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ABSTRACT

This paper introduces an innovative approach for automatic generation control (AGC) of multi-area diverse-sources of the interconnected systems under a restructured scenario. In this work, proportional-integral (PI), proportional-integral derivative (PID), and 2-degree of freedom PID (2-DOF-PID) controllers are proposed to stabilise the variations in the system parameters at distinct loading conditions. Different types of metaheuristic optimisation methods like teaching–learning-based optimisation (TLBO) and cuckoo search algorithms are suggested to acquire the optimal gain values of the proposed controllers. To alleviate the frequency and inter-area power line deviations, the cuckoo tuned 2-DOF-PID controller has rendered better dynamic performances in terms of overshoot, settling time, and undershoot over other control approaches. Further, the robustness of the system has been ascertained while varying the loading circumstances and system specifications up to ±25% from their prescribed values which helped to exhibit the ability of the proposed method.

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KEYWORDS
Automatic generation control; cuckoo search algorithm; deregulated power system; sensitivity analysis

Nomenclature

f	System frequency in Hz
i	Represents the area as subscript
B_i	Frequency bias coefficient in p.u MW/Hz
R_i	Speed regulation constant in Hz p.u MW
T_{gi}	Time constant of governor in sec
T_{ti}	time constant of turbine in sec
T_{r1}	time constant of reheat turbine in sec
T_{wi}	Hydro- turbine time constant in sec
K_{Pi}	Gain constant of power system in Hz/p.u
T_{Pi}	Time constant of power system in sec
ΔF_i	Frequency change of ith area in Hz
T_F	Teaching factor
n	Number of nests
ΔP_{tie_i}	Deviation of tie-line power in p.u
$\Delta P_{\text{d}i}$	Load of each ith area in MW
T_{ij}	Tie-line synchronising coefficient
$\Delta_{\text{Pr efi}}$	Reference power in MW
U_i	The control signal of ith area
t_s	Time of simulation range in seconds
t	Time in sec
J	Objective function
K_P	Proportional gain
K_i	Integral gain
K_D	Derivative gain
M_d	Mean value of each subject

List of abbreviations

AGC	Automatic Generation control
GENCOs	Generation Companies
TRANSCOs	Transmission Companies
DISCOs	Distribution Companies
ISO	Independent System Operator
apf	ACE participation factor
DPM	DISCO Participation Factor
PI	Proportional plus Integral
ISE	Integral Square Error.
TLBO	Teaching–Learning-Based Optimisation
BFOA	Bacteria Foraging Optimisation Algorithm
ACE	Area Control Error
cpf	Contract participation factor
PID	Proportional Integral Derivative
2-DOF-PID	Two degree of freedom PID
CS	Cuckoo Search
DE	Differential Evolution

1. Introduction

The modern power system is struggling with numerous challenges due to incorporating an extensive range of sustainable energy sources, vast production units, usage of electricity with power electronic systems. As it has been interconnected with distant control areas, a small load perturbation (SLP) may have to get in any area. This may lead to change the system parameters such as frequency, voltage, and tie-line power then the system becomes unhealthy. Numerous control strategies have been attempted to balance power production and demand without violating the electrical parameters. Automatic generation control (AGC) is one of the efficient control techniques is to alleviate

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the variations in frequency and tie-line power (Arya and Kumar 2017b; Arya and Kumar 2016).

Nowadays, several countries are deploying various kinds of policies for reforming their electrical structure. The significant objectives of reshaping the conventional electrical system are to strengthen the economic efficiency of the country, to yield the reliable power supply for consumers at reasonable prices. The restructured power system is built with different entities such as generation companies (GENCOs), transmission companies (TRANSCOs), distribution companies (DISCOs), and an independent contract administrator (ICA). On the behalf of the government sector, all power transactions are being monitored by the ICA. Different sorts of power agreements have existed in an open market scenario namely, unilateral based, bilateral type, and contract violation (Bakken and Grande 1998). The AGC mechanism plays a pivotal role in the liberalised system with diverse sources for keeping the tie-line power and frequency within nominal values.

Researchers have studied the effect of AGC with distinct control strategies in the liberalised power system is reported briefly. Previous studies have primarily concentrated on traditional methods such as integral (I), proportional-integral (PI), integral double derivative (IDD), and proportional integral derivative (PID) for mitigating the frequency problems (Arya and Kumar 2017a; Saikia, Nanda, and Mishra 2011). Since the conventional methods having several limitations, alternative control techniques are requiring to be examined the AGC under a deregulated environment.

A few researchers (Sahu et al. 2016; Sahu, Panda, and Rout 2013) have been investigated the AGC system with multi-sources using the two-degree of freedom proportional integral derivative (2 DOF-PID) approach. Debbarma and Dutta (2016) implemented the fractional order proportional integral derivative (FOPID) controllers in the AGC for regulating the differences in frequency and tie-line power. Though there were many investigations about AGC with single and two-degree of freedom controllers, few of them concentrated on the 2DOF-PID controllers after deregulation. Hence, it is pivotal to do intensive carry out on the AGC system with 2DOF-PID controllers under a competitive scenario.

For acquiring the requisite gain values of the controllers, different kinds of optimisation methods have been evolved. Many metaheuristic algorithms such as Gases Brownian Motion Optimisation (GBMO) (Zamani, Barakati, and Yousofi-Darmian 2016), Simulated Annealing (SA) (Panigrahi et al. 2006), Improved Particle Swarm Optimisation (IPSO) (Hou et al. 2011), Bacterial Foraging Optimisation (BFO) (Gupta et al. 2014), Bat Algorithm (BA) (Kallannan et al. 2018), Firefly Algorithm (FA) (Gorripotu, Sahu, and Panda 2015), and Teaching–Learning-Based Optimisation (TLBO) (Khamari et al. 2019) are applied to the AGC system for optimising the system reliability. Ghoshal (2004) have suggested the Particle Swarm Optimisation (PSO) in the AGC of a thermal system for tuning the fuzzy-PID controller.

Besides, the modified Harmonic Search Algorithm (MHSA) is introduced in the AGC system with a general type2 fuzzy-PI (GT2FPI) controller for alleviating the non-linear problems (Khooban et al. 2017). The results of the AGC with GT2FPI has achieved a prolific performance rather than other control methods like PID, interval type2 fuzzy-PI (IT2FPI), and fuzzy-PID (FPID). Another recent nature-inspired heuristic approach is cuckoo search (CS) (Debbarma et al. 2016), which was suggested by Xin-she Yang in 2010. It should be noted from the above literature, nevertheless, that limited reports of CS algorithms are available on the AGC system under a liberalised environment. Consequently, it is significant to investigate the AGC system with CS method for acquiring the optimal gain parameters after deregulation.

Given the above literature, this paper aims to ascertain the following:

(1) To develop and construct the AGC of the two-area restructured system with thermal-hydro power units.
(2) To incorporate the single degree and 2DOF controllers into the proposed system and utilised the cuckoo search and TLBO optimisation methods for obtaining the finest gain values of the proposed controllers.
(3) To verify the dynamic transient responses of the system with proposed control strategies and determine the efficient controller and optimisation approach.
(4) To ascertain the system robustness by varying the system parameters and loading situations from +25% to −25% from their scheduled limits.

2. Investigation of system

Since an inequity between the complete power production and demand associated with the power losses, the system area control error (ACE) would be increased. The objective of every individual area is to suppress the ACE, thus the system could be stabilised (Bhatt, Roy, and Ghoshal 2010). In this work, the two-are interconnected AGC system with thermal-hydro power units has been considered under a restructured scenario. Area1 has two thermals plants, whereas area2 has two hydropower units and is represented in Figure 1. The information on the suggested model is indicated in the Appendix.

The restructured power system has different kinds of transactions such as pool-co, bilateral, and contract violation agreements under the supervisory of ICA. Accordingly, the DISCOs have no contract with other areas of GENCOs in pool-co based operations, as well as the DISCOs have more freedom and flexibility to choose their power seller in any area for bilateral transactions. Since each area comprises more than one GENCO, the ACE is to give out in the middle of the areas in the AGC system. Further, the constants are rendered from ACE to participate in GENCOs are known as 'area participation factors (apf)'. The total value of the area participation factor must be equal to one.

In addition, for area1, it is represented with apf_1, apf_2, besides apf_3, apf_4 for area2. It is mainly depending on the participation of GENCOs in each area. Mostly, GENCOs and DISCOs have been more than once in the liberalisation system. Hence, DISCOs have more independence and a great opportunity to select the power seller in either their area or any other areas and contract them (Rakhshani and Sadeh 2010).

In this regard, every individual area consists of the two GENCOs and DISCOs. The equivalent DPM is:

$$\mathrm{DPM} = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \quad (1)$$

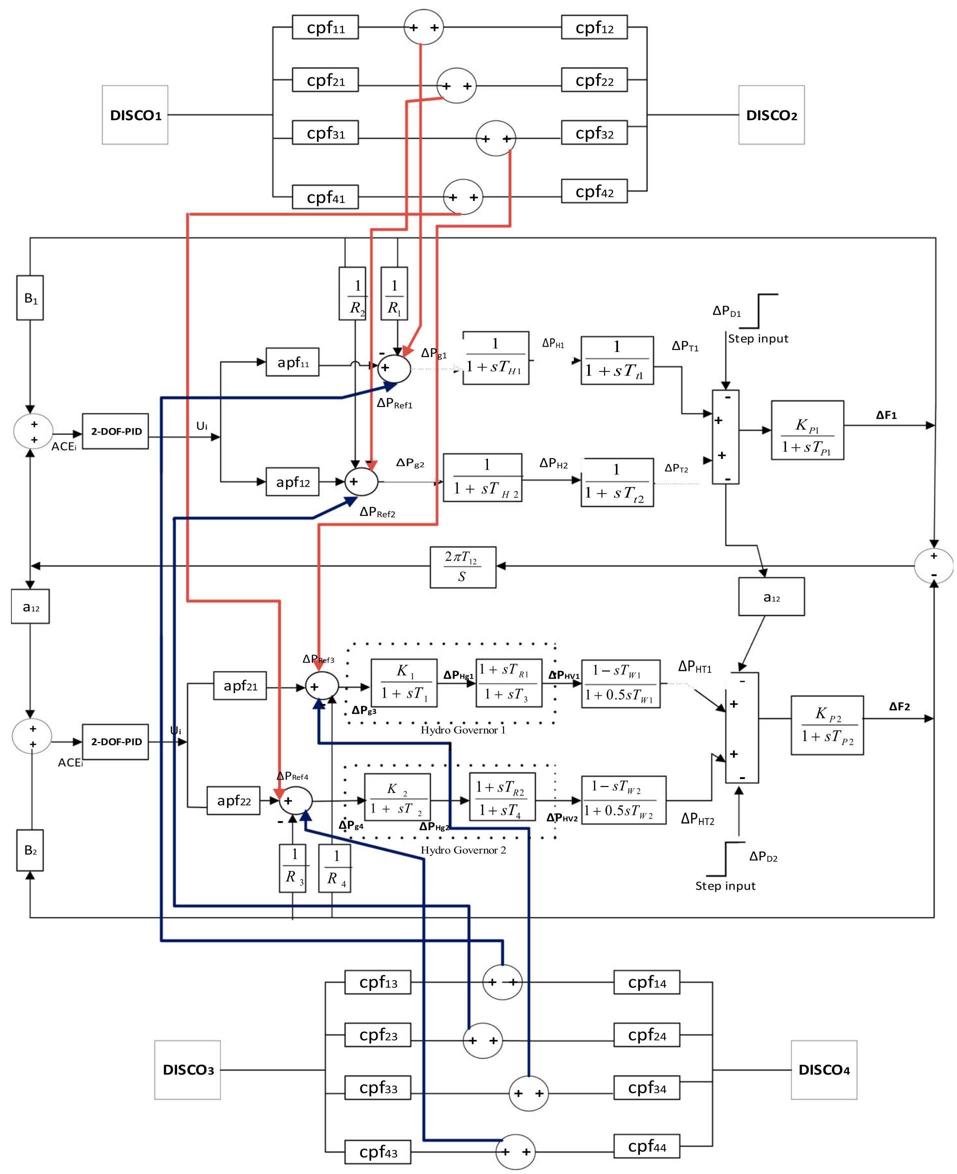


Figure 1. Two area four-unit interconnected system.

In DISCOs participation matrix (DPM), cpf is the contract participation factor and off-diagonal elements are illustrated in one area DISCOs demand to contract remaining area GENCOs (20).

The scheduled power flow within interconnected areas is:

$$\Delta P_{\text{tie12,nominal}} = \sum_{i=1}^{2}\sum_{3}^{4} \text{cpf}_{ij}\Delta P_{dj} - \sum_{3}^{4}\sum_{1}^{2} \text{cpf}_{ij}\Delta P_{dj} \quad (2)$$

Enlarged the equation form (2) can be expressed as:

$$\Delta P_{\text{tie,nominal}} = (\text{cpf}_{13} + \text{cpf}_{23})\Delta P_{d3} + (\text{cpf}_{14} + \text{cpf}_{24})\Delta P_{d4} - (\text{cpf}_{31} + \text{cpf}_{41})\Delta P_{d1} - (\text{cpf}_{32} + \text{cpf}_{42})\Delta P_{d2} \quad (3)$$

Also, measure the error between inter areas at any moment.

$$\Delta P_{\text{tie12,error}} = \Delta P_{\text{tie12,actual}} - \Delta P_{\text{tie12,nominal}} \quad (4)$$

From (4), the error in power between inter areas could have produced the ACE signal in the normal AGC system.

ACE means the combination of frequency bias and tie-line error

$$c_1(t) = \text{ACE}_1 = \Delta P_{\text{tie12,error}} + B_1\Delta F_1 \quad (5)$$

$$c_2(t) = \text{ACE}_2 = \Delta P_{\text{tie12,error}} + B_2\Delta F_2 \quad (6)$$

where

$$B_1 = \frac{1}{R_1} + D_1, B_2 = \frac{1}{R_2} + D_2 \quad (7)$$

R_1, R_2 are speed regulations of area1, and area2 and damping coefficients of generators are D_1, D_2.

GENCOs have delivered the contracted power, then it may be represented as:

$$\Delta P_{gi} = \sum_{j=1}^{\text{DISCO}=4} \text{cpf}_{ij} X \Delta P_{dj} \quad (8)$$

It can expand as:

$$\Delta P_{gi} = \text{cpf}_{i1} X \Delta P_{\text{DISCO1}} + \text{cpf}_{i2} X \Delta P_{\text{DISCO2}} + \text{cpf}_{i3} X \Delta P_{\text{DISCO3}}$$

$$+ \text{cpf}_{i4} X \Delta P_{\text{DISCO4}} \quad (9)$$

In case of contracted violation then ΔP_{gi} becomes:

$$\Delta P_{gi} = (\text{cpf}_{i1}.\text{DISCO}_1) + (\text{cpf}_{i2}.\text{DISCO}_2) + (\text{cpf}_{i3}.\text{DISCO}_3) + (\text{cpf}_{i4}.\text{DISCO}_4) + (\text{apf}_{j1}.\text{un - contracted power}) \quad (10)$$

Besides, the load on area1 is $\Delta P_{d1} = \Delta P_{\text{DISCO1}} + \Delta P_{\text{DISCO2}}$, area 2 is $\Delta P_{d2} = \Delta P_{\text{DISCO3}} + \Delta P_{\text{DISCO4}}$.

3. 2-DOF-PID controller design

A classical proportional-integral derivate (PID) controller is a closed-loop mechanism for controlling the system at distinct uncertainties and it is more prevalently utilised in industrial applications. It is low in cost, simple design has a rigid structure, easily adjusts its parameters, and offers quite a great control performance. Moreover, three modes are involved in this structure like proportional, integral, and derivate modes (Sharma, Hote, and Prasad 2019). Concerning this, the rise time can be declined by the proportional controller. Nevertheless, it is incapable to regulate the steady-state and transient state errors. On the other hand, an integral control would be removed from the steady-state error but unable to eliminate the transient error. The derivate control reduces the maximum overshoot and appreciates the transient outcome.

The Proportional integral (PI) technique is also performed a great role in industrial applications. Moreover, this controller does not reduce the rise time and steady-state error because of the absence of the derivate technique. In recent decades, there has been a number of researches on the AGC with 2DOF controllers, however, limited examinations have existed on the AGC of the deregulated system with a 2DOF-PID controller. The 2DOF-PID approach is constituted by modification of PID, and overcome the restrictions of the PID. In the contrast, the 2DOF-PID controllers have two setpoint weights on proportional and derivate controls as well as strengthens the steady-state outcome of the system. Figure 2 demonstrated the arrangement of the 2DOF-PID.

$$X(S) = bK_P + \frac{K_I}{S} + \frac{CK_{ds}}{T_F S + 1} \quad (11)$$

$$Y(S) = -\left[K_P + \frac{K_I}{S} + \frac{K_{ds}}{T_F S + 1}\right] \quad (12)$$

where $X(S)$ is the source information, $U(S)$ is a closed-loop system, $Y(S)$ is system outcome. b, c is the setpoint weights of the proportional and derivative controller, respectively. The gain constants of the control method are K_P, K_I, K_D, and T_F represents the time of the derivative filter.

In this work, PI, PID, and 2-DOF-PID approaches are proposed for stabilising the oscillations in frequency during various disturbances. Moreover, TLBO and cuckoo search approaches are presented in the AGC of the restructured system for optimising the suggested controllers and improve the system transient performance. The ambition of current work is to emphasise the privilege of the cuckoo search over the TLBO algorithm, as well as to demonstrate the predomination of the 2-DOF-PID controller rather than conventional PI and PID techniques. Thereupon, an integral square error (ISE) indices are contemplated as the objective function and written below (Nandi, Shiva, and Mukherjee 2017; Rao, Savsani, and Vakharia 2012):

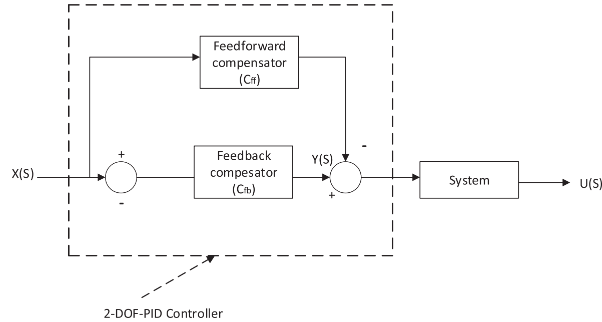


Figure 2. Block diagram of 2-DOF-PID controller.

$$\text{ISE} = \int_0^{t_s} (\Delta F_1)^2 + (\Delta F_2)^2 + (\Delta P_{tie1})^2 .dt \quad (13)$$

Here ΔF_1, ΔF_2 are the changes in system frequency for area1, area2, and ΔP_{tie1} deviation in power between interconnected areas. t_s is a range of simulation time.

4. Cuckoo search algorithm (CS)

4.1. Cuckoo breeding behaviour

It is motivated to require brood parasitism of the cuckoo family by laying their eggs in the nests of alternative birds. Furthermore, some of the female cuckoos resemble the colours and patterns of the eggs near to host groups (Mareli and Twala 2018). The male and female cuckoo can be identified by colours. Slate grey represents the male and reddish-brown indicates female cuckoos. Thereupon, the female cuckoo can visit 50 host nests at the time of the breeding season. When the host birds can recognise the cuckoo eggs in the nest, they may have a chance either to move them far or merely give up their nest and construct another nest at a new location. It has minimised the probability of eggs being given up and enhances their replicate nature. Besides, the cuckoo birds always pick the nest, where the host bird laid their eggs. Typically, the cuckoo bird eggs are hatched before than host bird eggs. Since the cuckoo chicks come out early, they have some instinct to throw the other host eggs. The cuckoo chicks thus shared the food in between them and become strong when food supplied by the host bird and the flow chat of cuckoo is demonstrated in Figure 3.

4.2. Levy flights

A levy flight procedure is a random walk therefore, recognises the step size distribution on the report of a heavy-tailed probability distribution. When the objective value is determined better than other selected eggs, then voluntarily a new location is occupied by that egg. The benefit of the cuckoo search algorithm is predominantly concentrated on what they want to inspect and leave (Pa) some sections of nests. The levy flights employ a search engine that is more appropriate to the CS for noticing each particular optimum in a design space as compared with the remaining algorithms (Dash, Saikia, and Sinha 2015).

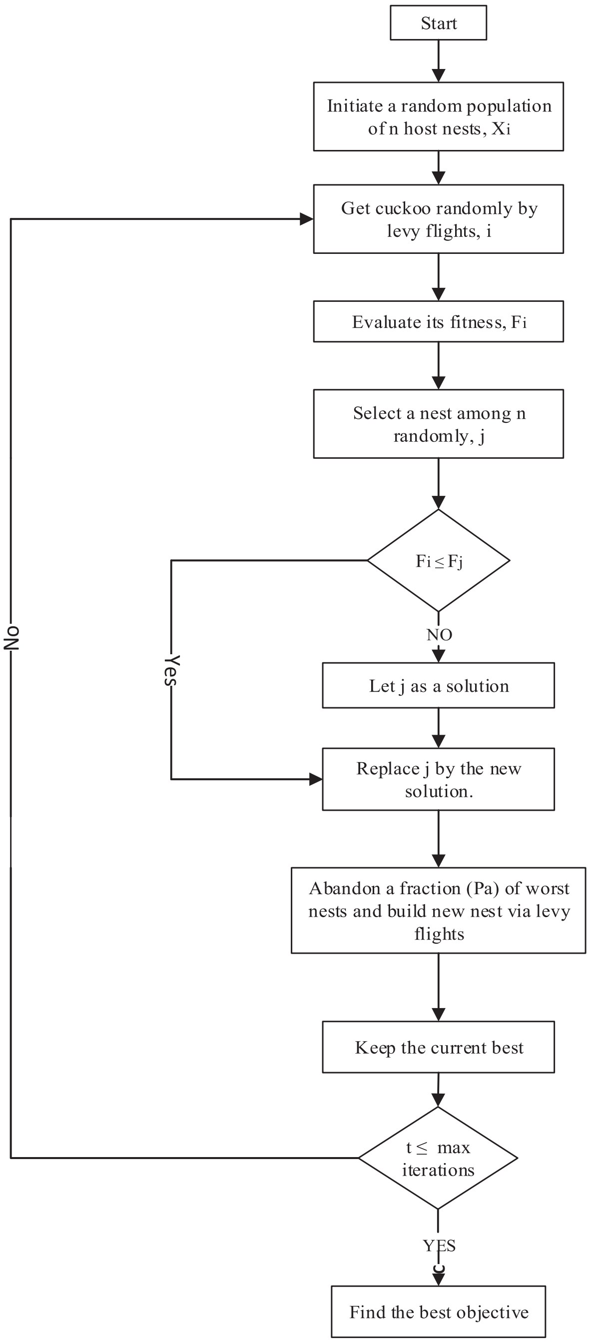


Figure 3. The flowchart of cuckoo search algorithm.

4.3. Implementation

Three rules are considered for implementing the CS as an optimisation algorithm such as (Basu and Chowdhury 2013):

(1) Cuckoos pick the nests in random order for placing their eggs and it has delivered one egg at one moment in randomly picked nests.
(2) The finest qualities of eggs (solutions) are shifted to the next generation as per elite theory.
(3) Numerous feasible host nests are established and the host bird can identify the strange egg with probability P ∈ [0, 1]. If the host bird had recognised the cuckoo egg, they could have thrown it away or departed from the nest and make a new nest.

5. Results and discussions

This work seeks to deliver more obvious examinations regarding the consequences of the AGC under a liberalised market. The objective of the present work is to investigate the AGC system with different control approaches for enriching the system dynamic performance. In this study, the two area four units deregulated market has been considered with thermal-hydro production units and represented in Figure 4. The two-area restructured system is evaluated with three power agreements like pool-co-based, bilateral type, and contract violation.

5.1. Pool-co

Considering the unilateral transaction, DISCOs of each area can agree with the same area of GENCOs only and no other areas. And, area1 has two DISCOs namely, DISCO1, DISCO2 along with it has two GENCOs in that same area, these are GENCO1 and GENCO2. Though the load increase on the area1, they should be contracted with the same area (area1) of the GENCOs. Besides, the DPM matrix is more useful to DISCOs contracts with the GENCOs. It is supposed that in each area DISCOs load demand is 0.10 p.u MW power from GENCOs and mentioned in the DPM matrix. The gain parameters of the proposed controllers are noted in Table 1. The contract transactions between DISCOs and GENCOs are represented in (14)

$$\mathrm{DPM} = \begin{bmatrix} 0.6 & 0.7 & 0 & 0 \\ 0.4 & 0.3 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{14}$$

The GENCOs power must be equal to the DISCOs contract power and the desired values such as ΔP_{G1}, ΔP_{G2}, ΔP_{G3}, ΔP_{G4} are calculated as per formulation in (15).

$$\begin{aligned} \Delta P_{G1} &= (0.6 * 0.1) + (0.7 * 0.1) + (0 * 0.1) + (0 * 0.1) \\ &= 0.13 \text{ pu MW} \end{aligned}$$

Table 1. Gain values of the tuned controllers at pool-co based transaction.

Controller	Gain parameters	Optimised by TLBO	Optimised by Cuckoo
PI	K_{P1}	0.012320	0.000723
	K_{p2}	4.934560	5.934707
	K_{I1}	0.110234	0.079072
	K_{I2}	0.016358	0.029163
PID	K_{P1}	0.013236	0.180495
	K_{p2}	3.334145	5.005119
	K_{I1}	0.099861	0.036099
	K_{I2}	0.005281	0.001252
	K_{D1}	0.002196	0.000012
	K_{D2}	0.001156	1.891426
2-DOF-PID	K_{P1}	0.00001	0.000002
	K_{p2}	3.52691	2.627645
	K_{I1}	0.00020	0.000010
	K_{I2}	0.00350	0.000513
	K_{D1}	0.00145	0.005452
	K_{D2}	5.96009	9.960097

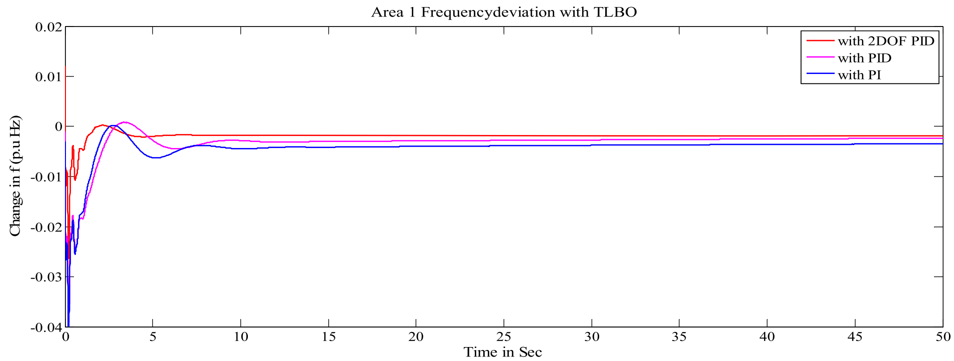


Figure 4. Frequency deviation in area 1 with TLBO for pool-co based.

$$\begin{aligned}\Delta P_{G2} &= (0.4*0.1)+(0.3*0.1)+(0*0.1)+(0*0.1)\\ &= 0.07 \text{ pu MW}\\ \Delta P_{G3} &= \Delta P_{G4}\\ &= (0*0.1)+(0*0.1)+(0*0.1)+(0*0.1)\\ &= 0 \text{ pu MW}\end{aligned} \tag{15}$$

Figures 4–6 exhibits the dynamic performance of the TLBO optimised the proposed controllers. Similarly, the dynamic performance of PI, PID, and 2DOF-PID with cuckoo search is presented in Figures 7–9. As noticed in the above Figures, the dynamic response of ΔF_1, ΔF_2, ΔP_{tie} settling times are 5, 3.5, 3.8 s based on cuckoo optimised 2-DOF-PID, as well as the settling times of TLBO optimised 2DOF-PID controller is 8, 6, 4.9 s. The mitigation rate of settling time is 37.5%, 41.6%, 28.94% for ΔF_1, ΔF_2, ΔP_{tie} as compared with the TLBO tuned 2DOF-PID. It has been recognised that the cuckoo optimised 2DOF-PID has appreciated the system dynamic performance during the various disturbances. The performance of the suggested controllers is mentioned in Table 2.

The power generations like ΔP_{G1} and ΔP_{G2} are demonstrated in Figures 10 and 11 with optimised 2-DOF-PID controllers. Based on the simulation outcomes, the cuckoo optimised 2DOF-PID controller provides less settling time and reached to the steady-state point as quickly as possible as compared with the TLBO tuned 2DOF-PID.

5.2. *Bilateral transaction*

In this case, all DISCOs have more liberty and flexibility to build an agreement with all GENCOs in any area. It is assumed that the

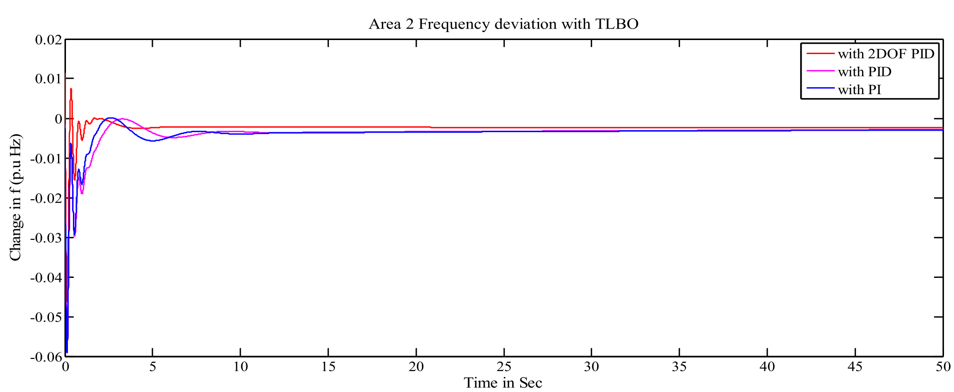


Figure 5. Frequency deviation in area 2 with TLBO for pool-co based.

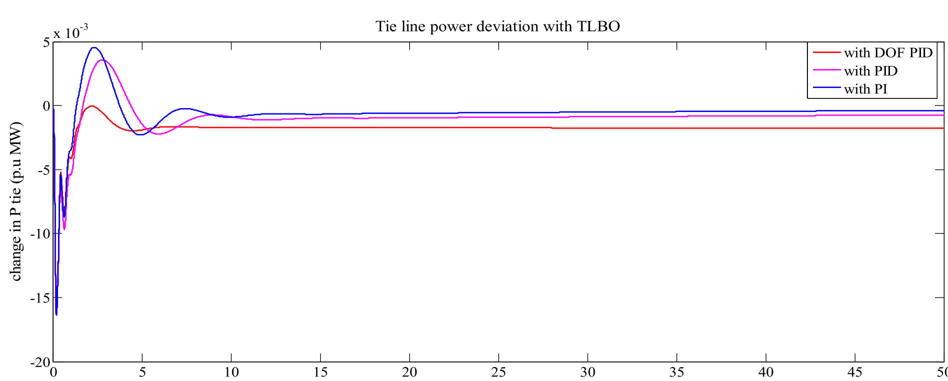


Figure 6. Tie-line power deviation with TLBO for pool-co based.

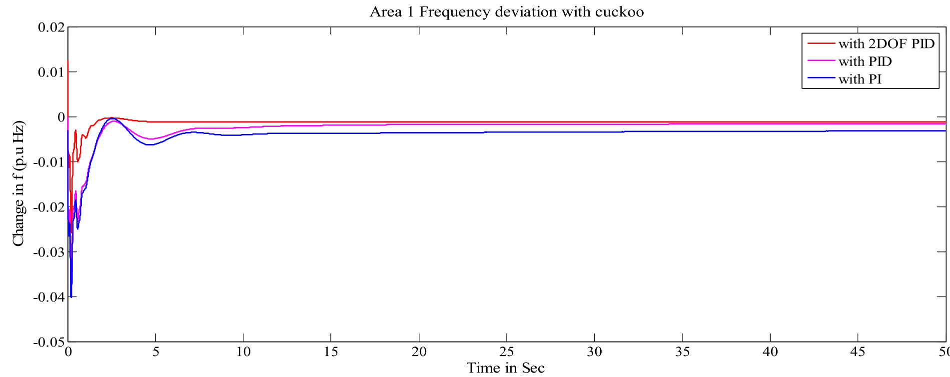


Figure 7. Area 1 frequency fluctuation with cuckoo for pool-co based.

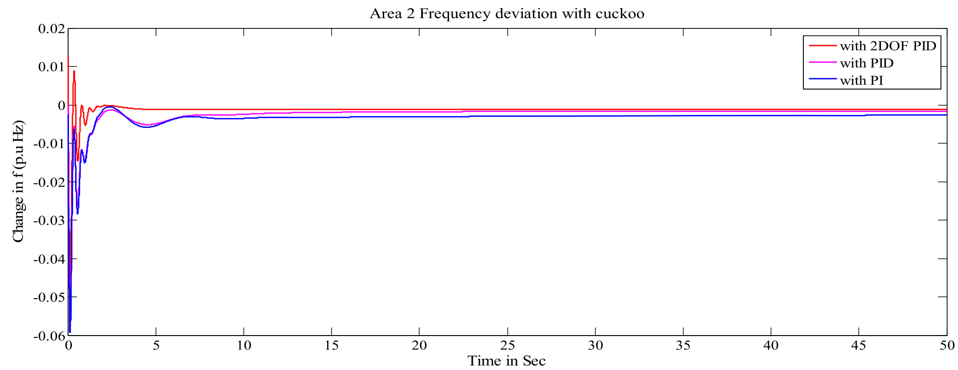


Figure 8. Area 2 frequency fluctuation with cuckoo for pool-co based.

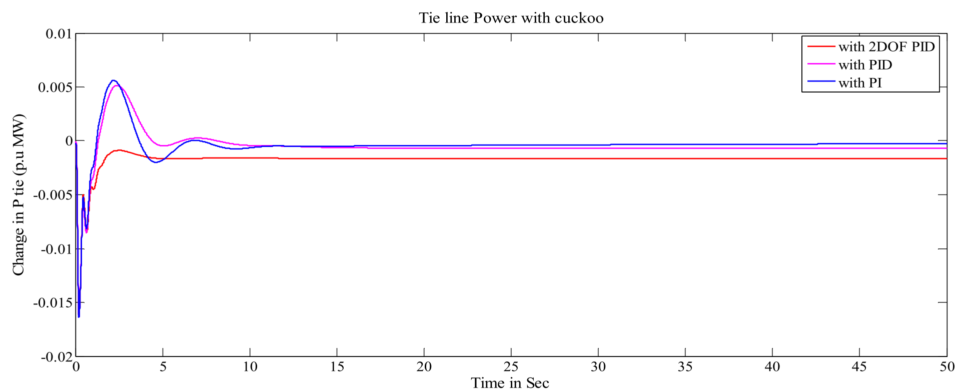


Figure 9. Tie-line power fluctuation with cuckoo for pool-co based.

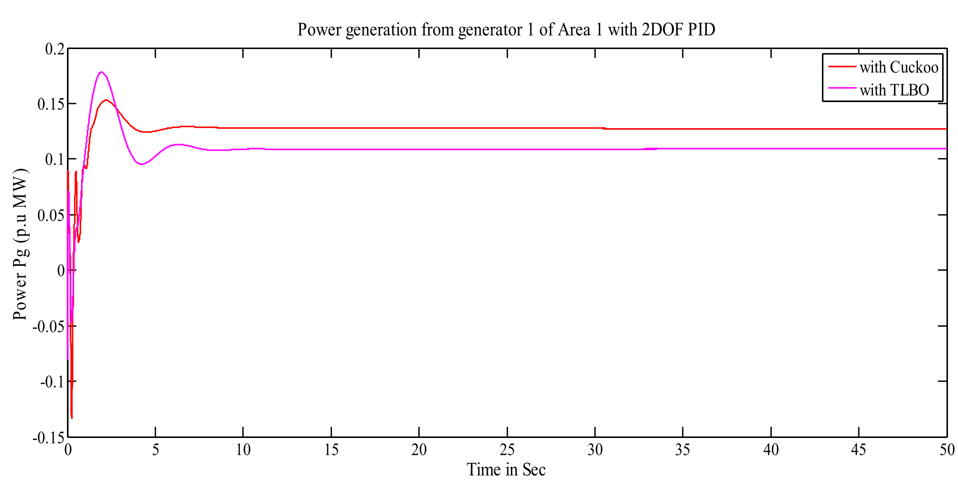


Figure 10. Change in generation of Genco1 (ΔP_{g1}) under pool-co based.

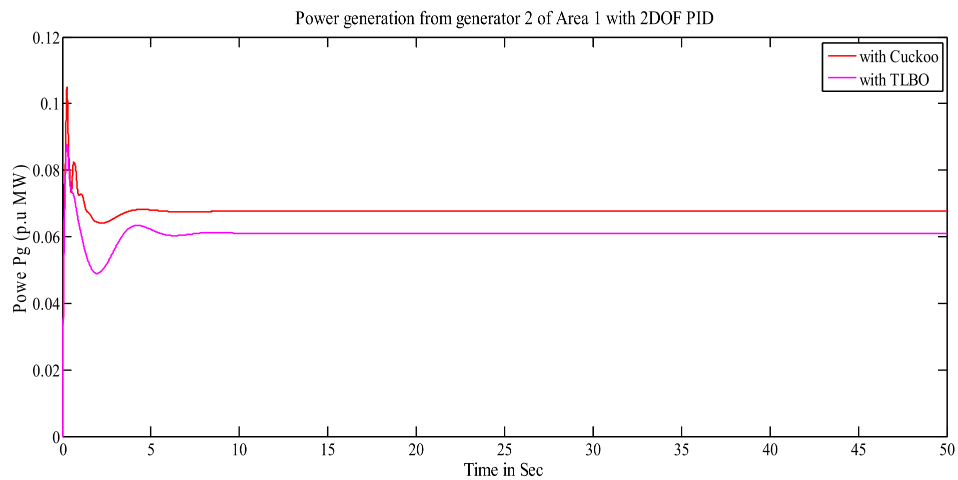


Figure 11. Change in generation of Genco2 (ΔP_{g2}) under pool-co based.

Table 2. Numerical values of overshoot (OS), undershoot (US) and settling time (ST).

Proposed controllers		Parameters	TLBO optimised	Cuckoo optimised
	ΔF_1	OS	0.023	0.019
		US	−0.038	−0.035
		ST	13	8.2
PI		OS	0.022	0.020
	ΔF_2	US	−0.058	−0.056
		ST	9.5	6.8
		OS	0.048	0.009
	ΔP_{tie}	US	−0.032	−0.018
		ST	12	8.2
ISE			6.125	2.926
	ΔF_1	OS	0.021	0.016
		US	−0.032	−0.025
		ST	9	7.5
PID		OS	0.018	0.015
	ΔF_2	US	−0.048	−0.042
		ST	8	6.2
		OS	0.041	0.008
	ΔP_{tie}	US	−0.022	−0.013
		ST	10.5	8.5
ISE			1.843	1.303
	ΔF_1	OS	0.015	0.012
		US	−0.025	−0.018
		ST	8	5
2-DOF-PID				
	ΔF_2	OS	0.012	0.011
		US	−0.032	−0.013
		ST	6	3.5
	ΔP_{tie}	OS	0.013	0.006
		US	−0.015	−0.007
		ST	4.9	3.8
ISE			1.283	0.365

DISCOs have the demand, 0.1 p.u MW relative to GENCOs as per the ensuring DPM matrix. In this respect, all DISCOs have agreed with all GENCOs and it is symbolised in (16).

$$\text{DPM} = \begin{bmatrix} 0.1 & 0.24 & 0.33 & 0.18 \\ 0.2 & 0.16 & 0.17 & 0.22 \\ 0.27 & 0.4 & 0.5 & 0 \\ 0.43 & 0.2 & 0 & 0.6 \end{bmatrix} \tag{16}$$

In the view of the DPM matrix, the off-diagonal elements are indicated as the DISCOs build agreement with another area of GENCOs. The nominal tie-line power flow can be calculated as in (17).

$$\begin{aligned} \Delta P_{\text{tie,nominal}} = {} & (0.33 + 0.17) \times 0.1 + (0.18 + 0.22) \\ & \times 0.1 - (0.27 + 0.43) \times 0.1 – (0.4 + 0.2) \times 0.1 \\ = {} & -0.041 \text{p.u MW} \end{aligned} \tag{17}$$

Figures 12–14 represent the dynamic response of ΔF_1, ΔF_2, ΔP_{tie} with TLBO and cuckoo tuned 2DOF-PID. These plotted descriptions are similar as stated in the pool-co transaction. The gains of the 2DOF-PID controller and performance of the system with proposed techniques are reported in Tables 3 and 4, respectively. The results of the numerical simulation indicate that the dynamic response of cuckoo tuned 2DOF-PID controller for area1 (ΔF_1), area2 (ΔF_2), and tie-line power (ΔP_{tie}) settling times are 4.5, 3.8, and 5.2 s, as well as 7, 4.5, 7.8 s for TLBO optimised 2-DOF-PID. It should be noted that the reduction percentage of settling time is 35.71%, 15.51%, and 33.33% as compared with the TLBO outcomes.

Figures 15–18 show the output production of GENCOs in the bilateral method when optimised the 2DOF-PID controller with cuckoo and TLBO algorithms. As referred to (9), the generation powers of GENCOs are $\Delta P_{g1} = 0.0851$ p.u MW, $\Delta P_{g2} = 0.075$ p.u MW, $\Delta P_{g3} = 0.117$ p.u MW, and $\Delta P_{g4} = 0.123$ p.u MW. Concerning this, the power generations of all GENCOs must be delivered the required amount of load demand at steady-state conditions. Moreover, the cuckoo optimised 2DOF-PID controller gave better dynamic outcomes about settling time and as rapidly as

Table 3. The 2-DOF-PID controller gain parameters in both cases.

		Bilateral transaction		Contract Violation	
Controller	Gain parameters	with TLBO	with Cuckoo Search	TLBO	Cuckoo Search
2-DOF-PID	K_{P1}	0.000016	0.000020	0.000010	0.000020
	K_{p2}	3.527645	2.627645	3.527645	2.627645
	K_{I1}	0.000020	0.000010	0.000020	0.000010
	K_{I2}	0.003503	0.000513	0.003503	0.000513
	K_{D1}	0.001458	0.005452	0.001458	0.005452
	K_{D2}	5.960097	9.960097	5.960097	9.960097

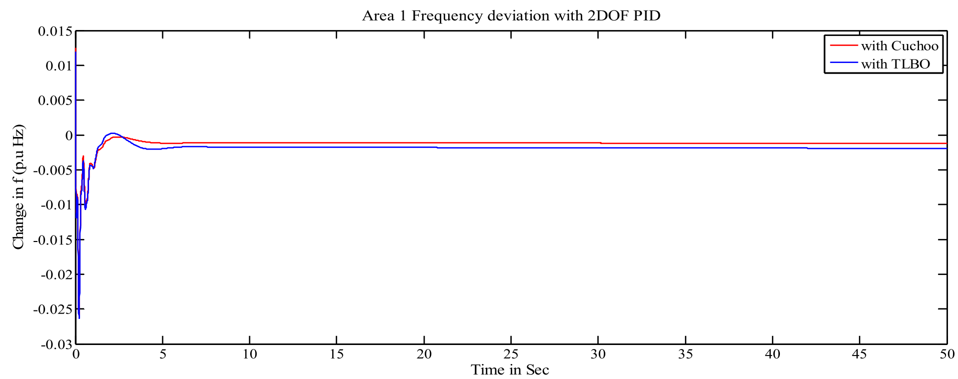


Figure 12. Frequency deviation in area 1 with cuckoo & TLBO for bilateral case.

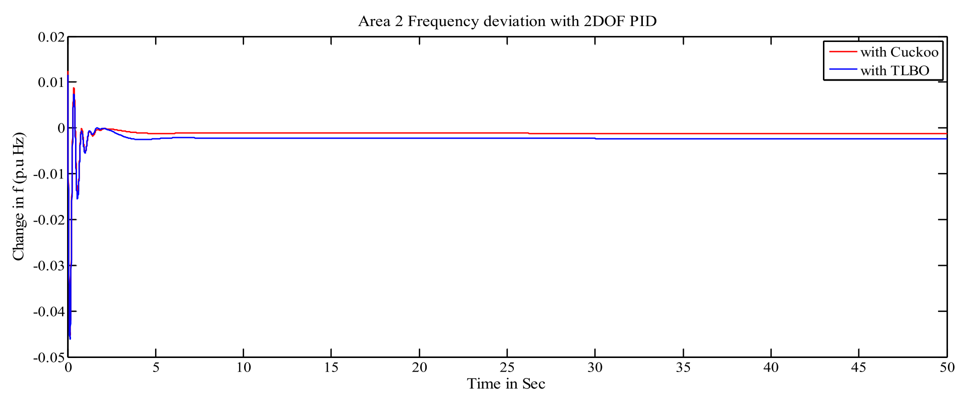


Figure 13. Frequency deviation in area 2 with cuckoo & TLBO for bilateral case.

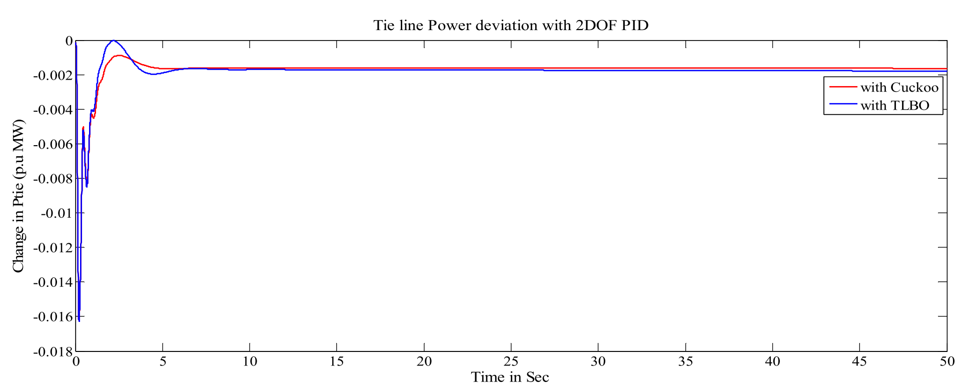


Figure 14. Tie-line power deviation with cuckoo & TLBO for bilateral case.

Table 4. The performance of 2-DOF-PID controller in both cases.

Controller		Parameters	Bilateral transaction		Contract Violation	
			With TLBO	With Cuckoo Search	With TLBO	With Cuckoo Search
	ΔF_1	OS	0.015	0.012	0.014	0.011
		US	−0.003	−0.002	−0.028	−0.016
		ST	7	4.5	5.3	4.1
2DOF-PID						
	ΔF_2	OS	0.020	0.015	0.019	0.012
		US	−0.018	−0.012	−0.045	−0.018
		ST	4.5	3.8	5	3.5
	ΔP_{tie}	OS	−0.001	−0.002	−0.0015	−0.0025
		US	−0.017	−0.009	−0.0165	−0.0085
		ST	7.8	5.2	7.6	5.5
ISE			1.125	0.360	1.166	0.181

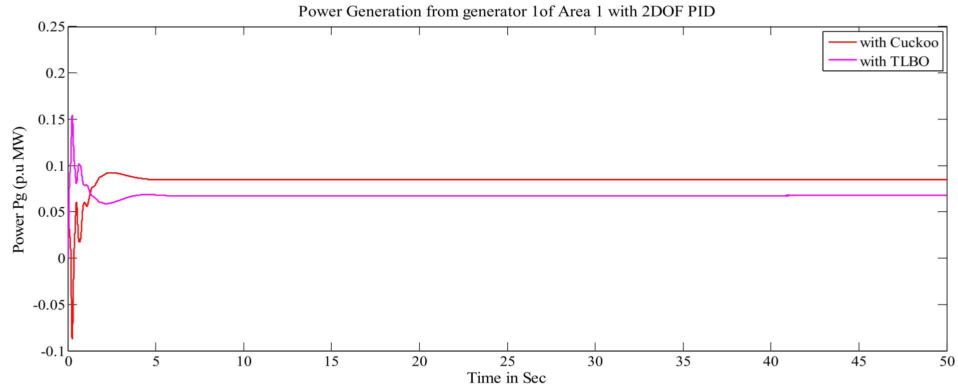


Figure 15. Power change in Genco1 (ΔP_{g1}) for bilateral case.

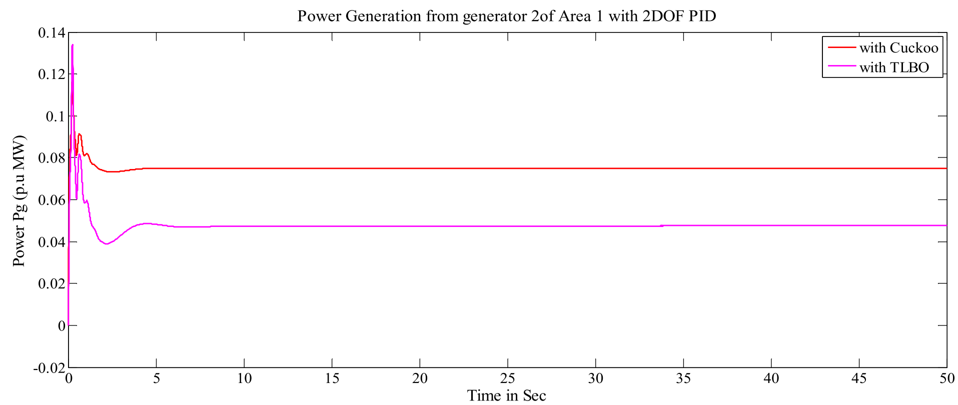


Figure 16. Power change in Genco2 (ΔP_{g2}) for bilateral case.

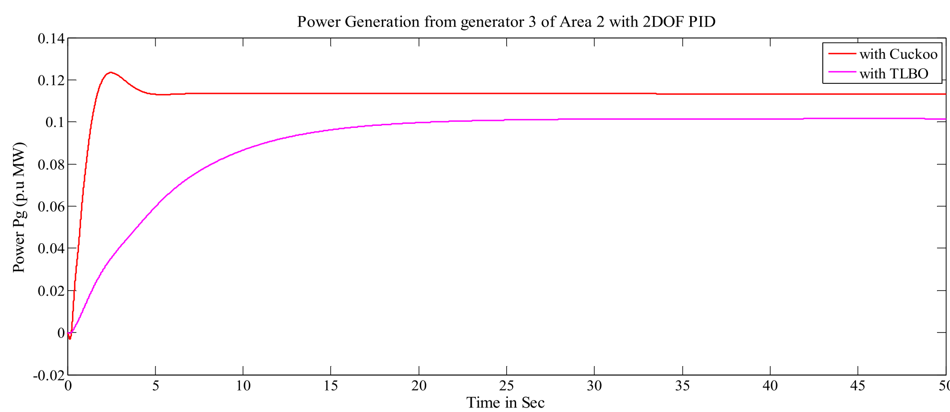


Figure 17. Power change in Genco3 (ΔP_{g3}) for bilateral case.

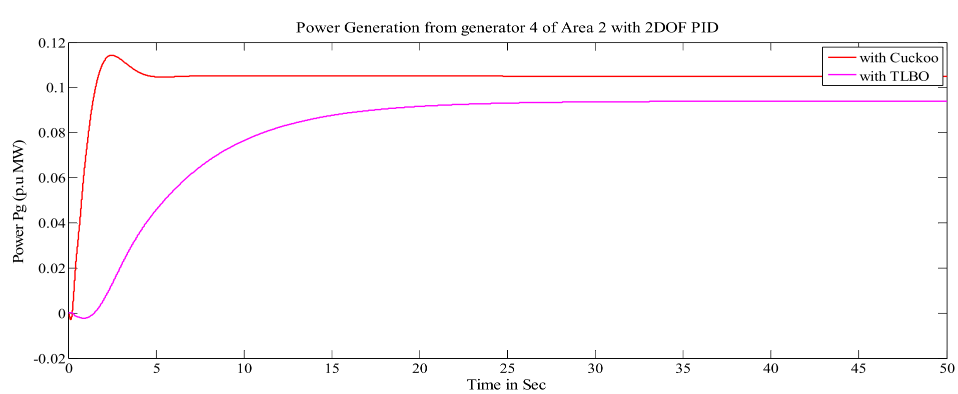


Figure 18. Power change in Genco4 (ΔP_{g4}) for bilateral case.

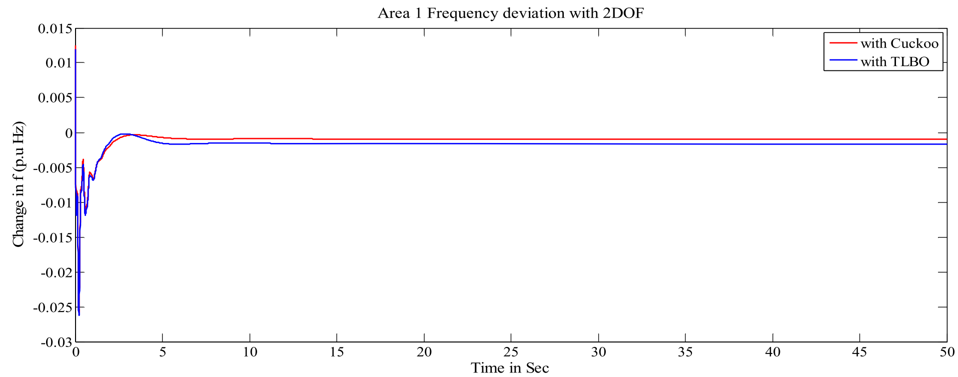


Figure 19. ΔF_1 in area 1 for contract violation.

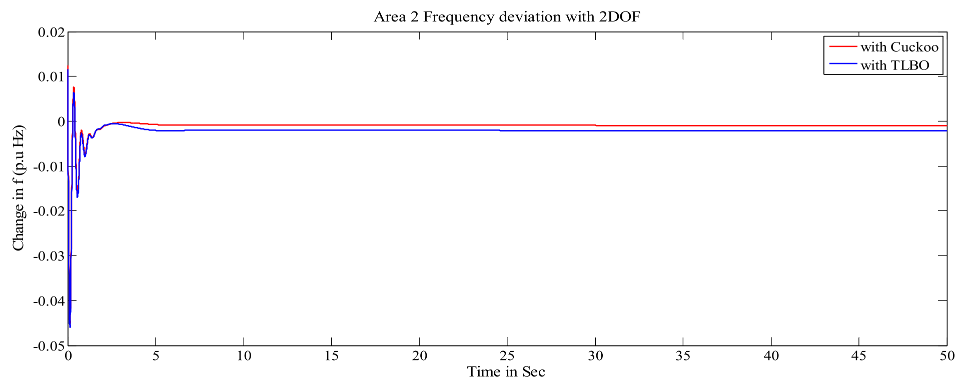


Figure 20. ΔF_2 in area 2 for contract violation.

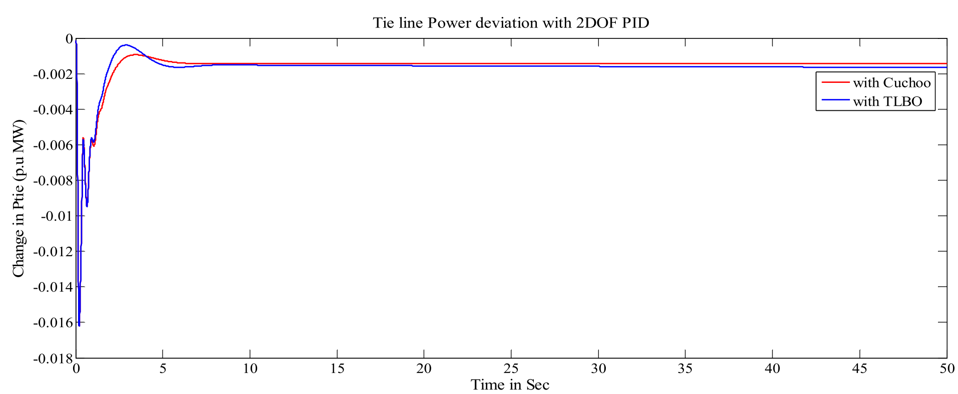


Figure 21. ΔP_{tie} for contract violation.

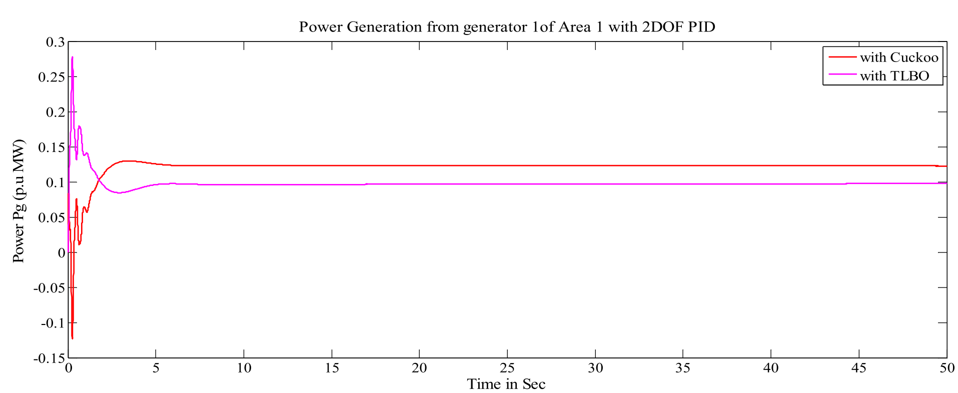


Figure 22. Genco1 power change (ΔP_{g1}) for contract violation.

possible to meet the steady-state point as compared with the TLBO performance.

5.3. Contract violation case

In this transaction, the DISCOs load having surplus power against the agreement then it would have violated the contract ethics. Therefore, the supplementary load power is joined to the same regional area of DISCOs. It is assumed that the DISCO1 supplementary load power is 0.10 p.u MW. The surplus power has deliberated on the same area of DISCOs.

Hence, the total load demand for area1:

$$\begin{aligned}\Delta P_{d1} &= \text{DISCO1 agreement load} + \text{DISCO2 agreement load} \\ &\quad + \text{Disagreement power} \\ &= 0.10 + 0.10 + 0.10 \\ &= 0.30 \text{ p.u MW}\end{aligned}$$

And, the area2 of the power is the same as in bilateral transactions that is 0.2 p.u MW, as well as the DPM matrix, is also similar as mentioned before.

Figures 19–21 represent the dynamic response of frequency and inter-area line power deviations in areas 1 and 2 under violated load demand. The dynamic response of area1 (ΔF_1), area2 (ΔF_2), and tie-line power (ΔP_{tie}) settling times are 4.1, 3.5, and 5.5 s for cuckoo optimised 2-DOF-PID, whereas 5.3, 5, and 7.6 s for TLBO tuned the 2-DOF-PID. It should be noted that the

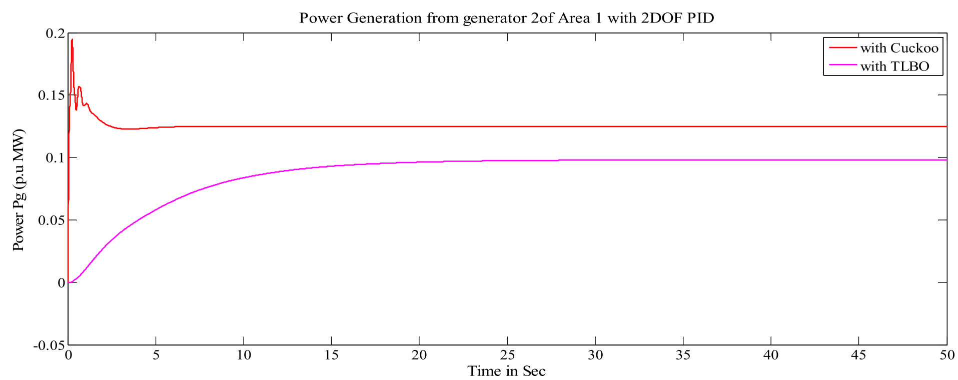


Figure 23. Genco2 power change (ΔP_{g2}) for contract violation.

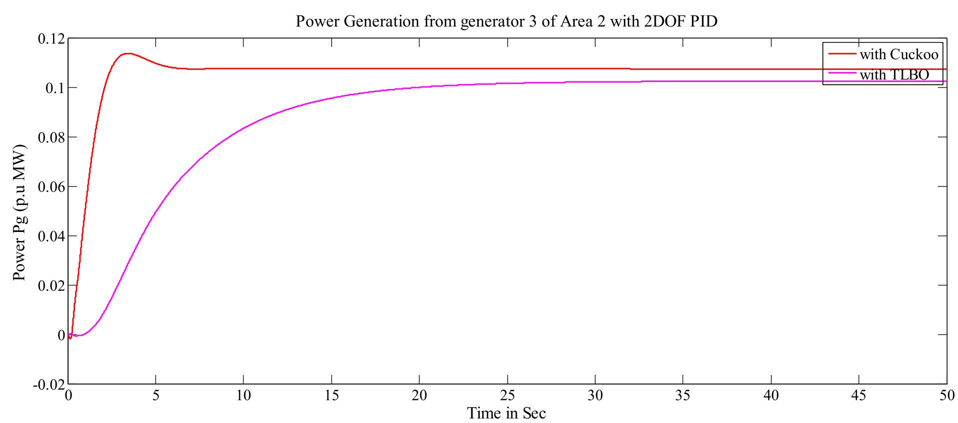


Figure 24. Genco3 power change (ΔP_{g3}) for contract violation.

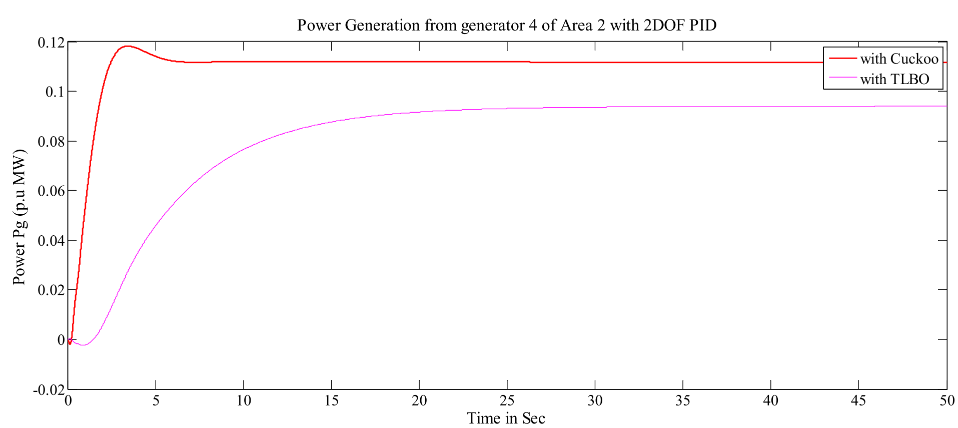


Figure 25. Genco4 power change (ΔP_{g4}) for contract violation.

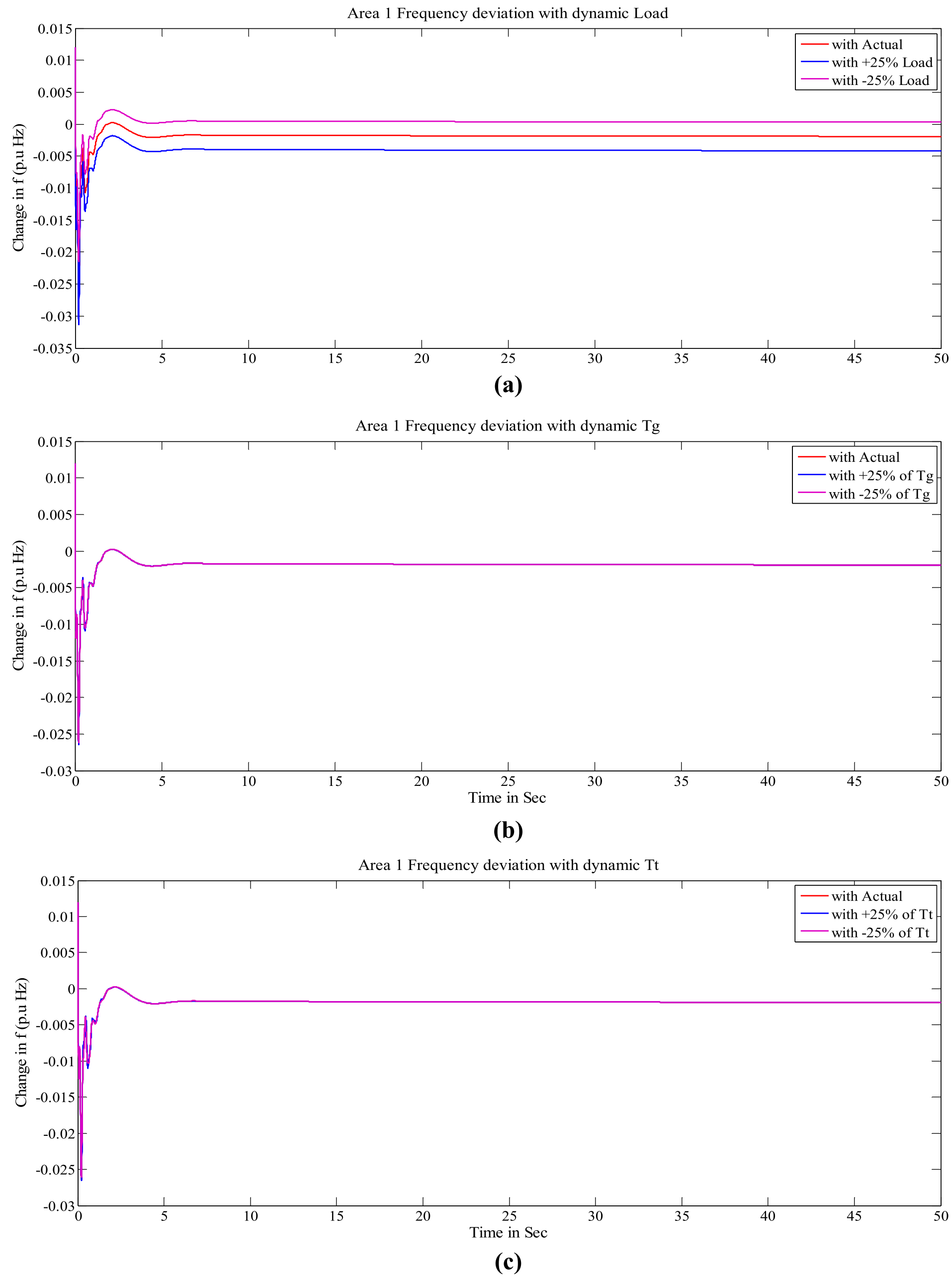


Figure 26. The report of frequency responses of area1(ΔF_1) based on suggested cuckoo 2-DOF-PID controller while deviating the system specifications and loading circumstances up to $\pm$25%: (a) changes in load (b) changes in T_g (c) deviation in T_t (d) changes in R (e) change in B.

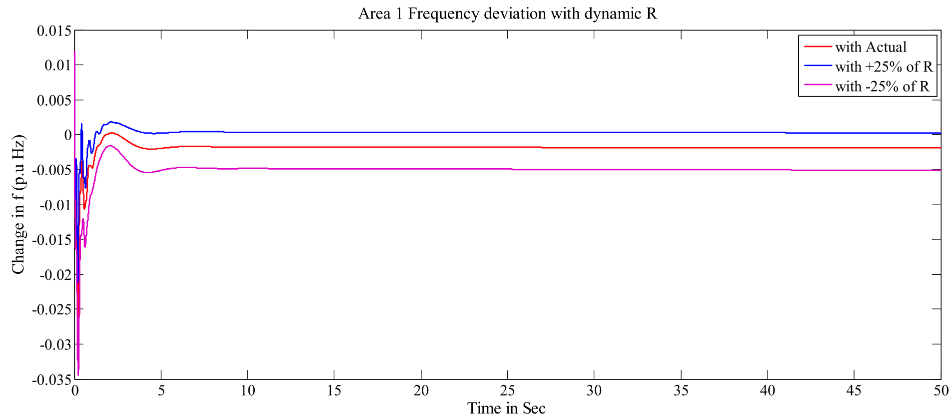
suppression rate of settling times are 22.64%, 30%, and 27.63% as compared to the performance of TLBO tuned 2-DOF-PID. The simulation outcomes revealed that the cuckoo optimised 2DOF-PID controller is greater productivity to mitigate the changes in frequency and tie-line power between interconnected areas at perturbations.

In this regard, the momentous subject is the power generation profile of GENCOs and it is demonstrated in Figures 22–25. Nevertheless, DISCO1 power generation is dissimilar to the previous case as a result of excessive power remained in area1. As considered to (10), the power generations are in area1 is $\Delta P_{g1} = 0.135$ p.u MW and $\Delta P_{g2} = 0.125$ p.u MW besides the area2 power generations is identical to bilateral transactions such as $\Delta P_{g3} = 0.117$ p.u MW, $\Delta P_{g4} = 0.123$ p.u MW.

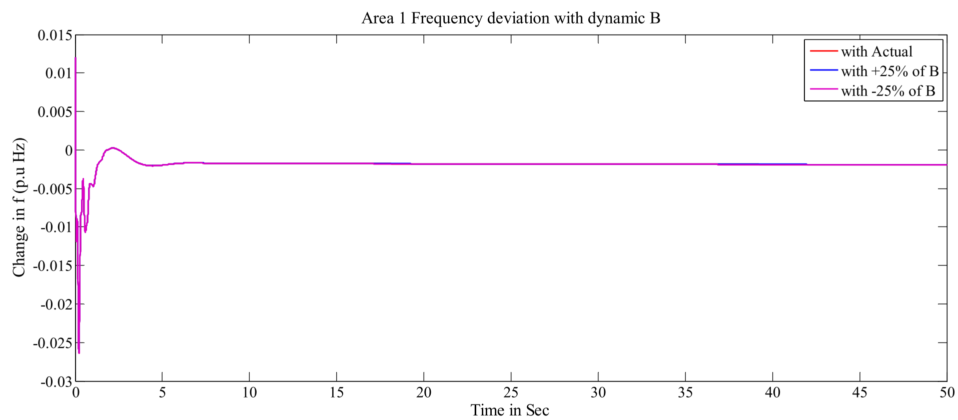
As per the simulation outcomes, the DISCO1 is met by only GENCO1 and GENCO2 due to violated load demand as well as the GENCO3 and GENCO4 are not influenced by the violated load power. The gain specifications and performance of the controller with optimisation approaches are indicated in Tables 3 and 4, respectively.

6. System robustness

Sensitivity analysis is implemented to analyse and observe the system's robustness while changing the loading situations and system specifications up to $\pm$25% from their scheduled values. In this regard, the time constant of the governor (T_G), speed regulation (R), the time constant of the turbine (T_t), frequency bias (B),



(d)



(e)

Figure 26. (Continued).

and loading circumstances are changed in the range of +25% to −25% from their prescribed limits. The analysis of the system robustness has been ascertained under pool-co transaction due to produce the finest performance as compared to other transactions. Besides, different kinds of system performances namely, settling time, peak overshoot, undershoot and integral square error (ISE) criterion are indicated in Table 5. In the light of Table 5, the suggested cuckoo optimised 2-DOF-PID worked as a robust method and does not require to bring back their parameters when the changes occur in the system parameters or loading conditions. Figure 26(a–e) illustrates the frequency deviation in area1 under pool-co-based transaction while varying the T_G, R, B, T_t, and load up to ±25% from their predetermined values. The simulation outcomes are indicated that the impact of changes in loading and system specifications on the system performance is insignificant.

Table 5. Damping characteristics of cuckoo optimised 2-DOF-PID controller at pool-co transaction.

		Cuckoo-2DOF-PID				
Parametric uncertainty	% change	Signal ΔF_1	Settling time (ST)	Undershoot (US)	Overshoot (OS)	ISE
Normal load	+25	ΔF_1	3.5	−0.032	0.005	1.441
	−25	ΔF_1	3.8	−0.028	0.013	1.734
T_g	+25	ΔF_1	4.5	−0.023	0.012	1.010
	−25	ΔF_1	4.8	−0.027	0.015	1.392
T_t	+25	ΔF_1	6.4	−0.017	0.0149	1.124
	−25	ΔF_1	6.5	−0.025	0.0151	1.345
R	+25	ΔF_1	4.5	−0.023	0.0045	0.900
	−25	ΔF_1	5.2	−0.031	0.0121	3.482
B	+25	ΔF_1	4.20	−0.028	0.0152	0.585
	−25	ΔF_1	4.18	−0.029	0.0149	0.729

7. Conclusion

In this study, two area four-unit AGC systems are examined with the various control strategies for alleviating the deviations in frequency and tie-line power under a restructured scenario. TLBO and cuckoo search algorithms are employed for tuning gain values of PI/PID/2DOF-PID. The simulation outcomes disclose that the cuckoo optimised 2DOF-PID has enriched the dynamic performance of the system in terms of settling time, undershoot, and overshoot at three transactions over TLBO acquired performances. Also, the system robustness is concealed by varying the system specifications such as T_G, T_t, R, B, and loading circumstances up to ±25% from their prescribed values. Finally, the cuckoo search optimised 2DOF-PID approach is rather productive to stabilise the changes in frequency and tie-line power in a liberalised power system.

Disclosure statement

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Appendix

System Specifications	$f = 60$ Hz, Power rating $= 1200$MW, Base power $= 1200$MW.
Thermal and hydro plant parameters	$T_{H1} = T_{G1} = T_{H2} = T_{G2} = 0.08$ s, $T_{t1} = T_{t2} = 0.3$ s, $K_{P1} = K_{P2} = 120$ Hz/p.u, $T_{P1} = T_{P2} = 20$ s, $R_1 = R_2 = R_3 = R_4 = 2.4$ Hz/p.u, $B_1 = B_2 = 0.425$ p.u MW/Hz, $T_{R1} = T_{R2} = 0.513$ s, $T_1 = T_2 = T_3 = T_4 = 10$ s, $K_1 = -0.3$, $K_2 = -0.2622$, $2\Pi T_{12} = 0.545$ p.u MW/Hz$a_{12} = a_{21} = -1$, $T_{W1} = T_{W2} = 1$ s.
Liberalisation power system details	Area control error (ACE) participation attributes:$apf_1 = apf_2 = 0.5 = apf_3 = apf_4 \Delta P_{DISCO1} = \Delta P_{DISCO2} = 0.1$p.u $= \Delta P_{DISCO3} = \Delta P_{DISCO4}$.