three states would constitute 27 patterns of operating gains.

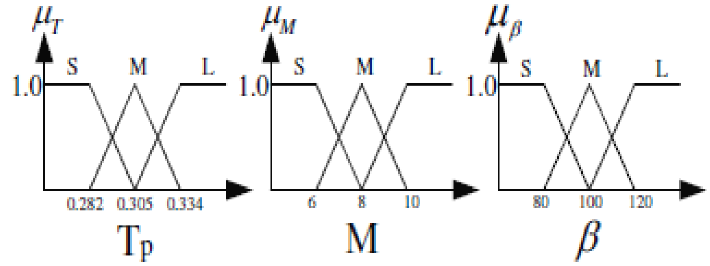

Figure4.1: Membership functions for variables T_P , M, and β

In this case, a Sugeno Type Fuzzy Inference System (STFIS) was adopted to calculate the off nominal gains. Unlike Mamdani type fuzzy inference approach, STFIS does not use the complicated Defuzzification process to derive the off nominal gains. As a result, STFIS is simpler to design faster for AGC calculation. Table 4.1 is used as a reference to design and develop the fuzzy base rule where T_P, M are taken online.

1) Construct the membership functions: When T_P , M, and β are monitored, the estimated values are fuzzified by the membership functions depicted in Fig. 4.1. The membership functions are to be used for fuzzification process.

2) Setting the Fuzzification rule: The available T_P, M, and β are classified into three subsets (S, M, L).

3) We can take the value of Frequency bias factor β which is equal to

$$\beta = 1/R_{eq} + D \qquad (4.5)$$

System investigated

Single area power system is investigated. Dynamic performance of system is observed for 1% step change. Simulation is carried on MATLAB.

Table 4.1: Integral gain corresponding to nominal systemparameters

Pattern	T_P	M	β	K_I	Pattern	T_P	M	β	K_I
1	0.334	6	80	5.63	15	0.305	8	120	5.23
2	0.334	6	100	6.21	16	0.305	10	80	4.34
3	0.334	6	120	6.55	17	0.305	10	100	5.28
4	0.334	8	80	5.33	18	0.305	10	120	5.30
5	0.334	8	100	5.80	19	0.282	6	80	3.90
6	0.334	8	120	6.11	20	0.282	6	100	4.18
7	0.334	10	80	4.59	21	0.282	6	120	4.41
8	0.334	10	100	5.15	22	0.282	8	80	3.83
9	0.334	10	120	5.97	23	0.282	8	100	4.14
10	0.305	6	80	4.82	24	0.282	8	120	4.31
11	0.305	6	100	5.13	25	0.282	10	80	3.84
12	0.305	6	120	5.39	26	0.282	10	100	4.00
13	0.305	8	80	5.05	27	0.282	10	120	4.29
14	0.305	8	100	5.08					

4.4 Simulation Results of single area system with integral controller and fuzzy gain scheduling.

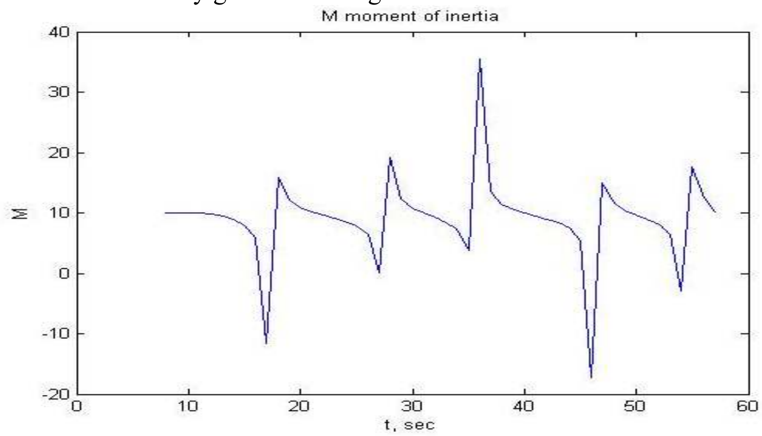

Figure 4.2: Online value of M(Moment of Inertia)

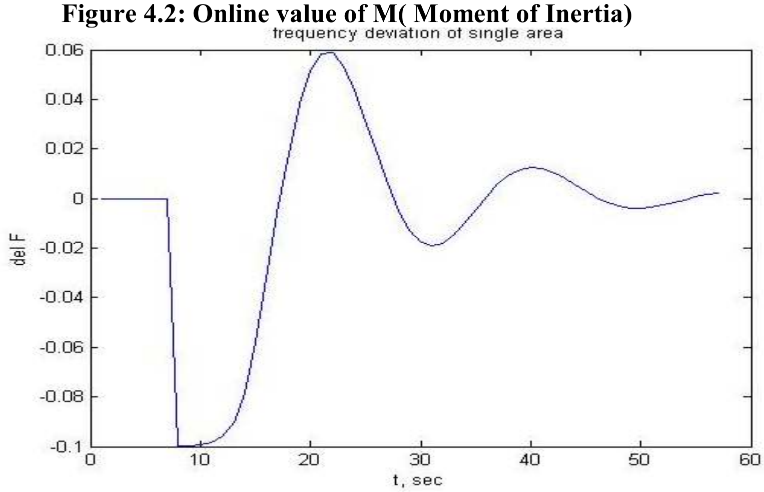

Figure 4.3: Frequency Deviation of Single area with integral controller

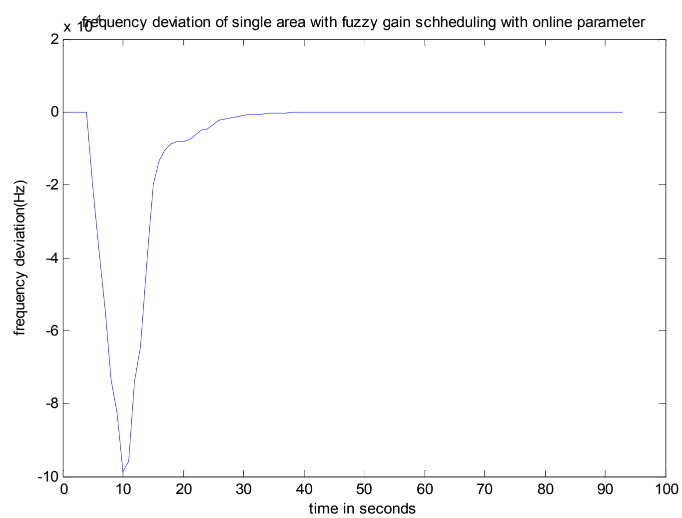

Figure 4.4: frequency deviation of single area with fuzzy gain scheduling (Blue for area one and Green for area 2)

4.5 Here this results shows changing of online parameter with load changes

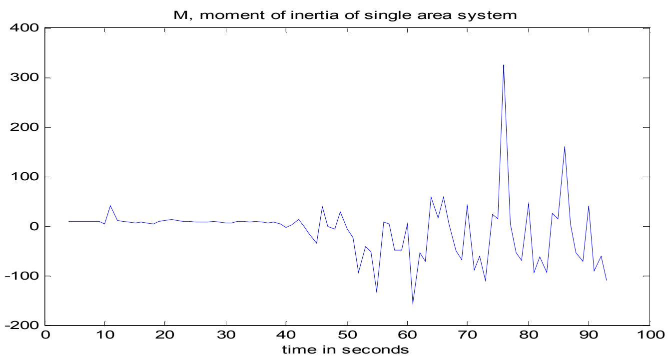

Figure 4.5: online value of M, moment of inertia of single area system fuzzy gain scheduling

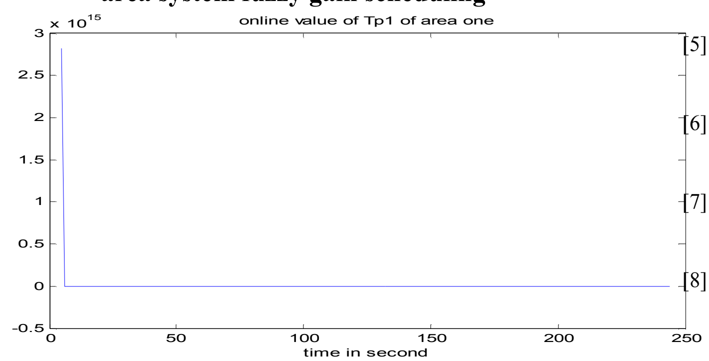

Figure 4.6: online value of Tp of single area diagram with fuzzy gain scheduling

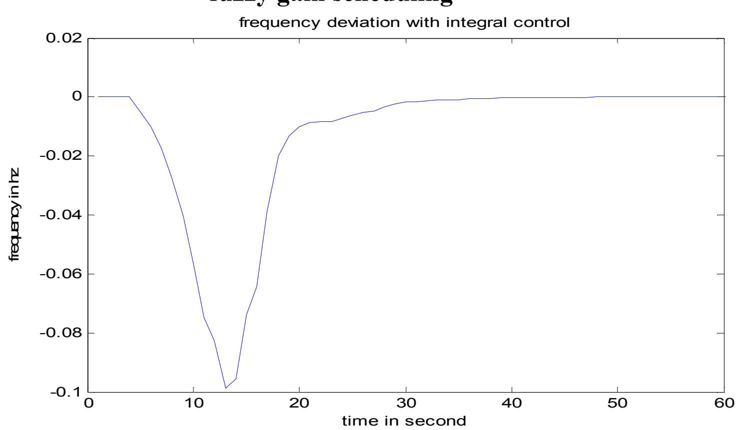

Figure 4.7: Frequency deviation in single area system with fuzzy controller

V. CONCLUSION

Firstly mathematical model of AGC in single area is presented & Integral controller is implemented, then estimate the online parameters of generation time constant (TP) and moment of inertia (M). Then Fuzzy Controller is implemented with generation time constant (TP) and moment of inertia (M) and freq bias coefficient β as inputs and integral gain (K) as output to fuzzy controller. Simulation is carried out on MATLAB and dynamic performance of system is observed.

We observed that adaptive fuzzy logic scheme to AGC problem enhanced the dynamic performance of single area system. Dynamic performance (Δf) in a single area system is better when compared to conventional controller.

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