Load Frequency Control of Two Area Interconnected Power System using SSSC with PID, Fuzzy and Neural Network Based Controllers

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***Abstract*—This paper presents the frequency control of a two area interconnected thermal and reheat thermal systems incorporating static synchronous series compensator (SSSC) to control the tie-line power transfer. Effectiveness of PID to control the system dynamics and minimize area control error (ACE) has been observed. The system dynamics is further improved by using fuzzy logic controller and neural network based controller. It shows the effectiveness of Fuzzy Logic Controller (FLC) over PID controller and neural network controller over FLC. The mathematical model of the system is also explained in this paper.**

***Index Terms*—Load Frequency Control (LFC), Area Control Error (ACE), PID Controller, Fuzzy Logic Controller, Adaptive Neuro-inference system, Static Synchronous Series Compensator (SSSC).**

I. INTRODUCTION

The frequency in a power system changes when there is a mismatch between generation and the electrical load. The Load Frequency Control (LFC) provides a way of matching the generation with the load so as the change in frequency and tie-line power is minimized [1] [2]. In the present-day power system hydro and thermal units are the main power producing units. A lot of work in the literature [2] [3] shows that thermal and hydro plants work as base load units. Hydro and thermal power plants differ from each other as the hydro power plant provides non-minimum phase characteristics which are not present in the thermal units. Two interconnected units like thermal and reheat-thermal are considered in this paper.

The interarea oscillations are very common in the interconnected power systems, these oscillations cause change in the frequency. There are different ways to damp out these oscillations and one of them is by using Flexible AC Transmission system (FACTS) devices. Hence LFC in the presence of FACT devices becomes interesting. Different FACTS devices like Static Synchronous Series Compensator (SSSC) [4], Thyristor Control Phase shifter (TCPS) [5], Unified Power Flow Controllers (UPFC) [6] Interline Power Flow (IPFC) and Thyristor Controlled Series Capacitors (TCSCS) [7] are being used to increase the power system reliability and power exchange. Subbaramaiah et al [8] have used SSSC and TCPS in two area power system.

PID controller has always remained the SSSC choice in LFC. PID is preferred because of its reliability, simplicity and low cost and also it is easy to operate. But the major disadvantage of PID is the proportional and derivative kick which causes sharp spikes and sudden overshoots. To overcome these short comings fuzzy logic controller is used, as it gives better results and reduces the overshoot. But there is one disadvantage in using fuzzy controller as it gives desired outputs corresponding to the given input. To overcome these disadvantages and to improve the system performance and make it fast Neural Network Controller is used. This is more advanced adaptive control strategy and it also produces fast response than other controllers (Demiroren et al).

II. SYSTEM INVESTIGATED

An interconnected two area thermal-reheat system is considered.Non-linearities such as generation rate constant GRC is considered for reheat-thermal power plant to get the realistic understanding of AGC problem.The transfer function of different components of power system is given in Figure 1. The parameters of the system considered are taken from ref [9]. Different controllers like PID,fuzzy and neural are considered separately as supplementary controllers. The performance of SSSC with different controllers is evaluated.The parameters considered are given in the appendix. The system performance is evaluated by considering a step load perturbation (SLP)

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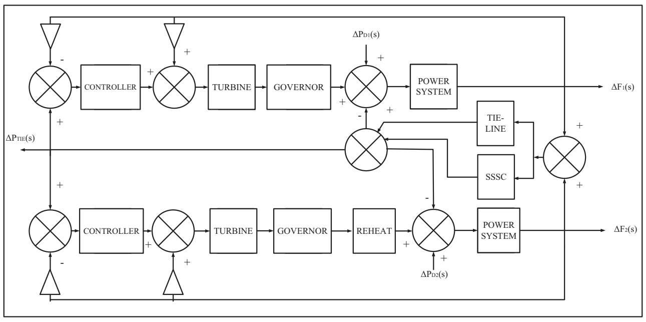

Fig. 1. Block diagram.

in both areas area1 and area2 for realistic studies.A brief description of generation rate constant (GRC) is given as under:

A. Generation rate constraint

The power generation in a power system can change only at a specified maximum rate which is known as Generation Rate Constraint (GRC). The effect of generation rate constraint is visible on the increment of settling time and overshoots of the system response. Presently a GRC of 3% /min is considered for thermal units [10]. The swing equation of a synchronous machine is given by

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \tag{1}$$

When a small change in speed takes place

$$\frac{d\Delta(\frac{\omega}{\omega_s})}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \tag{2}$$

In per unit we have

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \tag{3}$$

Now taking Laplace transform of equation (3) we get

$$\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_e(s)] \tag{4}$$

This can be represented by a block diagram as,

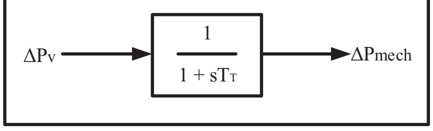

Fig. 2. Turbine Model.

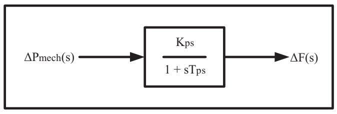

Fig. 3. Block diagram of load.

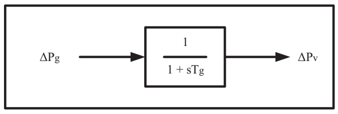

Fig. 4. Block diagram of governor model.

B. LOAD MODELLING

Load on a power system comprises of resistive load which is independent of frequency and inductive load which is sensitive to the frequency. The sensitivity of inductive load depends on speed-load characteristics. This can be shown by a mathematical relation as:

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{5}$$

Where ΔP_L represents the resistive load or the load which is independent of frequency, and D, $\Delta\omega$ is the load which depends on frequency. The value of D is written as the ratio of percent change in load to percent change in frequency.

C. PRIME MOVER MODELLING

The prime movers can be hydraulic turbines for waterfalls, steam turbines, gas and nuclear turbines. The modelling of turbine is related to the change in mechanical power outputΔP_m to the change in steam valve position ΔP_V. The modelling of a non-reheat turbine with only one-time constant is given as:

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1 + T_T(s)} \tag{6}$$

D. GOVERNOR MODELLING

The transfer function model of governor is given by the following equation:

$$\Delta P_V(s) = \frac{1}{1 + T_g(s)}\Delta P_g(s) \tag{7}$$

This can be represented by a block diagram as under:

E. TIE-LINE MODELLING

The tie-line connects two power systems together and the power transfer from one area to another area takes place through it. If there is an increase of load in a particular area, power from the other area flows through tie-line to compensate for the change. Mathematically power through the tie-line can be expressed as:

$$P_{12}^0 = \frac{|V_1^0||V_2^0|}{X}\sin(\delta_1^0 - \delta_2^0) \tag{8}$$

Where,δ_1^0, δ_2^0 = power angles of the two machines.

When a small disturbance occurs in the angles the tie-line power deviates to

$$\Delta P_{12} = T_{12}(\Delta\delta_1^0 - \Delta\delta_2^0) \tag{9}$$

Where,

$$T_{12} = \frac{|V_1^0||V_2^0|}{X}\cos(\delta_1^0 - \delta_2^0) \tag{10}$$

is the synchronizing torque The relationship between the frequency deviation$\Delta f$and angle is given as under

$$\begin{aligned}\Delta f &= \frac{1}{2\pi}\frac{d(\delta_0 + \Delta\delta)}{dt} \\ &= \frac{1}{2\pi}\frac{d(\Delta\delta)}{dt}\end{aligned} \tag{11}$$

$$\Delta\delta = 2\pi\int \Delta f dt \tag{12}$$

$$\Delta P_{12} = 2\pi T_{12}\Big(\int \Delta f_1 dt - \int \Delta f_2 dt\Big) \tag{13}$$

Taking Laplace transform of above equation we get

$$\Delta P_{12} = \frac{2\pi T_{12}}{s}(\Delta f_1(s) - \Delta f_2(s)) \tag{14}$$

III. CONTROL METHODOLOGY USED

A. SSSC

The static synchronous series compensator is used for stablising the area frequency and tie-line power devations by controlling the tie-line power exchange.The SSSC is connected in series with the tie-line between the areas which are interconnected, hence it can be represented by a series of voltage source which are connected togather.The expression for power when using sssc in the tie-line [10] can be represented in terms of frequency deviation as under:

$$\Delta P_{sssc}(s) = \frac{(1+T_1 s)(1+T_3 s)}{(1+T_2 s)(1+T_4 s)}\frac{K_{sssc}}{1+T_{sssc}}\Delta\omega_s(s) \tag{15}$$

Here T_{sssc} and K_{sssc} are the time constants and gain of SSSC and the change in frequency$\Delta\omega_s(s)$ is the input to the SSSC controller.

B. PROPORTIONAL INTEGRAL DERAVATIVE CONTROLLER (PID)

Proportional Integral Derivative (PID) is the most commonly available controller. PID controller improves the dynamic response of the system and eliminates the study state error. A finite zero is added to the open loop transfer function of the plant by the derivative controller and hence it improves the transient response [11]. The system type is increased by one with the help of Integral controller which adds a pole at the origin, that in turn reduces study state error to zero which is caused by the step change. Trail and error method has been used to determine the tuned values of proportional, integral and differential gains The transfer function of PID is given as:

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s \tag{16}$$

C. FUZZY LOGIC CONTROLLER

Fuzzy logic controller has lot of applications in power system. FLC works on the basis of knowledge acquisition process. A fuzzy system has a membership function associated with each fuzzy set and here fuzzy IF-THEN rule is used for controlling the process. The horizontal range of membership functions is obtained by optimisation of error generated by PID controller. In the given system the LFC comprises of sudden load variations in the power system which result in the frequency change and this frequency deviation should be in the permissible limits [11]- [14].

Fuzzification:
It is the way of converting real-valued variable into fuzzy variable.
Rule base:
The rule-base used is IF-THEN rule it consists of a set of rules. The rule base is a combination of a set of fuzzy rules. The information is carried out by the membership functions.
De-Fuzzification:
Defuzzification is the way of converting the fuzzy variable into the real value which is known as crisp-value due to this it is used in the controlling process. The block diagram representation of de-fuzzification is given below. The controlling action of FLC is decided by the fuzzy rule base.

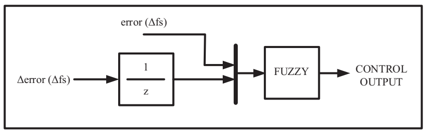

Fig. 5. Block diagram of fuzzy logic controller.

The performance of the controller is based on de-fuzzification, membership function and rule base. The error signal (Δ f_s) is generated from the governor, which is given as input to FLC. The fuzzy rule base and the membership-function comprise of five variables these are (NB, NS, ZZ, PS and PB) for the two inputs and two output system as represented in the diagram and the rule-base table.

TABLE I
FUZZY RULE BASE.

ACE/DACE	***NB***	***NS***	***ZZ***	***PS***	***PB***
NB	S	S	M	M	B
NS	S	M	M	B	VB
ZZ	M	M	B	VB	VB
PS	M	B	VB	VB	VVB
PB	B	VB	VB	VVB	VVB

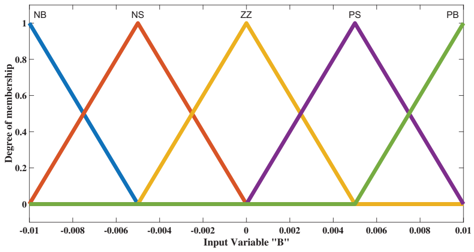

Fig. 7. Membership function of input two DACE.

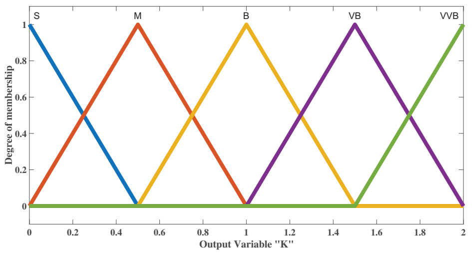

Fig. 8. Membership function of output K.

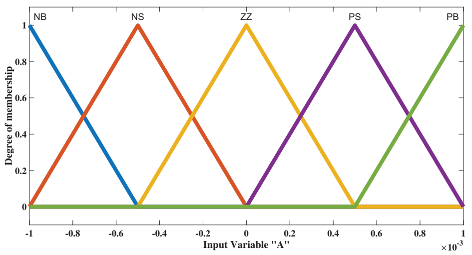

Fig. 6. Membership function of Input one ACE.

D. NEURAL NETWORK CONTROLLER

The information is processed by the neurons in the neural network system nad that is why it is named so. The signal is transmitted from one neuron to another neuron through the connecting links These links are associated with weight and the incoming signal is multiplied with the weights and input signal of the neural network. The output is obtained by giving the activation function to the net input. Neural network has vast applications [15]. The block diagram of NN is shown in fig 10. The network is so adjusted that if the inputs are same, then the response will also be same. The unknowns of the system can also be represented as the inverse of the system which is being controlled for this case we can use NN controller (Hykin 1994) Neuron can have more than one input, this is shown in the fig 10. The inputs $p_1, p_2, p_3.........p_n$ and the weights $w_{1,1}, w_{1,2}.........w_{1,R}$ of the weight matrix w. The bias b associated with neuron is summed with the weighted inputs to produce the net-input neuron n.

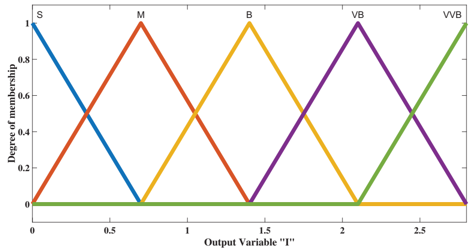

Fig. 9. Membership function of output I.

Multi-input neuron

$$n = w_{1,1}p_1 + w_{1,2}p_2 + ... + w_{1,R}p_R + b \tag{17}$$

In matrix form

$$n = w_p + b \tag{18}$$

Matrix w has only one row. This can be written as;

$$a = f(w_p + b) \tag{19}$$

Log-sigmoid function is most commonly used transfer function. This is shown in Fig.12.

This converts input from 0-1.

$$a = \frac{1}{1 + e^{-n}} \tag{20}$$

It is used in multilayer networks which are trained through back propagation algorithm. The control signals for the governor are the output signals of NN controller. The data for the training of NN is obtained by making a reference model NN and applying to the system with step perturbances.

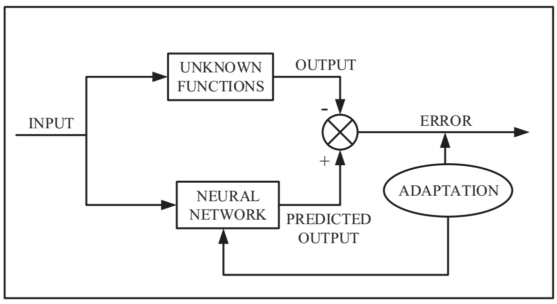

Fig. 10. Neural Network Function Approximator.

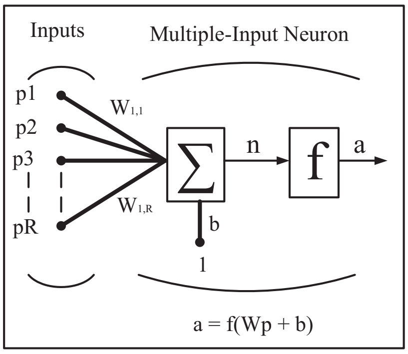

Fig. 11. Neural Stucture.

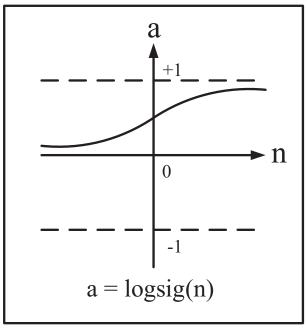

Fig. 12. Log-sigmoid transfer function.

IV. SIMULATION RESULTS

The two area interconnected model is simulated with different controllers and the following results have been obtained from Fig 13 to Fig 20. Various types of controllers used are PID, Fuzzy logic controller and Neural Network based controller. The performance of the controllers have been summed up in Table 2. It has been observed that performance of Neural network based controller is better than Fuzzy Logic controller which in-turn is better than PID controller.

The settling time of system considered is brought to 32s by using PID controller which is further improved and brought down to 20s by replacing PID with FLC and hence improves the system performance. FLC is then replaced by NN controller to Steady the results and it is observed that settling time is further improved and brought down to 5s from 20s. This shows the superiority of NN controller.

TABLE II
SETLING TIME (S).

Controllers	***Area 1***	***Area 2***
PID	32	32
Fuzzy	20	20
Neural Network	5	5

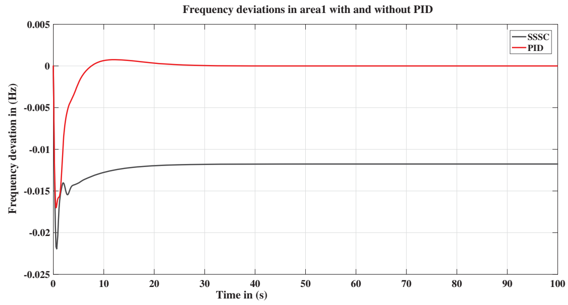

Fig. 13. Comparison of frequency deviations in area1 without and with PID.

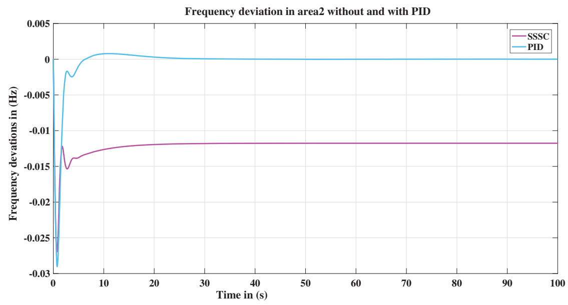

Fig. 14. Comparison of frequency deviations in area1 without and with PID.

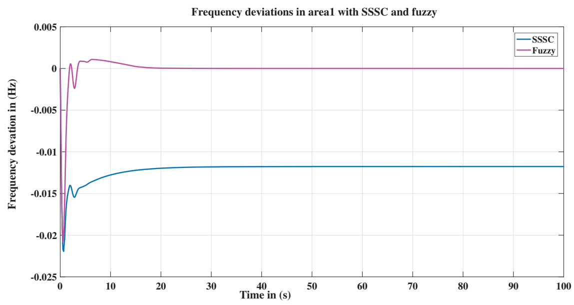

Fig. 15. Comparison of frequency deviations in area1 with and without fuzzy.

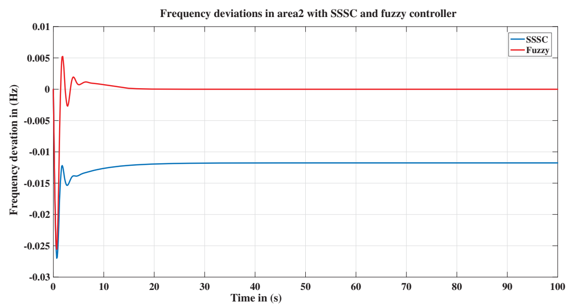

Fig. 16. Comparison of frequency deviations in area2 with and without fuzzy.

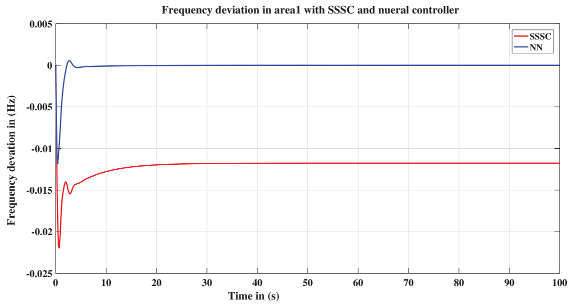

Fig. 17. Comparison of frequency deviations in area1 with and without Neural Network.

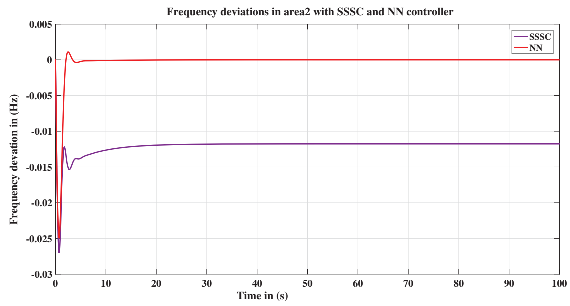

Fig. 18. Comparison of frequency deviations in area2 with and without Neural Network.

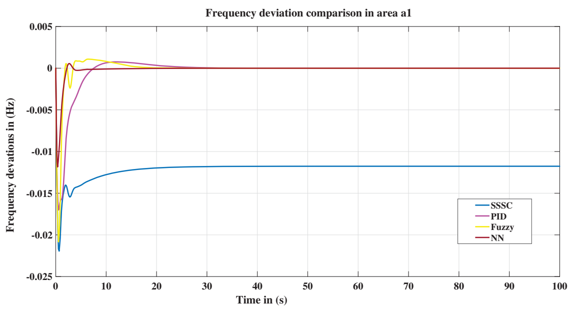

Fig. 19. Comparison of frequency deviation in area 1.

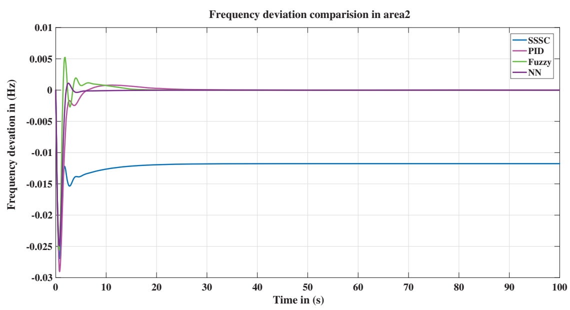

Fig. 20. Comparison of frequency deviation in area 2.

V. Conclusion

With the use of FACTS devices like SSSC in the tie-line,not only is the overshoot in frequency and the settling time of the system improved, but it also improves the tie-line power transferred. However the error in the system still present and can be removed by applying different control strategies like PID, Fuzzy and NN Controllers. The steady state error is brought to zero and the system overshoot is minimized by using self tuned PID controller with SSSC. Fuzzy logic controller reduces the settling time and brings the steady state error to zero quickly. The NN controller gives best results among the three controllers used, hence the overshoot is less with NN controller as compared to PID and fuzzy controllers. Further NN controller reduces the settling time and gives better results than PID and fuzzy logic controllers.

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