DESIGN OF LUS-TLBO BASED PD-FUZZY-PID CASCADED CONTROLLER FOR AGC OF A THREE AREA POWER SYSTEM

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Abstract: This paper presents a hybrid Local Unimodal Sampling (LUS)-Teaching Learning Based Optimization (TLBO) optimized Proportional-Derivative-fuzzy-Proportional-Integral-Derivative (PD-FPID) cascaded controller to study the load frequency control (LFC) issue in a three area interconnected thermal power system considering generation rate constraint (GRC). Initially hybrid LUS-TLBO optimized conventional PD-PID cascaded controller is used and the result acquired is matched with that of Bat Algorithm optimized conventional PD-PID cascaded controller. It is proved that the proposed LUS-TLBO based PD-PID cascaded controller is revealing better dynamic performance in all aspects i.e. in terms of settling time, undershoot and overshoot. Then the study is extended to inspect dynamic behaviour of the same power system employing a novel PD-FPID cascaded controller optimized by the proposed hybrid LUS-TLBO algorithm. It is again proved that the proposed LUS-TLBO optimized PD-FPID cascaded controller is performing better as compared to LUS-TLBO based conventional PD-PID cascaded controller. A step load disturbance of 1% is applied in area1 and integral time absolute error (ITAE) is chosen as objection function in designing the proposed controller. Again sensitivity analysis of the proposed PD-FPID cascaded controller is conducted by varying the system parameters and it is seen that the proposed cascaded controller is less sensitive to parametric variations, and therefore there is no need to reset the controller parameters for wide deviation in system parameters.

Keywords: Automatic Generation Control (AGC), Load Frequency Control (LFC), Fuzzy Logic Controller (FLC), Local Unimodal Sampling (LUS), Teaching Learning Based Optimization (TLBO).

1. Introduction:

Stability and reliability of power systems significantly depends upon the deviation of frequency from its nominal value. Severity of this problem is more prominent in interconnected power system. Maintaining the frequency at its nominal value under adverse situation has been a challenging task for researchers/design engineers. Frequency deviation and exchange of tie-line power are two major issues in LFC problem. The main function of LFC is to maintain nominal frequency and to keep tie-line power exchanges as per schedule by taking into account the power generation at maximum economic level [1].

LFC issue in interconnected power system was first introduced by Elgard and Fosha [2]. LFC in single area with multi-source generation is proposed by Singh et al. [3]. In [4] for a single isolated hydro-generator system the transient speed response is discussed. Kam and Kocaarslan [5] have stated the use of fuzzy implementation for gain scheduling of conventional PI controllers. In [6] a robust PID controller is employed for LFC of a two area hydro power system. Sahu et al. [7] have proposed a DE optimized two degrees freedom PID controller for LFC of a two area thermal system taking governor deadband nonlinearity in to account. Farahani et al. [8] have employed lozi map-based chaotic algorithm (LCOA) based PID controller for LFC of a two area thermal system. S. R. Khuntia & S. Panda [9] have implemented an artificial neural network fuzzy interface system (ANFIS) based controller for LFC of a three unequal area hydrothermal interconnected system in order to obtain a suitable dynamic response. In [10], controller designed through polar fuzzy logic (PFC) is employed to reduce the computational burden and memory requirements. The projected controller is employed to study the transient study of a three area power systems and evidenced to be superior as compared to PI controller. Further they extended their work by making the PFC adaptive using genetic algorithm optimization technique and finally claimed the superiority of the adaptive PFC-GAF. Panda et al. [11] have reported the application of hybrid bacteria foraging optimization algorithm and particle swarm optimization (hBFOA–PSO) technique based PI controller for LFC of a two area interconnected thermal power system. Then they extended the use of the above PI controller to study the dynamic performance of LFC for a three area interconnected hydrothermal system. Genetic algorithm (GA) and PSO based fuzzy logic controller for a three area thermal-hydro interconnected power system are proposed by Sinha et al. [12]. A novel fuzzy PI controller based on tabu search algorithm for LFC of interconnected power system is presented in [13]. To reduce and stabilize the frequency oscillation in a two area interconnected thermal power system, fuzzy logic based superconducting magnetic energy storage (SMES) units are used by Hemeida [14]. A fast acting adaptive LFC based on GA-fuzzy approach for interconnected multi-thermal power system is proposed by Ghoshal in [15]. For LFC in restructured power system, a multi-stage fuzzy-PID controller is implemented by Shayeghi et al. [16]. C. S. Indulkar & B. Raj [17] acclaimed fuzzy controller based for AGC study in a two area power system and the result found is compared with that of integral controller. Chang & Fu [18] introduced a PI controller based on fuzzy gain scheduling for LFC of a four area power system considering GRC and control deadbands.

In this article a PD-FPID cascaded controller is designed to enhance the dynamic performance of a three area power system. In most of the research works design of fuzzy-PID controller is based on manual tuning of the controllers' gains using several trial and error runs. This is a time taking process and also it is not guaranteed that the designed controller is optimum. Therefore in this article a hybrid LUS-TLBO algorithm is used to optimally design the proposed PD-FPID cascaded controller. LUS-TLBO algorithm is hybridization of local a local (i.e. LUS) and a global (i.e. TLBO) algorithm.

Local search algorithms are simple, robust and gradient free but may fail measurably in searching the optimum solution over a wide area. Global search techniques are very useful over wide search space but may yield optimal/near optimal solution. In order to take the advantages of both local and global search algorithms, in this paper a maiden attempt has been made to hybridize LUS [19-20] and TLBO algorithm [21-22] to optimally design PD-FPID cascaded and conventional PD-PID cascaded controllers for LFC of a three area interconnected power system. The results obtained are compared with that a Bat algorithm PD-PID cascaded controller for the same power system [23] and found to be dynamically performing better in terms of less undershoot, overshoot, settling time and number of oscillations of system frequency and tie-line power deviations. The remaining sections of the paper are arranged as follows. Section2 describes the three area thermal power system. The overviews of the proposed controllers and hybrid optimization technique are presented in sections3 & 4 respectively. A simulation result is discussed in section5. Finally section6 concludes the article.

2.   System under study:

In this study LFC of a three area reheat type thermal power system with GRC of 3% is considered. Area1, area2 and area3 having generating capacity of 2000 MW, 6000 MW and 12000 MW respectively are taken in the transfer function model as shown in the Figure 1. Each area is equipped with a PD-FPID cascaded controller and a sudden step load change of 1% is applied in area1 to study the behaviour of the overall system. The proposed controller is designed by taking integral time absolute error (ITAE) as objective function and it is minimized using hybrid LUS-TLBO algorithm to find optimum gains of the proposed controllers. Inputs to the projected PD-FPID controller are area control errors (ACEs) of the respective areas. The proposed hybrid LUS-TLBO optimisation technique is employed to optimally tune the controller gains to reduce the ACEs to zero. Expressions of ACEs for different control areas are given by

$$ACE_1 = B\Delta f_1 + \Delta P_{tie,13} \tag{1}$$

$$ACE_2 = B\Delta f_2 + \Delta P_{tie,12} \tag{2}$$

$$ACE_3 = B\Delta f_3 + \Delta P_{tie,23} \tag{3}$$

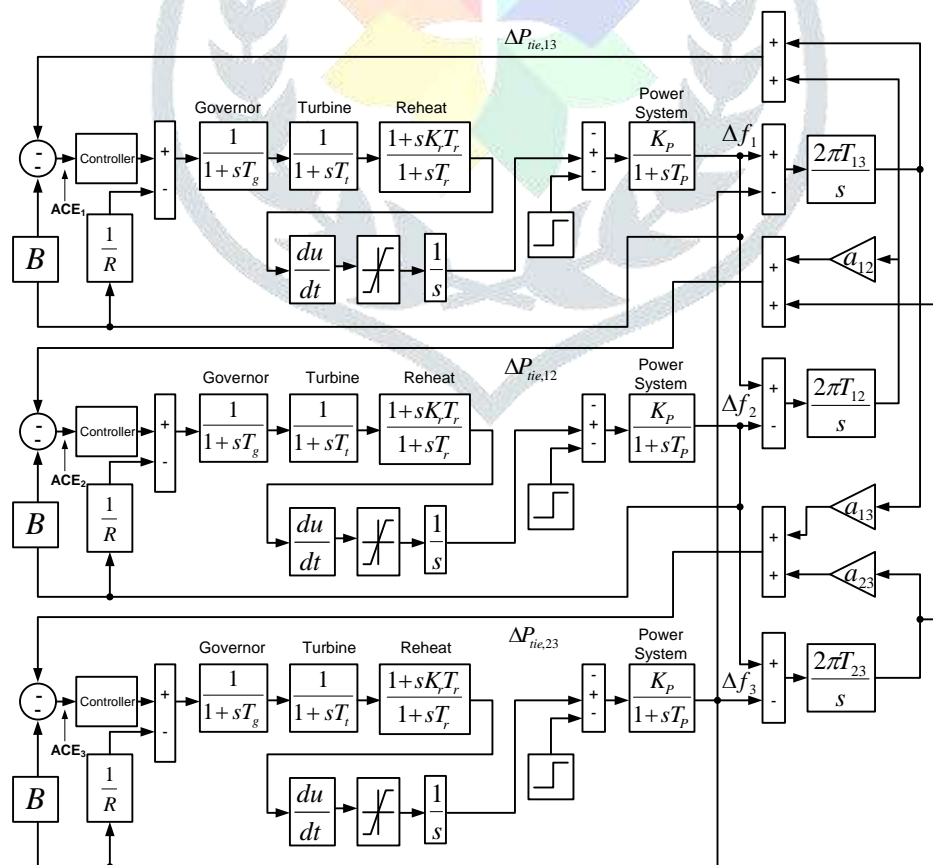Various parameters of the three area power system are depicted in Table1.

FIGURE 1: Transfer function model of three area thermal power system [23].

**TABLE 1:** Parameters of the three area power system [23].

Parameters	Nominal values	Parameters	Nominal values
Governor time constant (T_g)	0.08 sec	Unit-1 rating (P_{r1})	2000 MW
Turbine time constant (T_t)	0.3 sec	Unit-1 rating (P_{r2})	6000 MW
Reheat time constant (T_r)	10 sec	Unit-1 rating (P_{r3})	12,000 MW
Power system time constant (T_P)	20 sec	$a_{12} = -P_{r1}/P_{r2}$	-1/3
Reheat gain (K_r)	0.5	$a_{23} = -P_{r2}/P_{r3}$	-1/2
Power system gain (K_P)	120 Hz/pu	$a_{13} = -P_{r1}/P_{r3}$	-1/6
Synchronizing coefficients (T_{12}, T_{13} and T_{23})	0.086 pu	Frequency bias constant (B)	0.425
Governor speed regulation (R)	2.4		

3.   PD-Fuzzy-PID cascaded controller structure:

A PD-FPID cascaded controlled process is shown in Figure 2. It consists of an outer loop also called master loop and an inner loop also called slave loop. The master loop decreases the severity of disturbance before it propagates into the slave loop which in turns stabilizes the process output more effectively and efficiently.

Input to the outer loop (PD controller) is ACE and its output $u_1(t)$ is compared with the frequency deviation Δf and the error signal $e_2(t)$ is fed to the inner loop (fuzzy-PID controller). Advantages of cascaded controller over single loop controller are

i.   The overall system's speed increases significantly if the response of the inner loop is faster than that of the outer loop.
ii.   If any disturbance occurs in the inner control loop, it is rectified immediately by the control action of inner loop itself there by not allowing it to propagate to the outer control loop.
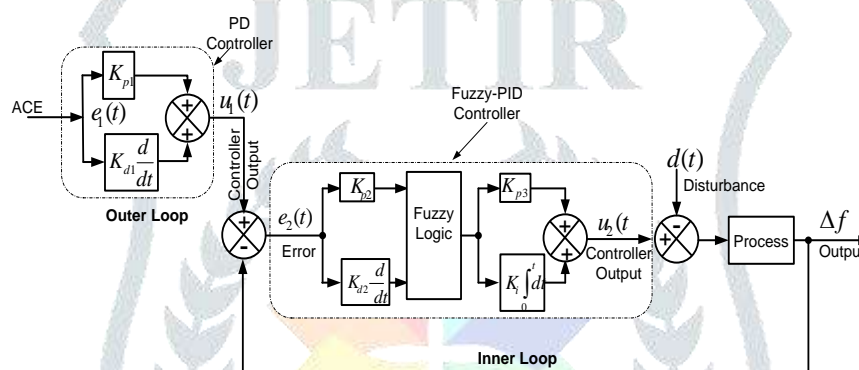
Figure 2: Structure of PD-FPID cascaded controller.

It is certified by numerous investigators that fuzzy logic controller (FLC) can securely handle various changes in operating point by online updating the controller parameters [24, 25]. In this paper a fuzzy-PID controller is chosen in the inner control loop in the structure as shown in the Figure 2 and the effectiveness of it is proved by comparing the result with that of conventional PID controller (in the inner loop) employed in a recently published article [23].

The fuzzy-PID controller shown in Figure 2 is a combination of fuzzy-PD and fuzzy-PI controller. The input to the fuzzy-PID controller is the error signal which is the output of the inner control loop. Any fuzzy logic system involves the following steps

i.   Fuzzyfication: - It is the process of conversion of crisp input to a linguistic variable with the help of membership functions. In this study five membership functions namely negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB) are considered. Structure of the membership function is shown in Figure 3.
ii.   Interface engine: - It converts the fuzzy input to fuzzy output using if-then type fuzzy rules. Since there are five membership functions for each input, 25 sets of fuzzy rules are required to get the fuzzy output. Rule base used in the proposed work is depicted in Table 2.
iii.   Defuzzification: - It is the process of conversion of fuzzy output into crisp. There are many defuzzification processes. In this paper the most common used centre of gravity defuzzification technique is used to obtain the crisp output.
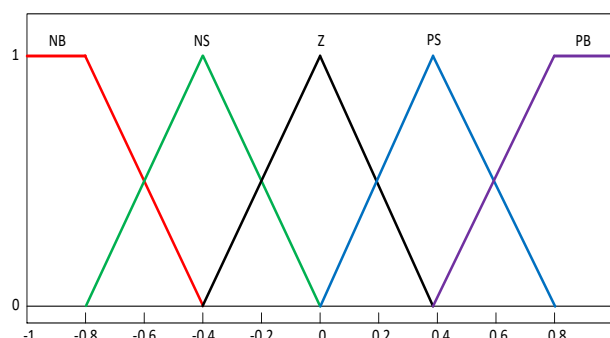
FIGURE 3: Structure of membership functions for input and output variables.

The proposed cascaded controller shown in Figure 2 has six gains, two in the outer control loop and the remaining four in the inner control loop. Each area of the interconnected power system shown in Figure 1 is equipped with a PD-FPID cascaded controller. So in total there are eighteen controller gains for the three cascaded controller. Performance of any controller depends on the suitable selection of these gains. In this article optimum PD-FPID cascaded controller gains are designed using hybrid LUS-TLBO algorithm.

TABLE 2: Rule base for the fuzzy logic controller.

ACE	$\dot{ACE}$				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

4. Application of hybrid LUS-TLBO algorithm to design optimum PD-FPID cascaded controller

As stated earlier LUS-TLBO algorithm is hybridization of a local (LUS) and a global (TLBO) optimization technique. Generally local search techniques are simple and gradient free but may not converge to local minima for a wider search space. Whereas global search techniques may fail to converge and yield optimum solution for problems having small number of fitness evaluation and less dimension or large number of fitness evaluation and huge dimension [19]. By taking the advantages of both local and global search techniques, in this paper LUS and TLBO optimization techniques are hybridized to optimally design the gains of PD-FPID cascaded controller for LFC of the three area thermal power system. Various steps involved in this hybridization technique are

i. Randomly generate the initial population $'x_i'$ within the search space and calculates its fitness.

LUS algorithm begins here.

ii. Randomly generate another vector $'a'$ within the sampling range $'d'$ and add it with the initial population $'x_i'$. Where, $d = x_{up} - x_{low}$. $'x_{up}'$ and $'x_{low}'$ are the upper and lower limit of the design variable respectively.

iii. Compute the fitness of newly generated population $'x_{i,new}'$ Compare the fitness and accept the better performing solution i.e. Accept $'x_{new}'$ if it does better otherwise accept $'x_i'$ and reduce the sampling range $'d'$.

End of LUS algorithm.
TLBO algorithm starts here.

iv. Select $'x_{new}'$ as initial population of TLBO algorithm.

v. Estimate $'m_{dif}'$ as the difference between the mean results and add it with $'x_{new}'$ to get the updated solution $'x_{new1}'$.

vi. Evaluate the performance of $'x_{new1}'$.

vii. Accept $'x_{new1}'$ if it performs better. Otherwise accept $'x_{new}'$.

viii. Permit the learners to interact and generate the new solution $'x_{new2}'$ out of the interaction.

ix. Select the final solution either from $'x_{new1}'$ or $'x_{new2}'$ depending on their performances.

End of TLBO algorithm.

x. Repeat steps $'ii - ix'$ until the ending conditions are met.

Flow chart of the hybrid LUS-TLBO algorithm is shown in Figure 4.

In this study the PD-FPID and PD-PID cascaded controllers are designed by choosing ITAE as objective function and minimizing it through hybrid LUS-TLBO algorithm. TLBO algorithm is parameter free and therefore the only controlling factor in this proposed hybrid algorithm is decreasing factor of LUS algorithm and its value is taken as 3 in this study. Number of population and maximum iteration number both are as taken as 100. The three area power system model is run for 50 times and the best gains out of 50 runs are presented in this work. Gains of the controllers are given in Table 3.
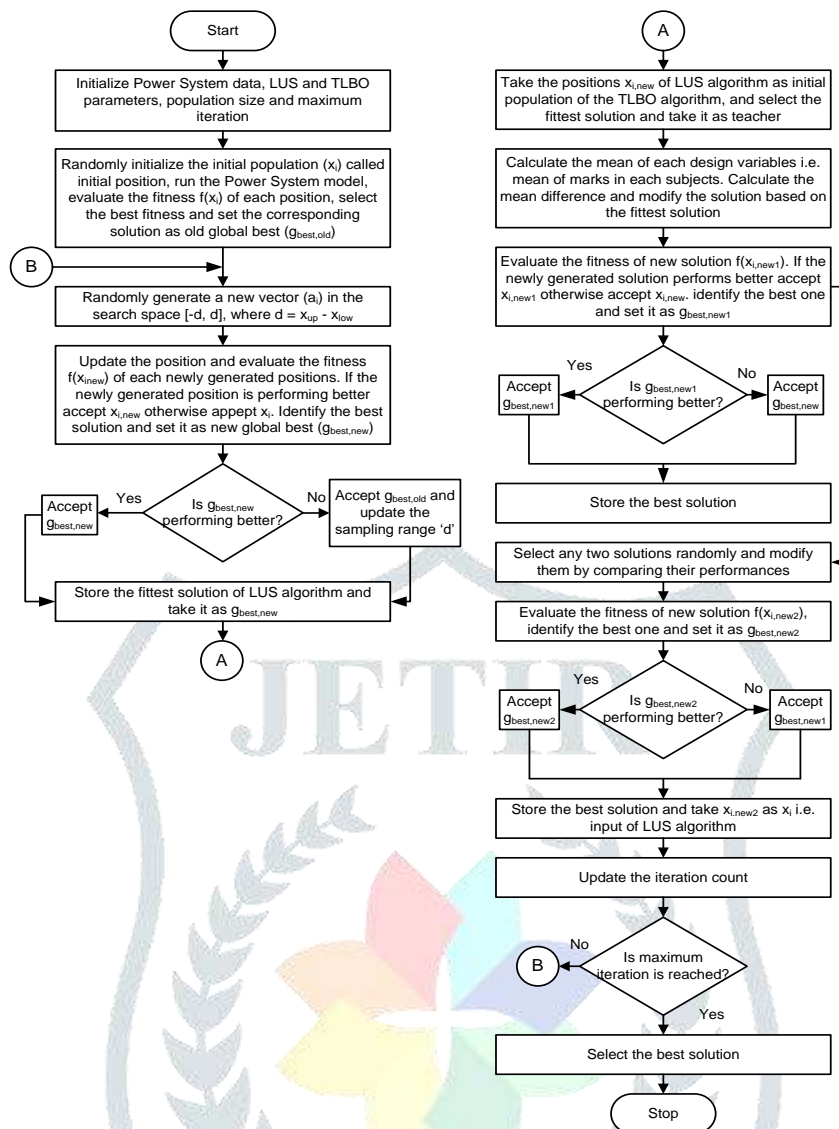
FIGURE 4: Flow chart of the hybrid LUS-TLBO algorithm.

TABLE 3: Hybrid LUS-TLBO optimized controller gains.

PD-FPID Cascaded			PD-PID Cascaded		
Control area	Controller gains		Control area	Controller gains	
Area1	K_{p1}	**1.9530**	Area1	K_{p1}	1.2478
	K_{d1}	**0.0100**		K_{d1}	0.0101
	K_{p2}	**1.5153**		K_{p2}	0.6647
	K_{d2}	**0.5132**		K_{i}	1.9988
	K_{p3}	**1.5743**		K_{d2}	0.2389
	K_{i}	**1.1416**			
Area2	K_{p1}	**0.4946**	Area2	K_{p1}	0.7358
	K_{d1}	**1.7563**		K_{d1}	0.9403
	K_{p2}	**1.1733**		K_{p2}	0.0103
	K_{d2}	**0.2653**		K_{i}	0.8038
	K_{p3}	**1.0666**		K_{d2}	0.6353
	K_{i}	**1.2732**			
Area3	K_{p1}	**0.4705**	Area3	K_{p1}	0.7359

K_{d1}	**1.0761**		
K_{p2}	**1.4071**	K_{d1}	1.3081
K_{d2}	**0.0824**	K_{p2}	0.4440
K_{p3}	**1.3726**	K_i	0.7588
K_i	**0.3128**	K_{d2}	1.4167

5. Simulation result and discussion

5.1 Dynamic response analysis

Dynamic behaviour of the three area thermal power system is examined by applying 1% step load change in area1. Frequency deviation in area1 $\left(\Delta f_1\right)$, area2 $\left(\Delta f_2\right)$ & area3 $\left(\Delta f_3\right)$ and tie-line power deviations $\Delta P_{tie,13}$, $\Delta P_{tie,12}$ & $\Delta P_{tie,23}$ are shown in Figures 5-10 respectively. Undershoot/overshoot $\left(U_{sh}/O_{sh}\right)$ and settling time $\left(T_s\right)$ of frequency and tie-line power deviations with LUS-TLBO based PD-FPID and PD-PID cascaded controllers and BAT algorithm optimized PD-PID cascaded controller [23] are depicted in Table 4. It is clear from Table 4 that the deviations in frequency and tie-line power are less with the proposed controller as compared to that of BAT algorithm optimized PD-PID cascaded and PID controller [23]. For better understanding a bar plot is given in Figure 11 for the comparison of deviations in frequency and tie-line power with different controller.

Figures 5-11 and Table 4 reveal that the projected LUS-TLBO based PD-FPID cascaded controller exhibit better dynamic performance as compared to the proposed LUS-TLBO algorithm based PD-PID cascaded controller. It is also seen that the proposed PD-FPID cascaded controller found to be superior to BAT algorithm optimized PD-PID cascaded and conventional PID controller [23]. Percentage improvement in $\left(U_{sh}/O_{sh}\right)$ and settling time $\left(T_s\right)$ of frequency and tie-line power deviation with LUS-TLBO based PD-FPID and PD-PID cascaded controller in comparison with BAT algorithm based PD-PID cascaded controller is shown Table 5 and Figure 12.
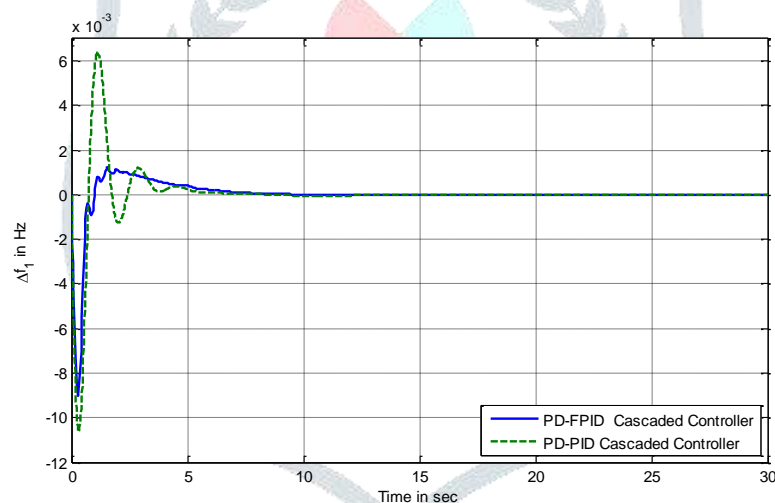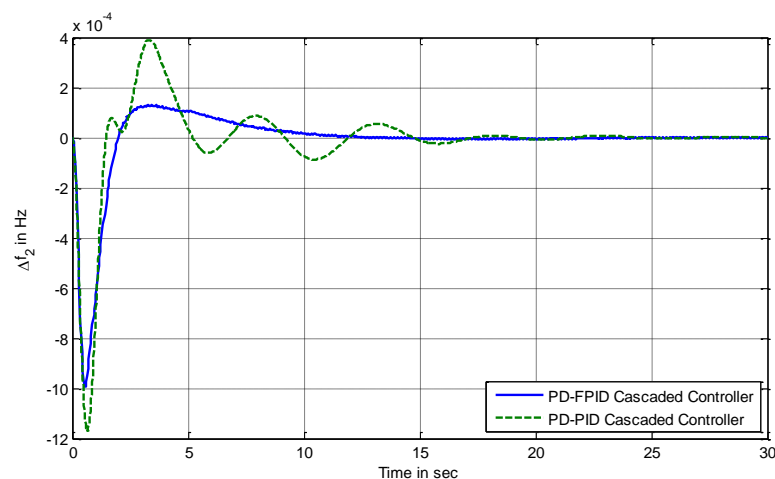

FIGURE 5: Frequency deviation in area1.
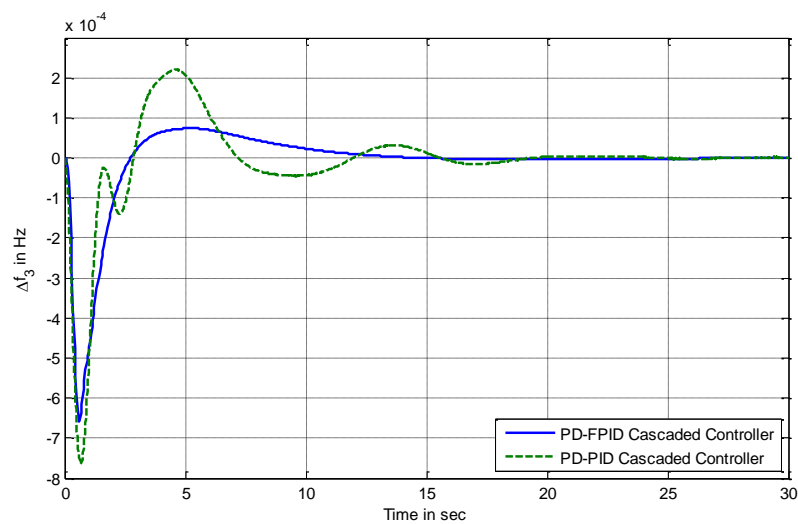

FIGURE 6: Frequency deviation in area2.

FIGURE 7: Frequency deviation in area3.
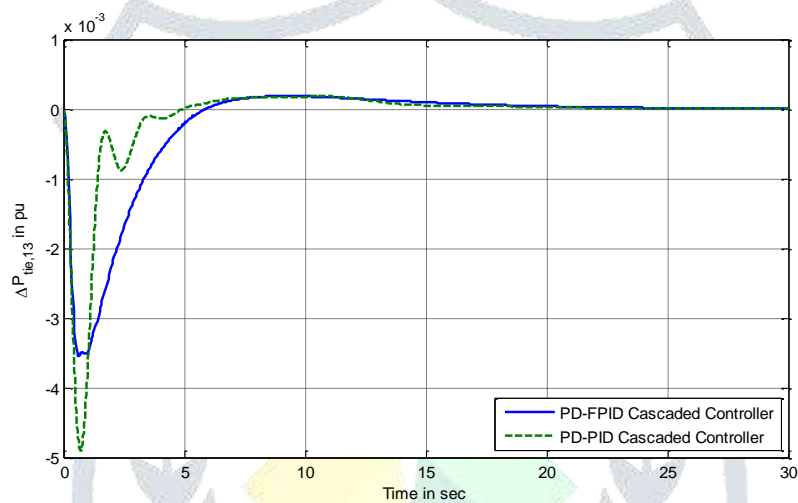

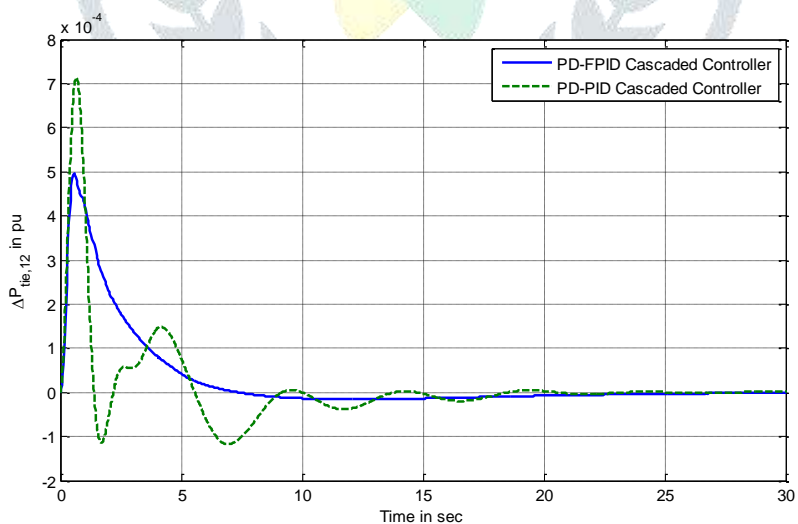**FIGURE 8:** Tie-line power deviation in the line connecting area1 with area3.

FIGURE 9: Tie-line power deviation in the line connecting area1 with area2.
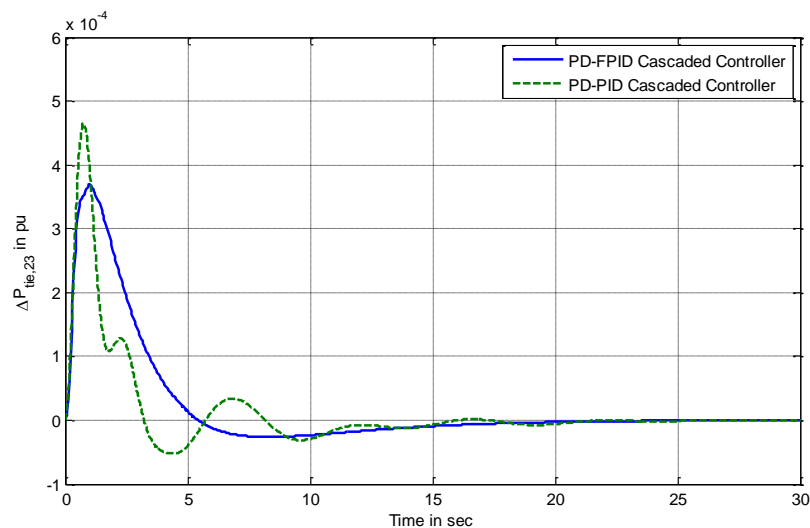
FIGURE 10: Tie-line power deviation in the line connecting area2 with area3.

TABLE 4: (U_{sh}/O_{sh}) and settling time (T_s) of frequency and tie-line power deviations.

		PD-FPID cascaded (TLBO)	PD-PID cascaded (TLBO)	PD-PID cascaded [23] (BAT)	Conventional PID [23] (BAT)
Δf_1	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**9.0045**	10.6351	23.7	26.8
	T_s in sec	6.029	**5.153**	30.02	36.83
Δf_2	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**0.9916**	1.1681	13.28	14.4
	T_s in sec	**1.529**	4.265	28.34	39.71
Δf_3	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**0.6574**	0.7636	--	--
	T_s in sec	**1.671**	5.126	--	--
$\Delta P_{tie,13}$	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**3.5370**	4.9055	8.1	6.9
	T_s in sec	5.017	**3.195**	44.58	68.44
$\Delta P_{tie,12}$	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**0.4974**	0.7148	10.0	-14.4
	T_s in sec	2.245	**1.2**	30.13	39.07
$\Delta P_{tie,23}$	$U_{sh}/O_{sh} \times 10^{-3}$ in Hz	**0.3694**	0.4655	--	--
	T_s in sec	2.442	**1.346**	--	--
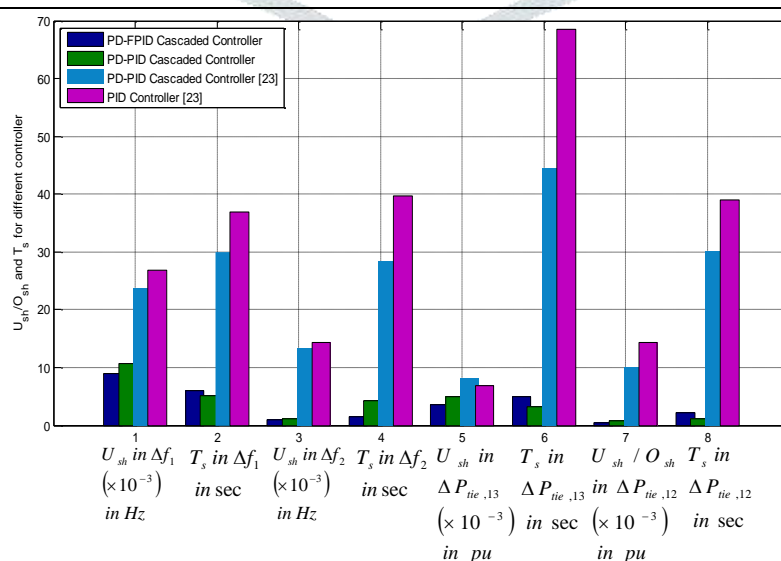
FIGURE 11: Comparison of Undershoot/overshoot (U_{sh}/O_{sh}) and settling time (T_s).

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Table 5: Percentage improvement in U_{sh}/O_{sh} and T_s.

CONTROLLER	Δf_1		Δf_2		ΔP_{tie13}		ΔP_{tie12}	
	U_{sh}	T_s	U_{sh}	T_s	U_{sh}	T_s	U_{sh}/O_{sh}	T_s
LUS-TLBO PD-FPID Cascaded	62.00	79.92	92.53	94.61	56.33	88.75	95.02	92.55
LUS-TLBO PD-PID Cascaded	55.13	82.83	91.20	84.95	39.44	92.83	92.85	96.02

It is clearly understood from Tables 4-5 and Figures 11-12 that the dynamic behaviour of the three-area thermal power system equipped with LUS-TLBO optimized PD-FPID cascaded controller is superior in terms of all the transient response factors like U_{sh}/O_{sh}, T_s and number of oscillation compared to BAT algorithm based PD-PID cascaded controller for the same power system under study [23].

5.2 Robustness analysis

To investigate the effectiveness of the proposed PD-FPID cascaded controller for parametric variation, a sudden step load disturbance of 1 % of rated load is applied in area1 and the system parameters are varied in the range [-50% to 50%] in steps of 25%. The results obtained given in Table 6 assure that the above said controller is robust and therefore the optimum controller gains using LUS-TLBO algorithm need not be retuned when the system is exposed to parametric variations.

TABLE 6: Dynamic response factors with parametric variations.

Parameters	% age deviation	Δf_1		Δf_2		$\Delta P_{tie,13}$		$\Delta P_{tie,12}$	
		U_{sh} (in Hz) (10^{-3})	O_{sh} (in Hz) (10^{-3})	U_{sh} (in Hz) (10^{-3})	O_{sh} (in Hz) (10^{-3})	U_{sh} (in pu) (10^{-3})	O_{sh} (in pu) (10^{-3})	U_{sh} (in pu) (10^{-3})	O_{sh} (in pu) (10^{-3})
T_g	-50%	-8.8362	1.1572	-0.9558	0.1427	-3.9443	0.2172	-0.0191	0.5274
	-25%	-8.9643	1.0968	-0.9611	0.1370	-3.7578	0.2049	-0.0186	0.5030
	+25%	-9.1192	1.5393	-1.0184	0.1197	-3.5505	0.1660	-0.0145	0.4992
	+50%	-9.2140	1.8518	-1.0516	0.1167	-3.5508	0.2226	-0.0277	0.5028
T_t	-50%	-8.8656	1.2658	-0.9502	0.1760	-4.3119	0.2461	-0.0329	0.5614
	-25%	-8.9577	1.1379	-0.9577	0.1549	-3.9019	0.2203	-0.0120	0.5114
	+25%	-9.1234	1.2283	-1.0325	0.1273	-3.5464	0.1731	-0.0209	0.5008
	+50%	-9.1910	1.3643	-1.0615	0.1300	-3.5670	0.1603	-0.0233	0.5042
K_r	-50%	-9.3964	1.2226	-1.1335	0.2266	-3.7496	0.3814	-0.0629	0.5268
	-25%	-9.1699	1.1653	-1.0483	0.1593	-3.6241	0.2750	-0.0371	0.5060
	+25%	-8.9554	1.0625	-0.9629	0.1235	-3.6593	0.1268	-0.0145	0.4965
	+50%	-8.9495	1.0500	-0.9412	0.1026	-3.6381	0.0771	-0.0211	0.4925
T_r	-50%	-9.0131	1.3342	-0.9933	0.1507	-3.5224	0.1391	-0.0101	0.4961
	-25%	-9.0074	1.1784	-0.9918	0.1420	-3.5308	0.1775	-0.0154	0.4968
	+25%	-9.0027	1.1760	-0.9913	0.1234	-3.5427	0.1829	-0.0156	0.4977
	+50%	-9.0034	1.1584	-0.9913	0.1174	-3.5460	0.1769	-0.0146	0.4980
K_p	-50%	-4.9414	0.6609	-0.5389	0.0742	-2.1582	0.1357	-0.0213	0.2991
	-25%	-7.0398	0.9234	-0.7821	0.1019	-2.9014	0.1619	-0.0181	0.4030
	+25%	-11.0882	1.4335	-1.2116	0.1660	-4.2943	0.2120	-0.0123	0.5940
	+50%	-12.9491	1.5471	-1.3834	0.1865	-4.8359	0.2420	-0.0139	0.6749
T_p	-50%	-16.8353	1.8945	-1.7179	0.2158	-5.8852	0.2647	-0.0122	0.8418
	-25%	-11.6649	1.4982	-1.2619	0.1532	-4.3408	0.2201	-0.0507	0.6148
	+25%	-7.4415	0.9819	-0.8233	0.1090	-3.0104	0.1629	-0.0171	0.4214
	+50%	-6.3893	0.8586	-0.7091	0.0955	-2.6731	0.1491	-0.0184	0.3725
B	-50%	-9.0188	1.2945	-1.3686	0.1454	-3.4204	0.2922	-0.0437	0.4418
	-25%	-9.0135	1.2453	-1.1530	0.1317	-3.4868	0.1898	-0.0200	0.4733
	+25%	-9.0260	1.0347	-0.8763	0.1293	-3.7394	0.1975	-0.0198	0.5173
	+50%	-9.1417	1.0454	-0.7953	0.1245	-3.8789	0.2001	-0.0163	0.5412
R	-50%	-9.0128	1.2924	-0.9716	0.1223	-3.5328	0.1936	-0.0131	0.4974
	-25%	-9.0036	1.1148	-0.9848	0.1260	-3.5319	0.1890	-0.0159	0.4969
	+25%	-9.0054	1.2448	-0.9974	0.1345	-3.5422	0.1822	-0.0184	0.4976
	+50%	-9.0061	1.1134	-1.0014	0.1373	-3.5450	0.1818	-0.0154	0.4978

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Similar findings are also observed with various step load patterns as shown in Figure 13 considering nominal system parameters. Frequency deviation in area (Δf_1) and tie-line power deviation through the line interconnecting area1 with area3 $(\Delta P_{tie,13})$ are shown in Figure 14 and Figure 15 respectively. Critical observation of both figures reveal that the variation of Δf_1 and $\Delta P_{tie,13}$ lie within tolerance band. Similar observations can also be made for other responses.
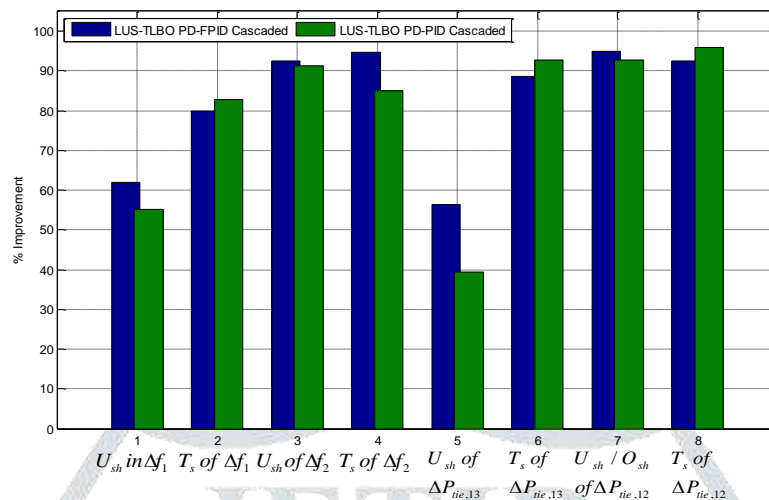
FIGURE 12: Percentage improvement in undershoot/overshoot $\left(U_{sh}/O_{sh}\right)$ and settling time $\left(T_s\right)$ using proposed cascaded controllers.
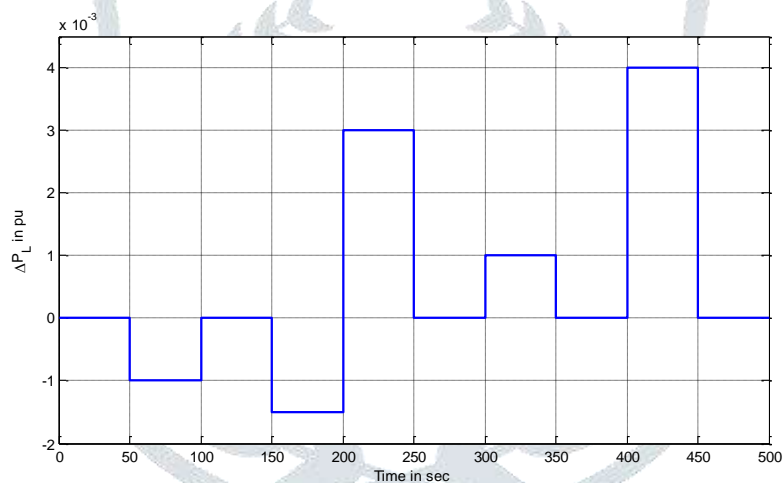
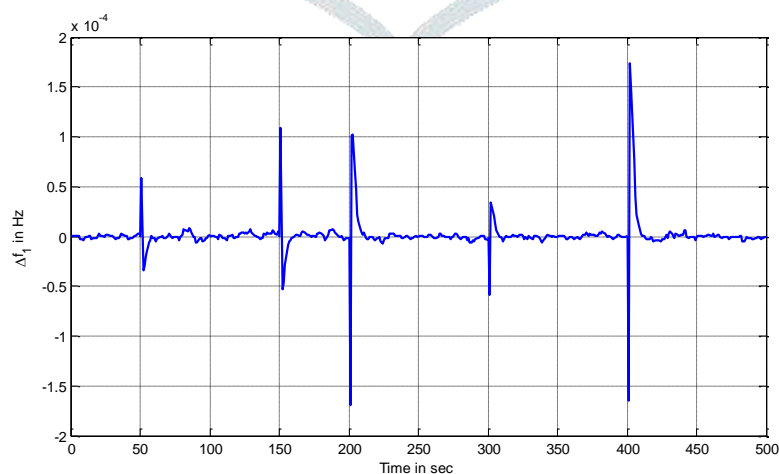

FIGURE 13: Loading pattern in area1.

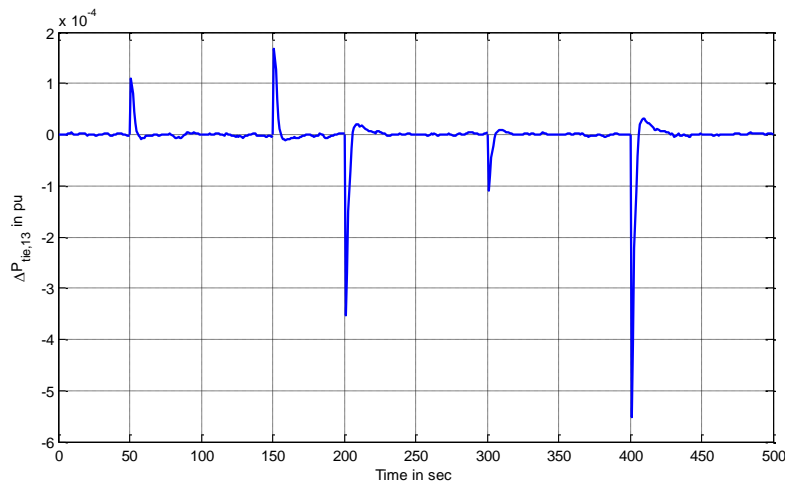**FIGURE 14:** Frequency variation in area1 with step load patterns (shown in Figure 13).

FIGURE 15: Tie-line power variation $\Delta P_{tie,13}$ with step load patterns (shown in Figure 13).

6. Conclusion

A proportional-derivative-fuzzy-proportional-integral-derivative (PD-FPID) cascaded controller and fuzzy-PID controller have been introduced in this article for improving the dynamic behaviour of AGC for a three area thermal power system with GRC. Performances of the proposed controllers are compared with that of a conventional PD-PID cascaded and PID controller for the same power system and it has been proved that PD-FPID is more effective in providing considerable improvements in system performance. Hybrid LUS-TLBO algorithm has been employed in optimally designing the gains of the proposed controllers. Sudden step load change of 1% has been applied in area1 to study dynamic characteristics of the system. Again robustness of the PD-FPID cascaded controller has been proved by varying both the system parameters and loading pattern.

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