PERFORMANCE EVOLUTION OF FRACTIONAL ORDER PI CONTROLLER USING PSO ALGORITHM FOR LFC IN A MULTI-AREA MULTI-SOURCE POWER SYSTEM

Ambika. B * Kamaraj.N
Department of Electrical and Electronics Engineering, Thiagarajar College of Engineering, Madurai, Tamil Nadu, India
Email-id: ambi_kab@yahoo.co.in

A b s t r a c t

In recent year's fractional calculus has wide attraction among the researchers for solving problems in the field of motion control, game theory, control system, power system and signal processing etc., In this paper, Fractional Order Proportional and Integral (FOPI) controller based Load Frequency Control (LFC) for multi-area multi-source power system is investigated. The single area multi source power system consists of thermal, hydro and gas power plants is extended in to multi area (four area) multi source LFC. Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA) techniques used to obtain FOPI controller parameters. A step load change of 1% of the rated power is given to each area for analyzing the performance of the test system. Dynamic response measures like overshoot, rise time and performance indices namely Integral Absolute Error (IAE) criterion of each area with step load change is evaluated. The results are compared with the performance of Integer Order Proportional plus Integral controller. Multi-area multi-source system shows better performance by using PSO based FOPI controller. The result reveals that the load perturbation does not affect the system performance.

Key Words: *Multi Source Multi Area, Load Frequency Control, Particle Swarm Optimisation Algorithm, Integer Order Proportional plus Integral controller, Fractional Order Proportional plus Integral controller*

Nomenclature

Δf_i	-	Small change in nominal system frequency of area i (Hz)
$\Delta P_{tie\ i,j}$	-	Change in tie line power connecting between area i and area j (p.u)
ACE	-	Area Control Error
LFC	-	Load Frequency Control
i	-	Subscript referred to area i, $i \in \{1, 2, 3, 4\}$
R_i	-	Speed regulation of area i (Hz/p.u.MW)
B_i	-	Frequency bias constant of area i (p.u MW/Hz)
ΔP_{Di}	-	Load change in area i
K_{ri}	-	Turbine coefficient of area i
T_{ti}	-	Turbine time constant of area i (s)
K_{pi}	-	$1/D_i$ (Hz/p.u.)
T_{pi}	-	$2H_i/f\ D_i$ (s)
K_{Pi}	-	Proportional gain of controller in area i
K_{Ii}	-	Integral gain of controller in area i
λ_i	-	Order of integral gain controller in area i.
H_i	-	Inertia constant
T_{ij}	-	Synchronizing coefficient
T_{gi}	-	Governor time constant (s)
T_{ri}	-	Steam turbine reheat time constant of area i (s)

1. Introduction

In general, power system comprising more number of generating units is divided into areas connected by tie-lines. In tie-line, power exchange taking place between other generating units or areas, causes frequency deviation error in the power system. It is well-known that if there is any mismatch between generation and demand in the power system it results in frequency deviation, causing system instability and deteriorates the system dynamic performances. During transmission, both the active and reactive power balance must be maintained between the generation and utilization. The Load Frequency Control (LFC) is used to maintain the nominal values of the system frequency and tie line power flow between different control areas when subjected to load variations. Also, acceptable level of power quality is maintained while monitoring both voltage and frequency within tolerance limits [1 - 5]. A brief literature review in the field of LFC for conventional and distribution generation systems and recent automatic generation control strategies in power system is proposed in [6, 7].

In recent years, the importance of controllers in power system is emerging. The gain parameters of the conventional PID controller can be found by Ziegler Nicholas and Cohen coon method [8]. Now a days many intelligent control algorithms and optimisation algorithm is used to obtain better gain values. Many authors proposed intelligent controller for LFC, Genetic Algorithm based fuzzy gain scheduling of PI controller for two area interconnected power system [9], ANFIS controller for Automatic Generation Control (AGC) in power system under deregulated environment [10], direct, indirect adaptive fuzzy logic controller (DIAFLC) for unknown interconnected LFC areas [11], two area interconnected thermal system for LFC using GA [12] and Multi objective Optimization Problem (MOP) for three control area power system is proposed in [13]. MOP is formulated to composite set of objective functions. Optimized PI controller parameters given by GA. Bacterial Foraging Optimization Algorithm (BFOA) based PID controller for multi area non reheat thermal system LFC with nonlinearities is proposed in [14, 15]. Other optimisation algorithms such as Firefly algorithm for three unequal area thermal reheat turbines with Generation Rate Constraint (GRC) Automatic Generation Control (AGC) using two degree of freedom fractional order PID controller [16], Cuckoo Search algorithm based Integral controller gain of a two area thermal system with Superconducting Magnetic Energy storage (SMES) in the AGC proposed in [17]. In reference [18], GA based two-degree of freedom of PID controller for a three area AGC system is proposed. LFC of a multi-source power system with I, PI and PID controller and the controller parameters are optimized by Differential Evolution (DE) algorithm. Also a HVDC link is considered in parallel with existing AC tie line for the interconnection of two areas that gives various performance measures such that settling time, overshoot and standard error criteria of tie line and frequency deviation subsequent step load perturbation is better projected in [19] and [20].

Alternatively, fractional order controller has been used in power system for getting better performance because of its real world fractional orders. Many researchers' works in this area of LFC. Some of the works are single area LFC with non-reheated, reheated and hydro turbines by fractional order PID controller. The controller shows better robustness towards $\pm$50% parametric uncertainty and disturbance rejection capability [21]. Three area power systems with different generating units LFC fractional order PID controller using Imperialist Competitive Algorithm (ICA) is proposed in [22].

From the literature, it is observed that Multi source Multi area power system LFC has to be explored more and also the importance of 'tie line' strength variations and its effect on system dynamic response to unequal ties which exist in practice in a multi area system has not been investigated. In this work, the idea of Multi Area Multi source is extended in to four area system with each area consists of three sources. Area Control Error (ACE) due to change in frequency of each area and tie line power between each generating units is used as objective function. Proposed system performance is analysed using Particle Swarm Optimisation (PSO) based Fractional Order Proportional and Integral controller (FOPI). The proposed controller performance is compared with Integer order proportional integral (IOPI) controller performance. Genetic Algorithm (GA) based FOPI controller performance is also investigated.

2. Description of the system

LFC maintains the power balance between generation and demand. If demand increases the frequency deviation error will occur. If this error is prolonged for long time LFC does not maintain the constant 50 Hz frequency and this error signal is called as Area Control Error (ACE), is given to the controller. In a single area system $ACE = \Delta f$, [2]

Where, Δf - frequency deviation due to demand or load change

Single area Control system is converted into four area systems by interconnected with them each other which form the tie lines and power deviation between neighbouring areas. Therefore frequency deviations and tie line power in the control areas are represented by separate frequencies and tie line power equations. Extended four area system block diagram is shown in Fig. 1.

The frequency deviation in each area, tie line power change between areas and important error parameter ACE due to step load change perturbation in each area is shown in Fig. 1 clearly.

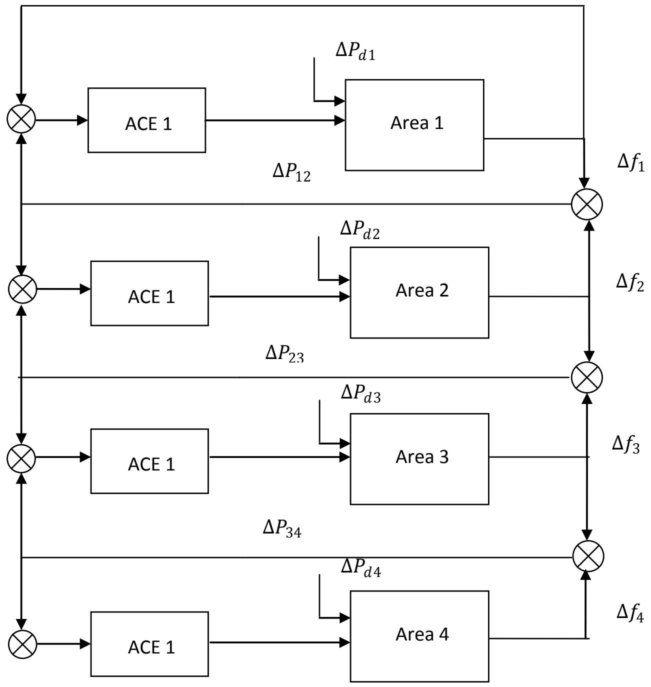


Fig.1 Block diagram representation of four area system

Single area system is considered to have three different sources like thermal, hydro and a gas power system and it is shown in Fig. 2. Consider each single area system having the rated capacity (P_{ri}) of 3000 MW and normal operating load as 2000 MW. Inertia constant H is 5 sec. Regulation (R) is 2 Hz/ p.u. MW i.e 4%. Using above data the power system transfer function model can be obtained as,

$$G_P(s) = \frac{K_P}{T_P S + 1} = \frac{75.187}{15.037S + 1} \qquad (1)$$

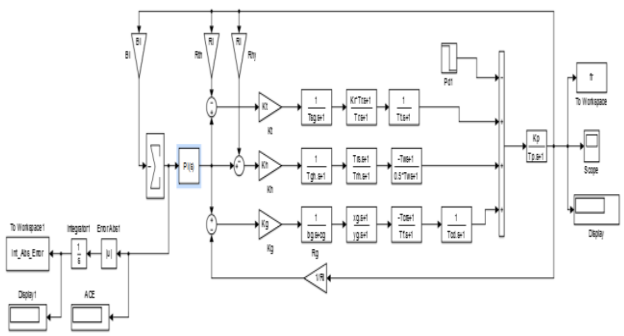


Fig.2 Transfer function model of single area system

Other elements in the power system model values are taken from [9, 12 and 15] and it is given in Appendix I. The investigation is carried out in all the areas.

The frequency deviations of each control area is given by,

$$\Delta f_1(s) = G_{p1}(s)\,[\Delta P_{T1}(s) - \Delta P_{D1}(s) - \Delta P_{12}(s)] \qquad (2)$$

$$\Delta f_2(s) = G_{p2}(s)\,[\Delta P_{T2}(s) - \Delta P_{D2}(s) - \Delta P_{23}(s)] \qquad (3)$$

$$\Delta f_3(s) = G_{p3}(s)\,[\Delta P_{T3}(s) - \Delta P_{D3}(s) - \Delta P_{34}(s)] \qquad (4)$$

$$\Delta f_4(s) = G_{p4}(s)\,[\Delta P_{T4}(s) - \Delta P_{D4}(s) - \Delta P_{43}(s)] \qquad (5)$$

Where,

$\Delta f_i(s)$ – Change in frequency in area i , $i = 1$ to 4

$G_{pi}(s)$ – Transfer function model of the turbine, governor of the power plants in area i.

$\Delta P_{Ti}(s)$ – Small change in power for $G_{pi}(s)$ in area i.

$\Delta P_{Di}(s)$ – Disturbance in each area

$\Delta P_{ij}(s)$ – Change in tie line power between area i to area j

Subscript denotes the number of area in the whole system.

Similarly, the Tie-line power deviations for the four area system is given by,

$$\Delta P_{12}(s) = \frac{2\pi T_{12}}{s}[\Delta f_1(s) - \Delta f_2(s)] \qquad (6)$$

$$\Delta P_{23}(s) = \frac{2\pi T_{23}}{s}[\Delta f_2(s) - \Delta f_3(s)] + \frac{2\pi T_{12}}{s}[\Delta f_1(s) - \Delta f_2(s)] \qquad (7)$$

$$\Delta P_{34}(s) = \frac{2\pi T_{34}}{s}[\Delta f_3(s) - \Delta f_4(s)] + \frac{2\pi T_{23}}{s}[\Delta f_2(s) - \Delta f_3(s)] \qquad (8)$$

Where, T_{12}, T_{23} and T_{34} – tie line power factor between areas

All the operating pool members' necessarily participate in the frequency control in addition to taking care of their own net interchange. i.e. at steady state both change in frequency and tie-line power must be zero. To obtain this, the input of the controller known as Area Control Error (ACE) is used. ACE for each area consists of a linear combination of frequency and tie-line power. Thus

$$ACE_1(s) = \Delta P_{12}(s) + B_1 \Delta f_1(s) \qquad (9)$$

$$ACE_2(s) = \Delta P_{23}(s) + B_2 \Delta f_2(s) \qquad (10)$$

$$ACE_3(s) = \Delta P_{34}(s) + B_3 \Delta f_3(s) \qquad (11)$$

$ACE_4(s) = \Delta P_{43}(s) + B_4 \Delta f_4(s)$
(12)
Where, B_1, B_2, B_3 and B_4 − Bias Constant

Then the ACE is given as input to the controller. The optimal value of the controller gain is achieved by the output of the constrained optimization of the Integral Absolute Error (IAE) performance indices. A lower and upper limit of the controller is the constraint. Then the optimization problem can be formulated as,
Minimize IAE (K_P , K_i) Subject to $K_p^{min} \le K_p \le K_p^{max}$ and $K_i^{min} \le K_i \le K_i^{max}$
And therefore,

$$IAE_1 = \int ACE_1 = \int \Delta P_{12}(s) + B_1 \Delta f_1(s) \quad (13)$$
$$IAE_2 = \int ACE_2 = \int \Delta P_{23}(s) + B_2 \Delta f_2(s) \quad (14)$$
$$IAE_3 = \int ACE_3 = \int \Delta P_{34}(s) + B_3 \Delta f_3(s) \quad (15)$$
$$IAE_4 = \int ACE_4 = \int \Delta P_{43}(s) + B_4 \Delta f_4(s) \quad (16)$$

3. Controller Design

3.1. PI Controller

General structure of the integer order PI controller is given by,

$$G_c(S) = K_p + \frac{K_i}{S} \quad (17)$$

Controller output is obtained by proportional of the error signal plus integral of the error signal. Here, the error signal is ACE. Adding controller causes an increase in order and type of the system, resulting in reduced steady state error. Transient characteristics of the system can be reduced by introducing the proportional term in the controller; introduction of integral term eliminates the steady-state error. Thus the PI controller improves the stability of the system. Each plant of the respective area of the governor reference power can be set by this PI controller in the LFC. The controller output is given by,

$$\Delta P_{ref} = \left(K_p + \frac{K_i}{S}\right) e(s) \quad (18)$$

Where, $e(s)$ −error signal = ACE

3.2. Fractional Order Controller

Fractional order controller works on the basis of fractional order calculus. It is a mathematical approach deals with derivatives and integrals of arbitrary and complex orders. Therefore, it adds a new dimension to understand and describe the basic nature and behaviour of complex systems in an improved way. In real world systems, the order of the differentiation and integration is fractional. Due to the non availability of the solution methods of fractional order differential equation, Integer order ordinary order differential equation (ODE) is used mostly for the analysis of the system. Now a day's TID (Tilted Integral Derivative) controller, CRONE controller and fractional lead-lag compensator is user for a fractional calculus. In MATLAB, FOMCON toolbox is used to analyse the fractional order system and fractional order controller design. Similar to integer order, Fractional order discrete model analysis, state space analysis and stability analysis are also available in fractional order system and controller.

Generally, in control system point of view, the system is analysed based on the following four cases. (i) Integer order system Integer order controller (IOIC) (ii) Integer order system fractional order controller (IOFC) (iii) Fractional order system integer order controller (FOIC) (iv) Fractional order system fractional order controller (FOFC). Fractional order controller works on the region of "plane" whereas in conventional integer order controller works on the concept of "point" [23 - 26].

Fractional calculus is a generalisation of integration and differentiation to non-integer order fundamental operators.

$$aD_t^r = \begin{cases} \frac{d^r}{dt^r} & ; R(r) > 0 \\ 1 & ; R(r) = 0 \\ \int_a^t (d\tau)^{-r} & ; R(r) < 0 \end{cases} \quad (19)$$

Where,

r is the order of the operation.

r ∈ R. But 'r' could also be a complex number.

Caputo and Riemann – Liouville differentiation and integral formula is defined to analyse the system. Similar to integer order differential equation fractional order differentiation and integration have various properties. Based on the above fractional order dynamic system is defined as,

$$a_n D^{\alpha_n} y(t) + a_{n-1} D^{\alpha_{n-1}} y(t) + \cdots\cdots + a_0 D^{\alpha_0} y(t) = b_m D^{\beta_m} u(t) + b_{m-1} D^{\beta_{m-1}} u(t) + \cdots\cdots + b_0 D^{\beta_0} u(t)$$

(20)

In LFC, the single area three source system is a 16^{th} order system. Here, the system taken for analysis have four areas, resulting in higher order thus the system becomes complex. Therefore for easy analysis simulation based on integer order transfer function model for four areas system and fractional order controller is used in this work. (i.e) integer order system with fractional order controller is used.

If the IOPI controller can be replaced by a fractional order PI controller, then the structure of the fractional order controller is given by,

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} \quad (21)$$

If $\lambda = 1$ FOPI controller is equivalent to integer order PI controller. Addition to the PI controller terms, introduction of the integral order term (λ) improves the transient behaviour and stability of the system. Input to the controller is ACE signal and the output of the fractional order controller is given by,

$$\Delta P_{ref} = e(s)(K_p + \frac{K_i}{s^{\lambda}}) \quad (22)$$

Gain values of the IOPI controller and FOPI controller and order of the FOPI controller parameters K_p, K_i *and* λ can be tuned by solving the following optimization problem based on the above equations.

$$K_p^{min} \leq K_p \leq K_p^{max} \quad (23)$$

$$K_i^{min} \leq K_i \leq K_i^{max} \quad (24)$$

$$\lambda^{min} \leq \lambda \leq \lambda^{max} \quad (25)$$

PSO and GA are commonly used optimisation methods to tune the controller parameters.

3.3. Particle Swarm Optimisation (PSO)

PSO is an intelligent optimization algorithm it belongs to a class of optimization algorithm called metaheuristics. PSO is based on swarm intelligence and it is inspired by social behaviour like bird flock and fish school. PSO is a simple optimization algorithm and it is successfully applied to numerous applications in various fields of science and engineering such as mesh processing, operations research, data mining and many other problems. Initially mathematical model for the PSO algorithm was developed by Kennedy and Eberhart in 1995. The developed mathematical modelling involves the population of swarm. The swarm of candidate solution is known as particles. Every particle is a candidate solution to the optimization problem to be solved. Every particle has its own position in the search space of optimization problem. Thus the search space is a set of all possible solution for the problem from which the best solution is obtained [12 - 13].

In the proposed system the optimized controller gain and order parameters can be obtained from the search space.

Let us consider, the particle is i, and the position of the particle is X_i, particle with time adjusts its position is $X_i(t)$. The next position $X_i(t+1)$ is obtained from $X_i(t)$ and speed i.e. velocity of the particle. The velocity is updated by using inertia, cognitive and social components. $P_i(t)$ and g(t) is the best particle position and velocity best. It is shown in Fig. 3

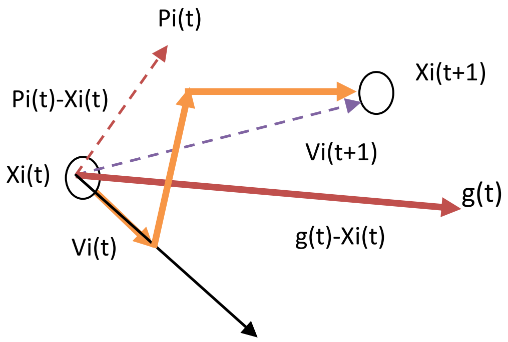


Fig.3 Velocity and position diagram of PSO algorithm

The position and velocity equations are given by,

$$V_i(t+1) = \omega\, V_i(t) + C_1\big(P_i(t) - X_i(t)\big) + C_2\big(g(t) - X_i(t)\big) \quad (26)$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (27)$$

$$V_{ij}(t+1) = \omega\, V_{ij}(t) + r_1 c_1 (P_{ij}(t) - X_{ij}(t)) + r_2 c_2 (g_j(t) - X_{ij}(t)) \quad (28)$$

And

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1) \quad (29)$$

Where,

$\omega\, V_{ij}(t) -$ *Inertia term*

c_1 *and* $c_2 -$ *Accelerating coefficients*

r_1 *and* $r_2 \sim U(0,1)$

$r_1 c_1 \left(P_{ij}(t) - X_{ij}(t)\right) -$ *Cognitive component*

$r_2 c_2 \left(g_j(t) - X_{ij}(t)\right) -$ *social component*

The output convergence is considered as the stopping criterion.

3.4. Genetic Algorithm

A genetic algorithm is a type of narrow search that reproduce evolution by taking a population of strings, which encode possible solutions, and combines them based on a fitness function to generate individuals that are robust. The algorithm starts with the group of solution known as initial population. Those solutions are pooled to produce the off springs are considered as the next generation of better solutions. New solutions are prepared from old ones using crossover and mutation. The first population wonders randomly. With each generation controller gain values becomes better. [12, 13, 14 and 17]

Steps involved in the GA

Step 1: Encode the problem in a binary string format.

Step 2: Arbitrary generation of a population is obtained.

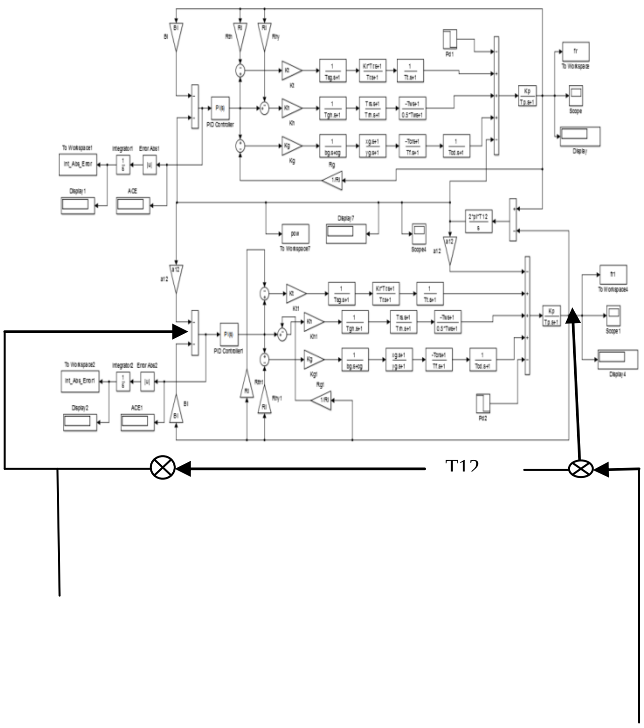
Step 3: Each solution of fitness function is computed.

Step 4: Select pairs of parent strings based on fitness function solution.

Step 5: Generate new string with crossover and mutation in anticipation of a new population has been formed.

Repeat steps 2 to 5 until get the optimum solution.

4. Simulation



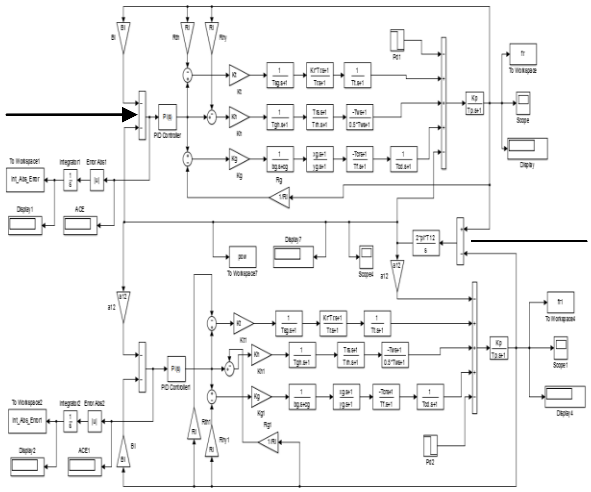


Fig.4 Four area interconnected Power System Model

The block diagram of the proposed multi-area multi-source power system is shown in Fig.4. The suitable parameters of the power system are given in Appendix I. The test system considered for the analysis is four area electric power systems and is connected by tie lines. By using synchronizing torque coefficient (T_{ij}), the capacity of the tie line is specified. The presented model is developed in MATLAB Simulink and Fractional order controller is developed in MATLAB – FOMCON toolbox. The transient performance for the four area interconnected power system is investigated by 1% step load change in all areas. In all areas, the change in frequency, tie line power change between areas and ACE are calculated.

5. Results and Discussion

The proposed four area test system is tested by, a step load change of 1% of rated capacity in all areas keeping biasing coefficients (B) and regulation factor (R) as constant. GA based PI controller and PSO based PI controller algorithms are used to get the optimum controller parameters. Also to design the optimal controller IAE is used as performance indices. The MATLAB simulations for FOPI controllers are carried out taking $\omega_l \ as \ 0.001 \ rad/sec \ and \ \omega_h \ as \ 50 \ rad/sec.$ The results obtained from GA based FOPI and PSO based FOPI optimum controller gain and order parameter values in all areas are listed in Table 1.

Table 1. Optimum gain values for different controllers

	Area 1	Area 2	Area 3	Area 4

	K_p	K_i	λ	K_p	K_i	λ	K_p	K_i	λ	K_p	K_i	λ
With out controller	NOT APPLICABLE											
PSO-FOPI (proposed)	18.6	17.9	12.0	12.90	4.904	0.86	12.90	4.90	5.21	12.9	4.904	7.43
PSO-IOPI	1.09	0.02	-	5.76	2.642	--	0.116	4.499	--	2.987	4.195	--
GA-FOPI	8.56	7.95	1.23	1.65	17.95	1.13	14.32	2.90	0.87	12.90	2.049	1.123

At the time of 20 sec. in simulation time, the 1% load change is applied to all areas for analysing the multi area system. Fig.5. to Fig.8. shows the $\Delta f_1 to \Delta f_4$ for without controller, PSO based IOPI controller and FOPI controller dynamic response. From equations (2) to (5) the frequency deviation of the control areas is found.

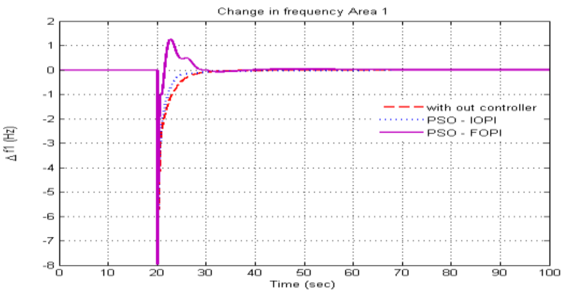


Fig.5. Frequency deviation in Area 1

The behaviour of the power system with PSO based FOPI controller is different, when compared to without controller and PSO based IOPI controller. Initially, the frequency deviation (i.e) overshoot is more in the proposed controller after the load perturbation.

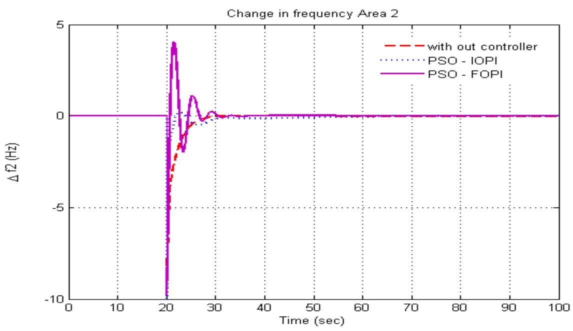


Fig. 6. Frequency deviation in Area 2

Even though for the sudden change in the set value of the frequency deviation, the proposed controller responds quickly for the corresponding load change and settles down earlier. Rise time is minimum when compared to other controllers.

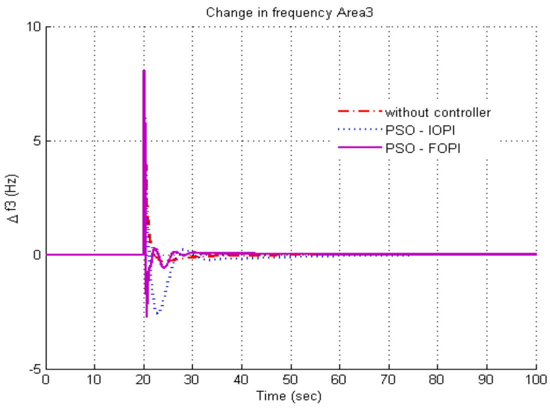


Fig. 7. Frequency deviation in Area 3

At a rate of proportional to the deviation the prime-mover input is corrected to the frequency deviation from its set value.

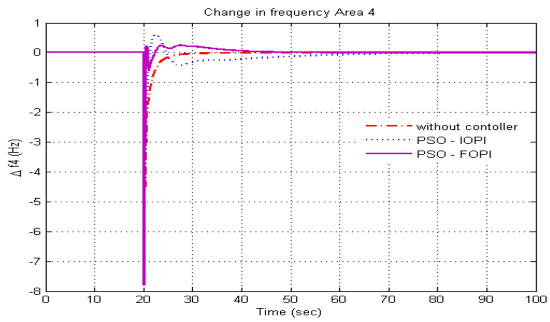


Fig. 8. Frequency deviation in Area 4

Due to variations in the frequency, the performance of the controller in the system is affected. The variations in the frequency change in all areas are listed in Table 2. It is observed that, in Table 2. some frequency deviation is found negative. This indicates the decrease in frequency, which necessitates increasing the governor speed, so that the other multi-area multi-source power system becomes stable.

Table2. Frequency Deviation

	Max. deviation	Without controller	PSO-FOPI	PSO-IOPI	GA-FOPI
Change in Frequency (p.u.	Δf_1	-0.3782	-0.0001929	-0.001772	0.006056
	Δf_2	0.8578	0.00017	0.0024	0.0060

Hz)			77	38	4
	Δf_3	-0.9353	-0.0002397	-0.002799	0.005956
	Δf_4	0.3985	0.0001966	0.003111	0.005862

Fig. 10 to Fig. 12 shows the tie line power deviation between neighbouring areas. Based on the Equations (6) to (8) the tie line power change between areas are found and its corresponding values are listed in Table.3

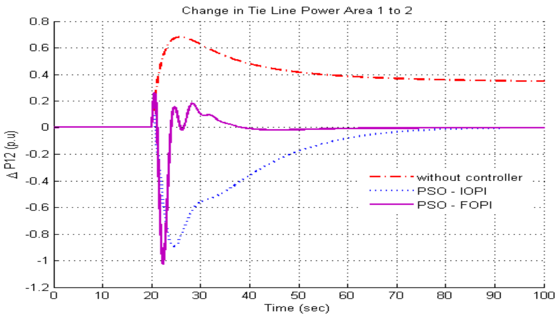


Fig. 9. Tie line power change between Area 1 and Area 2

In multi-area multi-source power system each area carries its own load. Even a small disturbance in any area, tie line power increases, will result in affect the overall system performance.

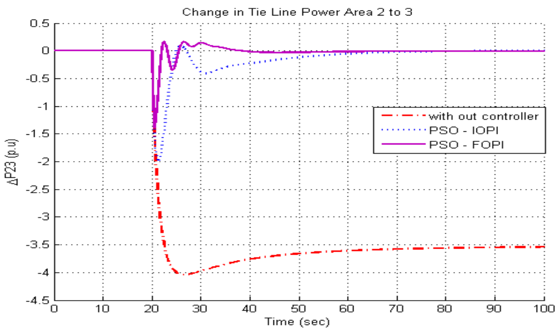


Fig. 10. Tie line power change between Area 2 and Area 3

Tie line power between different areas shown in Fig. 10 to Fig.12 Without controller the tie line power cannot reach the set value. In IOPI controller the response oscillates and takes more settling time. But in the case of proposed fractional order PI controller overshoot in governor speed is reduced, settling time and rise time is minimum.

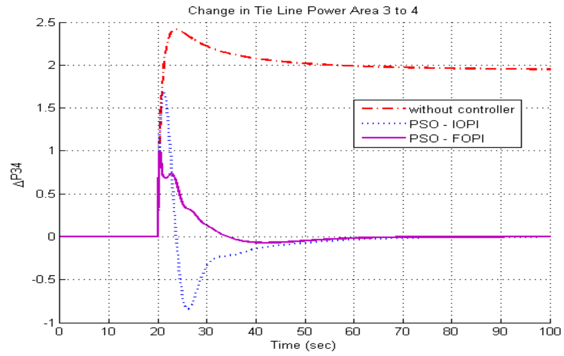


Fig. 11. Tie line power change between Area 3 and Area 4

From Fig. 5 to Fig. 12 , it is found that the frequency deviation and tie line power deviation are different in each area. Thus the more stable response is obtained with tie line power control in one area and frequency control in other areas.

Table.3 Deviation in tie line power

		Without controller	PSO-FOPI	PSO-IOPI	GA-FOPI
Change in Tie Line Power (p.u. MW/Hz)	ΔP_{12}	0.3459	0.0003736	-0.002623	-0.001891
	ΔP_{23}	-3.534	0.0002742	0.001793	-0.004201
	ΔP_{34}	1.948	-0.0002654	-0.004895	0.00704

Change in tie line power values between areas are given in above table. For a 1% step load change at rated capacity, 0.01 p.u. power deviation occurs. Table shows that PSO based FOPI controller gives the minimum deviation in tie line power.

Table.4 Area Control Error

		Without controller	PSO-FOPI	PSO-IOPI	GA-FOPI
Area Control Error (ACE)	ACE_1	0.3459	0.00008691	0.001027	0.00072
	ACE_2	3.88	0.0003471	0.0006096	0.0002943
	ACE_3	6.482	0.0004362	0.001876	0.00747
	ACE_4	1.948	0.0003501	0.0008521	0.00567

Any load change in the system, increases the tie-line power deviation, which is compensated by LFC. From the change in frequency and tie line power deviation ACE is manipulated based on the Equations (9) to (12) and it is listed in Table 4. Proposed controller minimises the ACE when compared to other controllers.

Table5. Performance indices

	Without	PSO based	PSO	GA based

		controller	FOPI(proposed)	based IOPI	FOPI
IAE	Δf_1	36.43	4.004	19.5	5.941
	Δf_2	368.3	7.438	10.3	7.838
	Δf_3	507.9	6.765	13.22	7.402
	Δf_4	184.4	6.885	9.19	9.447

Integral absolute of area control error is calculated as performance indices corresponding to the equations (13) to (16), and it is shown in Table 5. Compared to IOPI controller 1% to 4% of the IAE is reduced in the proposed controller.

The transient response characteristics values are listed in Table.6

Table 6. Transient response

		Without controller	PSO based FOPI (proposed)	PSO based IOPI	GA based FOPI
Δf_1	Overshoot (%)	5.78	4.334	1.7692	3.44
	Rise time	0.673	0.000185	0.9347	0.0965
Δf_2	Overshoot (%)	6.89	2.7010	4.0883	3.447
	Rise time	0.3689	0.0001996	0.1237	1.673
Δf_3	Overshoot (%)	3.89	1.1626	6.2437	5.563
	Rise time	0.0133	0.00073	0.0033	0.1267
Δf_4	Overshoot (%)	9.005	3.5491	2.4525	1.6236
	Rise time	5.703	0.3581	0.003267	1.078
ΔP_{12}	Overshoot (%)	9.862	0.0913	3.4057	6.712
	Rise time	9.778	0.0032	0.4392	0.076
ΔP_{23}	Overshoot (%)	2.876	0.05579	5.1866	0.06529
	Rise time	14.3638	0.0039	1.0712	0.9867
ΔP_{34}	Overshoot (%)	7.9889	0.23479	1.7287	0.04711
	Rise time	9.7075	0.0034	1.9733	1.4554

The Table.6 shows the transient response of the LFC. Percentage overshoot is increased in frequency deviations while tie line power deviation percentage overshoot is reduced. Moreover, the rise time is less in the proposed controller. From the results, it is clear that PSO based FOPI controller is suitable for the proposed multi area (four) multi source (three) test system.

Comparison with previous work

Table 7. Performance comparison from existing Literature

Type of the system	Two area	Three thermal area	Three area	Three area	Four area system
Reference Number	[12]	[16]	[18]	[22]	Proposed work

Controller	GA based PID	FOPID	GAPTDFPID	PID	FOPID	PSO-IOPI	PSO-FOPI
Δf_1	0.0079	--	0.001	0.010	0.009	0.001	0.0001
Δf_2	0.0035	--	0.001	0.012	0.001	0.002	0.0001
Δf_3	--	--	0.001	0.011	0.001	0.002	0.0002
Δf_4	--	--	--	--	--	0.003	0.0001
$\Delta P_{tie\,1}$	0.00046	--	0.08	0.140	0.110	0.002	0.0003
$\Delta P_{tie\,2}$	--	--	0.01	0.062	0.005	0.001	0.0002
$\Delta f_{tie\,3}$	--	--	0.00	0.115	0.161	0.004	0.0002
IAE	--	0.0017	--	--	--	--	--

The simulation results are compared with the already available literatures presented in Table 7. It reveals that the proposed LFC technique greatly improves the system performance.

Convergence Graph

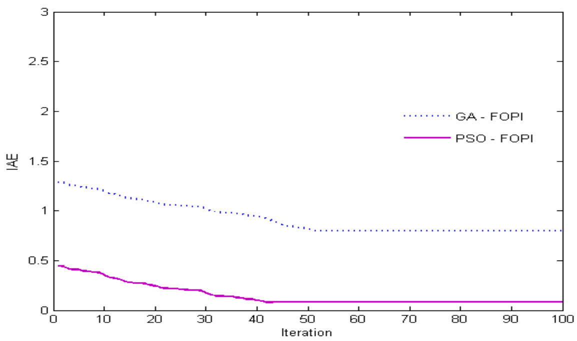


Fig.12 Convergence plot

Fig.13 shows the convergence plot for the GA based FOPI and PSO based FOPI. PSO Optimisation algorithm shows improved result.

6. Conclusion

The proposed multi-area multi-source power system gain and order parameters of the FOPI controller are tuned by PSO algorithm. For the first time in LFC a four area with multi source power systems is examined in this work. For a 1% step load change in each area, system response in terms of rise time and percentage overshoot is found improved. IAE of the change in frequency in each area and tie line power between areas is taken as the objective function. Simulation results show that PSO based FOPI controller is robust and its operation works well for the LFC system besides the step load perturbation. The proposed controller performance is compared with the IOPI controller performance and without controller. GA based FOPI controller design is also investigated. Proposed controller performed well against for multi-area multi-source with step load change.

Acknowledgement The authors acknowledge the Department of EEE, Principal and the Management of Thiagarajar College of Engineering, Tamilnadu, India, for their constant support in doing this research work.

Appendix I.

Nominal parameters of system are:

$B_i = 0.4312$	$T_{12} = 0.0433$
$R_i = 2.4$	$a_{12} = 1$
$K_t = 0.543478$	$\mathrm{K_h} = 0.32608$
$K_g = 0.130438$	$f = 50\,Hz$
$T_{ps} = [1\ \ 11.49/0.214\ 1\ ]$	$T_{sg} = 0.08$
$T_t = 0.3$	$K_r = 0.3$
$\mathrm{T_r} = 10$	$\mathrm{T_{gh}} = 0.2$
$T_{rs} = 5$	$T_{rh} = 28.75$
$T_w = 1$	$b_g = 0.05$
$c_g = 1$	$y_g = 1$
$X_g = 0.6$	$T_{cr} = 0.01$
$T_f = 0.23$	$T_{cd} = 0.2$
$\mathrm{K_{dc}} = 1$	$\mathrm{T}_{dc} = 0.2$
$\mathrm{K}_{ps} = [1\ 68.9566 * 3]$	

References

[1] Kundur P. *Power system stability and control*. New York: McGraw-Hill; 1994.

[2] Elgerd OI. *Electric energy systems theory – an introduction. 2nd ed*. Tata McGraw Hill; 2007.

[3] O.I. Elgerd and C. E. Fosha, Jr., "*Optimum megawatt-frequency control of multi-area electric energy systems,"* IEEE Transactions on Power Application System, 1970, 4, 556-563,

[4] C. Concordia, L. K. Kirchmayer, "*Tie-Line Power & Frequency Control of Electric Power Systems*", AIEE Transactions, 1953, 72 part III, 562-572.

[5] C. Concordia, L. K. Kirchmayer, *"Tie-Line Power & Frequency Control of Electric Power Systems-Part II*, AIEE Transactions, 1954, 73 part III-A, 133-141.

[6] S.K. Pandey, S.R. Mohanty, N. Kishor, *A literature survey on load frequency control for conventional and distribution generation power systems*, Renewable and Sustainable Energy Reviews. 2013, 25, 318–334.

[7] O. Singh, P. Tiwari, *A Survey of Recent Automatic Generation Control Strategies in Power Systems*, International Journal of Emerging Trends in Electrical and Electronics, 2013, 7, .

[8] I.J. Nagrath and M.Gopal *"Control System Engineering"* Fifth Edition, New Age International Publisher, New Delhi

[9] P. Taylor, C.S. Chang, W. Fu, F. Wen, *Load Frequency control using Genetic- Algorithm based fuzzy gain scheduling of PI controllers*, Electric Machines & Power Systems, 2007, 37–41.

[10] Baghya Shree.S and Kamaraj.N, *AGC for multisource deregulated power system using ANFIS controller*, International Transactions on Electrical and Energy systems. 2016, 1-14.

[11] H.A. Yousef, K. Al-kharusi, M.H. Albadi, *Load Frequency Control of a Multi-Area Power System : An Adaptive Fuzzy Logic Approach*, Electrical power and Energy Systems, 2014, 68, 384-395.

[12] R. Regar, R. Jangid, K. Parikh, *Load Frequency Control of Two Area System Using Genetic Algorithm*, International Journal of Engineering Research & Technology, 2017, 6, 180–186

[13] F. Daneshfar, H. Bevrani, *Multiobjective design of load frequency control using genetic algorithms*, International Journal of Electrical Power and Energy Systems. 2012, 42, 257–263.

[14] E.S. Ali, *BFOA based design of PID controller for two area Load Frequency Control with nonlinearities*, International Journal of Electrical Power and Energy Systems. 2013, 51 224–231.

[15] J. Nanda, S. Mishra, L.C. Saikia, *"Maiden Application of Bacterial Foraging-Based Optimization Technique in Multiarea Automatic Generation Control,"* IEEE Transaction on Power Systems, 2009, 24, .

[16] S. Debbarma, L. Chandra, N. Sinha, *Automatic generation control using two degree of freedom fractional order PID controller*, International Journal of Electrical Power and Energy Systems. 2014, 58, 120–129.

[17] S. Chaine, M. Tripathy, *Design of an optimal SMES for automatic generation control of two-area thermal power system using Cuckoo search algorithm*, Journal of Electrical Systems Information Technology. 2015, 2, 1–13.

[18] A.R. Meena, S.S. Kumar, *Design of GA Tuned Two-degree Freedom of PID Controller for an Interconnected Three Area Automatic Generation Control System*, International Journal of Science and Technology. 2015, 8, 1–10.

[19] B. Mohanty, S. Panda, P.K. Hota, *Controller parameters tuning of differential evolution algorithm and its application to load frequency control of multi-source power system*, International Journal of Electrical Power Energy Systems. 2014, 54, 77–85.

[20] B. Mohanty, S. Panda, *Differential evolution algorithm based automatic generation control for interconnected power systems with non-linearity*, Alexandria Engineering Journal. 2014, 53, 537–552.

[21] S. Sondhi, Y. V Hote, *Fractional order PID controller for load frequency control*, Energy Conversion and Management. 2014, 85, 343–353.

[22] S.A. Taher, M.H. Fini, S.F. Aliabadi, *Fractional order PID controller design for LFC in electric power systems using imperialist competitive algorithm*, Ain Shams Engineering Journal. 2014, 5, 121–135

[23] Z. Li, L. Liu, S. Dehghan, Y. Chen, D. Xue, *A review and evaluation of numerical tools for fractional calculus and fractional order controls*, 7179 (2015).

[24] Y. Luo, Y. Quan, C. Yang, Y. Guo, *Tuning fractional order proportional integral controllers for fractional order systems*, 2010, 20, 823–831.

[25] H. Li, Y. Luo, Y. Chen, *A Fractional Order Proportional and Derivative (FOPD) Motion Controller: Tuning Rule and Experiments*, 2010, 18, 516–520.

[26] *Functional Fractional Calculus for System Identification and Controls*, Springer, 2008