

# A Hybrid Fuzzy AGC in a Competitive Electricity Environment

H. Shayeghi, , A. Jalili

**Abstract**--This paper presents a new Hybrid Fuzzy (HF) PID type controller based on Genetic Algorithms (GA's) for solution of the Automatic generation Control (AGC) problem in a deregulated electricity environment. In order for a fuzzy rule based control system to perform well, the fuzzy sets must be carefully designed. A major problem plaguing the effective use of this method is the difficulty of accurately constructing the membership functions, because it is a computationally expensive combinatorial optimization problem. On the other hand, GAs is a technique that emulates biological evolutionary theories to solve complex optimization problems by using directed random searches to derive a set of optimal solutions. For this reason, the membership functions are tuned automatically using a modified GA's based on the hill climbing method. The motivation for using the modified GA's is to reduce fuzzy system effort and take large parametric uncertainties into account. The global optimum value is guaranteed using the proposed method and the speed of the algorithm's convergence is extremely improved, too. This newly developed control strategy combines the advantage of GA's and fuzzy system control techniques and leads to a flexible controller with simple structure that is easy to implement. The proposed GA based HF (GAHF) controller is tested on a three-area deregulated power system under different operating conditions and contract variations. The results of the proposed GAHF controller are compared with those of Multi Stage Fuzzy (MSF) controller, robust mixed  $H_2/H_\infty$  and classical PID controllers through some performance indices to illustrate its robust performance for a wide range of system parameters and load changes.

**Keywords**--AGC, Hybrid Fuzzy Controller, Deregulated Power System, Power System Control, GAs.

## I. INTRODUCTION

GLOBAL analysis of the power system markets shows that the frequency control is one of the most profitable ancillary services at these systems. This service is related to the short-term balance of energy and frequency of the power systems. The most common methods used to accomplish frequency control are generator governor response (primary frequency regulation) and Automatic Generation Control (AGC). The goal of AGC is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighboring control areas. From the mechanisms used to manage the provision this service in ancillary markets, the bilateral contracts or competitive offers stand out [1].

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During the past decade, several proposed AGC scenarios have attempted to adapt traditional AGC schemes to the change of environment in the power systems under deregulation [2-4]. In a deregulated power system, each control area contains different kinds of uncertainties and various disturbances due to increased complexity, system modeling errors and changing power system structure. As a result, a fixed controller based on classical theory is not certainly suitable for the AGC problem. It is desirable that a flexible controller be developed. Efforts have been made to design automatic generation controllers with better performance to cope with parameter changes, using various adaptive neural networks and robust methods [5-10]. The proposed methods show good dynamical responses, but robustness in the presence of model dynamical uncertainties and system nonlinearities were not considered. Also, some of them suggest complex state feedback or high order dynamical controllers, which are not practical for industry practices. Recently, some authors proposed fuzzy PID methods to improve the performance of AGC problem [11-13]. It should be pointed out that it requires a three-dimensional rule base. This problem makes the design process is more difficult. In order to overcome this drawback and focus on the separation PD part from the integral part, a GA based Hybrid (GAHF) PID controller with a fuzzy switch is presented in this paper. This is a form of behavior based control where the PD controller becomes active when certain conditions are met. The resulting structure is a controller using two-dimensional inference engines (rule base) to reasonably perform the task of a three-dimensional controller. The proposed method requires fewer resources to operate and its role in the system response is more apparent, i.e. it is easier to understand the effect of a two-dimensional controller than a three-dimensional one [14 -16]. This newly developed control strategy combines fuzzy PD controller and integral controller with a fuzzy switch. Exact tuning of membership functions is one of the importance and essential step toward the design of any successful fuzzy controllers. On the other hand, extraction of an appropriate set of membership functions from the expert may be tedious, time consuming and process specific. Thus, in order to reduce fuzzy system effort a modified GA is being used for optimum tuning of membership functions in the proposed HF controller. Genetic algorithms are very simple, robust, global search techniques, have excellent properties for optimization and do not require any human expert or explicit training data. However, the global optimal value is not guaranteed using the classical method and speed of algorithms convergence is extremely reduced, too. To overcome this drawback, a modified GA based on the hill climbing method is proposed to improve optimization synthesis such that the global optimal value is guaranteed. Moreover, the proposed fitness function

is very simple which tries to ensure that controller operates over the entire input space with a good settling time [17-19].

The proposed GAHF controller is tested on a three-area restructured power system under different operating conditions in comparison with MSF [14], robust mixed  $H_2/H_\infty$  [8] and classical PID controllers through the Figure of Demerit (FD) and the Integral of Time multiplied Absolute value of the Error (ITAE) performance indices. Results evaluation show that the proposed method achieves good robust performance for wide range of system parameters and load changes in the presence of system nonlinearities and is superior to the other controllers. Moreover, the proposed control strategy has simple structure and does not require an accurate model of the plant and fairly easy to implement which can be useful for the real world complex power system.

## II. GENERALIZED AGC MODEL

In the deregulated power systems, the vertically integrated utility no longer exists. However, the common AGC objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area, still remain. The deregulated power system consists of GENCOs, TRANSCOs and DISCOs with an open access policy. In the new structure, GENCOs may or may not participate in the AGC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. Thus various combinations of possible contracted scenarios between DISCOs and GENCOs are possible. All the transactions have to be cleared by the Independent System Operator (ISO) or other responsible organizations. In this new environment, it is desirable that a new model for AGC scheme be developed to account for the effects of possible load following contracts on system dynamics.

Based on the idea presented in [8], the concept of an 'Augmented Generation Participation Matrix' (AGPM) to express the possible contracts following is presented here. The AGPM shows the participation factor of a GENCO in the load following contract with a DISCO. The rows and columns of AGPM matrix equal the total number of GENCOs and DISCOs in the overall power system, respectively. Consider the number of GENCOs and DISCOs in area  $i$  be  $n_i$  and  $m_i$  in a large scale power system with  $N$  control areas. The structure of AGPM is given by:

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \quad (1)$$

Where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

For  $i, j = 1, \dots, N$  and

$$s_i = \sum_{k=1}^{i-1} n_k, \quad z_j = \sum_{k=1}^{j-1} m_k \quad \& \quad s_1 = z_1 = 0$$

In the above,  $gpf_{ij}$  refers to 'generation participation factor' and shows the participation factor of GENCO  $i$  in total load following requirement of DISCO  $j$  based on the contract. Sum of all entries in

each column of AGPM is unity. The diagonal sub-matrices of AGPM correspond to local demands and off-diagonal sub-matrices correspond to demands of DISCOs in one area on GENCOs in another area.

Block diagram of the generalized AGC scheme in a restructured system is shown in Fig. 1. The nomenclature used is given in Appendix A. Dashed lines show interfaces between areas and the demand signals based on the possible contracts. These new information signals are absent in the traditional AGC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the AGC task and  $\sum_{j=1}^{n_i} \alpha_{ji} = 1$ . We can write [20]:

$$d_i = \Delta P_{Loc,j} + \Delta P_{di}, \quad \Delta P_{Loc,j} = \sum_{j=1}^{m_i} \Delta P_{Lj-i}, \quad \Delta P_{di} = \sum_{j=1}^{m_i} \Delta P_{ULj-i} \quad (2)$$

$$\eta_i = \sum_{j=1 \& j \neq i}^N T_{ij} \Delta f_j \quad (3)$$

$$\zeta_i = \Delta P_{tie,i,sch} \sum_{k=1 \& k \neq i}^N \Delta P_{tie,ik,sch} \quad (4)$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_i} \sum_{i=1}^{m_k} apf_{(s_i+j)(z_k+i)} \Delta P_{L(z_k+i)-k} - \sum_{i=1}^{n_k} \sum_{j=1}^{m_i} apf_{(s_k+i)(z_i+j)} \Delta P_{L(z_i+j)-l} \quad (5)$$

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i \quad (6)$$

$$\rho_i = [\rho_{1i} \cdots \rho_{ki} \cdots \rho_{ni}], \quad \rho_{ki} = \sum_{j=1}^N \left[ \sum_{l=1}^{m_j} gpf_{(s_k+i)(z_j+l)} \Delta P_{Ll-j} \right] \quad (7)$$

$$\Delta P_{m,k-i} = \rho_{ki} + apf_{ki} \Delta P_{di}, \quad k = 1, 2, \dots, n_i \quad (8)$$

$P_{m,ki}$  is the desired total power generation of a GENCO  $k$  in area  $i$  and must track the demand of the DISCOs in contract with it in the steady state.

A three-area power system, shown in Fig. 2 is considered as a test system to illustrate the effectiveness of the proposed control strategy. It is assumed that each control area includes two GENCOs and one DISCO. The power system parameters are given in Tables 1 and 2.

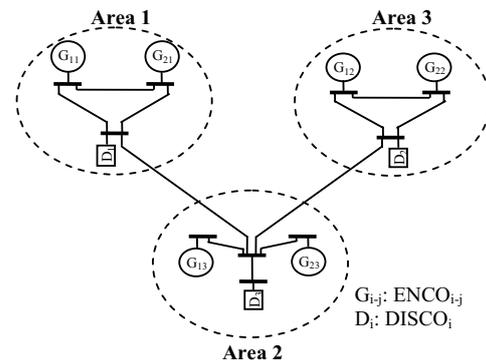


Fig. 2 A three-area restructured power system

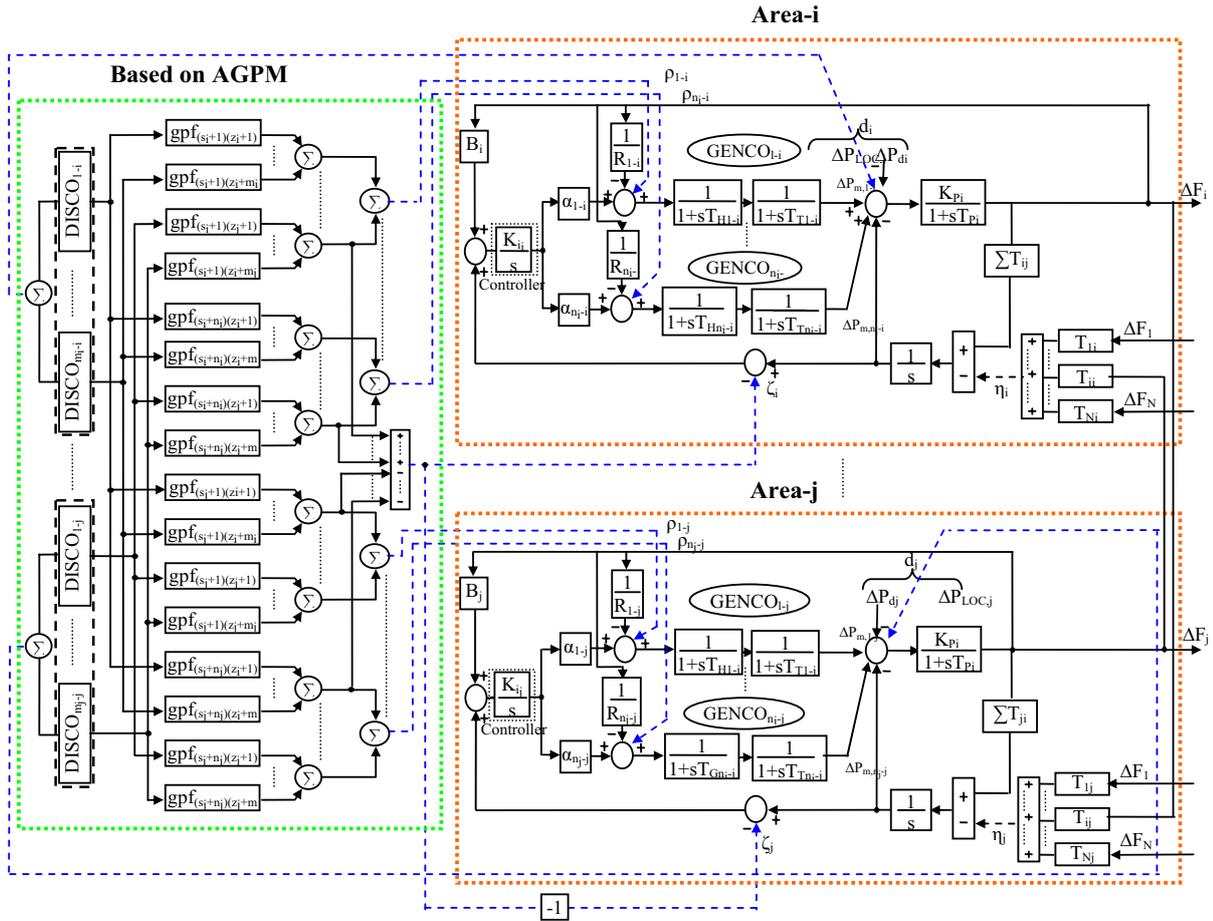


Fig. 1 The generalized AGC scheme in the restructured system

TABLE I  
CONTROL AREA PARAMETERS

| Parameter        | Area -1                            | Area -2 | Area -3 |
|------------------|------------------------------------|---------|---------|
| $K_p$ (Hz/pu)    | 120                                | 72      | 91      |
| $T_p$ (sec)      | 20                                 | 14.3    | 10.6    |
| $B$ (pu/Hz)      | 0.8675                             | 0.785   | 0.87    |
| $T_{ij}$ (pu/Hz) | $T_{12} = T_{13} = T_{23} = 0.545$ |         |         |

TABLE II  
GENCOs PARAMETER

| MVA <sub>base</sub><br>(1000MW)<br>Parameter | GENCOs ( $k$ in area $i$ ) |      |      |      |      |      |
|--|----------------------------|------|------|------|------|------|
|  | 1-1                        | 2-1  | 1-2  | 2-2  | 1-3  | 2-3  |
| Rate (MW)                                    | 1000                       | 800  | 1100 | 900  | 1000 | 1020 |
| $T_T$ (sec)                                  | 0.36                       | 0.42 | 0.44 | 0.4  | 0.36 | 0.4  |
| $T_H$ (sec)                                  | 0.06                       | 0.07 | 0.06 | 0.08 | 0.07 | 0.08 |
| $R$ (Hz/pu)                                  | 2.4                        | 3.3  | 2.5  | 2.4  | 2.4  | 3.3  |
| $a$  | 0.5                        | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  |

### III. GA-BASED HYBRID FUZZY AGC

GA's are search algorithms based on the mechanism of natural selection and natural genetics that operate without knowledge of the task domain and utilize only the fitness of evaluated individuals. In general, reproduction, cross-over and mutation are the three basic operators of GA's. They can be considered as a general-purpose optimization method and have been successfully applied to search and optimization [20-21].

During evolution, GA's require only information the quality of the fitness value produced by each parameter set. This differs from many optimization methods require- ing derivative information or complete knowledge of the problem structure and parameter. Hence, the GA is more suitable to deal with the problem of lacking experience or knowledge than other searching methods in particular, when the phenomena being analyzed are describable in terms of rules for action and learning processes.

Fuzzy logic control is one of the most successful areas in the application of fuzzy theory and is excellent alternatives to the conventional control methodology when the processes are too complex for analysis by conventional mathematical techniques [22-23]. Because of the complexity and multi-variable conditions of the power system, conventional control methods may not give satisfactory solutions. On the other hand, their robustness and reliabil-

ility make fuzzy controllers useful for solving a wide range of control problems in power systems. In this paper, a modified GA-based HF controller is proposed for the solution of AGC problem. The motivation of using the proposed GAHF controller is to take large parametric uncertainties, system nonlinearities and minimize of area load disturbances into account. As HF controller is elaborately explained in author's pervious paper [14]. Here, we points out only the salient features of it briefly. This control strategy combines fuzzy PD controller and integral controller with a fuzzy switch. The fuzzy PD stage is employed to penalize fast change and large overshoots in the control input due to corresponding practical constraints. The integral stage is also used in order to get disturbance rejection and zero steady state error.

It should be noted that the exact tuning of membership functions in the HF control strategy is very important to achieve the desired level of system robust performance. Because it is a computationally expensive combinatorial optimization problem and also extraction of an appropriate set of membership function from the expert may be

tedious, time consuming and process specific. In order to overcome this drawback and reduce fuzzy system effort and cost, a modified GA based on the hill climbing method is being used to optimal tune of membership functions in the proposed HF controller. Fig. 3 shows the structure of the proposed GAHF controller for the solution of AGC problem. In the proposed structure, input values are converted to truth-value vectors and applied to their respective rule base. The output truth-value vectors are not defuzzified to crisp value as with a single stage fuzzy logic controller but are passed onto the next stage as a truth value vector input. The darkened lines in Fig. 3 indicate truth value vectors.

In this effort, all membership functions are defined as triangular partitions with seven segments from -1 to 1. Zero (ZO) is the center membership function which is centered at zero. The partitions are also symmetric about the ZO membership function as shown in Fig. 4. The remaining parts of the partition are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

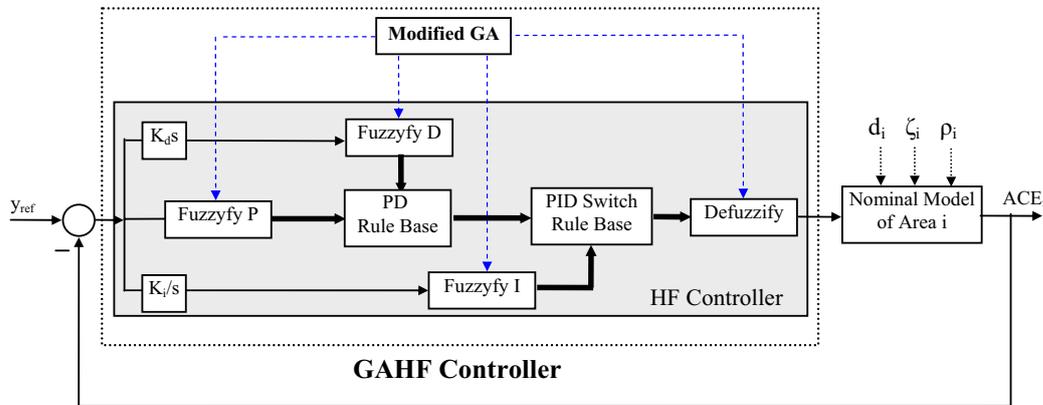


Fig. 3 Structure of the proposed GAMSF control strategy

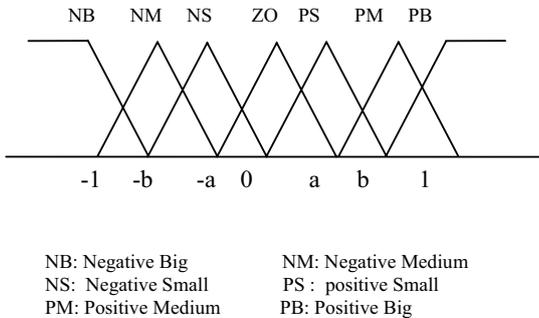


Fig. 4. Symmetric fuzzy partition

There are two rule bases used in the HF controller. The first is called the PD rule bases as it operates on truth vectors form the error ( $e$ ) and change in error ( $\Delta e$ ) inputs. A typical PD rule base for the fuzzy logic controller is given in Table 3. This rule base responds to a negative input from either error ( $e$ ) or change in error ( $\Delta e$ ) with a negative value thus driving the system to ward the com-manded value. Table 4 shows a PID switch rule base. This rule base is designed to pass through the PD input if the PD input is not in zero fuzzy set. If the PD input is in the zero fuzzy set, then

the PID switch rule base passes the integral error values ( $\int e$ ). This rule base operates as the behavior switch, giving control to PD feedback when the system is in motion and reverting to integral feedback to remove steady state error when the system is no longer moving. The operation used to determine the consequence value at the intersection of two input fuzzy value is:

$$c_{ij} = \Pi(a_i * b_j), \quad i, j = 1, 2, \dots, N_m \quad (9)$$

Where,  $a_i$  is the membership value of  $i^{th}$  fuzzy set for a given  $e$  input, and  $b_j$  is likewise for a  $\Delta e$  input. The operator used to determine the membership value of the  $k^{th}$  consequence set is:

$$C_k = \sum c_{ij}, \quad i, j = 1, 2, \dots, N_m \quad (10)$$

TABLE III  
PD RULE BASE

|   |    | $\Delta e$ |    |    |    |    |    |    |
|---|----|------------|----|----|----|----|----|----|
|   |    | NB         | NM | NS | ZO | PS | PM | PB |
| e | NB | NB         | NB | NB | NB | NM | NS | ZO |
|   | NM | NB         | NB | NB | NM | NS | ZO | PS |
|   | NS | NB         | NB | NM | NS | ZO | PS | PM |
|   | ZO | NB         | NM | NS | ZO | PS | PM | PB |
|   | PS | NM         | NS | ZO | PS | PM | PB | PB |
|   | PM | NS         | ZO | PS | PM | PB | PB | PB |
|   | PB | ZO         | PS | PM | PB | PB | PB | PB |

TABLE IV  
PID SWITCH RULE BASE

|   |    | PD Values |    |    |    |    |    |    |
|---|----|-----------|----|----|----|----|----|----|
|   |    | NB        | NM | NS | ZO | PS | PM | PB |
| e | NB | NM        | NS | NB | PS | PM | PB | NM |
|   | NM | NM        | NS | NM | PS | PM | PB | NM |
|   | NS | NM        | NS | NS | PS | PM | PB | NM |
|   | ZO | NM        | NS | ZO | PS | PM | PB | NM |
|   | PS | NM        | NS | PS | PS | PM | PB | NM |
|   | PM | NM        | NS | PM | PS | PM | PB | NM |
|   | PB | NM        | NS | PB | PS | PM | PB | NM |

The defuzzification uses the weighted average method where  $C_k$  is the peak point of the  $k^{th}$  output fuzzy membership function.

$$d = \frac{\sum C_k * c_k}{\sum C_k} \quad k=1, \dots, N. \text{ (sets in output point)} \quad (11)$$

A. Membership functions Tuning strategy by GA

In the proposed GAHF controller, we must tune the linguistic hedge combinations which are difficult to be contributed according to human experience and knowledge. To acquire an optimal combination, we adopt the modified GA's as the search method to improve the speed of convergence and find the global optimum value of fitness function. In this work, the GA module works offline. Classical GA searches the optimal or near optimal linguistic hedge combination according to the controlled plants. According to Fig. 4 for exact tuning of used membership functions in the proposed method we must find the optimal value for  $a$  and  $b$  parameters, where  $0 < a < b < 1$ . Fig. 5 shows the flowchart of the modified GA approach for optimization. In this algorithm, the classical GA is used to find near optimal global value and then the proposed hill climbing method is used to find global optimum value.

Before proceeding with the GA approach, there are two preliminaries to be finished.

1) *Definition of suitable coding*: one of the most attractive problems in GA's is coding the solution space. According to Fig. 4, there are two parameters to tune of membership functions ( $a$  and  $b$  parameters). Thus, the order of parameters is coded into the chromosome (individual). A chromosome represents a candidate solution of the problem. In this method, a solution candidate is expressed by binary coding. Consequently,  $a$  and  $b$  parameters for the ACE,  $\Delta$ ACE,  $\int$ ACE and output membership functions are expressed in term of string consisting of 0 and 1 as shown in Fig. 6. From this figure it can be seen that length of the chromosome is 40 gene (bit). The solution candidate expressed by a string is called an individual and a set of individual is called a population.

2) *Choice of fitness functions*: the second preliminary to be finished is choosing the problem-dependent fitness function. Different fitness functions promote different GA behaviors, which generate fitness value providing a performance measure of the problem considered [24]. In the present study, evaluation of  $f(ITAE)$  is an alternative of the conventional maximization of fitness function, which defined as follows:

$$f(ITAE) = \frac{1}{1 + MSE(ITAE)} \quad (12)$$

Where,

$$MSE(ITAE) = \frac{\sqrt{\sum_{i=1}^3 ITAE_i}}{3}, \quad ITAE_i = \int |ACE_i| dt$$

After deciding these two preliminaries, we should choose the genetic operators. This algorithm consists of elitism selection and three kinds of genetic operators which are selection, crossover, and mutation to create new generation.

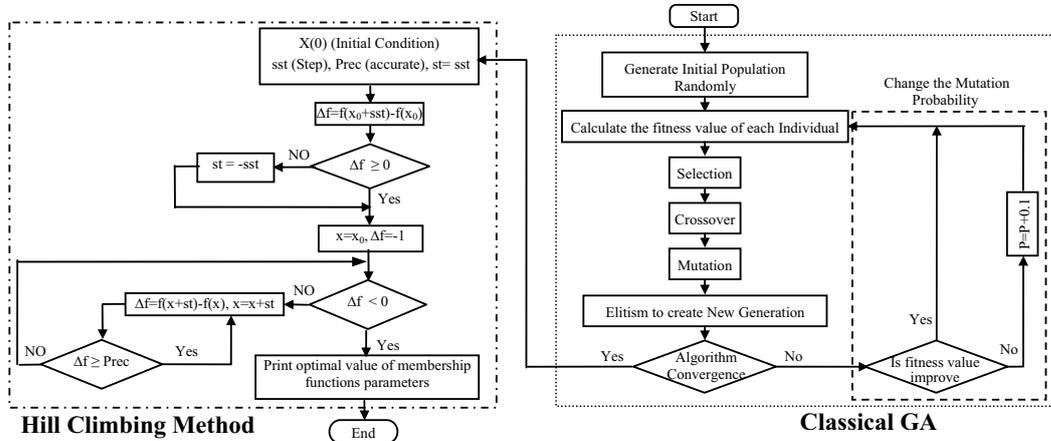


Fig. 5. Flowchart of the proposed modified GA based on the hill climbing method.

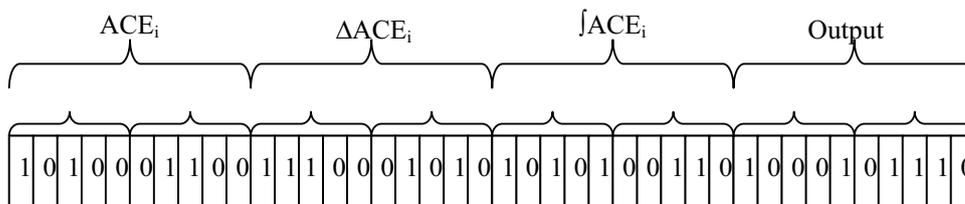


Fig. 6 String encoding membership function

3) *Selection*: selection chooses the individuals in the population as parent individuals to create offspring for the next generation, whose purpose is to emphasize the fitter individuals in the population in hopes that their offspring will in turn have even higher fitness. In this work, the roulette wheel selection is adopted.

4) *Crossover*: Instead of the single-point cross-over, we adopt the two-point crossover. For example, the parent individuals  $h_1$  and  $h_2$  given to be crossed over at the points  $k$  and  $l$  with the crossover probability  $P_c$ . Results in new off-spring  $h'_1$  and  $h'_2$  are expressed as:

$$h'_i = \begin{cases} h_{2i} & k < i < l \\ h_{1i} & \text{otherwise} \end{cases} \quad (13)$$

$$h'_2 = \begin{cases} h_{1i} & k < i < l \\ h_{2i} & \text{otherwise} \end{cases}$$

- 1) *Mutation*: A position of each gene with probability  $P_m$  which is a possible candidate for the mutation is selected randomly and then value of gene, 0 or 1, changed to, 1 or 0, respectively.
- 2) *Elitism*: Elitism guarantees that the best string individual survives until the last generation. Among parents and their children that are generated by crossover and mutation individuals that they have the best fitness function only survive to the next generation. Size of individuals in the next generation is the same as the initial population size.

In order to acquire better performance, several parameters for GA's should be set appropriately. In this work, these parameters are listed in Table 5.

TABLE V  
GA SET PARAMETERS

|                      |      |
|----------------------|------|
| Number of generation | 200  |
| Population size      | 30   |
| Crossover rate       | 0.97 |
| Mutation rate        | 0.08 |

The genetic algorithms are powerful search techniques to optimization, but some well-known disadvantage in GA are poor convergence of the classical GA near the global optimum and convergence to the suboptimum. In order to overcome these drawbacks, the following procedures are being used in the proposed modified GA:

- 1- In each iteration, probability of the mutation ( $P_m$ ) is changed according to Fig. 5 if the fitness function value does not improve in comparison with the previous generation. This method guarantees algorithm convergence to the near optimum solution.
- 2- In order to overcome to poor convergence of classical GA to global optimum value and improve the convergence speed, result of the classical GA is being used for the hill climbing method as initial conditions (Fig. 5).

Here, the modified GA evolution procedure is applied to exact tune of membership functions of the proposed MSF controller for the solution of LFC problem. After 34 generation, we can obtain optimum hedge linguistic terms of the membership functions. Fig. 7 shows the convergence of classical GA. The Results of membership function set values are listed in Table 6. Fitness value

by classical GA is 0.10237 that is improved to 0.11241 by the proposed hill climbing method.

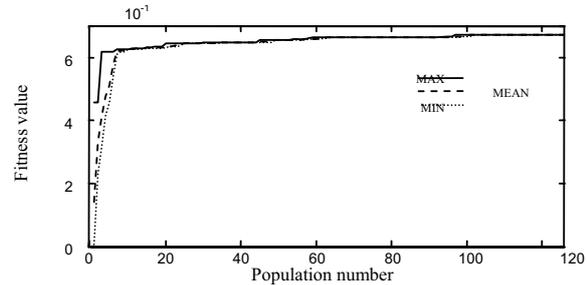


Fig. 7 GA Convergence

TABLE VI  
OPTIMAL VALUES OF PARAMETERS a AND b

| Membership function | Classical GA |        | Modified GA |        |
|---------------------|--------------|--------|-------------|--------|
|                     | a            | b      | a           | b      |
| ACE <sub>i</sub>    | 0.2250       | 0.5806 | 0.2258      | 0.5806 |
| ΔACE <sub>i</sub>   | 0.323        | 0.7419 | 0.323       | 0.7419 |
| ∫ACE                | 0.4829       | 0.9811 | 0.4839      | 0.9811 |
| output              | 0.4655       | 0.9192 | 0.4645      | 0.9291 |

#### IV. SIMULATION RESULT

In the simulation study, the linear model of turbine  $\Delta PV_{ki}/\Delta PT_{ki}$  in Fig. 1 is replaced by a nonlinear model of Fig. 8 (with  $\pm 0.03$  limit). This is to take GRC into account, i.e. the practical limit on the rate of the change in the generating power of each GENCO. The results in Ref. [20,25] indicated that GRC would influence the dynamic responses of the system significantly and lead to larger overshoot and longer settling time. The proposed GAHF controller is applied for each control area of the restructured power system as shown in Fig. 2. To illustrate robustness of the proposed control strategy against parametric uncertainties and contract variations, simulations are carried out for four cases of the possible contracts under various operating conditions and large load demands. Performance of the proposed GAHF controllers is compared with the MSF, robust mixed  $H_2/H_\infty$  and PID controllers.

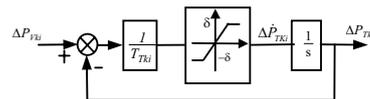


Fig. 8 A nonlinear turbine model with GRC

##### A. Case 1

In this scenario, DISCOs have the freedom to have a contract with any GENCO in their or another areas. Consider that all the DISCOs contract with the available GENCOs for power as per following AGPM. All GENCOs participate in the AGC task.

$$AGPM^T = \begin{bmatrix} 0.25 & 0.5 & 0 & 0.25 & 0 & 0 \\ 0.25 & 0 & 0.25 & 0.25 & 0.25 & 0 \\ 0 & 0 & 0.75 & 0 & 0 & 0.25 \end{bmatrix}$$

It is assume that a large step load 0.1 pu MW is demanded by each DISCOs in all areas. Power system responses with 25% decrease in system parameters are shown in Figs. 9-10. Using the proposed method, the frequency deviation of the all areas are quickly driven back to zero and has small settling time. Also the tie-line power flow properly

converges to the specified value, of Eq. (5), in the steady state case (Fig. 9), i.e.;  $\Delta P_{tie21, sch}=0$  and  $\Delta P_{tie23, sch}=-0.05 pu MW$ . As shown in Fig. 11, the actual generated powers of GENCOs properly reach to the desired value in the steady state case as given by Eq. (8). i.e.:

$$\begin{aligned} \Delta P_{m,1-1} &= 0.05 pu.MW, \Delta P_{m,2-1} = 0.05 pu.MW. \\ \Delta P_{m,1-2} &= 0.1 pu.MW, \Delta P_{m,2-2} = 0.05 pu.MW. \\ \Delta P_{m,1-3} &= 0.025 pu.MW, \Delta P_{m,2-3} = 0.025 pu.MW \end{aligned}$$

### B. Case 2

In this case, It may happen that a DISCO violates a contract by demanding more power than that specified in the contract. This excess power must be reflected as a local load of the area but not as the contracted demand and taken up by GENCOs in the same area. Consider case 1 again with modification that DISCO of areas 1, 2 and 3 demands 0.1, 0.04 and 0.02 puMW of excess power respectively. The total local load in areas is computed as:

$$\begin{aligned} \Delta P_{Loc,1} &= 0.1+0.1=0.2, \Delta P_{Loc,2} = 0.1+0.04=0.14, \\ \Delta P_{Loc,3} &= 0.1+0.02=0.12. pu MW \end{aligned}$$

Power system responses in this scenario with 25% increase in system parameters are shown in Fig. 11. Using the proposed method, the frequency deviation of all areas and tie-line power flows are quickly driven back to zero and have small settling time. Also the tie-line power flows properly converges to the specified value, Eq. (5), in the steady state, i.e.:  $\Delta P_{tie21, sch}=0$  and  $\Delta P_{tie31, sch}=-0.05 pu MW$

### C. Case 3

In this case, performance of the proposed GAHF controller is compared with mixed  $H_2/H_\infty$  controller [8] to evaluate its

robustness. The robust controller is dynamic type, has been proposed to achieve multi-objective of AGC subject to some uncertainties and area load disturbance (see Ref. [8] for more detail) and is given by the following transfer functions for each area:

$$\begin{aligned} K_{1mix}(s) &= \frac{-0.0161s^2 + 0.0099s - 0.0097}{s^3 + 10.984s^2 + 21.5941s + 12.1933} \\ K_{2mix}(s) &= \frac{-0.0147s^2 + 0.0092s - 0.0148}{s^3 + 10.17s^2 + 19.673s + 15.478} \\ K_{3mix}(s) &= \frac{-0.01617s^2 + 0.00107s - 0.0101}{s^3 + 12.181s^2 + 24.9846s + 14.4173} \end{aligned} \quad (14)$$

Consider case 2 again. The power system responses in this case with 25% increase in system parameters are shown in Fig. 12. It can be seen that the proposed controller achieves good robust performance.

### D. Case 4

Consider case 2 again. Assume, in addition to the specified contracted load demands 0.1 pu MW, a bounded random step load change as a large uncontracted demand as shown in Fig. 14 appears in each control area, where:

$$-0.05 \leq \Delta P_{di} \leq +0.05 pu MW$$

The propose of this scenario is to test the robustness of the proposed controller against uncertainties and random large load disturbances. The power system responses in this case with 25% decrease in system parameters are shown in Figs. 13 and 15. the simulation results demonstrate that the proposed control strategy track the load fluctuations and meet robustness for a wide range of load disturbances and possible contract scenarios under plant parameter changes.

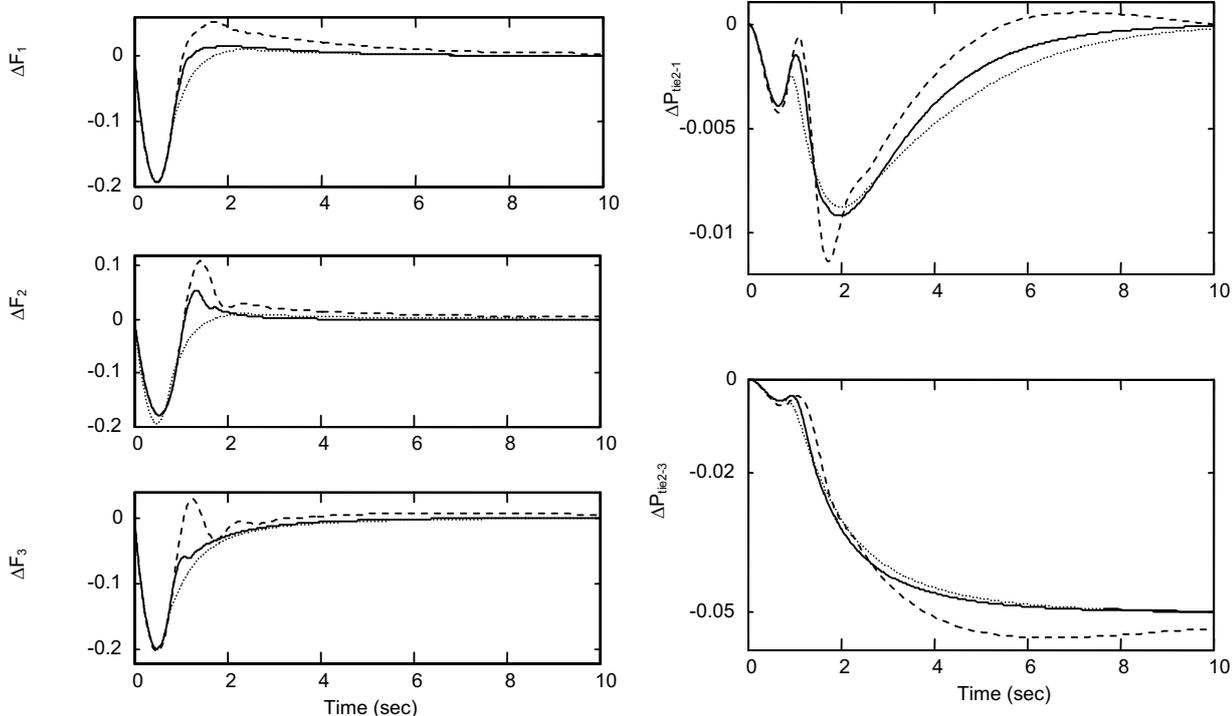


Fig. 9 Deviation of frequency and tie lines power flows; Solid (GAHF), Dotted (MSF) and Dashed (PID)

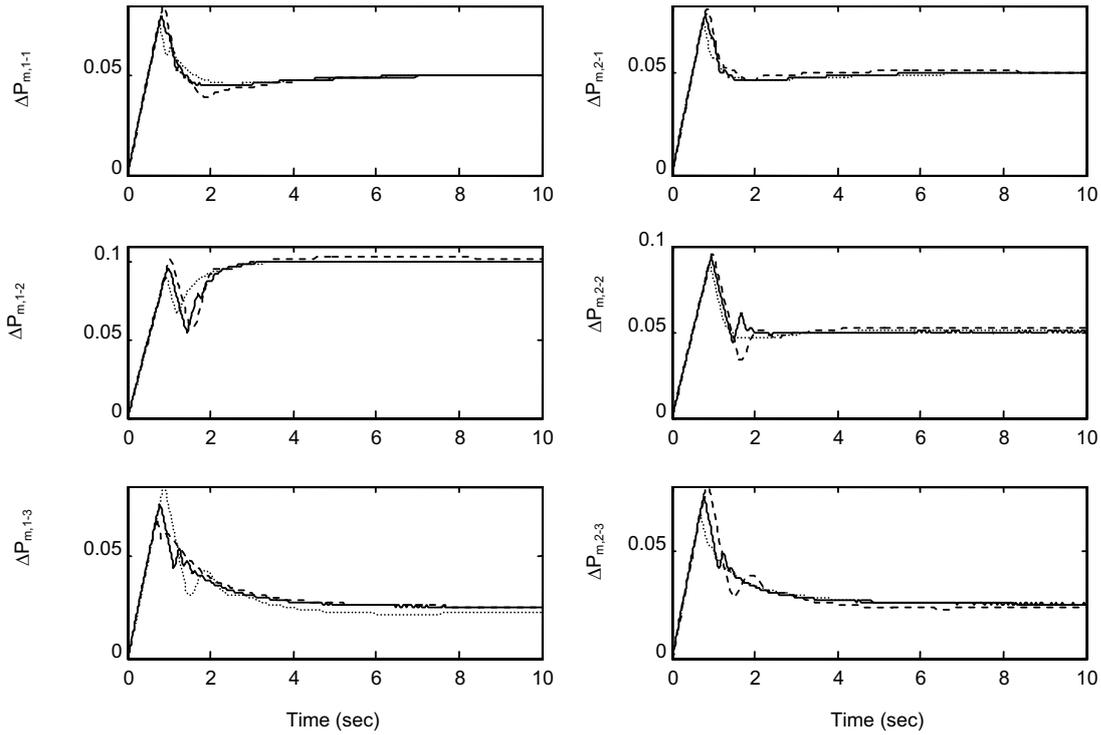


Fig. 10 GENCOs power changes; Solid (GAHF), Dotted (MSF) and Dashed (PID)

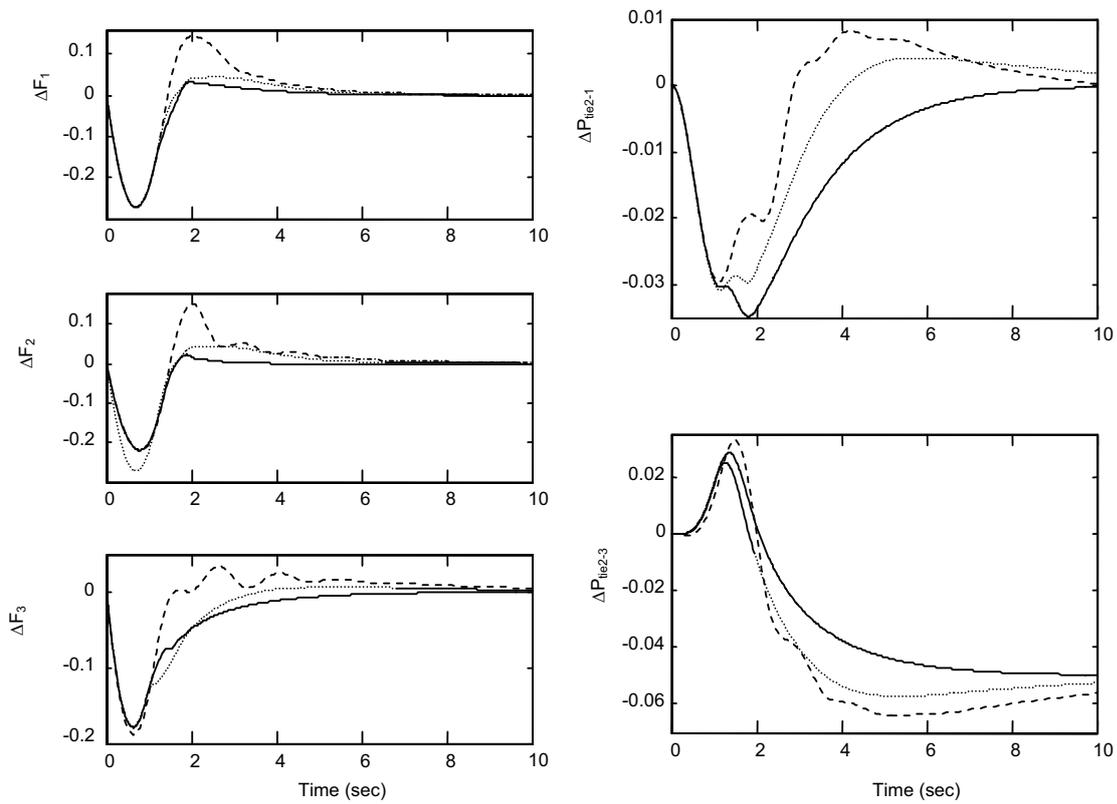


Fig. 11 Deviation of frequency and tie lines power flows; Solid (GAHF), Dotted (MSF) and Dashed (PID)

To demonstrate performance robustness of the prop-osed method, the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are being used as:

$$ITAE = \int_0^{10} (|ACE_1(t)| + |ACE_2(t)| + |ACE_3(t)|) dt \tag{15}$$

$$FD = (OS \times 100)^2 + (US \times 40)^2 + (Ts \times 3)^2 \tag{16}$$

Where, Overshoot (OS) Undershoot (US) and settling time (for 3% band of the total load demand in area1) of frequency deviation area 1 is considered for evaluation of the FD. Numerical results of performance robustness for

cases 1 and 2 are listed in Tables 7-8, whereas the system parameters are varied from -25% to 25% of the nominal values. Figure 16 shows the maximum variation percent of ITAE and FD from their values in the nominal conditions.

*Remark 5.1:* Examination of Fig 16 reveals that the proposed control strategy achieves good robust performance against parametric uncertainties and is superior to other controllers.

*Remark 5.2:* The worst case, as seen from Tables 7-8, occurs when the all system parameters have been had +25% increasing from their nominal values.

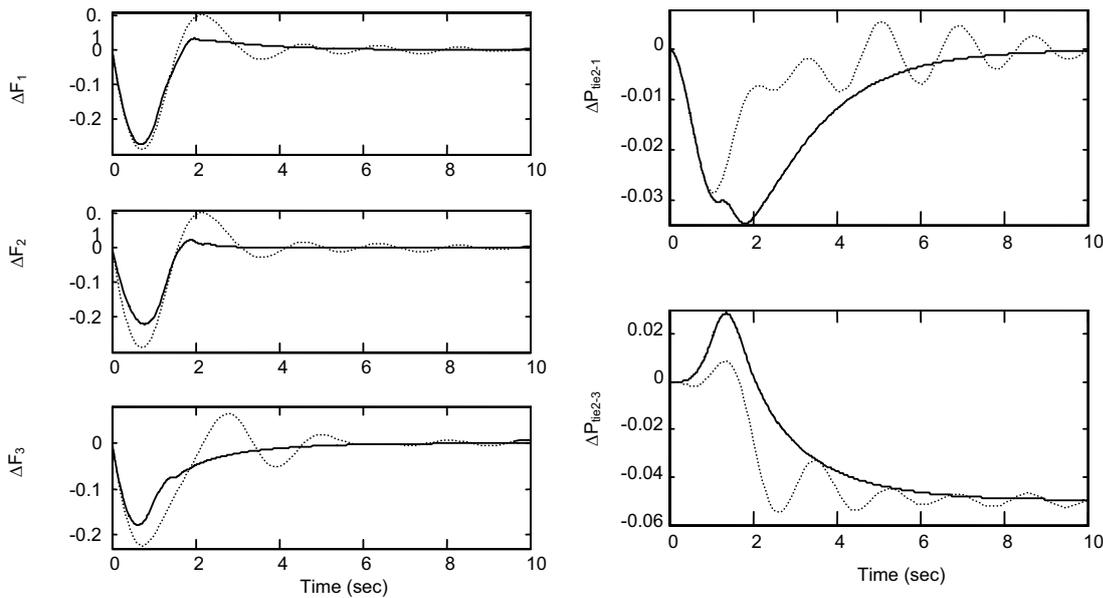


Fig. 12 Deviation of frequency and tie lines power flows; Solid (GAHF), Dotted (Mixed  $H_2/H_\infty$ )

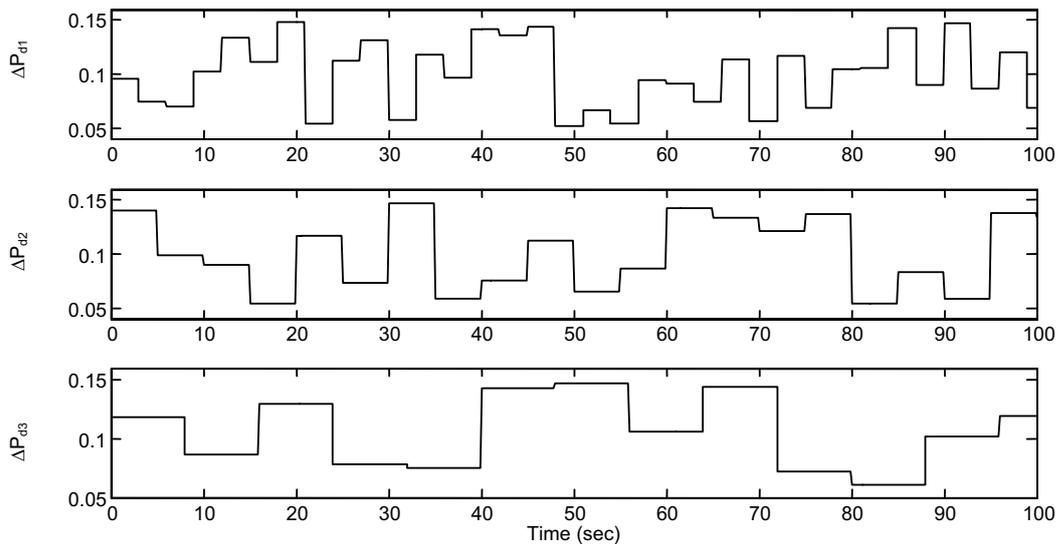


Fig. 13 Random disturbance load patterns in areas 1, 2 and 3

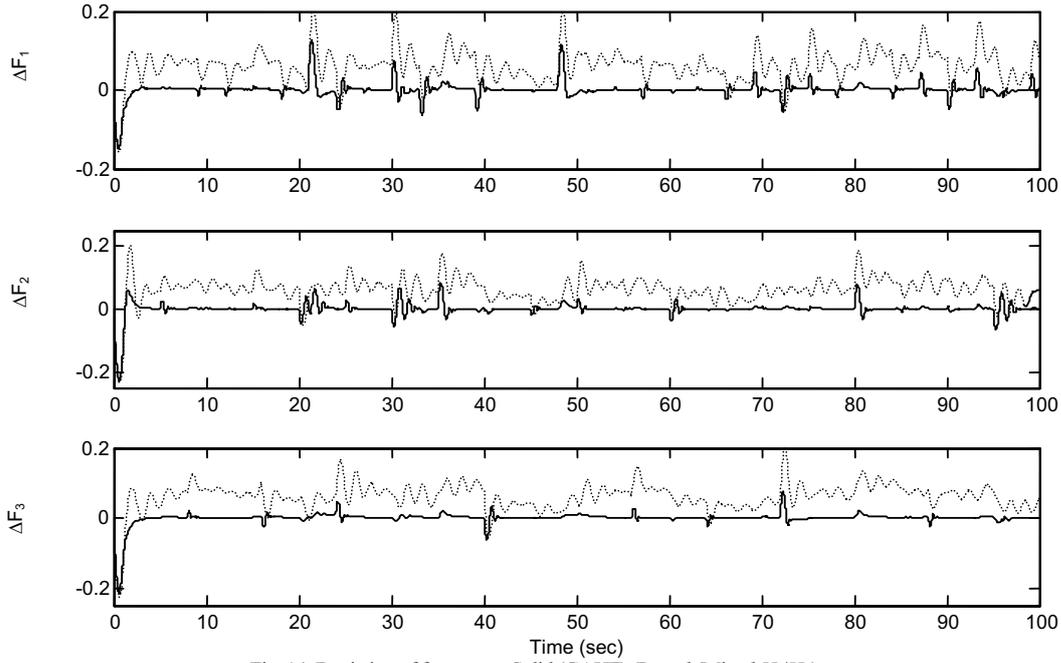


Fig. 14 Deviation of frequency; Solid (GAHF), Dotted ( $H_2/H_\infty$ )

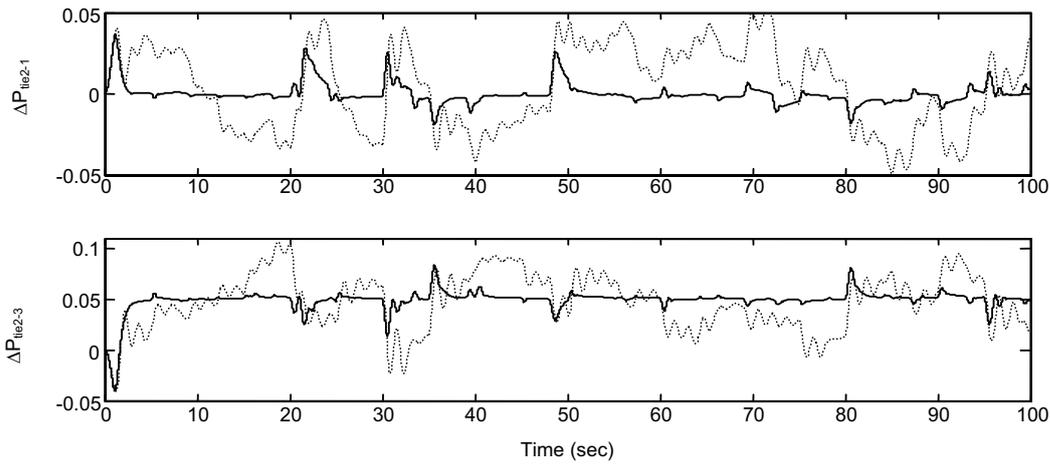


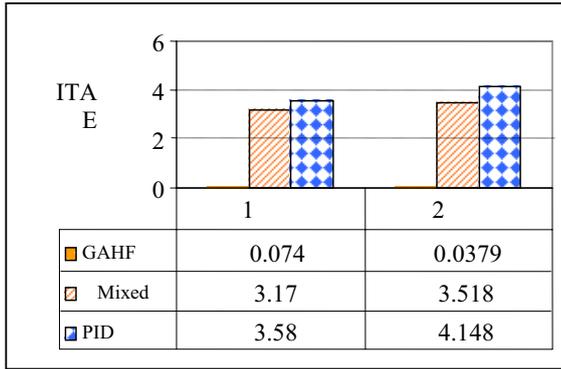
Fig. 15 Deviation of tie lines power flows; Solid (GAHF), Dotted ( $H_2/H_\infty$ )

TABLE VII  
PERFORMANCE INDEX OF ITAE

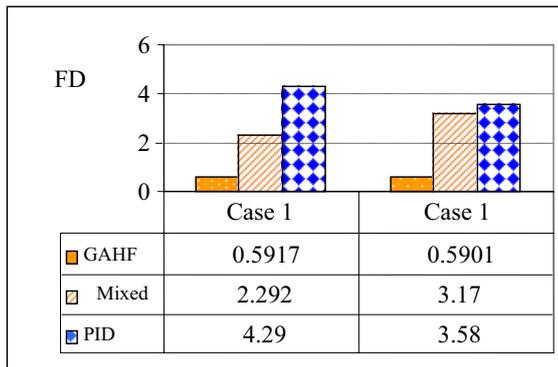
| Test No. | Parameter Changes (%) | Case 1 |                      |        | Case 2 |                      |       |
|----------|-----------------------|--------|----------------------|--------|--------|----------------------|-------|
|          |                       | GAHF   | Mixed $H_2/H_\infty$ | PID    | GAHF   | Mixed $H_2/H_\infty$ | PID   |
| 0        | Nominal               | 14.9   | 76.5                 | 101.0  | 55.4   | 188.3                | 278.8 |
| 1        | -5                    | 14.8   | 71.0                 | 100.4  | 55.0   | 182.2                | 276.9 |
| 2        | +5                    | 15     | 81.9                 | 101.6  | 55.9   | 195.5                | 280.3 |
| 3        | -10                   | 14.7   | 67.3                 | 99.7   | 54.6   | 181.4                | 274.5 |
| 4        | +10                   | 15.1   | 85.9                 | 102.17 | 56.3   | 204.2                | 281.7 |
| 5        | -15                   | 14.8   | 63.4                 | 98.71  | 54.5   | 182.7                | 271.6 |
| 6        | +15                   | 15.3   | 89.7                 | 102.81 | 56.8   | 216.4                | 283.0 |
| 7        | -20                   | 14.8   | 63.5                 | 97.53  | 54.1   | 187.6                | 268.2 |
| 8        | +20                   | 15.6   | 94.4                 | 103.36 | 57.1   | 229.7                | 284.2 |
| 9        | -25                   | 14.9   | 68.9                 | 97.19  | 54.1   | 206.3                | 264.7 |
| 10       | +25                   | 16.0   | 101.4                | 103.9  | 57.5   | 241.3                | 285.2 |

TABLE VIII  
PERFORMANCE INDEX OF FD

| Test No. | Parameter Changes (%) | Case 1 |                      |       | Case 2 |                      |        |
|----------|-----------------------|--------|----------------------|-------|--------|----------------------|--------|
|          |                       | GAHF   | Mixed $H_2/H_\infty$ | PID   | GAHF   | Mixed $H_2/H_\infty$ | PID    |
| 0        | Nominal               | 45.7   | 117.3                | 173.1 | 301.6  | 638.2                | 773.9  |
| 1        | -5                    | 49.3   | 121.7                | 180.7 | 327.6  | 708.4                | 583.3  |
| 2        | +5                    | 42.4   | 113.8                | 163.1 | 279.6  | 582.8                | 705.2  |
| 3        | -10                   | 53.6   | 126.1                | 190.6 | 355.6  | 811.2                | 944.4  |
| 4        | +10                   | 39.6   | 112.0                | 156.6 | 359.3  | 537.3                | 655.5  |
| 5        | -15                   | 58.8   | 137.5                | 203.6 | 389.6  | 946.6                | 1056.9 |
| 6        | +15                   | 37.1   | 109.8                | 148.8 | 242.2  | 497.5                | 614.3  |
| 7        | -20                   | 65.1   | 143.1                | 218.3 | 430.8  | 1219.1               | 1196.6 |
| 8        | +20                   | 34.8   | 113.0                | 136.5 | 225.7  | 465.3                | 547.9  |
| 9        | -25                   | 72.7   | 178.3                | 241.5 | 479.55 | 1458.6               | 1382.4 |
| 10       | +25                   | 32.9   | 112.0                | 127.9 | 212.8  | 327.6                | 542.3  |



a)



b)

Fig. 16. Maximum variation percent of performance indices under cases 1 and 2: a) ITAE b) FD

*Remark 5.3:* we have considered different cases for AGC control of a three-area power system. The simulation results show that in comparison with the PID, MSF and robust mixed  $H_2/H_\infty$  controllers, the system performance is significantly improved by the GAHF controller designed in this paper for a wide range of load disturbances and possible contract scenarios under different plant parameter changes even in the presence of GRC.

## V. CONCLUSION

In this paper, a new GA based hybrid fuzzy controller is proposed for solution of the AGC problem in a deregulated power system. This newly developed control strategy combines advantage a fuzzy PD and integral controllers with a fuzzy switch to achieve the desired level of robust performance, such as frequency regulation, tracking of load demand and disturbance attenuation under load fluctuation for a wide range of the plant parameters changes and system nonlinearities. In order for a fuzzy rule based control system to perform well, the fuzzy sets must be carefully designed. A major problem plaguing the effective use of rule based fuzzy control system is the difficulty of accurately constructing the membership functions. Because, it is a computationally expensive combinatorial optimization problem. For this reason, a modified GA based on the hill climbing method is being used to optimal tune of membership functions automatically to reduce fuzzy system effort and cost. The effectiveness of the proposed method is tested on a three-area restructured power system for a wide range of load demands and disturbances under different operating conditions. The following

conclusions can be drawn about the proposed method.

1. Due to non-model base, it can be used to control a wide range of complex and nonlinear systems.
2. It is effective and ensures robust performance for a wide range operating conditions under plant parameter changes and system nonlinearities.
3. It does not require an accurate model of the AGC problem, has simple structure and easy to implement. Moreover, the design process is less demanding than that of other controllers.
4. The system performance characteristics in terms of 'ITAE' and 'FD' indices reveal that this control strategy is a promising control scheme for the AGC problem in the deregulated power systems.

## APPENDIX A: NOMENCLATURE

|             |   |
|-------------|---|
| $F$         | area frequency  |
| $P_{Tie}$   | net tie-line power flow                                     |
| $P_T$       | turbine power   |
| $P_V$       | governor valve position                                     |
| $P_C$       | governor set point  |
| $ACE$       | area control error  |
| $apf$       | ACE participation factor                                    |
| $\Delta$    | deviation from nominal value                                |
| $K_P$       | subsystem equivalent gain                                   |
| $T_P$       | subsystem equivalent time constant                          |
| $T_T$       | turbine time constant                                       |
| $T_H$       | governor time constant                                      |
| $R$         | droop characteristic  |
| $B$         | frequency bias  |
| $T_{ij}$    | tie line synchronizing coefficient between area $i$ and $j$ |
| $P_d$       | area load disturbance                                       |
| $P_{Lj-i}$  | contracted demand of Disco $j$ in area $i$                  |
| $P_{ULj-i}$ | un-contracted demand of Disco $j$ in area $i$               |
| $P_{m,j-i}$ | power generation of GENCO $j$ in area $i$                   |
| $P_{Loc}$   | total local demand  |
| $\eta$      | area interface  |
| $\zeta$     | scheduled power tie line power flow deviation               |

## APPENDIX B: OPTIMAL PID GAIN SETTING

A performance index:

$$J_i = \int_0^{\infty} t (|ACE_i(t)|) dt \quad (17)$$

is used for obtaining the optimum PID gain setting. While for optimizing the PID gain setting of area 1, areas 2 and 3 are considered uncontrolled and a step load perturbation of 10% of nominal load is considered in area 1. Fig. 18 shows  $J_i = f(K_I, K_P)$  for several values of  $K_{dl}$  for a 10% step load perturbation in area 1. Using the same procedure, the optimum values of the PID controllers gain for the other areas are obtained and listed in Table 9.

TABLE IX  
PID CONTROLLER GAINS

| Area  | Area -1 | Area -2 | Area -3 |
|-------|---------|---------|---------|
| $K_P$ | 0.9     | 1       | 0.8     |
| $K_I$ | 0.7     | 0.4     | 1       |
| $K_d$ | 0.9     | 0.8     | 0.3     |

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