DESIGN OF LOAD FREQUENCY CONTROLLER USING MULTI OBJECTIVE BASED BAT ALGORITHM

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Abstract: *In this paper, load frequency control (LFC) of a two area system connected by a single tie-line is considered. The objective of LFC is to maintain generation-demand balance of an area by adjusting the outputs in response to the deviations in frequency and tie-line power on regulating units. A new meta-heuristic BAT Algorithm based on multi objectives and Pole placement techniques are used to design the LFC controllers like Integral (I) and Proportional Integral Derivative (PID) for their optimal gain setting values. BAT Algorithm is formulated from the echolocation behavior of bats. The objective of LFC and settling time are considered as the multi objectives for BAT algorithm. Simulations through MATLAB demonstrate that the conventional approach does provide good performances but with long settling time, whereas the proposed BAT algorithm on other hand satisfies all objectives thus ensuring system stability.*

Keywords: *Load Frequency Control, Pole placement technique, Integral, Proportional Integral Derivative, BAT Algorithm.*

1. Introduction

Power system stability could be defined generally as a property of the Power system, which gives it the ability to remain in equilibrium state or regain that state after occurrence of disturbance. Different controllers should be employed to enhance power system stability for low frequency oscillations. The problem is further complicated by continuous variation in power system operating conditions.

Automatic generation control (AGC) for the interconnected power systems provides control signals to regulate the output power of controllable generators in a prescribed area. In response to changes in system frequency and tie-line power, it maintains the scheduled frequency of system and establishes interchange with other areas within a predetermined limit. The task of AGC to regulate the power flow among many areas while maintaining the frequency constant is called Load frequency control (LFC).

For a number of years, LFC problem has been one of the most important topics in the interconnected power systems operation. There are two principal aspects for LFC of an interconnected power system i.e., the maintenance of frequency and exchange of power over inter area tie-lines on their scheduled values. The LFC objective is to maintain the balance of area generation–demand by adjusting the regulating units in response to frequency and tie-line power deviations. The design of PI control strategy based automatic generation control (AGC) regulators using optimal control theory is discussed in [1]. Ali M. Yousef in [2] proposed Load-frequency control (LFC) where control signal is synthesized by multiplying the state variables of the power system with determined gain matrix without solving any non-linear algebraic Riccati equation.

A large number of controllers are employed to maintain power system operation in a normal state. The state of the system changes, as demand fluctuates from its normal operating value. To maintain the LFC system at a normal operating state, different types of controllers based on variable structure control theory [3-6] and optimal control theory [7-10] have been developed in the past. Despite of the powerful control strategies, these controllers failed to appeal to the industry because for LFC, the realization of such controllers is tedious and costly. On the other hand, simple classical LFC controllers for their inherent simplicity, low cost and easy realization are becoming popular with the industry [11]. Most of the load frequency

controllers are mainly composed of integral (I) or proportional integral (PI) controllers.

In the present work, the proposed BAT algorithm is compared with well known technique called pole placement technique for designing the LFC controllers. Here BAT algorithm is based on multi objectives. The multi objectives considered are integral of sum of squares of incremental frequency deviation of area1 and area 2, incremental change in tie line power, settling time. Individually when one objective is concentrated the other objective may not be satisfied. So here multi objective optimization is considered to satisfy all objectives. In the following sections, the algorithm is described in detail and implemented in designing the load frequency controllers for a two-area system.

2. Load Frequency Control

For large scale power systems which consist of inter-connected control areas, load frequency is important to keep the frequency and inter area tie line power near to the scheduled values. The input mechanical power is used to control the frequency of the generators and the change in the frequency and tie-line power are sensed, which is a measure of the change in rotor angle.

A well designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude.

Some of the reasons for restricting the variation of system frequency
1. The speed of AC motors is based on the power supply frequency and there are situations for high priority of consistency of speed.
2. The electric clocks are driven by the synchronous motors. The clock's accuracy depends on an integral of the frequency error.
3. The normal system frequency is 50 Hertz and even for deviations of $\pm 5\%$ in system frequency, the blades of turbine get damage.
4. It is not desired for power transformer to function in under frequency. If the frequency falls beneath the desired level, affects the efficiency of transformer and overheating of the transformer winding.

5. Also the effect of operation of subnormal frequency is more seriously viewed in the case of thermal plants.

3. Load Frequency Controllers

Different load frequency controllers (LFC) like Integral (I) controller, Proportional Integral (PI controller), Integral Derivative (ID) controller and Proportional-Integral-Derivative (PID) controllers are used for maintaining area frequency and tie line power for their scheduled values in the single or multi area system. In the paper the optimal gain settings of two different controllers like I and PID controllers are determined.

3.1 *With Integral Control action*:

With an Integral controller case in the system the control law for area i is [11]

$$U_i = -K_{Ii} \int ACE_i(t)dt. \tag{1}$$

Where ACE_i is 'area control error' and K_{Ii} is gain value of I controller in area i.

In conventional control scheme of figure 1, from state variables x_8 and x_9, the control inputs u_1 and u_2 are built as shown below.

$$u_1 = -K_{i1}x_8 = -K_{i1} \int ACE_1 \, dt$$
$$u_2 = -K_{i2}x_9 = -K_{i2} \int ACE_2 \, dt \tag{2}$$

In the optimal control scheme, the feedbacks from all the nine states generate these control inputs.

3.2 *With Proportional Integral Derivative Control action*:

The PID controller is used to improve the dynamic response as well as reduce steady state error.

In the system with a Proportional Integral Derivative controller case, the control law for area i is

$$U_i = -K_{Pi}. ACE_i(t) - K_{Ii} \int ACE_i(t) \, dt - K_{Di}. A\dot{C}E_i(t)$$

K_{Pi} , K_{Ii} and K_{Di} are gain values of PID controller in area i.

From the above equation the control inputs u_1 and u_2 are constructed as shown below.

$$u_1 = -K_{P1}\dot{x}_8 - K_{I1}x_8 - K_{D1}\ddot{x}_8$$
$$u_2 = -K_{P1}\dot{x}_9 - K_{I2}x_9 - K_{D2}\ddot{x}_9$$

Two techniques called pole placement techniques [12] and BAT algorithm [13] are used for designing these controllers. In the next section BAT algorithm and its steps for algorithm are discussed.

4. BAT Algorithm

The Bat Algorithm is an optimization algorithm based on the echolocation behavior of bats. All bats use echolocation to sense distance, and they also know the difference between food/prey and background barriers in some magical way. The capability of echolocation of bats is fascinating as these bats can find their prey and discriminate different types of insects even in complete darkness. The advanced capability of echolocation of bats has been used to solve different optimization problems. Echolocation of bats works as a type of sonar in bats, emits a loud and short pulse of sound, waits as it hits into an object and after a fraction of time, the echo returns back to their ears. Thus, bats can compute how far they are from an object. In addition, this amazing orientation mechanism makes bats being able to distinguish the difference between an obstacle and a prey, allowing them to hunt even in complete darkness. Based on the behavior of the bats, new and interesting meta heuristic optimization technique called Bat Algorithm is proposed. Such technique has been developed to behave as a band of bats tracking prey/foods using their capability of echolocation.
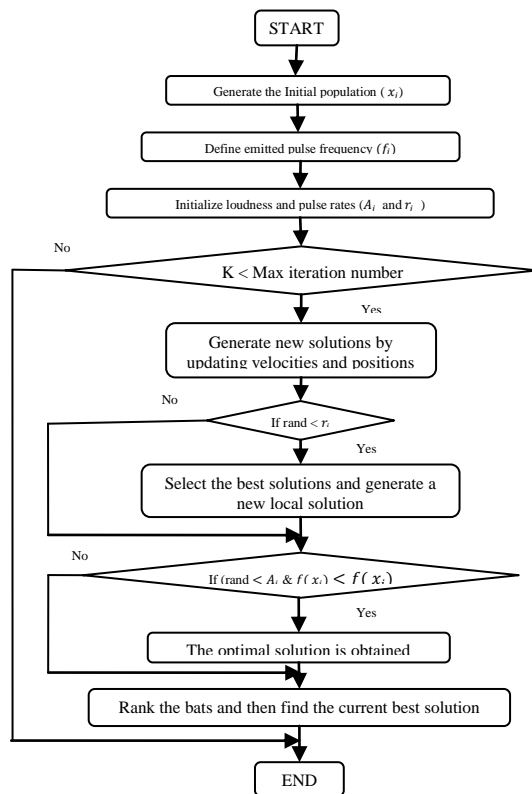

Fig. 1 Flow Chart of BAT algorithm

The flowchart of the BAT algorithm is shown in the figure 1.

4.1. Steps for Implementation of BAT Algorithm

1. Specify the parameters of BAT algorithm for the given load flow problem.

2. For the individuals x_i, generate the initial population. The settings of boundaries for the initial population is given by

$$x_i^{min} < x_i < x_i^{max} \qquad (3)$$

3. Determine the fitness value for the initial population.

4. Bats fly randomly with a fixed frequency f_{min} at position x_i with velocity v_i by varying wavelength λ and loudness A_0 to search for food or prey. The wavelength (or frequency) can be adjusted automatically of their emitted pulses and also the rate of pulse emission $r \in [0,1]$ are adjusted depending on the nearness of their target.

5. It is assumed that the loudness can vary from a large magnitude A_0 to a minimum value A_{min}.

6. Firstly, the frequency f_i, velocity v_i and initial position x_i are initialized for each bat. The virtual bat movement is given by up-dating their position and velocity using (4), (5) and (6) for time step t given as follows:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \qquad (4)$$
$$x_i^t = x_i^{t-1} + v_i^t \qquad (5)$$
$$v_i^t = v_i^{t-1} + (x_i^t - x_*)f_i \qquad (6)$$

Here β denotes a random number generated within the interval. The space and the range of movement of bats is controlled from the result of equation (2).

Initially, frequency is assigned to each bat randomly. which is uniformly drawn from $[f_{min}, f_{max}]$. The variable x_* represents the current global best solution located after comparing the solutions among all the n bats.

The constraint violations handled are shown in the equation

If $x_i^t > x_i^{max}$ then $x_i^t = x_i^{max}$ and $\qquad (7)$
if $x_i^t > x_i^{max}$ then $x_i^t = x_i^{max}$ $\qquad (8)$

7. Once a solution is selected among the best current solution, a new solution is generated locally for each bat using random walk:

$$x_i^{new} = x_i^{old} + \sigma A_{mean}^{old} \qquad (9)$$

where σ is random number and A_{mean}^{old} is average loudness of all the bats at this time step.

5. Two area load frequency control

Two area thermal-thermal (non reheat) system is considered as shown in the figure. The control inputs u_1 and u_2 are created by a linear combination of all the system states (full state feedback) and are referred as ΔP_{C1} and ΔP_{C2}. The disturbance inputs w_1 and w_2 are considered.

The area control error (ACE) is as a linear combination of the incremental frequency and the tie line power. Thus ACE for control area 1 and area 2 is given by the equations 1 and 2 respectively [14].

$$ACE_1 = \Delta P_{tie,1} + b_1 \Delta f_1 \tag{10}$$
$$ACE_2 = \Delta P_{tie,2} + b_2 \Delta f_2 \tag{11}$$

For formulating the state variable model, the feedback loops are opened and state variables are defined as block outputs having either an integrator or a time constant.

5.1 State Space Modelling

The composite block diagram without any controller is shown in the figure 2 given in [14]. To obtain the state space model the differential equations are described for each individual block in the figure in terms of state variables

The state space model is given by the equations

$$x_1 = \frac{K_{ps1}}{1 + T_{ps1}s}(x_2 - x_7 - w_1) \tag{12}$$

$$\dot{x}_1 = -\frac{1}{T_{ps1}}x_1 + \frac{K_{ps1}}{T_{ps1}}x_2 - \frac{K_{ps1}}{T_{ps1}}x_7 \quad \frac{K_{ps1}}{T_{ps1}}w_1 \tag{13}$$

$$x_2 = \left(\frac{1}{1 + T_{t1}s}\right)x_3 \tag{14}$$

$$\dot{x}_2 = -\frac{1}{T_{t1}}x_2 + \frac{1}{T_{t1}}x_3 \tag{15}$$

$$x_3 = \left(u_1 - \frac{1}{R_1}x_1\right)\left(\frac{1}{1 + T_{sg1}s}\right) \tag{16}$$

$$\dot{x}_3 = -\frac{1}{R_1 T_{sg1}}x_1 - \frac{1}{T_{sg1}}x_3 + \frac{1}{T_{sg1}}u_1 \tag{17}$$

$$x_4 = \frac{K_{ps2}}{1 + T_{ps2}s}(-(-a_{12}x_7) - w_2 + x_5) \tag{18}$$

$$\dot{x}_4 = -\frac{1}{T_{ps2}}x_4 + \frac{K_{ps2}}{T_{ps2}}x_5 + \frac{a_{12}K_{ps2}}{T_{ps2}}x_7 - \frac{K_{ps2}}{T_{ps2}}w_2 \tag{19}$$

$$x_5 = \frac{1}{1 + T_{t2}s}x_6 \tag{20}$$

$$\dot{x}_5 = -\frac{1}{T_{t2}}x_5 + \frac{1}{T_{t2}}x_6 \tag{21}$$

$$x_6 = \frac{1}{1 + T_{sg2}s}\left(u_2 - \frac{1}{R_2}x_4\right) \tag{22}$$

$$\dot{x}_6 = -\frac{1}{R_2 T_{sg2}}x_4 - \frac{1}{T_{sg2}}x_6 + \frac{1}{T_{sg2}}u_2 \tag{23}$$

$$x_7 = \frac{2\pi T_{12}}{s}(x_1 - x_4) \tag{24}$$

$$\dot{x}_7 = 2\pi T_{12}x_1 - 2\pi T_{12} \tag{25}$$

$$x_8 = \frac{1}{s}(x_7 + b_1 x_1) \tag{26}$$

$$\dot{x}_8 = b_1 x_1 + x_7 \tag{27}$$

$$x_9 = \frac{1}{s}(b_2 x_4 - a_{12} x_7) \tag{28}$$
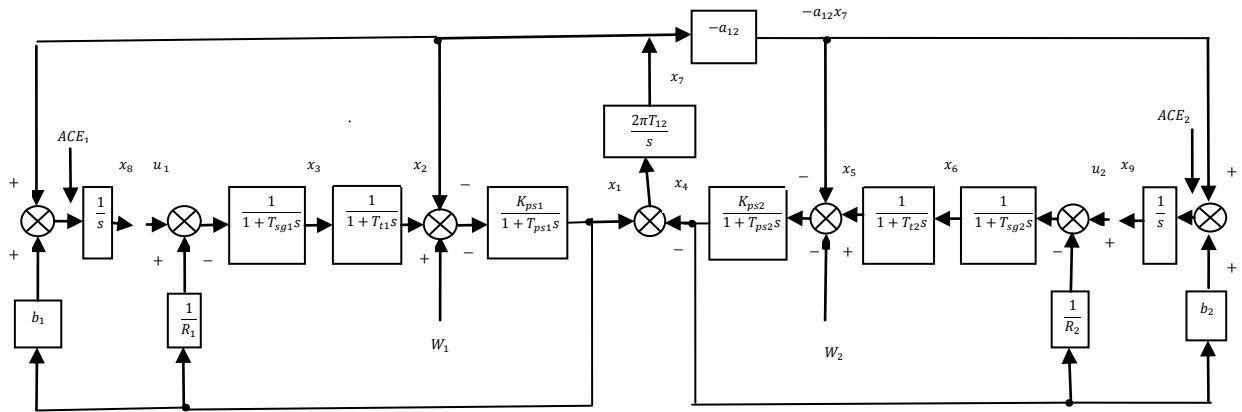
$$\dot{x}_9 = b_2 x_4 - a_{12} x_7 \tag{29}$$

Fig. 2 State space model of a two area thermal-thermal system.

The nine equations 12 to 29 can be organized in the following vector matrix form [14].

$$\dot{X} = AX + BU + FW \tag{30}$$

Where X, U and F are the state, control and disturbance vectors respectively and A, B and F are real constant matrices having appropriate dimensions. The state, control and disturbance vectors are defined as

$$x = [x_1 \ x_2 \ x_3 \ ... \ x_9]^T = [\Delta f_1 \ \Delta P_{G1} \ \Delta P_{SG1} \ \Delta f_2 \ \Delta P_{G2} \ \Delta P_{SG2} \ \Delta P_{tie12} \ \int ACE_1 dt \ \int ACE_2 dt]$$
= state vector

$$u = [u_1 \ u_2]^T = [\Delta P_{C1} \ \Delta P_{C2}] = \text{control vector}$$

$w = [w_1 \ w_2]^T = [\Delta P_{D1} \ \Delta P_{D2}] = $ disturbance vector

While the matrices A, B and F are defined below:

$A =$

$$\begin{bmatrix} -\frac{1}{T_{ps1}} & \frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 & -\frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1 T_{sg1}} & 0 & -\frac{1}{T_{sg1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{ps2}} & \frac{K_{ps2}}{T_{ps2}} & 0 & \frac{a_{12} K_{ps2}}{T_{ps2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_2 T_{sg2}} & 0 & -\frac{1}{T_{sg2}} & 0 & 0 & 0 \\ 2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 \\ b_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & b_2 & 0 & 0 & -a_{12} & 0 & 0 \end{bmatrix}$$

(31)

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{T_{sg1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{sg2}} & 0 & 0 & 0 \end{bmatrix}$$

(32)

$$F^T = \begin{bmatrix} -\frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_{ps2}}{T_{ps2}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(33)

5.2 Transfer Function

By assuming that the two areas are identical, the parameters of the system are given by [14]

$T_{sgi} = 0.4$ s, $T_{ti} = 0.5$ s, $T_{ps} = 20$ s, $K_{ps} = 20$,

$R = 3$, $b = 0.425$, $K_i = 0.09$ $2\pi T_{12} = 0.05$

By substituting the above values in the state space matrices and converting, the following transfer functions are obtained

The transfer function for the step change in the load in area1 as input and frequency deviation in area1 as output is given by

$$G_{11}(s) = \frac{-5\,s^6 - 45.25\,s^5 - 154.7\,s^4 - 285.3\,s^3 - 360.8\,s^2 - 270\,s - 31.25}{s^7 + 9.1\,s^6 + 31.65\,s^5 + 69.17\,s^4 + 120.5\,s^3 + 116.8\,s^2 + 105.4\,s + 21.38}$$

(34)

The transfer function for the step change in the load in area1 as input and change in tie line power as output is given by

$$G_{12}(s) = \frac{-0.25\,s^5 - 2.263\,s^4 - 7.675\,s^3 - 13.7\,s^2 - 16.15\,s - 10.69}{s^7 + 9.1\,s^6 + 31.65\,s^5 + 69.17\,s^4 + 120.5\,s^3 + 116.8\,s^2 + 105.4\,s + 21.38}$$

(35)

6. Design Of Optimal Load Frequency Control:

The optimum gain settings of controllers like Integral (I), Proportional Integral Derivative (PID) are determined in the Load frequency controller design. The approach for design of the LFC controllers is given by two methods. They are given by.

1. Pole Placement Technique
2. BAT algorithm

For the design approach, u_1 and u_2 are provided by the integral of ACEs as shown in the equations 1 and 2.

The design of I and PID controllers by using Pole placement technique is discussed in [12]. By following the steps for BAT algorithm[given in section III, the controllers are designed for BAT algorithm. Here the values of gain settings of the controllers are considered as the individuals. The optimal gain settings are designed using BAT algorithm based on combination of some multi objectives. The multi objectives considered are integral of sum of squares of incremental frequency deviation of area 1 and area 2, incremental change in tie line power and settling times of araea1 and area2. Thus the BAT algorithm is based on the minimization of the objective function given below.

$$J = \int_0^t (\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie12}^2)dt + ST_1 + ST_2$$

(36)

Where ST_1 and ST_2 are the settling times in area 1 and area 2 respectively

7. Simulation Results

For the design of controllers by using BAT algorithm, the assumed control parameters values are shown in table 1.The optimal gain settings of the controllers using Pole placement technique and BAT algorithm design are given in table 2. The pattern of eigen values of the system with I, PID using Pole placement and BAT algorithm are given in the table 3.

Table 1. BAT algorithm control parameters values.

Parameter	Designation	Value
n	Population Size	20
n_g	Number of generation	100
f_{min}	Frequency Minimum	00
f_{max}	Frequency Maximum	01
A	Loudness	0.15
r	Pulse rate	0.7

Table 2. Gain settings for Integral, PID Controllers

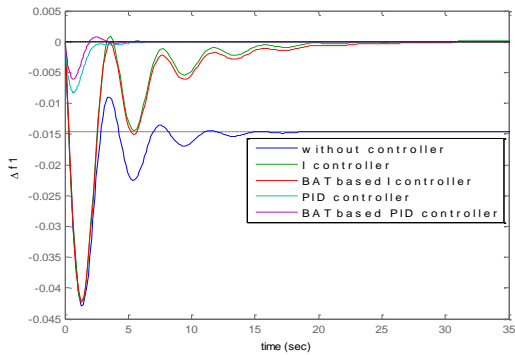| Controller	I	PID
Pole placement technique	K_I= 0.090	K_D= 0.165 K_P= 0.772 K_I= 0.760
By BAT algorithm	K_I= 0.080	K_D= 0.31 K_P= 0.850 K_I= 1.480

Fig.3. Change in frequency in area1 due to step load(0.01pu) disturbance

Figures 3 and 4 gives the responses of change in frequency in area 1 and change in tie line power respectively due to step load disturbance of 0.01 p.u.in area 1. The figures shows the comparison of without controller, I controller, PID controller, BAT based I and PID controllers. The settling time values of figure 2 and 3 by these different approaches are given in the table 4 and 5 respectively.

It is observed in the table 4 that the settling time values with I controller using pole placement technique is 8.17. By using BAT based I controller the settling time reduces to 7.71. Similarly with PID controller the settling time is 5.70 but by using BAT technique the settling time falls to 4.77.

Table 3. Pattern of eigen values with I, PID and BAT based I and PID controllers

With out Controller	With Integral Controller	With BAT Integral Controller
0	-3.7463	-3.7480
0	-3.7258	-3.7274
-3.7654	-0.2293+1.552i	-0.2333+1.5543i
-3.7437	-0.2293-1.552i	-0.2333-1.5543i
-0.2729+1.58i	-0.342+1.4196i	-0.3468+1.4226i
-0.2729-1.58i	-0.342-1.4196i	-0.3468-1.4226i
-0.39+1.46i	-0.2771	-0.2750
-0.39-1.46i	-0.0885	-0.0810
-0.2604	-0.1197	-0.1084

With PID Controller	With BAT PID Controller
-3.7557	-3.7560
-3.6825	-3.6837
-1.0657 + 1.799i	-1.0424+1.932i
-1.0657 - 1.799i	-1.0424-1.932i
-0.3361+1.5091i	-0.3409+1.5108i
-0.3361-1.5091i	-0.3409-1.5108i
-0.6918	-0.9106
-0.1259	-0.1334
-0.1054	-0.1120

Table 4. Settling time values of the system with controllers for output of deviation in frequency in area1 (in fig.2)

Controller	I Controller	PID Controller
With Conventional Controller	8.17	5.70
With BAT based Controller	7.71	4.77

Similarly in the table 5, with I controller using pole placement technique the settling time value is 1.59. It is reduced to 1.52 by using BAT based controller. With conventional PID controller the settling time is 1.23 but by using BAT technique the value is 1.15.
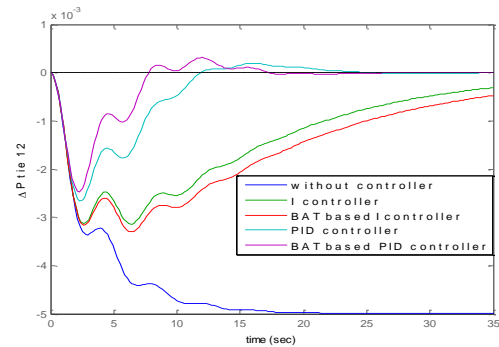

Fig.4. change in tie-line power due to step load (0.01 pu) disturbance

Table 5. Settling time values of the system with controllers for output of deviations in tie line power (in figure 3)

Controller	I Controller	PID Controller
With Conventional Controller	1.59	1.23
With BAT based Controller	1.52	1.15

Thus, simulation results shows that individually when each controller is considerd, the approach of meta-heuristic algorithm such as BAT algorithm based on multi objectives gives

better result than that of conventional pole placement technique. When the two controllers are compared PID controller settles much faster than I controller.

8. Conclusion

In this paper, load frequency control (LFC) problem of a two area interconnected power system is considered. Two controllers like I, PID are incorporated to obtain zero steady state error in frequency and tie line-power. A multi objective based BAT inspired algorithm is proposed to design the controllers. In single objective optimization, one attempts to obtain the best design or decision, which is usually the global minimum or global maximum depending on optimization problem.But on the other hand to satisfy all the objectives, multi objective optimisation like objective of LFC and settling time is considered. Simulations studies through MATLAB show that the conventional approach does provide good performances but with long settling time. The proposed multi objective BAT algorithm based controllers on other hand provides better results satisfying settling time thus ensuring system stability. Over all analysis reveals that conventional and BAT based PID compared to that of I controller gives best dynamic response to step load change (0.01 pu) in area 1 for a two area system.

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