

EVOLUTIONARY HYBRID GENETIC-FIREFLY ALGORITHM FOR OPTIMIZING LFC REGULATION IN A DEREGULATED POWER SYSTEM

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Abstract: This paper proposes an Evolutionary Hybrid Genetic-Firefly algorithm to optimize proportional (K_p), Integral (K_i), and Derivative (K_d) gains of a PID controller using IATE criteria as a performance criteria. In deregulated power system the maintenance of the real power balance between the GENCOs and DISCOs in an interconnected power system is an important issue and should be governed by ISO in order to meet the possible contracted bilateral transactions between the GENCOs and DISCOs in a secured manner. The present work focuses on regulating load frequency control ancillary service in a deregulated scenario with integration of potentially developing combined cycle gas fired power plants. The proposed control strategy is investigated on a two-area interconnected power system consisting of Hydro-Thermal unit in the area-I and Thermal-Gas unit in area-II. The main objective of optimization is to improve the dynamics of LFC such as improving of the transient response of frequency and tie-line power oscillations and to optimize the Power generated by various GENCOs according to the scheduled bilateral contracts. The simulation results show the PID controller tuned by the proposed Genetic-Firefly algorithm (GA-FA) exhibits a considerable improvement in dynamic performance of LFC.

Key words: Bilateral contracts, Deregulated power system, Hybrid Genetic-Firefly algorithm, LFC dynamics.

1. Introduction

Automatic generation control is one of the most important ancillary services to be maintained in a deregulated power system for minimizing frequency deviations, imbalances of generation and load demand, for regulating tie-line power exchange, facilitating bilateral contracts among various GENCOs and DISCOs and to maintain a reliable operation of the interconnected transmission system in a multi area power system. The requirement to improve the efficiency of power production and delivery and with intense participation of independent power producers has motivated restructuring of the power sector. In deregulated scenario, market operators such as independent system operator (ISO) are responsible for maintaining the real time balance of generation and

load for minimizing frequency deviations and regulating tie-line flows, and facilitates bilateral contracts spanning over various control areas. The demand being constantly fluctuating and increasing, and hence there is a need to expand the generation by introducing new potential generating plants such as gas fired power plants. Earlier the gas power plants were limited in applications with relatively low running hours such as for peaking and emergency duty, due to their high operating costs and limited power outputs. With the advent of gas turbines with rating of well over 400 MW combined with steam turbines, provide very high thermal efficiency and thus a large capacity systems allowing the combined cycle to emerge as a major source of base load power plants primarily operating on gaseous fuels [14]-[15]. The gas turbines due to its fast control can transit from idle to full power in time scale as short as few mill seconds with a response time of 5-10 seconds for most intermediate sized gas turbine electric power generating systems, this ability to follow the load rapidly is particularly well suitable to provide adequate ancillary services rapidly in deregulated power system.

The paper is organized as follows: Section II presents the detailed concepts of deregulated power system and its model in SIMULINK platform. In section III, the PID controllers as a supplementary controller for maintaining the LFC regulation is discussed. Section IV presents an overview of the proposed Hybrid Genetic-Firefly Algorithm and its implementation aspects. The section V emphasizes on the simulation of the controller with the proposed algorithm in a two area deregulated power system by considering the possible bilateral transactions between GENCOs and DISCOs. Finally the results, discussions and conclusions were presented in section VI and VII.

2. 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]-[2], [10]-[12].

With the emerging or various independent power producers (IPPs) in the power market motivates the necessity of deregulation of the power system where 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 is no longer an integral part of the electricity supply, as they used to be in the vertically integrated power industry structure. In a deregulated 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] - [2], [10]-[12]. As there are several GENCOs and DISCOs in the deregulated structure, agreements/contracts should be established between the DISCOs and GENCOs within 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 area or with interconnected areas. Thus, there can be various combinations of the possible contracted scenarios between DISCOs and GENCOs in an interconnected multi area deregulated power system. In a deregulated power system a DISCO having contracts with GENCOs in its own area is known as "POOL transactions" and with GENCOs of another control area are known as "Bilateral transactions". In a Restructured AGC system, a DISCO asks/demands power from a particular GENCO or GENCOs within the area or from the interconnected area, thus, as a particular set of GENCOs are supposed to follow the load demanded by a DISCO, these demands are specified by *contract participation factors* and the pu MW load of a DISCO. The load demand information signals must flow from a DISCO to a particular GENCO specifying corresponding demand. These signals will carry information as to which GENCO has to follow a load demanded by which DISCO. The block diagram modal of two area deregulated power system is depicted in Fig. 1. The concept of DISCO Participation Matrix (DPM) [1], [2], [11], [12] 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. The DPM is defined by:

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{1j} & \dots & cpf_{1n} \\ cpf_{21} & cpf_{22} & cpf_{2j} & \dots & cpf_{2n} \\ cpf_{31} & cpf_{32} & cpf_{3j} & \dots & cpf_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ cpf_{n1} & cpf_{n2} & cpf_{nj} & \dots & cpf_{nn} \end{bmatrix} \quad (1)$$

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,

$$\Delta P_{di} = \Delta P_{LOCi} + \Delta P_{UCi} \quad (3)$$

$$\text{Where } \Delta P_{LOCi} = \sum \Delta P_{LCi} \quad (4)$$

The scheduled contracted power exchange in tie-line is given by:

$$\Delta P_{tieij}^{scheduled} = (\text{Demand of DISCOs in area } j \text{ from GENCOs in area } i) - (\text{Demand of DISCOs in area } i \text{ from GENCOs in area } j) \quad (5)$$

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

$$\Delta P_{tieij}^{actual} = \frac{2\pi T_{ij}}{s} (\Delta f_i - \Delta f_j) \quad (6)$$

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

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

ΔP_{tieij}^{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:

$$ACE_i = B_i \Delta f_i + \Delta P_{tieij}^{Error} \quad (8)$$

The total power supplied by ith GENCO is given by:

$$\Delta P_{gki} = \Delta P_{mki} + apf_{ki} \sum \Delta P_{UCi} \quad (9)$$

$$\text{Where } \Delta P_{mki} = \sum_{j=i}^N cpf_{ij} \Delta P_{Lcj} \quad (10)$$

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. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the LFC task, such that:

$$\sum_{j=1}^{m_i} apf_{ij} = 1 \quad (11)$$

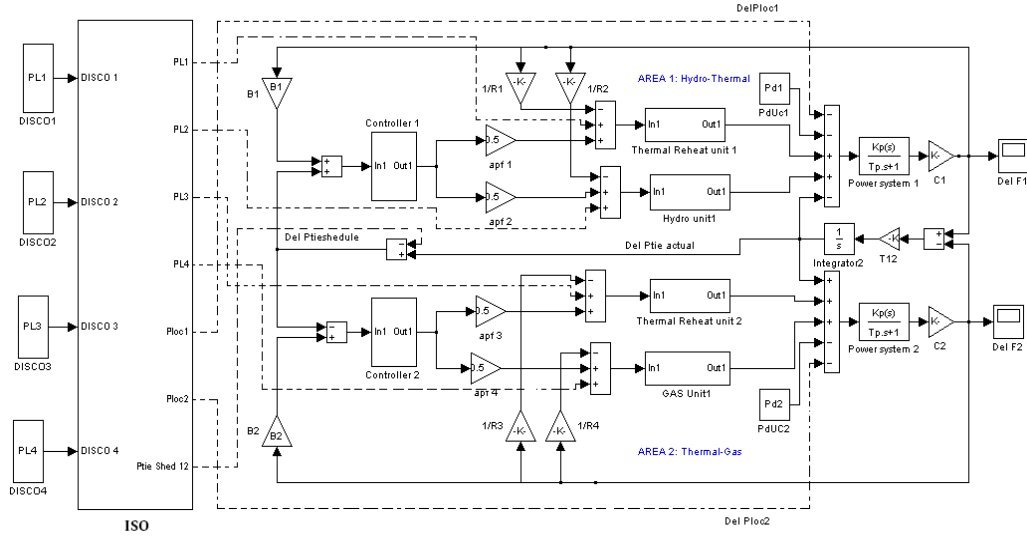


Fig. 1. Block diagram representation of two area Deregulated power system

3. AGC Controller

Several control strategy such as integral 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 integral 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 [7]-[9]. In this paper emphasis is made on application and optimization of Proportional-Integral-Derivative (PID) controller using evolutionary hybrid genetic firefly algorithm.

3.1. PID Controller

The most popular approach adopted for AGC in an inter-connected power system is the use of Proportional-Integral-Derivative (PID) controller [6]-[8]. 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 PID controller is given by:

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

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 classical numerical analyses is tedious and time consuming. In this strategy, using ITAE as a performance criterion to be optimize the PID gains are tuned using hybrid genetic-firefly algorithm to improve the dynamics of LFC in a deregulated power system.

4. Evolutionary Hybrid genetic-firefly algorithm

4.1. 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 [9], [13], [19]. 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.

4.1.1. 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 gains of the PID controller parameters: proportional (K_p), Integral (K_i), Derivative (K_d), of PID controller is modeled as its genes.

4.1.2. 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:

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

Where $e(t)$ = error considered.

The fitness function to be minimized is given by:

$$J = \int_0^{Tsim} (\sum ACE_i) dt + FD \quad (14)$$

$$\text{Where } FD = \alpha_1 OS + \alpha_2 TS \quad (15)$$

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

4.1.3. 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 [9], [13],[19]. 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.

4.1.4. 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], [13], [19]. In this paper simple arithmetic crossover is adopted.

4.1.5. 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],[19]. In the proposed work Uniform mutation is adopted.

4.1.6. Elitism

Elitism is a technique to preserve and use previously found best solutions in subsequent generations of

EA [9], [13]. In an elitist EA, the population's best solutions cannot degrade with generation.

4.2. Firefly Algorithm (FA)

The Firefly Algorithm (FA) is a metaheuristic, nature-inspired, optimization algorithm which is based on the social flashing behaviour of fireflies, or lighting bugs. It was developed by Dr. Xin She Yang at Cambridge University in 2007, and it is based on the swarm behaviour such as fish, insects, or bird schooling in nature [5]. Its main advantage is the fact that it uses mainly real random numbers, and it is based on the global communication among the swarming particles i.e., the fireflies, and as a result, it emerges as an effective for multi objective optimization. The flashing light is produced by a process of bioluminescence, and serves as the functioning signals to attract (communication), mating partners and to attract potential prey. In addition, flashing may also serve as a protective warning mechanism. The light intensity at a particular distance from the light source follows the inverse square law. That is as the distance increases the light intensity decreases. Furthermore, the air absorbs light which becomes weaker and weaker as there is an increase of the distance. The flashing light can be formulated in such a way that it is associated with the objective function to be optimized. This makes it possible to formulate new metaheuristic algorithms [5], [16], [17].

The firefly algorithm has three particular idealized rules which are based on some of the major flashing characteristics of real fireflies. These are the following:

1. All fireflies are unisex, and they will move towards more attractive and brighter ones regardless their gender.
2. The degree of attractiveness of a firefly is proportional to its brightness which decreases as the distance from the other firefly increases due to the fact that the air absorbs light. If there is not a brighter or more attractive firefly than a particular one, it will then move randomly.
3. The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem.

The main steps of the FA start with initializing a swarm of fireflies, each of which is determined the flashing light intensity. During the iterations a pairwise comparison of light intensity, the firefly with lower light intensity will move toward the higher one. The moving distance depends on the

attractiveness. After moving, the new firefly is evaluated and updated for the light intensity. During iteration process, the best-so-far solution is iteratively updated. The pairwise comparison process is repeated until termination criteria are satisfied.

4.2.1. Population initialization

Each encoded operation is randomly selected and sequenced until all operations are drawn in order to create a firefly, which represents a candidate solution. This random selection is repeated to generate a swarm of fireflies with the required size. The population generated in Genetic algorithm is used as initial population for Firefly algorithm.

4.2.2. Firefly evaluation:

The next stage is to measure the flashing light intensity of the firefly, which is the objective function to be optimized. The objective functions defined by the equations (13) to (15) were used for evaluation the light intensities of the fireflies.

4.2.3. Attractiveness

As light intensity decreases with the distance from its source and light is also absorbed in the media, so we should allow the attractiveness to vary with degree of absorption. The light intensity $I(r)$ varies with distance r monotonically and exponentially. That is:

$$I = I_0 e^{-\gamma r} \quad (16)$$

Where I_0 the original light intensity and γ is the light absorption coefficient. As firefly attractiveness is proportional to the light intensity seen by adjacent fireflies, thus the attractiveness β of a firefly can be defined by

$$\beta = \beta_0 e^{-\gamma r^m} \quad m > 1 \quad (17)$$

Where, r_{ij} is the distance between any two fireflies, β_0 is the initial attractiveness at $r=0$, and γ the absorption coefficient which controls the decrease of the light intensity.

4.2.4. Distance

The distance between any two fireflies i and j , at positions x_i and x_j , respectively, can be defined as a Cartesian or Euclidean distance as follows

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2} \quad (18)$$

4.2.5. Movement:

The movement of a firefly i which is attracted by a more attractive (i.e., brighter) firefly j is given by the following equation

$$x_{i+1} = x_i + \beta_0 e^{-\gamma r^2} (x_j - x_i) + \alpha (\text{rand} - 0.5) \quad (19)$$

The second term is due to the attraction while the third term is the randomization with α being the randomization parameter.

4.3. Hybridization

The main motivation for the hybridization of different algorithmic concepts is to exploit and combine the advantages of individual algorithm strategies. Firefly algorithm has some disadvantage such as trapping into several local optimums. Firefly algorithm do local search as well and sometimes can't get rid of them. In order to enhance global search and generate new solutions in Firefly algorithm is to combine genetic algorithm with firefly algorithm for a new generation which may find better solutions and make a balance between global and local search. Also it can get rid of trapping in to several local optimums. In this algorithm the idealized rules of the firefly algorithm is combined together with the evolutionary strategy, i.e. the survival of the fitness strategy of the genetic algorithm. Genetic algorithm searches the solution space for global minimum and the Firefly algorithm improves the precession of the potential candidate solution. Schematically, the hybrid Genetic-Firefly algorithm (GA-FA) can be summarized as the pseudo code:

Begin

Define the objective function $F(x)$:

Generate initial population of fireflies x_i ; $i=1, 2, \dots, n$

Light intensity/Fitness value of population i is determined by objective function $F(x_i)$

Define the firefly algorithm parameters α , γ , β_0 .

Define Genetic algorithm parameters p_c , p_m

While $itr \leq Maxgen$

Apply evolutionary Genetic algorithm operators

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

Crossover: Generate an offspring population Child,

if $pc > \text{rand}$,

Choose one best solutions x from the population based on the light intensity/fitness value and random solution y from the population for crossover operation. Using a crossover operator, generate offspring and add them back into the population.

Child₁ = r parent₁ + $(1 - r)$ parent₂;

Child₂ = r parent₂ + $(1 - r)$ parent₁;

end if

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
 for $i=1:n$
 for $j=1:n$
 Light intensity $I(x)$ is determined by objective function $F(x_i)$
 If $I_i < I_j$
 Then move firefly i towards firefly j (move towards brighter one)
 end if
 Attractiveness varies with distance r via $\exp[-\gamma r]$
 Evaluate new solutions and update light intensity
 end for j loop
 end for i loop
 Fitness assignment: Evaluate new solutions and update light intensity.
 Stopping criterion: If the maximum number of generations has reached then terminate the search otherwise go to next iteration
 end while
 end

5. Simulation

The dynamic performance is investigated on a two area power system consisting two GENCOs and two DISCOs in each area with each GENCO demanding a load demand of 0.1pu MW contracted towards the GENCOs according to the Bilateral contracts established between various GENCOs and DISCOs.

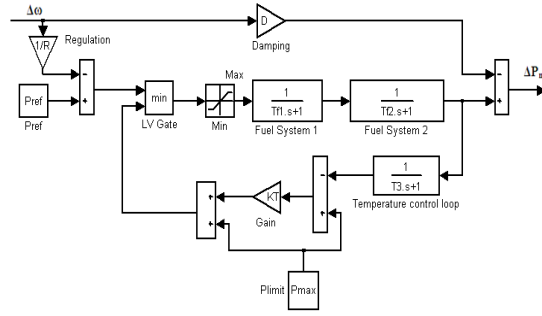


Fig.2. GAST Governor model

The GAST model [14], [15] used for simulation studies for representing the dynamic behavior of gas power turbine governor systems is shown in Fig.2. The simulation is done in MATLAB / SIMULINK platform.

5.1. 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 I and II.

$$DPM = \begin{bmatrix} 0.40 & 0.25 & 0.00 & 0.30 \\ 0.30 & 0.25 & 0.00 & 0.00 \\ 0.10 & 0.25 & 0.50 & 0.70 \\ 0.20 & 0.25 & 0.50 & 0.00 \end{bmatrix}$$

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.6:

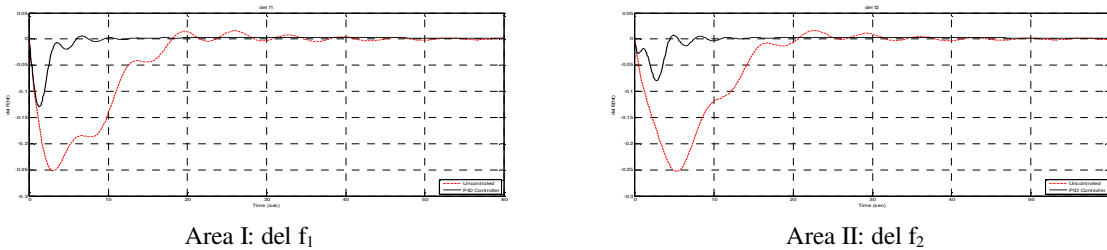


Fig. 3. Frequency deviations in two areas

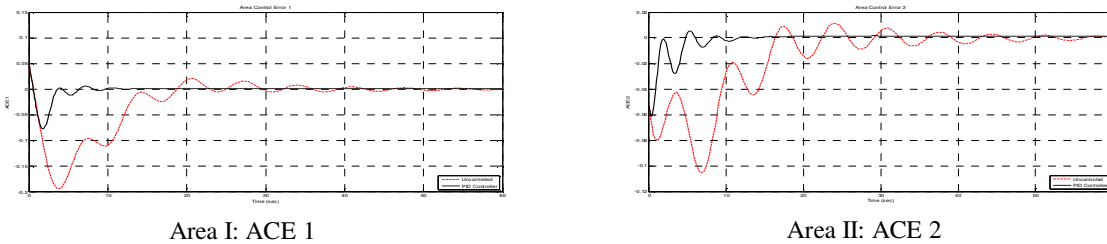
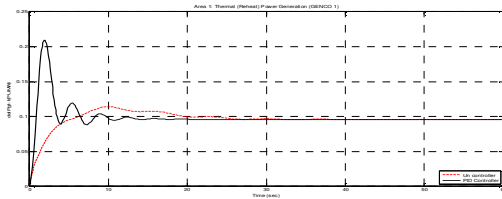
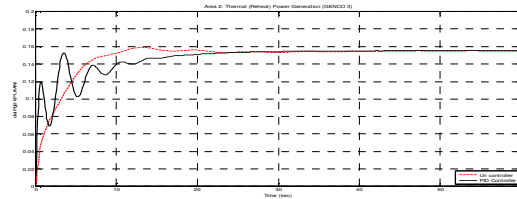


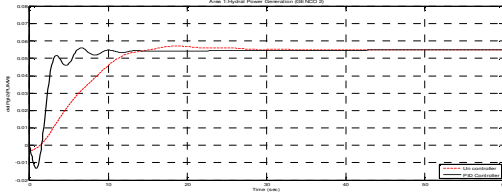
Fig. 4. Area Control Error (ACE) in two areas



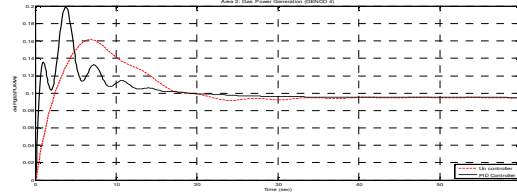
Area I: GENCO 1



Area II: GENCO 3



Area I: GENCO 2



Area II: GENCO 4

Fig. 5. GENCOs Power generation in two areas

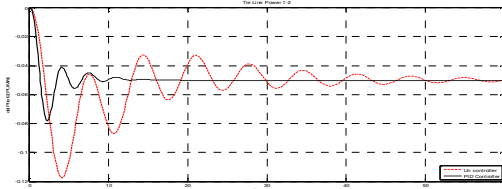


Fig. 6. Tie-line power deviations

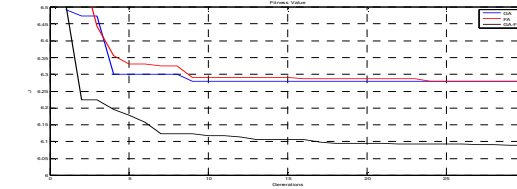


Fig. 7. Convergence characteristics

6. Results and Discussions

The simulation results shown in Fig. 3 demonstrate the frequency deviations in two areas, following a load demand of 0.1 pu MW step load demand contracted by DISCOs in each area. It can be seen that the dynamics of the frequency with respect to its peak overshoot and settling time is improved considerably with PID controller and at steady state the frequency of each GENCO is back to its nominal values. Fig.5 shows the change in generation of GENCOs according to the schedule governed by the ISO. At steady state the generation of each GENCO matches the load contracted by DISCOs as scheduled by ISO. Due to the bilateral contracts existing between GENCOs and DISCOs of interconnected areas, the tie-line power converges to scheduled values at steady state shown in Fig.6. The generation of various GENCOs and tie-line power in the interconnector is summarized in the table-1.

Table 1: GENCOs Power Generation

	Scheduled	PID Control
GENCO 1	0.095	0.095
GENCO 2	0.055	0.055
GENCO 3	0.155	0.155
GENCO 4	0.095	0.095
del Ptie 1-2	-0.05	-0.05

The optimal value of the controller obtained by the proposed Hybrid Genetic-Firefly algorithm for the

considered operating condition is summarized in the table 2.

Table 2: Optimal values of PID Controller

Scenario	Area I			Area II		
	Kp	Ki	Kd	Kp	Ki	Kd
Bilateral contracts	-9.8	-0.077	-4.51	-9.05	-0.18	-5.38

The time domain specification such as Overshoot and settling time for frequency dynamics for the operating conditions considered is shown in table 3.

Table 3: Time domain specifications

	Uncontrolled case		PID Control	
	Maximum frequency excursion (Hz)	Settling time (sec)	Maximum frequency excursion (Hz)	Settling time (sec)
del f_1	0.2524	18.24	0.1297	6.93
del f_2	0.2531	16.56	0.0794	9.00

The performance measure ITAE for frequency deviations is calculated for the considered operating conditions and the results are tabulated in table 4.

Table 4: Performance measure for frequency deviations

		uncontrolled	PID Control
Bilateral contracts	del f_1	11.5031	1.86
	del f_2	11.2082	1.71

7. Conclusions

From simulation results the dynamic response obtained for various operating conditions, it is inferred that the implementation of PID controller optimized by proposed Genetic-Firefly Algorithm results in an appreciable improvement in dynamics of frequency and tie-line oscillations, reduction in magnitude of overshoot, converging to the nominal values at steady state within convincing settling time. The simulation results show the ability of the controller to track the load scheduled by ISO effectively and holding the frequency of GENCOs and tie-line power in the interconnectors at their nominal values. From the convergence characteristics it is inferred that the proposed algorithm converges rapidly to the optimal solution with in less number of iterations and search the optimal parameters precisely. The overall performance of PID controller tuned by the proposed algorithm exhibits improved dynamic performance over a wide range of operating conditions.

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