Application of artificial intelligence in load frequency control of interconnected power system

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Abstract

This paper presents the use of artificial intelligence to study the load frequency control of interconnected power system. In the proposed scheme, a control methodology is developed using Artificial Neural Network (ANN) and Fuzzy Logic controller (FLC) for interconnected hydro-thermal power system. The control strategies guarantees that the steady state error of frequencies and inadvertent interchange of tie-lines power are maintained in a given tolerance limitations. The performances of the controllers are simulated using MATLAB/SIMULINK package. A comparison of Fuzzy controller and ANN controller based approaches shows the superiority of proposed ANN based approach over Fuzzy one for different loading conditions (1% and 2% step load variations). The simulation results also tabulated as a comparative performance in view of settling time and peak over shoot.

Keywords: Load Frequency Control(LFC), Fuzzy Logic Controller, ANN Controller, Area Control error(ACE), Tie-line, MATLAB / SIMULINK.

1. Introduction

Automatic Generation Control (AGC) or Load Frequency Control is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. An interconnected power system can be considered as being divided into control area, all generators are assumed to form a coherent group (George et al, 2001). Load Frequency Control (LFC) is being used for several years as part of the Automatic Generation Control (AGC) scheme in electric power systems. One of the objectives of AGC is to maintain the system frequency at nominal value (50 hz). In the steady state operation of power system, the load demand is increased or decreased in the form of Kinetic Energy stored in generator prime mover set, which results the variation of speed and frequency accordingly. Therefore, the control of load frequency is essential to have safe operation of the power system (Kothari et al. 2003; Kundur, 1994; Wadhawa, 2007).

Automatic generation control (AGC) is defined as, the regulation of power output of controllable generators within a prescribed area in response to change in system frequency, tie-line loading, or a relation of these to each other, so as to maintain the schedules system frequency and / or the established interchange with other areas within predetermined limits (Elgerd, 1971). Therefore, a control strategy is needed that not only maintains constancy of frequency and desired tie-power flow but also achieves zero steady state error and inadvertent interchange. Among the various types of load frequency controllers, the most widely employed is the conventional proportional integral (PI) controller. The PI controller is 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 (Talaq et al. 1999; Arvindan et al. 2009). Therefore, there is need of a controller which can overcome this problem. The Artificial Intelligent controller like Fuzzy and Neural control approach is more suitable in this respect. Fuzzy system has been applied to the load frequency control problems with rather promising results (Nanda et al, 2003). The salient feature of these techniques is that they provide a model- free description of control systems and do not require model identification. The fuzzy controller offers better performance over the conventional controllers, especially, in complex and nonlinearities associated

system. In (Mangla et al. 2004) Fuzzy control was applied to the two region interconnected reheat thermal and hydro power system. However, it is demonstrated good dynamics only when selecting the specific number of membership function, so that the method had limitation. To over come this Artificial Neural Network (ANN) controller, which is an advance adaptive control configuration, is used because the controller provides faster control than the others (Demiroren et al. 2001).

   In this paper, the performance evaluation based on Fuzzy controller and Artificial Neural controller for two areas interconnected hydro-thermal power plant is proposed. To enhance the performance of fuzzy and neural controller sliding surface is included. The sliding concept arises due to variable structure concept (VSC). 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; in many cases invariant control system result. The term 'invariant' means that the system is completely insensitive to parametric uncertainty and external disturbances (John et al; 1993, Kumar et al. 1985).

2. The Investigated Power System

   The detailed block diagram modeling of two area thermal-hydro power system for load frequency control investigated is shown in figure 1. An extended power system can be divided into a number of load frequency control areas interconnected by means of tie lines. Without loss of generality one can consider a two- area case connected by single tie line (Surya-Prakash et al.2009).
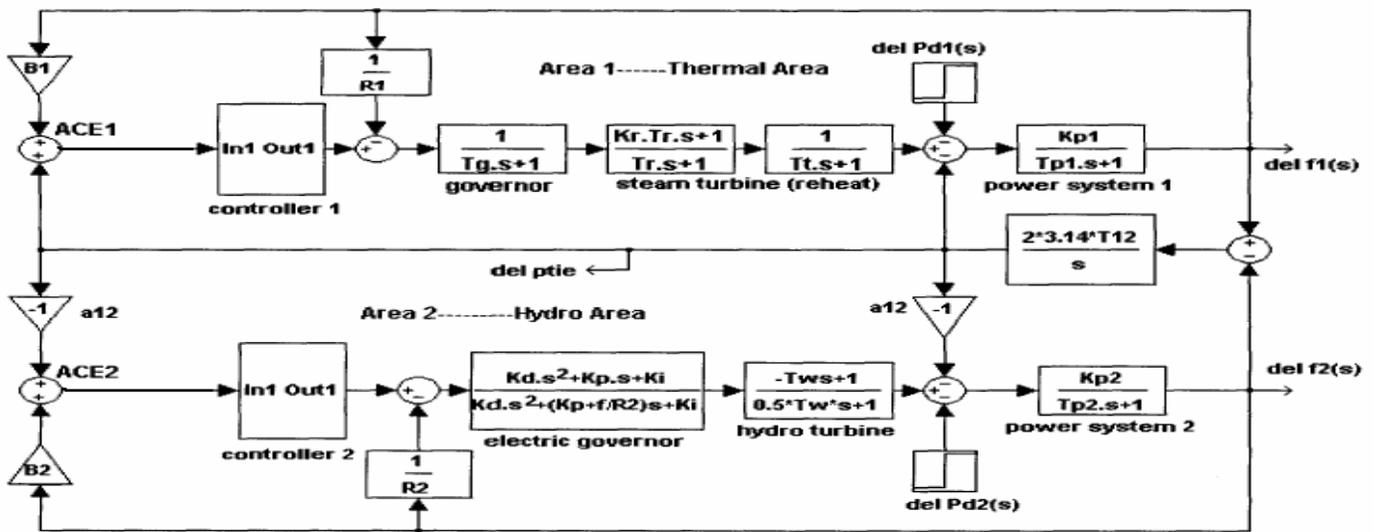

Fig. 1 : Block diagram model of hydro-thermal reheat power system.

The control objectives are as follows:

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

   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. Since a tie line transports power in or out of an area, this fact must be accounted for in the incremental power balance equation of each area.

2.1 Modeling of the tie-line : The power transfer equation through tie line is given by,

$$P_{12} = \frac{|V_1||V_2|}{x} \sin(\delta_1 - \delta_2)$$ (1)

considering area 1 has surplus power and transfers to area 2
P_{12} = Power transferred from area 1 to 2 through tie line.

$$P_{12} = \frac{|V_1|.|V_2|}{X_{12}} . \sin(\delta_1 - \delta_2)$$ (2)

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 is given by the following equation

$$\Delta P_{12}(s) = \frac{2\pi T^o}{s}\left(\Delta f_1(s) - \Delta f_2(s)\right) \tag{3}$$

T^0 = Torque produced

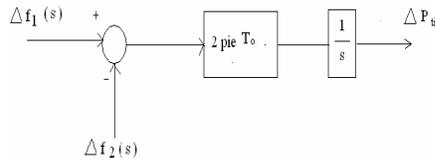The above equation can be represented as in Fig. 2

Fig. 2 : Block Diagram Representation of a Tie -Line

2.2 Tie line Control: In normal operation the power on the tie-line follows from the equation i.e.

$$\left[\Delta P_{T1}(s) - \Delta P_{E1}(s) - \Delta P_{12}(s)\right] = \frac{2H_1}{f_o}s\Delta f_1(s) + B_1\Delta f_1(s) \tag{4}$$

$$= \frac{2H_1}{f_0}\Delta f_1(s)B_1\left[\frac{1}{B_1}s + 1\right] \tag{5}$$

If $\dfrac{2H_1B_1}{f_o} = \dfrac{1}{K_{P1}}$

$\dfrac{1}{B_1} = T_{P1}$

Equation (4) can be written as

$$\Delta f_1(s) = G_{P1}(s)\left[\Delta P_{T1}(s) - \Delta P_{E1}(s) - \Delta P_{12}(s)\right] \tag{6}$$

$$G_{P1}(s) = \frac{K_{P1}}{1 + sT_{P1}} \tag{7}$$

$$\Delta P_{12} = \Delta P_{21}$$

Where ΔP_E is real load change

Due to the action of turbine controllers, the generator increases its output by the amount ΔP_T .

The net surplus power $\Delta P_T - \Delta P_E$ will be absorbed by the system.

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

In these control areas, ACE1 and ACE2 are made linear combination of frequency and tie line power error.

$$ACE_1 = \Delta P_{12} + b_1 \Delta f_1 \tag{8}$$

$$ACE_2 = \Delta P_{21} + b_2 \Delta f_2 \tag{9}$$

where the constant b1 & b2 are called area frequency bias of area 1 and area 2 respectively.
Now $\Delta PR\ 1$ and $\Delta PR\ 2$ are mode integral of ACE1 and ACE2 respectively.

$$\Delta PR\ 1 = -\ Ki\ _1 \int_0^t (\Delta P\ _{12} + b_1 \Delta f\ _1) dt \tag{10}$$

$$\Delta PR\ 2 = -\ Ki_2 \int_0^t (\Delta P_{21} + b_2 \Delta f\ _2) dt \tag{11}$$

Taking Laplace transform of the above equation, we get

$$\Delta PR\ _{1\ (s)} = -\ \frac{Ki\ _1}{s} \big[\Delta P_{12}(s) + b_1 \Delta f_1(s)\ \big] \tag{12}$$

$$\Delta PR\ _{2\ (s)} = -\ \frac{Ki\ _2}{s} \big[\Delta P\ _{21}(s) + b_2 \Delta f_2(s)\ \big] \tag{13}$$

The step changes ΔP_{D1} and ΔP_{D2} are applied simultaneously in control area 1 and 2 respectively. When steady state conditions are reached, the output signals of all integrating blocks will be constant and their input signal must become zero.

i.e. $\Delta P_{12} + b_1\ \Delta f_1 = 0$ (input of integrating block $-\frac{Ki\ _1}{s}$) $\tag{14}$

$\Delta P_{21} + b_2\ \Delta f_2 = 0$ (Input of integrating block $-\frac{Ki_2}{s}$) $\tag{15}$

$\Delta f_1 - \Delta f_2 = 0$ (Input of integrating block $-\frac{2\ \pi\ T\ _{12}}{s}$) $\tag{16}$

$$\Delta P_{12} = \Delta P_{tie,1} \quad\text{and}\quad \Delta P_{21} = \Delta P_{tie,2}$$

Therefore $\dfrac{\Delta P_{tie,1}}{\Delta P_{tie,2}} = -\ \dfrac{T_{12}}{T_{21}} = -\ \dfrac{1}{a_{12}} =$ constant $\tag{17}$

Hence $\Delta P_{tie,1} = \Delta P_{tie,2} = 0$

$\Delta PR\ _1 = \Delta PR\ _2$,

And $\Delta f_1 = \Delta f_2 = 0$

Thus, under steady condition change in the tie- line power and frequency of each area is zero. This has been achieved by integration of ACEs in the feedback loops of each area (Surya-Prakash et al. 2009). Control methodology used (FLC & ANN) is mentioned in next preceding sections.

3. Fuzzy Logic Control

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, 1985). 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. The out put of a fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variables. There are many methods of defuzzification, out of which smallest of maximum method is applied in making fuzzy inference system (Ross, 1985).

3.1. SOM (Smallest of Maximum) Method: This is also called first (or last of maximum) and this method uses the overall output or union of all individual output fuzzy sets C_k to determine the smallest value of the domain with maximum z membership degree in

C_k (Ross, 1985). The equation for z^* are as follows:

$$z^* = \inf_{z \in z} \{z \in z \,|\, \mu c_k(z) = hgt(c_k)\} \tag{18}$$

The Fuzzy logic control consists of three main stages, namely the fuzzification interface, the inference rules engine and the defuzzification interface (Ha, 1998). For Load Frequency Control the process operator is assumed to respond to respond to variables error (*e*) and change of error (*ce*).
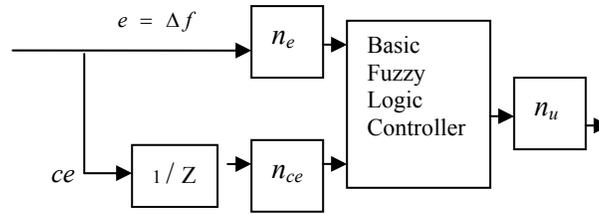
Fig. 3   Block diagram of a Fuzzy Logic controller

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.

$$\Delta Pc = F[n_c \, e(k), \quad n_{ce} \, ce(k)] \qquad (19)$$

Where n_e and n_{ce} are the error and the change of error scaling gains, respectively, and F is a fuzzy nonlinear function. FLC is dependant to its inputs scaling gains (Ha, 1998). The block diagram of FLC is shown in Fig 3,. n_u is output control gain (Talaq et al. 1999). 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 as follows:

L(*e, ce*) = { NB, NM, ZE, PM, PB},
Where,   NB = Negative Big,
         NM = Negative Medium,
         ZE = Zero,
         PM = Positive Medium,
         PB = Positive Big

Fuzzy logic controller has been used in hydro-thermal interconnected areas. Attempt has been made to examine with five number of triangular membership function (MFs) which provides better dynamic response with the range on input (error in frequency deviation and change in frequency deviation) i.e universe of discourse is -0.25 to 0.25. The numbers of rules are 25.

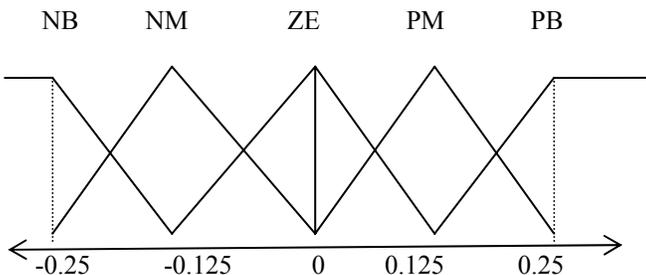The membership functions (MFs) for the input variables are shown in Fig.4.

Fig.4 : Membership Function for the control input variables

Table 1. Fuzzy inference rule for Fuzzy Logic Control

Input		e(k)				
		NB	NM	ZE	PM	PB
	NB	NB	NB	NM	NM	ZE
	NM	NB	NB	NM	ZE	ZE
ce(k)	ZE	NM	NM	ZE	PM	PM
	PM	ZE	PM	PM	PB	PB
	PB	ZE	ZE	PM	PB	PB

4. 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. 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 (Hykin, 1994).
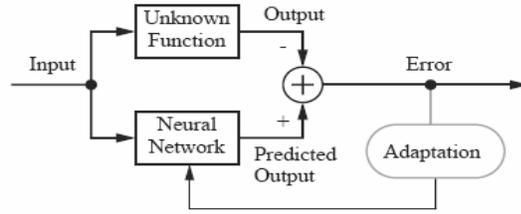
Fig. 5 Neural Network as Function Approximator

A neuron has more than one input. A neuron with inputs is shown in Fig. 6. The individual inputs $p_1, p_{2,....} p_R$ are each weighted by corresponding elements $w_{1,1}, w_{1,2,...} w_{1,R}$ of the weight matrix W. The neuron has a bias b, which is summed with the weighted inputs to form the net input n.
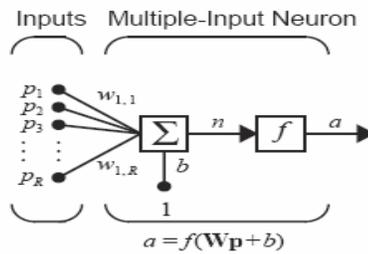
Fig. 6 Multi input neuron model

$$n = w_{1,1}p_1 + w_{1,2}p_2 + ... + w_{1,R}p_R + b \qquad (20)$$

This expression can be written in matrix form:

$$n = w_p + b \qquad (21)$$

Where the matrix w for the single neuron case has only one row. Now the neuron output can be written as

$$a = f(w_p + b) \qquad (22)$$

One of the most commonly used functions is the log-sigmoid transfer function, which is shown in Figure 7.
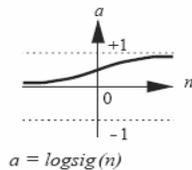
Fig.7 Log-Sigmoid Transfer Function

This transfer function takes the input (which may have any value between plus and minus infinity) and squashes the output into the range 0 to 1, according to the expression:

$$\qquad (23)$$

$$a = \frac{1}{1 + e^{-n}}$$

The log-sigmoid transfer function is commonly used in multilayer networks that are trained using the back propagation algorithm, in part because this function is differentiable.

4.1 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.

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.
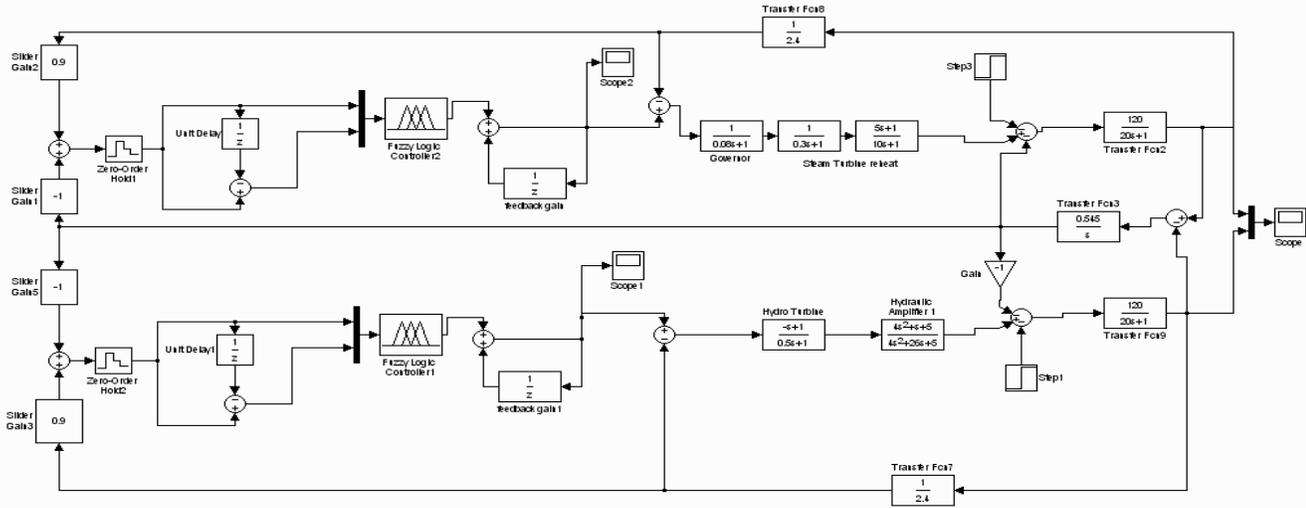
Fig. 8 Simulink Model of two area interconnected hydro-thermal reheat plant with Fuzzy controller.
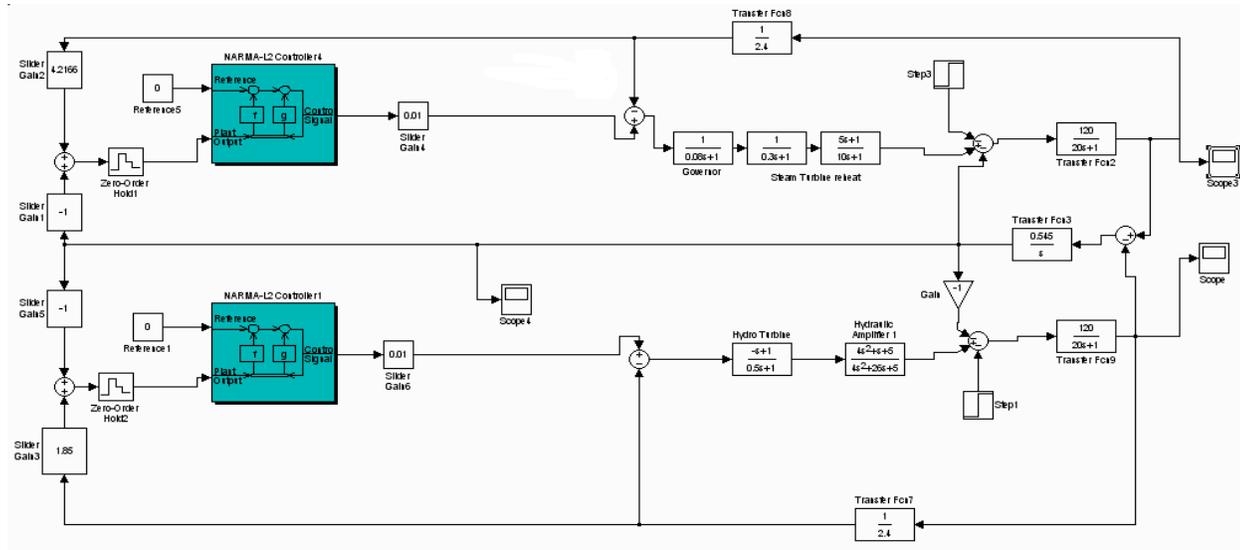
Fig. 9 Simulink Model of two area interconnected Hydro-Thermal Reheat plant   with Neural Network controller

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.

5. Simulation and Result

In this presented work, Thermal-hydro interconnected power system have been developed with fuzzy logic and ANN controllers to illustrate the performance of load frequency control using MATLAB/SIMULINK package. The parameters used for simulation are given in appendix. Two types of Simulink models are developed with fuzzy controller and ANN controller based as shown in Fig. 8 and Fig.9, respectively to obtain better dynamic behavior.

Refer to Simulink models, frequency deviation plots for thermal and hydro both cases are drawn combined and separately for 1% and 2% step load changes in system frequency and tie-line power as shown in Fig. 10-22 respectively.
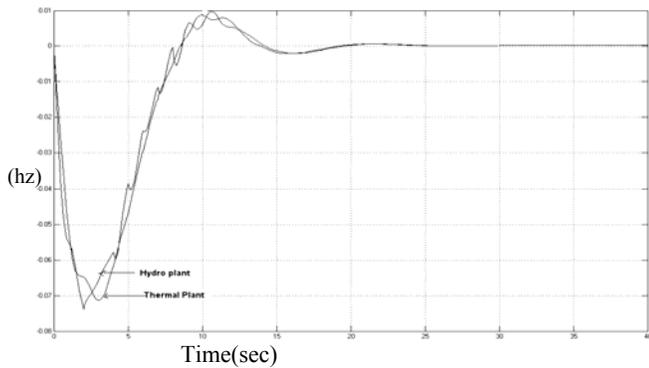

Fig.10 Combined Response of Hydro-thermal plant
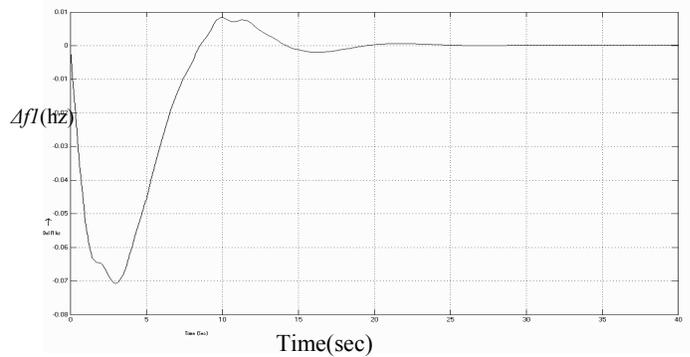with fuzzy controller(1% load variation).

Fig. 11 Change in frequency (thermal plant) –Fuzzy
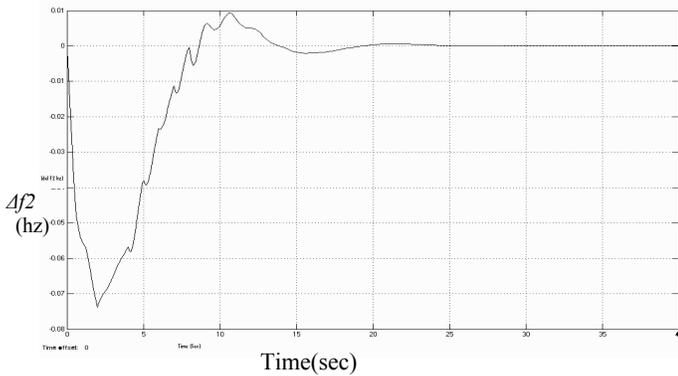with controller (Δf_1) (1% load variation).

Fig. 12 Change in frequency (Hydro plant)- Fuzzy controller (Δf_2)
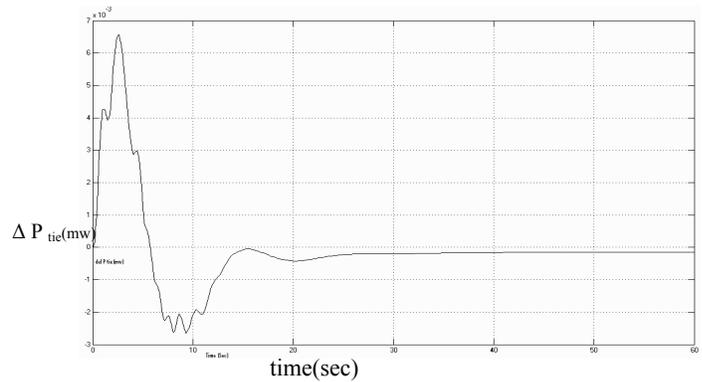(1% load variation.)

Fig. 13 Change in Tie-line power (hydro-thermal plant)
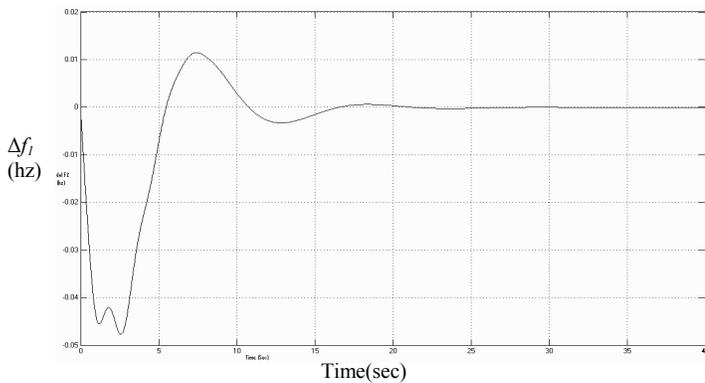with fuzzy control (ΔP_{tie}) (1% load variation).

Fig. 14 Change in frequency (Thermal plant) with ANN controller (Δf_1)
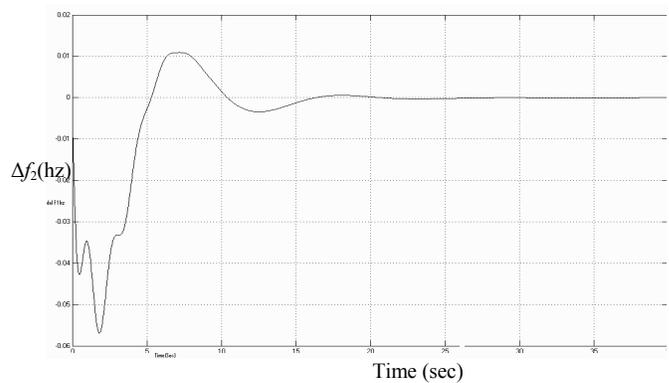(1% load variation).

Fig.15 Change in frequency (Hydro plant)
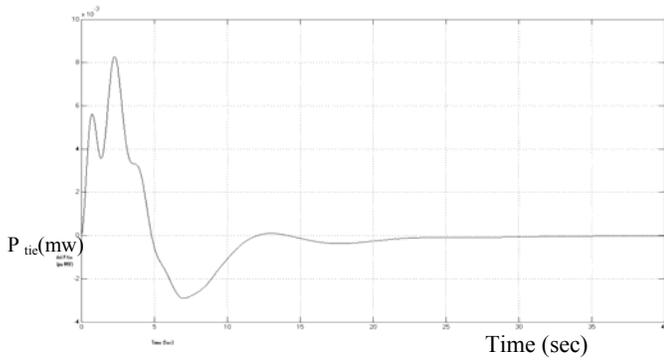with ANN controller (Δf_2) (1% load variation).

Fig. 16 Change in Tie-line power (hydro-thermal plant)
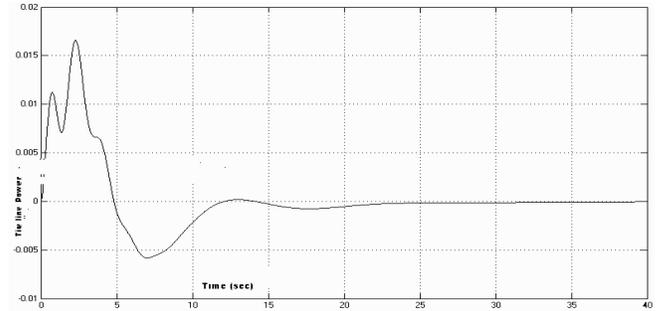with ANN controller (ΔP $_{tie}$) (1% load variation).

Fig. 17 Change in Tie-line power (hydro-thermal plant)
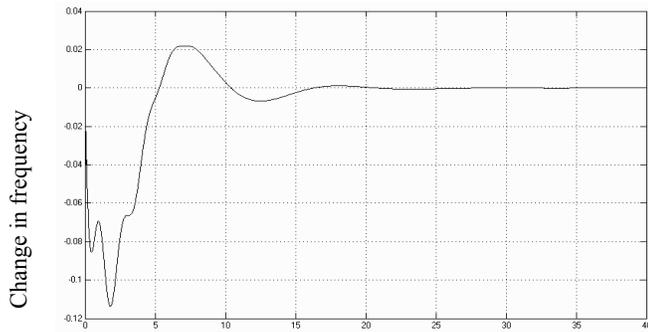With ANN controller   (2% load variation)

Fig. 18 Change in frequency (hydro plant)
with ANN controller (Δf_1) (2% load variation).

Fig.19 Change in frequency (thermal plant)
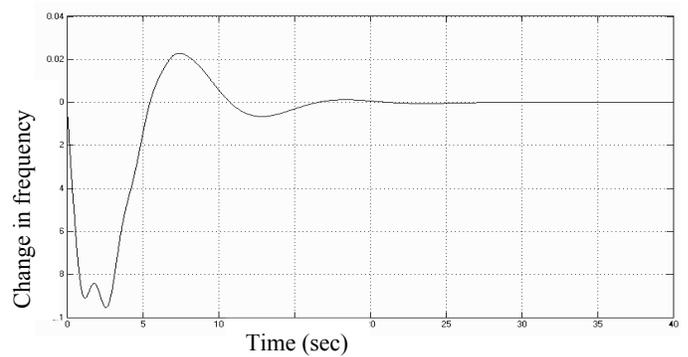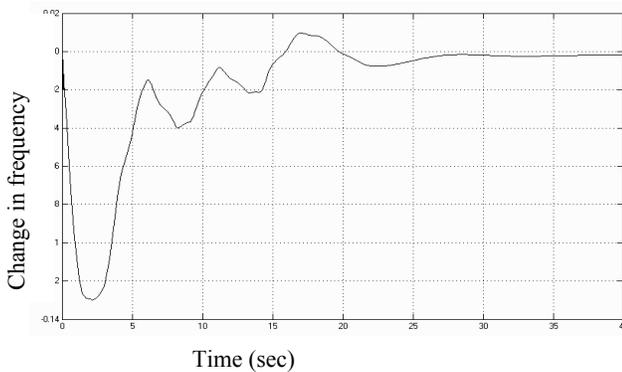with ANN controller   (Δf_2) (2% load variation).

Fig. 20   Change in frequency (Thermal plant)
with fuzzy controller (Δf_1) (2% load variation).
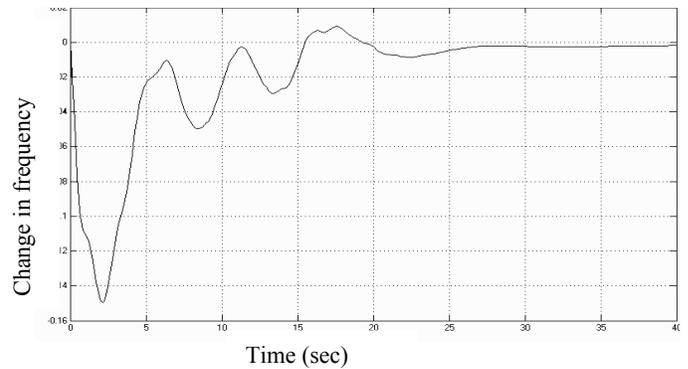

Fig.21 Change in frequency (Hydro plant)
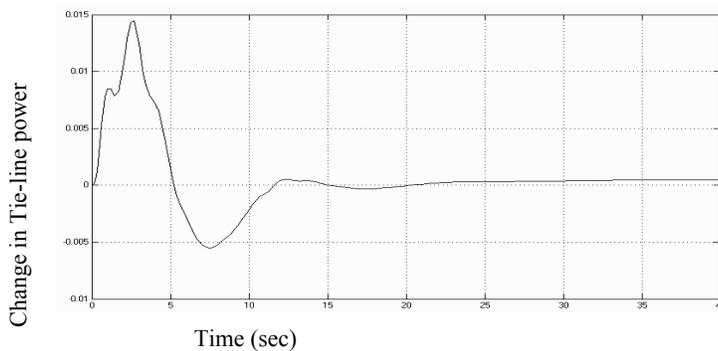With   fuzzy controller (Δf_2) (2% load variation).

Fig. 22 Change in Tie-line power (hydo-theraml plant) with fuzzy control (Δ P $_{tie}$) (2 % load variation).

With 1% and 2% step load change in both Hydro-Thermal Reheat areas with fuzzy controller and ANN controller, the steady state error is minimized to zero. Settling time and maximum peak overshoot in transient condition for both change in system frequency and change in tie-line power for different loading conditions are given in table 2-5 respectively. By this proposed method the responses obtained are better than the previous works already reported in (Gayadhar et al. 2009; Ram et al. 2010; Anand et al., 2009; Shayeghi et al. 2004).

Table: 2. Comparative study of settling time (1% load variation)

Controllers	Δf_1 Area 1 (sec)	Δf_2 Area 2 (sec)	ΔP_{tie} (sec)
Fuzzy	23	23	27
ANN	17	17	23

Table: 3. Comparative study of peak overshoots (1% load variation)

Controllers	Δf_1 Area 1 in pu	Δf_2 Area 2 in pu	ΔP_{tie} in pu
Fuzzy	0.071	0.075	0.0035
ANN	0.045	0.055	0.003

Table: 4. Comparative study of settling time (2 % load variation)

Controllers	Δf_1 Area 1 (sec)	Δf_2 Area 2 (sec)	ΔP_{tie} (sec)
Fuzzy	28	28	25
ANN	17	17	23

Table: 5. Comparative study of peak overshoots (2 % load variation)

Controllers	Δf_1 Area 1 in pu	Δf_2 Area 2 in pu	ΔP_{tie} in pu
Fuzzy	0.13	0.15	0.015
ANN	0.09	0.11	0.015

6. Conclusions

With 1% load variation in power system the results shown in Tables 2 to 5 are obtained. The Intelligent control approach (Fuzzy Controller and ANN controller) with inclusion of slider gain provides better dynamic performance and reduces the oscillation of the frequency deviation and the tie line power flow in each area in hydro-thermal combination. Form the above table it is clear that responses obtained, reveals that ANN controller with sliding gain provides better settling performance than Fuzzy. By increasing the percentage deviation in load power, the ANN controller tries to maintain the settling time as previous one but peak overshoot changes slightly. In Fuzzy control approach by changing percentage load deviation the settling time is increased and peak overshoot as well. Therefore, the intelligent control approach using ANN concept is more accurate and faster than the fuzzy control scheme even for complex dynamical system at different loading conditions.

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Appendix

Parameters are as follows:
f = 50 Hz, R_1 =R_2= 2.4 Hz/ per unit MW, Tg = 0.08 sec, Tp=20 sec
P tie, max = 200 MW
Tr = 10 sec   kr = 0.5,
H_1 =H_2 = 5 sec P_{r1} = P_{r2} =2000MW
Tt = 0.3 sec   Kp$_1$=Kp$_2$ = 120 Hz.p.u/MW
Kd =4.0   ki = 5.0   Tw = 1.0 sec
D_1 =D_2= 8.33 * 10^{-3} p.u MW/Hz.

Nomenclature
F :   Nominal system frequency
P_{ri} :   Area rated power, H_i: Inertia constant
ΔP_{Di} :   Incremental load change
ΔPg_i :   Incremental generation change
Di = $\dfrac{\Delta P_{Di}}{\Delta fi}$
T_{12} :   Synchronizing coefficient, T_g:Steam governor time constant
K_r :   Reheat constant, T_r : Reheat time constant
T_t :   Steam turbine time constant
R_i :   Governor speed regulation parameter
B_i: Frequency bias constant
T_{pi} :   2Hi / f * Di, K_{pi}: 1/ Di
K_j :   Integral gain
K_d, K_p, K_i : Electric governor derivative, proportional and

integral gains, respectively.

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

Q : Reactive Power, V_f : Field voltage of generator field winding, ΔPc : Speed changer position

R: Speed regulation of the governor

K_H :   Gain of speed governor

T_H :Time constant of speed governor

K_1, K_2, K_3, K_4, K_5 :   Constants

K_p : 1/B= Power system gain

T_p: 2H / B f_0 =   Power system time constant

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