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Performance Evaluation of Hybrid Intelligent Controllers in Load Frequency Control of Multi Area Interconnected Power Systems

Surya Prakash and Sunil Kumar Sinha

***Abstract*—**This paper deals with the application of artificial neural network (ANN) and fuzzy based Adaptive Neuro Fuzzy Inference System(ANFIS) approach to Load Frequency Control (LFC) of multi unequal area hydro-thermal interconnected power system. The proposed ANFIS controller combines the advantages of fuzzy controller as well as quick response and adaptability nature of ANN. Area-1 and area-2 consists of thermal reheat power plant whereas area-3 and area-4 consists of hydro power plant with electric governor. Performance evaluation is carried out by using intelligent controller like ANFIS, ANN and Fuzzy controllers and conventional PI and PID control approaches. To enhance the performance of intelligent and conventional controller sliding surface is included. The performances of the controllers are simulated using MATLAB/SIMULINK package. A comparison of ANFIS, ANN, Fuzzy, PI and PID based approaches shows the superiority of proposed ANFIS over ANN & fuzzy, PI and PID controller for 1% step load variation.

***Keywords*—**Load Frequency Control (LFC), ANFIS, ANN & Fuzzy, PI, PID Controllers, Area Control Error (ACE), Tie-line, MATLAB / SIMULINK.

I. Introduction

LOAD frequency control is part of Automatic Generation Control (AGC) which is defined as the regulation of power out put of controllable generator within prescribed limit in response to change in system frequency or tie-line loading or the relation of these two each other. Many developments have taken place in the structure of power system since its inception. All over the world, most of the power utilities have been operating in interconnected fashion due to numerous economical, technical and environmental considerations. The power transmission network plays an important role in transporting electrical power in bulk from one power pool to other and to distantly located load centers. Main objective of Automatic

Generation Control (AGC) is to balance the total system generation against system load losses so that the desired frequency and power interchange with neighboring system is maintained. Any mismatch between generation and demand causes the system frequency to deviate from the nominal value. This high frequency deviation may lead to system breakdown. AGC comprises a load frequency control (LFC) loop and an automatic voltage regulator (AVR) loop interconnected power systems regulate power flows and frequency by means of an AGC. LFC system provides generator load control via frequency zero steady-state errors of frequency deviations and optimal transient behavior are objectives of the LFC in a multi-area interconnected power system [1], [2]-[5].

Literature survey shows that most of earlier work in the area of LFC pertains to interconnected thermal system and relatively lesser attention has been devoted to the LFC of multi area interconnected hydro-thermal system [7]. The PI & PID controllers are very simple for implementation and gives better dynamic response, but their performances deteriorate when the complexity in the system increases due to disturbances like load variation boiler dynamics [6], [7]. Therefore, there is need of a controller which can overcome this problem. The Artificial Intelligent controllers like Fuzzy and Neural control approaches are more suitable in this respect. Fuzzy system has been applied to the load frequency control problems with rather promising results. [8], [9], [15], [16], [19], [20], [25]. The salient feature of these techniques is that they provide a model- free description of control systems and do not require model identification when selecting the specific number of membership function [9], so this has some limitation to over come this Artificial Neural Network (ANN) and ANFIS controllers are introduced, those have advance adaptive control configuration [10], [20], [21]. LFC or AGC is one of the most important issues in electric power system design and operation for supplying sufficient and reliable electric power with good quality. The main aim of LFC for power system are to ensure zero steady state error for frequency deviations, to minimize unscheduled tie line power flows between neighboring control areas and to maintain acceptable overshoot and settling time on the frequency and tie line power deviation [22], [23], [24].

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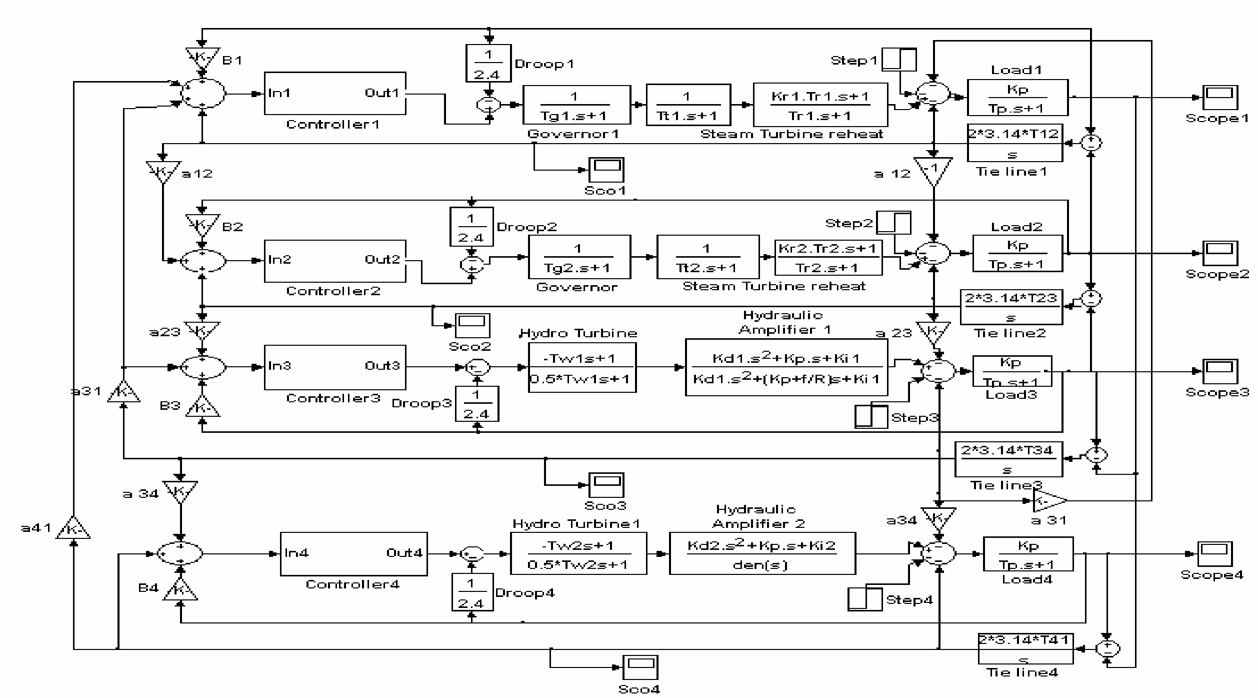

Fig. 1 MATLAB Model of four area hydro-thermal reheat power system

The main objectives of the present paper are the following:

1. To consider four area hydrothermal system under perturbation in a single area and simultaneously in all areas, and then obtain system dynamic responses with Fuzzy, ANN and ANFIS, PI and PID controllers.
2. To present a systematic and comprehensive approach for designing ANN, Fuzzy and ANFIS based controller.
3. To compare the results of all five controllers to investigate the superiority of controller.
4. To compare the ANFIS controller results with already published result of Swati[26], Sudha[27] and Parmar[28] and, then analyze the dynamic performance obtained with the above control strategy, i.e., ANFIS based controller.

II. Multi Area Power System Investigated

The four area power system connected by tie-line is shown in Fig. 1.

A. Modeling of the Tie-Line

Considering area 1 has surplus power and transfers to area 2.

P_{12} = Power transferred from area 1 to 2 through tie line. Then power transfer equation through tie-line is given by

$$P_{12} = \frac{|V_1|.|V_2|}{X_{12}}.\text{Sin}(\delta 1 - \delta 2) \qquad (1)$$

where

δ_1 and δ_2 = Power angles of end voltages V_1 and V_2 of equivalent machine of the two areas respectively.

X_{12} = reactance of tie line.

The order of the subscripts indicates that the tie line power is define positive in direction 1 to 2.

For small deviation in the angles and the tie line power changes with the amount i.e. small deviation in δ_1 and δ_2 changes by $\Delta\delta 1$ and $\Delta\delta 2$,

Power P_{12} changes to $P_{12} + \Delta P_{12}$

Therefore, Power transferred from Area 1 to Area 2 as given in [11] is

$$\Delta P_{12}(s) = \frac{2\pi T^o}{s}\left(\Delta f_1(s) - \Delta f_2(s)\right) \qquad (2)$$

T^0 = Torque produced

In this paper, the performance evaluation based on ANN, Fuzzy and ANFIS control technique for four areas interconnected thermal-hydro power plant is proposed. The sliding concept arises due to variable structure concept. The objective of VSC has been greatly extended from stabilization to other control functions. The most distinguished feature of VSC is its ability to result in very robust control systems and external disturbances [12], [13].

B. Objective of Control Areas

The main objective of the control areas are as follows:

1. Each control area as for as possible should supply its own load demand and power transfer through tie line should be on mutual agreement.
2. Each control areas should controllable to the frequency control. [11]

In an isolated control area case the incremental power ($\Delta P_G - \Delta P_D$) was accounted for by the rate of increase of stored kinetic energy and increase in area load caused by increase in frequency. The state variable for each of areas are $\Delta Pi\,(i = 1,...., 4)$ and state space equation related to the variables are different for each areas.

$$\Delta P_1(k) = \Delta P_{12}(k) + a_{41}\Delta P_{41}(k) \quad (3)$$

$$\Delta P_2(k) = \Delta P_{23}(k) + a_{12}\Delta P_{12}(k) \quad (4)$$

$$\Delta P_3(k) = \Delta P_{34}(k) + a_{23}\Delta P_{23}(k) \quad (5)$$

$$\Delta P_4(k) = \Delta P_{41}(k) + a_{34}\Delta P_{34}(k) \quad (6)$$

Tie-line bias control is used to eliminate steady state error in frequency in tie-line power flow. This states that the each control area must contribute their share to frequency control in addition for taking care of their own net interchange.

Let ACE_1 = area control error of area 1
ACE_2 = Area control error of area 2
ACE_3 = Area control error of area 3
ACE_4 = Area control error of area 4

In this control, ACE_1, ACE_2 and ACE_3 are made linear combination of frequency and tie line power error [11].

$$ACE_1 = \Delta P_{12} + b_1 \Delta f_1 \quad (7)$$

$$ACE_2 = \Delta P_{23} + b_2 \Delta f_2 \quad (8)$$

$$ACE_3 = \Delta P_{34} + b_3 \Delta f_3 \quad (9)$$

$$ACE_4 = \Delta P_{41} + b_4 \Delta f_4 \quad (10)$$

Where the constant b_1, b_2, b_3 & b_4 are called area frequency bias of area 1, area 2, area 3 and area 4 respectively.

Now ΔPR_1, ΔPR_2, ΔPR_3 and ΔPR_4 are mode integral of ACE_1, ACE_2, ACE_3 and ACE_4 respectively.

Control methodology used (FLC & ANN) is mentioned in the next preceding sections.

III. Control Methodology

A. Automatic Controller

The task of load frequency controller is to generate a control signal *Ui* that maintains system frequency and tie-line interchange power at predetermined values. The proportional and integral (PI) control scheme is shown in Fig. 2 [30].

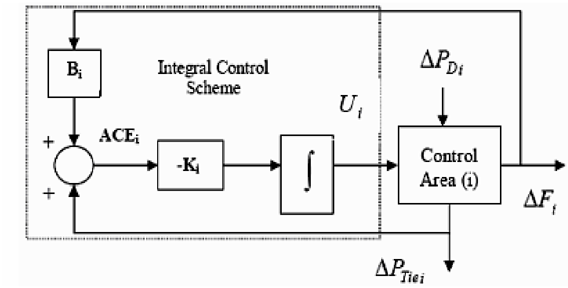

Fig. 2 Conventional PI Controller Installed on i[th] Area

$$U_i = -K_i \int_0^T (ACE_i)dt = -K_i \int_0^T (\Delta P_{tie\,i} + B_i \Delta f_i)dt \quad (11)$$

Taking the derivative of equation (11) yields;

$$U_i = -K_i (ACE_i) = -K_i (\Delta P_{tie\,i} + B_i \Delta f_i) \quad (12)$$

B. Fuzzy Logic Controller

Fuzzy logic is a thinking process or problem-solving control methodology incorporated in control system engineering, to control systems when inputs are either imprecise or the mathematical models are not present at all. Fuzzy logic can process a reasonable number of inputs but the system complexity increases with the increase in the number of inputs and outputs, therefore distributed processors would probably be easier to implement. Fuzzification is process of making a crisp quantity into the fuzzy (Ross, 1995). They carry considerable uncertainty. If the form of uncertainty happens to arise because of imprecision, ambiguity, or vagueness, then the variable is probably fuzzy and can be represented by a membership function.

Defuzzification is the conversion of a fuzzy quantity to a crisp quantity, just as fuzzification is the conversion of a precise quantity to a fuzzy quantity. There are many methods of defuzzification, out of which smallest of maximum method is applied in making fuzzy inference system. The Fuzzy logic control consists of three main stages, namely the fuzzification interface, the inference rules engine and the defuzzification interface [15], [16]. For Load Frequency Control the process operator is assumed to respond to variables error (*e*) and change of error (*ce*). The fuzzy logic controller with error and change in error is shown in Fig. 3.

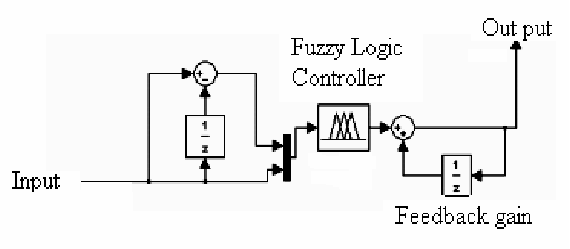

Fig. 3 Model of Fuzzy Logic Controller

The variable error is equal to the real power system frequency deviation (Δf). The frequency deviation Δf, is the difference between the nominal or scheduled power system frequency (f_N) and the real power system frequency (f). Taking the scaling gains into account, the global function of the FLC output signal can be written as.

$$\Delta Pc = F\,[n_c\, e(k), \quad n_{ce}\, ce(k)] \tag{13}$$

where n_e and n_{ce} are the error and the change in error scaling gains, respectively, and F is a fuzzy nonlinear function. FLC is dependant to its inputs scaling gains (Ha, 1998). A label set corresponding to linguistic variables of the input control signals, *e(k) and* ce(k), with a sampling time of 0.01 sec is given Attempt has been made to examine with Seven number of triangular membership function (MFs) namely Negative Big(NB), Negative Medium(NM), Negative Small (NS), Zero(ZO), Positive Small(PS), Positive Medium (PM) and Positive Big(PB) are used. The range on input (error in frequency deviation and change in frequency deviation) i.e universe of discourse is -0.25 to 0.25 and -0.01 to 0.01 The numbers of rules are 49.

TABLE I
FUZZY INFERENCE RULE FOR FUZZY LOGIC CONTROLLER

Input		*e(k)*						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
ce(k)	**NB**	PB	PB	PB	PB	PM	PM	PS
	NM	PB	PM	PM	PM	PS	PS	PS
	NS	PM	PM	PS	PS	PS	PS	ZO
	ZO	NS	NS	NS	ZO	PS	PS	PS
	PS	ZO	NS	NS	NS	NS	NM	NM
	PM	NS	NS	NM	NM	NM	NB	NB
	PB	NS	NM	NB	NB	NB	NB	NB

C. Artificial Neural Network (ANN) Controller

ANN is information processing system, in this system the element called as neurons process the information. The signals are transmitted by means of connecting links. The links process an associated weight, which is multiplied along with the incoming signal (net input) for any typical neural net. The output signal is obtained by applying activations to the net input. The field of neural networks covers a very broad area [17], [18].

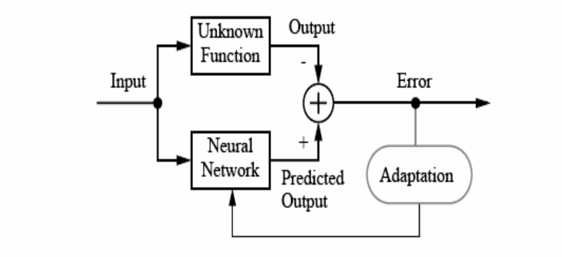

Fig. 4 Neural Network as Function Approximator

Neural network architecture the multilayer perceptron as unknown function are shown in Fig 5, which is to be approximated. Parameters of the network are adjusted so that it produces the same response as the unknown function, if the same input is applied to both systems. The unknown function could also represent the inverse of a system being controlled; in this case the neural network can be used to implement the controller [17].

D. NARMA-L2 Control

The ANN controller architecture employed here is a Non linear Auto Regressive Model reference Adoptive Controller. This controller requires the least computation of the three architectures. This controller is simply a rearrangement of the neural network plant model, which is trained offline, in batch form. It consists of reference, plant out put and control signal. The controller is adaptively trained to force the plant output to track a reference model output. The model network is used to predict the effect of controller changes on plant output, which allows the updating of controller parameters. In the study, the frequency deviations, tie-line power deviation and load perturbation of the area are chosen as the neural network controller inputs [17]. The outputs of the neural network are the control signals, which are applied to the governors in the area. The data required for the ANN controller training is obtained from the designing the Reference Model Neural Network and applying to the power system with step response load disturbance. After a series of trial and error and modifications, the ANN architecture provides the best performance. It is a three-layer perceptron with five inputs, 13 neurons in the hidden layer, and one output in the ANN controller. Also, in the ANN plant model, it is a three-layer perceptron with four inputs, 10 neurons in the hidden layer, and one output. The activation function of the networks neurons is *trainlm* function.300 training sample has been taken to train 300 no of epochs. The proposed network has been trained by using the learning performance. Learning algorithms causes the adjustment of the weights so that the controlled system gives the desired response.

E. Hybrid Neuro Fuzzy (HNF) Controller

In recent years, Hybrid Neuro-Fuzzy (HNF) approach has considerable attention for their useful applications in the fields like control, pattern recognition, image processing, etc [20], [26]. In all these applications there are different neuro-fuzzy applications proposed for different purposes and fields. HNF results are obtained from fusion of neural network and fuzzy logic.

1. Neuro Fuzzy Modeling

The general algorithm for a fuzzy system designer can be synthesized as Fuzzification, Fuzzy Inference and Defuzzification [29]. From the beginning, a fuzzy-style inference must be accepted and the most popular are Mamdani-style inference and Sugeno-style Inference [14], [19], [20].

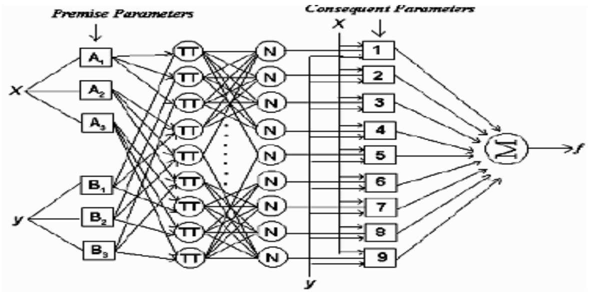

Fig. 5 Architecture of a Two-Input Sugeno Fuzzy Model with Nine Rules

The basic steps followed for designing the ANFIS controller in MATLAB/Simulink is outlined:

1. Draw the Simulink model with fuzzy controller and simulate it with the given rule base.
2. The first step for designing the ANFIS controller is collecting the training data while simulating the model with fuzzy controller.
3. The two inputs, i.e., ACE and d(ACE)/dt and the output signal gives the training data.
4. Use anfisedit to create the ANFIS .fis file.
5. Load the training data collected in Step 2 and generate the FIS with gbell MF's.
6. Train the collected data with generated FIS up to a particular no. of Epochs.
7. Save the FIS. This FIS file is the neuro-fuzzy enhanced ANFIS file[29]

2. Training and Checking: ANFIS

The number of epoch is determined according to the above parameters and to the excepted error measure fixed by the user. The training and checking data are given below:

Number of nodes: 53, Number of linear parameters: 16, Number of nonlinear parameters: 24, Total number of epoch: 80, Number of training data pairs: 51, Number of checking data pairs: 51, Number of fuzzy rules: 16.

The range of error is as below:

1	0.000527979	0.00470353
2	0.000611368	0.00492588

The *gbell* MFs is taken. The frequency deviation Δf, is the difference between the nominal or scheduled power system frequency (f_N) and the real power system frequency (f).

3. ANFIS (Adaptive Neuro-Fuzzy Inference System)

This is more complex than Fuzzy inference System (FIS), but users have some limitations: only zero-order or first-order Sueno fuzzy models, AND Method: Prod, OR Method: max, Imlication Method: prod, Aggregation Method: max, Defuzzification Method: wtaver(weighted average). On the other hand, users can provide to ANFIS their own number of MFs(num MFs) both for input and outputs of the fuzzy controller, the number of training and checking data sets (numPts), the MF's type (mfType), the optimization criterion for reducing the error measure(usually defined by the number of the squired difference between actual and linearized N curve) [20], [26].

The great advantage of Neuro-fuzzy design method comparing with fuzzy design method consists in the small number of in put and output MFs (usually 2…4), which implies the same maximum number of rules. Thus, the rule base and the occupied memory became very small.

IV. Simulation and Results

In this presented work, different models of four area hydro-thermal reheat interconnected power system have been developed by using fuzzy logic, ANN and ANFIS and PI, PID controllers to illustrate the performance of load frequency control using MATLAB/SIMULINK package. The parameters used for simulation are given in appendix [12]. Frequency deviation plots for thermal and hydro cases are obtained separately for 1% step load change in system frequency and tie-line power as shown in Fig. 6-26 respectively.

Dynamic responses of four areas power system using PI controller is are given below:

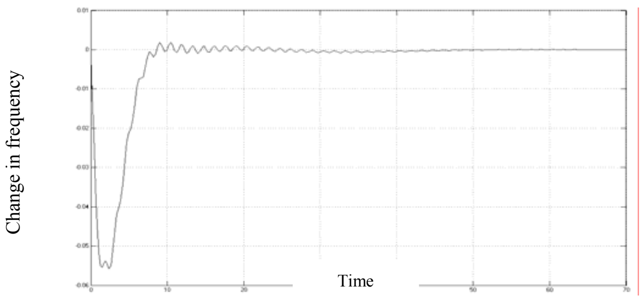

Fig. 6 Change in frequency (thermal plant) – with PI controller (Δf)

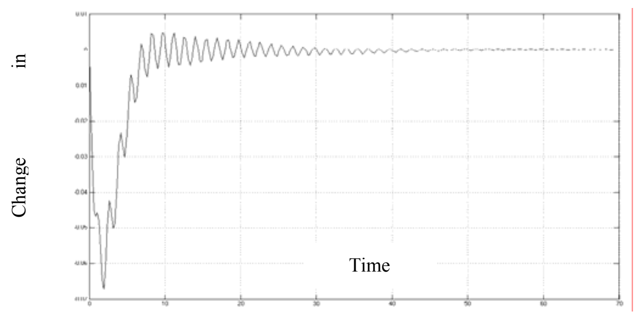

Fig. 7 Change in frequency (Hydro plant)- with PI controller(Δf)

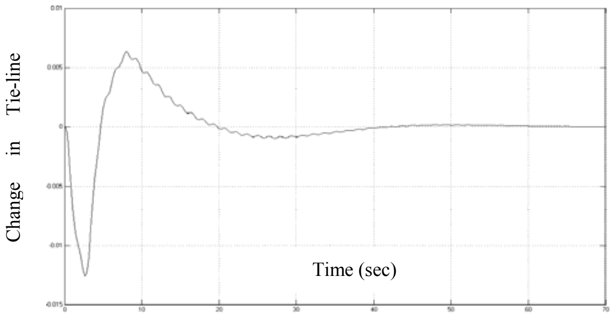

Fig. 8 Change in Tie-line power(thermal plant) with PI control

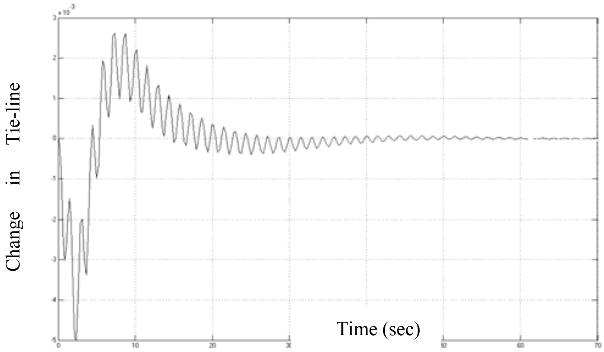

Fig. 9 Change in Tie-line power (hypothermal plant) with PI control

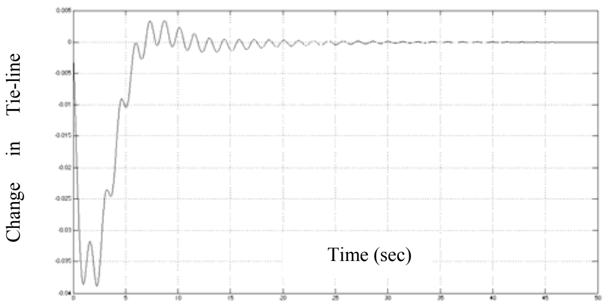

Fig. 10 Change in Tie-line power (thermal-hydro plant) with PI control

The developed model with PI controller has been simulated and responses obtained above in Fig. 6-10 reveals that PI controller reduces the steady state error in frequency deviation and also maximum peak over shoot. The settling time is limited to 64 sec. in case of frequency deviation of thermal plant and 70 sec. for hydro plant. The deviation in the tie-line power is also limited to 70 sec.

The dynamic responses of four areas power system using PID controller is are given below:

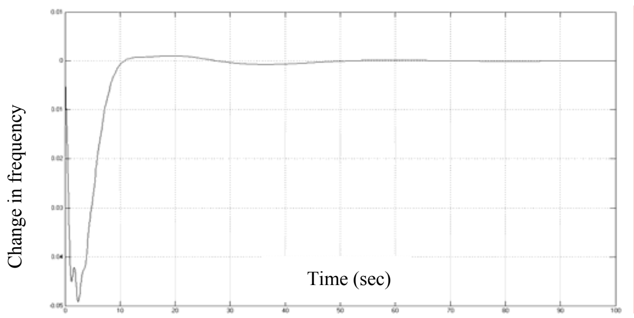

Fig. 11 Change in frequency (thermal plant) – with PID controller (Δf)

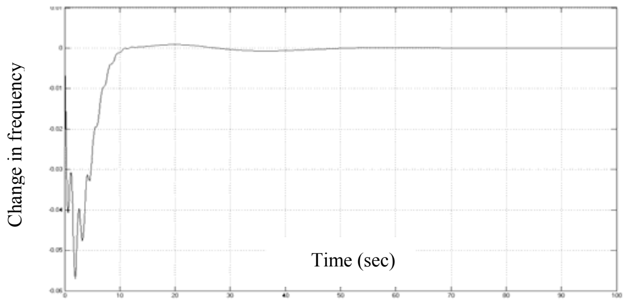

Fig. 12 Change in frequency (hydro plant)- with PID controller (Δf)

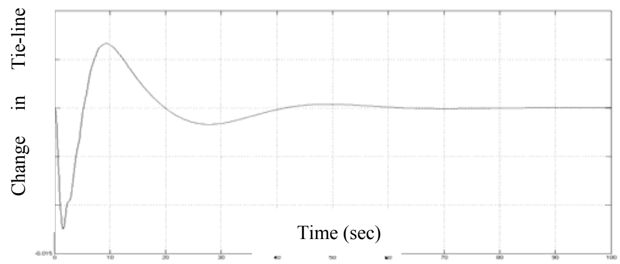

Fig. 13 Change in Tie-line power (thermal plant) with PID control (ΔP_{tie})

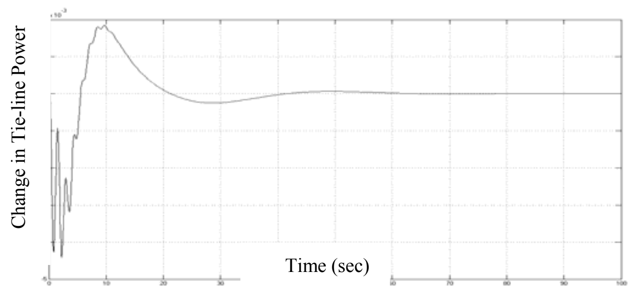

Fig. 14 Change in Tie-line power (hydro plant) with PID control (ΔP_{tie})

The developed model with PID controller has been simulated and responses obtained above in Fig. 11-14 reveals that PID controller reduces the steady state error in frequency deviation and also maximum peak over shoot. The settling time is limited to 60 sec. in case of frequency deviation of

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thermal plant and 60 sec. for hydro plant. The deviation in the tie-line power is also limited to 60 sec. The Number of oscillations are also reduced. Dynamic responses of four areas power system using Fuzzy controller is are given below:

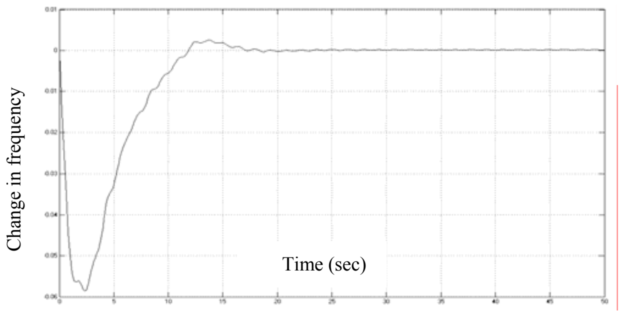

Fig. 15 Change in frequency (thermal plant) – with Fuzzy controller

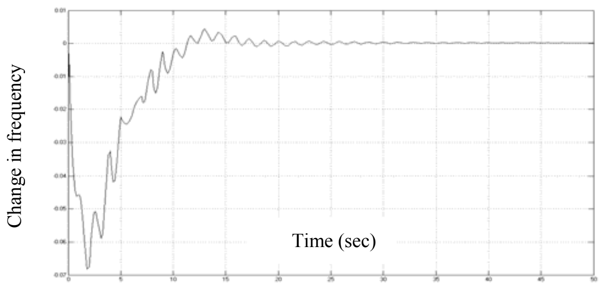

Fig. 16 Change in frequency (hydro plant) – with Fuzzy controller

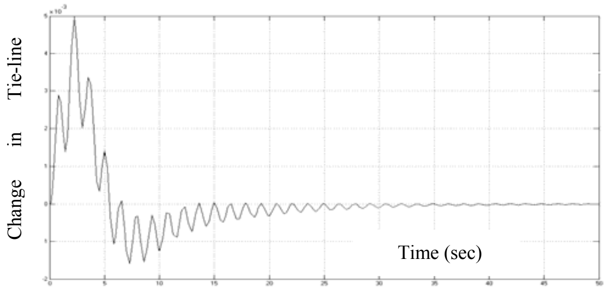

Fig.17 Change in Tie-line power (thermal plant) with Fuzzy Controller

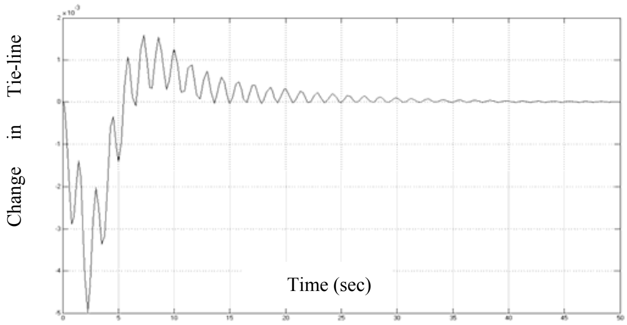

Fig.18 Change in Tie-line power (hydro plant) with Fuzzy Controller

The developed model with Fuzzy controller has been simulated and responses obtained above in Fig. 15-18 reveal that fuzzy controller further reduces the steady state error in frequency deviation and also maximum peak over shoot. The settling time is limited to 45 sec. in case of frequency deviation of thermal plant and 48 sec. for hydro plant. The deviation in the tie-line power is also limited to 45 sec. The settling time and peak over shoot is much lesser than the PI and PID controller. Dynamic responses of four areas power system using ANN controller is are given below:

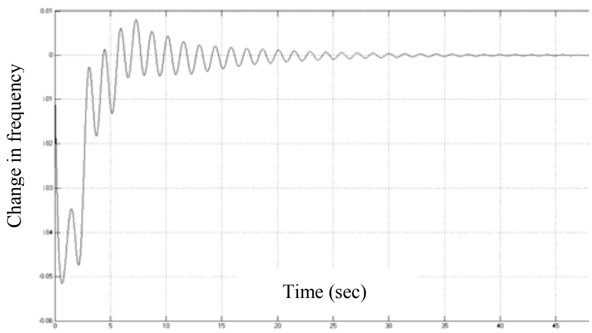

Fig. 19 Change in frequency (Thermal plant) with ANN controller

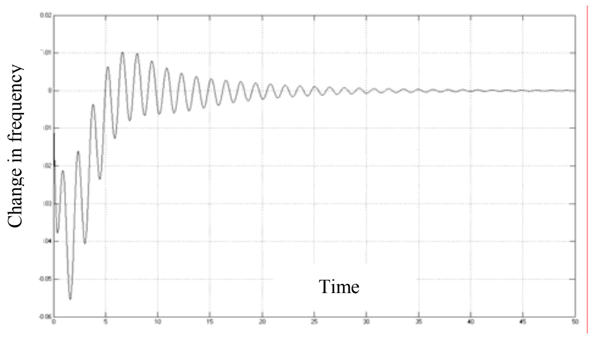

Fig. 20 Change in frequency (hydro plant) with ANN controller

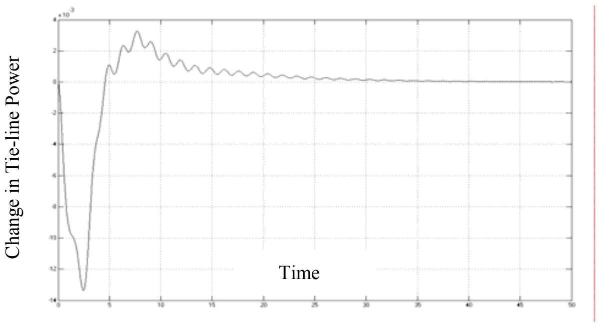

Fig. 21 Change in Tie-line power (hydro thermal plant) with ANN

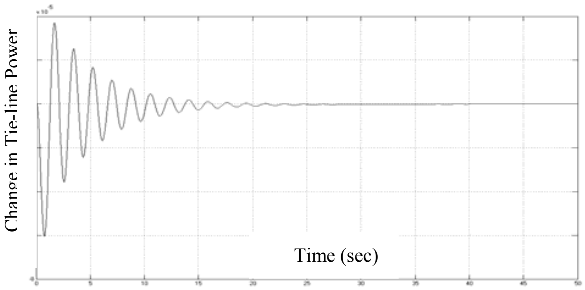

Fig. 22 Change in Tie-line power (thermal hydro plant) with ANN

The developed model with Artificial Neural Network (ANN) controller has been simulated and responses obtained above in figure 19-22 reveal that ANN controller further reduces the steady state error in frequency deviation and also maximum peak over shoot. The settling time is limited to 40 sec. in case of frequency deviation of thermal plant and hydro plant as well. The deviation in the tie-line power is also limited to 30 sec. The settling time and peak over shoot is much lesser than the PI, PID and Fuzzy controllers.

Dynamic responses of four areas power system using ANFIS controller is are given below:

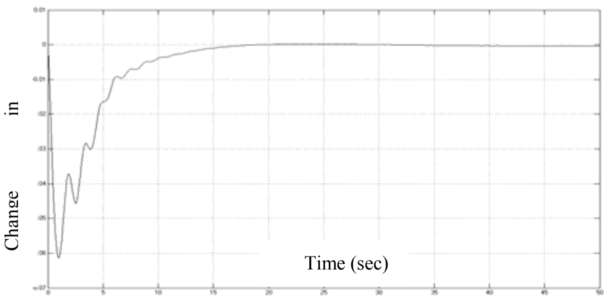

Fig. 23 Change in frequency (Thermal plant) with ANFIS controller

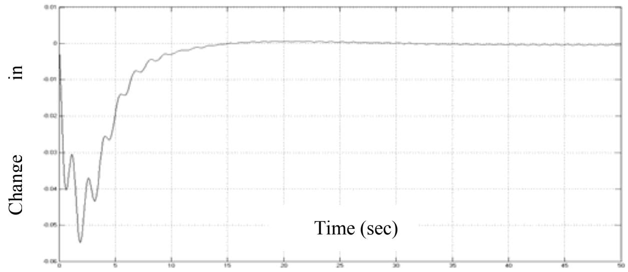

Fig. 24 Change in frequency (Hydro plant) with ANFIS controller

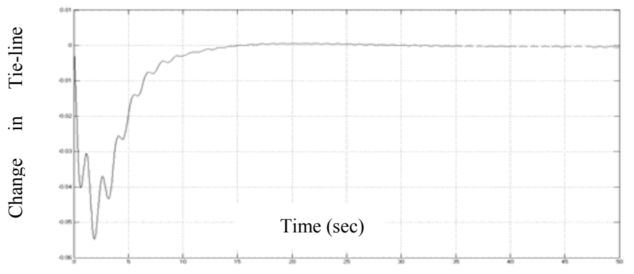

Fig.25 Change in Tie-line power (thermal hydro plant) with ANFIS

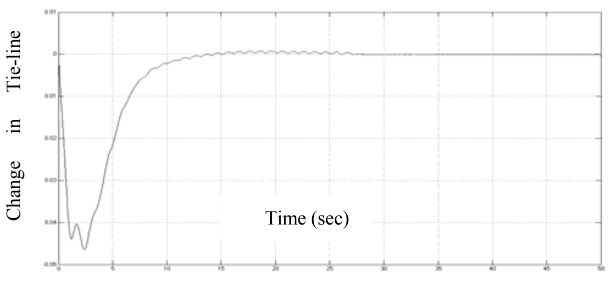

Fig. 26 Change in Tie-line power (thermal hydro plant) with ANFIS

The developed model with ANFIS controller has been simulated and responses obtained above in Fig. 23-26 reveal that ANFIS controller further reduces the steady state error in frequency deviation and also maximum peak over shoot. The settling time is limited to 18 sec. in case of frequency deviation of thermal plant and 17 sec. for hydro plant. The deviation in the tie-line power is also limited to 15 sec. for thermal and 27 sec. for hydro plant. The settling time and peak over shoot is much lesser than the PI, PID, Fuzzy and ANN controllers.

The above simulation results shows that the proposed ANFIS based controllers tracks the load changes and achieve good robust performance than conventional PI, PID and other intelligent control(Fuzzy & ANN) approach with 1% load variation in power system. Conventional PI, PID and Intelligent (Fuzzy and Neuro-Fuzzy) control approach with inclusion of slider gain provides better dynamic performance and reduces the steady state error and oscillation of the frequency deviation and the tie line power flow in each area in hydro-thermal combination of four area interconnected power system. Settling time and maximum peak overshoot in transient condition for both change in system frequency and change in tie-line power are given in table II & III, respectively.

TABLE II
COMPARATIVE STUDY OF SETTLING TIME

Controllers	Area 1 (sec)	Area 2 (sec)	Area 3 (sec)	Area 4 (sec)	Thermal-thermal (sec)	Hydro-thermal (sec)
PI	64	64	70	65	65	70
PID	60	60	60	50	62	60
Fuzzy	45	45	45	48	40	45
ANN	40	40	40	40	30	35
ANFIS	18	18	17	17	15	27

TABLE III
COMPARATIVE STUDY OF PEAK OVERSHOOTS

Controllers	Δf Area 1 (pu)	Δf Area 2 (pu)	Δf Area 3 (pu)	Δf Area 4 (pu)	ΔP_{tie} Thermal-thermal (pu)	ΔP_{tie} Hydro-thermal (pu)
PI	-0.055	-0.055	-0.067	0.066	-0.0145	-0.05
PID	-0.049	-0.049	-0.057	-0.062	0.005	-0.0042
Fuzzy	-0.059	-0.06	-0.068	-0.065	0.005	-0.012
ANN	-0.038	-0.038	-0.055	-0.051	-0.006	-0.013
ANFIS	-0.061	-0.061	-0.054	-0.054	-0.052	-0.045

By varying 1% step load, the above responses reveals that the steady state error in dynamic change in frequency and tie-line power are reduced to zero and settling time and peak overshoot is plotted and tabulated in Table II and Table III. ANFIS controller has minimum settling time and peak overshoot in frequency response than other four proposed controller.

V. CONCLUSIONS

In this paper, automatic generation control of four area interconnected hydro thermal power system is investigated. In order to demonstrate the effectiveness of proposed method, the control strategy based on Neuro-fuzzy, ANN and conventional PI & PID technique is applied. The performance of proposed controller is evaluated through the simulation. The results are tabulated in Table II and III respectively. Analysis reveals that the proposed technique gives good results and uses of this method reduce the peak deviation of frequencies, tie-line power, time error and inadvertent interchange. It can be concluded that ANFIS controller with sliding gain provides better settling performance than Fuzzy, ANN and conventional PI &PID one. Therefore, the intelligent control approach using Neuro-Fuzzy concept is more accurate and faster than the fuzzy, ANN, PI and PID control scheme even for complex dynamical system.

APPENDIX

Parameters are as follows:

f = 50 Hz, $R_1 = R_2 = R_3 = R_4$ =2.4 Hz/ per unit MW, T_{gi}= 0.08 sec, T_{pi}=20 sec; $P_{tie,\,max}$ = 200 MW ; Tr = 10 sec ; Kr = 0.5, $H_1 = H_2 = H_3 = H_4$ =5 sec ; P_{ri}=2000MW, T_{ti} = 0.3sec ; $K_{p1}=K_{p2}=K_{p3}=K_{p4}$ = 120 Hz.p.u/MW ;K_d =4.0;

Ki = 5.0 ; Tw = 1.0 sec; D_i =8.33 * 10^{-3} p.u MW/Hz.; $B_1=B_2=B_3=B_4$=0.425 p.u. MW/hz; a_i=0.545; a=2*pi*T_{12}=2*pi*T_{23}=2*pi*T_{34}=2*pi*T_{41}=0.545,

delP_{di}= 0.01

Nomenclature

i: Subscript referring to area (*i*=1,2,3,4)
f : Nominal system frequency
H_i: Inertia constant; ΔP_{Di} : Incremental load change
ΔPg_i : Incremental generation change
$Di = \frac{\Delta P_{Di}}{\Delta fi}$; T_r : Reheat time constant
T_g: Steam governor time constant; K_r : Reheat constant,
T_t : Steam turbine time constant; B_i: Frequency bias constant
R_i : Governor speed regulation parameter
T_{pi} : 2Hi / f * Di, K_{pi}: 1/ Di
K_t: Feedback gain of FLC
T_w : Water starting time, *ACE* : Area control error
P: Power, *E* : Generated voltage
V: Terminal voltage, δ Angle of the Voltage V
$\Delta\delta$: Change in angle, ΔP: Change in power
Δf : Change in supply frequency;
ΔPc : Speed changer position
R: Speed regulation of the governor
K_H : Gain of speed governor
T_H : Time constant of speed governor
K_p : 1/B= Power system gain
T_p: 2H / B f_0 = Power system time constant

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