

NEW TECHNIQUES FOR TUNING OF PID LOAD FREQUENCY CONTROLLER OF INTERCONNECTED ELECTRIC POWER SYSTEM

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Abstract: This paper investigates new techniques for tuning of PID Load Frequency Control of multi area electric power system having different turbines. The gain values of controller are optimized using different Metaheuristic Algorithms. The robustness and validity of designed controllers were checked on multi area interconnected power system with various Step Load variations.

Finally, the performance of proposed controllers was compared with conventional controller in MATLAB environment and from the result it has been proved that the proposed controller exhibits superior performance than conventional controller for various Step load and uniformly distributed random loads.

Key words: PID Tuning, Electric Power System, Automatic Generation Control, Random Load variations.

1. Introduction.

As the demand changes the system voltage and frequency deviate from the initial values causing an unpredictable small amount of change in the state of the system. An automatic control system is assigned to detect the change and it initiates a set of counter control actions in order to nullify effectively and at the earliest any deviation in the state of the system. In any interconnected system deviation of the state of the system may well disturb the state of economic operation and may even cause overloads on the interconnecting ties with the risk of having lost the continuity of operation. The obvious way to maintain a perfect power balance at each bus could be to continuously keep the generated powers in balance with the changing load power P_D and Q_D . The real power is controlled through the turbine torque while the reactive power is controlled via exciter [9,10].

Automatic control of generators involves two major control loops in power system equipped with large generators. These two major loops are *Automatic Voltage Regulator* (AVR) and *Automatic Load Frequency Control* (ALFC) loops. This paper mainly concentrated on Load Frequency Control (LFC). The ALFC loop regulates the real power output & corresponding frequency of the generator power

output. The primary ALFC loop senses the turbine speed and controls the operation of the control valves of turbine power input via the speed governor. When the power system is subjected to sudden load increments (ΔP_D), the turbine output ΔP_T is increased to a new value as rapidly as the primary ALFC loop permits. However, this load increase causes negative frequency error. It causes a slow growing positive integrator output and a corresponding increase in power reference setting. The signal (Δf) fed to the integrator is known as *Area Control Error* (ACE). *Integral* control will give rise to zero static frequency error following a step load change i.e the secondary ALFC loop eliminates the frequency error. In order to keep values of system frequency and tie-line power within the limit during the sudden and normal load conditions, there is several control techniques have been proposed for the LFC of power system. The same authors have explained a critical literature survey on different control strategies of power system LFC [5].

In this paper, Ant Colony Optimization (ACO) and Pattern Search (PS) PID tuning methods were used for Load Frequency Control (LFC) in three area interconnected power system. The performance of ACO-PID & PS-PID were compared with conventional PID controller. Pattern Search Optimization is a new optimization method and is used for solving the different optimization issues [3]. In this paper Ant Colony Optimization and Pattern Search technique was implemented for tuning the parameters of PID controllers of three area interconnected power system.

2. Design of Electrical Power System.

The main difference between Load Frequency Control of multi-area system and that of single area system is, the frequency of each area of multi-area system should return to its nominal value and also the net interchange through the tie-line should return to the scheduled values. So a composite measure, called area control error (ACE), is used as the feedback variable. A decentralized controller can be tuned assuming that there is no tie-line exchange power, $P_{tiei} = 0$. In this case the local feedback control will be $u_i = -K_i(s)B_i \Delta f_i$.

Thus load frequency controller for each area can be tuned independently. To illustrate the decentralized PID tuning method, consider a Three-Area electric power system with load perturbations. The system frequency deviation Δf_i , the deviation in the tie-line power flow ΔP_{tiei} , load disturbance ΔP_{Li} [11].

If the load increases, the speed of the alternator reduces slightly. The governor of any thermal unit reacts to this speed variation and permits the entry of some more steam from the boiler to turbine which increases the speed. Many forms of the governor system have been devised all of which includes, the variation of the turbine-alternator shaft speed as the basis on which the change of position of the turbine. Typical speed droop characteristics for most governor range between 5 to 10%. The block diagram of speed governor system is shown in Figure 1 [8].

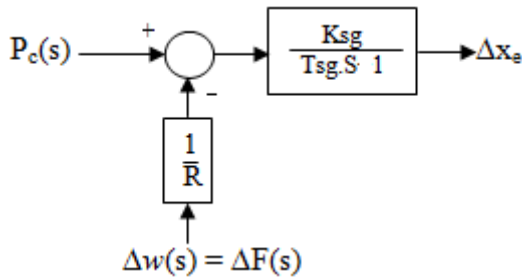


Fig. 1. Speed Governor with drooping characteristics

The transfer function of speed governor with drooping characteristics is

$$G_{sg}(s) = \frac{1}{(1 + sT_{sg})} = \frac{NUM_{sg}(s)}{DEN_{sg}(s)}$$

Turbine dynamics are very important because they also affect the overall response of the generating plant to load changes. *Non-reheat turbines* are first-order units and its block diagram is shown in Figure 2.

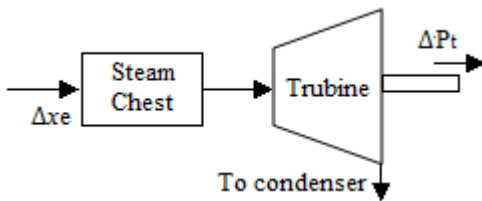


Fig. 2. Non-Reheat Steam Turbine

The transfer function of the non-reheat turbine is represented as

$$G_{nr}(s) = \frac{1}{(1 + sT_t)} = \frac{NUM_t(s)}{DEN_t(s)}$$

After passing the control valve the high pressure steam enters the turbine via the steam-chest that introduces time delay T_{nt} usually in order of 0.2 - 0.5s. The *Reheat turbines* are modeled as second-order units because of presence of high and low steam pressure. It is more efficient and is used for modern-day large sets. The above model is modified to get Reheat Steam turbine as shown in Figure 3.

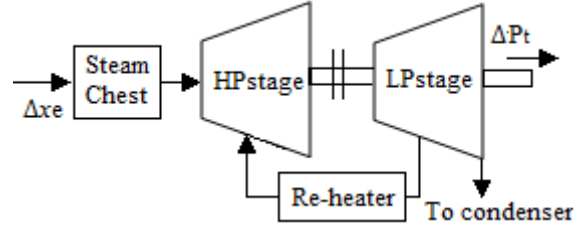


Fig. 3. Reheat Steam Turbine

The overall transfer function of Reheat turbine is

$$Gr(s) = \frac{1 + sCT_r}{(1 + sCT_t)(1 + sT_{lpr})} = \frac{NUM_t(s)}{DEN_t(s)}$$

The Generator which is supplying local load and is not supplying power to another area via a tie-line. Suppose there is a real load change of ΔP_D . Due to the action of the turbine controllers, the generator increases its output by the amount ΔP_G . The net surplus power $\Delta P_G - \Delta P_D$ will be absorbed by the system of generator with load damping (D) effect (see Figure 4).

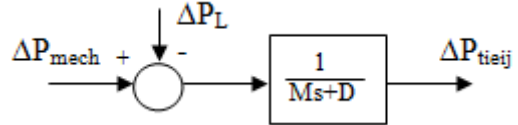


Fig. 4. Generator with load damping

The transfer function of generator with load damping or power system is

$$G_{ps}(s) = \frac{1}{(D + Ms)} = \frac{K_{ps}}{(1 + sT_{ps})} = \frac{NUM_{sg}(s)}{DEN_{sg}(s)}$$

Practically, all power systems now a days are interconnected by number of tie-lines with the neighboring areas. When the frequency variations in two areas are different, a power exchange occurs through the tie-line between the connected two areas.

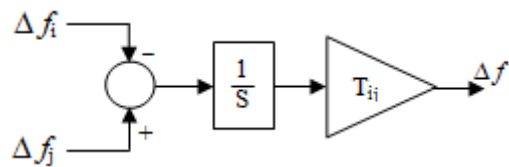


Fig. 5. Tie-line Connections

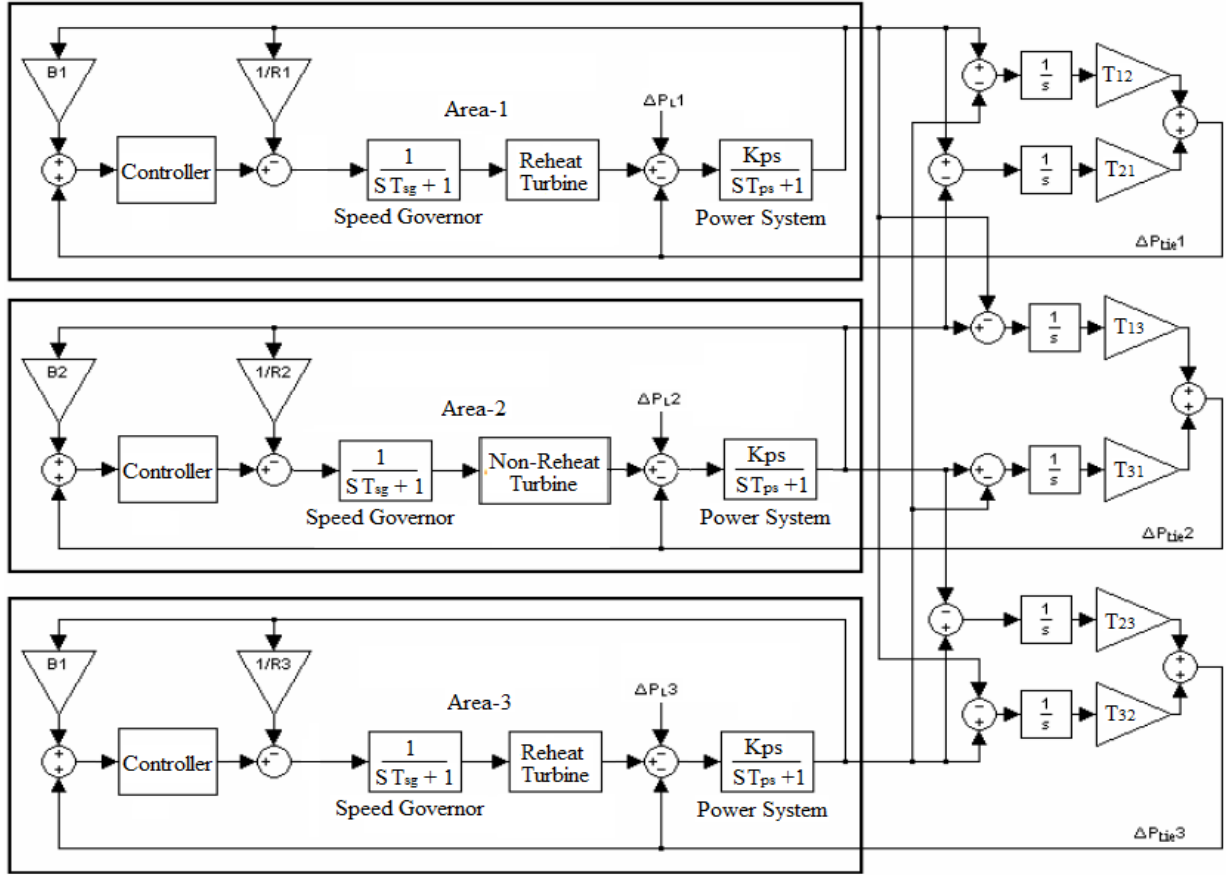


Fig. 6. Three Area Interconnected Electric Power System with Step Load Variations.

The Figure 5 shows the block diagrams of Tie-line connection. The Laplace transform of tie line is

$$\Delta P_{tieij}(s) = \frac{T_{ij}(\Delta F_i(s) - \Delta F_j(s))}{s}$$

Where ΔP_{tieij} is tie line power exchange between areas i and j , and T_{ij} is the tie-line synchronizing coefficient between area i and j .

By connecting all above blocks, we can get the overall block diagram of an interconnected electric power system. The Figure 6 shows the block diagram representation of three area interconnected electric power system with step load variations. Let area 1, 2, 3 are non identical systems with Reheat, Non-reheat and Reheat turbines in all three areas respectively and the disturbances applied to the system are step variations.

The transfer functions of all three areas of interconnected power system are as follows (see appendix-I for Turbine, Speed Governor and Power system parameters) [1, 2]:

$$\text{For } i^{\text{th}} \text{ Area, } G_i(s) = \frac{\text{NUMsg}(s) \text{ NUMt}(s) \text{ NUMps}(s)}{\text{DENsg}(s) \text{ DENt}(s) \text{ DENps}(s) + \text{NUMsg}(s) \text{ NUMt}(s) \text{ NUMps}(s)/R_i} B_i$$

$$\text{For Area-1, the transfer function is } G_1(s) = \frac{48.75s + 16.25}{s^4 + 16s^3 + 44.312s^2 + 55s + 16.25}$$

$$\text{For Area-2, the transfer function is } G_2(s) = \frac{106.25}{s^3 + 15.88s^2 + 42.46s + 106.25}$$

$$\text{For Area-3, the transfer function is } G_3(s) = \frac{53.125s + 10.625}{s^4 + 15.98s^3 + 44.05s^2 + 58.41s + 10.625}$$

3. PID Load Frequency Controller Tuning.

$$G_c(s) = K_p + \frac{K_i}{s} + sK_d = K_p(1 + \frac{1}{sT_i} + sT_d)$$

For industrial plant process, the conventional PID controllers are most commonly used. There are several prescriptive rules used for tuning of PID controller. The parallel form of a PID controller has transfer function [4]:

Where K_p = Proportional Gain constant; K_i = Integral Gain constant; T_i = Reset Time constant = K_p/K_i , K_d = Derivative gain constant; T_d = Derivative time constant. The tuning of PID load frequency controller of multi-area power system that it has to bring frequency of each area to its nominal value and also the change in tie-line power should return to the scheduled values. So the combination of both, called Area Control Error (ACE), is used as feedback variable. In this paper three different types PID controllers were designed i.e Conventional controller, Metaheuristic (*Ant Colony* and *Pattern Search* based) Controller.

3.1 Conventional Controller

Zhuang and Atherton were proposed optimum setting algorithms for a PID controller. The general form of the optimum criterion is

$$J_n(\theta) = \int_0^\infty t^n [e(\theta, t)]^2 dt$$

Where θ is the PID controller parameter vector and $e(\theta, t)$ is the error which passes through controller. There are three different optimum criteria for tuning of PID controller, those are Integral Squared Error (ISE) criterion, Integral Squared Time weighted Error (ISTE) criterion and Integral Squared and Time Squared Error (IST²E) criterion. The optimal parameters are obtained by minimizing the above equation [4,7].

3.2 Metaheuristic Controller

Recently, most of the researchers focused on new algorithms called Metaheuristic. A Metaheuristic is a set of algorithm concepts that can be used to define heuristic methods applicable to wide set of different applications. The use of Metaheuristic has significantly increased the ability of finding very high quality solutions to hard and practically relevant combinatorial optimization problems in a reasonable time [11].

3.2.1 Ant Colony Optimization:

A particularly successful Metaheuristic inspired by the behavior of real Ants. Starting Ant system, a

number of algorithmic approaches based on the very same ideas were developed and applied with considerable success to a variety of combinatorial optimization problems from academic as well as from real world applications. The ACO Metaheuristic has been proposed as a common framework for the existing applications and algorithmic variants of a variety of Ant algorithms. Ants are able to find the shortest path between a food source and the nest without the aid of visual information, and also to adapt to a changing environment. It was found that the way ants communicate with each other is based on pheromone trails. While ants move, they drop a certain amount of pheromone on the floor, leaving behind a trail of this substance that can be followed by other ants. The more ants follow a pheromone trail, the more attractive the trail becomes to be followed in the near future. The basic idea is illustrated in Figure 7.

Two ants start from their nest (left) and look for the shortest path to a food source (right). Initially, no pheromone is present on either trails, so there is the same chance of choosing either of the two possible paths. Suppose one ant chooses the upper trail, and the other one the lower trail. The ant that has chosen the upper (shorter) trail will have returned faster to the nest. As a result, there is a greater amount of pheromone on the upper trail as on the lower one. The probability that the next ant will choose the upper (shorter) trail will be higher. More ants will choose this trail, until all ants will follow the shorter path.

The following algorithmic skeleton shows the *pseudo-code* for Ant Colony Algorithm for optimization problems [6].

Procedure ACO Metaheuristic

```
Set parameters, initialize pheromone trails
while (termination condition not met) do
  Construct Ants Solutions
  Apply Local Search    % optional
  Update Pheromones
end
end
```

In this paper, Number of Ants (NA) is 100, Number of Iterations (ITR) are 100, Number of parameters are 3 and evaporation rate (ρ) is 0.95.

3.2.2 Pattern Search:

The Pattern Search (PS) Algorithm generates a sequence of iterates with non-increasing objective function values. Iteration is divided into two phases: an optional search and a local poll.

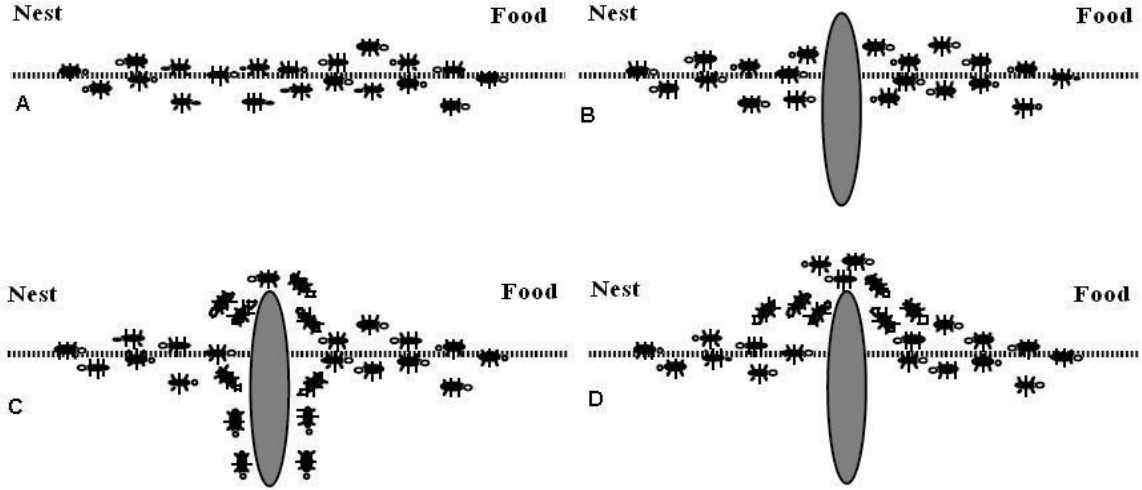


Fig. 7. (a) Real ants follow a path between nest and food source. (b) An obstacle appears on the path: Ants choose whether to turn left or right with equal probability. (c) Pheromone is deposited more quickly on the shorter path. (d) All ants have chosen the shorter path.

In the search step $f(s)$ is evaluated at a finite number of points on a mesh to one that yields a lower $f(s)$ value than the incumbent. Mesh is a discrete subset of bounded search space with lower and upper boundaries.

Mesh:

$$M_k = \{ S_k + \Delta_k D_z : z \in Z_+^D \} ; \quad (a)$$

Where D is a +ve spanning set, Δ_k is mesh size parameter, S_k is a mesh local optimizer.

Poll set:

$$\{ S_k + \Delta_k d : d \in D_k \} \quad (b)$$

Pseudo code of Pattern Search Algorithm

Step - I : Let S_0 be such that $f(S_0)$ is finite and M_0 be the initial mesh defined by $\Delta_0 > 0$, & D_0 . Set the iteration counter k to 0.

Step - II : Perform the search and possibly the poll steps until an improved mesh point S_{k+1} with the lowest so far $f(s)$ values is found on the mesh M_k defined by Eq.(a). Evaluate $f(s)$ on the poll set defined in Eq.(b).

Step-III: If the search or the pole produced an improved mesh point, i.e a feasible iterate $x_{k+1} \in M_k \cap \Omega$ for which $f(S_{k+1}) < f(S_k)$, then update $\Delta_{k+1} \geq \Delta_k$ by $\Delta_{k+1} \geq T^{w_k} \Delta_k$.

For $0 < T^{w_k} < 1$ where $T > 1$ is a rational number that remains constant over all iterations, and $w_k \geq 0$ is an integer. If, $f(S_k) < f(S_k + \Delta_k d)$ for all $d \in D_k$, set $S_{k+1} = S_k$, update $\Delta_{k+1} < \Delta_k$ by $w_k \leq -1$.

Increase k by $k+1$ and go back to **Step-I**.

In order find the Performance Index of all above controllers, Integral of Time multiply Absolute Error (ITAE) of deviations of frequency and tie-line power of all area were considered as objective function. Accordingly, the objective function is defined as [12]

$$J = \int_0^{t_s} t(\Delta f_i + \Delta P_{tieij})^2 dt$$

Where t_s is simulation time.

Above objective function is minimized by considering the following constraints:

$$\begin{aligned} K_P^{\min} < K_P < K_P^{\max} \quad K_I^{\min} < K_I < K_I^{\max} \\ K_D^{\min} < K_D < K_D^{\max} \end{aligned}$$

4. Simulation Result and Analysis.

The robustness and validity of the designed controllers are explained by the following illustrations by considering various step load variations in three area interconnected electric power system having different turbines in respective areas. The parameters of all three areas are collected from various steam power stations in India and are shown in appendix-I.

4.1 Illustration -I

Let the step load perturbations as $dP_{L1} = 0.01pu$, $dP_{L2} = 0.01pu$ and $dP_{L3} = 0.01pu$ are applied to Area-I, Area-II and Area-III respectively at $t = 0sec$. The figures 8(a) to 8(c) shows the variations in frequency for applied load power disturbances in three areas respectively. Similarly, the figures 9(a) to 9(c) shows the variations in Tie Line Power variations for applied load power disturbances in three areas respectively.

Table 1 Optimized values of PID Controller

Area-i	Conventional Controller			Ant Colony Optimization			Pattern Search Algorithm		
	K_P	K_I	K_D	K_P	K_I	K_D	K_P	K_I	K_D
Area-I	6.0241	3.6946	0.9717	7.5762	6.9697	1.705	14.1607	17.9244	6.2195
Area-II	2.7969	3.7178	0.4173	4.1053	5.8268	1.705	2.766	8.8002	1.0729
Area-III	5.7858	3.7821	0.9095	7.833	6.9697	1.5986	12.4074	16.877	4.6455

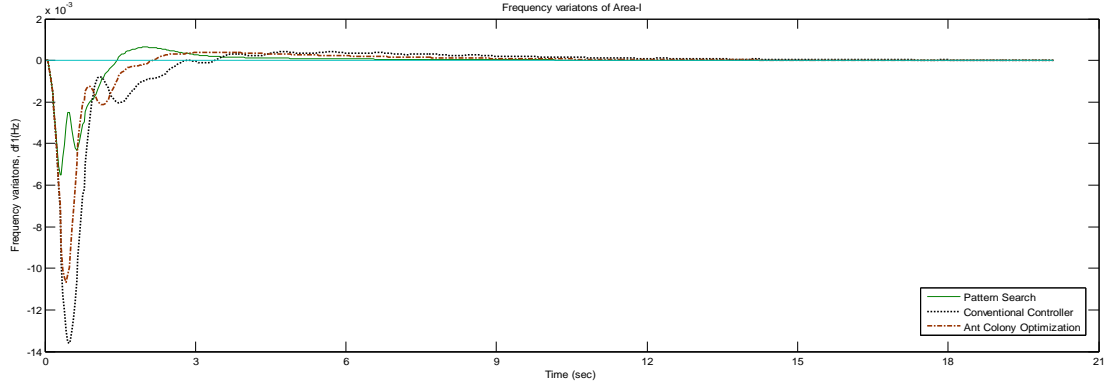


Fig. 8(a). Frequency variations in Area-I, df1 (Hz)

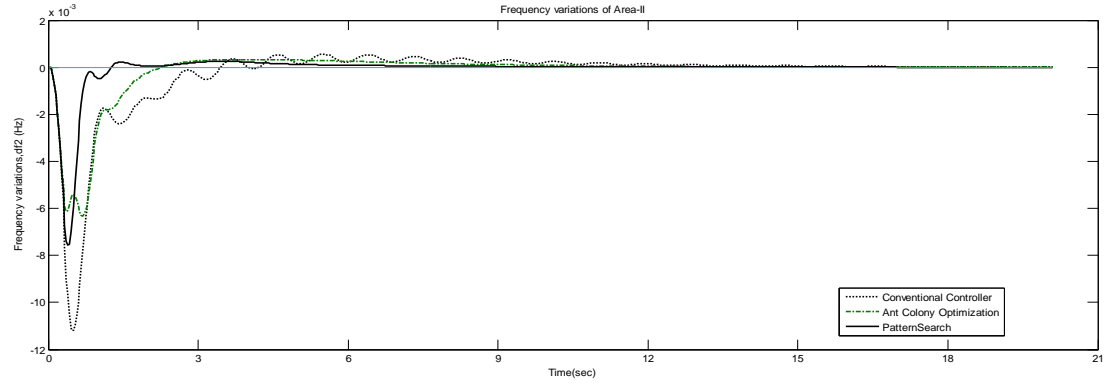


Fig. 8(b). Frequency variations in Area-II, df2 (Hz)

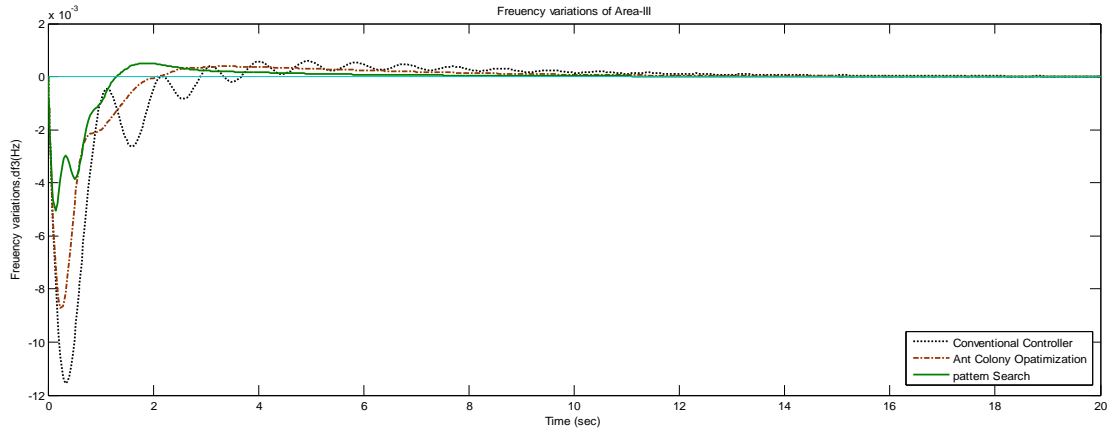
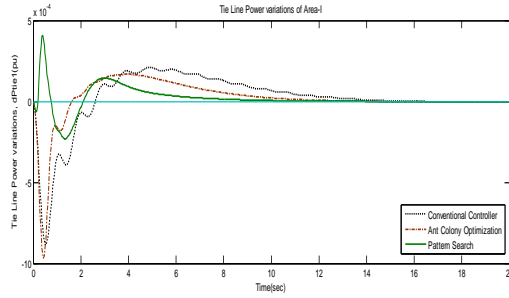


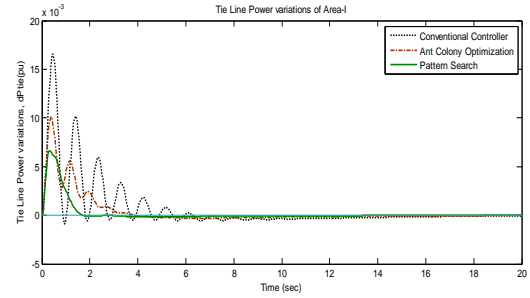
Fig. 8(c). Frequency variations in Area-III, df3 (Hz)

The figure from 9(a) -9(c) shows Tie-Line Power variations in three areas for load disturbances as $dP_{L1} = dP_{L2} = dP_{L3} = 0.01\text{pu}$ and figures from 10 (a) -10(c)

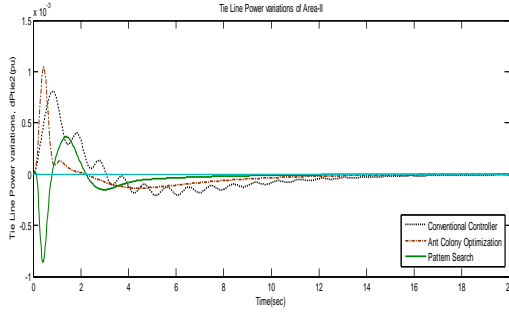
shows Tie-Line Power variations in three areas for load disturbances as $dP_{L1} = 0.01\text{pu}$, $dP_{L2} = 0.1\text{pu}$ and $dP_{L3} = 0.15\text{pu}$.



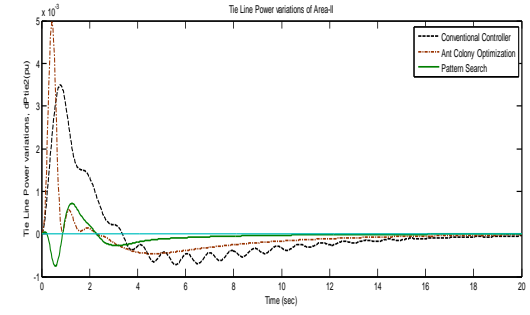
9(a)



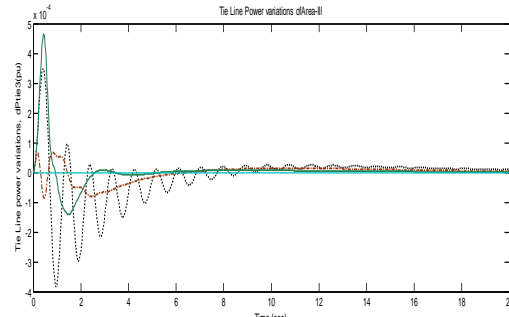
10(a)



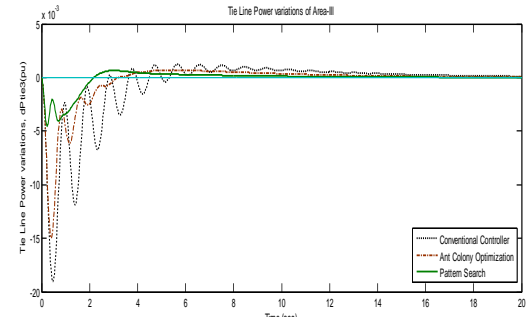
9(b)



10(b)



9(c)



10(c)

4.2 Illustration -II

Now let the step load perturbations as $dP_{L1} = 0.01\text{pu}$, $dP_{L2} = 0.05\text{pu}$ and $dP_{L3} = 0.1\text{pu}$ are applied to Area-I, Area-II and Area-III respectively at $t = 0\text{sec}$. The figures from 11(a) to 11(c) shows the variations in

frequency for applied load power disturbances in all three areas respectively. Similarly, the figures from 10(a) to 10(c) shows the variations in Tie Line Power variations for applied load power disturbances in all three areas respectively.

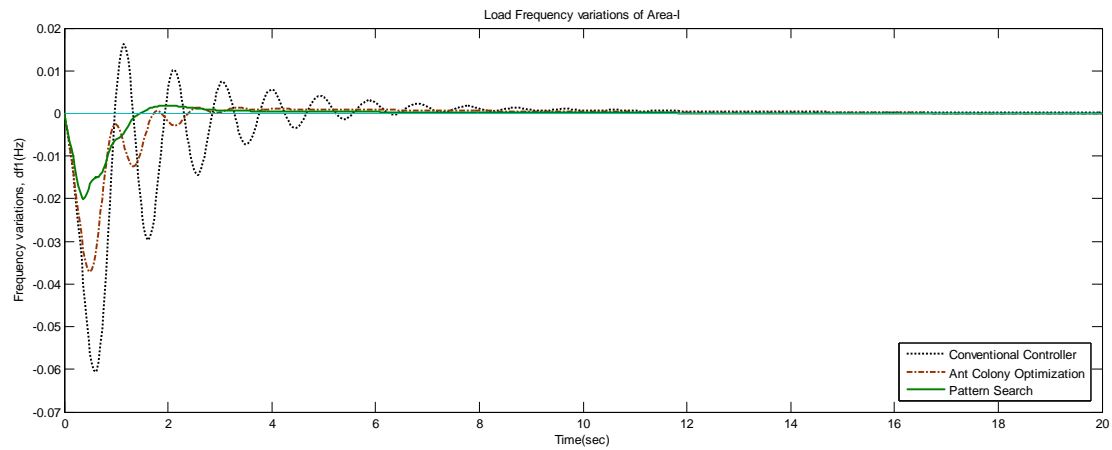


Fig. 11(a). Frequency variations in Area-I, df1 (Hz)

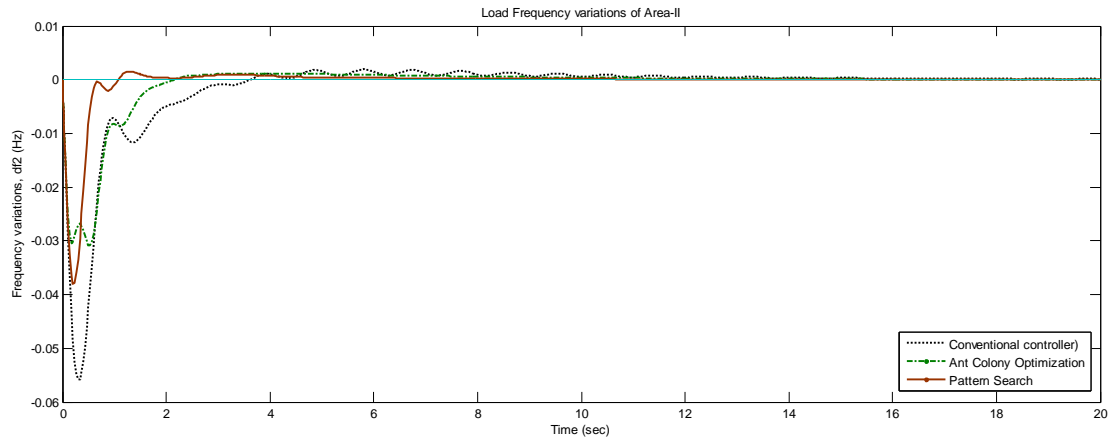


Figure 11(b). Frequency variations in Area-II, df2 (Hz)

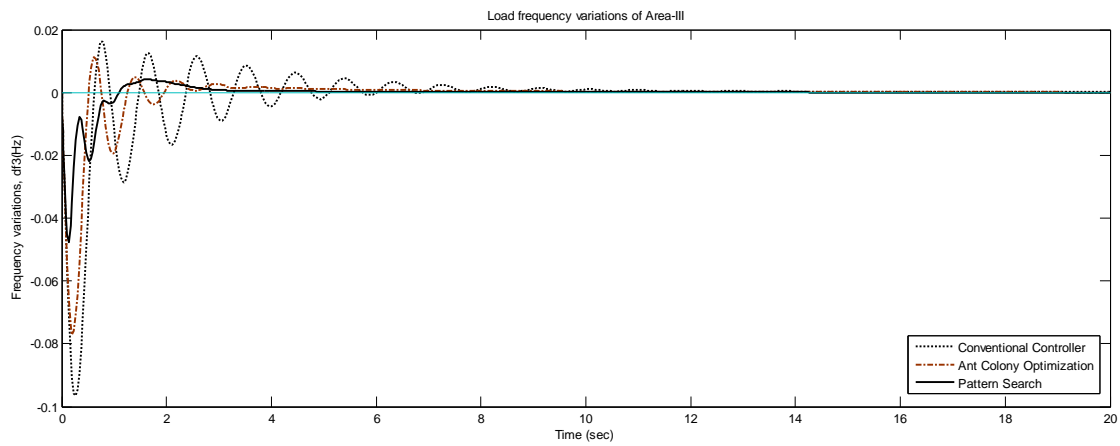


Figure 11(c). Frequency variations in Area-III, df3 (Hz)

The following Tables 2 and 3 shows the summary of above simulation results including various step load variations, to check the performance and validity of the designed controller.

Table 2 Performance of Three area Electric Power System with $dP_{L1} = dP_{L2} = dP_{L3} = 0.02\text{pu}$

Area-i	Conventional Controller		Ant Colony Optimization (ACO)			Pattern Search Algorithm (PSA)		
	1 st peak over shoot	Settle Time	1 st peak over shoot	Settle Time	Improvement in settle time *	1 st peak over shoot	Settle Time	Improvement in settle time *
Area-I	-0.0136	17.80	-0.0107	12.80	39.06	-0.0055	5.80	190.70
Area-II	-0.0112	17.20	-0.0063	14.10	22.00	-0.0076	9.00	91.10
Area-III	-0.0128	17.52	-0.0105	12.25	33.16	-0.0053	5.65	187.15

Table 3 Performance of Three area Electric Power System with $dP_{L1} = 0.01\text{pu}$, $dP_{L2} = 0.05\text{pu}$, $dP_{L3} = 0.1\text{pu}$

Area-i	Conventional Controller		Ant Colony Optimization (ACO)			Pattern Search Algorithm (PSA)		
	1 st peak over shoot	Settle Time	1 st peak over shoot	Settle Time	Improvement in settle time *	1 st peak over shoot	Settle Time	Improvement in settle time *
Area-I	-0.0607	23.21	-0.0372	22.15	4.80	-0.0201	13.25	75.17
Area-II	-0.0558	22.00	-0.0308	18.12	21.40	-0.038	10.45	110.5
Area-III	-0.0964	22.10	-0.0771	20.80	6.25	-0.0475	15.75	40.31

*compared to conventional controller

4.3 Illustration -III

The robustness and validity of the designed controllers are also verified by applying the uniformly distributed random load on investigated power system. The output of the uniformly distributed random load is repeatable for the given seed. The upper and lower

band limits of uniformly distributed random load are ± 0.01 respectively. The Figures 12(a) – 12(c) shows the suppression of frequency variations of all three areas for uniformly distributed random loads respectively.

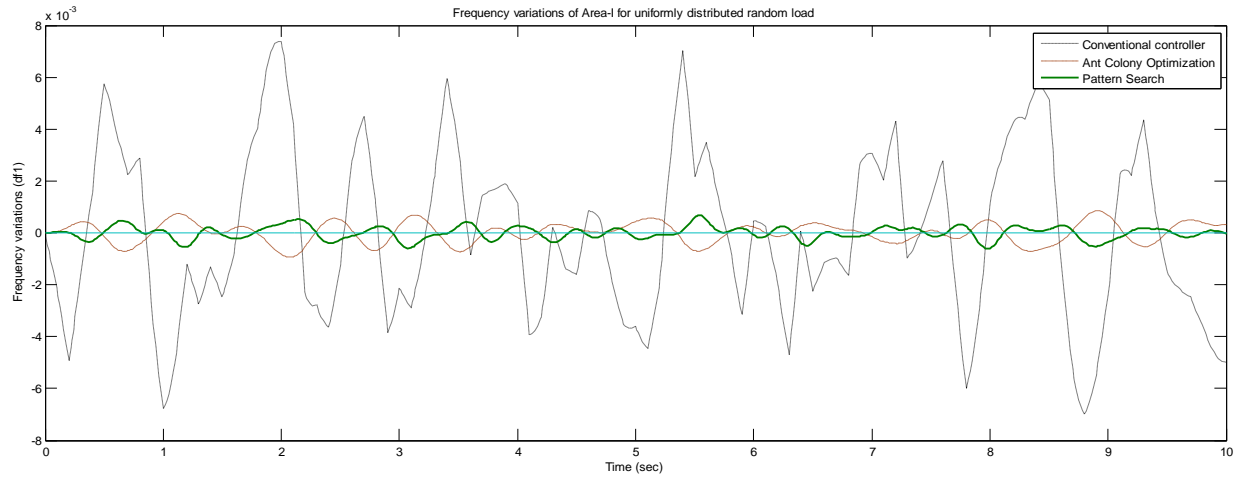


Fig. 12(a). Frequency variations in Area-I, df1 (Hz)

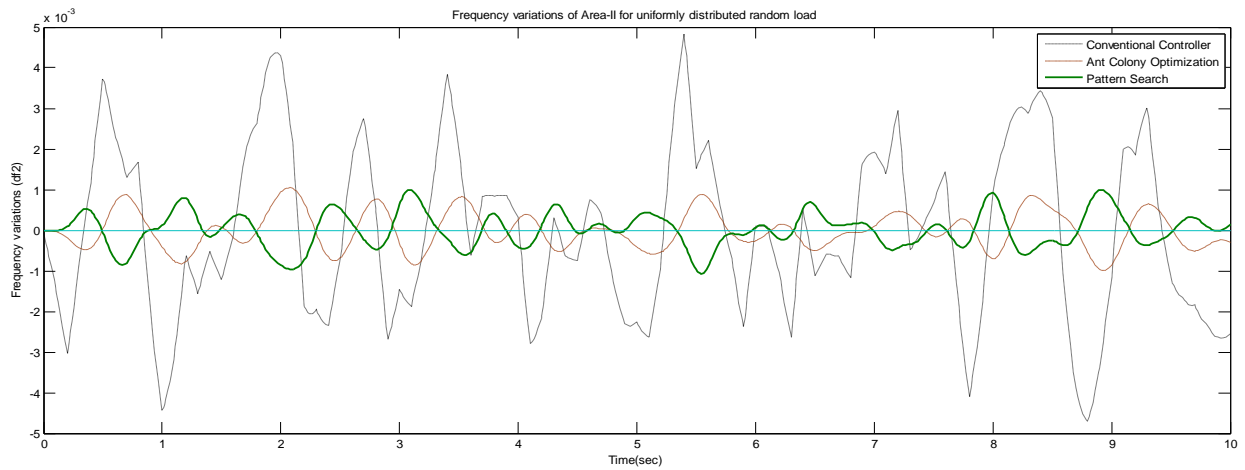


Fig. 12(b). Frequency variations in Area-II, df2 (Hz)

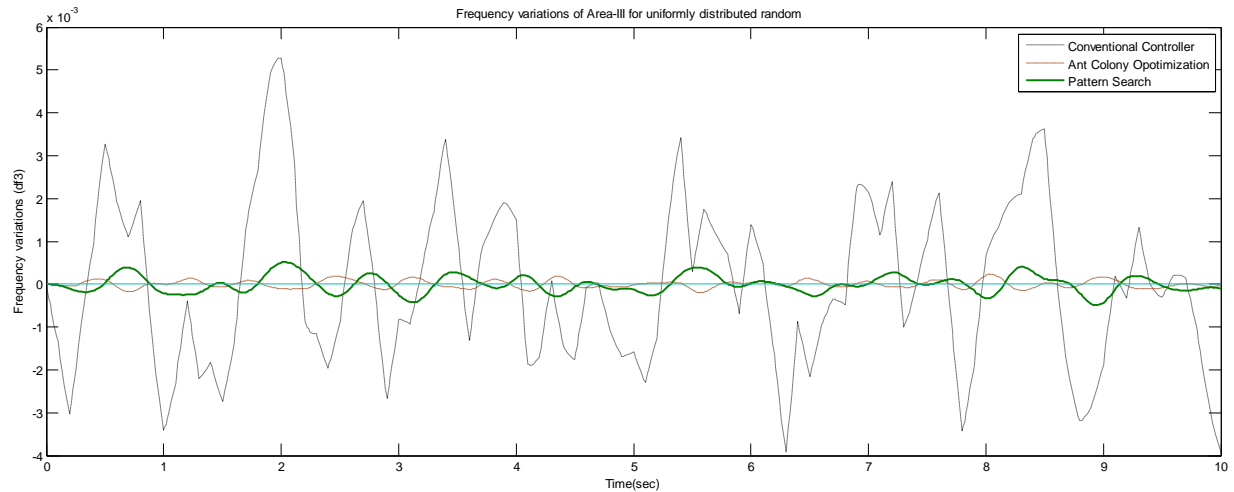


Fig. 12(c). Frequency variations in Area-III, df3 (Hz)

5. Conclusions

In this paper tuning PID controller using Metaheuristic algorithms has been proposed for load frequency control of interconnected electric power systems. From the simulation result, it can be concluded that the Metaheuristic controllers gives superior and better results than conventional controller. The Metaheuristic controller exhibits good performance and have more validity than that of conventional controller for various load variations.

With the Metaheuristic tuning algorithms, the controller designed by Pattern Search algorithm gives superior performance of three area interconnected power system with various step load variations than Ant Colony Optimization and Conventional controller.

Appendix - I

The nominal parameters of three area interconnected Electric Power System (Reheat – Nonreheat – Reheat) are collected from various Thermal power plants in India and are as given in below Table 4. For Area-I, the data is obtained from Sothern Grid and Neively Lignite Corporation, Tamil Nadu, India. Area-II data is from RTPP, Muddanuru, A.P. India. Area-III data is from Lanco Power Generation, Sri Kalhasthi, A.P. India.

Table 4. Nominar parameters of turbine in all three areas.

Parameters	Area-I	Area-II	Area-III
Speed Governor Time constant	0.08	0.08	0.08
Speed Governor Regulation	2.4	2	2.4
Power System Gain Constant	20	15	20
Turbine Time Constant	0.3	0.3	0.3
Coefficient of re-heat steam turbine (HP)	0.3	-	0.53
Reheat Time Constant (LP)	10	-	10

Rated capacity $P_r = 2000\text{MW}$; $P_{ti\max} = 200\text{ MW}$; $(\delta_1 - \delta_2) = 30^\circ$; Rated frequency $f^0 = 60\text{Hz}$, $D_i = 8.33 \times 10^{-3}$; Syn. Co-efficient $T_{ij} = 0.545$.

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