Robust Tuning of PID Controller to Optimize Bilateral Contracts in Deregulated Power System Using Evolutionary Algorithms

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Abstract :-**In this paper an attempt is made to present feasible and practical methods to optimize the bilateral contracts in a deregulated power system. Using ITAE as performance criteria to be optimize, the PID controller parameter gains K_p, K_d, K_I are optimized using Evolutionary Real coded Genetic Algorithm (RCGA). The main goal of the optimization method is to improve the dynamics, such as reducing the overshoot, minimizing settling time, improving of the transient response of frequency and tie-line power deviations in an interconnected multiarea deregulated power system. The feasibility and robustness of the algorithm is investigated on a two area interconnected power system consisting of thermal plants in deregulated environment. The dynamics of frequency deviations and tie-line power deviations were investigated by considering the possible bilateral contracts between various GENCOs and DISCOs in both areas using DISCO participation matrix (DPM). The results obtained by the proposed method show a considerable improvement in the dynamic response of frequency and tie-line power in an interconnected deregulated power system. The robustness against parameter uncertainties is investigated using sensitivity analysis.**

Keywords**- Bilateral contracts, Deregulation, PID controller, LFC dynamics, Real coded genetic algorithm.**

I. INTRODUCTION

Automatic generation control is the one of the most important ancillary services required to be maintained for minimizing frequency deviations, imbalance of generation and load demand, and for regulating tie-line power exchange, facilitating bilateral contracts spanning over several control areas and to maintain a reliable operation of the interconnected transmission system. Several control strategy such as PI control, optimal control, variable structure control have been used to control the frequency and to maintain the scheduled regulation between the interconnected areas. One major advantage of PI controller is that it reduces the steady state error to zero, but do not perform well under varying operating conditions and exhibits poor dynamic performance [6]-[8]. The controller based on optimal control and variable structure control needs feedback of most of state variables of the system which is practically difficult to have access and measure them in a large interconnected system. The most popular approach adopted for AGC in an inter-connected power system is the use of Proportional-Integral-Derivative (PID) controller. The parameters of a PID controller are usually tuned manually or using trial-and-error approach or by conventional control methods. These tuning methods are tedious and are incapable of obtaining good dynamical performance for a wide range of operating conditions [6]-[8]. Evolutionary based real coded genetic algorithms are used to optimize the controller gains to optimize the dynamics of LFC. The stability and robustness against the parameter uncertainties is investigated by sensitivity analysis.

II. MULTI-AREA DEREGULATED POWER SYSTEM

The electrical industry over the years has been dominated by an overall authority known as vertical integrated utility (VIU) having authority over generation, transmission and distribution of power within its domain of operation [1]-[3], [11]. With the emerging or various independent power producers (IPPs) in the power market motivates the necessity of deregulation of the power system were the power can be sold at a competitive price performing all functions involved in generation, transmission, distribution and retail sales. With restructuring the ancillary services are no longer an integral part of the electricity supply, as they used to be in the vertically integrated power industry structure. In a competitive environment, the provision of these services must be carefully managed so that the power system requirements and market objectives are adequately met. The first step in deregulation is to unbundle the generation of power from the transmission and distribution however, the common LFC goals, i.e. restoring the frequency and the net interchanges to their desired values for each control area remains same. Thus in a deregulated scenario generation, transmission and distribution is treated as separate entities [1], [6]-[11]. As there are several GENCOs and DISCOs in the deregulated structure, agreements/ contracts should be established between the DISCOs and GENCOs with in the area or with interconnected GENCOs and DISCOs to supply the regulation. The DISCOs have the liberty to contract with any available GENCOs in its own or other areas. Thus, there can be various combinations of the possible contracted scenarios between DISCOs and GENCOs. A DISCO having contracts with GENCOs in another control area are known as "Bilateral transactions" and within same area is known as "POOL transactions". The concept of DISCO Participation Matrix (DPM) [1], [2], [11] is introduced to express these possible contracts in the generalized model. DPM is a matrix with the number of rows equal to the number of GENCOs and the number of columns equal to the number of DISCOs in the overall system. The entities of DPM are represented by the contract participation factor *(cpf_{ij})* which corresponds to the fraction of total load contracted by any $DISCO_j$ towards any $GENCO_i$:

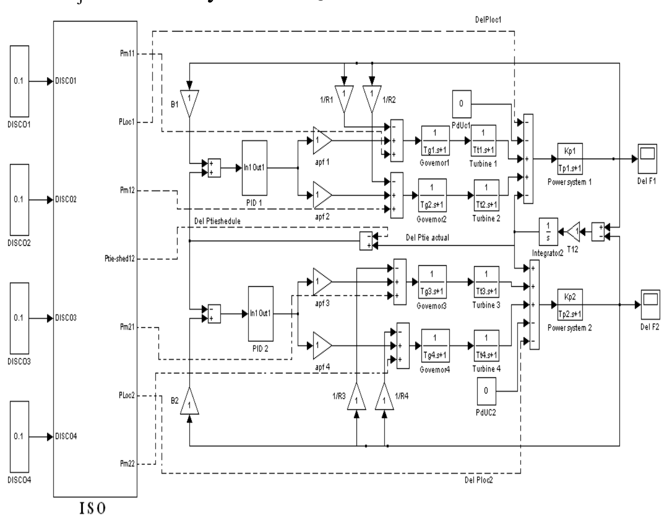

Figure.1. Block diagram representation of two area **Deregulated** power system

$$DPM= \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{1j} & . & . & cpf_{1n} \\ cpf_{21} & cpf_{22} & cpf_{2j} & . & . & cpf_{2n} \\ cpf_{i1} & cpf_{i2} & cpf_{ij} & . & . & cpf_{in} \\ . & . & . & . & . & . \\ cpf_{n1} & cpf_{n2} & cpf_{n3} & . & . & cpf_{nn} \end{bmatrix} \quad (1)$$

The sum of all entries in each column of DPM is unity.

$$\sum_i cpf_{ij} = 1 \quad (2)$$

Under steady state the power equations in deregulated environment are,

$$\Delta P_{d\,i} = \Delta P_{LOC\,i} + \Delta P_{UC\,i} \quad (3)$$

$$\text{Where } \Delta P_{LOC\,i} = \sum \Delta P_{LC\,i} \quad (4)$$

The scheduled contracted power exchange is given by:

$\Delta P_{tie12}^{scheduled}$= (Demand of DISCOs in area2 from GENCOs In area1) - (Demand of DISCOs in area1 from GENCOs in area2) (5)

The actual power exchanged in Tie-line is given by:

$$\Delta P_{tie12}^{actual} = \frac{2\pi T12}{s}(\Delta f_1 - \Delta f_2) \quad (6)$$

At any time the tie-line power error is given by:

$$\Delta P_{tie12}^{Error} = \Delta P_{tie12}^{actual} - \Delta P_{tie12}^{scheduled} \quad (7)$$

ΔP_{tie12}^{Error} vanishes in the steady-state as the actual tie-line power flow reaches the scheduled power flow. This error signal is used to generate the respective ACE signals as in the traditional scenario:

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{tie12}^{Error} \quad (8)$$

$$ACE_2 = B_2 \Delta f_2 + a_{12} * \Delta P_{tie12}^{Error} \quad (9)$$

Where $a_{12} = -P_{r1}/P_{r2}$

The total power supplied by i[th] GENCO is given by:

$$\Delta P_{gki} = \Delta P_{mki} + apf_{ki} \sum \Delta P_{UC\,i} \quad (10)$$

$$\text{Where } \Delta P_{mki} = \sum_{j=i}^{N} cpf_{ij}\, \Delta P_{Lcj} \quad (11)$$

ΔP_{gki} is the desired total power generation of a $GENCO_i$ in area k and must track the contracted and un-contracted demands of the DISCOs in contract with it in the steady state.

III. PID CONTROLLER FOR AGC

In AGC the conventional control strategy such as Proportional-integral control provides zero steady state deviation, but it exhibits poor dynamic response of frequency and tie-line power in an interconnected power system [6], [7]. Also the designing of state feedback controller based on optimal control theory and variable structure control for improving the performance of load frequency problem is a complex task as it is difficult to measure and have access to most of the state variables of the system and hence such controllers are not practical for a large interconnected power system [7]. The most popular approach adopted for AGC in an inter-connected power system is the use of Proportional-Integral-Derivative (PID) controller [7]. In LFC problem the frequency deviations and the deviations in the tie-line are weighted together as a linear combination to a single variable called the Area control error (ACE), and is used as a control signal that applies to governor set point in each area. By taking ACE as the system output, the control vector for a conventional PID controller is given by:

$$U_i = -\left[K_{pi}ACE_i + K_{Ii}\int ACE_i\,dt + K_{di}\frac{d(ACE_i)}{dt}\right] \qquad (12)$$

Where K_p, K_d, K_I are the proportional, derivative and integral gains of PID controller. It is well known that the conventional method to tune gains of PID controller with numerical analyses is tedious and time consuming. In this strategy, using ITAE as a performance criterion to be optimize the conventional PID gains are tuned using Real coded Genetic algorithms to improve the dynamics of LFC in a deregulated power system.

IV. EVOLUTIONARY ALGORITHMS

In traditional approach sequential optimization, several iterations are required to determine the optimal parameters for an objective function to be optimized. When the number of parameters to be optimize is large the classical techniques requires large number of iterations and computation time [5]. The evolutionary algorithms such as Genetic algorithms emerges as an alternative for optimizing the controller gains of a multiarea AGC system more effectively than the traditional methods [9].

1. Real Coded Genetic algorithm

Genetic algorithm (GA) is an optimization method based on the mechanics of natural selection. In nature, weak and unfit species within their environment are faced with extinction by natural selection. The strong ones have greater opportunity to pass their genes to future generations. In the long run, species carrying the correct combination in their genes become dominant in their population. Sometimes, during the slow process of evolution, random changes may occur in genes. If these changes provide additional advantages in the challenge for survival, new species evolve from the old ones. Unsuccessful changes are eliminated by natural selection. In real-coded genetic algorithm (RCGA), a solution is directly represented as a vector of real parameter decision variables, representation of the solutions very close to the natural formulation of the problem [4], [9]. The use of floating-point numbers in the GA representation has a number of advantages over binary encoding. The efficiency of the GA gets increased as there is no need to encode/decode the solution variables into the binary type.

1.1 Chromosome structure

In GA terminology, a solution vector known as an individual or a chromosome. Chromosomes are made of discrete units called genes. Each gene controls one or more features of the chromosome [9]. The chromosome consisting of PID parameters in both areas is modeled as its genes.

PID $_1$			PID $_2$		
Kp_1	Ki_1	Kd_1	Kp_2	Ki_2	Kd_2

Fig 2: Chromosome structure

1.2 Fitness-Objective function evaluation

The objective here is to minimize the deviation in the frequency and the deviation in the tie line power flows and these variations are weighted together as a single variable called the ACE. The fitness function is taken as the Integral of time multiplied absolute value (ITAE) of ACE [1], [2]. An optional penalty term is added to take care of the transient response specifications viz. settling time, over shoots, etc. Integral of time multiplied absolute value of the Error (ITAE), is given by:

$$ITAE = \int_0^{Tsim} t\left|e(t)\right|dt \qquad (13)$$

Where $e(t)$= error considered.
The fitness function to be minimized is given by:

$$J = \int_0^{Tsim}\left(\beta_1\left|\Delta f_1\right| + \beta_2\left|\Delta f_2\right| + \left|\Delta P_{Tie12}^{Error}\right|\right)dt + FD \qquad (14)$$

Where FD=α_1 OS+ α_2 TS (15)

Where Overshoot (OS) and settling time (TS) for 2% band of frequency deviation in both areas is considered for evaluation of the FD [10].

1.3 Selection

Selection is a method of selecting an individual which will survive and move on to the next generation based on the fitness function from a population of individuals in a genetic algorithm. In this paper tournament selection is adopted for selection [4], [8], [9]. The basic idea of tournament selection scheme is to select a group of individuals randomly from the population. The individuals in this group are then compared with each other, with the fittest among the group becoming the selected individual.

1.4 Crossover
The crossover operation is also called recombination. This operator manipulates a pair of individuals (called parents) to produce two new individuals (called offspring or children) by exchanging corresponding segments from the parents' coding [9], [11]. In this paper simple arithmetic crossover is adopted.

1.5 Mutation
By modifying one or more of the gene values of an existing individual, mutation creates new individuals and thus increases the variability of the population [9]. In the proposed work Uniform mutation is adopted.

1.6 Elitism
Elitism is a technique to preserve and use previously found best solutions in subsequent generations of EA [7], [9]. In an elitist EA, the population's best solutions cannot degrade with generation.

2. Pseudo code for the proposed RCGA

Step 1: Initialization
Set gen=1. Randomly generate N solutions to form the first population, $P_{initial}$. Evaluate the fitness of solutions in $P_{initial}$. Initialize the probabilities of crossover *(pc)* and mutation (*pm*).

While (gen ≤ Max number of generations)

Step 2: Selection
Select the individuals, called *parents* that contribute to the population at the next generation. In the proposed GA tournament selection is used.

Step 3: Crossover
Generate an offspring population Child,
if pc >rand,
3.1. Choose one best solutions x from $P_{initial}$ based on the fitness values and random solution y from the population for crossover operation.
3.2. Using a crossover operator, generate offspring and add them back into the population.

$Child_1 = r\, parent_1 + (1 - r)\, parent_2;$
$Child_2 = r\, parent_2 + (1 - r)\, parent_1;$

end if

Step 4: Mutation
Mutation alters an individual, parent, to produce a single new individual, child.
if pm >rand,
Mutate the selected solution with a predefined mutation rate.
end if

Step 5: Fitness assignment
The fitness function defined by Eqs. (14) is minimized for the feasible solution

Step 6: Elitism
The selected number of Elite solutions (best solutions) is preserved in subsequent generations in the population.

Step 7: stopping criterion
If the maximum number of generations has reached then terminate the search and return to the current population, else, set gen=gen+1and go to Step 2.

end while

The values of GA operator used for optimization is presented in appendix B.

V. SIMULATION

To investigate the performance of the proposed RCGA, a two area power system consisting of two GENCOs and two DISCOs in each area is simulated by considering a load demand of 0.1puMW contracted by GENCOs in each area. The concept of a "*DISCO participation matrix*" (DPM) is used for the simulation of contracts between GENCOs and DISCOs. In a Restructured AGC system, a DISCO asks/demands a particular GENCO or GENCOs within the area or from the interconnected area for load power. Thus, as a particular set of GENCOs are supposed to follow the load demanded by a DISCO, information signals must flow from a DISCO to a particular GENCO specifying corresponding demands. The demands are specified by *contract participation factors* and the pu MW load of a DISCO. These signals will carry information as to which GENCO has to follow a load demanded by which DISCO. The simulation is done in MATLAB/SIMULINK platform and the power system parameters used in [1] is used for simulation and were presented in appendix A.

The GENCOs in each area participates in ACE defined by the following *apfs:*

$apf_1 = 0.75;$ $apf_3 = 0.5;$

$apf_2 = 1 - apf_1 = 0.25;$ $apf_4 = 1 - apf_3 = 0.5;$

1. Scenario I: Bilateral transactions
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 DPM. All GENCOs participate in the LFC task. It is assumed that a large step load 0.1 pu is demanded by each DISCOs in areas 1 and 2.

```
DPM=[ 0.4  0.25 0.0 0.3
      0.3  0.25 0.0 0.0
      0.1  0.25 0.5 0.7
      0.2  0.25 0.5 0.0];
```

The frequency deviations of two areas, GENCOs power generation, Tie-line power flow and Area control error for the given operating conditions is depicted in Fig.3 to Fig.7:

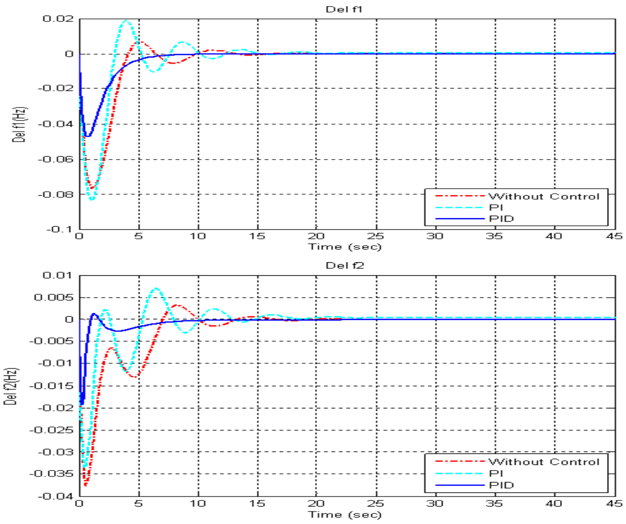

Fig.3: Frequency deviation in Area 1 and Area 2

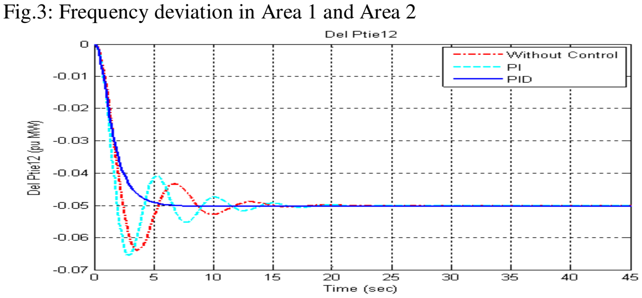

Fig.4: Tie line power $\Delta P_{tie12\text{- Scheduled}}$

The bilateral contracts existing between GENCOs and DISCOs of area 1 and area 2, the tie-line power converges to a steady state value of $\Delta P_{tie12\text{-schedule}}$=-0.05 puMW.

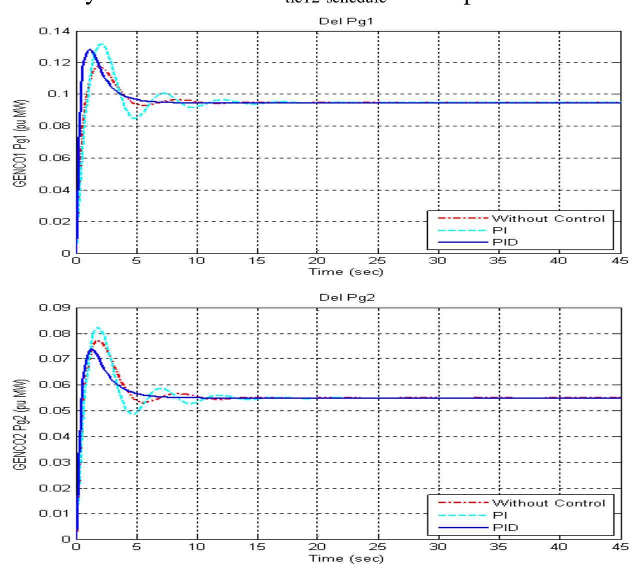

Fig.5: GENCOs Power generation in Area 1

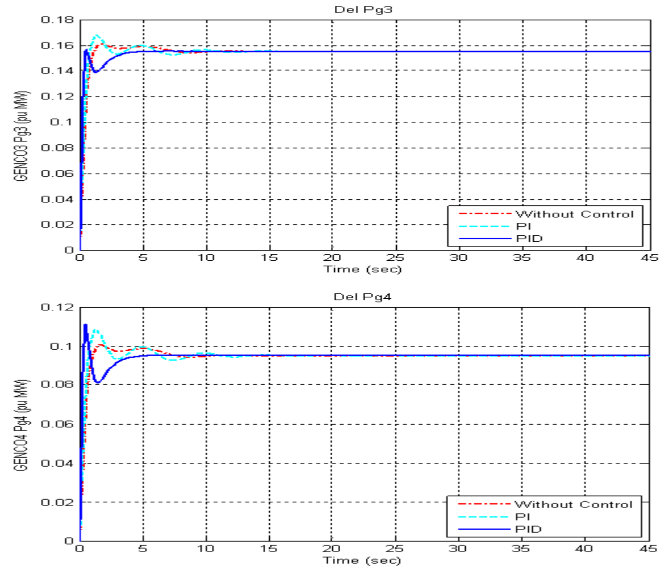

Fig.6: GENCOs Power generation in Area 2

From simulation results shown in Fig.5 and Fig. 6, in steady state the total generation should match the total demand contracted by the DISCOs, Thus the generation in area 1 and area 2 converges to:

$\Delta P_{g1\text{-}1}$= 0.095 pu MW, $\Delta P_{g2\text{-}1}$= 0.055 pu MW

$\Delta P_{g3\text{-}2}$= 0.155 pu MW, $\Delta P_{g4\text{-}2}$= 0.095 pu MW

Total Load=0.1x4=.4 pu MW

Total Generation=0.095+0.055+0.155+0.095=0.4 pu MW

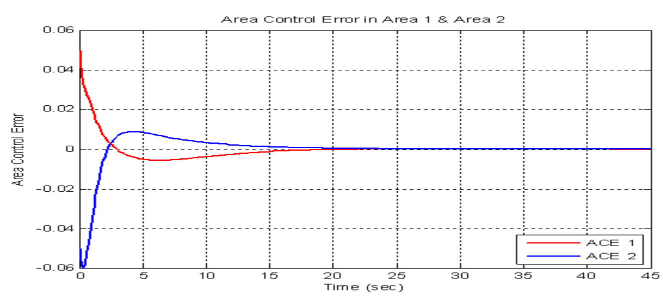

Fig.7: Area Control Error in Area 1 and Area 2

2. Scenario II: Contract violation

It may happen that a DISCO violates a contract by demanding more power than that specified in the contract. This un-contracted power must be supplied by the GENCOs in the same area as the DISCO. Consider scenario I with a modification that DISCOs in area 1 demands additional 0.05 pu MW of un-contracted power in excess. Let $\Delta P_{L,uc1}$=0.05pu. This excess power should be supplied by GENCOs in area 1 and the generation in area 2 remain unchanged. The frequency and Tie-line deviations, power generated by GENCOs and Area control error were depicted in Fig: 8 to Fig. 12:

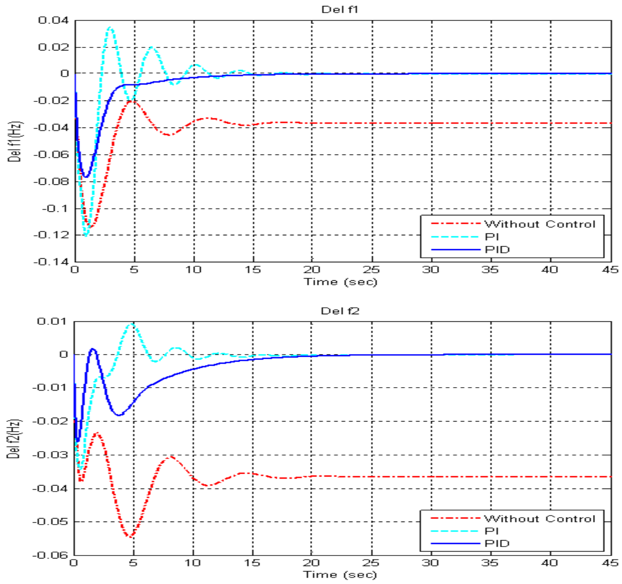

Fig.8: Frequency deviation in Area 1 and Area 2

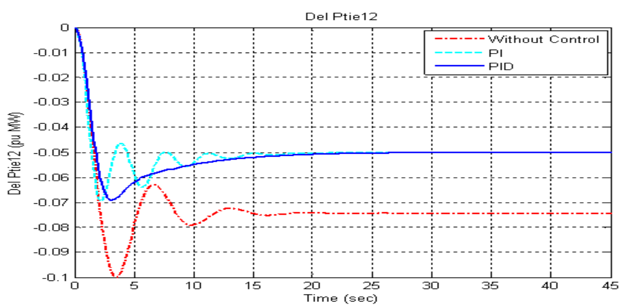

Fig.9: Tie line power $\Delta P_{tie12\text{- Scheduled}}$

The bilateral contracts existing between GENCOs and DISCOs of area 1 and area 2, the tie-line power converges to a steady state value of $\Delta P_{tie12\text{-schedule}}$=-0.05 puMW.

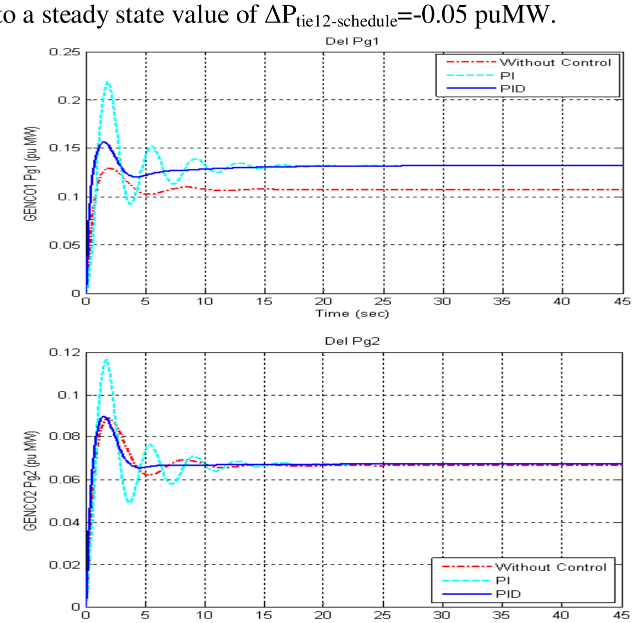

Fig.10: GENCOs Power generation in Area 1

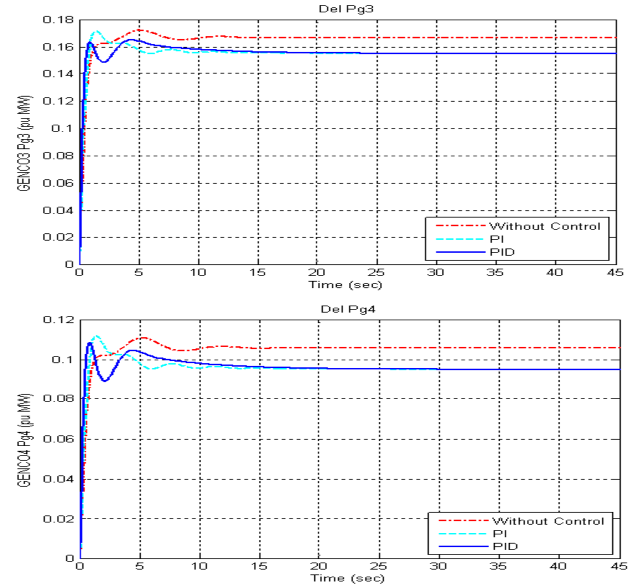

Fig.11: GENCOs Power generation in Area 2

From simulation results shown in Fig.10 and Fig.11, in steady state the total generation should match the total demand contracted by the DISCOs, Thus the generation in area 1 and area 2 converges to:

$\Delta P_{g1\text{-}1}$= 0.1325 pu MW, $\Delta P_{g2\text{-}1}$= 0.0675 pu MW

$\Delta P_{g3\text{-}2}$= 0.1550 pu MW, $\Delta P_{g4\text{-}2}$= 0.0950 pu MW

Total Load=0.1x4+0.05=0.45 pu MW

Total Generation=0.1325+0.0675+0.155+0.095=0.45pu MW

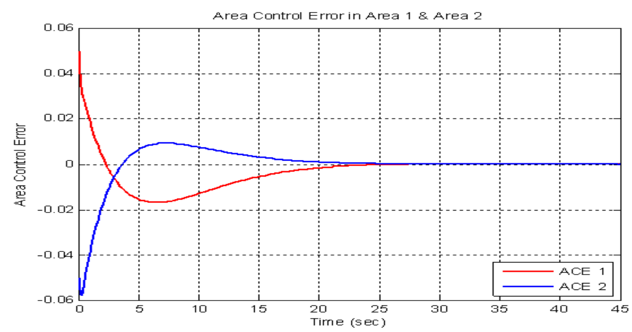

Fig.12: Area Control Error in Area 1 and Area 2

VI. ROBUSTNESS ANALYSIS

The effectiveness and robustness of controller against parameter uncertainties is investigated by varying the nominal values of PID controller obtained by real coded genetic algorithm from −10% to 10%. The corresponding variations in frequency deviations and Tie-line power dynamics applied for the scenario I were shown in Fig: 13-Fig 14.

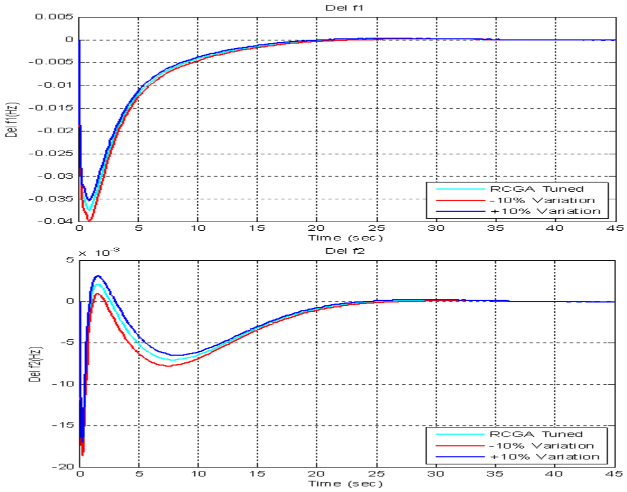

Fig.13: Frequency deviation with parameter variation in Area 1 and Area 2

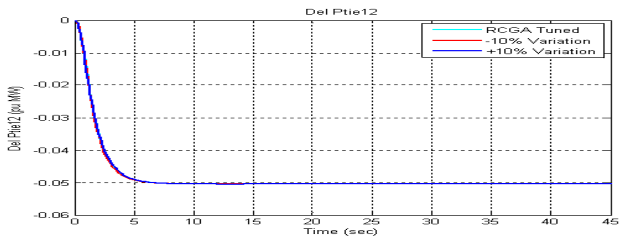

Fig.14: Tie-line power deviation with parameter variation

The variations in frequency deviations and Tie-line power dynamics to parameter variations applied for the scenario II were shown in Fig: 15-Fig 16.

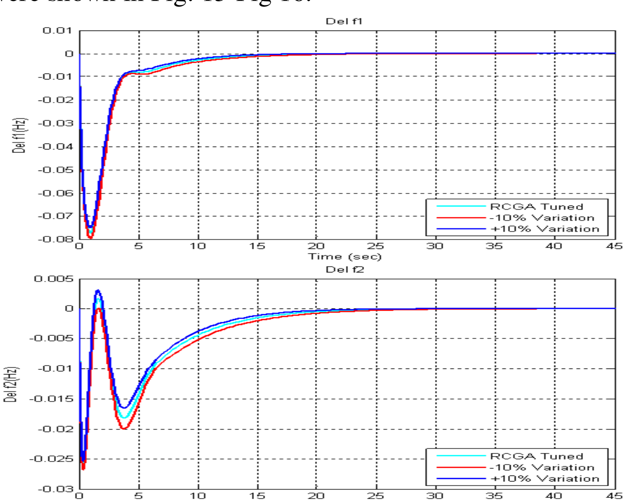

Fig.15: Frequency deviation with parameter variation in Area 1 and Area 2

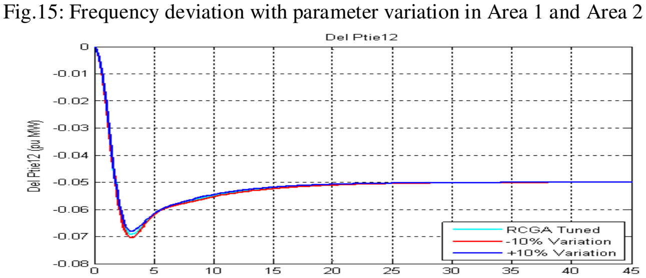

Fig.16: Tie-line power deviation with parameter variation

VII. RESULTS AND DISCUSSIONS

For the two area restructured power system considered, the dynamic response for various operating conditions were analyzed by simulating the Bilateral contracts between the GENCOs and DISCOs. The gains of PID controller is tuned using real coded genetic algorithm, the values obtained for different operating conditions were tabulated in table 1

Table 1: PID parameters obtained by RCGA for different operating conditions

Scenario	PID in Area I			PID in Area II		
	K_{p1}	K_{i1}	K_{d1}	K_{p2}	K_{i2}	K_{d2}
Scenario I	-1.4252	-0.0399	-2.2993	-2.0368	-0.0083	-3.6182
Scenario II	-0.9070	-0.2905	-1.3212	-1.1245	-0.3120	-1.1211

The convergence characteristic of the objective function given in Eq. (14) with the algorithm is shown in Fig. 17.

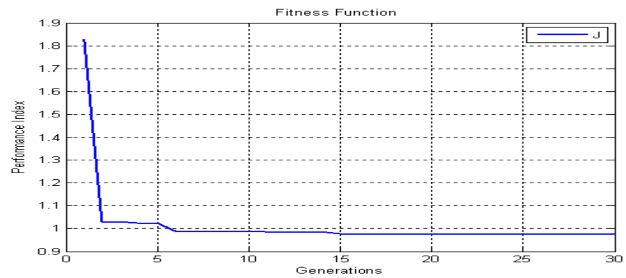

Fig.17. Convergence characteristic of the objective function

VIII. CONCLUSIONS

The dynamic responses obtained for various operating conditions were obtained. PID controller parameters obtained by real coded genetic algorithm have resulted in an appreciable reduction in magnitude of overshoot, converging to steady state without much oscillation and within convincible settling time for Δf_1, Δf_2, and ΔP_{tie12}. The robustness analysis to investigate the sensitivity of the controller against the parameter uncertainty shows stable dynamics for frequency and tie-line deviations. From the convergence characteristics it is inferred that the proposed algorithm converges with in less number of iterations. The simulation results show that the Evolutionary RCGA- based tuning of load frequency controllers are superior in all aspects.

APPENDIX A: Parameters values of power system

Parameters	Area 1		Area 2	
T_{ti} (sec)	0.4	0.375	0.375	0.4
T_{gi} (sec)	0.075	0.1	0.075	0.0875
R_i (pu/Hz)	3	3.125	3.125	3.375
K_{pi}	127.5		127.5	
T_{pi} (sec)	25		31.25	
B_i (pu/Hz)	0.532		0.495	
T_{12} (pu/Hz)	0.543			

APPENDIX B: Genetic algorithm parameters

Parameter	Value
No of population	100
Maximum no of generations	30
Crossover	Arithmetic
Crossover probability (*pc*)	0.95
Mutation	Uniform
Mutation probability (*pm*)	0.1
Elitism	Yes
No. of Elite solutions	2

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