



# Teaching–learning based optimization algorithm based fuzzy-PID controller for automatic generation control of multi-area power system



Binod Kumar Sahu<sup>a</sup>, Swagat Pati<sup>a</sup>, Pradeep Kumar Mohanty<sup>a</sup>, Sidhartha Panda<sup>b,\*</sup>

<sup>a</sup> Department Electrical Engineering, Institute of Technical Education and Research (ITER), Siksha 'O' Anusandhan University, Bhubaneswar 751030, Odisha, India

<sup>b</sup> Department of Electrical and Electronics Engineering, Veer Surendra Sai University of Technology (VSSUT), Burla 768018, Odisha, India

## ARTICLE INFO

### Article history:

Received 3 February 2014

Received in revised form

26 September 2014

Accepted 24 November 2014

Available online 2 December 2014

### Keywords:

Automatic generation control (AGC)

Teaching–learning based optimization (TLBO) algorithm

Fuzzy logic controller (FLC)

Proportional–integral–derivative (PID) controller

## ABSTRACT

This paper deals with the design of a novel fuzzy proportional–integral–derivative (PID) controller for automatic generation control (AGC) of a two unequal area interconnected thermal system. For the first time teaching–learning based optimization (TLBO) algorithm is applied in this area to obtain the parameters of the proposed fuzzy-PID controller. The design problem is formulated as an optimization problem and TLBO is employed to optimize the parameters of the fuzzy-PID controller. The superiority of proposed approach is demonstrated by comparing the results with some of the recently published approaches such as Lozi map based chaotic optimization algorithm (LCOA), genetic algorithm (GA), pattern search (PS) and simulated algorithm (SA) based PID controller for the same system under study employing the same objective function. It is observed that TLBO optimized fuzzy-PID controller gives better dynamic performance in terms of settling time, overshoot and undershoot in frequency and tie-line power deviation as compared to LCOA, GA, PS and SA based PID controllers. Further, robustness of the system is studied by varying all the system parameters from –50% to +50% in step of 25%. Analysis also reveals that TLBO optimized fuzzy-PID controller gains are quite robust and need not be reset for wide variation in system parameters.

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## 1. Introduction

An interconnected power system should generate, transport and distribute the electric energy at nominal system frequency and terminal voltage. But system frequency depends upon the balance between the generated active power and the active power that is consumed [1]. Due to sudden disturbances or some other reasons if the generated active power becomes less than the power demand, the frequency of generating units tends to decrease and vice versa. This causes the system frequency to deviate from its nominal value which is undesirable. To damp out the frequency deviation quickly and to keep the tie-line power at its scheduled value, Automatic generation control (AGC) concept is used. AGC plays a vital role in power system in maintaining nominal frequency and scheduled tie-line power flow during normal operating condition as well as under small perturbations. The design of AGC system for each generating

unit eventually controls the system frequency and tie-line power flow between different control areas of an interconnected power system. Therefore AGC plays a vital role in automation of power system. Nuclear units are generally used to supply base load because of their high efficiency and they do not take part in automatic generation control. Gas power generation is a small percentage of the total power generation and is suitable to supply the varying power demand. Hydro power plants operate with various constraints like water availability and regulations. However the role of AGC cannot be avoided in thermal power systems.

Literature survey reveals that, early works on automatic generation control was introduced by Cohn [2] in 1957. In 1970 the concept of modern optimal control for AGC in an interconnected power system was introduced by Elgerd [3]. The gain scheduling control method for AGC of interconnected power system was proposed by Lee et al. [4]. Talaq and Al-Basri [5] have suggested an adaptive fuzzy gain scheduling method for conventional PI controller. Pingkang et al. [6] have optimized the gains of PI and PID controllers using real coded genetic algorithm in a two-area interconnected power system. Maldonado et al. [7] have used PSO to

\* Corresponding author. Tel.: +91 9438251162.  
E-mail address: [panda.sidhartha@gmail.com](mailto:panda.sidhartha@gmail.com) (S. Panda).

optimize interval type-2 fuzzy controller. Melin et al. [8] have used a new chemical optimization paradigm to optimally design type-2 and type-1 fuzzy controller to track autonomous mobile robots. Castillo and Melin [9] have presented a review of different methods used to interval type-2 fuzzy controller. Castillo et al. [10] have proposed a new design methodology of type-2 fuzzy models. Valdez et al. [11] have presented a comprehensive review of some optimization techniques in which parameter adaptation is taken care by fuzzy logic. Melin et al. [12] have developed a new method to adjust the social and cognitive parameters ( $c_1$  and  $c_2$ ) of PSO using fuzzy logic. Valdez et al. [13] have proposed a new optimization technique combining GA and PSO in which fuzzy logic is used to combine the results of GA and PSO in best possible way. Castillo et al. [14] have described the use of hierarchical genetic algorithms to optimize fuzzy logic in the area of intelligent control. Abdell-Magid and Abido [15] have proposed the tuning of AGC for an interconnected reheat thermal system using PSO. Yesil et al. [16] have suggested the self-tuning fuzzy-PID type controller for AGC. Gozde and Taplamacioglu [17] have used Artificial Bee Colony (ABC) optimization algorithm to study the dynamic performance of AGC in a two-area interconnected thermal power system. Nanda et al. [18] have used Bacterial Foraging (BF) optimization algorithm to determine several important parameters of interconnected three unequal area thermal systems. Abraham et al. [19] have presented the analysis of AGC of a hydrothermal interconnected system with generation rate constraints (GRCs). Ali and Abd-Elazim [20] have used bacteria foraging optimization technique to obtain the optimum gains of a PI controller. Abraham et al. [21] have analyzed AGC of two-area interconnected hydrothermal power system by taking thyristor controlled phase shifter (TCPS) in series with the tie line. Rout et al. [22] have applied differential evolution algorithm to determine the gains of a PI controller for AGC of a two-area interconnected system. A hybrid BFOA-PSO technique is employed in [23] to tune the PI controller parameters of two and three-area power system.

In this paper the dynamic performance of a fuzzy-PID controlled AGC system for a two-area interconnected thermal power system

has been studied. Classical techniques of determining the optimum gains of the fuzzy-PID controller may fail to give optimal solution while solving harder constrained problems with large number of variables or in a large search space. Previous research works in many area related to fuzzy-PID controller have selected the input and output scaling factors of the controller after going through several hit and trial runs. The performance of the controller mainly depends on the proper selection of these parameters and it is very difficult to get the optimum values using hit and trial method.

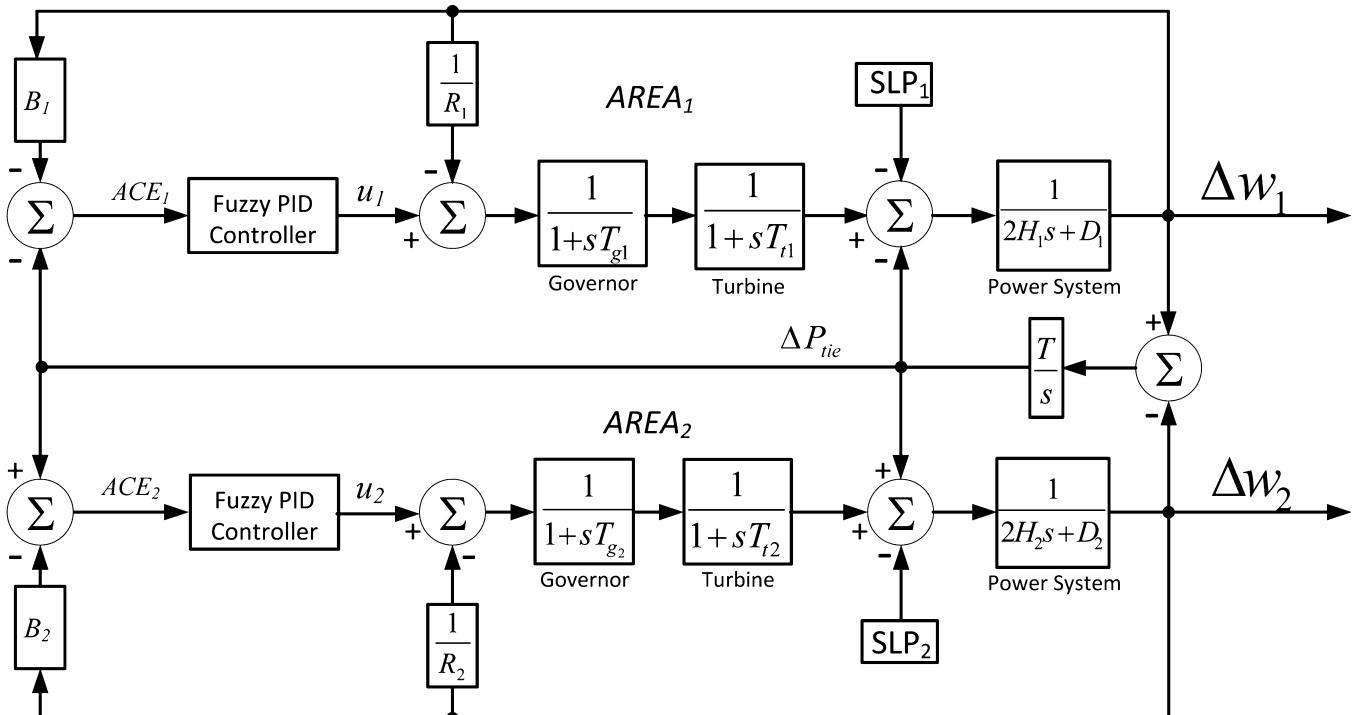
The main contribution of the work is to use a fuzzy-PID controller for AGC of a two unequal area interconnected thermal system with input and output scaling factors optimized by a recently developed optimization technique called Teaching-learning based optimization (TLBO) algorithm proposed by Rao et al. [24,25].

Performance of many optimization techniques depends on proper selection of certain control parameters. For example, GA [26] needs mutation rate and crossover rate, PSO [27,28] uses the inertia weight ( $w$ ), social and cognitive parameters ( $C_1$  and  $C_2$ ), DE [29,30] uses scaling factor ( $F$ ) and crossover rate (CR), etc. Selection of these parameters plays a very crucial role in the performance of the algorithms. However teaching-learning based optimization (TLBO) algorithm does not require any controlling parameter. Since it is a parameter free algorithm, it is simple, effective and faster which motivates many researchers to use this algorithm in their own research area.

Therefore, TLBO technique is used for the first time in this area and also proved to be performing better in terms of settling time, overshoot and undershoot than other optimization techniques such as Lozi map based chaotic optimization algorithm (LCOA), genetic algorithm (GA), pattern search (PS), and simulated annealing (SA) [31].

## 2. Two-area power system model

A fuzzy-PID controlled two unequal area interconnected non-reheat type thermal power system is shown in Fig. 1 [31]. It consists



**Fig. 1.** Transfer function model of the two-area interconnected thermal system [31].

**Table 1**

Transfer function of different components used in the two-area system [31].

| Elements         | Transfer function         |
|------------------|---------------------------|
| Governor         | $TF_g = \frac{1}{1+sT_g}$ |
| Turbine          | $TF_t = \frac{1}{1+sT_t}$ |
| Load and machine | $\frac{1}{2Hs+D}$         |

of two unequal areas namely area1 and area2. To make the system more realistic, time constants and parameters of different values are taken for area1 and area2. Each control area has its own central facility called the energy control centre to monitor the system frequency and the tie-line power flow. Transfer functions of different components of the proposed two-area system are given in Table 1.

Linear combination of frequency error and tie line power error is known as the area control error. Area control errors are taken as input to the fuzzy-PID controllers. Output of the fuzzy-PID controller is  $u_1$  and  $u_2$ . ACEs for the two-area system shown in Fig. 1 are

$$ACE_1 = \Delta P_{12} + B_1 \Delta w_1 \quad (1)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta w_2 \quad (2)$$

where  $\Delta P_{12}$  and  $\Delta P_{21}$  are the change in tie line power in area1 and area2. When the system is subjected to a small disturbance, ACEs are used as actuating signal to reduce  $\Delta P_{tie}$  and  $\Delta w$  to zero when steady state is reached. The input and output scaling factors of the fuzzy-PID controller must be chosen properly to improve the transient performance of the system.

### 3. Fuzzy-PID controller

#### 3.1. Fuzzy-PID controller structure

Structure of fuzzy-PID controller for area1 of the power system is shown in Fig. 2 [32]. It basically comprises of a fuzzy PI and fuzzy PD controller. Performance of the fuzzy-PID controller depends on the input scaling factors  $K_1$  and  $K_2$  and output scaling factors  $K_3$  and  $K_4$ . A similar kind of fuzzy-PID controller is also equipped in area2 with input scaling factors  $K_5$  and  $K_6$  and output scaling factors  $K_7$  and  $K_8$ . Therefore in designing an optimum fuzzy-PID controller these gains ( $K_1-K_8$ ) must be selected properly in order to achieve better dynamic response for the closed loop system. The desired dynamic response should have minimum settling time with a small or no overshoot and undershoot when subjected to a small step load perturbation. Different conventional techniques to determine these gains are: trial and error method, Zeigler–Nichols method etc. But these conventional methods may not yield optimum controller gains. In the past few decades different optimization techniques have been used in many engineering fields. In this paper a recently developed optimization technique called TLBO algorithm is employed to get the optimum values of controller gains in order to extract better dynamic performance from the fuzzy-PID controlled AGC system. TLBO algorithm used in this proposed work is clearly elaborated in Section 4.

For the fuzzy logic controller (FLC) the inputs ACE and rate of change of ACE and the output  $u_1$  are transformed into five linguistic variables namely NB (Negative Big), NS (Negative Small), Z (Zero),

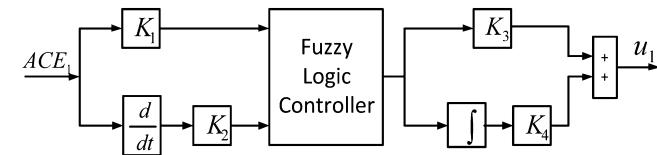


Fig. 2. Fuzzy-PID controller of area1 [32].

| Table 2<br>Fuzzy rules for the inputs and output. |              |    |    |    |    |
|---|--------------|----|----|----|----|
| ACE   | $\Delta ACE$ |    |    |    |    |
|   | NB           | NS | Z  | PS | PB |
| NB  | NB           | NB | NB | NS | Z  |
| NB  | NB           | NB | NB | Z  | PS |
| Z   | NB           | NS | Z  | PS | PB |
| PS  | NS           | Z  | PS | PB | PB |
| PB  | Z            | PS | PB | PB | PB |

PS (Positive Small) and PB (Positive Big). Triangular membership function shown in Fig. 3 is used for both the inputs and the output. A similar kind of controller is also employed in area2.

#### 3.2. Fuzzy controller rule base

Since each variable of the fuzzy controller (two inputs and one output) has 5 membership functions, 25 rules are required to generate a fuzzy output. The rule base of the fuzzy logic controller is given in Table 2. Fuzzy rules play major role in the performance of fuzzy logic controllers and therefore, in this paper the rules are investigated extensively by studying the dynamic behaviour of the system. The firing strength of the fuzzy control rules are obtained by using Mamdani interface engine.

#### 3.3. Defuzzification

The output of the interface engine is a fuzzy value and therefore it must be converted to a real value. The process of conversion of a fuzzy value to a real value with which the physical system can deal is known as defuzzification. The very popular centre of gravity method of defuzzification is used to determine the required real value control output for the two-area power system.

### 4. Teaching–learning based optimization (TLBO) algorithm

Teaching–learning based optimization (TLBO) algorithm [24,25] was introduced by Rao et al. Since then this algorithm has become a very popular and powerful optimization algorithm and applied in many engineering fields. It gives a high-quality solution in minimum time and exhibits very good stable convergence characteristic. The working process of TLBO consists of two parts: (i) teacher phase and (ii) learner phase. In teacher phase students (learners) learn from teachers and in learner phase students learn through interaction between learners (students). Different steps involved in TLBO algorithm are:

#### 4.1. Initialization

In this step the initial population of size  $[NP \times D]$  is randomly generated, where NP indicates size of population i.e. number of learners and D indicates the dimension of the problem i.e. number of subjects offered. The  $i$ th column of the initial population represents the marks secured by different learners in  $i$ th subject.

$$\text{Initial population } X = \begin{bmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,D} \\ x_{2,1} & x_{2,2} & \dots & x_{2,D} \\ \vdots & \vdots & & \vdots \\ x_{NP,1} & x_{NP,2} & \dots & x_{NP,D} \end{bmatrix}$$

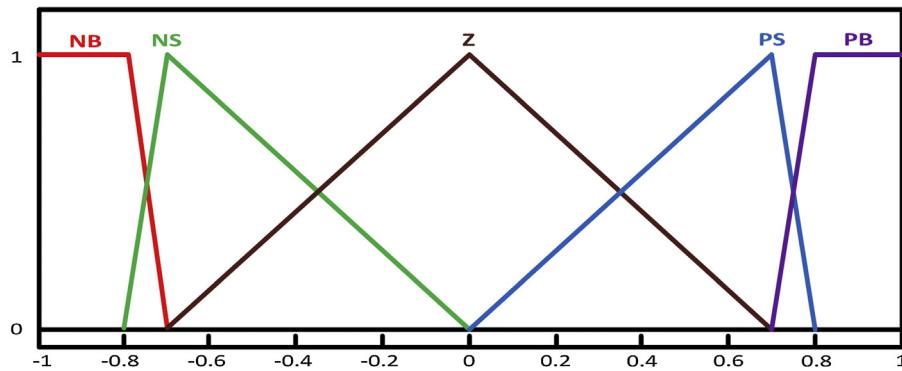


Fig. 3. Membership functions for the two inputs and output.

**Table 3**

Optimum fuzzy-PID controller gains and value of objective function with TLBO algorithm.

| Controller | Controller gains of area1 |        |        |        | Controller gains of area2 |        |        |        | Value of objective function $f$ |
|------------|---------------------------|--------|--------|--------|---------------------------|--------|--------|--------|---------------------------------|
|            | $K_1$                     | $K_2$  | $K_3$  | $K_4$  | $K_5$                     | $K_6$  | $K_7$  | $K_8$  |                                 |
| Fuzzy-PID  | 1.9857                    | 1.9968 | 1.6870 | 1.9876 | 1.3469                    | 1.5512 | 0.8098 | 0.5043 | $3.7288 \times 10^{-4}$         |

#### 4.2. Teacher Phase

In this phase each teacher tries to improve the mean result of a class in the subject assigned to him. As the teacher trains the learners he or she is assumed to be a highly learned person and taken as the best learner i.e. the best solution  $X_{best}$  is identified and assigned as teacher.

The mean value of each column i.e. the mean value of the marks obtained by different students for each subject is calculated as

$$M_d = [m_1, m_2, \dots, m_D] \quad (3)$$

where  $m_i$  is the mean value of marks obtained by learners in the  $i$ th subject.

The difference between the mean results in a particular subject and the result of corresponding teacher is given by

$$M_{diff} = \text{rand}(0, 1)[X_{best} - T_F M_d] \quad (4)$$

where,  $T_F$  is the teaching factor and  $\text{rand}(0,1)$  is a random number between 0 and 1. Value of  $T_F$  is taken as either 1 or 2 and is decided randomly using Eq. (5).

$$T_F = \text{round}[1 + \text{rand}(0, 1)] \quad (5)$$

The existing population is updated using Eq. (6)

$$X_{new} = X + M_{diff} \quad (6)$$

Elements of  $X_{new}$  are accepted if  $f(X_{new}) < f(X)$  else elements of  $X$  are accepted, where  $f(X)$  is the value of objective function.

#### 4.3. Learner phase

In this stage a learner select a student randomly and tries to improve his knowledge by means of interaction. A learner improves his knowledge by interaction if the other learner has acquired more knowledge than him. The learning process in this stage is as follows:

Randomly select two learners  $X_i$  and  $X_j$  such that  $i \neq j$ .

$$X_{new} = X_i + \text{rand}(0, 1)(X_j - X_i), \quad \text{iff } f(X_i) < f(X_j) \quad (7)$$

Else

$X_{new} = X_i + \text{rand}(0, 1)(X_j - X_i)$ . Accept  $X_{new}$  if it performs better.

#### 5. Choice of objective function

As stated earlier in this work, the main and foremost aim of AGC is to make the value of area control error (ACE) zero as quick as possible. In order to achieve this, the cost function  $f$  has been taken as:

$$f = \int_0^t |\Delta w_1 - \Delta w_2| \cdot t \, dt \quad (8)$$

where,  $dt$  is a very small time interval,  $\Delta w_1$  and  $\Delta w_2$  are the change in frequency in area1 and area2 respectively. In this study, a step load perturbation of 2% is applied in area1 and TLBO algorithm is run for 100 times to get the optimal values of fuzzy-PID controller gains. Number of population and maximum number of iteration are also taken as 100. Optimum gains of PID controller and value of objective function ( $f$ ) with TLBO algorithm are given in Table 3. Optimum gains of PID controller and value of objective function for different algorithms are given in Table 4 [31]. It is clear from Tables 3 and 4 that the value of objective function is very less for TLBO optimized fuzzy-PID controlled AGC system as compared to

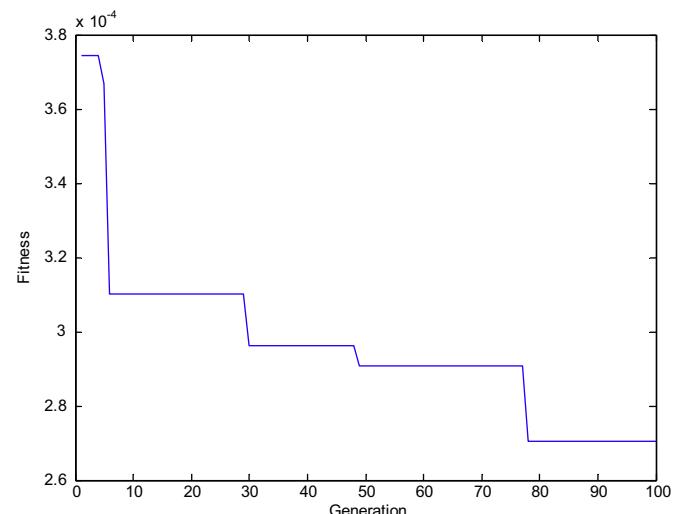


Fig. 4. Convergence curve for TLBO algorithm.

**Table 4**

Optimum gains of PID controller and value of objective function for different optimization algorithms [31].

| Algorithm | Controller gains of area1 |          |          | Controller gains of area2 |          |          | Value of objective function $f$ |
|-----------|---------------------------|----------|----------|---------------------------|----------|----------|---------------------------------|
|           | $K_{p1}$                  | $K_{i1}$ | $K_{d1}$ | $K_{p2}$                  | $K_{i2}$ | $K_{d2}$ |                                 |
| LCOA      | 0.9390                    | 0.7998   | 0.5636   | 0.5208                    | 0.4775   | 0.7088   | 0.0065                          |
| GA        | 0.6003                    | 0.6204   | 0.5224   | 0.3000                    | 0.7319   | 0.3654   | 0.0086                          |
| PS        | 0.9180                    | 0.7439   | 0.5873   | 0.5497                    | 0.6312   | 0.0980   | 0.0073                          |
| SA        | 0.9470                    | 0.7599   | 0.5681   | 0.2362                    | 0.0108   | 0.0809   | 0.0069                          |

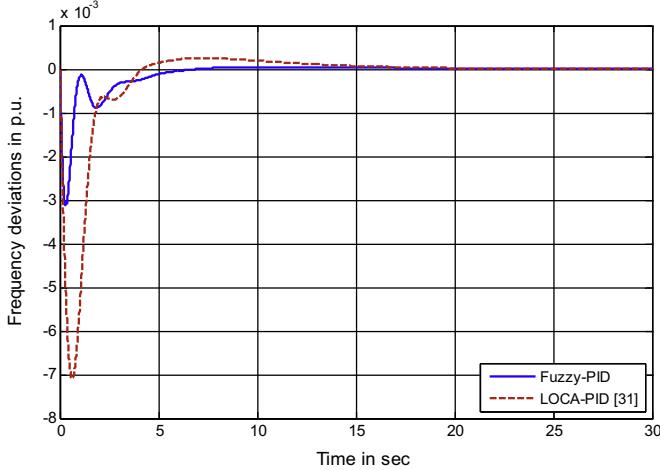


Fig. 5. Frequency deviations in area1 ( $\Delta w_1$ ).

PID controlled AGC system tuned by other algorithms. Convergence characteristic of TLBO algorithm is shown in Fig. 4.

## 6. Result analysis

Dynamic performance of the proposed fuzzy-PID controlled AGC for the two-area power system is studied by applying a step load perturbation (SLP) of 20% in area1. Result obtained is compared with that of a recently published work proposed by Farahani et al. [31]. Frequency deviation in area1 ( $\Delta w_1$ ), frequency deviation in area2  $\Delta w_2$ , tie-line power deviation ( $\Delta P_{tie}$ ) and the governor output variations in area1 ( $\Delta P_{gov}$ ) due to a sudden application of 0.2 p.u. perturbation in area1 are shown in Figs. 5–8 respectively.

From Figs. 5–8 it is clear that the TLBO optimized fuzzy-PID controlled AGC for the two-area power system gives better dynamic response when subjected to a sudden increase in the power

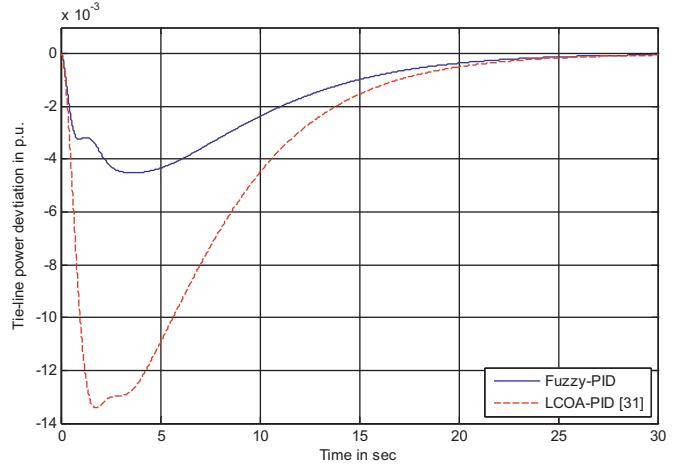


Fig. 7. Tie-line power deviation ( $\Delta P_{tie}$ ).

demand. Settling times ( $T_s$ ), peak undershoots ( $U_{sh}$ ) and peak overshoots ( $O_{sh}$ ) of  $\Delta w_1$ ,  $\Delta w_2$  and  $\Delta P_{tie}$  are depicted in Table 5.

From Table 5 it is clear that the settling times, undershoots and overshoots of  $\Delta w_1$ ,  $\Delta w_2$  and  $\Delta P_{tie}$  are less when the optimum fuzzy-PID controller gains obtained from TLBO algorithm are used to study the dynamic behaviour of the system. Settling times of  $\Delta w_1$ ,  $\Delta w_2$  and  $\Delta P_{tie}$  with fuzzy-PID controller are 52.44%, 36% and 5.38% respectively less than that of LCOA optimized PID controller. Undershoots of  $\Delta w_1$ ,  $\Delta w_2$  and  $\Delta P_{tie}$  with fuzzy-PID controller are 56%, 71.41% and 66.42% respectively less than that of LCOA-PID controller. Overshoot in  $\Delta w_1$  with fuzzy-PID controller is 79.6% less than that of LCOA-PID controller. Thus in all aspect the proposed fuzzy-PID controller performs better than the conventional PID controller. A clear pictorial representation of settling times, undershoots and overshoots are shown in Figs. 9–11, respectively.

In Fig. 8, it is seen that governor works more efficiently with TLBO algorithm optimized fuzzy-PID controller as compared to the

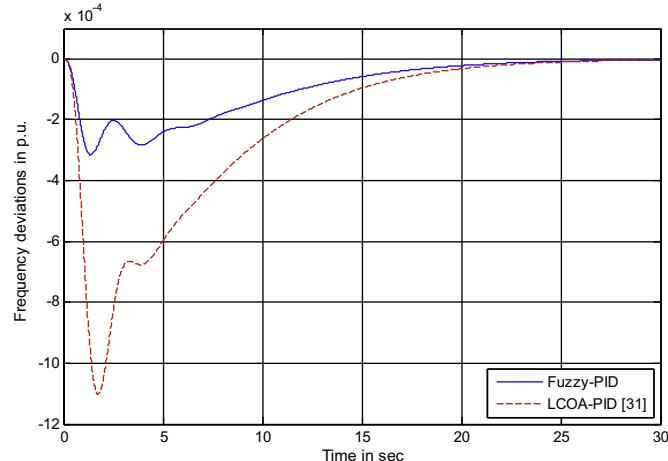


Fig. 6. Frequency deviation in area2 ( $\Delta w_2$ ).

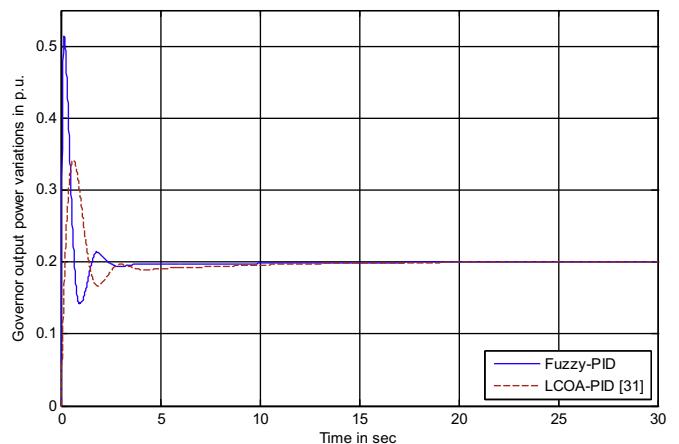
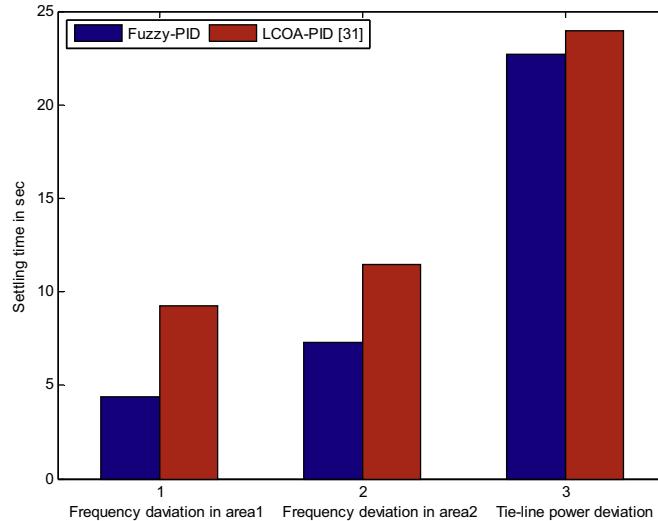


Fig. 8. Governor output power variation ( $\Delta P_{gov}$ ) in area1 for different algorithms.

**Table 5**

Settling time (0.02% band), undershoot and overshoot of  $\Delta w_1$ ,  $\Delta w_2$  and  $\Delta P_{tie}$ .

|                  | Settling time ( $T_s$ ) in s |               | Undershoot ( $U_{sh} \times 10^{-4}$ ) in p.u. |               | Overshoot ( $O_{sh} \times 10^{-4}$ ) in p.u. |               |
|------------------|------------------------------|---------------|--|---------------|---|---------------|
|                  | Fuzzy-PID                    | LCOA-PID [31] | Fuzzy-PID                                      | LCOA-PID [31] | Fuzzy-PID                                     | LCOA-PID [31] |
| $\Delta w_1$     | 4.39                         | 9.23          | -31.2810                                       | -70.9301      | 0.5255  | 2.5766        |
| $\Delta w_2$     | 7.32                         | 11.44         | -3.1551  | -11.0361      | 0   | 0             |
| $\Delta P_{tie}$ | 22.68                        | 23.97         | -45.0876                                       | -134.2560     | 0   | 0             |

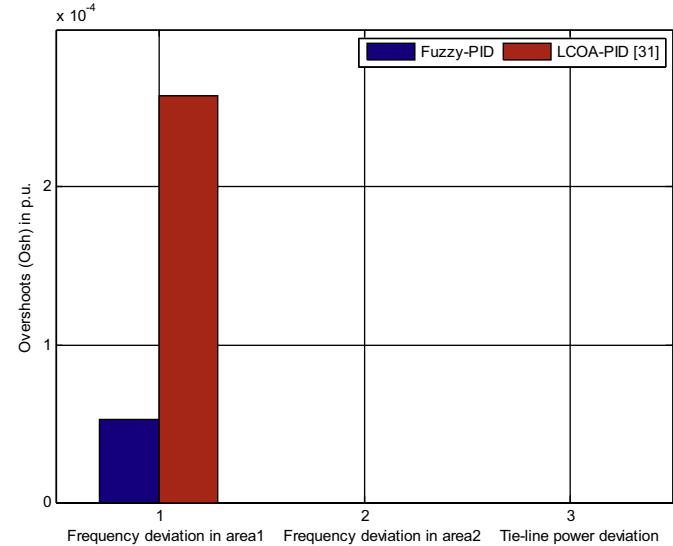
**Fig. 9.** Comparison of settling times.

conventional PID controller. From all the above analysis, facts and figures it is observed that the proposed TLBO algorithm optimized fuzzy-PID controller for the two-area system gives better transient response as compared to LCOA optimized PID controller [31].

Frequency variations in area1 and area2 for different changes of load in area1 and area2 are shown in Figs. 12–15. It is clear from these figures that the proposed fuzzy-PID controller makes the power system to give better dynamic performance in terms of less settling time and less oscillation even for a load change of 50%.

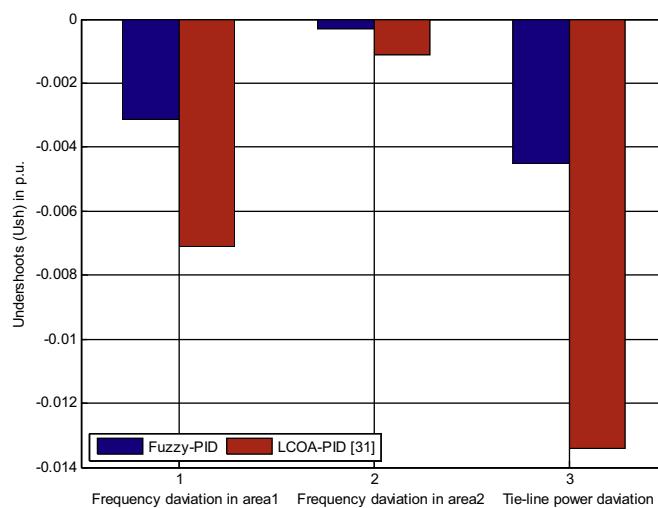
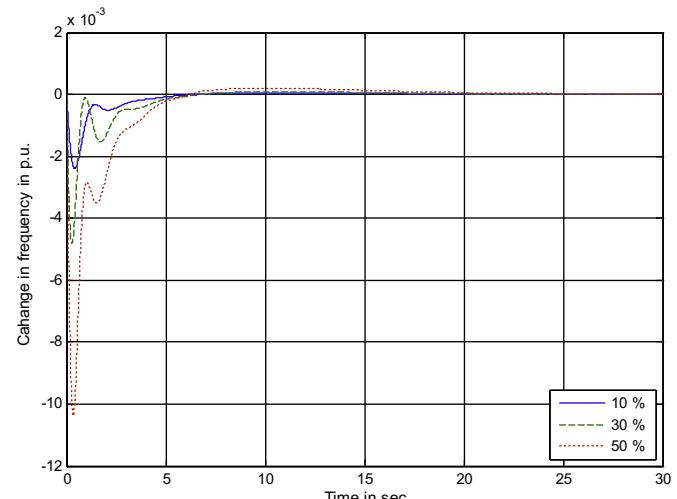
## 7. Robustness analysis

All the parameters of the two-area interconnected system are varied from -50% to 50% in steps of 25% to check the robustness of

**Fig. 11.** Comparison of overshoots.

the system. A step load perturbation of 20% is applied to area1 and the optimum fuzzy-PID parameters obtained from TLBO algorithm are used to test the robustness. Result obtained from robustness analysis is given in Table 6. Similar kind of robustness analysis is also carried out for the LCOA optimized PID controller for the same system and result is depicted in Table 7.

Statistical analysis like maximum value, minimum value, average value and standard deviation of settling times, peak undershoots and peak overshoots obtained from Tables 6 and 7 are depicted in Table 8. From Tables 6–8, it is seen that the TLBO optimized fuzzy-PID controlled AGC system is quite robust towards parametric variation over a wide range.

**Fig. 10.** Comparison of undershoots.**Fig. 12.** Frequency variations in area1 for different changes of load in area1.

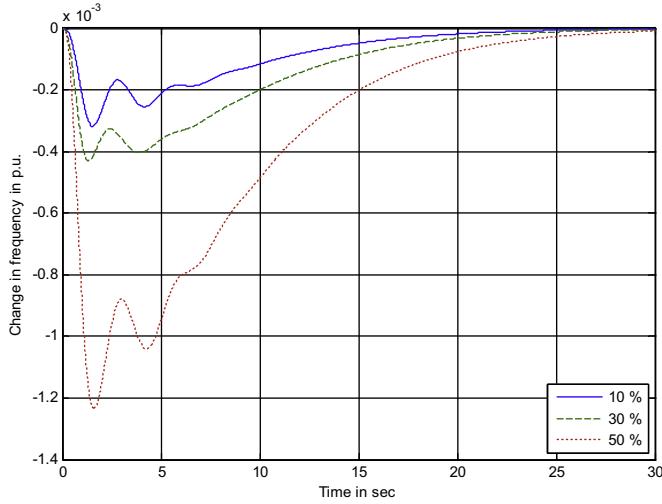


Fig. 13. Frequency variations in area2 for different changes of load in area1.

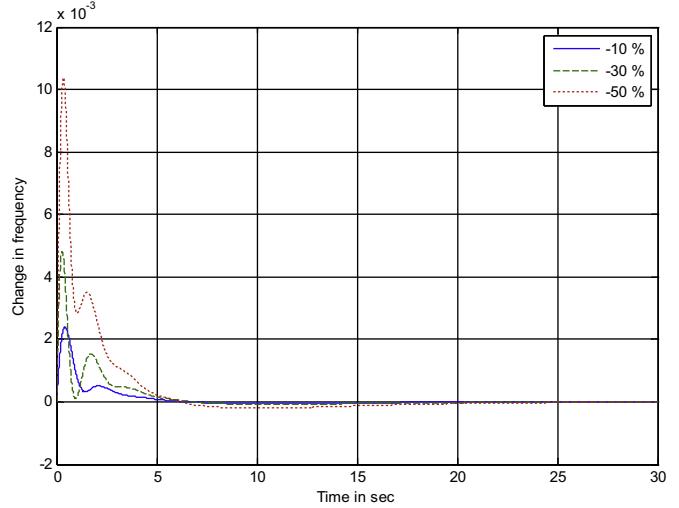


Fig. 14. Frequency variations in area1 for different changes of load in area2.

**Table 6**Variation of settling time  $T_s$ , overshoot ( $O_{sh}$ ) and undershoot ( $U_{sh}$ ) with TLBO optimized fuzzy-PID controller due to parameter variation.

| Parameters | % age deviation | $\Delta w_1$ |  |  | $\Delta w_2$ |  |  | $\Delta P_{tie}$ |  |  |
|------------|-----------------|--------------|--|--|--------------|--|--|------------------|--|--|
|            |                 | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s)     | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) |
| $T_{t1}$   | -50             | 5.00         | -22.3485                               | 0.7297                                 | 9.82         | -3.6052                                | 0                                      | 24.53            | -61.9868                               | 0                                      |
|            | -25             | 4.67         | -26.8951                               | 0.6077                                 | 8.5          | -3.1093                                | 0                                      | 23.6             | -52.0091                               | 0                                      |
|            | +25             | 3.06         | -35.1212                               | 3.2761                                 | 4.78         | -3.6726                                | 0                                      | 21.49            | -42.1073                               | 0                                      |
|            | +50             | 3.17         | -38.3428                               | 7.9778                                 | 4.56         | -4.1873                                | 0                                      | 19.91            | -44.5802                               | 0                                      |
| $H_1$      | -50             | 4.83         | -49.3569                               | 0.8261                                 | 10.65        | -5.0192                                | 0                                      | 24.88            | -74.3863                               | 0                                      |
|            | -25             | 4.10         | -34.9305                               | 3.9465                                 | 6.78         | -2.4962                                | 0                                      | 22.55            | -42.2008                               | 0                                      |
|            | +25             | 4.32         | -35.6329                               | 0.7629                                 | 9.59         | -4.9628                                | 0                                      | 23.89            | -65.1534                               | 0                                      |
|            | +50             | 4.36         | -36.7647                               | 0.9084                                 | 10.35        | -5.8918                                | 0                                      | 24.34            | -75.0411                               | 0                                      |
| $D_1$      | -50             | 4.38         | -31.3918                               | 0.526                                  | 7.28         | -3.158                                 | 0                                      | 22.66            | -44.9473                               | 0                                      |
|            | -25             | 4.39         | -31.3365                               | 0.5258                                 | 7.3          | -3.1566                                | 0                                      | 22.67            | -45.0235                               | 0                                      |
|            | +25             | 4.39         | -31.2253                               | 0.5253                                 | 7.34         | -3.1536                                | 0                                      | 22.7             | -45.1616                               | 0                                      |
|            | +50             | 4.4          | -31.1696                               | 0.5251                                 | 7.36         | -3.1521                                | 0                                      | 22.71            | -45.2375                               | 0                                      |
| $T_{g1}$   | -50             | 4.71         | -24.9017                               | 0.7067                                 | 9.44         | -3.6853                                | 0                                      | 24.1             | -60.7137                               | 0                                      |
|            | -25             | 4.5          | -28.0041                               | 0.592                                  | 8.18         | -3.1851                                | 0                                      | 23.3             | -51.0025                               | 0                                      |
|            | +25             | 4.12         | -34.1687                               | 3.5128                                 | 6.58         | -3.3073                                | 0                                      | 21.99            | -43.2365                               | 0                                      |
|            | +50             | 4.31         | -37.0018                               | 7.5601                                 | 4.55         | -3.6115                                | 0                                      | 21.22            | -44.1824                               | 0                                      |
| $R_1$      | -50             | 5.28         | -30.6693                               | 2.8996                                 | 8.11         | -2.6745                                | 0                                      | 24.34            | -42.5259                               | 0                                      |
|            | -25             | 4.53         | -31.0667                               | 0.4578                                 | 7.65         | -2.9754                                | 0                                      | 23.21            | -44.4539                               | 0                                      |
|            | +25             | 4.02         | -31.4143                               | 0.5759                                 | 7.08         | -3.2734                                | 0                                      | 22.35            | -45.7928                               | 0                                      |
|            | +50             | 3.74         | -31.5032                               | 0.6209                                 | 6.92         | -3.3588                                | 0                                      | 22.16            | -46.3925                               | 0                                      |
| $B_1$      | -50             | 12.27        | -66.6843                               | 2.214                                  | 12.68        | -10.8087                               | 0                                      | 21.27            | -128.9906                              | 0                                      |
|            | -25             | 4.95         | -47.1984                               | 1.1244                                 | 10.84        | -6.526                                 | 0                                      | 23.05            | -82.7306                               | 0                                      |
|            | +25             | 3.93         | -26.7228                               | 2.5543                                 | 10.84        | -1.9923                                | 0                                      | 22.4             | -33.433                                | 0                                      |
|            | +50             | 3.7          | -25.6579                               | 1.3769                                 | 10.84        | -1.9821                                | 0                                      | 23.05            | -33.6716                               | 0                                      |
| $T$        | -50             | 4.85         | -31.4616                               | 0.6363                                 | 10.84        | -1.8056                                | 0                                      | 30.00            | -29.82                                 | 0                                      |
|            | -25             | 4.57         | -31.3714                               | 0.6045                                 | 6.75         | -2.4496                                | 0                                      | 26.59            | -38.3793                               | 0                                      |
|            | +25             | 4.26         | -31.1899                               | 0.4309                                 | 7.34         | -3.816                                 | 0                                      | 20.28            | -50.9621                               | 0                                      |
|            | +50             | 4.17         | -31.0983                               | 0.3352                                 | 7.24         | -4.437                                 | 0                                      | 18.66            | -56.0837                               | 0                                      |
| $T_{t2}$   | -50             | 4.38         | -31.281                                | 0.5141                                 | 7.41         | -2.8251                                | 0                                      | 22.77            | -45.0838                               | 0                                      |
|            | -25             | 4.39         | -31.281                                | 0.5207                                 | 7.3          | -2.964                                 | 0                                      | 22.74            | -45.0049                               | 0                                      |
|            | +25             | 4.38         | -31.281                                | 0.5304                                 | 7.56         | -3.3173                                | 0                                      | 22.6             | -45.1766                               | 0                                      |
|            | +50             | 4.36         | -31.281                                | 0.5429                                 | 6.05         | -3.4613                                | 0                                      | 22.57            | -45.2438                               | 0                                      |
| $H_2$      | -50             | 4.37         | -31.2813                               | 0.5361                                 | 7.3          | -3.6211                                | 0                                      | 22.55            | -45.309                                | 0                                      |
|            | -25             | 4.41         | -31.2811                               | 0.5299                                 | 6.8          | -3.3446                                | 0                                      | 22.61            | -44.8989                               | 0                                      |
|            | +25             | 4.38         | -31.281                                | 0.5216                                 | 7.32         | -3.0296                                | 0                                      | 22.73            | -45.0858                               | 0                                      |
|            | +50             | 4.38         | -31.2809                               | 0.5156                                 | 7.18         | -2.9651                                | 0                                      | 22.76            | -44.9307                               | 0                                      |
| $D_2$      | -50             | 4.39         | -31.281                                | 0.5246                                 | 7.33         | -3.2261                                | 0                                      | 22.81            | -45.0033                               | 0                                      |
|            | -25             | 4.39         | -31.281                                | 0.5250                                 | 7.32         | -3.1904                                | 0                                      | 22.75            | -45.0445                               | 0                                      |
|            | +25             | 4.39         | -31.281                                | 0.5260                                 | 7.31         | -3.1206                                | 0                                      | 22.62            | -45.1317                               | 0                                      |
|            | +50             | 4.39         | -31.281                                | 0.5267                                 | 7.31         | -3.0869                                | 0                                      | 22.56            | -45.1766                               | 0                                      |

Table 6 (Continued)

| Parameters | % age deviation | $\Delta w_1$ |  |  | $\Delta w_2$ |  |  | $\Delta P_{tie}$ |  |  |
|------------|-----------------|--------------|--|--|--------------|--|--|------------------|--|--|
|            |                 | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s)     | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) |
| $T_{g2}$   | -50             | 4.39         | -31.281                                | 0.5224                                 | 7.28         | -2.8287                                | 0                                      | 22.76            | -44.9859                               | 0                                      |
|            | -25             | 4.39         | -31.281                                | 0.5255                                 | 7.24         | -3.0034                                | 0                                      | 22.74            | -44.9936                               | 0                                      |
|            | +25             | 4.38         | -31.281                                | 0.5245                                 | 7.55         | -3.2873                                | 0                                      | 22.61            | -45.226                                | 0                                      |
|            | +50             | 4.37         | -31.281                                | 0.5347                                 | 7.86         | -3.4058                                | 0                                      | 22.63            | -45.3795                               | 0                                      |
| $R_2$      | -50             | 4.31         | -31.281                                | 0.6094                                 | 8.24         | -2.8331                                | 0                                      | 19.44            | -47.7888                               | 0                                      |
|            | -25             | 4.36         | -31.281                                | 0.5441                                 | 7.2          | -2.9353                                | 0                                      | 21.13            | -46.1546                               | 0                                      |
|            | +25             | 4.41         | -31.281                                | 0.5207                                 | 7.17         | -3.3115                                | 0                                      | 23.85            | -44.2406                               | 0                                      |
|            | +50             | 4.43         | -31.281                                | 0.5189                                 | 6.95         | -3.4292                                | 0                                      | 24.61            | -43.5402                               | 0                                      |
| $B_2$      | -50             | 4.57         | -31.281                                | 0.0366                                 | 9.56         | -4.124                                 | 0                                      | 14.52            | -40.4977                               | 0                                      |
|            | -25             | 4.46         | -31.281                                | 0.3133                                 | 8.44         | -3.5721                                | 0                                      | 18.64            | -43.1586                               | 0                                      |
|            | +25             | 4.33         | -31.281                                | 0.6865                                 | 6.14         | -2.8294                                | 0                                      | 25.85            | -46.6026                               | 0                                      |
|            | +50             | 4.29         | -31.281                                | 0.8106                                 | 4.12         | -2.5674                                | 0                                      | 28.15            | -48.0587                               | 0                                      |

Table 7

Variation of settling time  $T_s$ , overshoot ( $O_{sh}$ ) and undershoot ( $U_{sh}$ ) with LCOA optimized PID controller due to parameter variation.

| Parameters  | % age deviation | $\Delta w_1$ |  |  | $\Delta w_2$ |  |  | $\Delta P_{tie}$ |  |  |
|-------------|-----------------|--------------|--|--|--------------|--|--|------------------|--|--|
|             |                 | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s)     | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) |
| $T_{t1}$    | -50             | 10.08        | -54.2978                               | 2.6003                                 | 11.68        | -8.974                                 | 0                                      | 24.35            | -130.6078                              | 0                                      |
|             | -25             | 10           | -59.8511                               | 2.5864                                 | 11.61        | -9.4533                                | 0                                      | 24.24            | -130.9102                              | 0                                      |
|             | +25             | 9.45         | -82.6484                               | 10.2548                                | 11.21        | -13.303                                | 0                                      | 23.62            | -160.9916                              | 0                                      |
|             | +50             | 10.04        | -94.4922                               | 30.9264                                | 10.72        | -15.9541                               | 0                                      | 23.16            | -195.2397                              | 0                                      |
| $H_1$       | -50             | 9.65         | -93.6572                               | 2.351523                               | 11.5         | -10.2069                               | 0                                      | 23.99            | -128.422                               | 0                                      |
|             | -25             | 9.75         | -79.4507                               | 2.453886                               | 11.47        | -10.7896                               | 0                                      | 23.98            | -129.719                               | 0                                      |
|             | +25             | 9.9          | -65.0873                               | 2.680282                               | 11.4         | -11.1306                               | 0                                      | 23.97            | -140.299                               | 0                                      |
|             | +50             | 9.96         | -60.749                                | 2.897376                               | 11.37        | -11.1423                               | 0                                      | 23.96            | -145.132                               | 0                                      |
| $D_1$       | -50             | 9.81         | -71.566                                | 2.592732                               | 11.42        | -11.1328                               | 0                                      | 23.98            | -135.212                               | 0                                      |
|             | -25             | 9.82         | -71.247                                | 2.584442                               | 11.43        | -11.0857                               | 0                                      | 23.98            | -134.729                               | 0                                      |
|             | +25             | 9.85         | -70.6176                               | 2.568063                               | 11.44        | -10.9929                               | 0                                      | 23.97            | -133.785                               | 0                                      |
|             | +50             | 9.86         | -70.3089                               | 2.560011                               | 11.45        | -10.9471                               | 0                                      | 23.96            | -133.324                               | 0                                      |
| $T_{g1}$    | -50             | 9.93         | -60.9929                               | 2.586085                               | 11.53        | -10.0947                               | 0                                      | 24.11            | -132.237                               | 0                                      |
|             | -25             | 9.88         | -66.0727                               | 2.577039                               | 11.48        | -10.5095                               | 0                                      | 24.04            | -131.772                               | 0                                      |
|             | +25             | 9.8          | -75.4489                               | 2.624849                               | 11.39        | -11.65                                 | 0                                      | 23.9             | -139.969                               | 0                                      |
|             | +50             | 9.83         | -79.6301                               | 4.76846                                | 11.34        | -12.3075                               | 0                                      | 23.83            | -147.287                               | 0                                      |
| [5pt] $R_1$ | -50             | 5.16         | -64.0578                               | 1.544557                               | 12.78        | -8.3644                                | 0                                      | 23.7             | -111.608                               | 0                                      |
|             | -25             | 9.64         | -68.2771                               | 2.102345                               | 11.9         | -9.9828                                | 0                                      | 23.75            | -123.124                               | 0                                      |
|             | +25             | 9.59         | -72.7772                               | 3.004907                               | 11.16        | -11.7822                               | 0                                      | 24.12            | -145.705                               | 0                                      |
|             | +50             | 9.32         | -74.1387                               | 3.535674                               | 10.99        | -12.3334                               | 0                                      | 24.22            | -154.309                               | 0                                      |
| $B_1$       | -50             | 14.54        | -92.3815                               | 5.661764                               | 12.19        | -16.0809                               | 0.048112                               | 17.82            | -202.12                                | 1.215169                               |
|             | -25             | 12.25        | -80.0408                               | 3.651996                               | 11.92        | -13.1415                               | 0                                      | 21.71            | -161.986                               | 0                                      |
|             | +25             | 3.43         | -63.9451                               | 1.936403                               | 10.84        | -9.46841                               | 0                                      | 25.13            | -114.167                               | 0                                      |
|             | +50             | 3.17         | -58.4241                               | 1.526347                               | 10.2         | -8.2563                                | 0                                      | 25.75            | -99.5795                               | 0                                      |
| $T$         | -50             | 11.51        | -71.8202                               | 2.294726                               | 13.88        | -5.99789                               | 0                                      | 30               | -81.7731                               | 0                                      |
|             | -25             | 10.82        | -71.3705                               | 2.532566                               | 12.58        | -8.6193                                | 0                                      | 29.65            | -108.469                               | 0                                      |
|             | +25             | 8.92         | -70.5081                               | 2.506833                               | 10.54        | -13.2838                               | 0                                      | 20.34            | -159.412                               | 0                                      |
|             | +50             | 8.07         | -70.0907                               | 2.369863                               | 9.84         | -15.3746                               | 0                                      | 17.85            | -182.741                               | 0.009398                               |
| $T_{t2}$    | -50             | 9.7          | -70.9315                               | 2.527385                               | 11.29        | -9.36188                               | 0                                      | 24.24            | -135.674                               | 0                                      |
|             | -25             | 9.77         | -70.9306                               | 2.551079                               | 11.36        | -10.2267                               | 0                                      | 24.11            | -134.831                               | 0                                      |
|             | +25             | 9.9          | -70.9298                               | 2.602388                               | 11.51        | -11.765                                | 0                                      | 23.84            | -133.884                               | 0                                      |
|             | +50             | 9.96         | -70.9295                               | 2.622835                               | 11.58        | -12.4134                               | 0                                      | 23.7             | -133.646                               | 0                                      |
| $H_2$       | -50             | 9.91         | -70.94                                 | 2.608008                               | 11.53        | -10.904                                | 0                                      | 23.77            | -131.18                                | 0                                      |
|             | -25             | 9.87         | -70.9336                               | 2.590903                               | 11.49        | -11.0994                               | 0                                      | 23.87            | -132.442                               | 0                                      |
|             | +25             | 9.8          | -70.928                                | 2.557503                               | 11.38        | -10.8908                               | 0                                      | 24.07            | -135.959                               | 0                                      |
|             | +50             | 9.75         | -70.9265                               | 2.536389                               | 11.33        | -10.7173                               | 0                                      | 24.17            | -137.453                               | 0                                      |
| $D_2$       | -50             | 9.84         | -70.9302                               | 2.56883                                | 11.38        | -11.257                                | 0                                      | 24.14            | -133.977                               | 0                                      |
|             | -25             | 9.84         | -70.9302                               | 2.572461                               | 11.41        | -11.147                                | 0                                      | 24.06            | -134.115                               | 0                                      |
|             | +25             | 9.83         | -70.9301                               | 2.580054                               | 11.46        | -10.9332                               | 0                                      | 23.89            | -134.39                                | 0                                      |
|             | +50             | 9.83         | -70.9301                               | 2.583988                               | 11.49        | -10.8293                               | 0                                      | 23.8             | -134.525                               | 0                                      |
| $T_{g2}$    | -50             | 9.77         | -70.9312                               | 2.550324                               | 11.36        | -9.97619                               | 0                                      | 24.11            | -135.205                               | 0                                      |
|             | -25             | 9.8          | -70.9306                               | 2.562848                               | 11.4         | -10.4935                               | 0                                      | 24.04            | -134.68                                | 0                                      |
|             | +25             | 9.87         | -70.9298                               | 2.591893                               | 11.47        | -11.5663                               | 0                                      | 23.9             | -133.932                               | 0                                      |
|             | +50             | 9.9          | -70.9296                               | 2.609981                               | 11.51        | -12.0604                               | 0                                      | 23.84            | -133.696                               | 0                                      |

Table 7 (Continued)

| Parameters | % age deviation | $\Delta w_1$ |  |  | $\Delta w_2$ |  |  | $\Delta P_{tie}$ |  |  |
|------------|-----------------|--------------|--|--|--------------|--|--|------------------|--|--|
|            |                 | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s)     | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) |
| $R_2$      | -50             | 10.27        | -70.9301                               | 2.992083                               | 13.49        | -8.68888                               | 0.015906                               | 18.54            | -140.185                               | 1.874955                               |
|            | -25             | 9.93         | -70.9301                               | 2.719507                               | 12.19        | -10.1069                               | 0                                      | 21.6             | -135.086                               | 0                                      |
|            | +25             | 9.84         | -70.9301                               | 2.499687                               | 10.95        | -11.7032                               | 0                                      | 25.22            | -133.78                                | 0                                      |
|            | +50             | 9.88         | -70.9301                               | 2.45931                                | 10.62        | -12.2024                               | 0                                      | 25.93            | -133.474                               | 0                                      |
| $B_2$      | -50             | 3.87         | -70.9304                               | 1.390152                               | 12.49        | -15.0368                               | 0.154486                               | 24.53            | -131.009                               | 5.655687                               |
|            | -25             | 7.74         | -70.9303                               | 2.07796                                | 12           | -12.7672                               | 0.006308                               | 18.06            | -132.649                               | 0.277947                               |
|            | +25             | 11.15        | -70.93                                 | 2.957181                               | 10.82        | -9.68419                               | 0                                      | 27.81            | -135.808                               | 0                                      |
|            | +50             | 12.14        | -70.9298                               | 3.256887                               | 10.16        | -8.59771                               | 0                                      | 30               | -137.297                               | 0                                      |

Table 8

Statistical analysis to compare the robustness of the fuzzy-PID controlled and LCOA-PID controlled AGC system.

| Statistical parameter | Controller | $\Delta w_1$ |  |  | $\Delta w_2$ |  |  | $\Delta P_{tie}$ |  |  |
|-----------------------|------------|--------------|--|--|--------------|--|--|------------------|--|--|
|                       |            | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s) | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) | $T_s$ (in s)     | $(U_{sh} \times 10^{-4})$<br>(in p.u.) | $(O_{sh} \times 10^{-4})$<br>(in p.u.) |
| Maximum value         | Fuzzy-PID  | 12.27        | -66.6843                               | 7.9778                                 | 12.68        | -10.8087                               | 0                                      | 30.00            | -128.9906                              | 0                                      |
|                       | LCOA-PID   | 14.54        | -94.4922                               | 30.9264                                | 13.88        | -16.0809                               | 0.1545                                 | 30.00            | -202.1200                              | 5.6557                                 |
| Minimum value         | Fuzzy-PID  | 3.06         | -22.3485                               | 0.0366                                 | 4.12         | -1.8056                                | 0                                      | 14.52            | -29.8200                               | 0                                      |
|                       | LCOA-PID   | 3.17         | -54.2978                               | 1.3902                                 | 9.84         | -5.9979                                | 0                                      | 17.82            | -81.7731                               | 0                                      |
| Average value         | Fuzzy-PID  | 4.51         | -32.6034                               | 1.1500                                 | 7.77         | -3.4949                                | 0                                      | 22.75            | -49.0754                               | 0                                      |
|                       | LCOA-PID   | 9.54         | -71.4670                               | 3.3433                                 | 11.48        | -11.0921                               | 0.0043                                 | 23.89            | -136.9905                              | 0.1737                                 |
| Standard deviation    | Fuzzy-PID  | 1.16         | 6.4383                                 | 1.5810                                 | 1.72         | 1.3336                                 | 0                                      | 2.28             | 14.8053                                | 0                                      |
|                       | LCOA-PID   | 1.91         | 7.4642                                 | 4.0928                                 | 0.71         | 1.9269                                 | 0.0224                                 | 2.41             | 19.3722                                | 0.8342                                 |

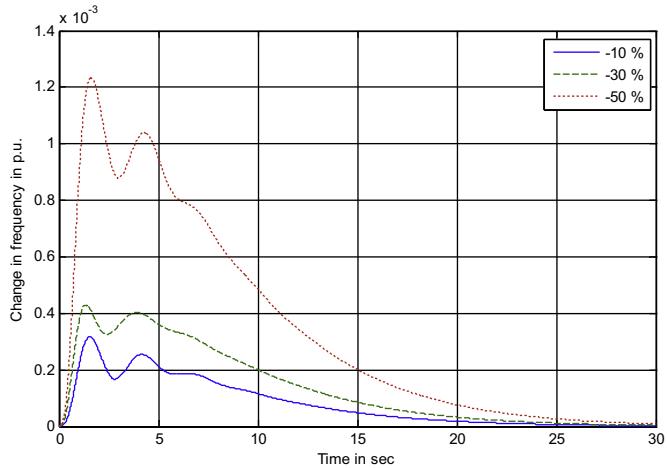


Fig. 15. Frequency variations in area2 for different changes of load in area2.

## 8. Conclusion

In this work, a novel fuzzy-PID controller is used to study the performance of AGC of a two unequal area interconnected thermal system. TLBO algorithm is used for the first time in this field to optimally tune the gains of the proposed fuzzy-PID controller. Dynamic performance of the TLBO algorithm optimized fuzzy-PID controller for AGC of a two unequal area interconnected thermal systems is compared with that of recently published heuristic approaches such as LCOA, GA, PS and SA based PID controller for the same system. It is observed that TLBO algorithm optimized fuzzy-PID controller gives better dynamic performance in terms of less settling time, less undershoot, less overshoot and less oscillation in frequency and tie-line power deviations following a step perturbation in area1 as compared to LCOA, GA, PS and SA based PID controllers. Robustness analysis of the proposed controller and LCOA-PID controller for the two-area power system

are also studied by varying various parameters of both the areas from -50% to 50% of nominal value in steps of 25%. Simulation result and statistical analysis reveal that TLBO optimized fuzzy-PID controllers are robust and therefore the parameters of proposed controllers need not be retuned under wide variations in system parameters and loading conditions.

## Appendix.

| System parameters | Meaning   | Values used in this work [31] |
|-------------------|---|-------------------------------|
| $f$               | Nominal system frequency                                | 60 Hz                         |
| $R_1$             | Regulation constant of area1                            | 0.05 MW/Hz                    |
| $R_2$             | Regulation constant of area2                            | 0.0625 MW/Hz                  |
| $B_1$             | Frequency bias constant of area1                        | 20.6 Hz/MW                    |
| $B_2$             | Frequency bias constant of area2                        | 16.9 Hz/MW                    |
| $SLP$             | Step load perturbation                                  | 0.2 p.u.                      |
| $T_{g1}$          | Time constant of governor of area1                      | 0.2 s                         |
| $T_{g2}$          | Time constant of governor of area2                      | 0.3 s                         |
| $T_{t1}$          | Time constant of turbine of area1                       | 0.5 s                         |
| $T_{t2}$          | Time constant of turbine of area2                       | 0.6 s                         |
| $H_1$             | Inertia constant of area1                               | 5.0                           |
| $H_2$             | Inertia constant of area2                               | 4.0                           |
| $D_1$             | Ratio of change in load to change in frequency of area1 | 0.6                           |
| $D_2$             | Ratio of change in load to change in frequency of area2 | 0.9                           |
| $T$               | Synchronizing coefficient                               | 2.0                           |

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