Load Frequency Control in Three-Area Interconnected Power System Using PID Tuning Based on Artificial Bee Colony Optimization

Nashwa Shaik and Benjamin Shimray

Abstract This work discusses the load frequency control of a three-area interconnected power system regulated employing a PID controller whose gain parameters are tuned using one of the optimization algorithms instigated and inspired by smart foraging or searching deportment of honey bees. The three-area power system depicted is assembled in such a way that the area-1 consists of a non-reheated turbine, area-2 consists of a reheated turbine while the third area consists of a combination of both non-reheated and reheated turbine units as the power consumed is profoundly generated by thermal power plants across the world and they exist to a greater degree. All the existing areas are equipped with PID controllers, and the objective function taken into account is Integral Time Absolute Error (ITAE). To subdue all the fluctuations attributed to the perturbations in the system and reacquire the frequency to the nominal quantity swiftly is primary intent of this work. The performance of the controller is simulated in the MATLAB/ SIMULINK version. The results depicted the swift settling down of the frequency deviations with minimum steady state error.

Keywords Load frequency control (LFC) · Artificial bee colony (ABC) · Area control error (ACE) · PID controller

1 Introduction

Generation, transmission, and distribution of electricity to various loads are what a power system network is meant for. It has been developed exceptionally over the last few decades by [1]. Various components connected in the network of power system are usually subtle to the flair of the electrical power attributes such as voltage and frequency and their continuity. The load on the power system varies continually from time to time while the frequency is related inversely with the variation in load and the frequency of the system is influenced by the variation in real power.

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V. Edwin Geo and F. Aloui (eds.), *Energy and Exergy for Sustainable and Clean Environment, Volume 2*, Green Energy and Technology,
https://doi.org/10.1007/978-981-16-8274-2_12

Frequency in fact is cresting on real power, and voltage veritably is contingent on the reactive power [2]. Regulation of power flow among various areas while maintaining the frequency constant is regarded as Load Frequency Control (LFC). The primary intentions of LFC in multiple area interconnected power system (PS) are to match the entire power system load, to manage the error in system electrical frequency to zero. To distribute the generation among the control areas for that there would be a matching between tie-line power flows and schedules of power flow by [2].

A power system in general comprises multiple areas of generating units which are interconnected together so that the power could be exchanged between the utilities. The electric energy attributes such as frequency, tie-line power flows, and voltage in interconnected systems have to be preserved within the prescribed limits of the nominal values.

LFC in interconnected power system can be obtained by several methods. To curtail the Area Control Error (ACE), the first proposed control methodology is Integral Control Action, but the activity of the system is restricted by its integral gain. PID type controller is considerably employed for the resolution of LFC problem irrespective of the potential of present control techniques with different structures due to their simplicity, reliability, faster operation, and efficiency.

The traditional methods such as trial and error method and Cohen-Coon are not able to provide fine robust performance. Also, the controllers in use conventionally have some other problems such as objectionable overshoot in speed and sluggish response owing to sudden load disturbance. The impediments in LFC are in devising a controller that is robust and in obtaining the optimal solution by optimizing its parameters effectively. To accomplish this, many optimization techniques are applied and accessible in literature such as Genetic Algorithm (GA), Differential Evolution Algorithm (DEA), Particle Swarm Optimization (PSO) technique, Bacterial Foraging Optimization (BFO) [3], Fuzzy Logic Control, and other intelligent techniques.

This work discusses the LFC for a three-area interconnected PS constituting of non-reheated thermal power turbine units and area comprising the combination of reheated and non-reheated thermal turbine power units. To display the effectiveness of the ABC technique, it is assimilated with Trial and Error method.

2 Modeling of Power System

A matter of contention to a power system operator is Automatic Generation Control (AGC). The robust frequency controller design for a multiple area has been an immense challenge in stability and control of PS. The modeling of a power system can be depicted as shown in Fig. 1.

The thermal power plant can be modeled where it contains speed governor, turbine, and generator.

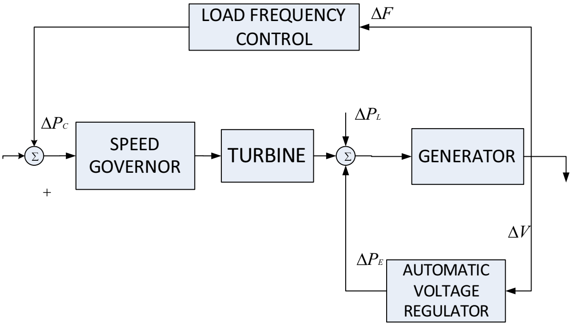

Fig. 1 Control loops in a synchronous generator

2.1 Modeling of Speed Governing System

The following order of events out turn by the command signals (ΔPC): the upward movement of the pilot valve, the movement of piston downwards when the oil with high pressure rushes on the upper portion of the piston, thereby opening the valve corresponding the steam suitably, the turbine speed spurs resulting in the frequency to mount.

2.2 Turbine Model

Changes in the opening of the steam valve (ΔYE) affect the response of the steam turbine with respect to the power output. The range of the time constant is 0.2 to 2.5 s.

2.3 Load-Generator Model

The frequency and the change or augmentation in the input power to the generator-load can be related as:

$$\Delta F(S) = \left(\frac{KPS}{1 + TPS}\right) * [\Delta PG(S) - \Delta PD(S)] \tag{1}$$

The isolated power system composing turbine, generator, governor, load, and a thermal power plant with a non-reheat turbine is illustrated in the Fig. 2.

Owing to the presence of various stages because of high and low steam pressure, the reheat turbine block can be modeled as a second order unit. The reheat turbine's transfer function can be denoted as:

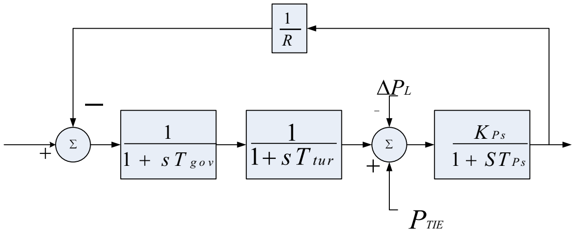

Fig. 2 Non-reheat turbine in a power system

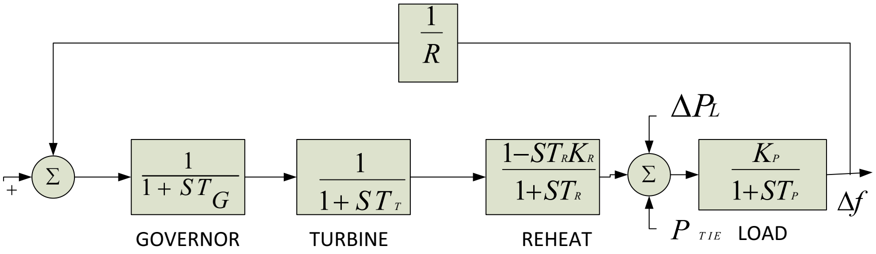

Fig. 3 Power system with a reheat turbine

$$GR(S) = \frac{1 + KrTrs}{1 + Trs} \tag{2}$$

where K_r denotes reheat time during the low pressure and Tr denotes reheat time during the high pressure. The block diagram of a thermal power plant with reheat turbine can be represented as in Fig. 3.

An interconnected PS in general is a category of control areas connected by tie lines. The motion of the valve because of the disturbances in three areas is given by [4].

$$\Delta xE1(S) = \left[\frac{1}{1 + STG1}\right]\left[\Delta PC1 - \frac{1}{R1}\Delta F1(S)\right] \tag{3}$$

$$\Delta xE2(S) = \left[\frac{1}{1 + STG2}\right]\left[\Delta PC2 - \frac{1}{R2}\Delta F2(S)\right] \tag{4}$$

$$\Delta xE3(S) = \left[\frac{1}{1 + STG3}\right]\left[\Delta PC3 - \frac{1}{R3}\Delta F3(S)\right] \tag{5}$$

The changes in power turbine are given by:

$$\Delta PC1 = \left[\frac{1}{1 + STt1}\right][\Delta E1(S)] \tag{6}$$

$$\Delta PC2 = \left[\frac{1}{1 + STt2}\right][\Delta E2(S)] \tag{7}$$

$$\Delta PC3 = \left[\frac{1}{1 + STt3}\right][\Delta E3(S)] \tag{8}$$

The frequency deviation in the three area is given by:

$$\Delta F1(S) = [\Delta PG1(S) - \Delta PD1(S) - \Delta PTIE1(S)]\left[\frac{KPS1}{1 + STPS1}\right] \tag{9}$$

$$\Delta F2(S) = [\Delta PG2(S) - \Delta PD2(S) - \Delta PTIE2(S)]\left[\frac{KPS2}{1 + STPS2}\right] \tag{10}$$

$$\Delta F3(S) = [\Delta PG3(S) - \Delta PD3(S) - \Delta PTIE3(S)]\left[\frac{KPS3}{1 + STPS3}\right] \tag{11}$$

The tie-line power deviation of three area:

$$\Delta PTIE1(S) = \frac{K12}{S}[\Delta F1(S) - \Delta F2(S)] + \frac{K13}{S}[\Delta F1(S) - \Delta F3(S)] \tag{12}$$

$$\Delta PTIE2(S) = \frac{K23}{S}[\Delta F2(S) - \Delta F3(S)] + \frac{K13}{S}[\Delta F2(S) - \Delta F1(S)] \tag{13}$$

$$\Delta PTIE3(S) = \frac{K31}{S}[\Delta F3(S) - \Delta F1(S)] + \frac{K32}{S}[\Delta F3(S) - \Delta F2(S)] \tag{14}$$

Area control error for three area is given by:

$$ACE1 = \Delta PTIE1 + B1\Delta F1(S) \tag{15}$$

$$ACE2 = \Delta PTIE2 + B2\Delta F2(S) \tag{16}$$

$$ACE3 = \Delta PTIE3 + B3\Delta F3(S) \tag{17}$$

2.4 Objective Function

A classical LFC is characterized by tie-line power flow control, and every area has a tendency to decline its ACE to zero. In each of the area, the control error comprises an incorporation of frequency and tie-line error. The individual area control errors (ACE) are the error input to the controllers which is given by:

$$ACE_i = \Delta P_{TIE,i} + Bi\Delta F \tag{18}$$

Where number of areas is represented by i. PID controllers along with the area control errors

$$UI = KP, IACEI + \int ACEIdt + KD, I\frac{d(ACEI)}{dt} \tag{19}$$

Here, the ITAE is used as an objective function for the LFC.

3 Artificial Bee Colony

Honeybees come in the group of insects that are most closely analyzed due to their foraging behavior, learning and memorizing, and characteristics of information sharing igniting interest in swarm intelligence research areas.

Karaboga and Bastruk, Akay and Karaboga [5] have proposed ABC algorithm for the optimization problems which is in accordance with the smart searching or foraging deportment of honeybees. The brilliant foraging deportment of honeybees warms is simulated by the algorithm. Being simple and robust, it has gained popularity and is basically having a random probability distribution. As it organizes and carries out global search and local search in every iteration, the likelihood of detecting the optimal gain specifications has notably been supplemented thus avoiding local optimum to a greater degree.

ABC constitutes of three categories of bees: employed bees, onlookers and scouts. A bee which goes to the food source which it has already been inspected by it previously is the employee bee. A bee which remains on the dance arena to select the food source is termed as the onlooker bee. A bee which carries out random investigation is a scout bee. By enacting the waggle dance, the bees communicate the flair of the food sources among themselves.

In ABC algorithm, the employed bees are identical in number to the onlooker bees and food or nectar sources surrounding the hive. The employee bee of which the food sources have been whipped by the rest of the bees of its kind becomes a scout.

The steps carried out in the ABC algorithm are as given by Akay and Karaboga [5]:

- Initialization
- Repeat
- Allocating a certain position of the nectar sources present in the memory to the employed bees
- Allocating a certain position of the food sources present in the memory to the onlookers.

- Dispatching scout bees to the investigating zone for the inspection of fresh food sources.
- UNTIL (meeting the requirements).

In ABC algorithm, every sequence of the foraging comprises three operations: To dispatch the employed bees to the fresh nectar sources and analyze the nectar contents, selection of the respective nectar sources by the onlooker bees after obtaining the details from employed bees and determining the quantity of nectar in the food sources, to dispatch the scout bees to the possible food sources.

Fig. 5 depicts the flowchart of ABC algorithm. At the stage of initialization, a random selection of a group of nectar sources is done by the bees and the nectar contents have been analyzed. After approaching the hive, the bees part the details on the nectar content with the onlookers remaining on the dance zone in the hive.

Next, each employed bee proceeds to the nectar source area which is sought by it during the last sequence according to the position existing in its memory, and selects a fresh food source with the aid of perceptible details that exists in the nearby arena of the current zone.

Now, an onlooker bee tends to choose a nectar source in accordance with the details on nectar content that is dispersed by the employed bees in the dancing zone. As the nectar quantity of a source is high, the possibility of choosing that nectar source by the onlooker is also higher. After reaching the chosen sector, it opts a fresh nectar source in the proximity of the existing one in the further is dependent on the contrast of the nectar source locations. While the nectar source is exploited by the bees, a scout bee determines a fresh nectar source randomly and replaces the exploited one by it.

At every sequence, not more than a single scout goes out to search a fresh nectar source while the employed bees remain equal in number with the onlookers.

In ABC algorithm, the nectar source location concerns a feasible resolution to the minimization problem while the quantity of nectar in a nectar source concerns the flair or fitness of the corresponding solution.

An employed or onlooker bee possibly generates a change in solution in its memory to find a fresh nectar source and determines the quantity of nectar or fitness value of the fresh nectar source or new solution.

The details perceived from the employed bees are evaluated and chosen with corresponding probability related to the quantity of the nectar by the onlooker bees. The employed bee generates a change in the location or solution in its memory and examines the quantity of nectar of the corresponding source only if the nectar quantity is more than the last one, the fresh location is memorized by the bee, forfeiting the last one.

The nectar source is selected by the onlooker bee based upon the probability value corresponding to the source which is evaluated by the expression Akay and Karaboga [5]:

$$PI = \frac{fiti}{\sum_{n=1}^{SN} fitn} \tag{20}$$

Here, fiti is fitness or flair of the solution '*i*' which is assessed by the employed bee and is proportionate to the nectar quantity of the nectar source in the location to generate a food location from the older one; the initial population is distributed randomly of SN solutions or the nectar source locations. ABC uses the following expression by Akay and Karaboga [5]:

$$Vij = Xij + \phi ij(Xij - Xkj) \tag{21}$$

Here, $k \epsilon \{1, 2, ., \mathrm{BN}\}, j \epsilon \{1, 2, \ldots, D\}$ are indices picked, k is obtained randomly and it is varied from *i* which is any casual value lying in the range [−1, 1]. It regulates the generation of a nearby food source location engulfing x_{ij}, and the change corresponds to the neighborhood food positions by the bee visually. As the variation between x_{ij} and x_{kj} declines, the concernment on the location x_{ij} declines too. Hence, as foraging reaches the optimum solution in the search volume, the stride length is accordingly declined. If a quantity generated by it outdoes beyond its predecided limit, the quantity is set to a permissible value. The parameter value surpassing its limit must be fixed to its limit.

In algorithm, a random production of a position and replacement of the abandoned source with it simulates it. If a location cannot revamp further using a predecided number of sequences called 'limit' then that nectar source is considered to be deserted.

Subsequent to the production of every candidate food source location 'v_{ij}', the bee evaluates the performance and is compared. Thus, the three parameters of control used in the basic ABC are: Population, limit, and Maximum Cycle Number (MCN).

In the ABC algorithm, the onlooker bees and employed bees conduct the operation of exploitation while the scout bees control the exploitation process.

3.1 ABC-Based PID Type of LFC

Though there have been significant developments in control technology, PID controllers are employed in most of the industries and in power system sectors as well due to their wide class performance, resilient performance for a wider range of operation [2, 3]. The operation of the PS is dependent on the tuning of the PID controllers' gain parameters with respect to the frequency deviations as the load changes.

The block diagram of ABC-tuned PID controller to resolve the LFC problem for every area of control is shown in the Fig. 4.

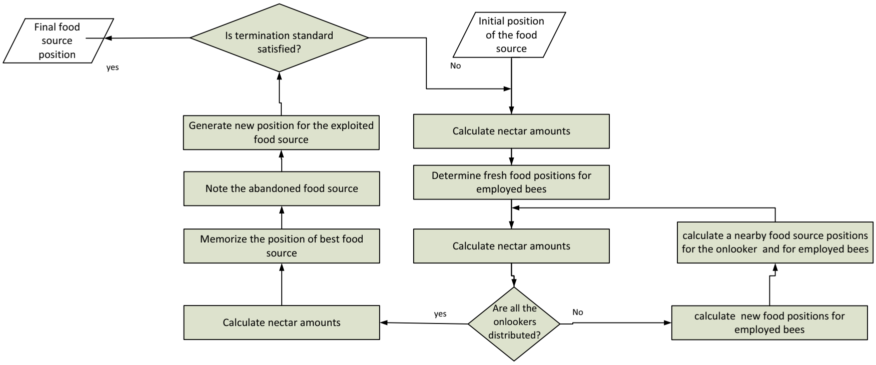

Fig. 4 Flowchart diagram for ABC algorithm

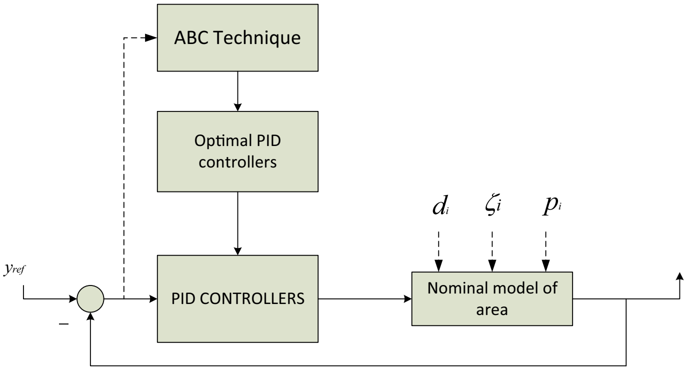

Fig. 5 ABC-based PID controller

The control vector in each control area for PID controller by considering *ACEi* as the system output is given by:

$$ui = kpiACEi + kli \int ACEidt + kdi \frac{d}{dt} ACEi \tag{22}$$

The gain parameters are modeled using ABC and then the PID controller produces a control signal that is applied to the set point of governor in all the areas. Integral Time Absolute Error is the objective function considered here. In order to calculate objective function, the time domain simulation is carried out for a certain simulation period. For improving the response of the system with reference to time of settling and peak overshoots, the objective function is minimized. The parameter bounds of PID controller to formulate the gain parameters can be composed as:

$$\begin{aligned} k_{Pi}^{\min} &\le k_{Pi} \le k_{Pi}^{\max} \\ k_{Ii}^{\min} &\le k_{Ii} \le k_{Ii}^{\max} \\ k_{Di}^{\min} &\le k_{Di} \le k_{Di}^{\max} \end{aligned} \tag{23}$$

Usual scale of the parameters optimized is [0.01–20].

4 Results of Simulation

A three-area PS interconnected is taken for the analysis of LFC. Area-1 comprises thermal plant with a reheated turbine, area-2 comprises thermal plant with a non-reheated turbine, and area-3 consists of a combined reheated and non-reheated thermal unit. Fig. 6 shows the proposed simulation model with ABC-PID controller. The MATLAB code using ABC algorithm has been run in MATLAB software.

ABC parameters considered for optimization are as follows: Population size = 100, Maximum number of iterations = 70, lower and upper limits are 0 and 10, and simulation time = 10 s. Simulation is done with 0.1pu step load perturbation in area-(1), area-(2), and area-(3), respectively. The optimized controller parameters, frequency deviations, are as shown (Figs. 7, 8, 9,10, 11, 12, 13, 14, 15, and 16. Tables 1, 2, and 3).

It can be perceived from the above results that the deviation in frequency when subjected a sudden disturbance settle down quickly with a minimum steady state error as desired contrasted with the trial and error values.

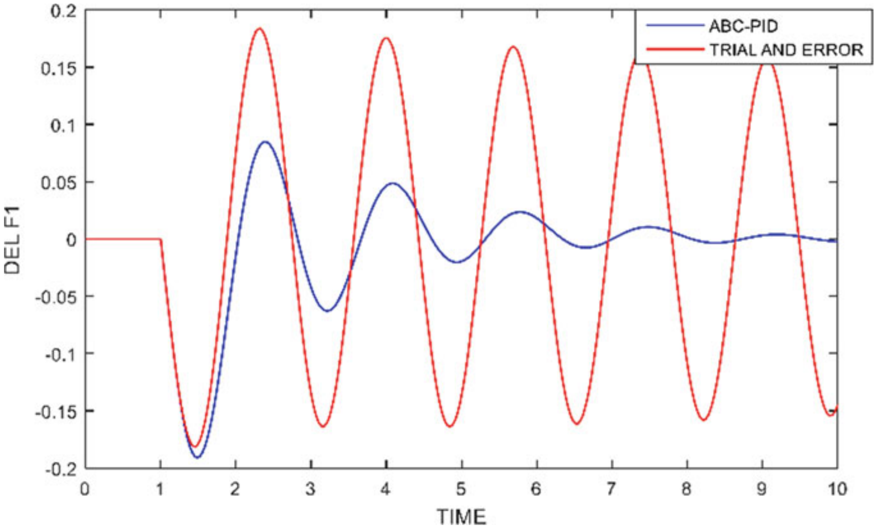

Fig. 7 Frequency fluctuation in area-1 due to 0.1pu step change in area-1

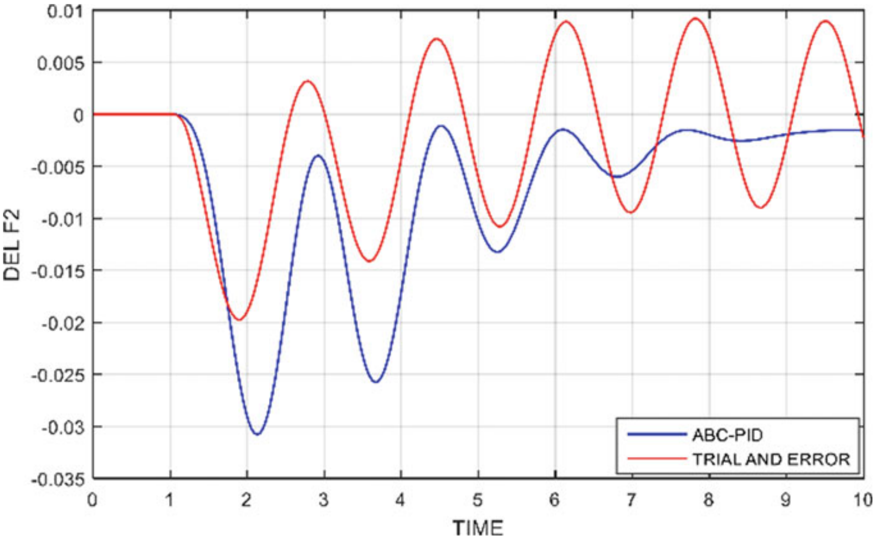

Fig. 8 Frequency fluctuation in area-2 due to 0.1pu step change in area-1

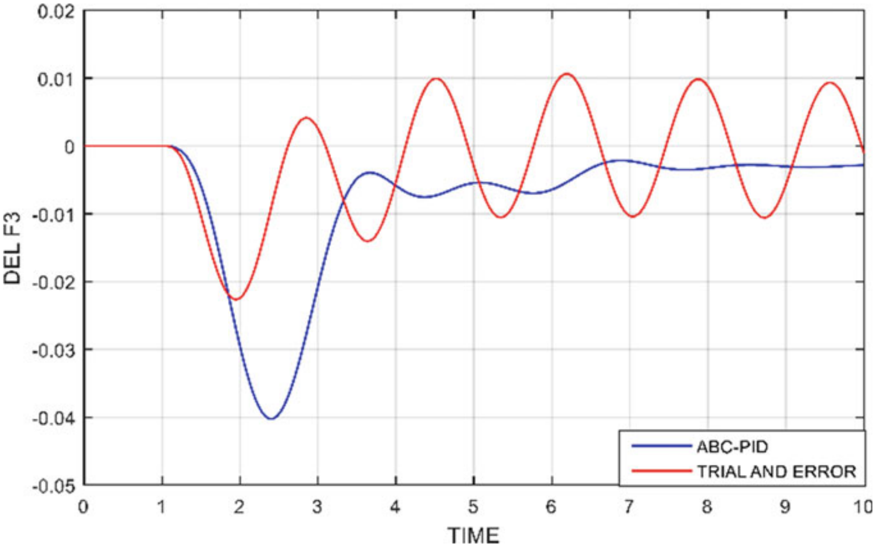

Fig. 9 Frequency fluctuation in area-3 due to 0.1pu step change in area-1

5 Conclusion

This work discusses the use of ABC-tuned PID controller in a three-area interconnected PS using dissimilar types of turbine in thermal power generating units

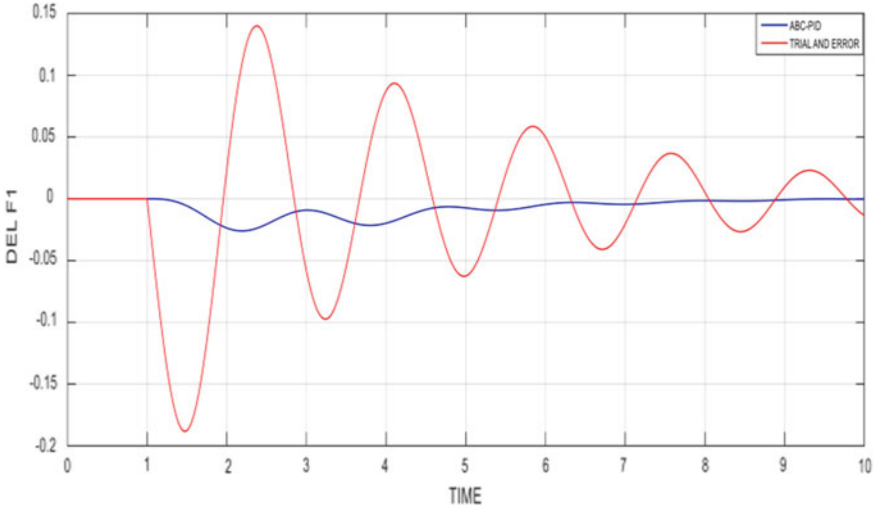

Fig. 10 Frequency fluctuation in area-1 due to 0.1pu step change in area-2

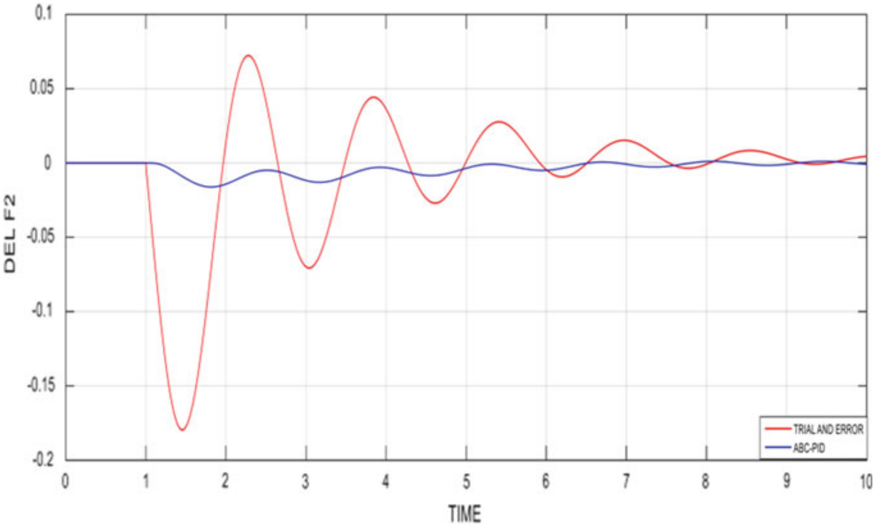

Fig. 11 Frequency fluctuation in area-2 due to 0.1pu step change in area-2

employing ITAE as the objective function due to its effectiveness. As most of the already existing systems are thermal based in India, it is particularly pressing to manage the existing systems in a productive way by handling the deviations in frequency and power through a nature-inspired algorithm.

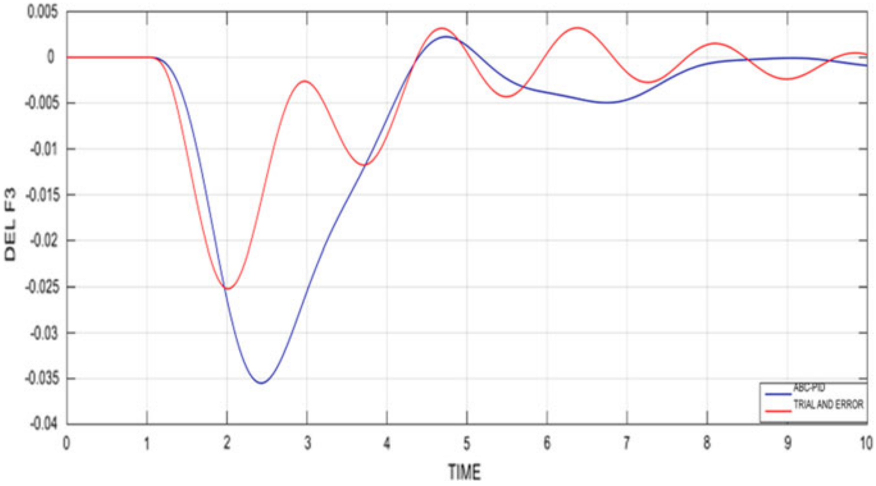

Fig. 12 Frequency fluctuation in area-3 due to 0.1pu step change in area-2

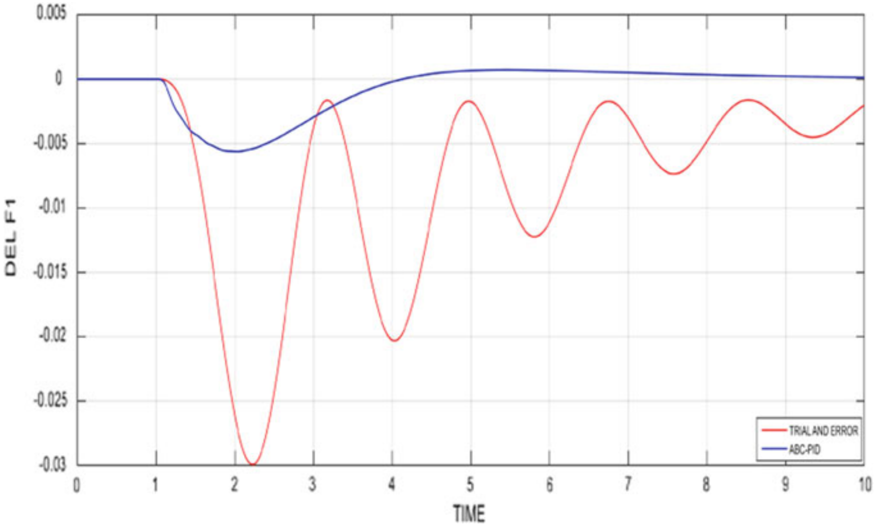

Fig. 13 Frequency fluctuation in area-1 due to 0.1pu step change in area-3

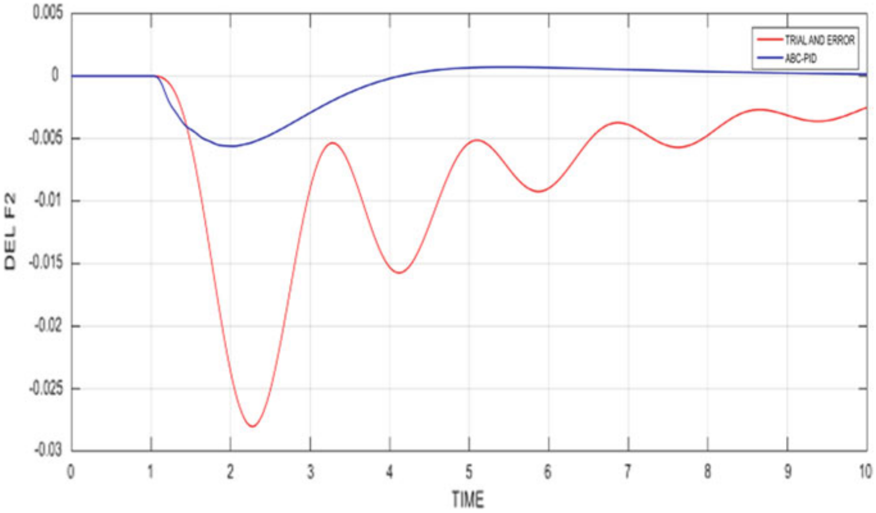

Fig. 14 Frequency fluctuation in area-2 due to 0.1pu step change in area-3

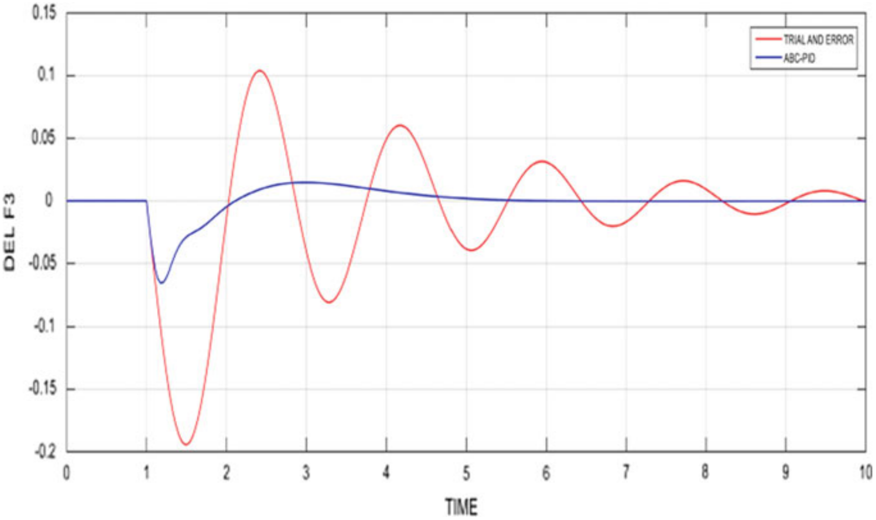

Fig. 15 Frequency fluctuation in area-3 due to 0.1pu step change in area-3

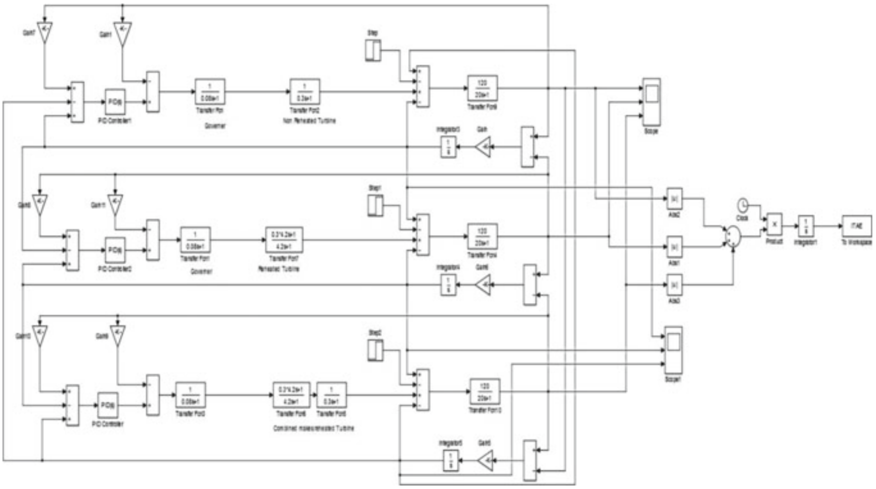

Fig. 16 Simulation diagram for three-area interconnected system

Table 1 Optimized values of gain parameters for PID controller for step disturbance in area-1

Trial and error	*kp*	*ki*	*kd*
1	1.4393	2.7177	1.468
2	1.8727	0.6127	0.5673
3	0.6995	1.1978	0.3485
ABC-PID			
1	1.2482	1.1228	0.0387
2	0.0384	0.5795	0.0344
3	1.2278	0.4532	0.3087

Table 2 Optimized values of gain parameters for PID controller for step disturbance in area-2

Trial and error	*kp*	*ki*	*kd*
1	1.4393	2.7177	1.468
2	1.8727	0.6127	0.5673
3	0.6995	1.1978	0.3485
ABC-PID			
1	0.3248	1.1239	0.0267
2	1.2356	0.4986	0.0325
3	1.2098	0.4329	0.2984

Table 3 Optimized values of gain parameters for PID controller for step perturbation in area-3

Trial and error	*kp*	*ki*	*kd*
1	1.4393	2.7177	1.468
2	1.8727	0.6127	0.5673
3	0.6995	1.1978	0.3485
ABC-PID			
1	0.3248	1.1239	0.0267
2	1.2356	0.4986	0.0325
3	1.2098	0.4329	0.2984

Acknowledgements The authors are filled with gratitude to NIT Manipur for its assistance and providing the useful data to accomplish this work.

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