Optimal PID design for Load frequency control using QRAWCP approach

Sandeep D. Hanwate and Yogesh V. Hote

Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee-247667, India. (e-mail: hanwate.sandeep@gmail.com).

Abstract: In this paper, a new approach is proposed to design optimal PID controller for load frequency control (LFC) problem. This scheme is based on Quadratic Regulator Approach with Compensating Pole (QRAWCP) technique. Application of this control law is done to both single area and multi-area power system based load frequency problem. In addition to the nominal situation, robustness of this controller is also tested on the same systems with respect to parametric uncertainty, external disturbances, and non-linearities like Generation Rate Constraint (GRC) and Governor Dead Band (GDB). The performance evaluation is done using Matlab & Simulink based simulations and the obtained results are compared with the performance achieved using the recent control strategies designed for LFC.

Keywords: Frequency regulation, load frequency control, parametric variation, PID control, power system.

1. INTRODUCTION

Nowadays, electricity demand of every country is increasing continuously, due to industrial revolution, technological developments, etc. However, in power delivery, the most critical issue is to provide uninterrupted power supply to the consumers in-spite of the presence of any parametric uncertainties or external disturbances by Kundur (1994). For stable and continuous operation, one of the ancillary services is the 'frequency regulation' or 'load following' utilized for the Load Frequency Control (LFC). The frequency of the generated voltage should be kept within the permissible limits. To tackle the problem of frequency regulation, output power changes with the continuously changing load demand as defined in Saxena and Hote (2013). If the input-output power balance is not maintained, the change in frequency occurs. Hence frequency control is an essential issue, which is achieved via speed governor mechanism. The role of the governor is to control the speed and load accordingly. If the load on the turbine increases, the speed of the governor decreases and vice-versa. Fig. 1 shows the general scheme of a generating unit, where V_r is the voltage demand and f is the reference frequency as discussed by Ramana (2010).

LFC has been in practice for several years as part of the automatic generation control (AGC) unit in electric power systems. AGC is a system for adjusting the power output of multiple generators at different power plants, in response to changes in the load as shown by Tyagi and Srivastava (2005); Prasad et al. (2014). Whenever there is a change load, frequency of the system changes from its nominal value. In the control literature, various control techniques have been implemented on the LFC problem. This frequency regulation concept can be traced back nearly hundred years from today. In 1932 Dryer (1932), and then in 1940 Estrada (1940), and Concordia

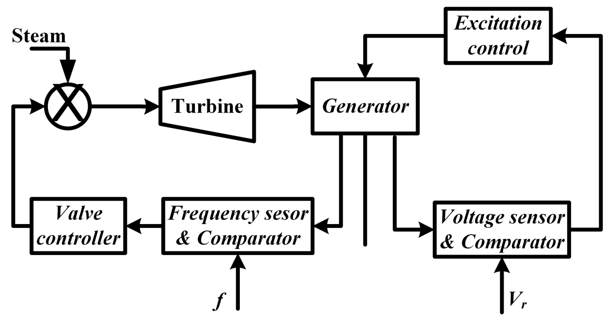

Fig. 1. General scheme of a generating unit

et al. (1941) have been working on frequency regulation issue. Since then in every decade, the research work has been carried on this LFC problem. However, in the last two decades, the electricity demand increased steeply due to population explosion, industrialization and urbanization, etc. So it is observed that, because of the frequency mismatches, we can see occurrences of interruption in power supply. To overcome this recently, many researchers have proposed methodologies to guarantee the uninterrupted power flow, such as, Saxena and Hote (2013, 2017); Masuda (2012) designed Internal Model Control (IMC) scheme using model order reduction for uncertain model. W. Tan (2010) presented a unified tuning of proportional-integral-derivative (PID) control, Anwar and Pan (2015) designed PID using frequency response matching with direct synthesis. In Saxena and Hote (2016), the researchers designed PID controller using Kharitonov's theorem for, perturbed multi-area systems and Hanwate et al. (2018) proposed adaptive policy for LFC. It is observed that, there are various non-linear control strategies reported in the control literature till date, which can outperform linear controllers; however, most of these are mathematically complicated and to implement in real time applications. Conversely, as PID controller is one of the simplest linear controller till date, it is used in augmentation with optimal control.

The PID controller offers simplicity, functionality, past good record of success, and the most profound solution to process industry and also to any real-time control problems, as defined in Astrom' and Hagglund (1995); Yun Li et al. (2006). The three terms of the PID controller provide improvement to both the transient and steady-state specifications of the control system response, described in Blevins (2012); Bazanella et al. (2016); Nair et al. (2016). The first tuning method for PID controllers was designed by Ziegler and Nichols (1942). Since then many of the research has been carried out on PID such as, Cohen-Coon, Chien, Hrones and Reswich (C-H-R), Internal Model Control (IMC), optimization such that, Particle Swarm Optimization (PSO) as done by Gaing (2004), Big-Bang Big-Crunch (BBBC) techniques Iruthayarajan and Baskar (2009), Linear Quadratic Regulator (LQR)-PID Hanwate and Hote (2017), Fuzzy PID, ANN-PID Padula et al. (2012), SBL-PID Tan (2005), FOPID Kumar et al. (2017); Sondhi and Hote (2014), etc. However, these methods have some merits and demerits, which improve on previous method either in terms of transient or steady state response. Tyagi and Srivastava (2005) designed LQR and Linear Quadratic Gaussian (LQG) controllers, but only presented for single area, and also did not consider non-linear constraints. Recently Hanwate and Hote (2018) designed quadratic regulator based PID for Sun tracker system, for disturbance rejection, however they did not extend the work for non-linearities of real-time system. So, in this paper, we designed an optimal PID controller for load frequency control using direct model based formula by Quadratic Regulator Approach with Compensating Pole(QRAWCP). For presenting the betterment of the proposed technique, we compared the results obtained for the single and multi-area cases, for practical issues such as non-linearities (Generation Rate Constraint (GRC) and Governor Dead Band (GDB)) and parametric uncertainties, with the recently designed PID controller and other control techniques. The comparison is carried out for three different cases, which are discussed later in the paper.

The rest of the paper is organized as follows. In Section 2, PID is designed using QRAWCP for LFC problem. Analysis of an isolated single area power system model and a two area power system, are simulated and the results are obtained in Section 3, for three different cases. Also, numerical comparison between these cases is done in this section, using integral performance indices. Finally, in Section 4, brief conclusion on the work done in this paper is presented, along with the future scope of research that may emanate from this work.

2. PID CONTROLLER DESIGN USING QRAWCP APPROACH FOR LFC

Fig. 2, shows the schematic of load frequency control using controller to compensate the deviation of Δf using proper control signal u. Till dated, the QRAWCP is only designed for sun tracker system by Hanwate and Hote (2018), but it has not discussed about performance in presence of non-linearities like GRC and GDB for the system. Using this

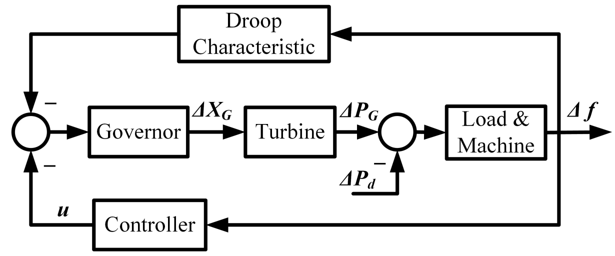

Fig. 2. Schematic of the proposed control system

Table 1. The LFC system variables.

Δf	Incremental frequency deviation (Hz)
ΔP_d	Load disturbance (p.u.MW)
f	Reference load frequency input
u	Control signal
K_P	Electric system gain
T_P	Electric system time constant (s)
K_G	Governor gain constant
T_G	Governor time constant (s)
K_T	Turbine gain constant
T_T	Turbine time constant (s)
R	Speed regulation due to governor action (Hz/p.u.MW)
ΔP_G	Incremental change in generator output (p.u.MW)
ΔX_G	Incremental change in governor valve position

QRAWCP approach, to design optimal PID controller, for single Non-reheated (NR) turbine and multi-area reheated turbine. Initially, the steps for the single area model are described, followed by a similar extension for multi area model.

Step 1: For the single area the transfer function $G(s)$ of LFC is given in (1), since $\Delta f(s) = G(s)U(s)$, we get,

$$G(s) = \frac{\mathcal{K}}{s^3 + b_2 s^2 + b_1 s + b_0} \quad (1)$$

where $\mathcal{K} = K_P K_T K_G/\sigma$, $b_0 = 1 + K_P K_T K_G/\sigma R$, $b_1 = (T_G + T_T + T_P)/\sigma$, $b_2 = (T_G T_T + T_G T_P + T_T T_P)/\sigma$ and $\sigma = T_G T_T T_P$. For multi-area power system, the system model of each control area is $B_i G$. Further, the state space model becomes, $\dot{x}(t) = Ax(t) + Bu(t)$ and $y(t) = Cx(t)$ and given in (2). Table 1 describes all the variables of LFC, which are considered from Saxena and Hote (2016).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -b_0 & -b_1 & b_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \mathcal{K} \end{bmatrix} u$$
$$y = [\,1\ 0\ 0\,] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (2)$$

In (2), $A \in \mathbb{R}^{m\times m}$, $B \in \mathbb{R}^{m\times l}$, and $C \in \mathbb{R}^{1\times m}$. The PID controller's transfer function is given by $C(s) = (\rho_d s^2 + s\rho_p + \rho_i)/s$, where, ρ_p = proportional gain, ρ_i= integral gain and ρ_d = derivative gain.

Step 2: The closed-loop characteristic equation for $C(s)$ and plant $G(s)$ is $\Delta(s) = 1+G(s)C(s)$, and equating $\Delta(s)$ to zero, we get,

$$s^4 + b_2 s^3 + (b_1 + \mathcal{K}\rho_d)\, s^2 + (b_0 + \mathcal{K}\rho_p)\, s + \mathcal{K}\rho_i = 0 \quad (3)$$

Step 3: Determine the control law by Linear Quadratic Regulator approach: The quadratic regulator approach is an optimal state feedback controller which is designed to minimize a specific quadratic cost function. The performance index is designed for constraints like u, y, error(e) or unconstrained objectives of linear time invariant (LTI)

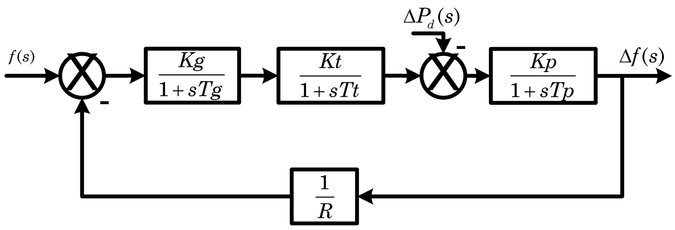

Fig. 3. Model of single area power system

system. The optimal control vector $u(t)$ is obtained from $u(t) = -\boldsymbol{\lambda}\, \boldsymbol{x}(t)$. So for here, unconstrained optimal action is considered. Therefore Performance Index (PI) of the system is defined as,

$$\psi = \int_0^\infty \left(x^T Q x + u^T R u\right) dt \tag{4}$$

where $Q \in \mathbb{R}^{m \times m}$ and $R \in \mathbb{R}^{l \times l}$ are symmetric positive semi definite and positive definite respectively. Here, for the LFC problem $m = 3$ and $l = 1$.

So then LTI system equation becomes,

$$\dot{x} = \tilde{A}x \tag{5}$$

where, $\tilde{A} = (A - B\lambda)$. Since A and B are controllable, then, eigenvalues of $\tilde{A}$ will be on left side of s-plane. Then (4) re-written as,

$$\psi = \int_0^\infty \left(x^T \ \left(Q + \lambda^T R \lambda\right) x\right) dt \tag{6}$$

assuming, $\frac{d}{dt}\left(x^T P x\right) = -\left(x^T \ \left(Q + \lambda^T R \lambda\right) x\right)$

$$\left(x^T \ \left(Q + \lambda^T R \lambda\right) x\right) = -x^T P \dot{x} - \dot{x}^T P x \tag{7}$$

Using (5) in (7) and then substituting in (6), we get,

$$\psi = -\int_0^\infty x^T \left[P\tilde{A} + \tilde{A}^T P\right] x dt \tag{8}$$

It is necessary condition that P must be positive definite matrix. By comparing (7) with (8), we get,

$$P\tilde{A} + \tilde{A}^T P = -\left(Q + \lambda^T R \lambda\right) \tag{9}$$

As $(A - B\lambda)$ is a stable, its eigen values are on left side of s-plane. Therefore, solving for a positive definite matrix P which can satisfy (9), the cost function can be obtain as,

$$\psi = \int_0^\infty \left(x^T \ \left(Q + \lambda^T R \lambda\right) x\right) dt \tag{10}$$

From (7), the $\psi = -x^T P x\big|_0^\infty$, so we can write as,

$$\psi = -x^T(\infty) P x(\infty) + x^T(0) P x(0) \tag{11}$$

Since (5) is asymptotically stable, and $x(\infty) \to 0$. Thus we get $\psi = x^T(0)Px(0)$. This is obtained in terms of initial condition.

Step 4: From (4), the minimization of ψ using pontryagin's minimum principle gives the state feedback control law $u = -\lambda x$. The feedback gain λ is found as:

$$\lambda = R^{-1} B^T P \tag{12}$$

Using this control further simplifying (5), we get Algebraic Riccati Equation(ARE) as,

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{13}$$

In (13), Q and R are selected in such a way that $Q = diag(q11, q22, q33)$ is $q11 > q22 > q33 > 0$ and $R = V^T V > 0$, where $V \in \mathbb{R}^m{}_{>0}$.

Step 5: Using ARE, (12), and (13), state feedback control gain λ is obtained as,

$$\lambda = [p_{13}\mathcal{K} \quad p_{23}\mathcal{K} \quad p_{33}\mathcal{K}] \tag{14}$$

Step 6: The closed-loop characteristic equation $(sI - \tilde{A})$ can be written as,

$$\begin{aligned} s^3 + \left(b_2 + p_{33}\mathcal{K}^2\right) s^2 + \left(b_1 + p_{23}\mathcal{K}^2\right) s + \\ \left(b_1 + p_{13}\mathcal{K}^2\right) = 0 \end{aligned} \tag{15}$$

Step 7: The order of the closed-loop system (3) is of fourth order and (15) is of third order. Therefore, in order to compare these two equations, we need to add one pole. According to QRAWCP methodology by augmenting one pole we get.

$$\begin{aligned} & s^4 + \left(\alpha_4 + \left(b_2 + p_{33}\mathcal{K}^2\right)\right) s^3 + \\ & \left(\left(b_1 + p_{23}\mathcal{K}^2\right) + \left(b_2 + p_{33}\mathcal{K}^2\right) \alpha_4\right) s^2 + \\ & \left(\left(b_1 + p_{13}\mathcal{K}^2\right) + \left(b_1 + p_{23}\mathcal{K}^2\right) \alpha_4\right) s + \\ & \left(b_1 + p_{13}\mathcal{K}^2\right) = 0 \end{aligned} \tag{16}$$

Comparing (16) with each independent coefficient of (3), α_4 can be calculated as,

$$\alpha_4 = -p_{33}\mathcal{K}^2 \tag{17}$$

The above (16) can be written in simplified form for the purpose of comparing as,

$$s^4 + p_1 s^3 + p_2 s^2 + p_3 s + p_4 = 0 \tag{18}$$

where,

$$\begin{aligned} p_1 &= p_{33}\mathcal{K}^2 + b_2 + p_{33}\mathcal{K}^2 \\ p_2 &= \left(b_1 + p_{23}\mathcal{K}^2\right) + \left(b_2 + p_{33}\mathcal{K}^2\right) p_{33}\mathcal{K}^2 \\ p_3 &= \left(b_1 + p_{13}\mathcal{K}^2\right) + \left(b_1 + p_{23}\mathcal{K}^2\right) p_{33}\mathcal{K}^2 \\ p_4 &= b_1 + p_{13}\mathcal{K}^2 \end{aligned}$$

Step 8: By comparing (3) and (18), we get parameters of $C(s)$ as follows,

$$\begin{aligned} \rho_p &= \frac{1}{\mathcal{K}}\left(b_1 + p_{13}\mathcal{K}^2 + \left(b_1 + p_{23}\mathcal{K}^2\right) p_{33}\mathcal{K}^2 - b_0\right) \\ \rho_i &= \frac{1}{\mathcal{K}}\left(b_1 + p_{13}\mathcal{K}^2\right) \\ \rho_d &= \frac{1}{\mathcal{K}}\left(p_{23}\mathcal{K}^2 + \left(b_2 + p_{33}\mathcal{K}^2\right) p_{33}\mathcal{K}^2\right) \end{aligned} \tag{19}$$

3. RESULTS AND ANALYSIS

In this section, we considered three different cases. Case 1 and 2 consider single-area with parametric uncertainty and hardware non-linearity constraints, respectively, while case 3 discusses the two-area scenario. From QRAWCP, PID parameters are obtained: $\rho_p = 6.5208$, $\rho_i = 8.7649$ and $\rho_d = 3.1385$ and using the parameters of single area LFC from Anwar and Pan (2015); Padhan and Majhi (2013); Saxena and Hote (2016), we simulated the model and controller in Matlab & Simulink environment.

3.1 Case 1: Single area for N-R turbine

The nominal parameters for single-area power system with N-R turbine is considered from Padhan and Majhi (2013). $K_P = 120$, $T_P = 20$, $K_T = 1$, $T_T = 0.3$, $K_G = 1$,

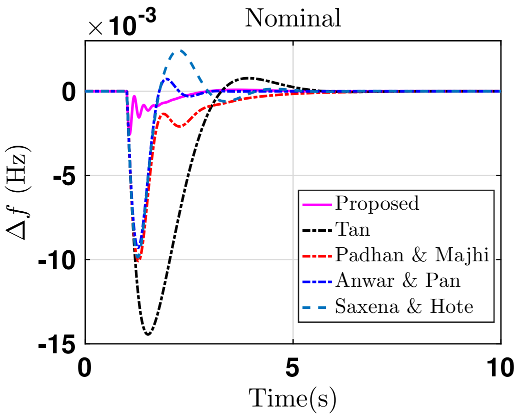

Fig. 4. Time response for nominal case of LFC

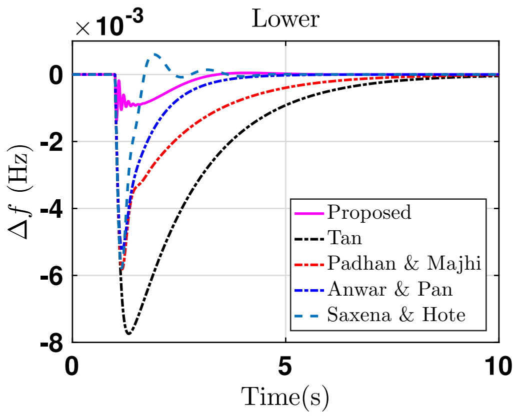

Fig. 5. Response under −50% lower parametric uncertainty of LFC

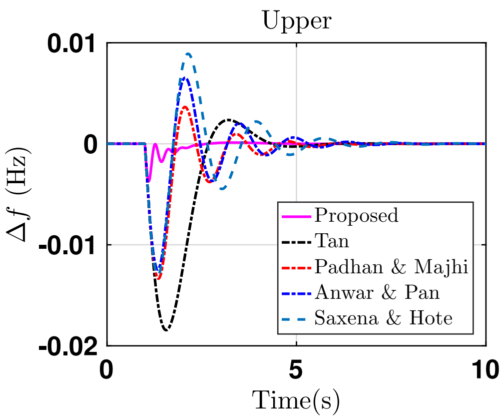

Fig. 6. Response under +50%upper parametric uncertainty LFC

$T_G = 0.08$, $R = 2.4$. In this case, to compare with proposed (QRAWCP-PID), we have considered recently designed PID controller from, W. Tan (2010), Padhan and Majhi (2013), Anwar and Pan (2015) and other technique through internal model control by Saxena and Hote (2013). Fig. 4 shows the time evolution of frequency variation for a sudden load disturbance of 0.01 p.u. MW, which is applied at 1 sec. It is seen that the QRAWCP scheme shows minimum undershoot in comparison to other approaches. Further, we analyze the controllers for ±50% parametric variation to its nominal value, for lower and upper bound.

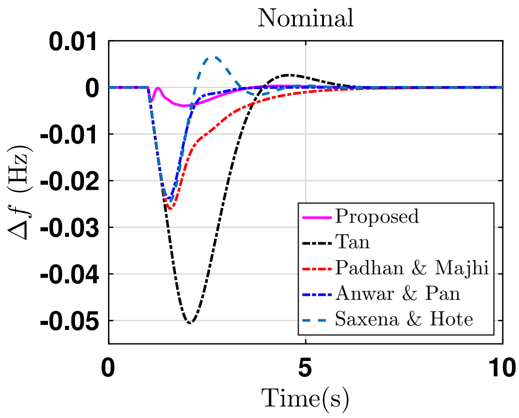

Fig. 7. Time response for nominal case of LFC with GRC and GDB

It is shown in Fig. 5 and 6, which also shows the frequency curve converges to zero with minimum undershoot and lesser time as compared to other considered approaches. This graphical analysis can also be measured numerically with integral performance indices such as Integral Square Error (ISE), Integral Absolute Error(IAE), Integral Times Squre Error (ITSE), Integral Time Absolute Error(ITAE). From Table 2, it is evident that using the proposed scheme, the deviation in frequency attains minimum value in both the cases.

3.2 Case 2: LFC considering GRC and GDB constraints

For this case, we have considered real-time non-linearities of generation rate constraint (GRC), and governor dead band (GDB). Their specifications are: GRC is 0.1 p.u./min. or 0.001667 p.u./sec. from W. Tan (2010); Saxena and Hote (2017) and GDB is 0.06% or 0.036 Hz/p.u. MW according to IEEE Standard-112 (1991). These are applied to the LFC configuration given in case 1. Fig. 7 illustrate the QRAWCP has better results in comparison to other PID controller techniques given in Tan (2005); Padhan and Majhi (2013); Anwar and Pan (2015), and also using IMC by Saxena and Hote (2013), which these shows large oscillation across load frequency Δf. Similar to case 1, ±50% parametric variation has been considered, as shown in Fig. 8 and 9, which represents robustness capability of proposed approach in comparison to others. The results obtained from the graphical analysis can be better understood using the integral performance indices values, given in Table 3, for respective control techniques including the proposed one. The values from this table clearly implies that the frequency of generated voltage suffers less variation, when controlled using QRAWCP approach.

3.3 Case 3: LFC for two area control

Extending the application of the proposed technique to two-area power system model in this case. The model assumed for this purpose consists of two reheated generators, one in each area. The schematic of the individual areas and their interconnections is shown in Fig. 10, which is taken from Padhan and Majhi (2013) and Anwar and Pan (2015). The dynamics of each area is same as for the single area case, with the addition of the interconnected Tie-Line power of $T_{i1} = T_{i2} = 4.2$ and frequency bias

Table 2. Performance indices for Non-reheated turbine($\times 10^{-4}$)

Methods	Nominal Plant				Lower -50% plant				Upper +50% plant			
	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE
Proposed	0.013	13.79	0.018	25.24	0.0087	12.73	0.014	24.61	0.022	14.52	0.028	24.96
Tan	1.777	177.7	3.026	348.1	0.696	157.0	1.396	428.8	2.524	202.7	4.229	391.9
Padhan & Majhi	0.393	76.63	0.562	150.5	0.191	76.36	0.340	196.5	0.790	110.4	1.205	222.9
Anwar & Pan	0.289	44.35	0.378	61.97	0.110	39.99	0.155	70.23	0.786	124.6	1.291	275.6
Saxena & Hote	0.350	65.55	0.492	117.5	0.073	22.34	0.089	32.80	1.084	160.9	1.982	387.4

Table 3. Performance indices at Non-linearities constraints GRC and GDB considered ($\times 10^{-4}$)

Methods	Nominal Plant				Lower -50% plant				Upper +50% plant			
	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE
Proposed	0.165	60.92	0.339	140.5	0.160	58.21	0.313	127.3	0.162	60.83	33.73	143.7
Tan	27.93	792.5	60.56	1864.4	13.55	719.8	31.24	2138.8	30.21	795.5	65.29	1828.6
Padhan & Majhi	5.129	352.5	9.423	815.8	3.551	351.0	7.296	969.2	5.738	352.5	10.33	806.4
Anwar & Pan	2.997	184.0	4.679	306.7	1.908	183.9	3.113	356.1	4.009	260.9	6.699	558.4
Saxena & Hote	3.412	231.8	5.612	456.3	0.953	92.53	1.332	147.5	6.062	426.1	12.85	1168.1

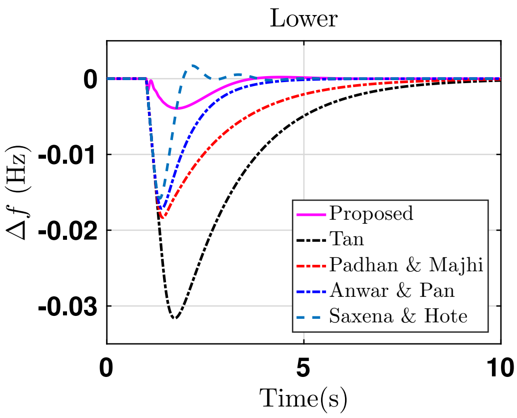

Fig. 8. Response under −50% lower parametric uncertainty of LFC with GRC and GDB

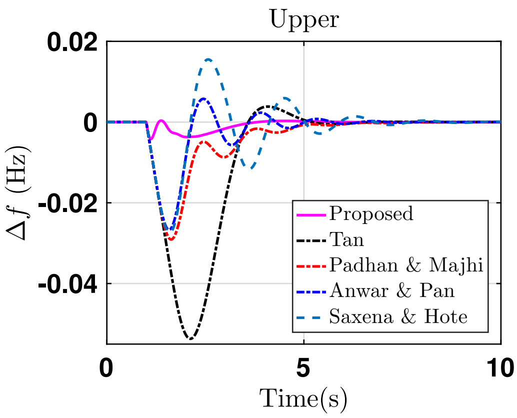

Fig. 9. Response under +50% upper parametric uncertainty LFC with GRC and GDB

is $B_1 = B_2 = 0.35$. The analysis with the two-area model is done by applying a load disturbance at 1 sec for ΔP_{d1}, and at 15 sec for ΔP_{d2}. The PID controller used for this analysis is kept same as used for the single area situation, and the magnitude of the injected disturbance is: $|\Delta P_{d1}| = |\Delta P_{d2}| = 0.01$ p.u.MW. The results of this analysis are shown in Fig. 11, which shows that the load frequency curve exhibits lesser undershoot and quicker convergence to zero, as compared to using other techniques reported so far.

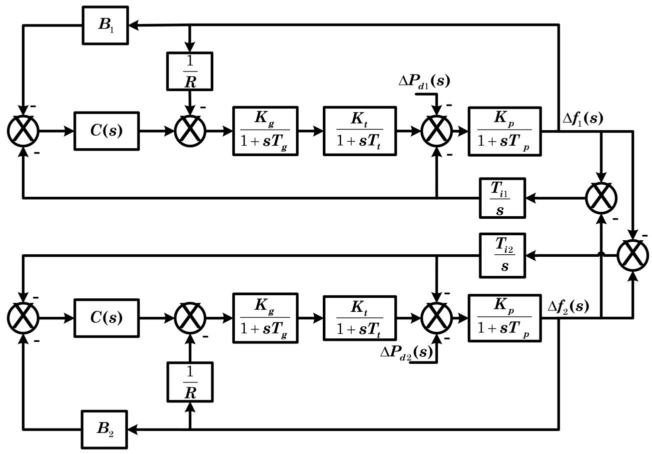

Fig. 10. Block diagram of multi two area power system

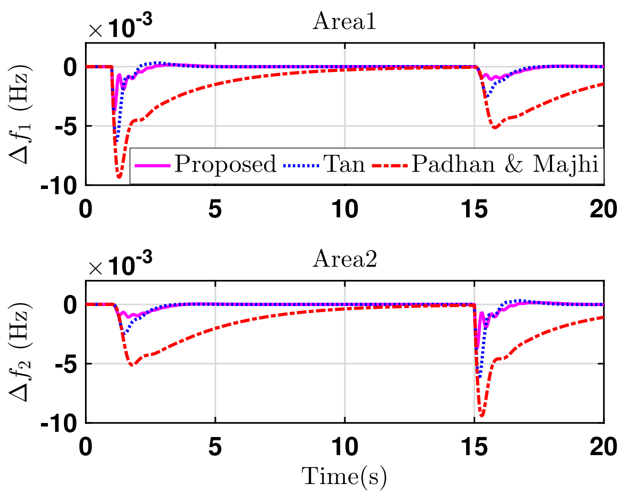

Fig. 11. Response of proposed scheme for Case 3 Multi area-2

4. CONCLUSION

A new model-based scheme for PID controller, based on LQR approach with an additional compensating pole, to address the LFC problem, is proposed. It is applied and compared with recent approaches reported for the same problem, in three different cases. In Case 1, discussion on single area with non-reheated turbine is made, followed by consideration of non-linearities such as GRC and GDB, in Case 2. Case 3 uses Case 1 for a two-area power system, with an exception that, instead of using non-reheated turbine for single area, reheated turbines are used in the two-area case. In all these cases, the control of load frequency is achieved by the proposed technique, that is, QRAWCP-PID, as well as the recent ones. Keen observation of the results obtained from these analysis clearly indicate that the proposed controller outperforms the existing ones, regarding the LFC problem, considering external disturbances and parametric variations. More clarity about the superiority of the proposed control logic is achieved by calculating and comparing the integral performance indices for each strategy.

REFERENCES

Anwar, M.N. and Pan, S. (2015). A new PID load frequency controller design method in frequency domain through direct synthesis approach. *Int. J. Electr. Power Energy Syst.*, 67, 560–569.

Astrom', K.J. and Hagglund, T. (1995). *PID Controllers: Theory, Design and Tuning.* ISA; 2nd Revised edition, 2nd edition.

Bazanella, A.S., Pereira, L.F.A., and Parraga, A. (2016). A New Method for PID Tuning Including Plants Without Ultimate Frequency. *IEEE Transactions on Control Systems Technology*, 1–8.

Blevins, T.L. (2012). PID Advances in Industrial Control. *IFAC Proceedings Volumes*, 45(3), 23–28.

Concordia, C., Crary, S.B., and Parker, E.E. (1941). Effect of Prime-Mover Speed Governor Characteristics on Power-System Frequency Variations and Tie-Line Power Swings. *Transactions of the American Institute of Electrical Engineers*, 60(6), 559–567.

Dryer, H.A. (1932). Frequency Regulation- The Fundamental Problem. *Electrical World*, 342.

Estrada, H. (1940). Regulation of System Load and Frequency. *Transacction of the A.S.M.E.*, 62(3), 221–232.

Gaing, Z.L. (2004). A Particle Swarm Optimization Approach for Optimum Design of PID Controller in AVR System. *IEEE Transactions on Energy Conversion*, 19(2), 384–391.

Hanwate, S. and Hote, Y.V. (2017). Relative Stability Analysis of Perturbed Cart Inverted Pendulum: An Experimental Approach. *IETE Technical Review*, 1–16. doi:10.1080/02564602.2017.1370396.

Hanwate, S., Hote, Y.V., and Saxena, S. (2018). Adaptive Policy for Load Frequency Control. *IEEE Transactions on Power Systems*, 33(1), 1142–1144.

Hanwate, S.D. and Hote, Y.V. (2018). Design of PID controller for sun tracker system using QRAWCP approach. *International Journal of Computational Intelligence Systems*, 11(1), 133–145.

IEEE Standard-112, . (1991). *112-1991 IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.*

Iruthayarajan, M.W. and Baskar, S. (2009). Evolutionary algorithms based design of multivariable PID controller. *Expert Systems with Applications*, 36(5), 9159–9167.

Kumar, N., Tyagi, B., and Kumar, V. (2017). Application of fractional order PID controller for AGC under deregulated environment. *International Journal of Automation and Computing*, 1–10.

Kundur, P. (1994). *Power system stability and control.* McGraw-Hill.

Masuda, S. (2012). PID controller tuning based on disturbance attenuation FRIT using one-shot experimental data due to a load change disturbance. *IFAC Proceedings Volumes*, 45(3), 92–97.

Nair, A.P., Selvaganesan, N., and Lalithambika, V. (2016). Lyapunov based PD/PID in model reference adaptive control for satellite launch vehicle systems. *Aerospace Science and Technology*, 51, 70–77.

Padhan, D.G. and Majhi, S. (2013). A new control scheme for PID load frequency controller of single-area and multi-area power systems. *ISA Trans.*, 52(2), 242–251.

Padula, F., Sandrini, R., and Cominardi, G. (2012). Adaptive PI Control of an Organic Rankine Cycle Power Plant. *IFAC Proceedings Volumes*, 45(3), 459–464.

Prasad, L.B., Gupta, H.O., and Tyagi, B. (2014). Application of policy iteration technique based adaptive optimal control design for automatic voltage regulator of power system. *International Journal of Electrical Power & Energy Systems*, 63, 940–949.

Ramana, N.V. (2010). *Power system operation and control.* Pearson.

Saxena, S. and Hote, Y.V. (2013). Load frequency control in power systems via internal model control scheme and model-order reduction. *IEEE Trans. Power Syst.*, 28(3), 2749–2757.

Saxena, S. and Hote, Y.V. (2016). Decentralized PID load frequency control for perturbed multi-area power systems. *International Journal of Electrical Power & Energy Systems*, 81, 405–415.

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

Sondhi, S. and Hote, Y.V. (2014). Fractional order PID controller for load frequency control. *Energy Conversion and Management*, 85, 343–353.

Tan, N. (2005). Computation of stabilizing PI and PID controllers for processes with time delay. *ISA transactions*, 44, 213–223.

Tyagi, B. and Srivastava, S. (2005). A LQG Based Load Frequency Controller in a Competitive Electricity Environment. *International Journal of Emerging Electric Power Systems*, 2(2), 1–13.

W. Tan (2010). Unified tuning of PID load frequency controller for power systems via IMC. *IEEE Trans. Power Syst.*, 25(1), 341–350.

Yun Li, Kiam Heong Ang, and Chong, G. (2006). PID control system analysis and design. *IEEE Control Systems Magazine*, 26(1), 32–41.

Ziegler, J.G. and Nichols, N. (1942). Optimum Settings for Automatic Controllers. *Transacction of the A.S.M.E*, 64, 759–768.