

## Adaptive Neuro-Fuzzy Scheduled Load Frequency Controller for Multi Source Multi Area System Interconnected Via Parallel AC-DC Links

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*Abstract:* The article focuses towards the development of an optimal secondary controller which could adapt with the varying system conditions to maintain the frequency and tie-line power flow variations within the nominal value. 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 via parallel AC-DC links. 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. On subjection to different load variations at different intervals of time, ANFIS tuned PI controller has retained the frequency and tie-line power variations for a robust multi source multi area system interconnected via parallel AC-DC links in a much faster way to its nominal values than other methods. The performance of the controller is evaluated based on performance indices.

*Keywords:* 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 inter-connected system [4-8]. When subjected to load change, a High Voltage Direct Current Transmission (HVDC) Line in anti-parallel with the High Voltage Alternating Current (HVAC) line [9-12] 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. ZN method as a conventional benchmark is used for tuning the gains of the PI controller [13-15]. 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 [16-17] 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 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 [18-22] 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 and retains the system frequency and tie-line power flow in nominal values. 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 [23]. 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 modelling of multi source multi area system with parallel AC-DC links, 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 Parallel AC-DC Links

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 parallel AC-DC tie-lines is shown in Figure 1.

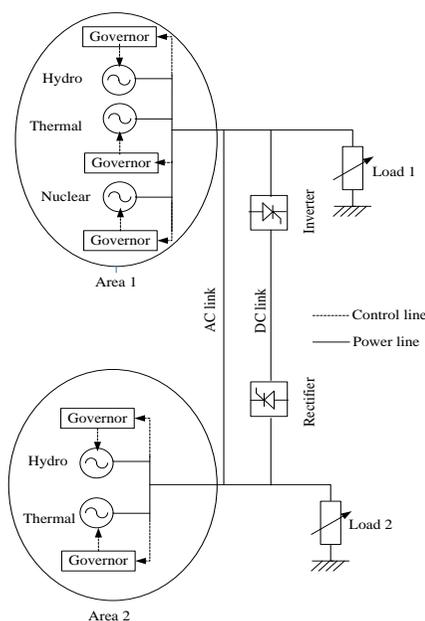


Figure 1. One-line diagram of multi source multi area interconnected via parallel AC-DC links

In thermal power plant [1-4], the turbine acts as the prime mover for the generator. The turbine gets the mechanical energy through steam from boiler. As demand increases, the difference between the generation and demand is indirectly sensed as change in frequency by the governor. The output of the speed governor is modeled as shown in Equation (1).

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

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 power w.r.t speed governor output and the generator output which provides the power to the power system is represented as shown in Equation (2) and Equation (3) respectively;

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

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

The characteristics of hydro turbines are different from thermal turbines. In hydro plants [4], 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 linearized model representing the performance of the speed governor is highlighted in equation (4);

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

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

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

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 is fully controlled depending upon the presence of a moderator i.e. either water or graphite. 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 water in its primary cooling/heat transfer circuit is pressurized water reactor (PWR) which 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 AC-DC links to an another area of Hydro and Thermal Power Plant is shown in Figure 2. 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 is required for flexible operation. In this work, PI controller [13-14] 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),

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

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

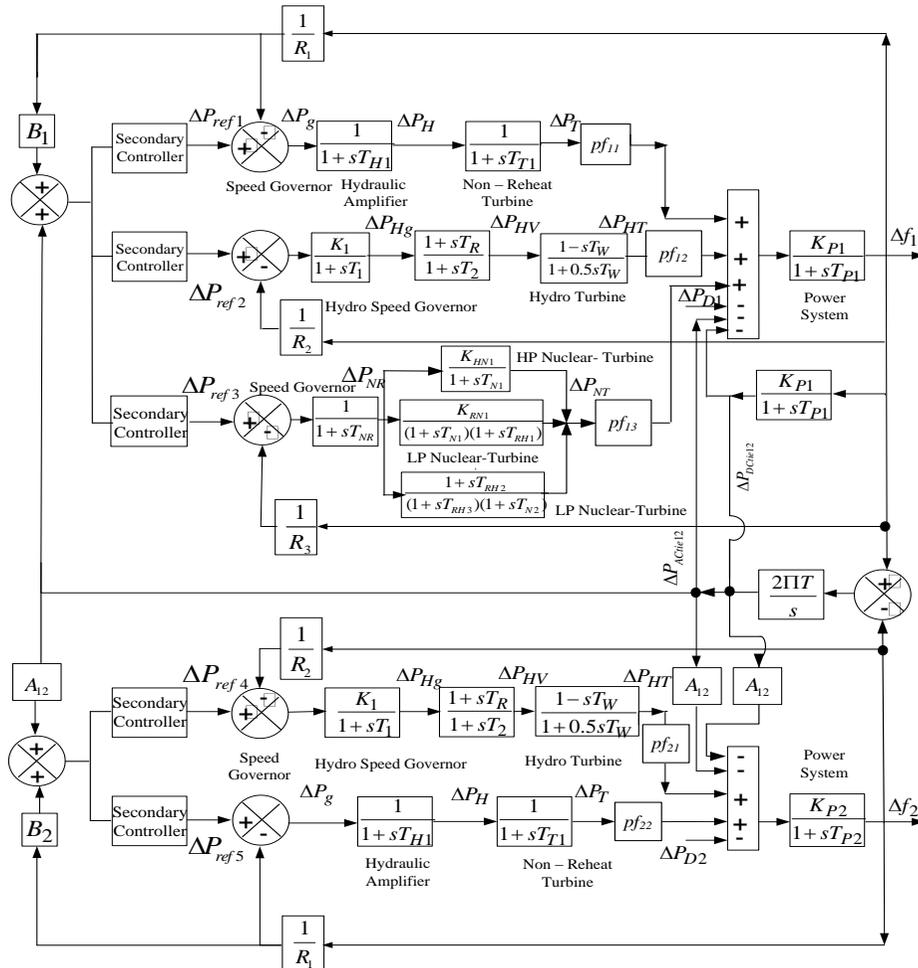


Figure 2. Linearized mathematical model of multi source multi area interconnected via parallel AC-DC links

### 3. Secondary Controller Tuning Methods

The secondary controller helps to support the power system along with the primary controller thus removing the frequency and tie-line power offset namely the steady state error which is not advisable for the system to persist. But, since the condition of the system is subjected to dynamic load variations at various intervals of time, a dynamic secondary controller (PI) is proposed in this work. Therefore, suitable secondary controller optimal values is identified by various methodologies which is proposed in the following sections.

*A. Zeigler Nichols (ZN) Tuning Method*

As a conventional bench mark, ZN method [13-15] is used for choosing the better value of controller gains. In this method, proportional gain ‘ $K_p$ ’ is increased maintaining integral gain ‘ $K_i$ ’ to zero.

The gain at the system oscillates is termed to be ultimate gain ‘ $K_u$ ’ and the difference between the peak for one cycle is termed to be ultimate time ‘ $T_u$ ’ is observed.

The PI controller gains computed using Zeigler Nichols’ method are 6.995 and 1.034 respectively in area 1 and area 2.

*B. 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 parallel AC-DC links.

In this work, GA technique [16-17] is used for tuning the PI controller. The algorithm adopted for tuning PI controller gains is as follows:

Step 1: Estimate ranges for the proportional and integral gains

Step 2: Randomly initialize the values for the controller gains

Step 3: 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

Step 4: 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.

Step 5: If Yes, stop.

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 parallel AC-DC links	Area 1	$K_{p1}$	1.0002
		$K_{i1}$	4.2896
		$K_{p2}$	2.7915
		$K_{i2}$	5.3155
		$K_{p3}$	4.5830
		$K_{i3}$	6.3600
	Area 2	$K_{p1}$	1.2173
		$K_{i1}$	5.0275
		$K_{p2}$	2.91001
		$K_{i2}$	4.7160

*C. 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 [18-20], 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 Figure 3.

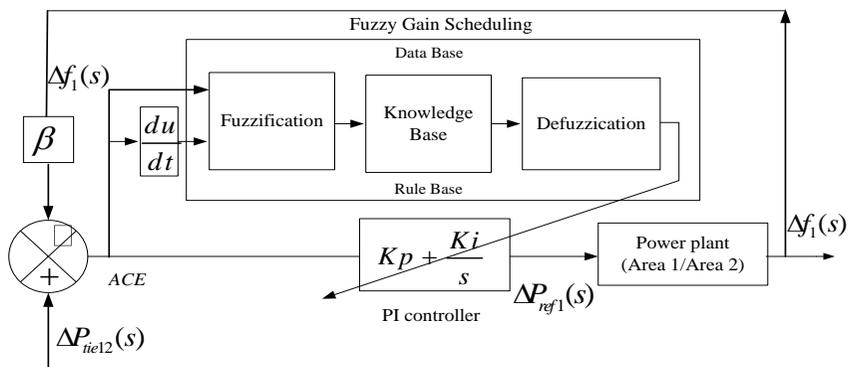


Figure 3. Schematic diagram of Fuzzy Gain Scheduling of PI controller

In this work, FGS has two inputs namely change in error  $ACE$  and rate of change in error  $(du/dt)$ .  $ACE$  or  $ACE^I$ . The FGS based on the knowledge changes the reference power setting of the governor  $\Delta P_{ref1}(s)$ . The two inputs and output are 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  $ACE^I$  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						
		LN	MN	SN	Z	SP	MP	LP
ACE <sup>I</sup>	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  $ACE^I$  is LN then output is LP.

#### D. Gain Scheduling using Adaptive Neuro-Fuzzy Inference System

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 [22-23]. 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 Figure 4.

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.

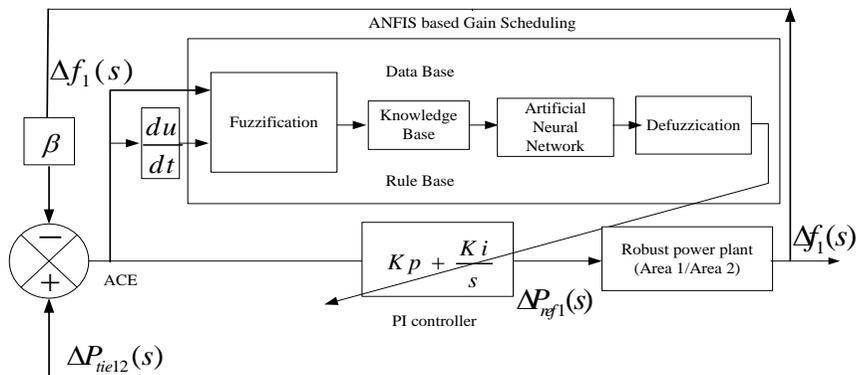


Figure 4. Schematic diagram of ANFIS based Gain Scheduling of PI controller

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.

Step 2: Set the input parameter of membership function and generate the ANFIS model.

Step 3: If the error minimized or converged? If Yes, get optimized FIS after training which would be adaptable gain values of the PI controller.

Step 4: 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.

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

#### 4. Results and Discussions

As discussed in Section 2, Figure 2 model of multi source multi area system with parallel AC-DC links is developed using MATLAB/ Simulink [24] without secondary controller. The system with parallel AC-DC links 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 Figure 5.

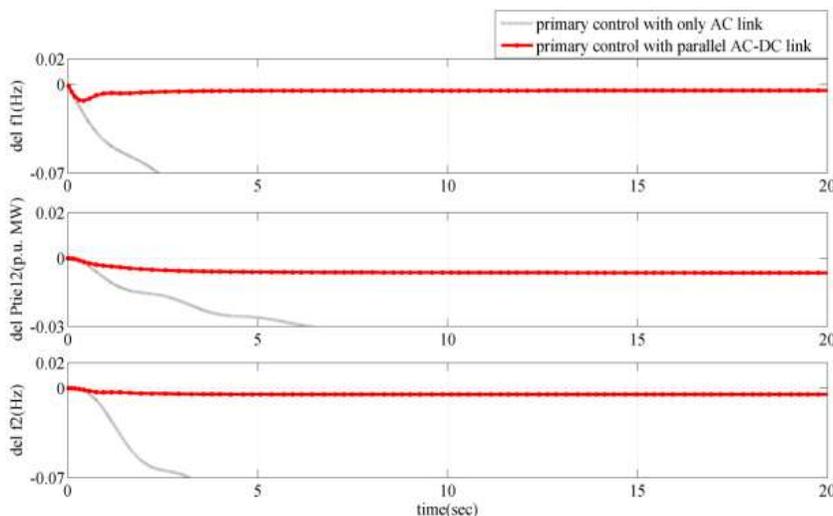


Figure 5. Response of multi source multi area interconnected via parallel AC-DC Links and with only AC link

From the above Figure, it clearly shows that with two-area interconnected via parallel AC-DC links and without HVDC tie-line on subjection to unit step load disturbance in area 1 has led to area frequency variations and tie-line power flow with reduced steady state error. Therefore, preferably with a parallel AC-DC link interconnecting areas would help in limiting the variations in area frequencies and tie-line power flow on load variations.

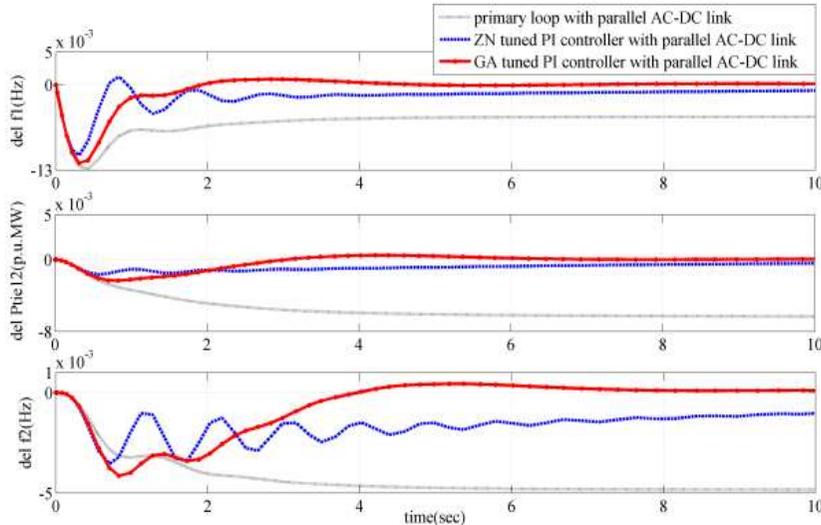


Figure 6. Comparison response of primary loop, ZN and GA tuned PI controller of multi source multi area interconnected via parallel AC-DC links

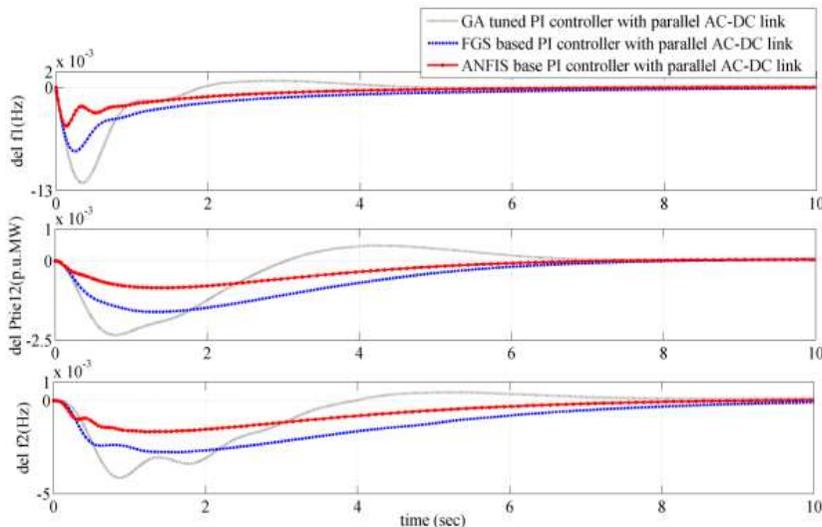


Figure 7. Comparison response of GA, FGS and ANFIS tuned PI controller of multi source multi area interconnected with parallel AC-DC links

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 parallel AC-DC links without the secondary controller is shown in Figure 6.

From the comparison response referring to Figure 6, 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 Figure 7.

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 3 which helps in judging the controller performance and proves ANFIS as suitable PI controller which helps in fine tuning the variations.

Table 3. 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

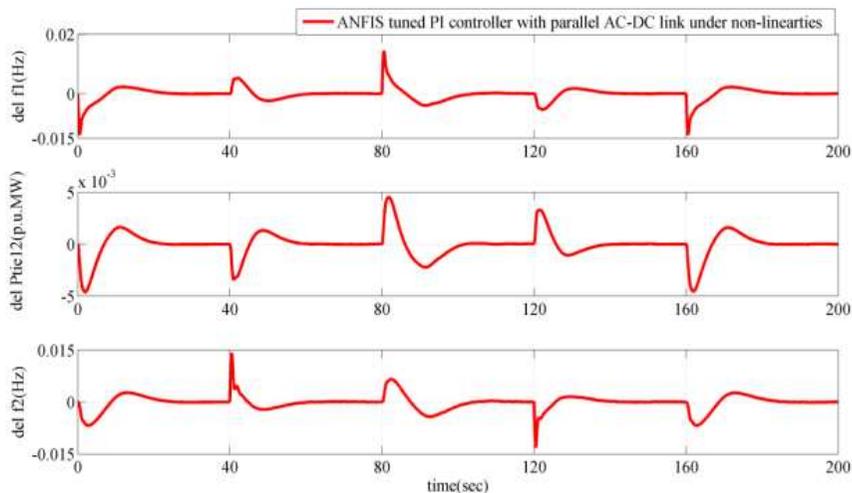


Figure 8. Response of ANFIS tuned PI controller of multi source multi area with parallel AC-DC links under non-linearities

From the Table 3, based on ISE and improvement in percentage comparison among the controllers, ANFIS tuned PI controller proves to be the suitable optimal secondary controller which helps in fine tuning of frequency and tie-line power flow and thus helps in retaining the values to its nominal value than other controllers. 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 parallel AC-DC links with ANFIS based PI controller is shown in Figure 8.

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 parallel AC-DC links which improved the area frequencies and tie-line power flow variations.

## 5. Conclusion

In this study, multi source multi area system interconnected via parallel AC-DC links is considered. The system was subjected to unit step load variations in area 1 alone. The limitation on speed governor characteristics would help 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 controller performance was justified through 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 thus retaining the system frequency and tie-line power flow variations within the rated value.

### Appendix

#### *Thermal 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;

$\beta_1 = \beta_2$  = Frequency bias constant of area1 and area2 = 0.425 p.u.MW/Hz;

#### *Hydro Power Plant:*

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

$T_1$  = 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:*

$K_{HN1}$  = 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;

#### *DC Link:*

$\Delta P_{DCtie12}$  = 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;

#### *AC Link:*

$\Delta P_{AC_{ie12}}$  = Change in the HVAC tie-line power flow in p.u.;

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

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