Solution of load frequency control through Jaya technique with unified power flow controller and redox flow battery

Avinash Panwar[1], Vinesh Agarwal[1], Gulshan Sharma[2], Kayode Timothy Akindeji[3], Narayanan Krishnan[4]
[1]Department of Electrical Engineering, School of Engineering and Technology, Sangam University, Bhilwara, India
[2]Department of Electrical Engineering Technology, University of Johannesburg, Johannesburg, South Africa
[3]Department of Electrical Power Engineering, Durban University of Technology, Durban, South Africa
[4]Department of Electrical & Electronics Engineering, Sastra Deemed University, Thanjavur, India

Article Info

Article history:

Received Oct 29, 2021
Revised Mar 17, 2022
Accepted Apr 1, 2022

Keywords:

Jaya optimization
Load frequency control
Redox flow battery
Two degree of freedom-PID
Unified power flow controller

ABSTRACT

This paper proposes the initial strategy of designing two degree of freedom proportional integral derivative (2DOF-PID) made load frequency control (LFC) action optimized using Jaya optimization algorithm for a hydro-hydro system. At first, the PID optimized through Jaya is used for hydro-dominated system, and the comparative analysis of all possible error definitions are carried out to show the benefits of selecting integral time absolute error (ITAE) for LFC. Then, 2DOF-PID is designed for the hydro governing system, and its performance is compared with other designs to show the efficacy of the present LFC about computed error values gain of the various models via graphical LFC. The results obtained through simulations are promising but oscillatory with greater settling time. Hence, the proposed controller is retuned by considering the unified power flow control (UPFC) in arrangement with the tie-line and redox flow battery (RFB) units in area-2, and it is further seen that the outcomes of the application show the prevalence of the proposed work.

Corresponding Author:

Gulshan Sharma
Department of Electrical Engineering Technology, University of Johannesburg
Johannesburg, South Africa
Email: gulshans@uj.ac.za

1. INTRODUCTION

The electrical generation and delivery systems of an interconnected power system must match operational standards to make system more reliable and reduces the generation reserve capacity requirements. The power generation areas are interconnected using AC tie-line, which encounter the frequency and tie-line power alterations from standard values. This is due to alteration in energy requirement of the customers over the complete day. Thus, the generators are equipped with the load frequency control (LFC) to minimize the generation-demand mismatch and, therefore, maintain frequency to its satisfactory constrain, i.e., ± 0.5 Hz [1]-[3] and set the tie-line power to its original value. The straight combination of frequency deviation and tie-line power control alter is named as area control error (ACE). In writing, different LFC procedures have been proposed to supply a straightforward and viable control to meet LFC guidelines. The control procedure based on classical controllers, i.e., PID, was earlier utilized in the LFC [4]. The wide-ranging investigations have been made to find effective controller methodologies i.e., full state LFC using modern control theory, control design using real-time observable states, and model predictive action are accessible for the LFC problem [5]-[7]. The idealistic implementation of the LFC is done by utilizing all states and then gain matrix is determined by optimizing specific performance index. Be that as it may, the plant model requires measuring all the system states, which is not a pragmatic approach. The analysts proposed similar concepts with easily accessible states to overcome this bottleneck. Later, the intelligent LFC actions founded on neural networks, fuzzy logic, multi-agent systems, nature-inspired intelligent optimization, and fusion of intelligent techniques have been proposed by analysts and control engineers worldwide to unravel the LFC issue [8]-[12].

Genetic algorithm (GA), in available optimization algorithm, has been widely utilized over other optimization algorithms and has demonstrated its capability to handle the complex and significant system problem of LFC. In Rerkpreedapong *et al.* [13], this technique is applied to discover and unravel the frequency control issue. In Passino [14], effective implementation is accomplished by optimizing linear matrix inequalities (LMI) by GA to solve the LFC problem. Though, Nanda *et al.* [15], the analysts detailed a few limitations in this technique. Further, the output of GA widely varies based on hyperparameter and objective function. The limitation of GA such as trap in local minima/maxima, the requirement of larger ephocs, and are efficiently tackled by particle swarm optimization (PSO) algorithm. PSO has a faster convergence rate, and adaptive weight vectors often help avoid convergence in local minima/maxima for the same degree of execution. Of late, the investigators have tried applying a more viable and formative computation strategy, i.e., bacteria foraging optimization (BFO) calculation, to effectively address the frequency control issue. It is modeled as per the behavior of E. coli microscopic organisms found in humans. Given its special dispersal and elimination technique, it can find the global optimum for fewer populations. These points of interest overcome the confinement of PSO and GA, i.e., avoid trapping in local minima/maxima, and demonstrated to be an effective methodology to design LFC controller. Ali and Abd-Elazim [16] displayed the efficacy of BFO over other algorithm bases LFC for interconnected vitality framework. In Panda *et al.* [17], the issue of LFC is overseen utilizing BFO optimized PI, and its predominance over GA is outlined for a two-area interconnected electrical framework. The hybrid BFO-PSO was proposed in [18] to find the perfect values of PI for the multi-area electrical systems. The predominance of BFO-PSO was seen over PSO, BFOA, GA, craziness-built PSO, and ANFIS. Thus, it is observed that intelligent optimization procedures are an effective way to design the frequency controllers, and the examiners continuously welcome the modern and capable optimization method in LFC, i.e., JAYA optimization [19]. On the other side, the researchers are also exploring diverse PID models these days, and one of the new advancements over standard PID is two degrees of freedom (2DOF) PID.

Furthermore, LFC designs were illustrated on a thermal model or hydro-thermal interlinked generation system. They lacked an appropriate and straightforward control plan for hydro governing frameworks because hydro turbines need higher time to respond to sudden load alteration than thermal turbines. The LFC abdicate of the hydro regulating framework are lazy and have diligent movements. Subsequently, the analysts and electric control engineers are dodging this framework to create a reasonable plan for LFC. Recent trends show that clean and green energy sources are getting worldwide acceptance to produce electric power such as hydro, bulk hydro, or micro-hydro. However, the operation of the existing power network in such sources becomes more complex. Hence, it is critical to examine a straightforward and compelling controller technique for such a crucial hydro-hydro framework. The modern and quick advancement of power electronic techniques has given rise to the advancement of flexible alternating current transmission (FACTS) frameworks to form strides the lesson of the electrical system and to agreeable control the electrical power flowing in any lines [20]-[25]. FACTS can control active and reactive power, improve the electrical output for sudden changes in control requirements, and guarantee the quality transmission of electrical essentialness to advanced clients. Redox flow battery (RFB) within the FACTS framework is the fast-acting reserve and responds immediately to active power demand. Therefore, the presence of such fast-acting reserves manages to damp out the electromechanical oscillation. If there is a sudden rise in the power demand, the stored energy in RFB is immediately utilized through the power conversion system, which comprises an inverter/rectifier system. Essentially it assimilates control amid the sudden discharge of loads. Be that as it may, it is not conceivable to put RFB in each region of the interconnected control framework due to financial reasons. Hence, unified power flow controller (UPFC) may prove to be effective, very cheaper, and can be introduced in arrangement with tie-line to advance the execution of the electrical vitality framework.

In this way, the shared action of RFB and UPFC with 2DOF-PID-JAYA is proposed and investigated for the LFC of the interlinked hydro system. In line with this, the novel contributions of this article are: To suggest a new plan for LFC of an interlinked hydro governing system based on 2DOF-PID. The accurate and precise gains of PID are accomplished through the JAYA optimization algorithm. At first, the PID is designed through JAYA for the hydro governing interconnected framework, and the LFC action is checked with regards to various definitions of errors such as IAE, ISE, ITAE, and ITSE for standard load alteration, and the correct error definition is chosen for the next level of study i.e., ITAE for the present LFC studies. In the next step, 2DOF-PID based LFC action effectively optimized through JAYA is designed for LFC of an interconnecting hydro governing framework, and the outcomes of the proposed LFC is compared with other LFC actions with regards to parameters 2DOF-PID, the value of ITAE and graphical LFC. It is observed that the output of 2DOF-PID is respectable in comparison to other LFC actions but still, the outcomes of LFC have greater overshoot continuous wavering, and that is why the proposed controller is explored once more with consideration of UPFC in the course of action with tie-line and RFB units presented at terminals of another area.

2. MODEL INFORMATION

To investigate capacity of 2DOF-PID develop via JAYA for LFC, an interlinked system having the hydro generating unit in respective areas is considered. The RFB model is incorporated in zone-2, seeing UPFC linked with tie-line. The linked hydro electrical framework given RFB and UPFC is well reveal in Figure 1.

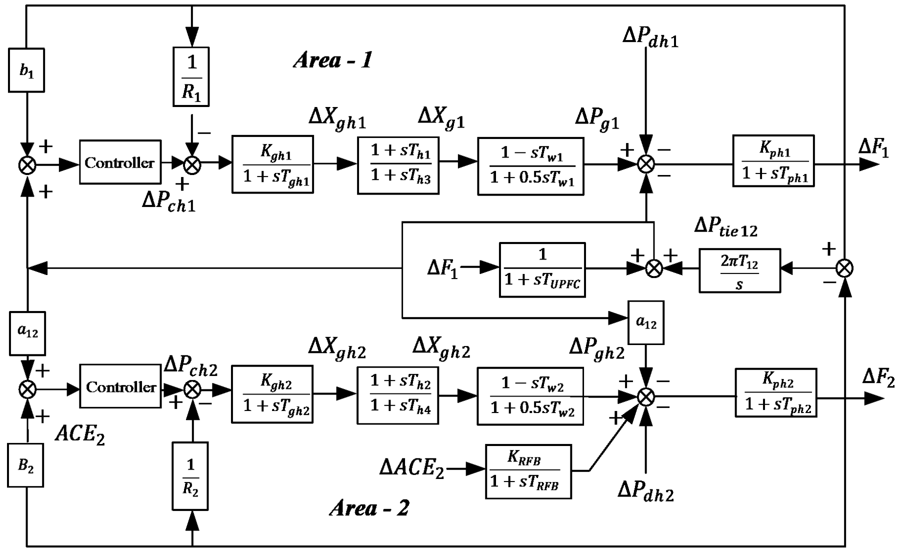


Figure 1. Inter-linked hydro governing model with UPFC and RFB

3. GENERATION RATE CONSTRAINTS AND DEAD-BAND DETAILS

In an interconnected electrical network, the change in generation as per the control action is restricted to avoid the wear and tear of the energy source and modeled as upper and lower bounds. The GRC limit is 270%/min (0.045pu/s) for increasing and 360%/min (0.06pu/s) for bringing down the generation. The schematic exchange work layout is given in Figure 2. Assist a non-linearity dead-band of 0.02% [12] is additionally joined within the hydro-hydro model as this non-linearity impacts the output of LFC controllers and makes it worse, but it is important to consider avoiding the damages to the various other equipment's connected in the hydro-hydro plant.

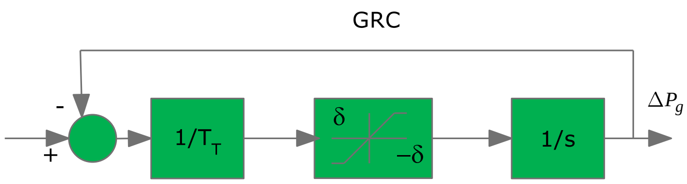


Figure 2. Turbine model with GRC

3.1. UPFC and RFB details

UPFC is capable enough to arrange the stream of power flow in tie-lines, thus displaying the prevalent execution and setting the standard voltage. With sudden electric power requirement variations, the execution of LFC of hydro frameworks is unsuccessful in showing the required LFC performance owing to the higher returning nature of hydro turbines. Subsequently, UPFC is introduced in arrangement association to tie-lines. The shunt converter given for UPFC presents the controlled shunt voltage such that the real/active component of the current in the shunt department equalizes the genuine control as required by the arrangement converter. The complex control at the tolerating conclusion of line is [20]:

$$P_{real} - jQ_{reactive} = \overline{V_r^*} I_{line} = \overline{V_r^*}\{(\overline{V_s} + \overline{V}_{se} - \overline{V}_r)/j(X)\} \quad (1)$$

where,

$$\overline{V}_{se} = |V_{se}|\angle(\delta_s - \phi_{se}) \quad (2)$$

In (2), V_{se} is the magnitude of series voltage, from (1), the real portion is expressed as (3).

$$P_{real} = \frac{|V_s||V_r|}{X} sin\,\delta + \frac{|V_s||V_{se}|}{X} sin(\,\delta - \phi_{se}) = P_0(\delta) + P_{se}(\delta, \phi_{se}) \quad (3)$$

In case Vse = 0, the real power is uncompensated, whereas the significance of the UPFC course of action voltage can be controlled between zero and Vse max. Subsequently, the phase angle can be coordinated between 0° to 360° at any control point. In LFC considers approximately, the UPFC based control action can be finished through taking exchange work portrayal [20]:

$$\Delta P_{UPFC}(s) = \left\{\frac{1}{1+sT_{UPFC}}\right\}\Delta F(s) \quad (4)$$

where TUPFC implies the time constant of UPFC, the RFB is modeled as a dynamic control source for area-2 with steady TRBF. RFB may be an inactive gadget, and thus its reaction for control is exceptionally quick compared to frequency alteration; the time steady of RFB is respected as seconds for the control plan. The modeling and transfer function domain of RFB is created in [21], as shown in Figure 3. The derived transfer function model of UPFC and RFB is considered to improve the hydrodominated LFC performance.

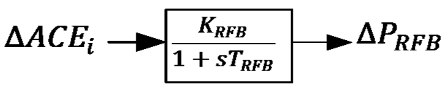


Figure 3. The depiction of RFB

3.2. Optimization problem

The thought behind optimization is to attain least objective work as characterized by the client for the considered framework demonstrate employing a characterized execution list (PI). The performance index for LFC is defined as the area control error from the interconnected electrical network. The various distinct performance indices are available in past LFC studies; however, integral time multiplied absolute error (ITAE) diminishes the settling time & peak overshoot, which other error definitions cannot finish. It is detailed and tried by the analysts and control engineers that ITAE ensures many time response specifications compared to other performance indexes. Consequently, the ITAE is utilized to assess the execution of 2DOF for the hydro framework.

The PI (J_n) for the nth control ranges are as takes after:

$$J_n = \int_0^{Tsim} (ACE).t.dt.$$

The application of optimization is to decide the controller picks up for which the ITAE has the least esteem. These gains are calculated after considering following constraints.

$$K_{Pn}^{min_{pn}{}_{pn}^{max}}$$

$$K_{in}^{min_{in}{}_{in}^{max}}$$

$$K_{dn}^{min_{dn}{}_{dn}^{max}}$$

$r_1^{min_1{}_1^{max}}$

$r_2^{min_2{}_2^{max}}$

The schematic representation of 2DOF-PID is given in Figure 4. The 2DOF-PID is designed by optimizing the parameters of the controller. The JAYA optimization algorithm is simulated to decide the ideal values of controller gains. The JAYA strategy was proposed by R. Venkata Rao in 2016 [19] and effectively tried in the present work as its application has not been tried on hydro-dominated LFC framework with the 2DOF-PID controller. The parameter-less JAYA algorithm has only one phase and is simpler to apply for LFC. The solution for *ith* iteration is modified as (5):

$$X'_{p,m,n} = X_{p,m,n} + r_{1,p,n}\left(X_{p,best,n} - \left|X_{p,m,n}\right|\right) - r_{2,p,n}\left(X_{p,worst,n} - \left|X_{p,m,n}\right|\right) \tag{5}$$

where, $X_{p,best,n}$ = best value of p variable in all population in nth iteration. $X_{p,worst,n}$ worst value of p variable in all population in n^{th} iteration. $X'_{p,m,n}$ = updated position of p variable for mth population in n^{th} iteration. $r_{1,p,n}, r_{2,p,n}$ two random number for the p^{th} variable during the n^{th} iteration in the range [0,1]. As per (5), $r_{1,p,n}\left(X_{p,best,n} - \left|X_{p,m,n}\right|\right)$ causes solution to move closer to best solution and $r_{2,p,n}\left(X_{p,worst,n} - \left|X_{p,m,n}\right|\right)$ causes solution to move away from the worst solution. The $X'_{p,m,n}$ is accepted only If it gives a better function value. These accepted function values in the current iteration become input to the next iteration. The steps for finding optimized solutions through the JAYA algorithm are given in Figure 5. The calculation was run 30 epochs, and the driving course of action obtained via 30 epochs is considered as final parameters for diverse structures of PID. Table 1 shows various structures of PID and calculated values. Table 2 shows the effect on objective work by joining UPFC and RFB with optimized controller outlined with framework non-linearity.

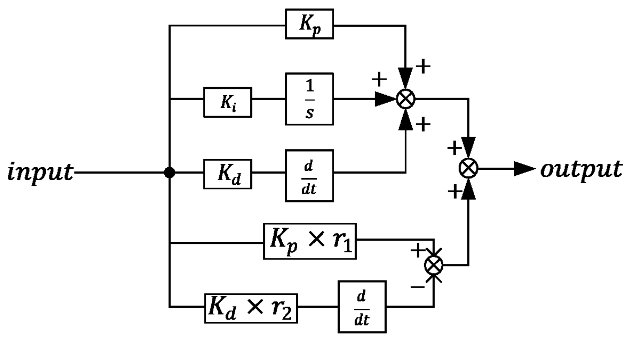


Figure 4. Structure of 2DOF-PID controller

Table 1. Comparative analysis of gains of various PID obtain via JAYA

Controllers	K_p	K_i	K_d	r_1	r_2	ITAE
PI	0.0529	-0.045	-	-	-	10.858
ID		-0.037	0.619	-	-	7.1952
PID	-0.3351	-0.048	0.447	-	-	4.9620
2DOF-PID	-0.3351	-0.048	0.447	-0.264	-0.054	4.7958

Table 2. Computed gains of 2DOF-PID with UPFC & RFB with respect to GRC and dead-band

Controllers	K_p	K_i	K_d	r_1	r_2	ITAE
2DOF-PID	-0.3351	-0.048	0.4478	-0.2648	-0.0548	4.7958
2DOF-PID+UPFC+RFB	-0.3351	-0.048	0.4478	-0.2648	-0.0548	12.497
2DOF-PID+UPFC+RFB+Retune	-2	-2	2	-2	0.6517	0.9478

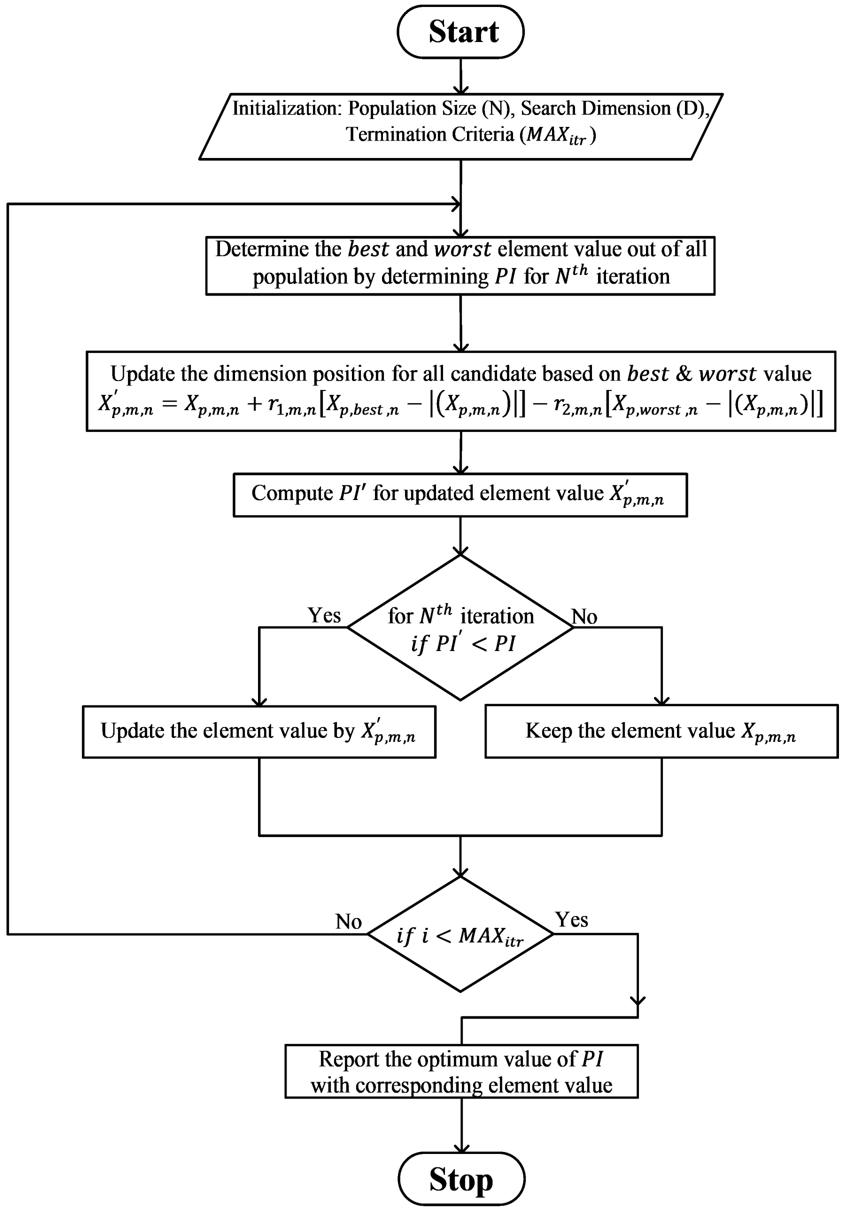


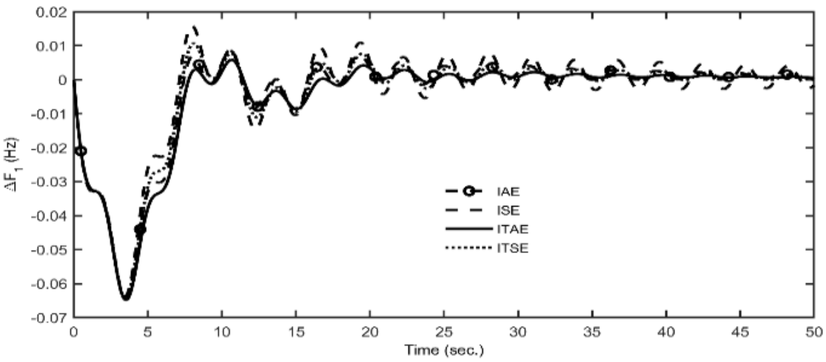
Figure 5. The execution steps of JAYA built PID controller

4. RESULT ANALYSIS

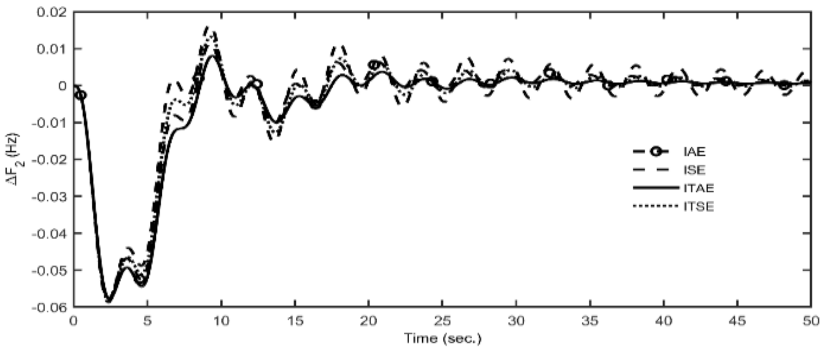
A linked hydro framework with hydro turbines in both control regions with the same capacity is utilized for the investigation. The inquiry about work explores the execution of such a hydro governing framework to demonstrate and propose an effective plan of 2DOF built PID. Its parameters are evaluated through the JAYA algorithm to assess the execution of control for LFC beneath differing working framework conditions.

To start with, the PID control is planned for LFC of the hydro control framework and measured for 1% load variation in area-1. The frequency and tie-power deviations are obtained and compared with different error values, and these results are shown in Figure 6(a)-(c). It is observed that frequency and tie-power deviations reach consistent original values quickly compared to other LFC actions.

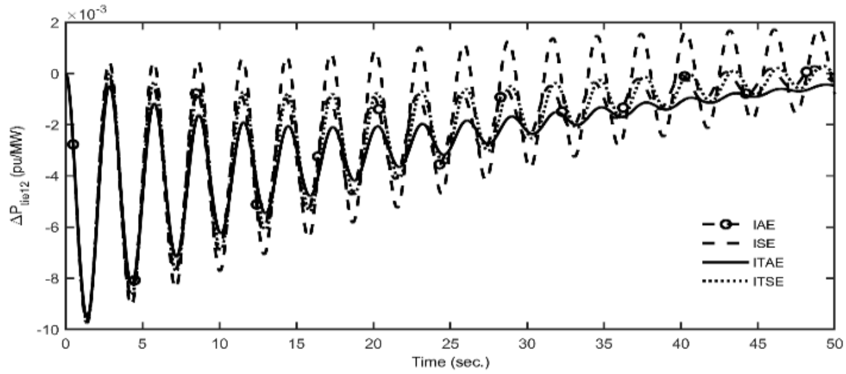
Additionally, it is also seen that oscillations damp out from LFC results after 25 seconds which is only possible through ITAE compared to other error values, and hence ITAE is the precise and accurate error for LFC and chosen for the rest of the LFC studies. Now, the 2DOF-PID is designed for the hydro governing system, and its outcomes are matched with PI, ID, and PID. The execution of 2DOF-PID founded on JAYA over other LFC actions are assessed on the premise of ITAE, and the comparative investigation of all LFC in terms of various parameters of controller and ITAE has appeared in Table 1.



(a)



(b)



(c)

Figure 6. LFC outcomes for 1% load alteration in area-1 obtain via PID: (a) frequency response of area-1, (b) frequency response of area-2, and (c) tie-line power response

The look of outcomes shows that the ITAE value obtained via 2DOF-PID (4.795867) is very less in comparison to PID (4.962033), ID (7.195234), and PI (10.85805), and it further shows the financial aspects of the implementation of LFC. The graphical outcomes appeared in Figure 7(a)-(c). It is observed that the performance of 2DOF-PID and PID is almost comparable in terms of overshoot, settling time, and getting back to reference value when optimized through JAYA. Though, the obtained ITAE is lesser for 2DOF-PID than PID when both are calculated through JAYA. On the other hand, the LFC outcomes obtained via ID for frequency and tie-power are free from oscillations, yet the overshoot is higher. The LFC outcomes offered by PI are worst considering all aspects of LFC under similar operating conditions. Though the LFC actions need further enhancement, the RFB is added to the model at terminal-2, UPFC aligns with tie-line, and 2DOF-PID is designed again through JAYA for the hydro governing system. The outcome of 2DOF-PID is assessed regarding ITAE and matched with 2DOF-PID+UPFC+RFB and with parameters reevaluated, i.e., 2DOF-PID+UPFC+RFB+Retune. The outcomes are listed in Table 2, and it is observed that there is an increase in the value of ITAE (12.49768) with the incorporation of UPFC and RFB concerning no UPFC and RFB with

2DOF-PID (ITAE: 4.795867) for the hydro governing framework. It is also observed that there is a further reduction in ITAE (0.947843) when all parameters are recalculated via JAYA for 2DOF-PID+UPFC+RFB and LFC non-linearity included in the hydro governing framework.

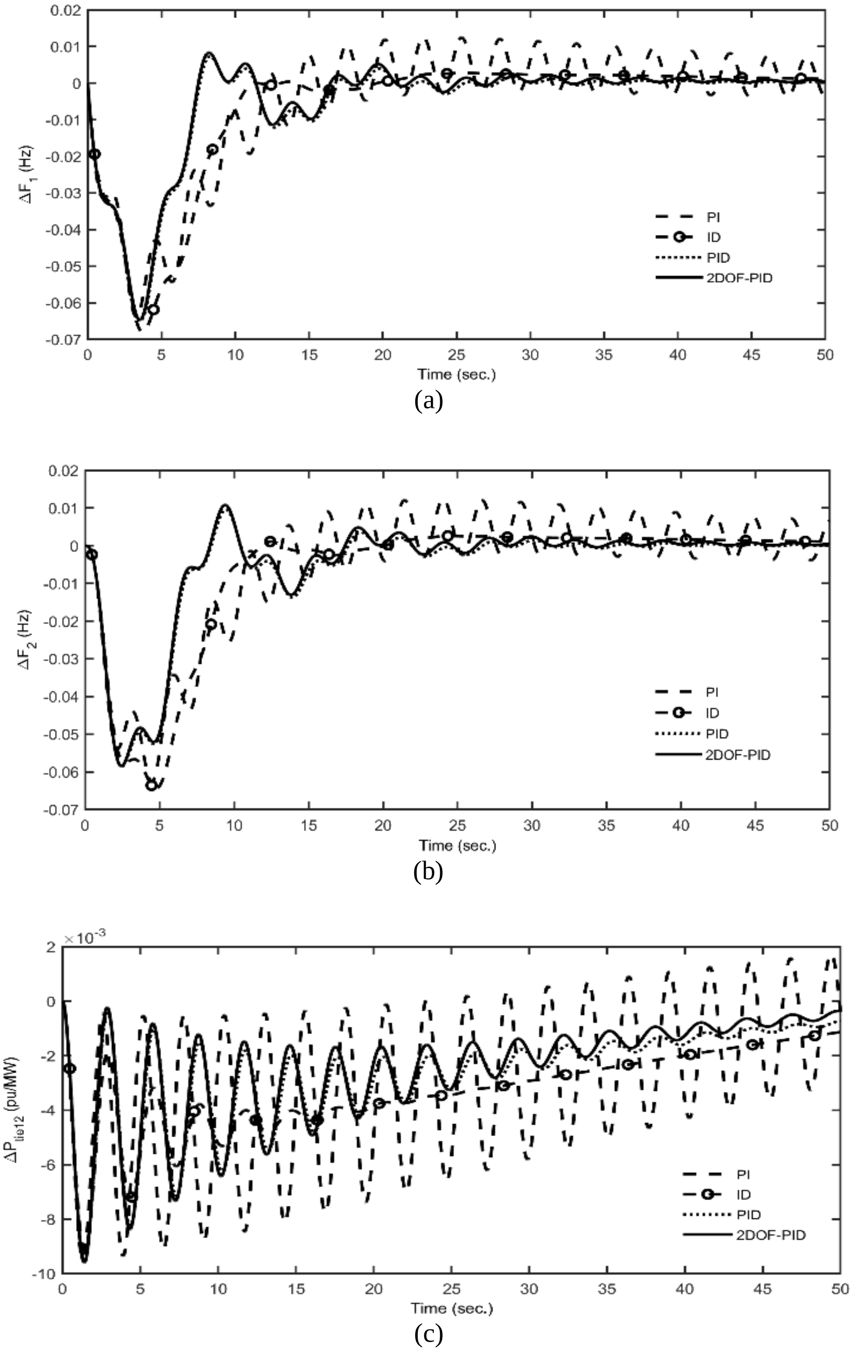


Figure 7. LFC outcomes for 1% load alteration in area-1: (a) frequency response of area-1, (b) frequency response of area-2, and (c) tie-line power response

The same effect is also observed in LFC outcomes of Figures 8(a)-(c), and it is clearly watch that there is a significant difference in LFC outcomes of 2DOF-PID with and without LFC non-linearity. Incorporating UPFC and RFB has improved the LFC outcomes greatly, even when non-linearities are present. At last, it is essential to note that all LFC responses show the lowest first peak, enhanced settling to reference value, and oscillation-free LFC outcomes for 2DOF-PID when recalculated via JAYA with UPFC-RFB.

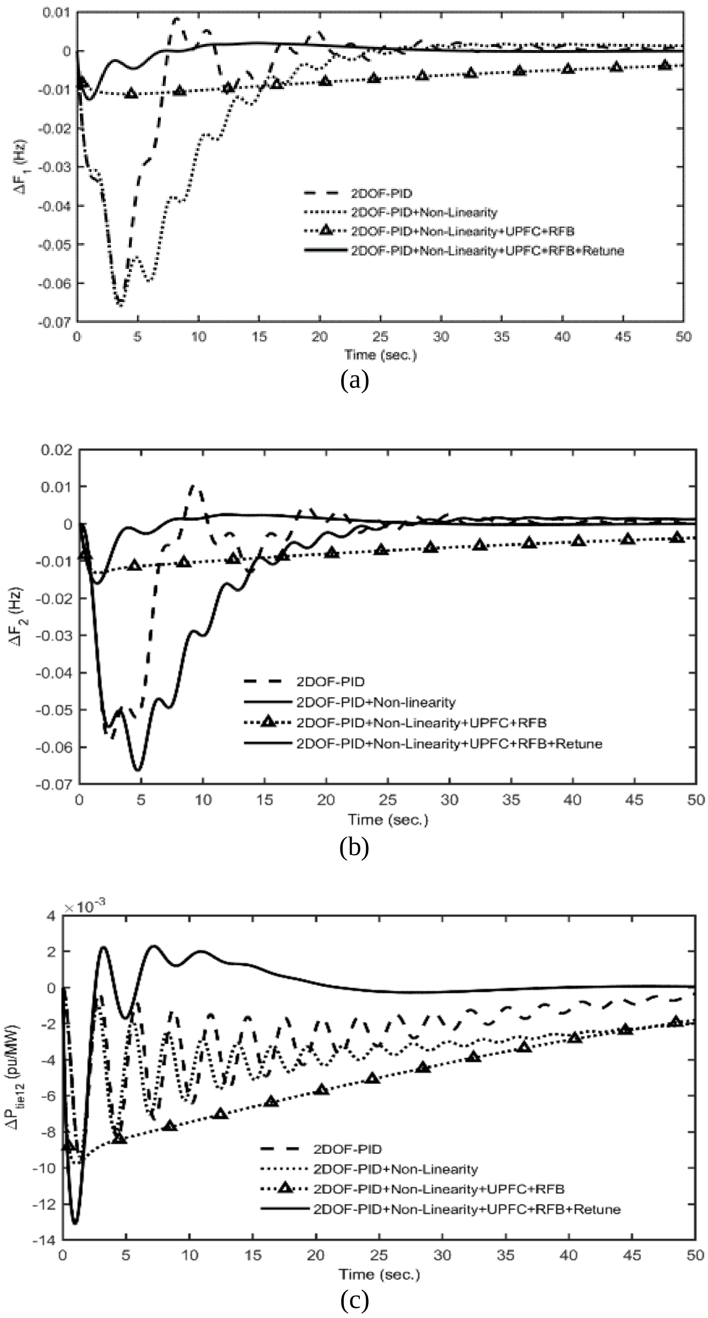


Figure 8. LFC outcomes for 1% load alteration in zone-1 i.e., in view of dead-band and GRC: (a) frequency response of area-1, (b) frequency response of area-2, and (c) tie-line power response

5. CONCLUSION

The current efforts are to propose 2DOF-PID successfully optimized through the JAYA optimization calculation for LFC having an interlinked hydro directing system. The 2DOF-PID orchestrate endeavored for 1% load adjustment in area-1 and appears up the dominance of JAYA enhanced 2DOF-PID over other LFC exercises. The proper selection of error values is crucial while designing the LFC actions for the hydro governing framework. It is observed that ITAE is one of the precise and accurate error definitions to consider while designing LFC action in comparison to ITSE, IAE, and ISE. The 2DOF-PID effectively optimized through JAYA is good enough to meet the LFC standards of hydro governing framework even in the presence of LFC non-linearity. Still, it needs further improvement to have better LFC action for such systems. The UPFC linking in the course of activity with tie-line seeing RFB in region-2 with JAYA augmented 2DOF-PID has well secured the deviations in a hydro governing system in the closeness of dead-band and GRC and moves forward the LFC results to an incredible degree. The reduction in ITAE gotten through JAYA optimized 2DOF-PID with UPFC and RFB appears to take a toll with reasonable arrange. The examinations uncover that the JAYA optimized 2DOF-PID with joint efforts from UPFC and RFB is practical, straightforward, and able to minimize the significant system frequency and tie-power deviations in the interlinked hydro governing system.

REFERENCES

[1] G. Sharma, Ibraheem, K. R. Niazi, and R. C. Bansal, "Adaptive fuzzy critic based control design for AGC of power system connected via AC/DC tie-lines," *IET-Generation Transmission and Distribution*, vol. 11, no. 2, pp. 560-569, 2017, doi: 10.1049/iet-gtd.2016.1164.

[2] G. Sharma, I. Nasiruddin, K. R. Niazi, and R. C. Bansal, "Robust automatic generation control regulators for a two-area power system interconnected via AC/DC tie-lines considering new structures of matrix Q," *IET-Generation Transmission and Distribution*, vol. 10, no. 14, pp. 3570-3579, 2016, doi: 10.1049/iet-gtd.2016.0321.

[3] G. Sharma, N. Krishnan, Y. Arya, and A. Panwar, "Impact of ultracapacitor and redox flow battery with JAYA optimization for frequency stabilization in linked photovoltaic-thermal system," *International Transactions on Electrical Energy Systems*, vol. 31, no. 5, 2021, doi: 10.1002/2050-7038.12883.

[4] Y. Arya, *et al.*, "AGC performance amelioration in multi-area interconnected thermal and thermal-hydro-gas power systems using a novel controller," *Engineering Science and Technology, an International Journal*, vol. 24, no. 2, pp. 384-396, 2021, doi: 10.1016/j.jestch.2020.08.015.

[5] G. Sharma, I. Nasiruddin, and K Rehman Niazi, "Optimal AGC of asynchronous power systems using output feedback control strategy with dynamic participation of wind turbines," *Electric Power Component and Systems*, vol. 43, no. 4, pp. 384-398, 2015, doi: 10.1080/15325008.2014.949916.

[6] T. H. Mohamed, H. Bevrani, A. A. Hassan, and T. Hiyama, "Decentralized model predictive based load frequency control in an interconnected power system," *Energy Conversion and Management*, vol. 52, no. 2, pp. 1208-1214, 2011, doi: 10.1016/j.enconman.2010.09.016.

[7] Y. Arya, "Effect of energy storage systems on automatic generation control of interconnected traditional and restructured energy systems," *International Journal of Energy Research*, vol. 43, no. 12, pp. 6475-6493, 2019, doi: 10.1002/er.4493.

[8] H. Bevrani and T. Hiyama, "Intelligent automatic generation control," Boca Raton: CRC press, 2011.

[9] A. Safari, F. Babaei, and M. Farrokhifar, "A load frequency control using a PSO-based ANN for micro-grids in the presence of electric vehicles," *International Journal of Ambient Energy*, vol 42, no. 6, pp. 688-700, 2021, doi: 10.1080/01430750.2018.1563811.

[10] Y. Arya, "Impact of hydrogen aqua electrolyzer-fuel cell units on automatic generation control of power systems with a new optimal fuzzy TIDF-II controller," *Renewable Energy*, vol. 139, pp. 468-482, 2019, doi: 10.1016/j.renene.2019.02.038.

[11] A. Demiroren, N. S. Sengor, and H. L. Zeynelgil, "Automatic generation control by using ANN technique," *Electric Power Components and Systems*, vol. 29, no. 10, pp. 883-896, 2001, doi: 10.1080/15325000152646505.

[12] Y. L. Abdel-Magid and M. M. Dawoud, "Optimal AGC tuning with genetic algorithms," *Electric Power Systems Research*, vol. 38, no. 3, pp. 231-238, 1996, doi: 10.1016/S0378-7796(96)01091-7.

[13] D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, "Robust load frequency control using genetic algorithms and linear matrix inequalities," in *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 855-861, May 2003, doi: 10.1109/TPWRS.2003.811005.

[14] K. M. Passino, "Biomimicry of bacterial foraging for distributed optimization and control," in *IEEE Control Systems Magazine*, vol. 22, no. 3, pp. 52-67, June 2002, doi: 10.1109/MCS.2002.1004010.

[15] J. Nanda, S. Mishra, and L. C. Saikia, "Maiden application of bacterial foraging-based optimization technique in multi-area automatic generation control," in *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 602-609, May 2009, doi: 10.1109/TPWRS.2009.2016588.

[16] E. S. Ali and S. M. Abd-Elazim, "Bacteria foraging optimization algorithm-based load frequency controller for interconnected power system," *International Journal of Electrical Power and Energy Systems*, vol. 33, no. 3, pp. 633-638, 2011, doi: 10.1016/j.ijepes.2010.12.022.

[17] S. Panda, B. Mohanty, and P. K. Hota, "Hybrid BFOA-PSO algorithm for automatic generation control of linear and non-linear interconnected power systems," *Applied Soft Computing*, vol. 13, no. 12, pp. 4718-4730, 2013, doi: 10.1016/j.asoc.2013.07.021.

[18] R. V. Rao, "Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems," *International Journal of Industrial Engineering Computations*, vol. 7, no. 1, pp. 19-34, 2016, doi: 10.5267/j.ijiec.2015.8.004.

[19] R. K. Sahu, T. S. Gorripotu, and S. Panda, "A hybrid DE-PS algorithm for load frequency control under deregulated power system with UPFC and RFB," *Ain Shams Engineering Journal*, vol. 6, no. 3, pp. 893-911, 2015, doi: 10.1016/j.asej.2015.03.011.

[20] R. Francis and I.A. Chidambaram, "Optimized PI+ load frequency controller using BWNN approach for an interconnected reheat power system with RFB and hydrogen electrolyser units," *International Journal of Electrical Power and Energy Systems*, vol. 67, pp. 381-392, 2015, doi: 10.1016/j.ijepes.2014.12.012.

[21] M. A. R. Shafei, A. N. Abd Alzaher, and D. K. Ibrahim, "Enhancing load frequency control of multi-area multi-sources power system with renewable units and including nonlinearities," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no. 1, pp. 108-118, 2020, doi: 10.11591/ijeecs.v19.i1.pp108-118.

[22] A. Panwar, G. Sharma, I. Nasiruddin, and R. C. Bansal, "Frequency stabilization of hydro–hydro power system using hybrid bacteria foraging PSO with UPFC and HAE," *Electric Power Systems Research*, vol. 161, pp. 74-85, 2018, doi: 10.1016/j.epsr.2018.03.027.

[23] A. Saha and L. C. Saikia, "Utilisation of ultra-capacitor in load frequency control under restructured STPP-thermal power systems using WOA optimised PIDN-FOPD controller," *IET Generation, Transmission & Distribution*, vol. 11, no. 13, pp. 3318–3331, 2017, doi: 10.1049/iet-gtd.2017.0083.

[24] M. Sharma, S. Dhundhara, Y. Arya, and S. Prakash, "Frequency stabilization in deregulated energy system using coordinated operation of fuzzy controller and redox flow battery," *International Journal of Energy Research*, vol. 45, no. 5, pp. 7457-7475, 2021, doi: 10.1002/er.6328.

[25] S. Dhundhara and Y. P. Verma, "Grid frequency enhancement using coordinated action of wind unit with redox flow battery in a deregulated electricity market," *International Transactions on Electrical Energy Systems*, vol. 30, no. 3, e12189, 2020, doi: 10.1002/2050-7038.12189.

BIOGRAPHIES OF AUTHORS

Avinash Panwar is presently working towards his Ph.D. at Department of Electrical Engineering, School of Engineering and Technology, SANGAM University, India. He has the qualifications of B.E., M. Tech from Institute of Technology & Management (Bhilwara), Shri BalaJi college of Engineering and Technology, (Jaipur), India respectively. His area of interest includes power system operation and control, renewable energy technology and applied soft computing. He can be contacted at email: apanwar84@gmail.com.

Dr. Vinesh Agarwal is presently working as Associate Professor in Department of Electrical Engineering, School of Engineering and Technology, SANGAM University, India. He has more than 18 years of teaching and industrial experience. He has the qualifications of B.E., M. Tech and Ph.D. from recognised institution of India. His area of interest includes Renewable Energy and Conventional Power Systems, which includes Wind, PV, Hybrid Power Systems, Distributed Generation, Grid Integration of Renewable Energy, FACTS, Power System, and Power Electronics and Smart Grid. He can be contacted at email: vinesh.agarwal@sangamuniversity.ac.in.

Dr. Gulshan Sharma is presently working as Senior Lecturer in Department of Electrical Engineering Technology, University of Johannesburg, South Africa. He has the qualifications of B. Tech, M. Tech and Ph.D. He is working as Academic Editor of International Transactions on Electrical Energy System, Hindawi. He is a Y rated researcher from NRF South Africa. His area of interest includes power system operation & control and application of AI techniques to the power systems. He can be contacted at email: gulshans@uj.ac.za.

Dr. Kayode Timothy Akindeji has a B. Sc and M. Sc (Electronic and Electrical Engineering) both obtained at Obafemi Awolowo University, Ile–Ife, Nigeria. He has completed his PhD (Electrical Engineering) from University of Kwa-Zulu Natal (UKZN), Durban, South Africa in 2022. He lectures at the Department of Electrical Power Engineering, Durban University of Technology (DUT). His research interest includes smart grids, renewable energy, distributed generation, and microgrid. He can be contacted at email: TimothyA@dut.ac.za.

Dr. Narayanan Krishnan received his B.E. in Electrical and Electronics engineering from Anna University, Chennai in 2008 and M. Tech in Power Systems in 2010 and Ph.D. degree in Electrical Engineering in 2016 from Malaviya National Institute of Technology, Jaipur (Rajasthan), India. Presently he is working as Assistant Professor in SASTRA Deemed University, Thanjavur, India. He is a Senior Member of IEEE Power and Energy Society, life member of Indian Society of Systems for Science & Engineering (ISSE). His areas of research interests are power system planning and operation. He can be contacted at email: narayanan.mnit@gmail.com.