Design of fractional PID for Load frequency control via Internal model control and Big bang Big crunch optimization

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Abstract: This paper presents a new technique for the design of an optimal fractional order PID controller for Load frequency control (LFC) in power systems. The proposed approach utilizes a unique combination of Big Bang Big Crunch (BB-BC) algorithm which is a recent soft computing technique and internal model control (IMC) scheme for the design of a fractional order PID controller and it also unifies the notion of order diminution with controller design. A detailed mathematical description of the proposed approach is elucidated in the paper. Since BB-BC is a stochastic search technique, hence a thorough statistical analysis of the response specifications is performed. To demonstrate the effectiveness of the proposed approach, an exhaustive comparative analysis in terms of time response specifications and performance indices is also carried out. It is inferred that the proposed approach is highly efficient tool and outperforms the recent techniques in the literature.

Keywords: Load frequency control, Statistical analysis, Big Bang Big crunch, Integral performance indices, PID control, Parameter uncertainty

1. INTRODUCTION

The performance of a large scale power system undergoes deterioration owing to the degradation in power quality caused by load perturbations which results in deviation in tie-line power interchange and fluctuation in area frequency. This necessitates the use of Load frequency control (LFC) to withstand load disturbances, parameter uncertainties and for the minimisation of unscheduled power flow between interconnected areas (Pandey et al. (2013)). Thus, LFC can be regarded as an optimization and a robustness control problem. Various advanced control strategies are proposed in literature like optimal control (Cavin et al. (1971)), sliding mode control (Vrdoljak et al. (2010)), PID control (Moon et al. (2001)), Internal model control (IMC) (Tan (2010), Saxena and Hote (2013)), etc. However, all these approaches encounter limitation of sluggish disturbance attenuation, especially in the presence of parameter uncertainties and load disturbances.

These days, the theory of fractional calculus has witnessed a tremendous popularity in system engineering and the control practitioners are closely focussing on the application of fractional calculus in the design of PID controllers. Fractional-order (FO) systems have attracted increasing interests, since many real-world physical systems are better characterized by FO differential equation (Monje et al. (2010)). A fractional order PID (FOPID) controller provides additional flexibility in the design phase over a simple integer order (IO) PID structure as it has five tuning parameters i.e., K_p, K_i , K_d, λ and μ instead of three in a classical IO controller. Various ways of tuning a FOPID controller are proposed in the literature (Doicin et al. (2016), Valério and da Costa (2006)). Besides these techniques, soft computing algorithms can also be used to tune a FOPID controller (Herreros et al. (2002)). It is pertinent to mention here that the different soft computing techniques require a specification on the bound of the solution space before their application to a problem. Until now, the bounds were intutively chosen, whereas in this paper IMC scheme will aid us in obtaining a suitable boundary of the search space. The choice of the upper and lower bounds on the optimization variables play an important role in the quality of the solution obtained and the rate of convergence of the solution.

In this paper, a new technique is presented for the tuning of the parameters of a FOPID controller via BBBC algorithm and IMC scheme for single area power system comprising of a non-reheated turbine. The single area power system is of third order, hence it is first reduced into second order via BBBC optimization algorithm (Erol and Eksin (2006)). In the next step, IMC is applied on the reduced order plant to obtain the parameters of the PID controller. The parameters, hence obtained are used to specify a suitable bound on the parameters of the FOPID controller to be tuned via BBBC algorithm. It aids in faster convergence of the solutions and an acceptable optimal solution can be obtained in as few as 10 iterations since we have chosen a tighter solution space via IMC scheme. The reason of choosing BBBC algorithm over other similar metaheuristic algorithms is its simplicity and proven track record of achieving more accurate results in order diminution and controller design problems (Desai and Prasad (2013), Bi-

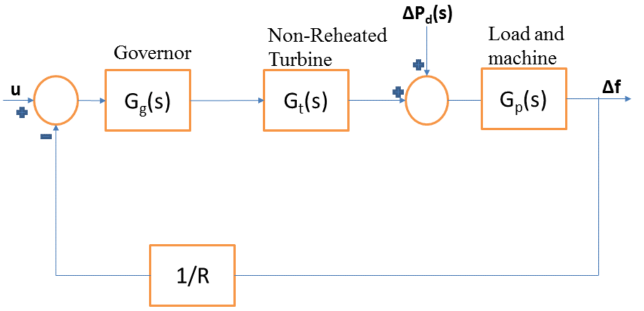

Fig. 1. Linear model of a single-area power system

radar et al. (2016)). Since BBBC is a stochastic optimization technique, hence a thorough statistical analysis of the controller parameters and the time response specifications is conducted to show the effectiveness of the proposed technique. Besides this, an exhaustive comparative analysis is done with respect to the recently developed techniques of LFC and the superiority of the proposed approach is shown in terms of faster disturbance rejection and the lower values of the integral error indices. The beauty of the proposed approach is that it combines a conventional technique such as IMC and a recent metaheuristic technique such as BBBC to achieve a good quality optimal solution for the given problem quickly. Once a controller is designed, it is crucial to check if it is robust to the presence of parametric uncertainty in the system, thus robustness analysis is also carried out in the paper. The results convey the efficiency and powerfulness of the proposed technique.

2. PROBLEM STATEMENT

A power system is typically a large-scale system consisting of complex nonlinear dynamics. However, for small load changes, it can be appropriately typified by a linear model, linearized about the operating point. The single area power system for LFC design consists of a governor $G_g(s)$, non-reheated turbine $G_t(s)$, load and machine $G_p(s)$ and the droop characteristics as illustrated in Fig.1. The dynamics of the individual components are described as follows:

$$G_g(s) = \frac{1}{T_g s + 1} \tag{1}$$

$$G_t(s) = \frac{1}{T_t s + 1} \tag{2}$$

$$G_p(s) = \frac{K}{T_p s + 1} \tag{3}$$

The nomenclature of different system parameters is given in Table 1.

The system model can be characterized by the following transfer function:

$$\Delta f(s) = T_u(s)\Delta u(s) + T_d(s)\Delta P_d(s) \tag{4}$$

where

$$T_u(s) = \left(\frac{G_g(s)G_p(s)G_t(s)}{1 + \frac{G_g(s)G_p(s)G_t(s)}{R}} \right) \tag{5}$$

$$T_d(s) = \left(\frac{G_p(s)}{1 + \frac{G_g(s)G_p(s)G_t(s)}{R}} \right) \tag{6}$$

Table 1. Nomenclature: Power system parameters

Δf	Incremental frequency deviation (Hz)
K	Electric system gain
ΔP_d	Load disturbance (p.u.MW)
R	Speed regulation due to governor action (Hz/p.u.MW)
T_g	Governor time constant (s)
T_p	Electric system time constant (s)
T_t	Turbine time constant (s)

Equation (4) clearly explains that LFC is primarily a disturbance rejection problem, in which the goal is to design a robust FOPID controller for a single area power system such that the effect of the load disturbances on Δf is minimum. The FOPID controller to be designed is of the form as given below:

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \tag{7}$$

Here K_p, K_i and K_d denote the proportional, gain, integral gain and the derivative gain and λ and μ are the fractional orders of the integral and derivative term respectively.

3. PROPOSED APPROACH

The proposed technique can be segregated into broadly two major steps. The first step involves the design of a IMC-PID controller for the power system. In the second step, we use BBBC optimization algorithm to design an optimal FOPID controller by using the PID parameters obtained in the first step as a means to specify a bound on the solution space.

The detailed mathematical formulation of the proposed technique is explained below.

3.1 Internal Model Control

Equations (1)-(6) show that even a single area power system is a third order system. Hence, we reduce it into second order before the application of IMC approach. In this paper, the order diminution is performed via BBBC algorithm since it is simple to understand and gives reduced order model which closely resembles the original system (Biradar et al. (2016)). Let the reduced order model be given by

$$G_R(s) = \frac{a_0 + a_1 s}{b_0 s^2 + b_1 s + b_2} \tag{8}$$

where $a_j, j = 0, 1$ and $b_i, i = 0, 1, 2$ are constant coefficients of s, and $b_i > 0$.

For the LFC problem, it is observed that the reduced order model obtained via BBBC is a non minimum phase system, thus we consider $a_1 < 0$. If $a_1 \geq 0$, a similar type of procedure can be applied as given herein.

Equation (8) can be re-written as

$$G_R(s) = \frac{a_0(1 + a_2 s)}{b_0 s^2 + b_1 s + b_2} \tag{9}$$

where $a_2 = \frac{a_1}{a_0} < 0$.

After obtaining the reduced order model, we apply IMC scheme to the LFC problem. Fig. 2 and Fig. 3 illustrate the

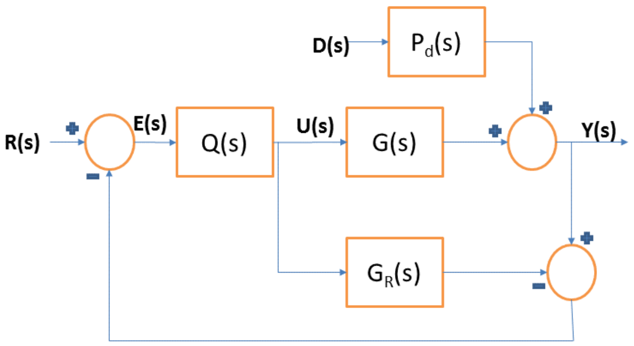

Fig. 2. IMC control scheme

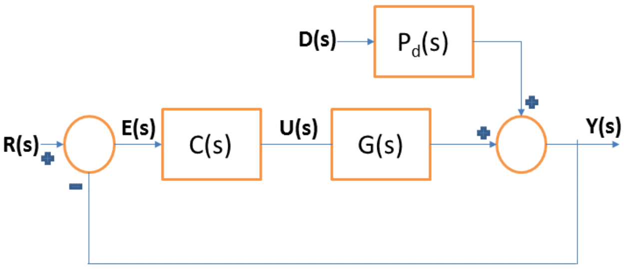

Fig. 3. IMC control scheme in classical feedback form

block diagrams of basic IMC structure and IMC structure in classical feedback form respectively. The plant model is factorized as

$$G_R(s) = G_{R-}(s)G_{R+}(s) \tag{10}$$

where $G_{R-}(s)$ and $G_{R+}(s)$ represent the minimum and non-minimum phase part respectively. Thus,

$$G_{R-}(s) = \frac{a_0}{b_0 s^2 + b_1 s + b_2} \tag{11}$$

$$G_{R+}(s) = 1 + a_2 s \tag{12}$$

Next, a filter is chosen of the form as given in (13).

$$F(s) = \frac{1}{(1+\delta s)^k} \tag{13}$$

Here, δ is intutively tuned. k is chosen such that IMC controller is physically realizable. For this problem, we consider $k = 1$.

Finally, the IMC controller is given by

$$Q(s) = F(s)G_{R-}^{-1}(s) = \frac{b_0 s^2 + b_1 s + b_2}{a_0(1+\delta s)} \tag{14}$$

In the classical feedback form, the PID controller can be written as

$$C_{IMC}(s) = \frac{Q(s)}{1 - G_R(s)Q(s)} \tag{15}$$

On substitution of values of $G_R(s)$ and $Q(s)$ from equations (9) and (14), we obtain

$$C_{IMC}(s) = \frac{b_1}{a_0\delta - a_1} + \frac{b_1}{a_0\delta - a_1}\frac{1}{s} + \frac{b_0}{a_0\delta - a_1}s \tag{16}$$

Equation (16) can be re-written as

$$C_{IMC}(s) = K_p + K_i\left(\frac{1}{s}\right) + K_d s \tag{17}$$

Table 2. Nomenclature: BBBC parameters

N	Population size
Ψ	Constant parameter which limits size of solution space
L	Lower bound of the variables in solution space
U	Upper bound of the variables in solution space
$maxite$	Maximum number of iterations
$iter$	Count of number of iterations
R	Uniformly distributed random numbers in (0,1)

where $K_p = \frac{b_1}{a_0\delta - a_1}$, $K_i = \frac{b_2}{a_0\delta - a_1}$ and $K_d = \frac{b_0}{a_0\delta - a_1}$.

Thus, we have obtained the parameters of a IMC-PID controller. In the next subsection, these parameters will aid us in choice of the bounds of the solution space for FOPID via BBBC algorithm.

3.2 BBBC optimization algorithm

BBBC is a global heuristic search technique discovered by Erol and Eksin based on the theory of evolution of the closed universe in the field of physics and astronomy. The BBBC algorithm involves two phases - BB phase, in which the candidate solutions are spread at random in the search space and the BC phase in which candidate solutions are drawn into a single representative point known as the center of mass (Erol and Eksin (2006)). The algorithm starts by the random generation of an initial population of feasible candidates. This uniform randomness is equivalent to energy dissipation in nature. The BB phase represents the search space exploration process, while the BC results in best solution exploitation. Table 2 depicts the nomenclature of BBBC parameters. The steps of standard BBBC algorithm are outlined as follows:

Step 1 Initialise the BBBC parameters i.e., N, $\Psi, maxite$ and set $'iter' = 1$. Select the lower bound of the FOPID parameters as $L = [p^{-1}K_p \;\; p^{-1}K_d \;\; p^{-1}K_i \;\; 0 \;\; 0]$ and the upper bound as $U = [pK_p \;\; pK_d \;\; pK_i \;\; 2 \;\; 2]$. Here K_p K_i and K_d are the PID parameters computed in (17). λ and $\mu \in (0{,}2)$. If $\lambda, \mu \geq 2$, the resulting controller would be of higher order and of a different form as compared to conventional PID controller. The factor p is intutively tuned.

Step 2 Generate N candidate solutions via uniform random distribution. This phase is the Big Bang phase (BBP). Let x_i be the vector describing the position of the i^{th} candidate solution. Thus, the elements of x_i are generated as

$$x_i = L + (U - L) \circ R, \qquad i = 1, 2, ..., N \tag{18}$$

Step 3 Compute the fitness function matrix for the N candidate solutions as $F = [f^1 \;\; f^2 \;\; ... \;\; f^N]^T$ where, $f^i = J(x_i)$, $f^i \in \mathbb{R}, i = 1, 2, ...N$ and $J(x_i)$ is the performance index function for the i^{th} candidate solution.

Step 4 Sort the fitness values in ascending order of their magnitudes. Let the least fitness value be represented by f^{iter}.

Step 5 Compute the centre of mass of the given candidate solutions. This phase is called Big crunch phase (BCP).

$$C^{iter} = \frac{\sum_{i=1}^{n} \frac{x_i}{f_i}}{\sum_{i=1}^{n} \frac{1}{f_i}} \tag{19}$$

Since our objective is the computation of the minimum value of the function, the algorithm uses the reciprocal of the function as a measure of fitness. Hence, the weighted mean of the candidate solutions is biased towards the region, where the performance function has its least value.

Step 6 Next, N new candidates are generated in the search space based on the knowledge of the centre of mass computed in the previous iteration using (20)

$$x_i^{iter+1} = C^{iter} + \frac{r_i \Psi (U - L)}{iter + 1} \tag{20}$$

Here r_i is a normal random number which is unique for every candidate solution, such that $r_i \in (0, 1]$.

Step 7 Compute the fitness function values for the new set of candidate solutions generated in Step 6. Then, go to Step 4. Thus, the successive BB phase and BC phase steps are carried out repeatedly until a stopping criterion has been met.

Step 8 When the maximum number of iterations have reached, we sort the least fitness values computed in Step 4 in an increasing order and find the solution corresponding to the least value of the performance index. Thus, the solution having lowest fitness value gives us the optimum FOPID parameters.

4. NUMERICAL STUDIES

Consider a power system plant model with a non-reheated turbine and droop characteristics as depicted in Fig. 1. The simulations are performed in MATLAB R2016a environment by using FOMCON toolbox for fractional order systems (Tepljakov et al. (2013)). The typical values of the LFC parameters are expressed in (21)

$$K = 120,\ T_g = 0.08,\ T_p = 20,\ T_t = 0.3,\ R = 2.4. \tag{21}$$

Using (21), the plant model in transfer function form is evaluated as

$$G(s) = \frac{250}{s^3 + 15.88s^2 + 42.46s + 106.2} \tag{22}$$

Equation (22) represents a third order underdamped system with poles at $s = -13.2858$, $-1.2971 + 2.5122i$, $-1.2971 - 2.5122i$. The proposed IMC scheme requires a reduced second order transfer function as the plant model. The reduced order model obtained via BBBC is given as

$$G_R(s) = \frac{-5s + 96.57}{5.4s^2 + 14s + 41.05} \tag{23}$$

It is obvious from Fig. 4 that the step response of the reduced order model is almost fully coincident to that of the full order system. The corresponding value of ISE is 6.7653×10^{-5}.

The conventional IMC-PID controller ($\delta = 0.1$) is obtained using equations (9)-(17) and is given by

$$C_{IMC}(s) = 2.0198 + 5.9923\left(\frac{1}{s}\right) + 0.7791s \tag{24}$$

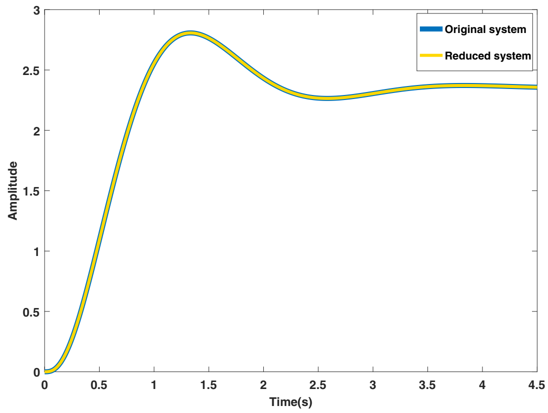

Fig. 4. Step response of the original system and the reduced order model obtained via BBBC algorithm

The typical parameters of the BBBC for the design of FOPID controller are taken as follows

$$N = 100, \Psi = 0.25, maxite = 100, p = 10 \tag{25}$$

Since $p = 10$, and using (24) in the Step 1 of subsection 3.2, we get $L = [0.20198\ 0.59923\ 0.07791\ 0\ 0]$ and $U = [20.198\ 59.923\ 7.791\ 2\ 2]$.

The final FOPID-BBBC controller having the least value of ISE obtained via the proposed technique is given by

$$C_{BBBC}(s) = 18.0695 + \frac{32.8666}{s^{0.6949}} + 4.6579s^{1.3258} \tag{26}$$

Fig. 5. illustrates the comparison of the disturbance rejection response for the nominal case of the proposed approach with Saxena's PID (Saxena and Hote (2017)), Sondhi's FOPID (Sondhi and Hote (2014)), Liu Routh PID, Liu Pade PID (Saxena and Hote (2013)) and Tan's IMC-PID (Tan (2010)). A step load disturbance $\Delta P_d = 0.01$ is applied to the system at $t = 2s$. It can be observed from Fig. 5 that the rejection of load disturbance is faster and accompanied with a minimal undershoot for the proposed scheme. The performance of the controller is quantified via various integral error indices like integral square error (ISE), integral absolute error (IAE) and integral time absolute error (ITAE). A thorough statistical analysis of the performance indices is performed in Table 3. In Table 3, the undershoot and overshoot are defined as the peak negative deviation and the peak positive deviation in the frequency respectively. Since, we had chosen a tight solution space for BBBC optimization algorithm via IMC control scheme, thus the variance and standard deviations of the time response specifications and controller parameters are extremely small in magnitude. A closer look reveals that even the worst case response is nearly optimal and one could stop the BBBC algorithm after as less than 10 iterations and be assured of a nearly optimal response, thus greatly reducing the simulation time.

The uncertainty in system parameters is a crucial issue in the modern day complex power systems. Thus, it of utmost importance that the LFC controller is robust to the effect of parametric uncertainty in the system. To investigate the robustness of the controller, the LFC parameters are perturbed by ±50% in the same manner as expressed in Sondhi and Hote (2014), i.e.,

Table 3. Performance Parameters obtained for FOPID via BBBC

Parameter	Min	Max	Mean	Var	Std
K_p	17.91532088	18.13605498	18.04203804	1.93484770×10^{-3}	4.39869038×10^{-2}
K_i	32.66146045	33.12713077	32.86819001	8.45057421×10^{-3}	9.19270048×10^{-2}
K_d	4.60408272	4.68989749	4.642443733	3.30024957×10^{-4}	1.81665890×10^{-2}
λ	0.68820845	0.71083348	0.69851186	1.86954940×10^{-5}	4.32382863×10^{-3}
μ	1.32108221	1.34214655	1.33199057	2.00500273×10^{-5}	4.47772569×10^{-3}
t_s	4.04151923	4.2567147	4.16944216	1.99846977×10^{-3}	4.47042478×10^{-2}
t_r	3.22668747×10^{-4}	3.63052749×10^{-4}	3.44575487×10^{-4}	6.31616028×10^{-11}	7.94742743×10^{-6}
Undershoot	9.03392500×10^{-4}	9.54825200×10^{-4}	9.29050369×10^{-4}	1.1046396×10^{-10}	1.05101837×10^{-5}
Overshoot	1.86539200×10^{-5}	3.37651200×10^{-5}	2.60463279×10^{-5}	8.49926057×10^{-12}	2.915349133×10^{-6}
ISE	1.58440974×10^{-7}	1.60148063×10^{-7}	1.59390015×10^{-7}	1.57634433×10^{-19}	3.97032030×10^{-10}
IAE	5.99981429×10^{-4}	6.21553431×10^{-4}	6.10587461×10^{-4}	2.13431837×10^{-11}	4.61986836×10^{-6}
ITAE	2.35540422×10^{-3}	2.55441129×10^{-3}	2.47971083×10^{-3}	1.03848684×10^{-9}	3.22255619×10^{-5}

Table 4. Comparison of performance indices for +50% bound on LFC parameters

	Nominal			Upper bound		
Design method	ISE	IAE	ITAE	ISE	IAE	ITAE
Proposed FOPID	1.5842×10^{-7}	6.1078×10^{-4}	2.4937×10^{-3}	2.7111×10^{-7}	6.8813×10^{-4}	2.6529×10^{-3}
Saxena's PID (2017)	1.4394×10^{-6}	1.0930×10^{-3}	3.3193×10^{-3}	9.0176×10^{-7}	9.4191×10^{-4}	3.0217×10^{-3}
Sondhi's FOPID (2016)	1.4051×10^{-5}	4.2337×10^{-3}	1.3574×10^{-2}	9.5663×10^{-6}	4.2132×10^{-3}	1.4148×10^{-2}
Liu Pade (2013)	8.4992×10^{-4}	8.1829×10^{-2}	4.8396×10^{-1}	8.4674×10^{-4}	7.9997×10^{-2}	4.7937×10^{-1}
Liu Routh (2013)	8.7026×10^{-4}	8.1662×10^{-2}	4.8317×10^{-1}	8.9553×10^{-4}	8.1173×10^{-2}	4.8120×10^{-1}
Tan's IMC-PID (2010)	1.3818×10^{-4}	1.5733×10^{-2}	4.5986×10^{-2}	9.5938×10^{-5}	1.5703×10^{-2}	5.1868×10^{-2}

Table 5. Comparison of performance indices for -50% bound on LFC parameters

	Nominal			Lower bound		
Design method	ISE	IAE	ITAE	ISE	IAE	ITAE
Proposed FOPID	1.5842×10^{-7}	6.1078×10^{-4}	2.4937×10^{-3}	2.7105×10^{-7}	6.8817×10^{-4}	2.6528×10^{-3}
Saxena's PID (2017)	1.4394×10^{-6}	1.0930×10^{-3}	3.3193×10^{-3}	4.4720×10^{-6}	1.8544×10^{-3}	4.9941×10^{-3}
Sondhi's FOPID (2016)	1.4051×10^{-5}	4.2337×10^{-3}	1.3574×10^{-2}	3.0642×10^{-5}	6.2275×10^{-3}	1.8801×10^{-2}
Liu Pade (2013)	8.4992×10^{-4}	8.1829×10^{-2}	4.8396×10^{-1}	9.0271×10^{-4}	8.3356×10^{-2}	4.8708×10^{-1}
Liu Routh (2013)	8.7026×10^{-4}	8.1662×10^{-2}	4.8317×10^{-1}	9.1782×10^{-4}	8.3285×10^{-2}	4.8710×10^{-1}
Tan's IMC-PID (2010)	1.3818×10^{-4}	1.5733×10^{-2}	4.5986×10^{-2}	2.5167×10^{-4}	2.0258×10^{-2}	5.9438×10^{-2}

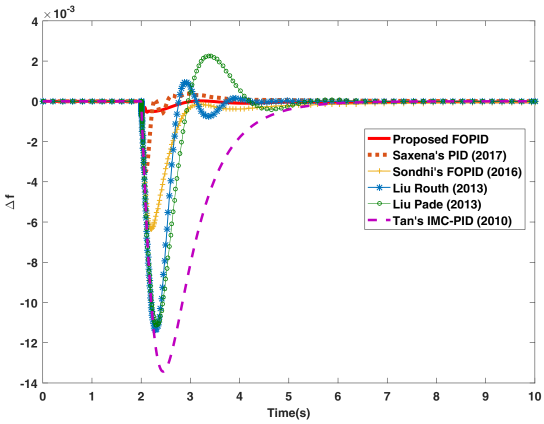

Fig. 5. Comparison of response of non-reheated power system using various controllers for nominal parameters.

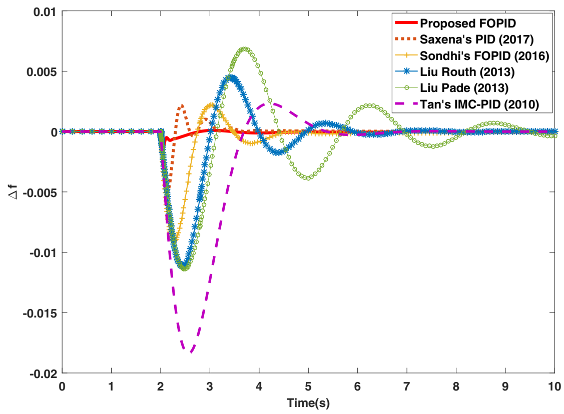

Fig. 6. Comparison of response of power system using various controllers for lower bound parameters.

$$K \in [60, 180],\ R \in [1.2, 3.6],\ T_g \in [0.04, 0.12],$$
$$T_p \in [10, 30],\ T_t \in [0.15, 0.45].$$

The proposed controller is implemented on the uncertain system and the corresponding disturbance rejection response is shown in Fig. 6 and Fig. 7 respectively. It can be seen that the proposed FOPID controller is able to effectively withstand parameter uncertainties and the frequency deviations settle to zero in minimum time with least overshoot for the proposed controller in comparison to other techniques of controller design. Table 4 and Table 5 enlist the performance indices for the nominal model, +50% and -50% uncertain model respectively. It is evident from the low values of ISE, IAE and ITAE, that the FOPID controller designed via the proposed scheme is capable of handling uncertainty in the plant parameters and reject the load fluctuations efficiently. Thus, we can conclude that the proposed scheme outperforms the recent techniques and is clearly the improved design for load frequency control.

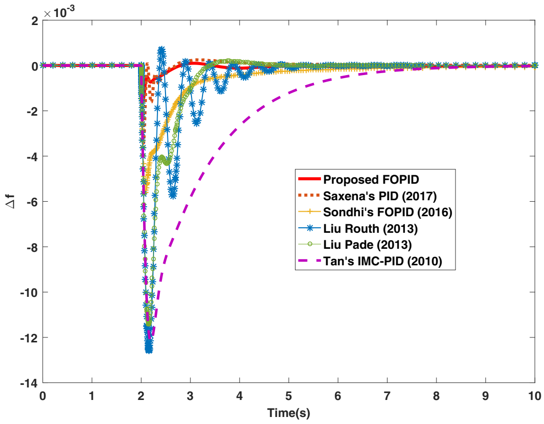

Fig. 7. Comparison of response of power system using various controllers for upper bound parameters.

5. CONCLUSION

This work presents the design of an optimal FOPID controller for the single area non reheated turbine power system via BBBC optimization algorithm and IMC scheme. The beauty of the proposed approach lies in the fast convergence of BBBC algorithm due to a suitable choice of the solution space and the extremely fast disturbance rejection capability accompanied by minimal overshoot and undershoot of the FOPID controller. The proposed scheme clearly outperforms the recent techniques of LFC controller design fron the literature. Due to space limitations, the proposed technique is demonstrated only for a single area power system with non-reheated turbine. The proposed work can be extended to the case of a power system with reheated turbine and hydro turbine. It may also be extended to a interconnected system, though in that case each control area is controlled independent of the other areas. Hence, a similar technique is applicable to a multi area interconnected system as well.

REFERENCES

Biradar, S., Hote, Y.V., and Saxena, S. (2016). Reduced-order modeling of linear time invariant systems using big bang big crunch optimization and time moment matching method. *Applied Mathematical Modelling*, 40(15), 7225 – 7244.

Cavin, R.K., Budge, M.C., and Rasmussen, P. (1971). An optimal linear systems approach to load-frequency control. *IEEE Transactions on Power Apparatus and Systems*, PAS-90(6), 2472–2482. doi: 10.1109/TPAS.1971.292858.

Desai, S.R. and Prasad, R. (2013). A new approach to order reduction using stability equation and big bang big crunch optimization. *Systems Science & Control Engineering*, 1(1), 20–27. doi: 10.1080/21642583.2013.804463.

Doicin, B., Popescu, M., and Patrascioiu, C. (2016). PID Controller optimal tuning. In *Proc. IEEE 8th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, 1–4. Ploiesti, Romania.

Erol, O.K. and Eksin, I. (2006). A new optimization method: Big Bang–Big Crunch. *Advances in Engineering Software*, 37(2), 106–111.

Herreros, A., Baeyens, E., and Perán, J.R. (2002). Design of PID-type controllers using multiobjective genetic algorithms. *ISA transactions*, 41(4), 457–472.

Monje, C.A., Chen, Y., Vinagre, B.M., Xue, D., and Feliu-Batlle, V. (2010). *Fractional-order systems and controls: fundamentals and applications.* Springer Science & Business Media.

Moon, Y.H., Ryu, H.S., Lee, J.G., and Kim, S. (2001). Power system load frequency control using noise-tolerable pid feedback. In *Proc. IEEE International Symposium on Industrial Electronics*, volume 3, 1714–1718. Pusan, South Korea. doi: 10.1109/ISIE.2001.931967.

Pandey, S.K., Mohanty, S.R., and Kishor, N. (2013). A literature survey on load-frequency control for conventional and distribution generation power systems. *Renewable and Sustainable Energy Reviews*, 25(Supplement C), 318 – 334. doi:10.1016/j.rser.2013.04.029.

Saxena, S. and Hote, Y.V. (2013). Load frequency control in power systems via internal model control scheme and model-order reduction. *IEEE Transactions on Power Systems*, 28(3), 2749–2757. doi: 10.1109/TPWRS.2013.2245349.

Saxena, S. and Hote, Y.V. (2017). Stabilization of perturbed system via IMC: An application to load frequency control. *Control Engineering Practice*, 64(Supplement C), 61 – 73. doi: 10.1016/j.conengprac.2017.04.002.

Sondhi, S. and Hote, Y.V. (2014). Fractional order PID controller for load frequency control. *Energy Conversion and Management*, 85(Supplement C), 343 – 353. doi: 10.1016/j.enconman.2014.05.091.

Tan, W. (2010). Unified tuning of PID load frequency controller for power systems via IMC. *IEEE Transactions on Power Systems*, 25(1), 341–350. doi: 10.1109/TPWRS.2009.2036463.

Tepljakov, A., Petlenkov, E., Belikov, J., and Finajev, J. (2013). Fractional-order controller design and digital implementation using FOMCON toolbox for matlab. In *Proc. IEEE Conference on Computer Aided Control System Design (CACSD)*, 340–345. IEEE, Hyderabad, India. doi:10.1109/CACSD.2013.6663486.

Valério, D. and da Costa, J.S. (2006). Tuning of fractional PID controllers with Ziegler–Nichols-type rules. *Signal Processing*, 86(10), 2771–2784.

Vrdoljak, K., Peri, N., and Petrovi, I. (2010). Sliding mode based load-frequency control in power systems. *Electric Power Systems Research*, 80(5), 514 – 527. doi: 10.1016/j.epsr.2009.10.026.