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Comparison of Integer and Non-integer Supplementary Controllers to Stabilize LFC Dynamics in a Deregulated Environment

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Abstract- The paper concerns with the comparison of integer and non-integer based PID supplementary controllers to stabilize the dynamics of load frequency control in a deregulated composite power system. In this context the performance of an integer based PID is compared against the non-integer based Fractional order PID controller. The controller performances is fortified by a FACTS based thyristor controlled phase angle regulator, used for the power flow control is used in the tie-lines to damp the power swings in tie-lines and thus improving the overall dynamics of LFC. The control strategy was implemented on a composite deregulated power system consisting of potential gas fired power plants along with hydro and thermal plants spanned in different areas. The decision variables of the controllers were optimized using differential evolution algorithm using integral time multiplied absolute error as the fitness function to minimize. The simulation result depicts an improved dynamic performance of non-integer Fractional order controller along with TCPAR over integer based controllers.

Keywords: LFC dynamics; deregulated power system; PID; FOPID; TCPAR; differential evolution algorithm.

1. INTRODUCTION

The modern deregulated power system structured as an interconnected power system consisting of diverse generation technologies, such a system responding to a disturbance in any area will invokes a wide range of dynamics due to the inherent inertia and regulation characteristics of diverse generators. The generating companies in such a competitive environment operating in unison may or mayn't participate in LFC task, thus the task of stabilizing the load frequency control in a composite deregulated power system is a joint venture and is a challenging issue, which otherwise may leads to frequency collapse and may force an island operation or may initiate a severe blackout. The primary objective of LFC is to maintain the frequency regulation and minimize the unscheduled tie-line power exchange in the interconnectors which is usually accomplished by a supplementary controller in each area. Due to the sluggish and insufficient response of the primary control (governor control), the power frequency deviations and tie-line deviations sustains for a long durations which can be suppressed by a secondary controller and further can be fortified by a FACTS based Thyristor controlled phase angle regulator (TCPAR).

Over the decades several authors has proposed different control strategies such as reduced order controller, optimal controller, integer based PID controller to regulate and control LFC dynamics. In the present context a non-integer based fractional order PID controller is compared against the integer based PID controller in stabilizing the LFC dynamics. In a non-integer FOPID controller, the integral and derivative orders are of fractional rather than integers. The inclusion of two more parameter adds more flexibility in design and makes it possible to further improve its performance over traditional PID controller. The power swing in the tie-lines due to disturbance in any of the areas, if suppressed by a fast acting device such as a TCPAR in the tie-lines will influence the overall dynamics of LFC without affecting the stability and security of the interconnected system. In the present work, the performance of non-integer based fractional order controller fortified by TCPAR is investigated and compared with the conventional PID controller.

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 ith 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 the GENCOs in an area in LFC task, such that $\sum_{k=1}^{n} apf_{ki} = 1$ and cpf_{ij} is the contracted participation factor which corresponds to the fraction of load contracted by any DISCO$_i$ towards a GENCO$_j$ in its own area or with interconnected area. At steady state, the scheduled 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:

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

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

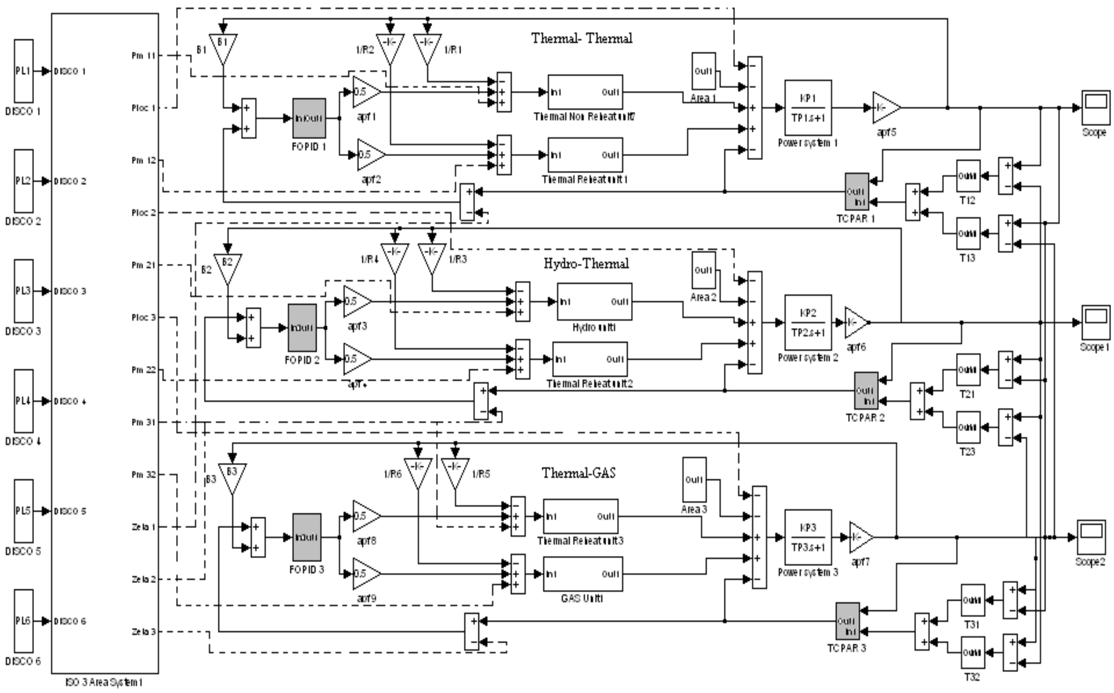


Figure 1. Three area composite deregulated power system

3. FRACTIONAL CALCULUS

The fractional order (non-integer) 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:

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

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:

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

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:

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

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.

3.1 Integer and non-integer PID Controllers

The Differential equation used to describe the generalized integer and non-integer PID controller is:

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

Applying Laplace transformation results in the transformed controller with continuos transfer function of the generalized controller is given by:

$$G_c(s) = \left(K_p + \frac{K_I}{s^{\lambda}} + s^{\mu} K_d\right) \quad \left.\begin{matrix} PID \text{ } if \text{ } \lambda, \mu = 1 \\ FOPID \text{ } if \text{ } \lambda, \mu > 0 \end{matrix}\right\} \tag{9}$$

By considering the integral and derivative orders to be integers $(\lambda = \mu = 1)$ the continuous transfer function of the integer type PID controller can be realized and for fractional values of $(\lambda \,\&\, \mu)$, the non-integer type fractional order PID controller can be realized. The error function $e(s)$ is modelled as the Area Control Error (ACE) in each area. Therefore, the output of the PID and FOPID controller is given by

$$G_c(s) = -\left(K_p + \frac{K_I}{s^{\lambda}} + s^{\mu} K_d\right) ACE_i \quad \left.\begin{matrix} PID \text{ } if \text{ } \lambda, \mu = 1 \\ FOPID \text{ } if \text{ } \lambda, \mu > 0 \end{matrix}\right\} \tag{10}$$

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 PID controller is depicted in Figure 2.

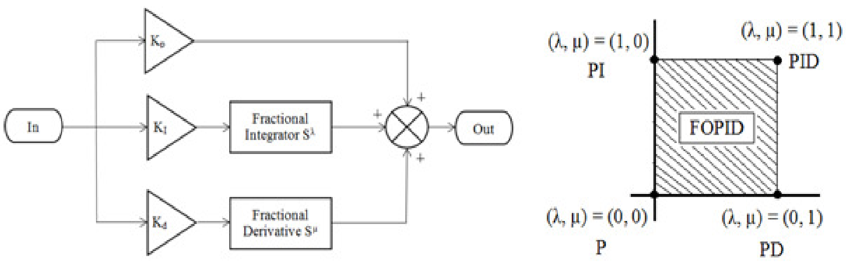


Figure 2. Generalized Fractional Order PID controller

As shown in Figure 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.

3.2 Decision variables

In FOPID controller, the five parameters $(K_P, K_I, K_d, \lambda, \mu)$ in each area and for a PID controller the parameters (K_P, K_I, K_d) were tuned using differential evolution algorithm based on design specifications i.e. to improve the dynamics of LFC and to maintain the LFC regulations for the contracts established between the GENCOs and DISCOs spanning over different control areas.

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].

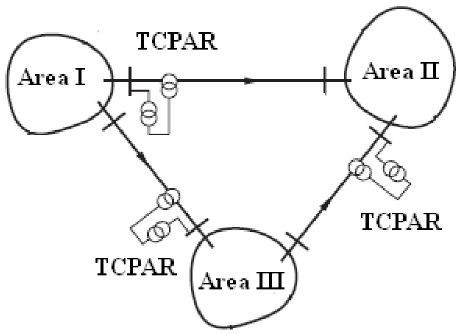


Figure 3. Test system with TCPAR in tie-lines

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 .

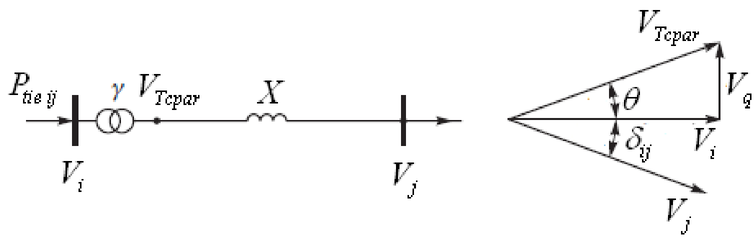


Figure 4. Single line diagram of TCPAR and phasor diagram

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 Figure 4,

$$\left.\begin{aligned} \sin\theta &= \frac{V_q}{V_{tcpar}} = \frac{\gamma V_i}{V_{tcpar}} \\ \cos\theta &= \frac{V_i}{V_{tcpar}} \end{aligned}\right\} \tag{11}$$

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

$$\left.\begin{aligned} P_{tie\,ij} &= \frac{V_{tcpar}V_j}{X}\sin(\delta_{ij}+\theta) \\ &= \frac{V_iV_j}{X}\sin\delta_{ij} + \gamma\frac{V_iV_j}{X}\cos\delta_{ij} \end{aligned}\right\} \tag{12}$$

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

$$\left.\begin{aligned} \Delta P_{tie\,ij} &= \frac{\partial P_{tie\,ij}}{\partial \delta_{ij}}\Delta\delta_{ij} + \frac{\partial P_{tie\,ij}}{\partial \gamma}\Delta\gamma \\ &= \frac{2\pi T_{ij}}{S}\left[\Delta f_1 - \Delta f_2\right] + T_{ij}\Delta\gamma \end{aligned}\right\} \tag{13}$$

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]. 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 control are frequency deviations Δf_i in each area.

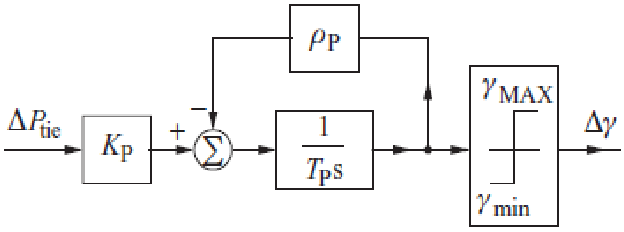


Figure 5. SIMULINK modal of TCPAR

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 [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. The evolutionary algorithms, on the other hand carry out a global search by evolving new feasible solutions, and are well suitable for real world problems. 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 modelled as a string of decision variables called genome, encoded as a candidate solution $x_{ig} = \{x_{i1}, x_{i2}, x_{i3}, \ldots x_{iD}\}$ where $i = 1, 2, 3, \ldots NP$. 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:

$$v_{i,g} = x_{i,best} + F * \left(x_{r,a} - x_{r,b} \right) \qquad (14)$$

Where F is the scaling factor which controls the length of the exploration vector [14]-[16].

5.2. Crossover Operation

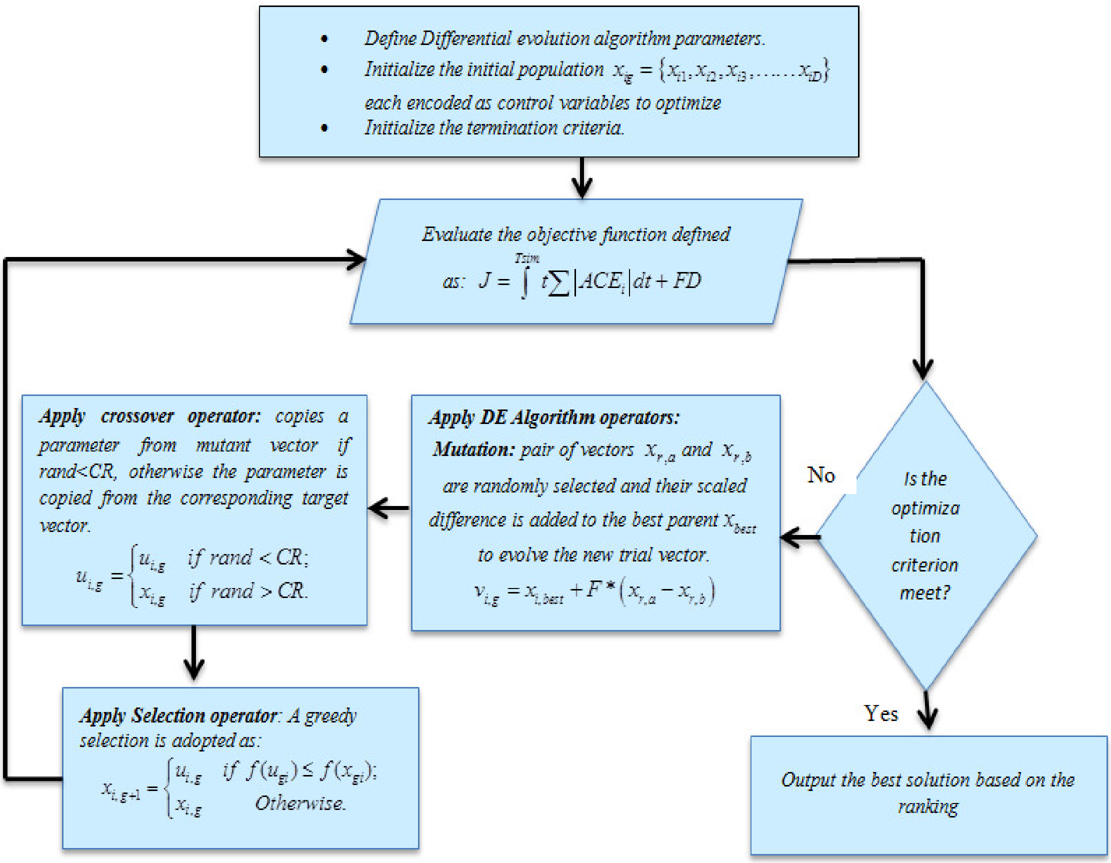
In order to acquaint diversity in population, crossover operation is implemented after mutation. In every generation the target vector is combined with the mutant to form another trial vector $u_{i,g}$. Popularly, the DE employs exponential crossover and binomial crossover mechanism for generating new 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:

$$u_{i,g} = \begin{cases} u_{i,g} & if \ rand < CR; \\ x_{i,g} & if \ rand > CR. \end{cases} \tag{15}$$

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:

$$x_{i,g+1} = \begin{cases} u_{i,g} & if \ f(u_{gi}) \le f(x_{gi}); \\ x_{i,g} & Otherwise. \end{cases} \tag{16}$$



Algorithm 1: Differential evolution algorithm

5.4. Fitness function

Using Integral of time multiplied absolute value of the Error (ITAE), the load frequency regulations is optimized to maintain the LFC regulations 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 The fitness function ITAE is given by:

$$J = \int_0^{Tsim} t \sum |ACE_i| \, dt + FD \tag{17}$$

Where $FD = \omega_1 * TS + \omega_2 * OS$. 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).

6. SIMULATION

The proposed control strategy was implemented on a three area power system spanned as thermal (Non-reheat)- thermal (reheat) in area I, hydro-thermal system in area II and thermal (reheat)-gas unit (GAST modal) in area III. In each area two DISCOs were modelled, having bilateral contracts with GENCOs in its own and in interconnected areas. The load demand in each area is modelled as a step load of 0.1 p.u contracted load demanded by each DISCOs in each area and also a load demand of 0.01 p.u un-contracted load is considered in each area to validate the controller performance in the event of violation of bilateral contracts. The GENCOs in each area assumed to contribute equally in LFC task and the bilateral contracts between the GENCOs and DISCOs were considered as:

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

The frequency deviations of three areas, Generation of GENCOs, Tie-line power flow and Area control error for the given operating conditions is depicted in Figure 6 to Figure 9.

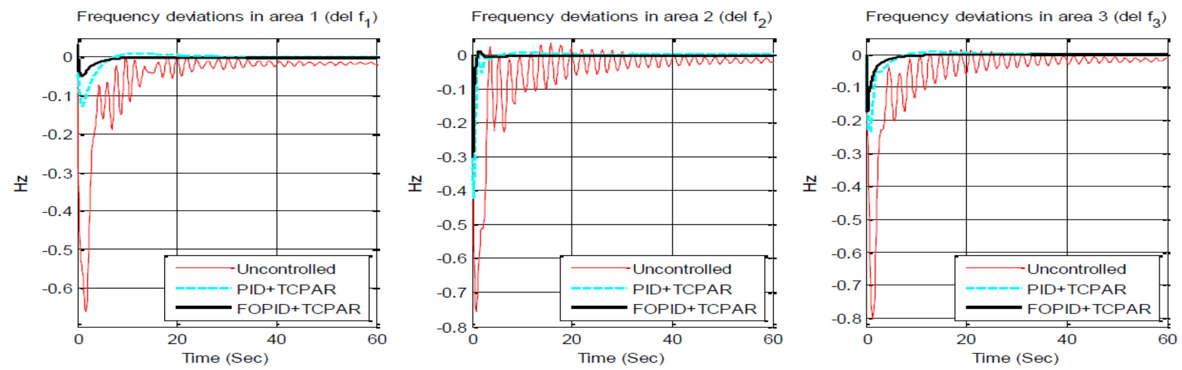


Figure 6 : Frequency deviations in each area

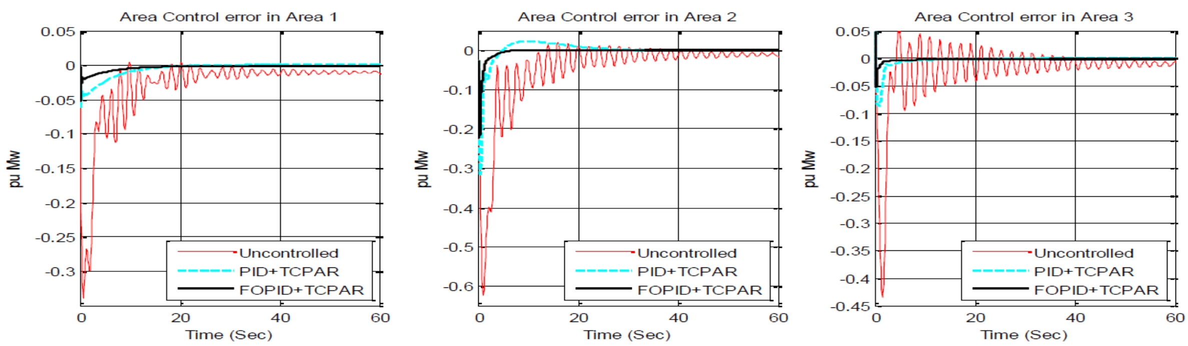


Figure 7 : Area Control Error in each area (ACE)

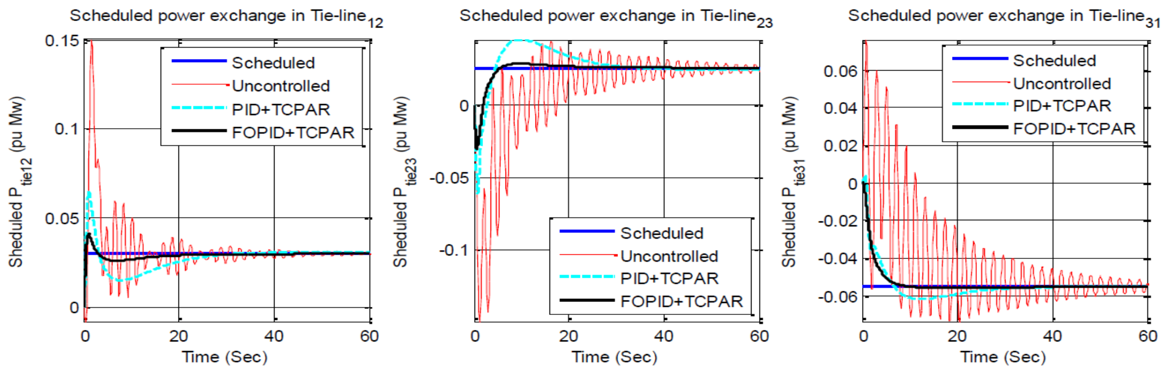


Figure 8: Scheduled power exchange in tie-lines

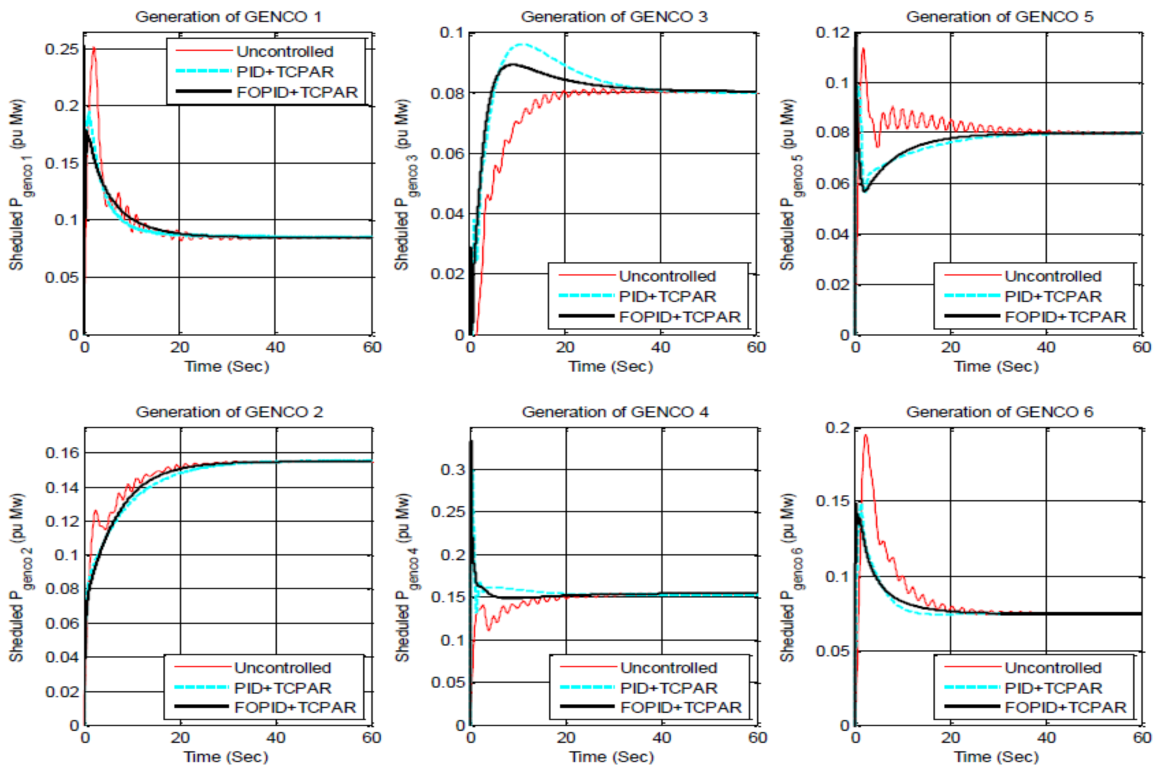


Figure 9: Generation of various GENCOs

7. RESULTS AND DISCUSSIONS

The effectiveness and robustness of the proposed strategy is investigated by applying an excess load demand than in the contracts in each area. Following to the load disturbance, the FOPID controller fortified by TCPAR effectively regulates the frequency, generation of various GENCOs and power exchange in the tie-lines according to the schedule governed by ISO. The performance of PID and FOPID controller fortified by TCPAR is depicted in table I and table II.

Table I: Time domain specifications for frequency dynamics

	Un controlled		PID		PID+TCPAR		FOPID		FOPID+TCPAR	
	Max del f	T settle	Max del f	T settle	Max del f	T settle	Max del f	T settle	Max del f	T settle
del f_1	0.663	53.8	0.175	6.45	0.128	7.02	0.0933	3.39	0.0496	3.09
del f_2	0.758	59.9	0.38	7.16	0.421	4.47	**0.295**	1.85	0.3	**1.03**
del f_3	0.803	59	0.25	6.67	0.237	7.26	0.178	**3.18**	**0.175**	3.46

Table II: Performance measures for the operating conditions

	Un controlled		PID		PID+TCPAR		FOPID		FOPID+TCPAR	
	Max del f	**T settle**	**Max del f**	**T settle**	**Max del f**	**T settle**	**Max del f**	**T settle**	**Max del f**	**T settle**
del f_1	1.0834	9.2982	0.0824	1.8376	0.0723	2.2450	0.0046	0.2968	**0.0040**	**0.2817**
del f_2	1.3587	15.150	0.1337	1.6108	0.1631	1.1768	0.0044	0.2386	**0.0042**	**0.1933**
del f_3	1.3572	13.621	0.1128	1.8042	0.1409	2.0318	0.0062	0.3835	**0.0036**	**0.3035**

From the time domain specifications, it is inferred that the implementation of non-integer FOPID controller fortified by TCPAR improves the overall dynamics in terms of maximum frequency excursion, settling time and steady state error. 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 other control strategies. From Figure. 8, 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 corresponding optimal values of the PID and FOPID in each area were tabulated in table III.

Table III: Optimal control parameters of PID and FOPID controller

Area	PID Controller	FOPID Controller
Area I	$-\left(3.7463+\frac{0.0554}{S}+9.9996S\right)$	$-\left(7.8989+\frac{0.3677}{S^{0.4023}}+8.5924S^{0.9511}\right)$
Area II	$-\left(3.6941+\frac{0.4838}{S}+2.1620S\right)$	$-\left(9.4544+\frac{0.4245}{S^{0.6211}}+2.7825S^{1.250}\right)$
Area III	$-\left(2.2697+\frac{0.0583}{S}+1.6536S\right)$	$-\left(10.00+\frac{0.1785}{S^{0.1520}}+6.9814S^{0.8811}\right)$

8. CONCLUSIONS

The paper has formulated a composite deregulated power system to investigate the influence of fractional order PID controller and Thyristor controlled phase angle regulator on the LFC regulations. 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 non-integer FOPID controller fortified by TCPAR in the tie-lines improves the overall LFC dynamics of interconnected areas.

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