COORDINATED TUNING OF FRACTIONAL ORDER PID AND TCPAR IN A COMPOSITE DEREGULATED POWER SYSTEM USING EVOLUTIONARY DIFFERENTIAL ALGORITHM

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Abstract: *The paper concerns with the stabilizing the dynamics of Load Frequency Control (LFC) in a deregulated power systems using supplementary controller fortified by tie line control. In a composite deregulated power system consisting of diverse generation technologies, the load disturbances in an area will influence the frequency and hence tie line power exchange which may influence the security of the interconnected power system. In the present work, a non-integer order Proportional Integral and Derivative (PID) controller is used to regulate the LFC regulation which is further fortified by a Thyristor-Controlled Phase Angle Regulator (TCPAR) in tie-lines to damp the power swings. Using Integral Time Multiplied Absolute Error (ITAE), the control parameters were optimized using differential evolution algorithm. The methodology was implemented on a composite three area deregulated power system with different possible contracts between the GENCOs and DISCOs spanning over wide areas. The simulation result depicts the improved dynamic performance of LFC with Fractional Order PID (FOPID) and TCPAR controller over a wide operating range.*

Key words: *LFC dynamics, Composite deregulated power systems, FOPID, TCPAR, Differential Evolution algorithm.*

1. Introduction

The modern deregulated power system consisting of diverse bulk power generating plants such as gas turbines, conventional and other generation technologies operating in unison, participates in the task of load frequency control. Such a diverse composite power system responding to disturbance in any area invokes wide range of dynamics due to their different inertia and regulation characteristics. These dynamics of frequency and tie line power exchange must be regulated, which otherwise may leads to frequency collapse and forces island operation or may initiate a severe blackout in an interconnected power system [1]-[4]. Hence it is necessary to regulate and stabilize the frequency and tie-line oscillations. Responding to the disturbance, the primary governor control is initiated to regulate the frequency which is insufficient and hence a secondary controller is employed, which will act in the direction of primary control to regulate and restore the frequency back to the nominal value.

Over the decades several authors has proposed different types of control strategy such as optimal control, variable structure control, PID controller to regulate the frequency regulations in a deregulated power system. Among the various controllers PID controller is popularly used due to its simplicity in realization and modelling [5]-[6]. In PID controller the order of derivative and integral is integer rather than fraction, extending this derivative and integral order from integer to fractional order provide more flexibility in design of the controller thereby controlling the wide range of dynamics. In fractional order $(PI^{\lambda}D^{\mu})$, besides integral (K_I), proportional (K_p) and derivative gain (K_D), the controller has additional integral order (λ) and derivative order (μ) as two more parameters. Thus the use of two extra operators adds more degree of freedom in design and makes it possible to further improve the performance over traditional PID controller [11]-[13]. Such a supplementary controller when fortified with a FACTS devices used for power flow control and damping power oscillation is capable of further damping and stabilizing the frequency and tie-line oscillations in an interconnected power system [8]-[10]. In the present context, the dynamics of LFC were stabilized using FOPID controller further fortified with TCPAR. The controller parameters were optimized using differential evolution algorithm with IATE as an objective function.

The paper is organized as follows: Section II presents the concepts of deregulated power system. Section III, deals with the fundamentals of FOPID controller for LFC. In section IV, the TCPAR is addressed. Section V presents an overview of the differential evolution Algorithm and its implementation aspects. The section VI is emphasized on the simulation of the controller in a three area deregulated power system. Finally the results, discussions and conclusions were presented in section VII and VIII.

2. Multi area Deregulated power system

A deregulated power system in its state consists of unbundled vertical integrated utility as different entities such as ISO, DISCOs, TRANSCOs, GENCOs etc. each of them having distinct role to play in the deregulated power system [1]-[4], [18]. In deregulated power system the DISCOs spanning over wide areas makes prior contracts with the GENCOs in its own area or with interconnected areas to supply the regulation. The DISCOs having contracts with GENCOs in its own area is known as *Pool transactions* and the contracts with GENCOs of interconnected area are known as *Bilateral transactions*. The concept of contract participation matrix is implemented to model these contracts, in which the element of the array represents the fraction of load demanded by a DISCO from the concern GENCO [1]. In a deregulated power system each GENCO has to follow the load under contracts and also any un-contracted loads by DISCOs in its own area, thus at steady state the total power generation by an i^{th} GENCO is [18]:

$$\Delta P_{gki} = \Delta P_{mki} + apf_{ki} \sum \Delta P_{UCi} \tag{1}$$

Where $\Delta P_{mki} = \sum_{j=1}^{n} cpf_{ij} \Delta P_{LCj}$ is the scheduled contracted power and $apf_{ki} \sum \Delta P_{UCi}$ is the un-contracted power demands in its own area.

apf_{ki} is the participation of GENCOs in a area in LFC task and cpf_{ij} is the contract participation factor which corresponds to the fraction of total load contracted by any $DISCO_i$ towards a $GENCO_j$ in its own area or with interconnected area. At steady state the schedule contracted power exchange in the tie-line is given by:

$$\Delta P_{tie\,ij}^{scheduled} = \begin{pmatrix} Demand\ of\ DISCOs \text{ in } area - j \\ from\ GENCOs \text{ in } area - i \end{pmatrix} - \begin{pmatrix} Demand\ of\ DISCOs \text{ in } area - i \\ from\ GENCOs \text{ in } area - j \end{pmatrix} \tag{2}$$

and the tie-line deviations is given by

$$\Delta P_{tie\,ij}^{error} = \Delta P_{tie\,ij}^{actual} - \Delta P_{tie\,ij}^{scheduled} \tag{3}$$

The change in frequency and tie-line power exchange is combined together as a single variable known as Area Control Error (ACE), which is then given to the controller in each area to bring the changes in generation to minimize the mismatch between the load demand and generation. The area control error in each area is given by:

$$ACE_i = \Delta P_{tie\,ij}^{error} + \beta_i \Delta f_i \tag{4}$$

The detailed model of the composite three area deregulated power system modeled in SIMULINK platform is depicted in fig. 1.

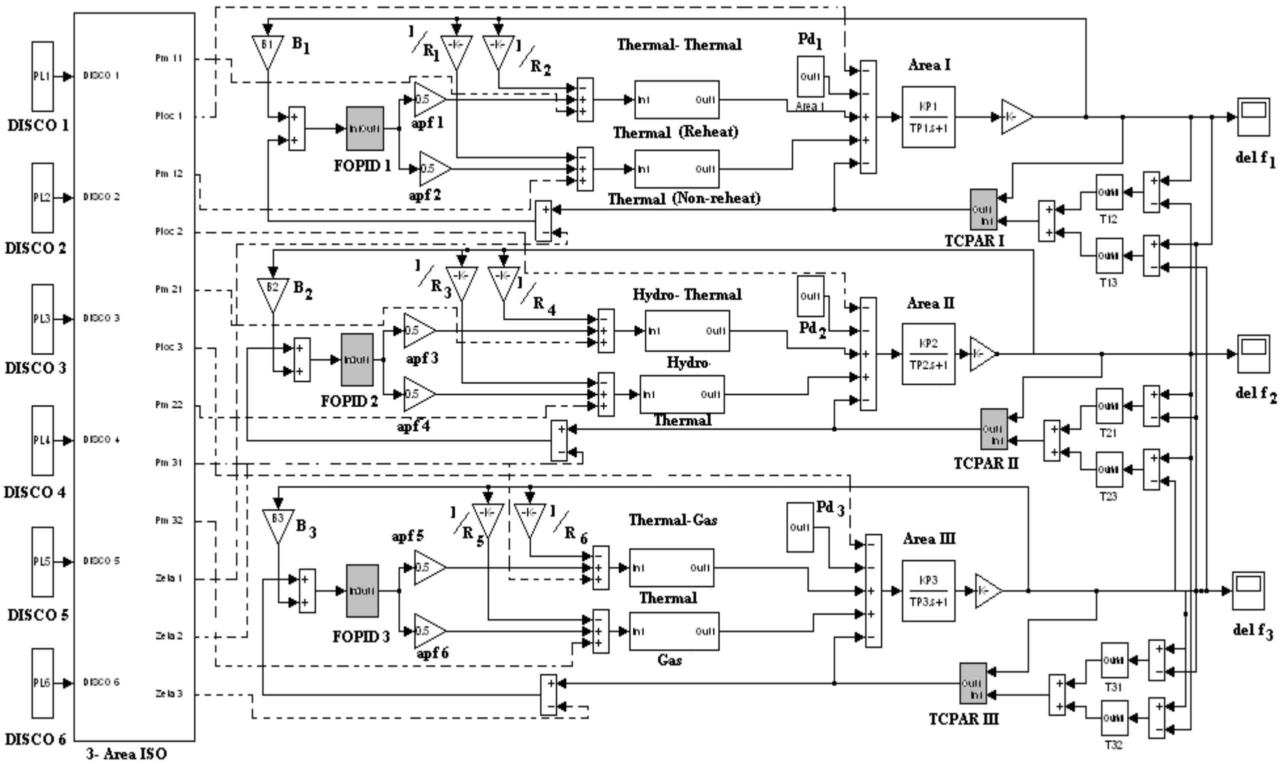

Fig.1. Three area composite deregulated power system

3. Fractional order controller

The conventional PID controller is most usual controller used in industrial applications due to its simplicity in modelling, implementation and tuning. A controller based on fractional order is implemented as a supplementary controller in the present context to optimize LFC regulations in a deregulated power system. Fractional Order Proportional-Integral-Derivative ($PI^{\lambda}D^{\mu}$) is a PID controller whose derivative and integral orders are of fractional rather than integers. With the inclusion of integral order (λ) and derivative order(μ) as a fraction, the controller has additional parameters to tune which allows more flexibility in design and to improve the wide operating space of the controller with respect to the load variations over conventional PID controller[11]-[13].

3.1 Fractional calculus

The fractional order controllers were originated from the branch of mathematics called Fractional calculus which deals with non-integer order derivatives and integrals. The earliest theoretical contributions in the domain were made by Euler and Lagrange and was further fortified by Liouville, Riemann and Holmgren. The results from Riemann and Liouville were unified and is accepted as the most admittable definition for fractional integral and derivatives [19].

For a primitive function $f(t)$ whose Laplace transform is $F(S)$, from the fundamentals, the Laplace inverse of n^{th} order integral operator $\frac{1}{S^n}, n \in R^+$ is expressed as:

$$\mathfrak{L}^{-1}\left\{ 1/S^n \right\} = \frac{t^{n-1}}{\Gamma(n)} \qquad (5)$$

The product of the Laplace functions $F(S)$ and $\frac{1}{S^n}$ in Laplace domain corresponds to convolution product in time domain, and is expressed as:

$$D^{-n} f(t) = \frac{t^{n-1}}{\Gamma(n)} * f(t) = \frac{1}{\Gamma(n)} \int_0^x f(t)(x-t)^{n-1} dt \quad (6)$$

Similarly the operator S^n in Laplace domain gives rise to an operator $\frac{d^n}{dt^n}$ in time domain. From the fundamentals, the iterating operation of fundamental derivative gives n^{th} derivative of the function is generalized as:

$$D^n f(x) = \lim_{h \to 0} h^{-n} \sum_{m=0}^{\infty} (-1)^m \frac{n!}{m!\Gamma(n-m+1)} f(x-mh) \quad (7)$$

The above equations (6) and (7) corresponds to Riemann–Liouville's definition for the fractional order integral and derivatives of order $n \in R^+$ respectively.

3.2 Fractional order PID Controller

The Differential equation used to describe the conventional PID controller is used to describe the fractional controller with integral and derivative orders as fractional. The differential equation for fractional controller is:

$$U_c(t) = \left(K_p e(t) + K_I D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \right) \qquad (8)$$

Applying Laplace transformation results in the transformed fractional PID controller with continuous transfer function of the controller given by:

$$G_c(s) = \left(K_p + \frac{K_I}{s^{\lambda}} + s^{\mu} K_d \right) \qquad (\lambda, \mu > 0) \quad (9)$$

The output of the controller is given by

$$U_c(s) = -\left(K_p + \frac{K_I}{s^{\lambda}} + s^{\mu} K_d \right) e(s) \qquad (10)$$

The error function $e(s)$ is modelled as the Area Control Error in each area. Therefore,

$$U_{ci}(s) = -\left(K_p + \frac{K_I}{s^{\lambda}} + s^{\mu} K_d \right) ACE_i \qquad (11)$$

The negative sign signifies that the real power command should decrease with an increase in frequency and should increase with decrease in frequency. The generalized fractional order PID controller is depicted in fig. 2.

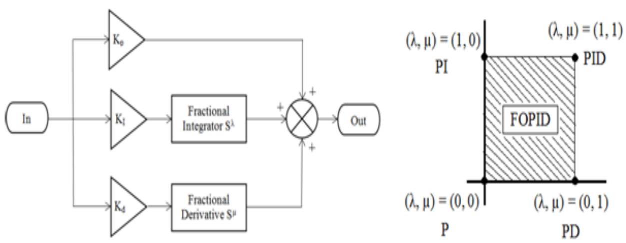

Fig.2. Generalized Fractional Order PID controller

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 the controller design.

3.3 Decision variables

In FOPID controller, the five parameters $(K_P, K_I, K_d, \lambda, \mu)$ in each area were tuned based on design specifications i.e. to improve the dynamics of LFC (Time domain specifications), to optimize the generation of various GENCOs and to regulate the power exchange in the interconnectors at the scheduled levels according to the contracts established between the GENCOs and DISCOs spanning over different control areas. Taking into account all of the constraints to meet, the optimal set of values $\left(K_P, K_I, K_d, \lambda, \mu\right)$ is investigated using differential evolution algorithm.

4. Thyristor controlled phase angle regulator

With the evolution of fast switching devices in power electronics leads to the development of advanced FACTS devices which are capable of controlling wide range of parameters to improve the overall dynamic and steady state behavior of the power system. In an interconnected power system, the tie-lines provided with such devices is capable of regulating the real power flow and also damp the power swings which arise due to the sudden load disturbance in any of the interconnected areas. TCPAR is a FACTS device that alters the relative phase angle between the system bus voltages and thus regulates the real power flow, provide power oscillation damping in the tie-line without deteriorating the system frequency [8]-[10].

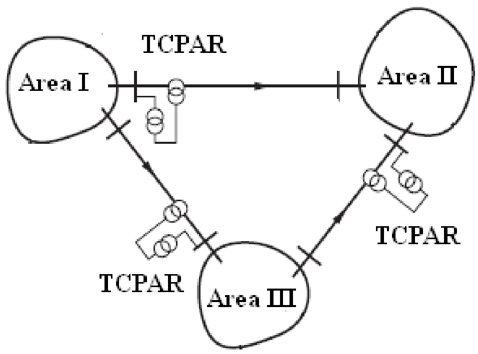

Fig.3. Test system with TCPAR in tie-lines

Typically, the TCPAR can be considered as a sinusoidal AC voltage source with controlled voltage magnitude and phase angle. TCPAR placed in the tie-line injects a voltage V_q which is in quadrature to the bus voltage V_i.

The phase angle of TCPAR is altered so as to increase the transmission handling capacity and also to regulate the power in tie-line. The TCPAR voltage is given by $V_{tcpar} = \gamma V_i$, where γ is the control variable [17].

From the phasor diagram shown in fig.4,

$$\left.\begin{aligned} Sin\theta &= \frac{V_q}{V_{Tcpar}} = \frac{\gamma V_i}{V_{Tcpar}} \\ Cos\theta &= \frac{V_i}{V_{Tcpar}} \end{aligned}\right\} \tag{12}$$

The real power flowing in the tie-line is given by

$$\begin{aligned} P_{tie\,ij} &= \frac{V_{tcpar} V_j}{X} Sin(\delta_{ij} + \theta) \\ &= \frac{V_{tcpar} V_j}{X}\left[Sin\delta_{ij} Cos\theta + Cos\delta_{ij} Sin\theta\right] \\ &= \frac{V_i V_j}{X} Sin\delta_{ij} + \gamma \frac{V_i V_j}{X} Cos\delta_{ij} \end{aligned} \tag{13}$$

The incremental change in the tie-line power is given by

$$\begin{aligned} \Delta P_{tieij} &= \frac{\partial P_{tieij}}{\partial \delta_{ij}} \Delta\delta_{ij} + \frac{\partial P_{tieij}}{\partial \gamma} \Delta\gamma \\ &= \frac{2\pi T_{ij}}{S}\left[\Delta f_i - \Delta f_j\right] + T_{ij} \Delta\gamma \end{aligned} \tag{14}$$

Where $T_{ij} = \frac{V_i V_j}{X} Cos\delta_{ij}$, the electrical stiffness of the tie-line connecting the areas i and j. Hence the power flow in the tie-line depends not only on power angle but also depends on the quadrature transformation ratio γ [17]. A schematic diagram of a TCPAR is shown in fig. 5. An integral type regulator with negative feedback is placed in the tie-line to regulate the real power flow and is vowed to damp the power swings in such a way that the frequency control executed by the central LFC is not disturbed. The input signals to the supplementary control are frequency deviations Δf_i in each area.

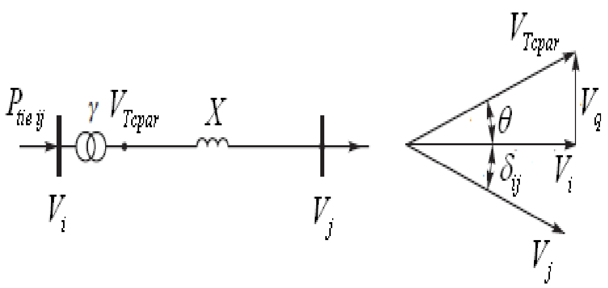

Fig.4. Single line diagram of TCPAR and phasor diagram

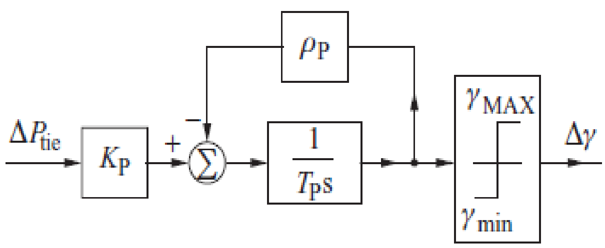

Fig.5. SIMULINK modal of TCPAR

5. Differential Evolution Algorithm

Differential Evolution algorithm is a stream of Evolutionary algorithms developed by Rainer Storn and Kenneth Price, for solving global optimal problems over continuous domain [19]. The conventional optimization techniques are based on trial and error method, such methods consumes huge computational time and cost to find the optimal solution, also they do not deal with the problems with multi modal optima or with discontinuities in the search space. The evolutionary algorithms, on the other hand carry out a global search by evolving new feasible solutions, and are well suitable for problems where the objective function is complex or does not exist in analytical form. Principally the differential evolution algorithm dominantly uses mutation as a search mechanism to produce diverse population and selection process to navigate the search towards the feasible solution in the most prominent region. The differential algorithm starts with initializing an initial population of uniformly randomized population NP, of D dimension, each individual is modelled as a string of decision variables called genome, encoded as a candidate solution $x_{i,g} = \{x_{i1}, x_{i2}, x_{i3}, \cdots\cdots x_{iD}\}$, where $i = 1, 2, \ldots, NP$. After the initializing the initial population, the DEA employs mutation, crossover and selection operations to generate new trial parameter vector [14]-[16], [19].

5.1. Mutation Operation

In each generation, NP competitions are held to determine the composition of the next generation. From the current population a parent vector known as target vector is selected for the mutation to form a trial vector. Among the various variants of DE, "DE/best/1" is used for generating the trial vector. In the strategy, a pair of vectors $x_{r,a}$ and $x_{r,b}$ are randomly selected from the current population and their scaled difference is added to the best parent $x_{i,best}$ to evolve the new trial vector. The strategy is expressed as:

$$v_{i,g} = x_{i,best} + F * (x_{r,a} - x_{r,b}) \tag{15}$$

Where F is the scaling factor which controls the length of the exploration vector and determines how far from point x_i the offspring should be generated. $x_{i,best}$ is the solution with best performance based on the fitness among the individuals of the population [14]-[16].

5.2. Crossover Operation

In order to acquaint population diversity, crossover operation is implemented after mutation. In every generation the target vector is combined with the mutant to form another trial vector u_{ig}. Popularly, the DE employs exponential crossover and binomial crossover mechanism for generating new solutions. Based on the crossover rate, binomial crossover is performed, in which operator copies a parameter from mutant vector if, $rand < CR$ otherwise the parameter is copied from the corresponding target vector[14]-[16]. The strategy is expressed as:

$$u_{i,g} = \begin{cases} v_{ig} & if\ rand < CR; \\ x_{ig} & if\ rand > CR. \end{cases} \tag{16}$$

5.3. Selection Operation

Selection process determines the next generation population which is likely the most promising feasible candidate solutions. A greedy selection is used in which for the each trial vectors generated, the fitness $f(u_i)$ is calculated which is then compared with $f(x_i)$. If the trial vector produces a fitness value which is less than the corresponding target vector, then the trial vector will replace the target vector and will become the population of next generation. Otherwise the target vector will persist in the population for the next generation [14]-[16]. The strategy is expressed as:

$$x_{i,g+1} = \begin{cases} u_{ig} & if\ f(u_{ig}) \le f(x_{ig}); \\ x_{ig} & Otherwise \end{cases} \tag{17}$$

5.4. Fitness function

Using Integral of time multiplied absolute value of the Error (ITAE), the load frequency regulations is optimized to maintain the scheduled regulations of various GENCOs and tie-line power exchange as governed by Independent System Operator (ISO). The frequency deviations and tie-line deviations are weighed together as a single variable called area control error (ACE) and is modelled as a fitness function to minimize [1]-[4]. An additional figure of demerit is added to the fitness function to improve the dynamic response viz. settling time, maximum frequency excursion and also to eliminate steady state deviations. The fitness function ITAE is given by:

$$J = \int_0^{T_{sim}} t \sum |ACE_i| \, dt + FD \tag{18}$$

Where $FD = \varpi_1 * TS + \varpi_2 * OS$. The Settling time (TS) for 2% band of frequency deviations and Overshoot (OS) in both areas is considered for evaluation of the figure of demerit (FD).

Schematically, the working principle of Differential Evolution Algorithm is summarized as the following pseudo code:

Begin
Generate the initial population of size NP
Define the objective function f
while $gen \le Maxgen$
  for $i = 1:NP$
    compute $f(x_i)$
  end
for $i = 1:NP$
  //Mutation//
    Select two random individuals x_{ra} *and* x_{rb}
    Select the best individual x_{best} *from the current population and compute the trial vector as:*

$$v_{i,g} = x_{i,best} + F*(x_{r,a} - x_{r,b})$$

  //Crossover//
    generate the offspring as:

$$u_{i,g} = \begin{cases} v_{ig} & \text{if } rand < CR; \\ x_{ig} & \text{if } rand > CR. \end{cases}$$

end
for $i = 1:NP$
  //Selection//
  select the individuals to next generation according to:

$$x_{i,g+1} = \begin{cases} u_{ig} & \text{if } f(u_{ig}) \le f(x_{ig}); \\ x_{ig} & \text{Otherwise} \end{cases}$$

end
end while

6. Simulation

A composite deregulated power system consisting of hydro-thermal unit in area-I, thermal-thermal with reheat & non-reheat type unit in area-II and thermal-gas unit in area-III, modelled as a three area power system shown in fig.1 is investigated for LFC dynamics using the proposed control strategy i.e. FOPID and TCPAR optimized with Differential evolution algorithm. The energy transactions between the GENCOs and DISCOs were facilitated by using the concept of participation matrix, which represents the possible contracts between the GENCOs and DISCOs. The possible contracts are expressed by the participation matrix as:

$$DPM = \begin{bmatrix} 0.25 & 0.00 & 0.25 & 0.00 & 0.30 & 0.00 \\ 0.50 & 0.25 & 0.00 & 0.25 & 0.20 & 0.30 \\ 0.00 & 0.50 & 0.25 & 0.00 & 0.00 & 0.00 \\ 0.25 & 0.00 & 0.50 & 0.75 & 0.00 & 0.00 \\ 0.00 & 0.25 & 0.00 & 0.00 & 0.50 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.70 \end{bmatrix}$$

For simulation, it is assumed that the DISCOs in each area demands a constant contracted load demand of 0.1 PUMW according to the contracts between them, also in addition to the contracted load a random un-contracted load demand is obligated on the GENCOs in each area as:

$$-0.05 \le P_{di} \le 0.05\ PUMW$$

The simulation results were depicted in fig. 6 to fig. 10.

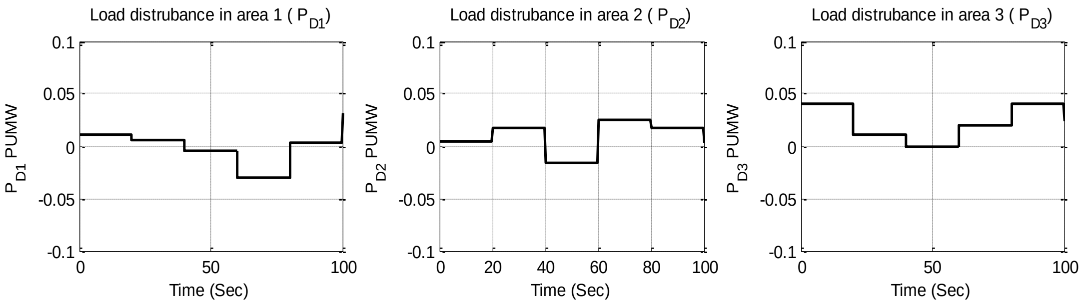

Fig.6. Load disturbance in each area

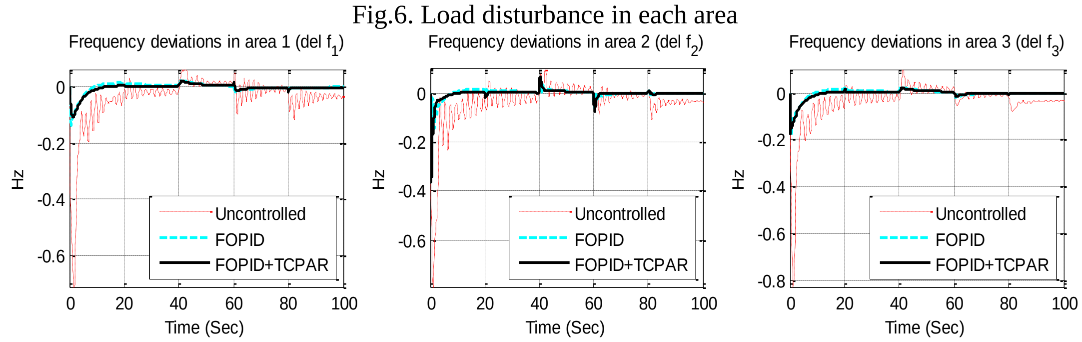

Fig.7. Frequency deviations in each area

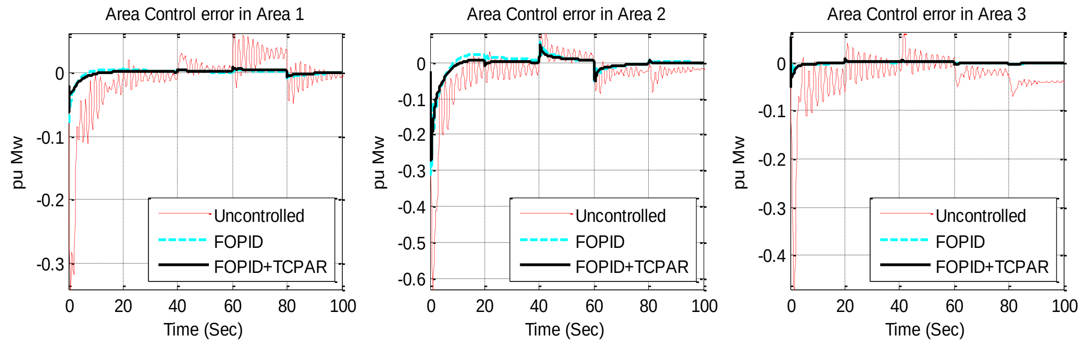

Fig.8. Area Control Error in each area (ACE)

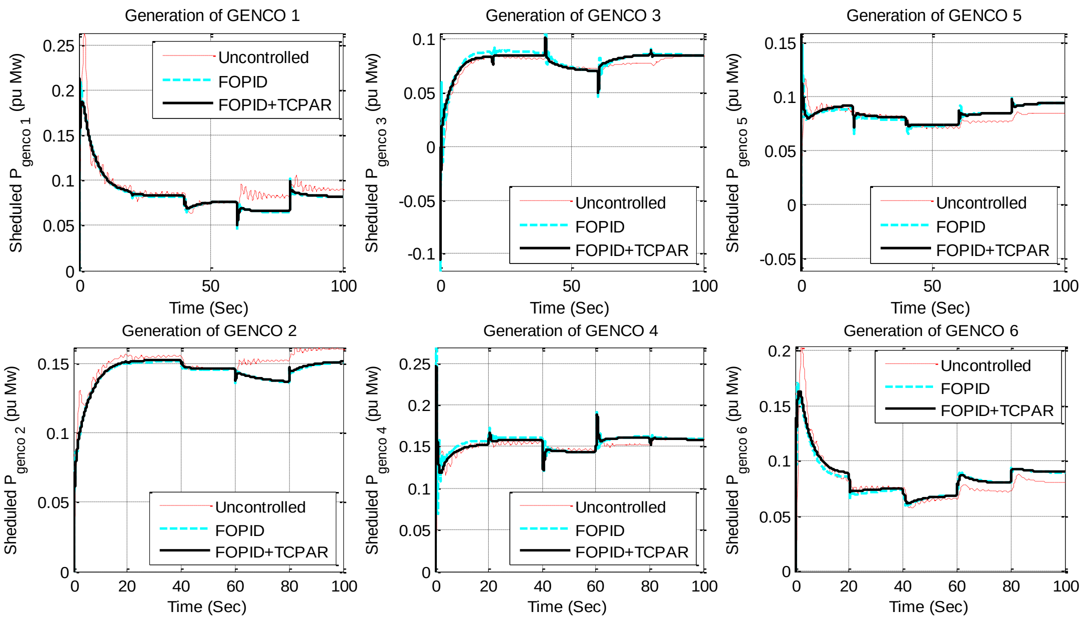

Fig.9. Generation of various GENCOs

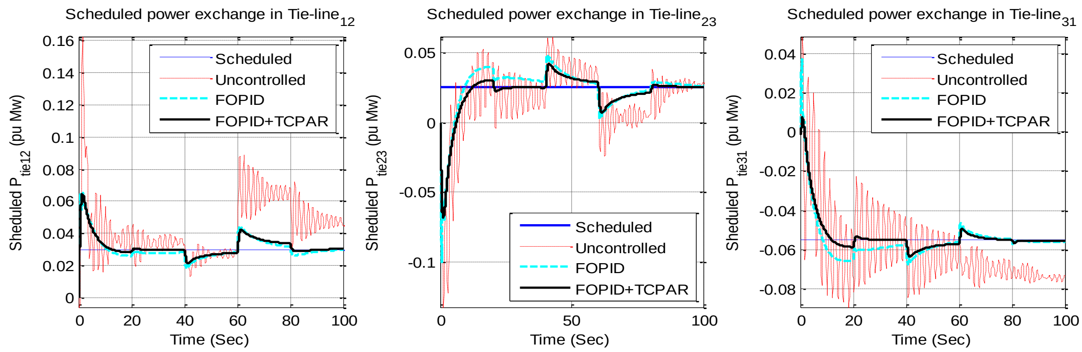

Fig.10. Scheduled power exchange in tie-lines

Table 1: Performance measures for different control strategies

Error	Un controlled			FOPID			FOPID+TCPAR		
	del f_1	del f_2	del f_3	del f_1	del f_2	del f_3	del f_1	del f_2	del f_3
ITSE	3.7793	4.1049	3.6227	0.7833	1.9907	1.0489	**0.1208**	**0.2321**	**0.1315**
ITAE	67.594	68.484	61.244	16.938	19.581	18.156	**10.1608**	**10.844**	**10.004**

Table 2: Optimal FOPID in each area

	Area I	Area II	Area III
FOPID Controller	$-\left[5.2065+\frac{0.4987}{S^{0.8097}}+5.234S^{0.9958}\right]$	$-\left[2.1659+\frac{0.1257}{S^{0.6250}}+2.851S^{0.9779}\right]$	$-\left[9.3251+\frac{0.2680}{S^{0.8826}}+8.098S^{1.0132}\right]$

7. Simulation results and discussions

The effectiveness and robustness of the proposed strategy against the uncertainties of load demand is investigated by applying random load disturbance in each area. Following to the load disturbance, the FOPID controller effectively regulates the generation of various GENCOs and power exchange in the tie-lines according to the schedule governed by ISO. Table 1 compares the performance measures of the system with and without the proposed control strategy. From the performance measures evaluated for frequency in each area, it is inferred that the implementation of FOPID further fortified by TCPAR effectively leads to minimal ITSE and ITAE errors than with FOPID alone. From fig. 10, it is inferred that even if the DISCOs demand excess power than what is contracted the control strategy effectively regulates the power exchange in the tie-lines at the scheduled value. The simulation results from fig. 7 to fig. 10 evidence the considerable improvement in LFC dynamics. The corresponding optimal values of the FOPID in each area were tabulated in table 2.

8. Conclusions

The paper has formulated a composite deregulated power system to investigate the influence of fractional order controller and Thyristor controlled phase angle regulator on the LFC regulations for a wide uncertainties in load demand. The simulation result evidences the improved dynamic response in terms of damping of oscillations, settling times of frequency and tie-line power deviations. The proposed strategy is effective in regulating the power exchange in the tie-lines and generation of various GENCOs. Hence the implementation of FOPID controller fortified by TCPAR in the tie-lines improves the overall LFC dynamics of interconnected areas.

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