Adaptive Neuro-Fuzzy Scheduled Load Frequency Controller for Multi Source Multi Area System Interconnected via Asynchronous Tie-line

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Abstract: - The article focuses towards the development of an optimal secondary controller which could adapt with the varying system conditions. For the analysis, a two area multi source system consisting of thermal, hydro and nuclear system in one area is interconnected with another area comprising of thermal and hydro system. On subjection to unit step load change in demand, the impact on frequency and tie-line power flow variations in multi source multi area is observed under MATLAB / Simulink environment. The fine tuning of frequency and tie-line power flow variations is achieved with the help of secondary controller. Optimal secondary Proportional Integral (PI) controller is chosen based on Zeigler Nichols' (ZN), Genetic Algorithm (GA), Fuzzy Gain Scheduling (FGS) and Adaptive Neuro-Fuzzy Inference System (ANFIS) tuning techniques. The performance of the controller is evaluated based on performance indices.

Key-Words: - Load Frequency Control (LFC), Zeigler Nichols' (ZN) Method, Genetic Algorithm (GA) Technique, Adaptive Neuro-Fuzzy Gain Scheduling (ANFIS) Technique, Integral Squared Error (ISE)

1 Introduction

In today's era of fast developing loads when compared to utilities have paved way towards reliable power supply. In interconnected system due to vast variations in loads, the frequency variations and tie-line power flow to be in limits is a challenging task. Load Frequency Control (LFC) plays a major key role in keeping the system operation and control intact [1-3]. Many of the researchers have contributed their work towards LFC in interconnected system [4-11]. When subjected to load change, a High Voltage Direct Current Transmission (HVDC) Line in anti-parallel with the High Voltage Alternating Current (HVAC) line [12-15] connecting two areas would result reduced area frequencies and tie-line power flow. In this work, for the analysis as a multi source thermal, hydro and nuclear of one area is interconnected via HVAC and HVDC anti parallel tie-line with another area of hydro and thermal system. When load changes in an interconnected system comprising of multi sources, the frequency and tie-line power flow varies, as such, primary control loop governed by the speed governor sets the system back to its nominal value. Due to the limitations in droop change of the speed governor which relies between 2-3%, the system settles nearer to the nominal value with a steady state error. For settling the system back to its nominal state, secondary controller comes into action.

As secondary controller, PI controller has achieved its par in control applications for its flexible operation [16-17]. ZN method as a conventional benchmark is used for tuning the gains of the PI controller [18]. To achieve optimal gain values of PI controller GA, PSO (Particle Swarm Optimization), SA (Simulated Annealing) techniques are used by many researchers under load frequency control issues. In this work, GA technique [19-22] is used for tuning the gain values of the PI controller which provides global optimal values. But, ZN and GA tuned PI controller gain values being fixed, it fails to vary the gain values with the system varying conditions. Therefore, FGS based on its efficient decision making [23-25] will help to vary the gain values of the controller with respect to varying system conditions. For effective gain scheduling to adapt with the system on wide varying conditions ANFIS [26] is used in this work. ANFIS considers the Fuzzy Inference System (FIS) to take the decision and further optimizes to adapt with the help of neural network to judge wide range of variations in the system. The controller performance is evaluated based on performance indices [27-28]. For practicality, as a case study, multi source multi area system is included with reheat steam turbine, boiler dynamics with the limits bounds to turbine operation namely Generation Rate Constraints (GRC) is considered to make the system highly robust in nature on a scale of wide varying characteristics of the system [29-30]. Instead of identical areas, the system is operated under non-identical areas approach. ANFIS based PI controller is used for adapting the controller gains with respect to wide change on system conditions to bring back the system area frequencies and tie-line power flow to its normal value. The discussion of the work starts with the section 2 which states about the modeling of multi source multi area system with asynchronous tie-line, Section 3 deals with the tuning methods adopted for secondary PI controller, Section 4 discusses with simulation results and case study and finally section 5 concludes the work.

2 Modeling of Multi Source Multi Area System Interconnected via Asynchronous Tie-line

For analysis, two similar areas interconnected via HVAC in anti-parallel with HVDC tie-line operating at a capacity of 2000 MW with nominal load of 1000 MW operating at 50Hz is taken into consideration. An area comprises of non-reheat steam turbine, hydro turbine and nuclear turbine driving a generator connected to a load is interconnected to another area of hydro turbine and non-reheat steam turbine driving the generator and load. The one-line diagram of multi source multi area interconnected via asynchronous tie-lines is shown in Fig 1.

In thermal power plant [2-5], the turbine acts as the prime mover for the generator. The turbine gets the mechanical energy through steam from boiler. The steam input to the turbine is controlled using the speed governor. When there is an increase in demand, the mismatch between the generation and demand is indirectly sensed by the governor in terms of change in frequency. The output of the speed governor is modeled as shown in Equation (1).

$$\Delta P_g(s) = \Delta P_{ref1}(s) - \frac{1}{R_1}\Delta f_1(s) \tag{1}$$

Depending on the sensed frequency value, the speed governor with the help of hydraulic amplifier alters the inlet valve position of steam, which in turn controls the frequency.

The turbine output w.r.t speed governor output is represented as shown in Equation (2)

$$\frac{\Delta P_T(s)}{\Delta P_g(s)} = \frac{1}{(1+sT_H)(1+sT_T)} \tag{2}$$

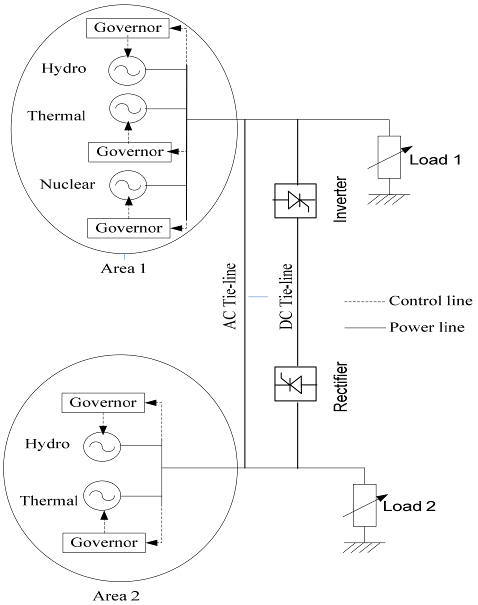

Fig.1 One-line diagram of multi source multi area interconnected via asynchronous tie-line

The turbine power output drives the generator which provides the electrical power to the power system. The transfer function of the power system comprising of generator with load disturbance is given in Equation (3)

$$\Delta P_T - \Delta P_{D1} = \frac{K_{P1}}{1+sT_{P1}}\Delta f_1 \tag{3}$$

The characteristics of hydro turbines are different from thermal turbines. In hydro plants [4-5], water is the source for producing mechanical energy to drive the turbine. Though it takes less time to start up, greater time lag prevails in the response during normal operation due to large water inertia. The mismatch between generation and demand is sensed indirectly in terms of change in frequency by the governor [5] which controls the water input to the turbine. The transfer function representing the performance of the speed governor is highlighted in Equation (4)

$$\Delta P_{Hg}(s) = \frac{K_1}{1+sT_1}(\Delta P_{ref2}(s) - \frac{1}{R_2}\Delta f_1(s)) \tag{4}$$

The output of the hydro turbine w.r.t. speed governor output is represented in Equation(5)

$$\frac{\Delta P_{HT}(s)}{\Delta P_{Hg}(s)} = \frac{(1+sT_R)(1-sT_W)}{(1+sT_2)(1+0.5sT_W)} \tag{5}$$

The turbine power output drives the generator which provides the electrical power to the power system whose transfer function is same as Equation (3). In nuclear power plant, the reactor core would contain 75 tons of uranium to produce an output of 1000 MW. In the reactor core the U-235 isotope fissions or splits, producing a lot of heat in a continuous process as a chain reaction. The process depends on the presence of a moderator such as water or graphite, and is fully controlled. The moderator slows down the neutrons produced by fission of the uranium nuclei so that they go on to produce more fission. The transfer function of nuclear speed governor is represented in Equation (6)

$$\Delta P_{NR}(s) = \frac{1}{(1+sT_{NR})}(\Delta P_{ref3}(s) - \frac{1}{R_3}\Delta f_1(s)) \quad (6)$$

The main design is the pressurized water reactor (PWR) which has water in its primary cooling/heat transfer circuit, and generates steam to drive the generator to meet the demand. The turbine model of tandem-compound type which has one High Pressure (HP) and two Lower Pressure (LP) section with High Pressure (HP) re-heater sections [6]. High pressure steam surpasses through the reheat the HP exhaust. Before entering the LP turbine the HP turbine exhausts Moisture-Separator-Reheater (MSR). This helps to reduce the moisture of the steam and erosion rates while passing through LP section of the turbine. The transfer function of LP and HP turbine respectively is represented in Equation (7) and Equation (8) respectively.

$$\frac{\Delta P_{NT}(s)}{\Delta P_{NR}(s)} = \frac{K_{RN1}}{(1+sT_{N1})(1+sT_{RH1})} + \frac{(1+sT_{RH2})}{(1+sT_{RH3})(1+sT_{N2})} \quad (7)$$

$$\frac{\Delta P_{NT}(s)}{\Delta P_{NR}(s)} = \frac{K_{HN1}}{(1+sT_{N1})} \quad (8)$$

The generator is driven by power output of the turbine which generates electrical power to the power system is represented in Equation (3). The tie-line interconnecting the two areas via HVAC and HVDC tie-line is modelled and written in transfer function as shown in Equation (9) and Equation (10) respectively.

$$\Delta P_{ACtie12}(s) = \frac{2\Pi T}{s}(\Delta f_1(s) - \Delta f_2(s)) \quad (9)$$

$$\Delta P_{DCtie12}(s) = \frac{K_{DC}}{1+sT_{DC}}(\Delta f_1(s) - \Delta f_2(s)) \quad (10)$$

The tie-line power flow includes the variation on HVAC and as well as on HVDC tie-line.The mathematical modeling with the governing equations explained above for the Governor-Turbine system of Thermal, Hydro and Nuclear plant of an area interconnected via asynchronous tie-line to an another area of Hydro and Thermal Power Plant is shown in Fig 2.

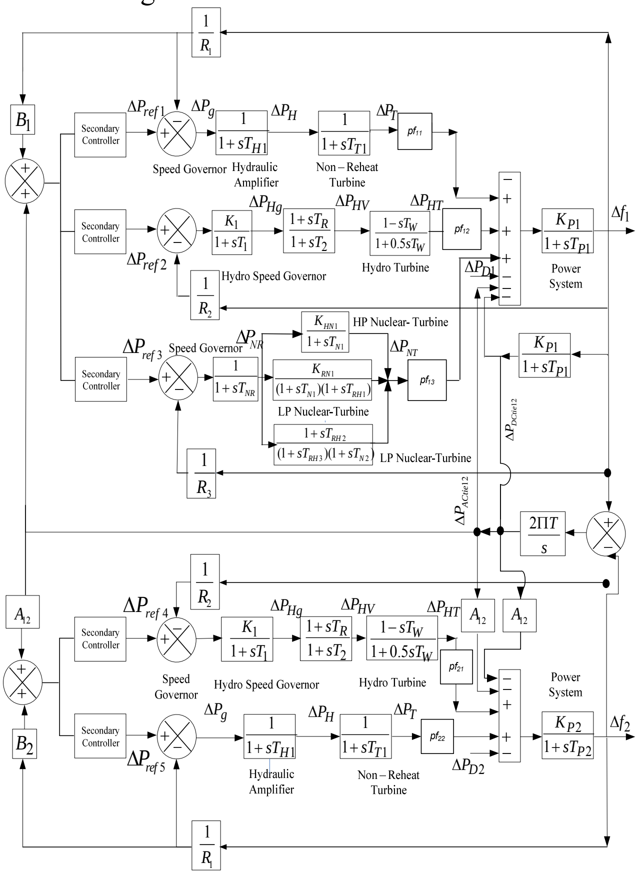

Fig.2 Transfer function model of multi source multi area interconnected via asynchronous tie-line

3 Tuning Methods of Secondary Proportional Integral (PI) Controller

The limitation of the primary speed governor action to 2-3% would not help the system to retain to its normal value on subjection to unit step load change in area 1. Therefore, secondary controller being flexible is required. In this work, PI controller [16-17] is used for fine tuning of frequency and tie-line power flow variations to bring the system to its normal value. The transfer function of PI controller is shown in Equation (11).

$$\Delta P_{ref1}(s) = (Kp + \frac{Ki}{s})(\Delta P_{tie12}(s) + \beta_1 \frac{1}{R_1}) \quad (11)$$

The secondary controller is connected to the multi source multi area system as shown in Fig 2. The various tuning methods for optimal choosing of controller gains are discussed below.

3.1 Zeigler Nichols' (ZN) Tuning Method

As a conventional bench mark, ZN method [18] is used for choosing the better value of controller gains. In this method, proportional gain '*Kp*' is increased maintaining integral gain '*Ki*' to zero. The gain at the system oscillates is termed to be ultimate gain '*Ku*' and the difference between the peak for one cycle is termed to be ultimate time '*Tu*' is noted down. The PI controller gains computed using Zeigler Nichols' method are 6.995 and 1.034 respectively in area 1 and area 2.

3.2 Genetic Algorithm (GA) Tuning Method

ZN tuned PI controller gain values are not the optimal one. Therefore, optimization techniques are adopted for obtaining optimal values of PI controller for the multi source multi area system interconnected via asynchronous tie-line. In this work, GA technique [19-20] is used for tuning the PI controller. The algorithm adopted for tuning PI controller gains is as follows:

Step1: Estimate ranges for the proportional and integral gains

Step2: Randomly initialize the values for the controller gains

Step3: On subjection to unit step load change in area 1; evaluate the objective function to minimize the integral squared error of area frequencies and tie-line power flow change on subjection to unit step load change in area 1

Step4: Is the convergence criteria of error minimization is met? If No, apply genetic operator by creating new ranges for the controller gains through reproduction, crossover and mutation and go to step3 and repeat the process.

Step5: If Yes, stop and PI controller gain values obtained are the optimal values to be considered in the plant.

The optimal gain values of the PI controller using GA technique are tabulated in Table 1.

Table 1. GA tuned PI controller gain values

Multi source multi area hydro thermal system interconnected with asynchronous tie-line	Area 1	Kp_1	1.0002
		Ki_1	4.2896
		Kp_2	2.7915
		Ki_2	5.3155
		Kp_3	4.5830
		Ki_3	6.3600
	Area 2	Kp_1	1.2173
		Ki_1	5.0275
		Kp_2	2.91001
		Ki_2	4.7160

3.3 Fuzzy Gain Scheduling (FGS) Tuning Method

The optimal values chosen by GA method also provide fixed gain values which don't change w.r.t varying system conditions. Therefore, FGS method [24-25] being much flexible and its decision making based on varying system conditions is considered in this work. The functional diagram of FGS in making the decision is shown in Fig 3.

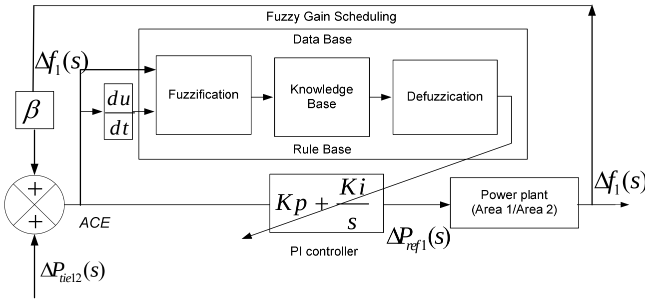

Fig.3 Schematic diagram of Fuzzy Gain Scheduling of PI controller

In this work, FGS has two inputs namely change in error *ACE* and rate of change in error *(du/dt).ACE* or *ACE*^{1}. The FGS based on the knowledge changes the reference power setting of the governor $\Delta P_{ref1}(s)$.

The two inputs and output is characterized with seven linguistic variable namely Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB). The NB and PB are of trapezoidal membership function to accommodate the error lying in the infinity region.

All other membership function is of triangular type. The input *ACE* range is between [-0.0171 0.0171] and the other input *(du/dt).ACE* or *ACE*^{1} range is between [-0.0283 0.0283], output range $\Delta P_{ref1}(s)$ is between [-0.005 0.005].

The rules are framed in such a way that it suits for both *Kp* and *Ki* which is furnished in Table 2.

Table 2. Fuzzy rules for scheduling *Kp* and *Ki*

ACE / ***ACE***^{1}	**LN**	**MN**	**SN**	**Z**	**SP**	**MP**	**LP**
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	MP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	MP	SP	Z	SN	SN	MN	LN
MP	SP	Z	SN	MN	MN	MN	LN
LP	Z	SN	MN	MN	LN	LN	LN

The rules are of IF AND THEN type. For example; If *ACE* is LN and *ACE*^{1} is LN then output is LP.

3.4 Gain Scheduling using Adaptive Neuro-Fuzzy Inference System (ANFIS)

The fuzzy system helps in to change the controller gains under varying system conditions and neural network proven its relevance in adapting towards the system conditions. Depending on wide variations of the system conditions FGS fails to provide control on the system which could be overruled by ANFIS [26]. The efficient decision making by the FIS correlated with the adaptive neural network would help to handle the system being highly robust. The functional diagram of ANFIS is shown in Fig4.

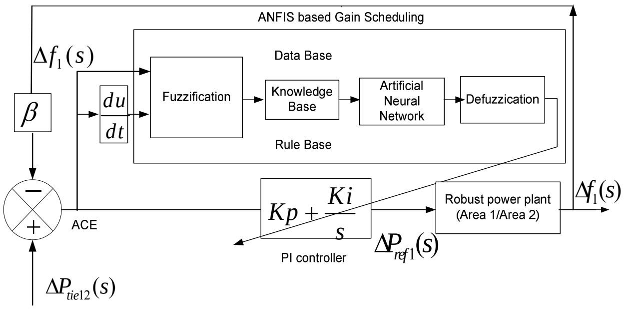

Fig.4 Schematic diagram of ANFIS based Gain Scheduling of PI controller

Based on the prior knowledge, FGS has scheduled the PI controller gains for the multi source multi area system subjected to load variations by reduced optimization search space. With this Neural network adapts by applying back propagation to the structured network to automate FIS parametric controller tuning.

The ANFIS algorithm is explained as follows:

Step 1: Load the training data obtained by the Fuzzy Inference System (FIS) comprising of two inputs and one output.

Step2: Set the input parameter of membership function and generate the ANFIS model.

Step3: If the error minimized or converged? If Yes, get optimized FIS after training which would be adaptable gain values of the PI controller.

Step4: If No, go to step 2 and proceed until converged.

The controller performance is evaluated based on Integral Squared Error (ISE) [27-28] which is represented in Equation 12.

$$ISE = \int (\Delta f_1^{\ 2} + \Delta P_{tie12}^{\ 2} + \Delta f_2^{\ 2}).dt \qquad (12)$$

4 Results and Discussions

As discussed in Section 2, Fig 2 model of multi source multi area system with asynchronous tie-line is developed using MATLAB/Simulink [31] without secondary controller. The system with asynchronous tie-line is subjected to unit step load disturbance in area 1 and its frequency and tie-line power flow variations is observed and compared without HVDC line. The comparison response with and without HVDC tie-line is shown in Fig 5.

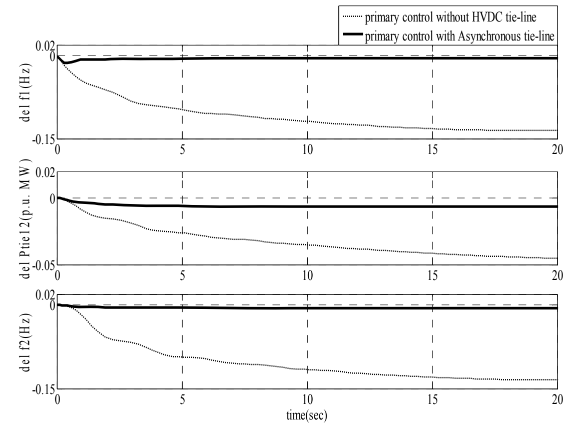

Fig.5 Comparison response of multi source multi area interconnected via Asynchronous Tie-line and without HVDC Tie-line

From the above figure, it clearly shows that with two-area interconnected via asynchronous tie-line and without HVDC tie-line on subjection to unit step load disturbance in area 1 has lead to area frequency variations and tie-line power flow with reduced steady state error. Therefore, preferably with a asynchronous tie-line interconnecting areas would help in limiting the variations in area frequencies and tie-line power flow on load variations. As discussed in section 3, due to the limitation in speed governor characteristics, PI controller would help the system to retain to its nominal value by fine tuning the variations. Therefore, as discussed in section 3.1 with gain values as highlighted and section 3.2 with GA method, the gain values as highlighted in Table 1 is included in multi source multi area system interconnected via asynchronous tie-line is compared without the secondary controller i.e. primary loop and is shown in Fig 6.

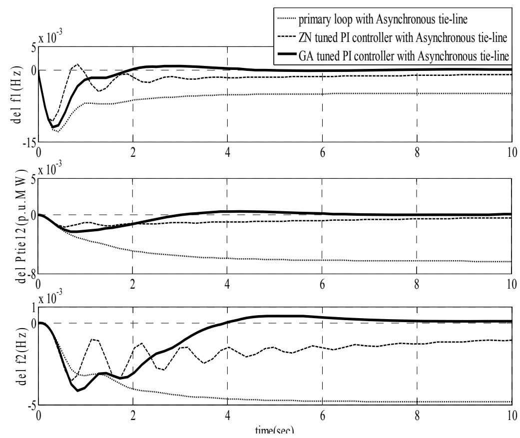

Fig.6 Comparison response of primary loop, ZN and GA tuned PI controller of multi source multi area interconnected via asynchronous tie-line

From the above comparison response, with secondary controller GA technique has given optimal PI controller gain values when compared to ZN tuned and without secondary controller. But, using GA technique PI controller gain values are fixed and doesn't changes w.r.t system conditions. Therefore, FGS is used for scheduling the gain values as discussed in section 3.3 and adapting the system w.r.t to increase in robustness of the system ANFIS as discussed in section 3.4 is incorporated in the system. The comparison response of ANFIS with FGS and GA technique tuned PI controller is shown in Fig 7.

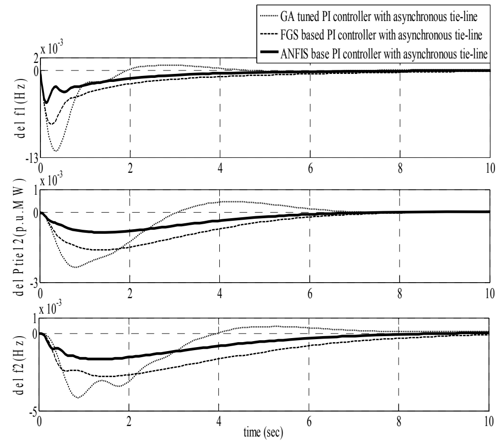

Fig.7 Comparison response of GA, FGS and ANFIS tuned PI controller of multi source multi area interconnected with asynchronous tie-line

From the above figure, it is quite evident that ANFIS based PI controller has reduced subsequently the variations in frequency and tie-line power flow with reduced peak overshoot and faster settling time to its nominal value when subjected to 1% load change in area 1.

The performance indices evaluated based on ISE is shown in Table 2 which helps in judging the controller performance. and proves ANFIS as suitable PI controller which helps in fine tuning the variations.

Table 2. Performance and percentage improvement of various controllers in multi source multi area hydro thermal system based on ISE

Secondary Controller	**ISE**
ZN tuned PI	0.0001077
GA tuned PI	9.715e-5
FGS	7.25e-5
ANFIS	2.22e-5
% Improvement	
GA (PI) w.r.t ZN (PI)	**9.79**
FGS (PI) w.r.t GA (PI)	**25.37**
ANFIS (PI) w.r.t FGS (PI)	**69.3**

From the Table 2, based on ISE and improvement in percentage comparison among the controllers, ANFIS tuned PI controller proves to be the suitable secondary controller which helps in fine tuning and achieving the system faster in action to its nominal value. The performance of the ANFIS based PI controller is tested under robust system by including the boiler dynamics, reheat steam turbine [1-3,30] in thermal power plant in both the areas, on subjection to increase and decrease of 1% load change during 0sec, 80sec and 160 sec in area 1 and area 2 operating at decrease and increase of 1% load change during 40sec and 120sec respectively. Instead of identical power system, area1 operating at a capacity of 800 MW and area 2 operating at a capacity of 1250MW. The system is simulated using MATLAB/Simulink, and the response of robust multi source multi area system interconnected via asynchronous tie-line with ANFIS based PI controller is shown in Fig 8.

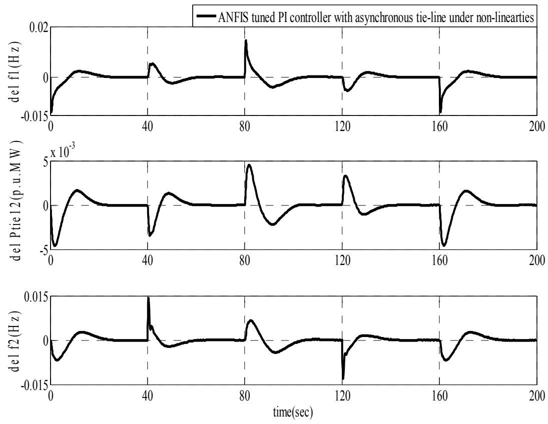

Fig.8 Response of ANFIS tuned PI controller of multi source multi area with asynchronous tie-line under non-linearities

From the above figure it clearly visualizes that ANFIS based PI controller is the best optimal adaptive controller for a robust multi source multi area system interconnected via asynchronous tie-line which improved the area frequencies and tie-line power flow variations.

5 Conclusion

In this study, multi source multi area system interconnected via asynchronous tie-line is considered. The system was subjected to unit step load variations in area 1 alone. The limitation on speed governor characteristics would help the system to retain to its nominal value but with area frequencies and tie-line power flow error. Therefore, PI controller was tuned using ZN, GA, FGS and

ANFIS techniques were used. The performance of the controller was evaluated based on ISE and judged that ANFIS based PI controller is the most optimal and best secondary controller which would adapt with the wide varying system conditions and helped in handling robust system.

Appendix

Thermal Power Plant:

R_1 =Speed regulation of thermal governor = 2 Hz/p.u. MW;

T_{H1} = Turbo governor time constant = 0.08 sec;

T_{T1} =Non-reheat turbine time constant = 0.3 sec;

$K_{P1} = K_{P2}$ = Power system gain constant of area1 and area2 = 120;

$T_{P1} = T_{P2}$ = Power system time constant of area1 and area2 = 20 sec;

ΔP_{D1} = ΔP_{D2} = Change in load demand power in area1 and area2 =0.01p.u;

β_1 = β_2 = Frequency bias constant of area1and area2 = 0.425 p.u.MW/Hz;

$\Delta P_{ref1} = \Delta P_{ref5}$ = Change in the reference power setting of the thermal speed governor in area 1 and area 2 respectively in p.u.;

$\Delta f_1 = \Delta f_2$ = Change in frequency of area 1 and area 2 respectively in Hz;

ΔP_g = Change in the governor output power in p.u.;

ΔP_{H1} = Change in hydraulic amplifier power output in p.u.;

ΔP_{T1} = Change in the non-reheat steam turbine output power in p.u.;

Hydro Power Plant:

$\Delta P_{ref2} = \Delta P_{ref4}$ = Change in the reference power setting of the hydro speed governor in area 1 and area 2 respectively in p.u.;

R_2 =Speed regulation of hydro governor = 2 Hz/p.u. MW;

ΔP_{Hg} = Change in the hydro governor system in p.u.;

ΔP_{HV} = Change in the mechanical-hydraulic hydro system in p.u.;

ΔP_{HT} = Change in the hydro turbine in p.u.;

K_1 = Hydro governor gain = 1;

T_1 = Hydro governor time constant = 48.7 sec;

T_R, T_2 = Hydro power plant time constants = 5.0 sec, 0.513 sec;

T_W = Water time constant = 1.0 sec;

Nuclear Power Plant:

ΔP_{NR} = Change in the nuclear speed governor output power in p.u.;

ΔP_{NT} = Change in the nuclear turbine output power in p.u.;

K_{HN1} =HP nuclear turbine gain = 0.2-2.0;

T_{N1} =HP nuclear turbine time constant = 0.5 sec;

K_{RN1} =LP nuclear two stage turbine gain = 0.3;

T_{RH1} = LP nuclear two stage turbine time constant = 7sec;

$T_{RH2} = T_{RH3}$ = LP nuclear two stage turbine time constant = 6sec and 10sec respectively;

T_{N2} = LP nuclear two stage turbine time constant = 9sec;

HVDC tie-line:

$\Delta P_{DCtie12}$ = Change in the HVDC tie-line power flow in p.u.;

K_{DC} = HVDC tie-line gain = 1.0;

T_{DC} = HVDC tie-line time constant = 0.2sec;

HVAC tie-line:

$\Delta P_{ACtie12}$ = Change in the HVAC tie-line power flow in p.u.;

$\Delta P_{tie12} = \Delta P_{tie21}$ = Change in the tie-line power flow from area1 to area 2 and area2 to area 1 respectively = total power flow in HVAC and HVDC tie-line in p.u.;

A_{12} =Synchronizing power co-efficient = -1;

T = Synchronizing coefficient =10% of area capacity = 0.1Cos δ_{12} = 0.0707;

Secondary PI Controller:

Kp = Proportional gain;

Ki = Integral gain;

s = Laplace operator;

ACE= Area Control Error;

ACE^1= Rate of change of Area Control Error;

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