Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

Shaik Farook ¹, Dr. P. Sangmeswara Raju ²

¹Research Scholar, Department of Electrical and Electronics Engineering, S.V. U College of Engineering, S.V. University, Tirupathi, Andhra Pradesh, India.
E-mail: farook_208@yahoo.co.in

²Professor, Department of Electrical and Electronics Engineering, S.V. U College of Engineering, S.V. University, Tirupathi, Andhra Pradesh, India.
E-mail: raju_ps_2000@yahoo.com

Abstract—This paper presents the application of Fractional Order PID controller as a supplementary controller to improve the dynamics of LFC in multi area deregulated power system. FOPID is a PID controller whose derivative and integral orders are of fractional rather than integer. The extension of derivative and integration order from integer to fractional order provides more flexibility in design of the controller, thereby controlling the wide range of dynamics of a system. Using ITAE as performance criteria to be optimize, the FOPID controller parameters: proportional (K_p), Integral (K_i), Derivative (K_d), integral order (λ), and the derivative order (µ) operators are optimized using Evolutionary Real coded Genetic Algorithm (GA) and Firefly algorithm (FA) as a hybrid algorithm (GA-FA). The feasibility and robustness of the controller is investigated on a three-area interconnected power system consisting of Thermal-Thermal unit in area-I, Hydro-Thermal unit in the area-II and Thermal-Gas unit in area-III. The dynamics of frequency deviations and tie-line power deviations were investigated by considering the possible contracts between various GENCOs and DISCOs of multi area deregulated power system using DISCO participation matrix (DPM). The simulation results show the proposed FOPID controller tuned by the proposed Hybrid Genetic-Firefly algorithm (GA-FA) exhibits improved dynamic performance over conventional PID controller.

Keywords –Automatic generation control, Deregulated Power System, FOPID controller, Hybrid GA-FF Algorithm, LFC Dynamics.

I. INTRODUCTION

Automatic generation control in deregulated power system is one of the most important ancillary services to be maintained for minimizing frequency deviations, imbalances of generation and load demand, for regulating tie-line power exchange, 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 motivated restructuring of the power sector. In deregulated scenario, market operators such as independent system operator (ISO) is responsible to perform the operational planning to determine the ancillary services that are required to maintain the real time balance between generation and load for minimizing frequency deviations and regulating tie-line, facilitating bilateral contracts spanning over various control areas, provide adequate security level for anticipated energy transactions, network configuration, and disturbance scenarios. 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 during emergency, due to their high operating costs and limited power outputs. With the advent of gas turbines with rating of well over 500 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 [18]-[19]. 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.

In this paper a fractional order controller is proposed as a supplementary controller to improve the dynamics of load frequency control. In recent years fractional order controller finds potential applications in the field of engineering and science [6]-[7], [23]-[27]. The FOPID controller is the expansion of the conventional PID controller based on fractional calculus. In FOPID besides proportional ($K_p$), integral ($K_i$) and derivative ($K_d$) gains, the controller has two more parameters: integral order ($\lambda$) and derivative order ($\mu$) as design specifications which provide greater flexibility in controller design.

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 fundamental mathematical concepts of fractional order controllers were discussed in brief. In section IV, the fractional order controllers as a supplementary controller for maintaining the LFC regulation is discussed. Section V presents an overview of the proposed Genetic-Firefly Algorithm and its implementation aspects. The section VI emphasizes on the simulation of the controller with the proposed algorithm in a three area deregulated power system. Finally the results, discussions and conclusions were presented in section VII and VIII.

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], [14]. 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] - [6], [11]-[17]. 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 or with other areas. Thus, there can be various combinations of the possible contracted scenarios between DISCOs and GENCOs. 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 particularGENCO 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 DISCO, these demands are specified by contract participation factors and the pu MW load of a DISCO. Information signals must flow from a DISCO to a particular GENCO specifying corresponding demand. Thesesignals will carry information as to which GENCO has to follow a load demanded by which DISCO. The block diagram modal of three area deregulated power system is depicted in Fig. 1.

The concept of DISCO Participation Matrix (DPM) [1], [2], [14], [15] 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$_i$ towards any GENCO$_j$. The DPM is defined by the matrix:
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

\[ DPM = \begin{bmatrix}
  cpf_{11} & cpf_{12} & cpf_{1j} & \cdots & cpf_{1n} \\
  cpf_{21} & cpf_{22} & cpf_{2j} & \cdots & cpf_{2n} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  cpf_{n1} & cpf_{n2} & cpf_{nj} & \cdots & cpf_{nn}
\end{bmatrix} \tag{1} \]

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

\[ \sum_j cpf_{ij} = 1 \tag{2} \]

Under steady state the power equations in deregulated environment are,

\[ \Delta P_{di} = \Delta P_{Loci} + \Delta P_{wci} \tag{3} \]

Where

\[ \Delta P_{Loci} = \sum \Delta P_{Lei} \quad \text{(Contracted load demand)} \tag{4} \]

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

\[ \Delta P_{tied}^{\text{scheduled}} = \text{(Demand of DISCOs in area } j \text{ from GENCOs in area } i) - \text{(Demand of DISCOs in area } i \text{ from GENCOs in area } j) \tag{5} \]

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

\[ \Delta P_{tied}^{\text{actual}} = \frac{2\pi T_{ij}}{S} \left[ \Delta f_i - \Delta f_j \right] \tag{6} \]

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

\[ \Delta P_{tied}^{\text{Error}} = \Delta P_{tied}^{\text{actual}} - \Delta P_{tied}^{\text{scheduled}} \tag{7} \]
\( \Delta P_{\text{Error}} \) 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:

\[
ACE_i = B_i \Delta f_i + \Delta P_{\text{Error}}^{ij}
\]  

(8)

The total power supplied by \( i^{th} \) GENCO is given by:

\[
\Delta P_{gki} = \Delta P_{mki} + apf_{ij} \sum \Delta P_{Uji}
\]  

(9)

Where

\[
\Delta P_{mki} = \sum_{j=1}^{N} cpf_{ij} \Delta P_{Lkj}
\]  

(10)

\( \Delta P_{gki} \) is the desired total power generation of a GENCO 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:

\[
\sum_{j=1}^{N} apf_{ij} = 1
\]  

(11)

III. FRACTIONAL ORDER CALCULUS

Fractional calculus is a field of mathematical analysis which studies the ability of taking real number power of the differential operator and integration operator. There are many definitions used to describe the fractional order function [23]-[26]. The well-established definitions include the Cauchy integral formula, the Grunwald–Letnikov definition, the Riemann–Liouville definition, and the Caputo definition. The Riemann–Liouville definition is the most frequently used definition in fractional-order calculus.

A. Grunwald-Letnikov: According to Grunwald-Letnikov generalization of fractional derivative and integration is as follows.

\[
D^\alpha f(x) = \lim_{h \to 0} h^{-\alpha} \sum_{m=0}^{\infty} \frac{(x-a)^m}{m! r(\alpha + m + 1)} f(x - mh)
\]  

(12)

for negative values of \( \alpha \)

\[
D^{-\alpha} f(x) = \lim_{h \to 0} h^{-\alpha} \sum_{m=0}^{\infty} (-1)^m \frac{r(\alpha + m)}{m!} f(x - mh)
\]  

(13)

B. Riemann - Liouville Derivative: Riemann-Liouville derivative is the most used generalization of the derivative. It is based on Cauchy’s formula for calculating iterated integrals. According to Riemann-Liouville derivative,

\[
D^\alpha f(x) = \frac{1}{\Gamma(\alpha)} \int_0^x \frac{f(t)}{(x-t)^{\alpha-1}} dt
\]  

(14)

C. Domain Transforms: The Laplace and Fourier transforms that serve to transform to the frequency domain can be used to get generalizations of the derivative valid for functions that allow such transformations. For fractional calculus the Laplace transform is defined as:

\[
L[D^\alpha f(x)] = s^\alpha F(s) - \sum_{m=0}^{n-1} s^m [D^{\alpha-m-1} f(0)]
\]  

(15)

IV. FRACTIONAL ORDER PID CONTROLLER

The classical Proportional-Integral-Derivative controller is most widely used controller for industrial applications due to its simplicity in realization and tuning. The extension of derivative and integration order from integer to fractional order provides more flexibility in design of the controller, thereby controlling the wide range of dynamics of a system [6], [7]. In fractional order controller besides proportional (\( K_p \)), Integral (\( K_i \)) and Derivative (\( K_d \)) constants the controller have additional integral order (\( \lambda \)), and the derivative order (\( \mu \)), thus the use of two extra operators adds two more degree of freedom to the controller and makes it possible to further improve the
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

performance of the traditional PID controllers [23]. Fractional order differential equation is used to describe the fractional order Proportional-Integral-Derivative controller (P$^\lambda$I$^\mu$D$^\nu$).

The differential equation of fractional order controller is described as

$$u(t) = -\left[K_p + K_i\frac{1}{s} + K_d s\right]e(t)$$  \hspace{1cm} (16)

Where $e(t)$ is the error signal and $u(t)$ is the control signal. The continuous transfer function of the FOPID controller is given by:

$$G_c(s) = -\left[K_p + \frac{K_i}{s^\lambda} + K_d s^\nu\right]e(t)$$  \hspace{1cm} (17)

As shown in Fig.2 the FOPID controller generalizes the conventional integer order PID controller and expands it from point to plane. This extension of integral and derivative order will provide much more flexibility and accuracy in PID controller design [25]. The optimal values of FOPID controller parameters for minimizing the fitness function are tuned using an Evolutionary Real Coded Genetic Algorithm (GA) and Firefly Algorithm (FA) as a hybrid evolutionary algorithm.

V. EVOLUTIONARY HYBRID GENETIC-FIREFLY ALGORITHM

In traditional methods such as sequential optimization approach require several iterations 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 [3]. The evolutionary algorithms such as Hybrid Genetic-Firefly algorithms emerges as an alternative for optimizing the controller gains of a multi-area AGC system more effectively than the traditional methods.

A. 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], [12], [28]. 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.

A.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 [12]. The chromosome consisting of
gains: proportional ($K_p$), Integral ($K_i$), Derivative ($K_d$), integral order ($\lambda$), and the derivative order ($\mu$) operators of FOPID controller is modeled as its genes.

A.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 \cite{1}, \cite{2}. An optional penalty term is added to take care of the transient response specifications viz. settling time, over shots, etc. Integral of Time multiplied Absolute value of the Error (ITAE), is given by:

$$ITAE = \int_0^{T_{sim}} t|e(t)| \, dt$$

(18)

Where $e(t)$= error considered.

The fitness function to be minimized is given by:

$$J = \int_0^{T_{sim}} \left( \sum ACE_i \right) \, dt + FD$$

Where $FD=\alpha_1 \text{OS} + \alpha_2 \text{TS}$

(19)

(20)

Where Overshoot (OS) and settling time (TS) for 2% band of frequency deviation in both areas is considered for evaluation of the FD \cite{13}.

A.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 \cite{4}, \cite{11}, \cite{12}. 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.

A.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 parent’s coding \cite{12}, \cite{14}. In this paper simple arithmetic crossover is adopted.

A.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 \cite{12}. In the proposed work Uniform mutation is adopted.

A.6. Elitism

Elitism is a technique to preserve and use previously found best solutions in subsequent generations of EA \cite{10}, \cite{12}. In an elitist EA, the population’s best solutions cannot degrade with generation.

B. 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 \cite{8}. 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 \cite{8}, \cite{21}, \cite{29}. 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.

B.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.

B.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 (18) to (20) were used for evaluation the light intensities of the fireflies.

B.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:

\[
I = I_0 e^{-\gamma r}
\]  

(21)

Where \( I_0 \) the original light intensity and \( \gamma \) is the light absorption coefficient. As firefly attractiveness is proportional to the light intensity seen by adjacent fireflies, thus the attractiveness \( \beta \) of a firefly can be defined by:

\[
\beta = \beta_0 e^{-\gamma r^m}
\]  

(22)

Where, \( r_{ij} \)is the distance between any two fireflies, \( \beta_0 \) is the initial attractiveness at \( r = 0 \), and \( \gamma \) the absorption coefficient which controls the decrease of the light intensity.

B.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:

\[
r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{ik} - x_{jk})^2}
\]  

(23)

B.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:

\[
x_{i+1} = x_i + \beta_0 e^{-\gamma r^m}(x_j - x_i) + \alpha (r_{rand} - 0.5)
\]  

(24)

The second term is due to the attraction while the third term is the randomization with \( \alpha \) being the randomization parameter.

C. 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-Fireflyalgorithm (GAFA) can be summarized as the pseudo code:

begin
Define the objective function \( F(x) \):
Generate initial population of fireflies \( x_i \); \( i = 1, 2, \ldots, n \)
Light intensity/Fitness value of population \( i \) is determined by objective function \( F(x_i) \)
Define the firefly algorithm parameters \( \alpha, \gamma, \beta_0 \).
Define Genetic algorithm parameters \( pc, pm \).
While \( irr \leq Maxgen \)
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 \( pc > rand \)
Choose one best solutions \( x \) from the population based on the light intensity/fittest value and random solution \( y \) from the population for crossover operation. 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
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
Algorithm 1: Hybrid Genetic-Firefly Algorithm

VI. SIMULATION

To investigate the performance of the proposed control strategy, a three-area interconnected power system consisting of Thermal-Thermal unit in area-I, Hydro-Thermal unit in the area-II and Thermal-Gas unit (GAST modal) in area-III is considered. In each area two GENCOs and two DISCOs are considered with each GENCO demanding a load demand of 0.1puMW contracted towards the GENCOs according to the bilateral contracts established between various GENCOs and DISCOs. Using ITAE as performance criteria to be optimize, the FOPID controller parameters: proportional \( (K_p) \), Integral \( (K_i) \), Derivative \( (K_d) \), integral order \( (\lambda) \), and the derivative order\( (\mu) \) operators are optimized using proposed Evolutionary Hybrid Genetic-Firefly algorithm. The simulation is done in
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

MATLAB 7/SIMULINK platform and the power system parameters [1], [18] used for simulation were presented in appendix A. The GAST model [16], [17] for simulation studies describing the dynamic behavior of gas power turbine governor systems is shown in Fig.3.

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

\[
\begin{align*}
apf_1 &= 0.5 \\
apf_2 &= 1 - apf_1 = 0.5 \\
apf_3 &= 0.5 \\
apf_4 &= 1 - apf_3 = 0.5 \\
apf_5 &= 0.5 \\
apf_6 &= 1 - apf_5 = 0.5
\end{align*}
\]

A. Scenario I: POOLco Transactions

In this scenario, GENCOs participate in the load following control of their areas only. The DISCOs demands/asks power from GENCOs in its own areas only. It is assumed that a large step load 0.1 pu MW is demanded by each DISCO in each area. The case of POOLco based contracts between DISCOs and available GENCOs are simulated using the following DPM.

\[
\begin{array}{cccccccc}
0.50 & 0.50 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.50 & 0.50 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.50 & 0.50 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.50 & 0.50 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.50 & 0.50 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.50 & 0.50
\end{array}
\]

The frequency deviations of three areas, GENCOs power generation, Tie-line power flow and Area control error for the given operating conditions is depicted in Fig.4 to Fig.6.

Figure 3. GAST Governor model

The frequency deviations in three areas

Figure 5. Tie-line power deviations
B. Scenario II: 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 within the area and with interconnected areas for power as per following DPM. All GENCOs participate in the LFC task. It is assumed that a large step load 0.1 pu MW is demanded by each DISCOs in three areas according to the bilateral contracts:

\[
\text{DPM} = \begin{bmatrix}
0.25 & 0.00 & 0.25 & 0.00 & 0.50 & 0.00 \\
0.50 & 0.25 & 0.00 & 0.25 & 0.00 & 0.00 \\
0.00 & 0.50 & 0.25 & 0.00 & 0.00 & 0.00 \\
0.25 & 0.00 & 0.50 & 0.75 & 0.00 & 0.00 \\
0.00 & 0.25 & 0.00 & 0.00 & 0.50 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00
\end{bmatrix}
\]

The frequency deviations of three areas, GENCOs power generation, Tie-line power flow and Area control error for the given operating conditions is depicted in Fig.7 to Fig.9.
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

C. Scenario III: Contract violation

It may happen that a DISCO violates a contract by demanding more power than that specified in the contract. Consider scenario B with a modification that DISCOs in each area demand additional 0.01 pu MW of uncontracted power in excess. Let $\Delta P_{\text{L,uc}}=0.01\text{pu}$. This excess power should be supplied by only contracted GENCOs in its own area and the power exchange in the interconnectors should remain unchanged. The frequency and Tie-line deviations, Area control error and power generated by GENCOs were depicted in Fig: 10 to Fig. 12.

Figure 9: GENCOs Power generation in three areas

Figure 10: Frequency deviations in three areas
VII. RESULTS AND DISCUSSIONS

A. Scenario I:

In this scenario the POOLco based transactions between the GENCOs and DISCOs were simulated with each DISCO demanding a load demand of 0.1 pu MW. Fig. 4 demonstrates the frequency deviations in three areas, following a load demand contracted by each DISCO in three areas. It can be seen that the dynamics of the frequency with respect to its peak overshoot, settling time and maximum frequency excursion is improved considerably compared with PID controller and at steady state the frequency of each GENCO is back to its nominal values. The steady state the generation of each GENCO for the POOLco transactions is shown in Fig. 6. From simulation results it is observed that the load demanded by the DISCOs is supplied by the DISCOs in its own area as scheduled by the ISO. Since there is no bilateral transactions the tie-line power in the interconnectors is converged to zero as shown in Fig. 5. The generation of various GENCOs and tie-line power in the interconnectors is summarized in the table-1.

B. Scenario II:

In this scenario the DISCO and GENCO will have contracts within its own area or with interconnected area and thus the power is exchanged between the interconnected areas according to the contracts scheduled between them. For the bilateral contracts considered the simulation results shows the ability of the FOPID controller to track the load demand effectively and holding the frequency of GENCOs and tie-line power in the interconnectors at their nominal values. At steady state the tie-line power exchange and the generation of each GENCO for the bilateral transactions is shown in Fig. 8 and Fig. 9 respectively. The generation of various GENCOs and tie-line power in the interconnectors is summarized in the table-1.

C. Scenario III:

The purpose of this scenario is to test the effectiveness of the proposed controller to track the load demands by GENCOs as scheduled by ISO in the event of contract violation by the DISCOs in each area. From simulation results it is observed that the excess power demanded by the DISCOs is supplied by the GENCOs in its own areas and the power exchanged in the interconnectors remains unchanged at the scheduled value as in the scenario II. At steady state the tie-line power exchange and the generation of each GENCOs for the scenario is shown in Fig. 11 and Fig. 12 respectively. The generation of various GENCOs and tie-line power in the interconnectors is summarized in the table-1.

Table 1: GENCOs power generation and Tie-line Power exchange for different scenarios
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario I: POOLco Transactions</th>
<th>Scenario II: Bilateral Transactions</th>
<th>Scenario III: Contract Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scheduled</td>
<td>FOPID Control</td>
<td>Scheduled</td>
</tr>
<tr>
<td>GENCO 1</td>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>GENCO 2</td>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>GENCO 3</td>
<td>0.100</td>
<td>0.100</td>
<td>0.075</td>
</tr>
<tr>
<td>GENCO 4</td>
<td>0.100</td>
<td>0.100</td>
<td>0.150</td>
</tr>
<tr>
<td>GENCO 5</td>
<td>0.100</td>
<td>0.100</td>
<td>0.075</td>
</tr>
<tr>
<td>GENCO 6</td>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>del Ptie 1-2</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>del Ptie 2-3</td>
<td>0.000</td>
<td>0.000</td>
<td>0.025</td>
</tr>
<tr>
<td>del Ptie 3-1</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.025</td>
</tr>
</tbody>
</table>

The performance measure ITAE for frequency deviations is calculated for the considered operating conditions and the results are tabulated in table – 2. Following step load change in three areas, the FOPID controller has better performance over conventional PID controller.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Uncontrolled</th>
<th>PID Control</th>
<th>FOPID Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>del f1</td>
<td>6.351</td>
<td>1.892</td>
</tr>
<tr>
<td></td>
<td>del f2</td>
<td>15.734</td>
<td>1.685</td>
</tr>
<tr>
<td></td>
<td>del f3</td>
<td>15.096</td>
<td>1.778</td>
</tr>
<tr>
<td></td>
<td>del f1</td>
<td>5.779</td>
<td>2.901</td>
</tr>
<tr>
<td></td>
<td>del f2</td>
<td>20.851</td>
<td>3.145</td>
</tr>
<tr>
<td></td>
<td>del f3</td>
<td>19.834</td>
<td>2.980</td>
</tr>
<tr>
<td></td>
<td>del f1</td>
<td>6.076</td>
<td>1.489</td>
</tr>
<tr>
<td></td>
<td>del f2</td>
<td>14.420</td>
<td>1.032</td>
</tr>
<tr>
<td></td>
<td>del f3</td>
<td>13.750</td>
<td>0.960</td>
</tr>
</tbody>
</table>

The convergence characteristics of individual GA, Firefly and Hybrid GA-FA techniques are depicted in Fig. 13. From the convergence characteristics it is clear that the hybrid genetic-firefly algorithm convergence within less number of iterations to the optimal values precisely compared to the individual strategy.

The optimal value of the controller obtained by the proposed hybrid GA-FA algorithm for the various operating conditions is summarized in the table 3.
The dynamics of LFC in the restructured power system is implemented in this paper. The inclusion of integral order (in less number of iterations. The overall performance of FOPID controller tuned by the proposed algorithm exhibits convergence characteristics; it is inferred that the proposed algorithm converges rapidly to the optimal solution with contracts. The simulation results show the ability of the controller to track the load fluctuations effectively and controller by GA-FA algorithm was tested with different scenarios on three areas power system under possible 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 effectiveness and robustness of the proposed controller by GA-FA algorithm was tested with different scenarios on three areas power system under possible contracts. The simulation results show the ability of the controller to track the load fluctuations 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. The overall performance of FOPID controller tuned by the proposed algorithm exhibits improved dynamic performance over conventional PID controller over a wide range of operating conditions.

### VIII. CONCLUSIONS

A fractional order controller as supplementary controller based on fractional order calculus for improving the overall dynamics of LFC in the restructured power system is implemented in this paper. The inclusion of integral order (λ) and the derivative order (μ) adds two more degree of freedom to the controller design and makes it possible to further improve the performance of the system over conventional PID controller. Using ITAE as performance criteria the FOPID controller parameters are optimized using Evolutionary Genetic and Firefly algorithm as a hybrid algorithm. From simulation results the dynamic response obtained for various operating conditions, it is inferred that the implementation of FOPID controller optimized by Evolutionary GA-FA 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 effectiveness and robustness of the proposed controller by GA-FA algorithm was tested with different scenarios on three areas power system under possible contracts. The simulation results show the ability of the controller to track the load fluctuations 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. The overall performance of FOPID controller tuned by the proposed algorithm exhibits improved dynamic performance over conventional PID controller over a wide range of operating conditions.

### APPENDIX - A

<table>
<thead>
<tr>
<th>Area I</th>
<th>Scenario I POOLco transactions</th>
<th>Scenario II Bilateral transactions</th>
<th>Scenario III Contract Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area I</td>
<td>$G_c(s) = - \left[ 7.4 + \frac{0.132}{\lambda s^{0.5}} + 4.945 s^{0.95} \right]$</td>
<td>$G_c(s) = - \left[ 5.39 + \frac{0.32}{\lambda s^{0.77}} + 5.61 s^{0.78} \right]$</td>
<td>$G_c(s) = - \left[ 8.74 + \frac{0.316}{\lambda s^{0.597}} + 4.86 s^{0.83} \right]$</td>
</tr>
<tr>
<td>Area II</td>
<td>$G_c(s) = - \left[ 8.08 + \frac{0.44}{\lambda s^{0.53}} + 2.99 s^{1.2} \right]$</td>
<td>$G_c(s) = - \left[ 6.96 + \frac{0.28}{\lambda s^{0.25}} + 2.88 s^{0.47} \right]$</td>
<td>$G_c(s) = - \left[ 8.12 + \frac{0.45}{\lambda s^{0.53}} + 3.06 s^{1.25} \right]$</td>
</tr>
<tr>
<td>Area III</td>
<td>$G_c(s) = - \left[ 5.78 + \frac{0.304}{\lambda s^{0.42}} + 7.38 s^{0.65} \right]$</td>
<td>$G_c(s) = - \left[ 9.45 + \frac{0.2}{\lambda s^{0.72}} + 4.72 s^{0.52} \right]$</td>
<td>$G_c(s) = - \left[ 3.18 + \frac{0.42}{\lambda s^{0.53}} + 4.49 s^{0.78} \right]$</td>
</tr>
</tbody>
</table>

### IX. REFERENCES


ISSN: 2319-1112 /V1N3: 317-332 ©IJAEEE
Decentralized Fractional Order PID Controller for AGC in a Multi Area Deregulated Power System


