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Automatic Generation Control of Multi-Area Power System with Generating Rate Constraints Using Computational Intelligence Techniques

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ABSTRACT

In a large inter-connected system, large and small generating stations are synchronously connected and hence all stations must have the same frequency. The system frequency deviation is the sensitive indicator of real power imbalance. The main objectives of AGC are to maintain constant frequency and tie-line errors with in prescribed limit. This paper presents two new approaches for Automatic Generation Control using i) combined Fuzzy Logic and Artificial Neural Network Controller (FLANNC) and ii) Hybrid Neuro Fuzzy Controller (HNFC) with gauss membership functions. The simulation model is created for four-area interconnected power system. In this four area system, three areas consist of steam turbines and one area consists of hydro turbine. The components of ACE, frequency deviation (ΔF) and tie line error (ΔP_{tie}) are obtained through simulation model and used to produce the required control action to achieve AGC using i) FLANNC and ii) HNFC with gauss membership functions. The simulation results show that the proposed controllers overcome the drawbacks associated with conventional integral controller, Fuzzy Logic Controller (FLC), Artificial Neural Network controller (ANNC) and HNFC with gbell membership functions.

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1. INTRODUCTION

AUTOMATIC generation control (AGC) is an important problem in power system operation and control. When ever a small load perturbation occurs, it causes the changes in tie-line power flow and frequency deviation (ΔF). Many investigations in the area of AGC of interconnected power systems have been carried out in the past [1]-[4] and number of control strategies have been proposed to improve the performance of AGC. In the application of optimal control techniques, the controller design is normally based on a fixed parameter model of the system derived by a linearization process. Power system parameters are functions of the operating point. Therefore as the operating conditions change, system performance with controllers designed for a specific operating point, most likely will not be satisfactory [2]. Consequently, the non-linear nature of the load frequency control (LFC) problem makes it difficult to ensure stability for all operating points when an integral controller is used [6],[7]. The application of adaptive control theory to the LFC problem eliminates some of the problems associated with classical and modern control [5]. In recent years, intelligent techniques such as artificial neural networks (ANN), fuzzy logic (FL) and genetic algorithms (GA), have gained increasing interest for the applications in LFC problem. Some such applications using ANN can be found in [8]-[10]. Design and experience with a FLC for Automatic Generation Control is explained in [11]. The method of constructing membership function using stored data and formation of rule base are given in [12]-[14].

In this paper, four-area interconnected power system is considered. First three areas consist of steam turbines and fourth area consists of hydro turbine. FLANNC and FLC to ANNC switching controller are used for AGC for four area power system. A simulation model is created for four-area interconnected power system and the performance of the following controllers is studied:

(i) Conventional integral controller
(ii) Fuzzy Logic Controller (FLC)
(iii) Artificial Neural Network controller (ANNC)
(iv) Combined Fuzzy Logic and Artificial Neural Network controller (FLANNC)

2. MODELING OF THE POWER SYSTEM FOR AGC

The multi-area AGC system used in this paper given in Fig.1 consists of four control areas, which are connected by tie lines. In each control area, all generators are assumed to form a coherent group. The four area interconnected power system consists of three re-heat thermal turbine units and one hydro unit.

The transfer function model of the four power system is given in [10], and system parameters are given in Table 1. Each area supplies power to its user pool and tie lines allows electric power to flow between areas. Therefore, any load disturbance in one area affects the frequency of its own area, frequency of other areas and tie line power flow of other areas. Due to this, the control system of each area needs information about the transient situation in all areas to bring the local frequency to its steady state value. The information about each area during perturbation is found in its frequency and the information about the other area in the perturbation is found in its tie-line power flow. In conventional control system, turbine reference power of each area is tried to be set to its nominal value by an integral controller and the input of the integral controller of each area is $B_i \, \Delta f_i + \Delta P_{tiei}$ (i=1,. 4) called Area Control Error (ACE) of the same area. Parameters B_i are chosen as $1/K_{pi}+1/R_i$.

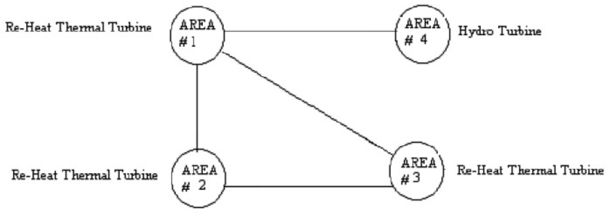

Fig .1 Schematic diagram of the power system with four areas

The three areas consist of steam turbines which has governor, re-heater with generation rate constraints. The hydro turbine in the fourth area is having generation rate constraint. Dead band effect of governor of hydro turbine and steam turbines are ignored for simplicity. By considering the matters mentioned above, the state space equations in discrete time domain are obtained as represented in Appendix. As a result, the state space equations of the power system including four areas are written in discrete time domain as follows:

$x(k) = Ax(k-1) + Bu(k-1) + G$ (1)

where G is a vector containing non-linear terms. The expressions of matrices A, B and G in Eq. 1: are obtained by arranging the equations given in Appendix A. The variables used in Appendix A are given in nomenclature. The input state variables of the four-area power system are given below

$x^T = [\Delta f_1, \Delta P_{R1}, \Delta P_{G1}, \Delta P_{ref\,1}, \Delta x_{E1}, \Delta P_{tie1}, \Delta f_2, \Delta P_{R2}, \Delta P_{G2}, \Delta P_{ref\,2}, \Delta x_{E\,2}, \Delta P_{tie2}, \Delta f_3, \Delta P_{R3}, \Delta x_{E3}, \Delta P_{tie3}, \Delta f_4, \Delta P_{G3}, \Delta P_{ref3}, \Delta P_{ref\,4}, \Delta x_{E4}, \Delta P_{R4}, \Delta P_{G4}, \Delta P_{tie4}]$ (2)

$u^T = [\Delta P_{D1}, \Delta P_{D2}, \Delta P_{D3}, \Delta P_{D4}]$ (3)

where the above parameters are given in nomenclature.

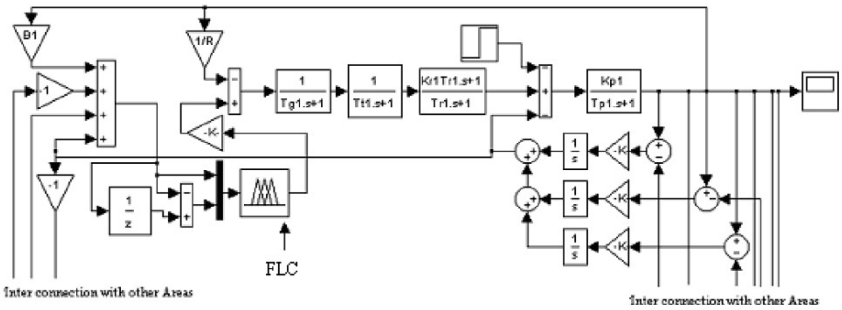

Fig 2. Transfer function simulation model of area1 controlled by FLC

The transfer function simulation model of area1 power system is shown in Fig.2. In practice, there is a maximum limit on the rate of change in the generating power of a conventional power plant. Hence, if the response of the applied controller and/or the load change is too fast under transient conditions, then system non-linearities will prevent its achievement. It follows that a controller designed for the unconstrained situation may not be suitable when the GRC is considered. The generation rate constraint (GRC) is taken into account by replacing the turbine block with non-reheat turbine (non-linear). In order to project physical constraints, generation rate limitations are chosen as 0.1 p.u./min (i.e. 0.0017 p.u. MW/s) for thermal area and 4.5% for hydro area [4].

Table 1: The parameters values of the power system

T_1 (area 4)	13s	$K_{p1,2,3}$	120	$\Delta P_{D1,2,3}$	0.01
$T_{p1,2,3}$	20s	$K_{r1,2,3}$	0.333	K_{p4}	80
T_2 (area 4)	0.513s	a_{ij}	1	$R_{1,2,3,4}$	2.4
$T_{s1,2,3}$	0.001s	$T_{r1,2,3}$	10s	T_w (area 4)	1s
T_3 (area 4)	10s	$T_{g1,2,3}$	0.2s	$\Delta P_{D1,2,3}$	0.01

$B_{1,2,3,4}$ value is designed by using the expression

$$B_{1,2,3,4} = 1/K_{pi} + 1/R_i \quad (4)$$

The three areas consist of steam turbines which have governor, re-heater with ramp rate constraints. The hydro turbine in the fourth area is having generation rate constraint. Dead band effect of governor of hydro turbine and steam turbines are ignored for simplicity [10].

3. DESIGN OF FLC

Fuzzy logic is a paradigm for an alternative design methodology, which can be applied in developing both linear and non-linear systems for embedded control. A full control design requires developing a set of control rules based on available inputs and designing a method of combining all rule conclusions. The design procedure is given as follows:

3.1. CHOICE OF PROCESS INPUT AND CONTROL OUTPUT

A first step is to choose the correct input signals to the fuzzy logic controller. For this controller, Area Control Error (ACE) and change in Area Control Error (ΔACE) signals are selected as input to the controller which is the contents of the rule-antecedent (If-part of a rule). The control output (u) signals (process input) represents the contents of the rule-consequent (then-part of the rule).

3.2. NORMALIZATION

Normalization performs a scale transformation and it also called input normalization. It maps the physical values of the current process state variables into a normalized universe of discourse. It also maps the normalized value of control output variable into its physical domain (output de-normalization). For this controller, normalization is obtained by dividing each crisp input on the upper boundary value for the associated universe.

3.3. FUZZIFICATION

Fuzzification is the process of making crisp value to fuzzy quantity. The quantities that are considered being crisp and deterministic are actually not deterministic at all. Fuzzification is related to the vagueness and imprecision in a natural language. It could be defined as a mapping from an observed input space to fuzzy sets in certain input universes of discourse. Fuzzification plays an important role in dealing with uncertain information, which might be objective or subjective in nature.

3.4. DETERMINATION OF MEMBERSHIP FUNCTION

The range of input and output variables is assigned with linguistic variables. These variables transform the numerical values of the input to fuzzy quantities. These linguistic variables specify the quality of the control. As the number of the linguistic variables increases, the computational time increases. Therefore a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. The Gauss membership function is chosen in this work. The input and output variables are assigned with 5 linguistic variables as follows:

1. The Area Control Error (ACE) is classified into:
   Negative maximum (ACE $_{-vemax}$); Negative medium (ACE□$_{-vemed}$); Zero (ACE_{zero}); Positive medium (ACE□$_{+vemed}$); Positive maximum (ACE $_{+vemax}$)
2. The change in Area Control Error (ΔACE) is classified into:
   Negative maximum (ΔACE $_{-vemax}$); Negative medium (ΔACE $_{-vemed}$); Zero (ΔACE_{zero}); Positive medium (ΔACE $_{+vemed}$); Positive maximum (ΔACE $_{+vemax}$)
3. The output of fuzzy logic controller u is classified into:
   Negative maximum (u_{-vemax}); Negative medium (u $_{-vemed}$); Zero (u $_{zero}$); positive medium (u $_{+vemed}$); Positive maximum (u_{+vemax}).

The input variable ACE and ΔACE lies with in the range of [-0.0188 0.001] and [-0.009.0.0188]. The control output 'u' lies in the range of [0 0.0123]. These input and output ranges are used for designing the FLC, in which each of input and output set is assigned with five linguistic variables and 25 rules are framed in fuzzy inference engine.

3.5 KNOWLEDGE BASE

The knowledge base of an FLC comprises of two components, a database and fuzzy control base. The concepts associated with a database are used to characterize fuzzy control rule. It should be noted that the correct choice of the membership function plays an essential role in the successful application. A lookup table based on discrete universes defines the output of a controller for all possible combinations of the input signals. A fuzzy system is characterized by a set of linguistic statements. It is in the form of "IF-THEN" rules; these rules are easily implemented by fuzzy conditional statements. In fuzzy logic the collection of fuzzy control rules, that are expressed as fuzzy conditional statements forms the rule set of an FLC. The decision table is given in Table. 2.

Table 2.: Rule base of the proposed FLC

Area Control Error (ACE)	Change in Area Control Error (ΔACE)				
	ACE –vemax	ACE –vemed	ACE Zero	ACE +vemed	ACE +vemax
ACE –vemax	u +vemax	u +vemax	u+vemax	u +vemed	u zero
ACE –vemed	u +vemax	u +vemax	u +vemed	u zero	u –vemed
ACE zero	u+vemax	u +vemed	u zero	u-vemed	u-vemax
ACE +vemed	u –vemed	u zero	u –vemed	u -vemax	u -vemax
ACE +vemax	u zero	u –vemed	u -vemax	u -vemax	u -vemax

The associated gauss membership function for input variable ACE and its derivative ΔACE are shown in Fig.3 and Fig.4. The output variable u is shown in Fig .5.

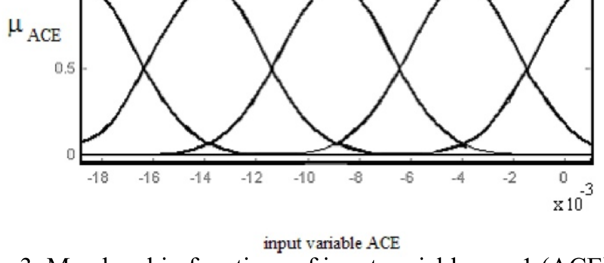

Fig.3. Membership functions of input variable area1 (ACE)

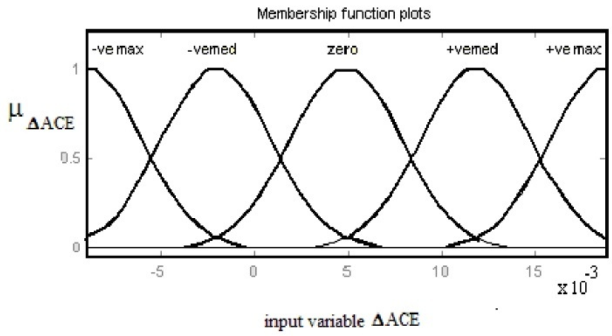

Fig 4.Membership functions of input variable area (ΔACE)

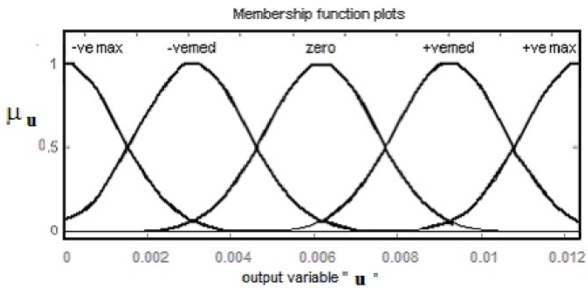

Fig 5.Membership functions of output variable area (u)

3.6. Defuzzification

This process is used to convert a fuzzy value back to the actual crisp output. To get the control output in fuzzy values, the max-min method is adopted in decision-making. The crisp control output (u) is obtained by centroid method which is given by,

$$u = \frac{\sum_{r=1}^{R} \mu_r' H_r}{\sum_{r=1}^{R} H_r} \quad (5)$$

where μ is the membership value of the variable recommending the fuzzy controller action, H_i is precise numerical value corresponding to that fuzzy controller action and i is the index of the fuzzy logic rules(i=1,….N), N is the total number of rules to be fired.

4. DESIGN OF ANNC

In four-area power system, frequency perturbation in each area has to be brought back to their steady state values. The ANN controller can be used to provide control input, which succeeds in this deed. ANN controller is indeed an adaptive nonlinear controller with control strategy defined by the learning rule used in changing the weights of the synaptic connections [10]. In this paper, a Multi Layer Perception network is trained between inputs Area Control Error (ACE: the components of ACE are □F and □P_{tie}) and change in Area Control Error (ΔACE) and control output (u) as given in Fig.6. The training is performed by using MATLAB 6.0 Neural Network Toolbox, wherein the learning rate and momentum are adjusted internally to minimize the mean square error with in the prescribed epochs.

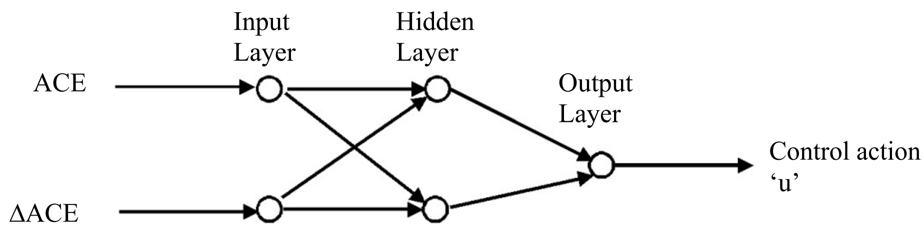

Fig 6. Structure of ANN

The structure of ANN is given as : {1x1 cell} of input, {2x1 cell} of layers, {1x2 cell} containing 1 output, {1x2 cell} target 1, {2x1 cell} containing 2 biases, {2x1 cell} containing 1 input weight and {2x2 cell} containing 1 layer weight. After the network is trained, an ANN control block is created using the command “gensim”. In ANNC, the training data and test data are formed in between ACE and ΔACE and control output ‘u’.

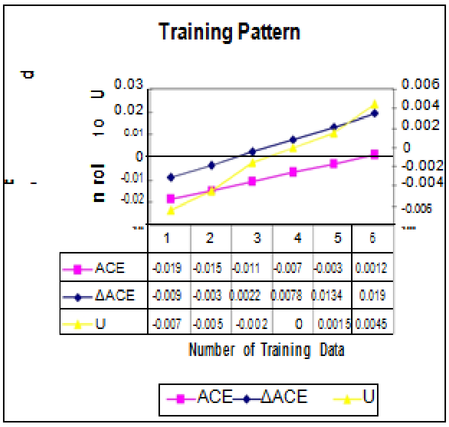

Fig 6.a Training Pattern of ACE, ΔACE and control action U

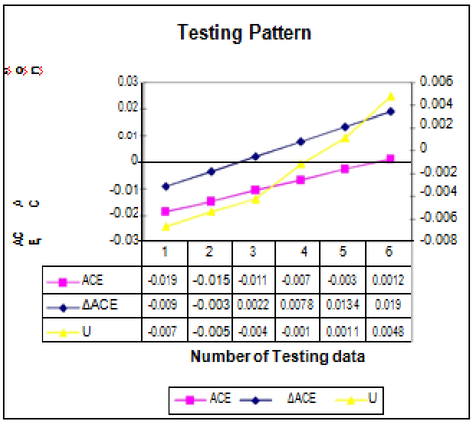

Fig 6.b Testing Pattern of ACE, ΔACE and control action U

5. FLANNC

The combination of Fuzzy system and Artificial Neural Network has the advantages of each of them. The output of FLC and ANNC are added together to get the required control output. The combination of this controller is called FLANNC. The block diagram of FLANNC is shown in Fig .7

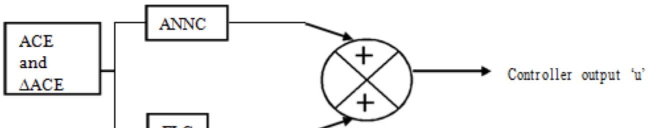

Fig. 7 Block diagram of FLANNC

6. HYBRID NEURO FUZZY CONTROLLER (HNFC)

A neuro-fuzzy system is a fuzzy system that uses a learning algorithm derived from neural network theory to determine its parameters (fuzzy sets and fuzzy rules) by processing data samples. Hybrid neuro-fuzzy results are obtained from fusion of neural network and fuzzy logic. Hybrid neuro-fuzzy system is designed using simulink / MATLAB 6.0.

Steps to design HNF controller [16] as follows:

1. Draw the simulink model with FLC and simulate it with the given rule base.
2. The first step to design the HNF controller is collecting the training data while simulating with FLC.
3. The two inputs, i.e., ACE and d(ACE)/dt and the output signal gives the training data.
4. Use anfisedit to create HNF.fis file.
5. Load training data collected in step.1 and generate the Fuzzy Inference System (FIS) with gauss MF’s.
6. Train the collected data with generated FIS upto particular number of Epochs.

The proposed scheme utilizes sugeno-type fuzzy inference system controller, with the parameters inside the fuzzy inference system decided by the neural-network back propagation method [17]. The ANFIS is designed by taking ACE and rate of change of ACE as inputs. Another HNFC is designed using gauss membership functions instead of gbell membership functions which is used in [16].

7. RESULT AND ANALYSIS

7.1. CONTROLLERS RESPONSE UNDER VARIOUS CONDITIONS

In this section, the performances of integral controller, FLC, ANNC and FLANNC are plotted under sudden increase in load and different ramp rates. The model is simulated up to 1000 sec for all the cases.

7.1.1. SUDDEN INCREASE IN LOAD

The model is tested for sudden increase in load by applying step input of 1%. The plot of ΔF and ΔP_{tie} of FLANNC is compared with FLC, ANNC and integral controller for four areas given in Fig 8. The performances of the controllers are given in Figs 8-9. From the figures, it can be observed that the first undershoot is same for all the controllers and the first overshoot is 0.04 for integral controller, 0.034 for both FLC, 0.022 for ANNC and FLANNC. From Fig 8.a, it is observed that FLC settles at 450 sec with 2% steady state error, ANNC settles at 470 sec with 2% steady state error and FLANNC settles at 420 sec with zero steady state error. Fig 8 shows the tie line error of the area 1.The performance of the FLANNC is better than other controllers in terms of settling time and steady state error.

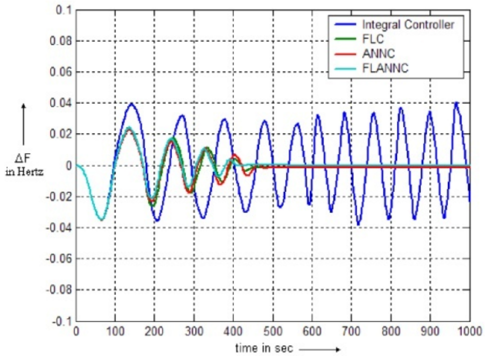

Fig 8.Performance of controllers for ΔF in Area 1 for increase in load

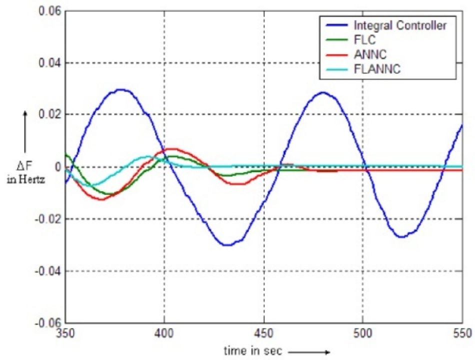

Fig. 8.a. Performance of controllers for ΔF in Area 1 for increase in load focused between 350sec -550 sec

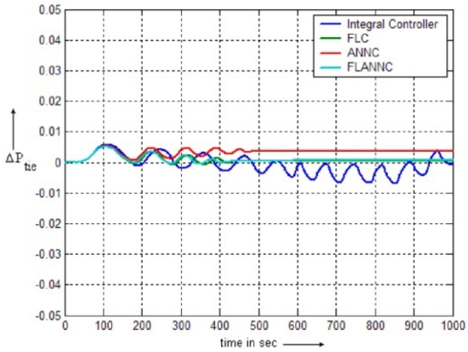

Fig. 9 Performance of controllers for ΔP_{tie} in Area 1 for increase in load

7.1.2 EFFECT OF RAMP RATES

In this model, for getting different ramp rates the values of T_{p1} and T_{p3} are chosen as 50. Figs 10-12 display the effect of low ramp rate on □F Area1and area 2. Fig 12 displays the response of ΔP_{tie} to the effect of low ramp rate in area 1.

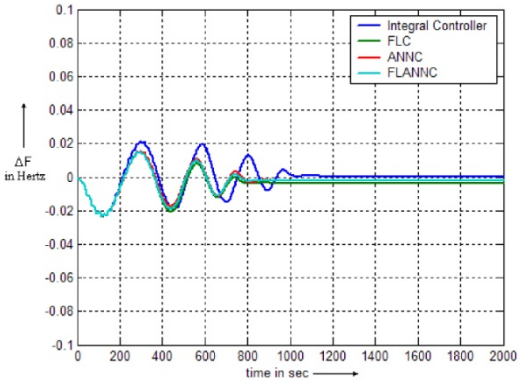

Fig 10 Response to lower ramp rate for Area 1 (T_{p1}=50)

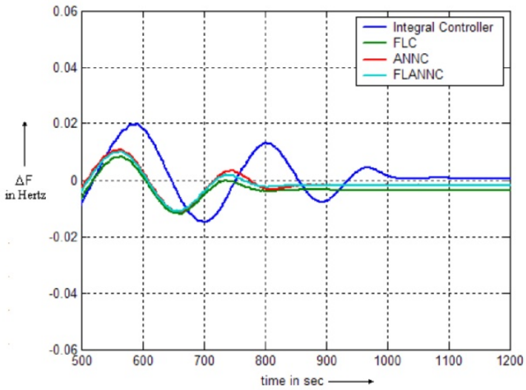

Fig 10.a. Response to lower ramp rate for Area 1 (T_{p1}=50) Focused between 500 sec -1200 sec

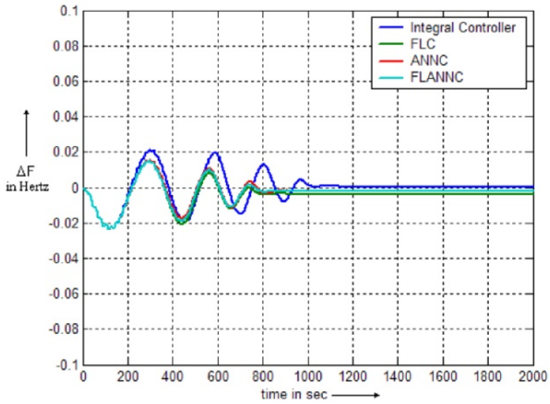

Fig 11 Response to lower ramp rate for Area 2(T_{p2} = 20)

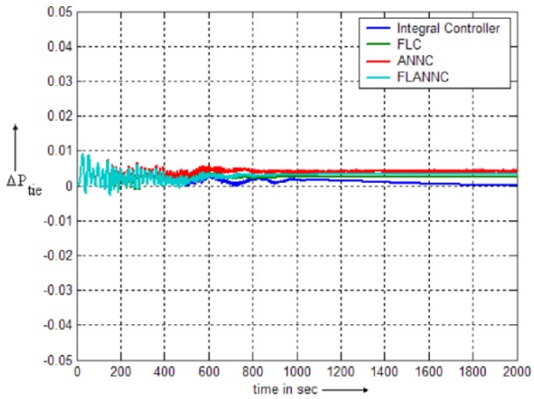

Fig 12 Response of P_{tie} for lower ramp rate in Area1(T_{p2} = 50)

The performances of the controllers are given in Figs 10-12. From the figures, it can be observed that the first undershoot is same for all the controllers and the first overshoot is 0.04 Hz for integral controller, 0.017 Hz for FLC, 0.018Hz for ANNC and 0.012 for FLANNC. From Fig 10.a, it is observed that integral controller settles at 1200 sec with 0.8% of steady state error, FLC settles at 800 sec with 2% steady state error, ANNC settles at 850 sec with 1% steady state error and FLANNC settles at 790 sec with 1% steady state error. The performance of the FLANNC is better than other controllers in terms of settling time and steady state error. Fig.10 and Fig.11 also indicates that if the ramp rate is low, the response of generator will be slow and settling time is higher. The model is simulated up to 2000 sec.

7.2. RESPONSE OF FLANNC AND HNFC

In this section, the performances of FLANNC is compared with HNFC with gbell membership functions and HNFC with gauss membership functions, under sudden increase in load, sudden decrease in load and different ramp rate. The model is simulated up to 1000 sec for all the cases. HNFC approach to AGC for two area system given in [16],[17] used gbell membership functions. In this work, HNFC with gauss membership functions is used to achieve AGC of four area system.

7.2.1. SUDDEN INCREASE IN LOAD

The model is tested for sudden increase in load by applying step input of 1%. The plot of ΔF and ΔP_{tie} of FLANNC, HNFC with gauss membership functions and HNFC with gbell membership functions are compared for four areas given in Fig 13 and Fig 14 for increase in load. From the figures, it can be observed that the first undershoot is same for all the controllers and the first overshoot is also same for all the controllers. The second undershoot 0.02 Hz for FLANNC, 0.028 Hz for HNFC with gauss membership functions 0.018Hz for HNFC with gbell membership functions. From Fig 13.a, it is observed that FLANNC settles at 440 sec with zero steady state error, HNFC with gauss membership function settles at 460 sec with 1% steady state error and HNFC with gbell membership functions settles at 475 sec with 3% steady state error. The performance of the FLANNC is better than HNFC with gauss membership functions controller and gbell membership functions controller in terms of settling time and steady state error.

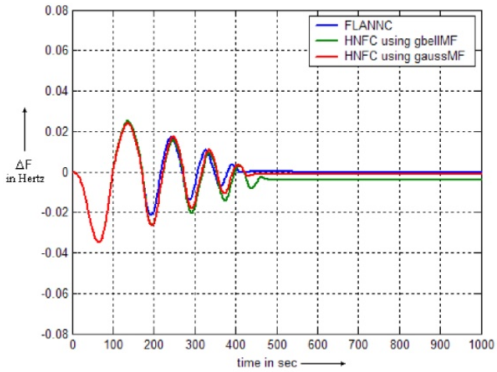

Fig. 13 Performance of controllers for ΔF in Area 1 for increase in load

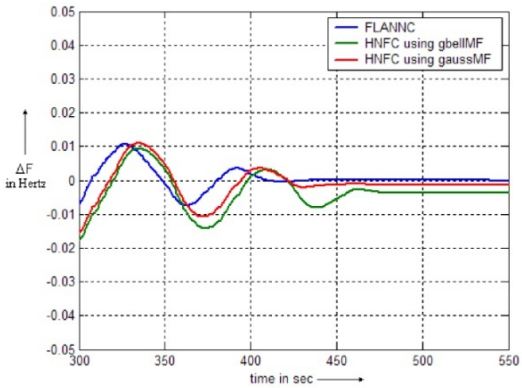

Fig. 13.a Performance of controllers for ΔF in Area 1 for increase in load Focused between 300 sec-550 sec

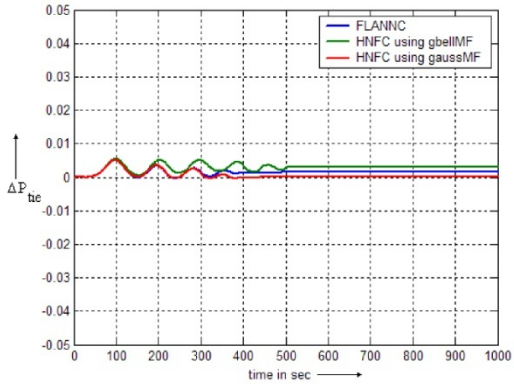

Fig. 14 Performance of controllers for ΔP_{tie} in Area 1 for increase in load

7.2.2. EFFECT OF RAMP RATES

In this model, for getting different ramp rates the values of T_{p1} and T_{p3} are chosen as 50. Figs 15-16 display the effect of low ramp rate in area 1and 2. Fig 15 and Fig 16 also indicates that if the ramp rate is low, the response of generator will be slow and settling time is higher. The model is simulated up to 2000 sec. Fig 15.a indicates the response to ramp rate for Area 1 (T_{p1}=50) focused between 500sec-1000sec.

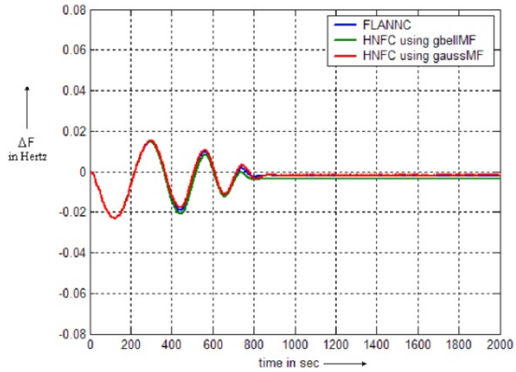

Fig 15 Response to ramp rate for Area 1 (T_{p1}=50)

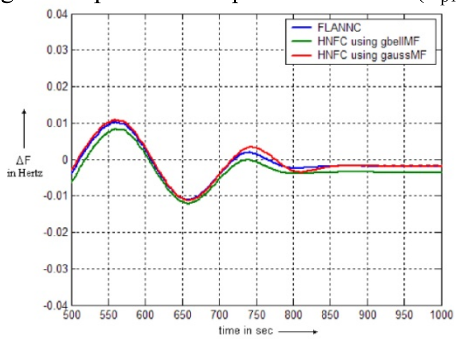

Fig 15.a Response to ramp rate for Area 1 (T_{p1}=50) Focused between 500sec-1000sec

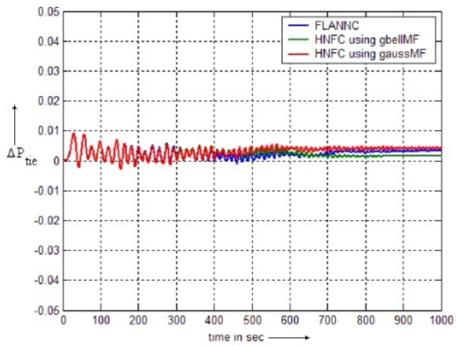

Fig 16 Response of ΔP_{tie} for lower ramp rate in Area1(T_{p2} = 50)

8. CONCLUSION

This paper presents new approaches for Automatic Generation Control using the FLANNC. The simulation model is developed for four-area interconnected power system using simulink/MATLAB 6.0. The FLANNC performance is compared with FLC, ANNC and conventional integral controller. From the result, it is concluded that FLANNC settles faster than FLC, ANNC and integral controller. The magnitude of □F with FLANNC is also small compared to other controllers. Recently, HNFC application to AGC is presented in [16],[17] in which gbell membership functions are used. In this work, the gbell membership functions are replaced by gauss membership functions. The performance of FLANNC, HNFC with gauss membership functions and HNFC with gbell membership are given in Figs. From the result, it can be concluded that HNFC with gauss membership functions are better than HNFC with gbell membership functions. FLANNC is better than FLC, ANNC, and HNFC with gauss membership functions and HNFC with gbell membership functions.

Appendix A

An extended power system can be divided into a number of load frequency control areas interconnected by means of tie lines as explained in [12]. Modern control theory is applied in this section to design an optimal AGC for a four area system.

Thermal Systems (Area 1 to 3)

$\Delta P_{refi}\,(k) = \Delta P_{refi}\,(k\text{-}1) - K_{Ii}T\,(Bi\Delta f_i\,(k\text{-}1) + \Delta P_i\,(k\text{-}1))$ (1)

$\Delta P_1\,(k\text{-}1) = \Delta P_{tie1}\,(k\text{-}1) + a_{31}\Delta P_{tie3}\,(k\text{-}1) + a_{41}\Delta P_{tie4}\,(k\text{-}1)$

$\Delta P_2\,(k\text{-}1) = \Delta P_{tie2}\,(k\text{-}1) + a_{12}\Delta P_{tie1}\,(k\text{-}1)$

$\Delta P_3\,(k\text{-}1) = \Delta P_{tie3}\,(k\text{-}1) + a_{23}\Delta P_{tie2}\,(k\text{-}1)$

$\Delta P_{tie1}(k) = \Delta P_{tie1}(k\text{-}1) + 2\pi T(\ T12 + T13 + T14\ )\Delta f_1(k\text{-}1) - 2\pi T(\ T_{12}\Delta f_2(k\text{-}1) + T_{13}\Delta f_3(k\text{-}1) + T_{14}\Delta f_4(k\text{-}1)\ )$

$\Delta P_{tie2}(k) = \Delta P_{tie2}(k\text{-}1) + 2\pi T(\ T_{21} + T_{23}\ )\Delta f_2(k\text{-}1) - 2\pi T(\ T_{21}\Delta f_1(k\text{-}1) + T_{23}\Delta f_3(k\text{-}1)\ )$

$\Delta P_{tie3}(k) = \Delta P_{tie3}(k\text{-}1) + 2\pi T(\ T_{31} + T_{32}\ )\Delta f_3(k\text{-}1) - 2\pi T(\ T_{31}\Delta f_1(k\text{-}1) + T_{32}\Delta f_2(k\text{-}1)\ )$

$\Delta x_{Ei}\,(k) = (1\text{-}T/T_{Gi})\,\Delta x_{Ei}\,(k\text{-}1) + T/T_{Gi}\,(\ \Delta P_{refi}(k\text{-}1) - 1/R_i\,\Delta f_i(k\text{-}1)\ )$ (2)

$\Delta P_{Ri}\,(k) = (1 - T/T_{Ti})\,\Delta P_{Ri}\,(k\text{-}1) + T/T_{Ti}\,\Delta x_{Ei}\,(k\text{-}1)$ (3)

$\Delta P_{Gi}\,(k) = (1 - T/T_{Ri})\,\Delta P_{Gi}\,(k\text{-}1) + K_{Ri}\Delta P_{Ri}\,(k) + (T/T_{ri} - K_{Ri})\,\Delta P_{Ri}\,(k\text{-}1)$ (4)

$\Delta f_i(k) = (\ 1 - T/T_{Pi}\ )\Delta f_i(k\text{-}1) + K_{Pi}T/T_{Pi} + (\ \Delta P_{Gi}(k\text{-}1) - \Delta P_{Di}(k\text{-}1)\ - \Delta P_{tiei}(k\text{-}1)\ )$ (5)

Where, Subscript i represents each thermal area in power system (i = 1, 2, 3).

Hydro System (Area 4)

$\Delta P_{ref4}\,(k) = \Delta P_{ref4}\,(k\text{-}1) - K_{I4}T\,(B4\Delta f_4\,(k\text{-}1) + \Delta P_4\,(k\text{-}1))$ (6)

$\Delta P_{tie4}\,(k) = \Delta P_{tie4}\,(k\text{-}1) + 2\pi T_{41}T\,(\Delta f_4\,(k\text{-}1) - \Delta f_1\,(k\text{-}1))$

$\Delta x_{E4}\,(k) = (1 - T/T_1)\,\Delta x_{E4}\,(k\text{-}1) + T/T_1\,(\Delta P_{ref4}\,(k\text{-}1) - 1/R_4\,\Delta f_4\,(k\text{-}1))$ (7)

$\Delta P_{R4}\,(k) = (1 - T/T_3)\,\Delta P_{R4}\,(k\text{-}1) + (T\text{-}T_2)/T_3\,\Delta x_{E4}\,(k\text{-}1) + T_2/T_3\,\Delta x_{E4}\,(k)$ (8)

$\Delta P_{G4}\,(k) = (1 - 2T/T_w)\,\Delta P_{G4}\,(k\text{-}1) + 2(1 + T/T_w)\,\Delta P_{R4}\,(k\text{-}1) - 2\Delta P_{R4}\,(k)$ (9)

$\Delta f_4\,(k) = (1 - T/T_{P4})\,\Delta f4\,(k\text{-}1) + K_{P4}T/T_{P4} + (\ \Delta P_{G4}(k\text{-}1) - \Delta P_{D4}(k\text{-}1) - \Delta P_{tie4}(k\text{-}1)\ )$ (10)

Here $\Delta P_4 = \Delta P_{tie4}$

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