DURBAN UNIVERSITY OF TECHNOLOGY

LOAD FREQUENCY CONTROL OF A HYDRO DOMINATING INTERCONNECTED POWER SYSTEM.

By

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DECLARATION

This dissertation is the student's own work, every cited work or text have been appropriately referenced. It has not been partially or fully submitted at any other University.

This research was duly supervised by Dr. Gulshan Sharma & Professor I. E. Davidson, at the Durban University of Technology.

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DEDICATION

This study is dedicated to God Almighty, who has given me life and a sound mind to be able to begin and bring to completion this phase of my life, to Him only be all the glory and praise.

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(Milan Joshi)

ABSTRACT

Energy is one of the vital figures that impact the development of civilization in the 21st century. It has been projected that by the year 2050, global energy needs will be satisfied by renewable sources. Among these renewable energy resources hydropower is available worldwide with relatively cheaper accessibility for most of the communities. Nevertheless, hydropower's control architecture raises concern for the system operators in terms of preserving the Load Frequency Control (LFC) services due to the elongated response time of hydro turbines in catering for the varying load demands. The varying load demands are inevitable in the power system due to different clients' energy consumption patterns at different times. This, therefore, places changing control framework requests as per the requirement of diverse clients. Hence, the research proposes and demonstrates the connection of the hydro-hydro framework through the AC tie-line for LFC. The Linear Quadratic Regulator (LQR) is a plan for hydro overseeing framework in discrete mode. The application derived is displayed through closed-loop feedback gains and closed-loop eigenvalues. In the expansion model, the positive effect of a Unified Power Flow Controller (UPFC) and Redox Flow Battery (RFB) in LFC studies is investigated.

This proposition moreover shows the joint endeavors of Fuzzy Logic (FL) as well as Proportional Integral Derivative (PID), with control gains well-calculated, through Particle Swarm Optimization (PSO) result into a robust FL-PSO-PID for LFC of the connected hydro framework. The different errors are defined to assess the yield as well as the execution of the FL-PSO-PID. The yield appears through a decline in blunder values as well as minimization in framework responses from accurate estimation for the LFC under various working conditions such as non-linearity, random load alteration, and parametric move as a result of a precise estimate. In the expansion, the effect of energy storage devices is also investigated to understand the enhancement provided frequency control of the hydro system, and the result obtained shows their effectiveness. Finally, the outcomes and future extent of this investigation work have been presented.

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LIST OF ACRONYMS AND SYMBOLS

f^0	Nominal system frequency (Hz)
I	Subscript referring to area (i = 1, 2)
H_{hi}	Per unit inertia constant (sec.)
ΔF_{hi}	Incremental change in frequency
ΔP_h	Incremental change in tie-line power flowing out of an area i (MW)
D_{hi}	Load frequency constant (p.u.MW/Hz)
ΔPg_{hi}	Incremental change in power generation
ΔPd_{hi}	Incremental change in load demand (p.u.MW/Hz)
$\Delta P\ c_{hi}$	Incremental change in speed changer position
ΔXg_{hi}	Incremental change in governor valve position
ΔXgh_{hi}	Intermediate output of hydro governor
Tg_{hi}	Speed governor time constant of area i (sec.)
R_{hi}	Speed regulation parameter (Hz/p.u.MW)
T_{wi}	Hydro turbine time constant (sec.)
Kg_{hi}	Speed governor gain of area i
Pr_{hi}	Rated area power output (MW)
M_{hi}	Effective rotary inertia (p.u.MW-sqsec.)
a_{12}	Area size ratio coefficient
B_{hi}	Frequency bias constant (p.u.MW/Hz)
ACE	Area control error
T_{12}	Coordinating coefficient of EHVAC transmission line
$T_{h1}, T_{h2}, T_{h3}, T_{h4}$	Time constants associated with hydro governor
K_{UPFC}	UPFC gain
T_{UPFC}	UPFC time constant
K_{RFB}	RFB gain
T_{RFB}	RFB time constant
LFC	Load Frequency Control
LQR	Linear Quadratic Regulator

PSO	Particle Swarm Optimization
PID	Proportional-Integral-Derivative
UPFC	Unified Power Flow Controller
RFB	Redox Flow Battery
UC	Ultra Capacitor

CHAPTER 1

INTRODUCTION TO SCENARIO OF POWER SYSTEM

1.1 Introduction

The power systems mean this is the interconnection of more than one control region by the tie lines. In a control region, the generators continuously shift their speed together (speed up or slow under) to maintain frequency and the corresponding power angle to the predefined values in both static and dynamic positions. If any sudden load variation occurs in a control region of an interconnected power system at that point, there will be frequency variation and tie-line power variation.

The two primary objectives of Load Frequency Control (LFC) are;

1. To preserve the actual frequency and the specified control yield (megawatt) in the connected power frameworks.
2. To regulate the change in tie-line power between regulated regions.

In case there's a little change in load power in a particular region power framework working at a set value of frequency at that point, it makes a mismatch in power equally for generation and demand. This mismatch issue is at first solved by dynamic vitality removal from the framework, as an outcome, falling of framework frequency happens. As the frequency continuously reduces, the power absorbed by the past load is also reduced. In huge power frameworks, the stability can be obtained by them at a specific point during the newly included load is distracted by decreasing the power consumed by the past load and power linked with kinetic vitality removed from the framework. Certainly, at a cost of frequency decrease, we are receiving this equilibrium. The framework makes approximately control activity to maintain this equilibrium and no governor activity is needed for this. The decrease in frequency under such situations is exceptionally huge.

Be that as it may, the governor is presented into activity and generator yield is expanded for a larger mismatch. Presently here the stability position is gotten when the newly included load is occupied by decreasing the power devoured by the past load, and the expanded generation by the governor movement. Hence, there's a decrease in the amount of dynamic vitality that is obtained from the framework to a large extent, but not totally. So the frequency decrease still exists for this section of balance. While for this situation, it is much smaller than the past one mentioned above. For the most part, that sort of balance got inside 10 to 12 seconds only behind the load growth. Then this governor's activity is named the primary controller.

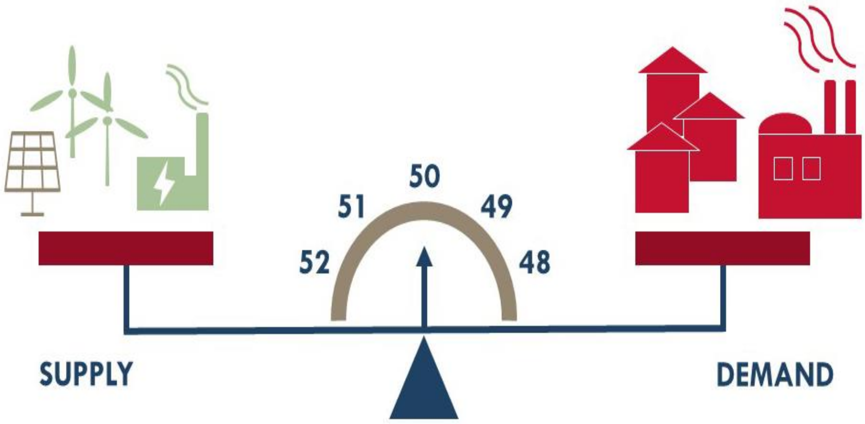


Figure 1.1 Supply V/S Demand

The science behind the presentation of governors' activity the framework frequency is still changed its pre-defined value, via additional various control methodologies it is required the frequency to take back to its pre-defined value. Expectedly Integral Regulators are adopted for this reason. The control is named a secondary controller (which is working next to the significant control procedure), making the framework frequency to its predefined value or near it. Though integral regulators are by and mostly slow in performance.

In a two-region interconnected power framework, where the two regions are combined through tie lines, the control region is provided by per region, and the tie lines between the regions permit the power stream. Though, the yield frequency of total, the regions are influenced due to a little change in a load in any of the regions so as the tie-line power stream is influenced. So the momentary circumstance knowledge of all different regions is required by a specific region's control framework to re-establish the pre-characterized rates of tie-line powers and region frequency. Each yield frequency determines the data around its possess region, and the tie-line power variation determines the report is almost the separate regions. For the case in a two-region power framework, the knowledge can be composed as $Bi\Delta fi + \Delta Ptie$. B = frequency bias, f = predefined frequency, And Ptie is the power in the tie-line. Typically, the Area Control Error (*Ace*) is the data to the controller.

1.2 Recent Status of Electric Power in South Africa

Presently the overall established capacity of electrical power in South Africa is approximately 52,811 MW. The division up of this power concurring to classify sorts of generating modes is fossil fuels 43,485 MW; low carbon (renewable, nuclear + imported) 9,326 MW. Due to different specialized, efficient, and environmental contemplations in South Africa, the electrical power-producing systems have been established in remote situations from load stations. In any case, they have to be work in a 2 interconnected design to participate in the advantages of appropriating inconstancy in generation mixtures and load designs and other innovative preferences. Hence, there is a demand for such transmission joins, which can successfully and effectively trade expansive electrical control parts between broadly divided power pools. As of now, a large transmission organize has been placed in South Africa to provide to the vitality requirements at sensibly great fetched and in a social-friendly environment.

Eskom's current difficulty is making Load Shedding throughout South Africa, which is of impressive attention to all South African nationals. The purpose for usually that Load Shedding features an adverse effect on the development of South Africans. All residential employments of power utilize power to perform their day-to-day family activities, which incorporate cooking, washing, and cleaning as a case, all of which need power.

Table 1.1: Generation Capacity in South Africa [1]

Type	Capacity (MW)
Coal	40,036
Gas turbine	3,449
Hydro	3,573
Wind	2,096
Nuclear	1,860
Solar PV	1,479
Solar CSP	400
Landfill gas	7.5
Imported Hydro	1,500
Total	52,811

Hence, on the off chance that electricity is not accessible, life's condition will be influenced. In expansion, Load shedding moreover contains a negative effect on the nation's businesses, which affects the economy and its residents. Load Shedding makes production under the circumstances for businesses, coming about in more limited production than the planned production arranges, which contrarily affects the economy. Misfortune of production comes about in below budgetary steadiness of the business and provides to work uncertainty for the citizens.

Since, the suggestions of Load Shedding are distant reaching in its results, since it shows both Common, Economic, and Political positions which perform a part within the country's advancement. Moreover, these results consequences in the Industrial development of the nation, which impacts the economy.

1.3 Interconnected Power System

Concurring to the commonsense point of view, the load frequency control issue of interconnected power framework is much extra critical than the separated (single region) power framework. However, the hypothesis and information of a separated power framework are similarly crucial for assuming the interconnected power system's general view [40].

Usually, at times, power frameworks are bound with their nearby regions, and the Load Frequency Control (LFC) Issue ended up a typical project. A few essential working opinions of an interconnected power framework is composed below:

1. The load ought to endeavor to be taken by their claim control regions beneath the everyday running situation, but a planned share of other individuals' loads, as commonly concurred upon.
2. Per the region must concur upon receiving, controlling, control techniques, and device advantageous for both typical and abnormal situations.

1.4 Two Region Power Scheme

In case there is an interconnection between two control regions through the tie-line, then that is named a two-region interconnected power framework. Fig. 1.2 appears a two-region power framework where the tie line permits each region supplies to its claim region and the power stream among the regions.

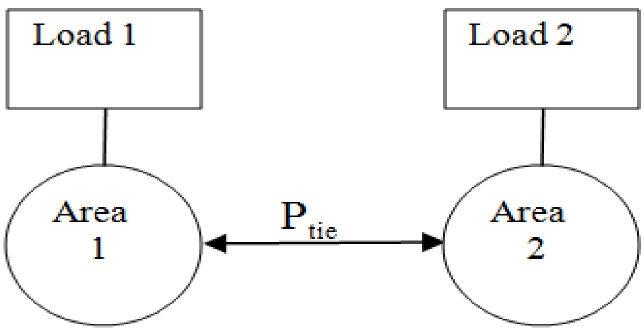


Figure 1.2 Two regions Interconnected system

In this example of two regions' power framework, an assumption is taken that each region is strong, and the tie line which interfaces the two regions is powerless. Here a single frequency is identified all through a single region;

implies the arrange region is ‘effective’ or ‘hard’. There may be any numbers of control regions in an interconnected power system [4].

1.5 Various Techniques to tackle LFC Problem

The requirement for the present-day control framework hypothesis has accomplished a significance in affecting the dynamic response of huge interconnected framework within the final two decades, such as optimal control, adaptive control, pole situation approach, and intelligent techniques. A brief depiction of these strategies is provided underneath.

1.5.1 Optimal Control

The controller plan issue is indicated by the method, the principle that is formulated within the execution record, and the appropriate control signal. A discrete-time show can portray the technique, whereas the execution file is composed as a scientific work to specify the cost (cost function). This stipulates the conditions given for the performance of the plant. The ideal plan system reduces this cost function to induce the perfect clarification of the control plan. This controller is one of the centralized sorts of controllers, where the per state of the framework is written among the subsystem and controllers [5,6].

1.5.2 Adaptive Control

The adaptive controller may be a controller that can adjust its performance in answer to variations within the method's dynamics and within the greatness and virtues of troubles. Adaptive controllers, too, have they claim parameters, which must be accepted. Controllers without any remotely balanced parameters can be planned for particular purposes in which the reason for control can be declared a monastery [12,13].

1.5.3 Pole Placement Technique

Within the post-placement strategy, the closed-loop poles of the method may be placed wherever within the problematic level in arrange to maintain the framework and provide the condition of any solidness edge or damping ratio.

Ordinarily, the factors of the conventional regulators (fixed-gain, lead-lag, and PID) are decided off-line at an ostensible working point to provide excellent achievement. In any case, the energetic framework reaction may relapse when the starting point fluctuates. The controllers, such as optimal and adaptive controllers, are forever complicated to execute in real power frameworks due to the large number of feedback factors delivered over large separations. It is complicated to a degree most of the optimal and adaptive controllers' input factors in expansion. It is additionally troublesome to determine the optimal arrangement when the framework estimate is huge as Riccati equation of Riccati's framework arrange is illuminated iteratively, and the adaptive control needs show classification in real-time, that's, time expending. For the pole placement technique, numerous warnings are to be analyzed, e.g., the closed-loop poles may require huge maintaining gains, which are constrained by physical limitations[21-24].

1.5.4 Intelligent Techniques

Modern strategies such as fuzzy logic, artificial neural networks, optimization algorithms, and proficient frameworks have been utilized in power framework utilization. Artificial intelligence's flourishing, which uses personal involvement in an extra loose form than the conventional scientific strategy, has invited more consideration to many artificial intelligent techniques[27-32].

1.6 Objectives of Thesis

The main aim of this thesis is to investigate the problem associated with load frequency control of interconnected power systems. It encompasses the design and mathematical modelling of various control techniques of a two region hydropower system.

(a) Mathematical Modeling of Interconnected Power systems:

Mathematical modelling of a two region interconnected hydropower system. Included in the modelling are the development of UPFC, RFB, UC and derived standards for the generator, load, speed turbine and governor.

(b) Linear Quadratic Regulator Design for LFC for Two regions interconnected System:

The design of a linear quadratic regulator (LQR) for a two region interconnected hydropower system. The dynamic response of frequency fluctuation and tie-line power stability is evaluated through the analysis of the feedback gain matrix.

(c) Fuzzy Controller Design for LFC problem:

The design of a fuzzy controller for a two region interconnected hydropower system. Included in the modelling are the development of UPFC, RFB and UC. Fuzzy inference frameworks of Mamdani type are utilized in the control technique. The dynamic response of frequency fluctuation and tie-line power stability is evaluated by fluctuating the frequency and tie line parameters.

(d) ***Testing Robustness of Fuzzy Controller:***

The effect of robustness is accomplished by testing a fuzzy controller with changing two parameters: frequency bias consistent and tie-line consistent to ±20% and ± 30 % of their nominal values.

1.7 Arrangement of Thesis

- **Chapter 1** discusses the introduction of the load frequency control (LFC) issue of interconnected electrical power framework. This chapter details different control levels and control techniques of this main issue of power framework control.
- **Chapter 2** gives a complete literature study on the load frequency control issue. Various strategies received by investigation to handle this problem so distant have been altogether analyzed.
- **Chapter 3** is approximately the control methodologies utilized in this thesis. Linear quadratic regulator plan for an optimal solution. The deals with issue recognizable proof and improvement of a mathematical model of two regions interconnected hydropower systems. Transfer functions of

different components utilized to create the final and most devoted block graph for this problem's reasonable arrangement are advanced.

- **Chapter 4** is approximately the second control methodologies utilized in this thesis. fuzzy-PSOPID control plans to solve two region interconnected power frameworks have been examined in this chapter.
- **Chapter 5** presents outcomes and investigation of the execution of proposed control designs on two regions frameworks. Simulations outcomes are displayed in a really elaborative way to agree on advanced control methodologies' significance and convenience. Diverse cases of two regions are taken to investigate the dynamic realization of the controller's multi-region frameworks, and robustness developed.
- **Chapter 6** concludes and proposes the future scope of the presented work.

CHAPTER 2

LITERATURE REVIEW

The electrical control time and exchange framework is developing rapidly with objectives of keeping up the system's standard and faithful the quality over the diverse working restriction of the framework. In organizing to make the electrical control and see the control ask considering the monetary way, the electrical control system worked in an interconnected method. This infers that tie-lines relate to different control locales. In extension, these control ranges have control interchange as per characterized agreement by the transmission scheme operator. Each control region should be empowered to see its own load demand taking care of the lawfully authoritative control via AC tie-line. The unbalance between electrical control and load demand thrust the scheme frequency and AC tie-line power away from the characterized esteem. Thus it impacts the quality and nonstop control conveyance to the cutting-edge power control clients.

The alteration in frequency and tie-power is narrow by Load Frequency Control (LFC) strategy. The modification of these indirect shape amounts is well-defined as Area Control Error (ACE) in LFC [2]. The part of LFC controllers is to connect the electrical produced control with electrical energy demand to limit or to set the ACE deviations to a null value. In this part, the starting endeavors were to arrange an LFC established on the conventional control hypothesis [3-4]. In any case, the picks up of standard LFC permit agreeable execution as a particular circumstance and incapable of supplying the desired control movement in arranged working conditions of the electrical imperativeness system. Subsequently, the investigators and researchers are trying to look for controller plans based upon specific advanced strategies created on modern control theory, such as optimal control by formulating and minimizing the performance index. In [5], authors have reduced the system deviations by including wind turbines in frequency control services and adequately designing the optimal controller for a power system with thermal power generation. The optimal control design with parallel AC/DC tie-lines was investigated in [6]. In [7], authors have solved LFC's problem of hydro governing turbines in interconnected control zones, and the system stability analysis was checked via closed-loop eigenvalues. Further, in [8], the optimal control design for LFC in a deregulated environment was presented, and the various market transaction was revealed because of thermal power generation. In [9], a new solution based on the Riccati equation to solve as well as to enhance the problem of optimal control was discussed.

Further, some of the authors have solved the optimal LFC [10-11] by considering only a few of the states that are seen easily while designing optimal controller, and its comparison was made on full states control law because of system stability well as considering control aspects implementation. In [12], LFC's problem was solved via designing robust control seeing various structures of state cost weighting matrix. Furthermore, some of the researchers have proposed advanced designs such as optimal structure [13], changing structure [14], and decentralized dual-mode [15] to address the LFC problem in an advanced way. However, due to complex designs, these models were hardly noticed in LFC studies.

Further, it is also noted that most of the LFC design created on optimal methodology was scheme and verified over the continuous period of the electrical supply frameworks. Very few investigation studies were obtainable based on the discrete analysis. The power plants are at far place from the central controllers, and the LFC records are tested & conveyed with the help of telecommunication networks to the central regulator with the sample of frequency and tie-power deviations or ACE in linear form. LFC controls effectively correct the generator output in discrete steps to boundary the ACE deviation to a zero rate. Therefore, the particular sampling period plays an essential part in accomplishing the necessary LFC reactions as well as it also plays a significant role in the stability of the interconnected power system for an unexpected disturbance.

Besides, it is also noted that the best of LFC designs were tested on thermal power plants or hydro-thermal or with the integration of renewable vitality sources, and the literature lags in providing an effective control strategy for hydro governing frameworks. This is because hydropower frameworks are basically unstable frameworks as the responding time of hydro turbines is much higher in assessment to thermal turbines for unexpected load modification. Hence, it needs further investigations and analysis.

Recently the application of artificial intelligent (AI) techniques such as fuzzy logic (FL), neural networks (NNs), and optimization algorithms were gaining momentum worldwide. The reason behind is these techniques perform well considering the non-linear model of the system as well as capable enough to perform under different operating conditions. Among these, the FL is the first choice of most of the researchers as FL can perform under various system operating conditions. In reference [16], the LFC problem was addressed by hybrid fuzzy control. In [17], authors have proposed the robust FL technique for LFC. In [18] the FL approach was designed and tested on the interconnected power system. In [19], authors have to design robust FL on interval type-II concept and its merits over conventional FL were shown. In [20], authors have to design fuzzy gain scheduling control for LFC to improve LFC outputs. On the other side, optimization techniques are also becoming popular among researchers and power engineers. However, most of the researchers are using the optimization algorithm to set the accurate gains of the auxiliary controller, i.e., proportional integral derivative (PID) [21-24].

Recently, researchers have linked the optimization technique with FL to have a robust and a kind of FL design, which can bear the system's full operating conditions. In [25], a two-region non-reheat thermal framework is used, and the gains of the fuzzy PI controller are optimized using a hybrid particle swarm optimization (PSO), and via a combination of pattern search (PS), and PSO technique. In [26-27], the Gaussian Particle Swarm Optimization (GPSO) algorithm is useful for defining the optimal values of the conclusion variables, which can also agree to the solidity of the frameworks by accepting a chaotic map by Gaussian function to equilibrium the seeking abilities of particles that encourages the computation effectiveness without disturbing the efficiency of the fuzzy controller. In [28], authors have design PSO-based PI-type fuzzy logic controllers for an interconnected energy system. Further, the optimum parameters of PID and FL-PID were calculated via modified grey wolf optimization (MGWO) algorithm in [29].

From the recent literature, it is seen that most of the designs were tested on thermal and linked hydro-thermal and very few or no investigations were performed to connect the concept of FL with optimization algorithm such as PSO in order to address the LFC of hydro system and hence it needs further investigations in order to find an accurate control design.

Modern improvement of power electronics production and its application to scheme and install flexible alternating current transmission systems (FACTS) have revolutionized the power industry. These strategies are accomplished enough to adjust the active and reactive power. Hence, it increases the steady-state, and dynamic performance of the system [30-39]. In [31], the Unified Power Flow Controller (UPFC) is placed in series to tie-line with Redox Flow Batteries (RFBs) in one of the zones of a linked system to improve the output of the system for sudden load disturbance. The suggested methodology's performance is evaluated at all potential power transactions in a deregulated power market. In [32], the LFC problem's enhancement was an address by using UPFC and hydrogen aqua electrolyzer (HAE). The optimized LFC considering RFB and interline power flow controller (IPFC) was discussed in [33]. In [34], the authors have tested RFB in multi-area restructured power frameworks. Further, the combination of Thyristor control phase shifter (TCPS) and Superconducting Magnetic Energy Storage (SMES), including wind turbines, was explored in [35].

Recently, ultra-capacitor (UC) has emerged out as a powerful energy storage device among the diverse members of FACTS. It has the proficiency to absorb the surplus power from the system in case the demand is less with regards to generation, and it also has the tendency to release stored power quickly in case the load demand is high in evaluation to power generation. Hence, it comes out to be a powerful energy storage device for LFC [36].

Furthermore, it is also noted that recently some of the researchers have started testing the various combination of FACTS across multiple control regions of LFC in order to enhance the LFC output [37-40]. An on-line tuning of the gain of an integral controller using electro-search optimization (ESO) supported by a modification called the balloon effect was shown in [41]. The frequency control system utilizing a mix of adaptive model predictive controller (AMPC) and recursive polynomial model estimator (RPME) linked with double fed induction generator wind turbines in [42]. The LFC studies also includes the robustness aspect and it is validated via two area four machine Kundur's test system in [43]. The generalised active disturbance rejection control (GADRC) technique that includes the plant model information to handle the problem caused due to communication delay was discussed in [44]. The LFC research also includes the testing of grasshopper optimization algorithm (GOA) to fine tune gains of FOPI-D [45-47]. In [48], multi verse optimization (MVO) technique was developed for LFC. Further, due to the advent of modern power technology in a wide area monitoring system (WAMS) the demand response will play a vital role in the development of the future power grid [49]. In [50] the LFC problem was explored in line with disturbances, uncertainty and parameteric disparities.

2.1 Summary

A comprehensive literature survey approximately load frequency control issue is displayed in this chapter. Different control strategies, such as classical, optimal, sub-optimal & robust, variable control, fuzzy, artificial intelligent (AI), optimization technique and other schemes proposed by investigating specialists like series UPFC connect to the existing AC tie line, energy storage and foundation of improved and open communication infrastructure have been completely examined.

CHAPTER 3

MATHEMATICAL MODELLING OF HYDRO POWER SYSTEM

3.1 Introduction

The electrical power generation and dispatch are growing quickly with limitations of keeping up the framework steadiness and unwavering quality over the organization's diverse working situations. In order to create electrical power and meet the persistent load requirement financially, the electrical power generation framework works in an interconnected design. This implies that diverse control regions are associated with AC tie-lines. In expansion, these control regions have power trade as per characterized contract by the delivery framework administrator. Encourage each control region should meet its claim real power demand despite dealing with the legally binding control via AC tie-line [4,24,25]. The disturbance between energy generation and demand powers the framework frequency and tie-line esteem to deflect from the initial framework values. Consequently, it influences quality, continuous, and reduced electric power transmission to present-day power customers. The frequency and tie-power variations are eliminated. The difference of these amounts in a straight arrangement is known as region controller error, and load frequency control valves must minimize ACE's esteem for little load disturbances. These controllers try to coordinate the actual power and demand on a time-by-minute basis and try to attain the balance within the power framework with zero or minimum ACE esteem by planning the most excellent control methodology well known as auxiliary control action [5-6]. LFC at first works to design auxiliary controllers through utilizing classical control theory. The conventional control theory is, in any case, restricted to the plot with a single input and single yield. The electrical energy framework may be a multiple-input and different yield framework issue. Hence, a few researchers have illustrated their intrigued in planning auxiliary controllers through solving the transfer function model of the framework nearby a working point and creating the state-space model and at last understanding the issue of a linear quadratic regulator (LQR) via minimization of performance index [5,8,9]. The optimal LQR plan for interconnected power framework with doubly fed induction generator (DFIG) was examined in [5]. In [8], the authors have explained the LFC issue considering the deregulated environment through planning effective LQR for LFC. In [9], the novel Riccati matrix equation arrangement for LFC was displayed through optimal control theory. In any case, it was famous that most of the LFC plan based on the LQR strategy was a plan and tried over the persistent phase of the electrical supply framework. Exceptionally few investigate considers were accessible on the premise of discrete investigation. These power plants are at distant places from the primary regulators, and the LFC information is sampled & transmitted with the assistance of media transmission channels to the primary controller with the sample of frequency and tie-power variations or ACE in linear form. In arrange to constrain the ACE variation to a zero esteem, LFC controls are working to alter the generator yield in discrete steps. Subsequently, the specific sampling time presents a significant performance in achieving the desired LFC reactions because it also plays a critical role in the steadiness of the interconnected power framework for a certain disturbance. In expansion to over, it is also famous that most of the LQR plan for LFC is a plan and tried analyzing thermal power plants or hydrothermal or with the combination of renewable vitality sources with thermal power plants and the literature slacks in giving an effective control plan for a hydro-hydro framework. Typically, due to the reality that hydro control frameworks are fundamentally unsteady framework, the replying time of hydro turbines is much higher than thermal turbines for certain load disturbance, the framework loses its solidness completely [21].

Recent advancement of power electronics activity and its utilization to plan and install Flexible Alternating Current Transmission System (FACTS) have brought the transformation in power management and these devices are able sufficient to control the active power as well as reactive power and thus it progresses consistent state and dynamic execution of the framework. A few of the FACTS are as of now investigate and tried for the LFC issue [28], and still, there is a scope to explore new and powerful FACTS in order to increase the value vitality delivery to the users. The Redox Flow Battery (RFB) and Ultra-Capacitor (UC) could be an unused FACTS and have high capability to store excess energy from the grid quickly and to loose rapidly and deliver to the system for sudden disturbances in the framework and can improve the output of the framework to a great extent. However, due to financial reasons, it is complicated to install these devices in each zone of the framework [33,35]. The unified power flow controller (UPFC) is additionally a part of FACTS and much lower in cost concerning other FACTS and has the capacity to fine limitation the power in either direction or, thus, it is connected in series with the tie-line [29,30].

3.2 Modelling of Interconnected Hydro Power System

3.2.1 System Model

A two-area connected electric power supply system is considering for the studies and has hydro turbines in both control areas. The control areas are linked via the AC tie-line. The system's model is given in Figure 3.1, and its transfer function complete representation is given in Figure 3.2.

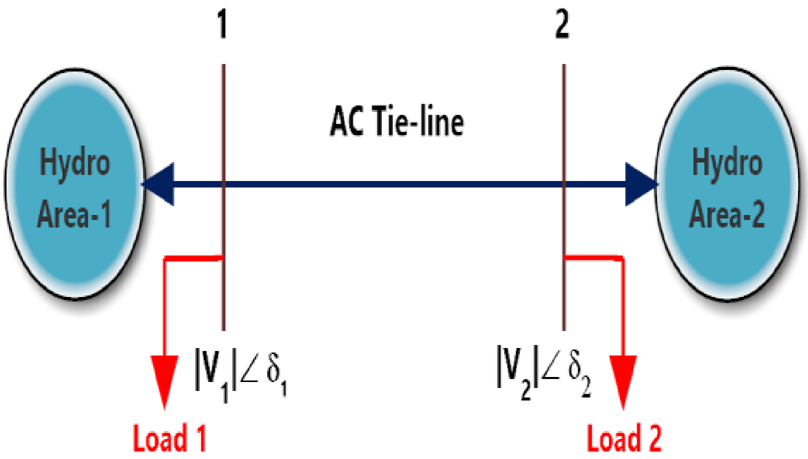


Figure 3.1 Schematic model of a power system under consideration.

3.2.2 LQR Modelling in Discrete Form

In today's work, LQR is an LFC plan for an interconnected power supply framework in discrete form. The LQR plan is a perfect control strategy and requesting of present-day control hypothesis to create a state-space controller. The LQR plan is steady and secure for the most significant utilization barring the uncontrollable frameworks. The LQR plan based on assessing the regulator gains for least esteem of taken a toll work in discrete shape;

$$x_{k+1} = Ax_k + Bu_k \tag{3.1}$$

The control signal for hydropower for both control areas are obtaining as follows;

$$u_k = -Kx_k \tag{3.2}$$

concerning developing cost function;

$$J(x_k) = \sum_{i=k}^{\infty} [x_i Q x_i + u_i R u_i] \tag{3.3}$$

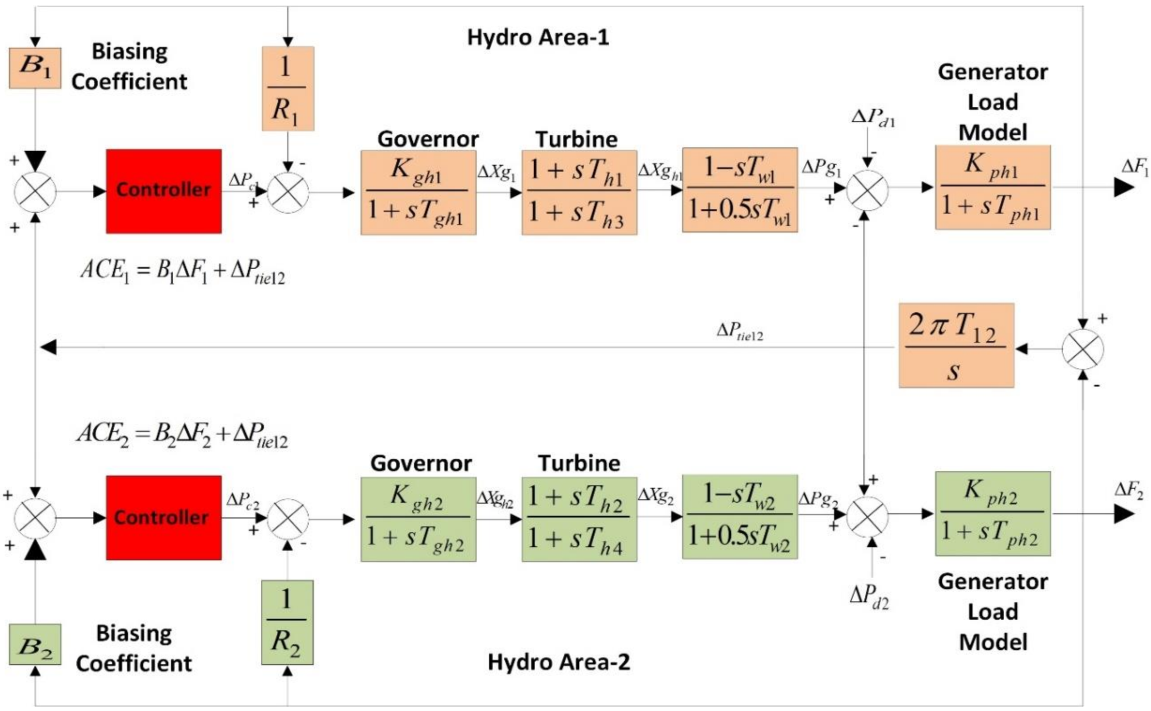


Figure 3.2 Transfer function model of interconnected hydro power for LFC.

and the feedback gain matrix for both areas can be calculated as;

$$K = (R + B^T PB)^{-1} B^T PA \tag{3.4}$$

Where P represents the solution of algebraic Ricatti Equation in discrete form as;

$$A^T PA - P - A^T PB(R + B^T PB)^{-1} B^T PA + Q = 0 \tag{3.5}$$

And the most important is that state cost weighting matrix and control cost weighting matrix should respect the following condition;

$$\begin{aligned} Q &= Q^T \geq 0 \\ R &= R^T > 0 \end{aligned} \tag{3.6}$$

Q and R's structure should be incompatible with the state matrix and control matrix dimension to solve the LQR problem in discrete form.

3.2.3 Modelling of UPFC

The UPFC can regulate the power stream in tie-line and in this way, appealing upgrade LFC execution & framework voltage. The LFC comes about for hydropower have maintained motions with settling time more significant than 20 seconds.

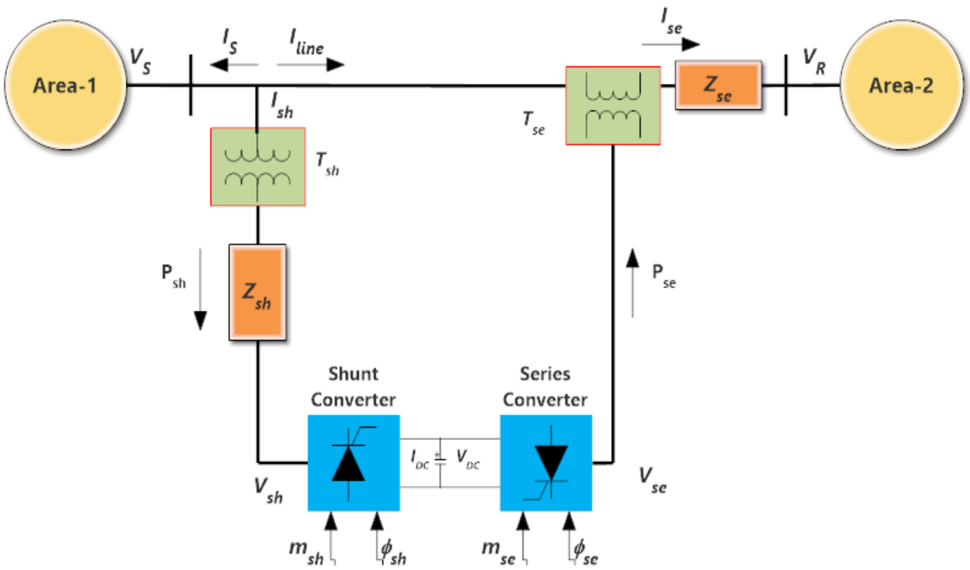


Figure 3.3 Integration of UPFC in interconnected hydro systems

Usually, due to the reality that the replying time of hydro turbines is higher and, consequently, UPFC is set up in arrangement association to tie-line in arranging to clammy the framework's variation as before long as conceivable. The point by point demonstration of UPFC interconnected within two control regions is appeared in Figure 3.3.

The mathematical modeling of UPFC is as follows [30], and the complex power at the receiving end of a line is:

$$P_{real} - jQ_{reactive} = \overline{V_r^*} I_{line} = \overline{V_r^*}\left\{\left(\overline{V_s} + \overline{V}_{se} - \overline{V}_r\right) / j(X)\right\} \tag{3.7}$$

and, $$\overline{V}_{se} = |V_{se}| \angle(\delta_s - \phi_{se}) \tag{3.8}$$

In the above equation, the V_{se} means the voltage magnitude in series and ϕ_{se} is the phase angle. By separating Eq^n. (3.7) into real & imaginary, the real part is as follows;

$$P_{real} = \frac{|V_s||V_r|}{X}\sin\delta + \frac{|V_s||V_{se}|}{X}\sin(\delta - \phi_{se}) \tag{3.9}$$

$$= P_0(\delta) + P_{se}(\delta,\ \phi_{se}) \tag{3.10}$$

In Eqn. (3.10) if $V_{se} = 0$, it means that real power is uncompensated & UPFC series voltage can be varied between the range of 0 and V_{se} to its maximum value. Finally, the phase angle is altered from 0^o to 360^o. Figure 3.4 shows the model of UPFC.

In LFC, the UPFC action in linear form is obtained via following transfer function representation [31];

$$\Delta P_{UPFC}(s) = \left\{\frac{1}{1 + sT_{UPFC}}\right\}\Delta F_1(s) \tag{3.11}$$

T_{UPFC} = UPFC time constant.

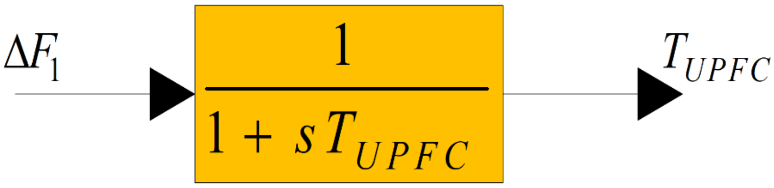


Figure 3.4. Transfer function of UPFC

3.2.4 RFB Modelling

The RFB is rechargeable batteries, and there's no impact on the growth of these batteries in case they are imposed more than once or release over and over and it has a fast-reacting time for unexpected load interruption. In expansion to load leveling, the RFB is one of the significant benefits for LFC's performance, and it also offers assistance in keeping up the control property. The RFB may be an inactive gadget and its time of performance is quick sufficient and consider as zero seconds in LFC considers. The transfer function demonstrate of RFB is as takes after [32] and shown in Figure 3.5;

$$\Delta P_{RFB}(s) = \left\{ \frac{K_{RFB}}{1+sT_{RFB}} \right\} \Delta F_2(s) \tag{3.12}$$

T_{RFB} = Time constant of RFB.

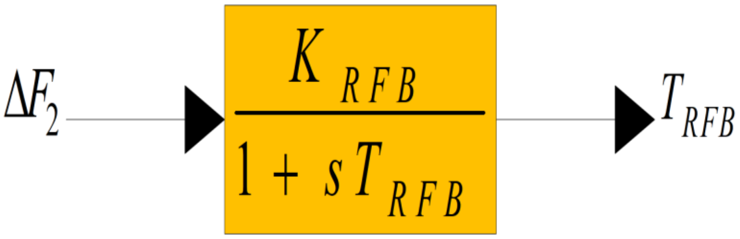


Figure 3.5. Transfer function of RFB

3.2.5 Model of Hydro Power

State vector

$$[X_1]^T = \begin{bmatrix} \Delta F_1 \Delta P_{g1} \Delta X_{g1} \Delta X_{gh1} \Delta F_2 \Delta P_{g2} \Delta X_{g2} \Delta X_{gh2} \\ \Delta P_{tie12} \int ACE_1 dt \int ACE_2 dt \end{bmatrix}^T \tag{3.13}$$

Control vector

$$[u_1] = \begin{bmatrix} \Delta P_{ch1} \\ \Delta P_{ch2} \end{bmatrix} \tag{3.14}$$

Disturbance vector

$$[P_{d1}] = \begin{bmatrix} \Delta P_{dh1} \\ \Delta P_{dh2} \end{bmatrix} \tag{3.15}$$

The control and disturbance vector will remain the same with UPFC & RFB, however, the elements of the state vector are as follows;

$$[X_2]^T = \begin{bmatrix} \Delta F_1 \Delta P_{g1} \Delta X_{g1} \Delta X_{gh1} \Delta F_2 \Delta P_{g2} \Delta X_{g2} \Delta X_{gh2} \\ \Delta P_{tie12} \int ACE_1 dt \int ACE_2 dt \Delta P_{UPFC} \Delta K_{RFB} \end{bmatrix}^T \tag{3.16}$$

3.2.6 System Matrices

The system matrices for designing the LQR are obtaining via solving the system's transfer function model, as given in Figure 2. The input matrix is of the order of $A = 11 \times 11$, and its non-zero values are;

$a_{1,1} = -\dfrac{1}{T_{ph1}}$	$a_{1,2} = \dfrac{K_{ph1}}{T_{ph1}}$	$a_{1,9} = -\dfrac{K_{ph1}}{T_{ph1}}$	
$a_{2,1} = \dfrac{2K_{gh1}T_{h1}}{R_1 T_{gh1} T_{h3}}$	$a_{2,2} = -\dfrac{2}{T_{w1}}$	$a_{2,3} = \dfrac{2}{T_{w1}} + \dfrac{2}{T_{h3}}$	$a_{2,4} = \dfrac{2T_{h1}}{T_{gh1}T_{h3}} - \dfrac{2}{T_{h3}}$
$a_{3,1} = -\dfrac{K_{gh1}T_{h1}}{R_1 T_{gh1} T_{h3}}$	$a_{3,3} = -\dfrac{1}{T_{h3}}$	$a_{3,4} = \dfrac{1}{T_{h3}} - \dfrac{T_{h1}}{T_{gh1}T_{h3}}$	
$a_{4,1} = -\dfrac{K_{gh1}}{R_1 T_{gh1}}$	$a_{4,4} = -\dfrac{1}{T_{gh1}}$		

$a_{5,5}=-\frac{1}{T_{ph2}}$	$a_{5,6}=\frac{K_{ph2}}{T_{ph2}}$	$a_{5,9}=\frac{K_{ph2}}{T_{ph2}}$	
$a_{6,5}=\frac{2K_{gh2}T_{h2}}{R_2T_{gh2}T_{h4}}$	$a_{6,6}=-\frac{2}{T_{w2}}$	$a_{6,7}=\frac{2}{T_{w2}}+\frac{2}{T_{h4}}$	$a_{6,8}=\frac{2T_{h2}}{T_{gh2}T_{h4}}-\frac{2}{T_{h4}}$
$a_{7,5}=-\frac{K_{gh2}T_{h2}}{R_2T_{gh2}T_{h4}}$	$a_{7,7}=-\frac{1}{T_{h4}}$	$a_{7,8}=\frac{1}{T_{h4}}-\frac{T_{h2}}{T_{gh2}T_{h4}}$	
$a_{8,5}=-\frac{K_{gh2}}{R_2T_{gh2}}$	$a_{8,8}=-\frac{1}{T_{gh2}}$		
$a_{9,1}=2\pi T_{12}$	$a_{9,5}=a_{12}2\pi T_{12}$		
$a_{10,1}=B_1$	$a_{10,9}=1$		
$a_{11,5}=B_2$	$a_{11,9}=a_{12}$		

The control matrix is of an order of 11×2 and its non-zero values are;

$b_{1,2}=-\frac{2K_{gh1}T_{h1}}{T_{gh1}T_{h3}}$	$b_{1,3}=\frac{K_{gh1}T_{h1}}{T_{gh1}T_{h3}}$	$b_{1,4}=\frac{K_{gh1}}{T_{gh1}}$
$b_{2,6}=-\frac{2K_{gh2}T_{h2}}{T_{gh2}T_{h4}}$	$b_{2,7}=\frac{K_{gh2}T_{h2}}{T_{gh2}T_{h4}}$	$b_{2,8}=\frac{K_{gh2}}{T_{gh2}}$

The disturbance matrix is of the order of 11×2 and non-zero values are;

$d_{1,1}=-\frac{K_{ph1}}{T_{ph1}}$	$d_{2,5}=-\frac{K_{ph2}}{T_{ph2}}$

The dimension of A will change 13×13 with the addition of UPFC & RFB

$a_{12,1}=\frac{1}{T_{UPFC}}$	$a_{12,12}=-\frac{1}{T_{UPFC}}$	
$a_{5,13}=\frac{K_{RFB}K_{ph2}}{T_{ph2}}$	$a_{13,5}=\frac{K_{RFB}}{T_{RFB}}$	$a_{13,13}=-\frac{1}{T_{RFB}}$

3.3 Summary

This chapter thoroughly examines the mathematical models of two regions interconnected control framework. Transfer function and state variable models for each component contributing to load frequency control issues of the interconnected framework have been formulated. Apart from the hydro turbine and non-linear demonstrate are moreover designed to form a framework more realistic. UPFC devises to connect to both regions, and RFB is connected to regions-2 is additionally joined in thinking almost for the advancement of energetic execution improvement and accomplishing the goals of load frequency control.

CHAPTER 4

FUZZY-PSO HYDRO POWER SYSTEM

4.1 Introduction

The electrical control time and exchange framework is developing rapidly with objectives of keeping up the system's standard and faithful the quality over the diverse working restriction of the framework. In organizing to make the electrical control and see the control ask considering the monetary way, the electrical control system worked in an interconnected method. This infers that tie-lines relate to different control locales. In extension, these control ranges have control interchange as per characterized agreement by the communication system operator. To begin with, empowering, individually control region sees its own load demand taking care of the lawfully authoritative control through AC tie-line. The derange between electrical control and load demand thrust the framework frequency and AC tie-line power away from the characterized esteem. Thus it impacts the superiority and nonstop control conveyance to the cutting edge power control clients. The alteration in frequency and tie-power is narrow by the LFC strategy. The modification of these indirect shape amounts is well-defined as Area Control Error (ACE) in LFC [11]. The part of LFC controllers is to connect the electrical produced control with electrical energy demand to limit or to set the ACE deviations to a null value. In this part, the starting endeavors were to arrange an LFC based on the conventional controller hypothesis [3, 21]. In any case, standard LFC picks permit agreeable execution as a particular circumstance and incapable of supplying the desired control movement in the electrical imperativeness system's arranged working conditions. Subsequently, the investigators and researchers are trying to look for controller plans based upon specific advanced strategies such as optimal control, control base on few states, changing structure base control, decentralized control, etc. to ensure a productive LFC for electrical imperativeness system [5, 10, 13-15].

The brilliant methodologies based on artificial intelligence [16], such as artificial neural networks and fuzzy logic, are picking up drive for electrical imperativeness systems to solve the LFC issues fruitfully. The fuzzy logic procedure ought to deal with differing sorts from instabilities and non-linearities with respect to progressed electrical systems, which show the fuzzy process to get a different empowering and effective instrument to understand this LFC issue of advanced imperativeness system. With respect to here, the sums of examining items are conceivable interior the LFC [17-20]. The effective Takagi-Sugeno created controller for LFC was demonstrated in [17] so that this creates a fuzzy system that runs perfectly for non-linearity and parametric alterations. The fuzzy methodology for interconnected LFC was made in [18]. The type-2 fuzzy-based specialist show to LFC considering GRC non-linearity was established in [19]. The Genetic Algorithm (GA) created fuzzy gain development control for LFC was presented in [20]. However, some investigators have observed some GA limitations, such as convergence issues and trap in local minima while finding optimal problems. The issues related to GA application have been lessened to an exceptional degree by the change of optimization method, i.e., PSO. PSO has lesser chances to trap into neighborhood ideal, and it additionally has less computational time for some degree of execution [25].

From the open examine work [25-29], it is perceived that most of the control methodologies are affirmed on thermal-thermal control models or hydro-thermal models, and the LFC composing lacks with apposite and direct control arrange for hydro administering framework. The reaction time of hydro turbines is much further related to thermal turbines, due to which the LFC yield of the hydro overseeing framework is drowsy and has continuous motions. The investigators and electric control engineers are evading this system to make a sensible controller arrange for LFC along these lines. As the show day world is affecting on the approach to a cleaner, and characteristic neighborly sources to create electric control such as hydro, be it bulk hydro or micro-hydro. The up and coming electrical imperativeness framework may be further complicated and will include hydro-ministered, interconnected control regions.

The cutting edge and fast progression of power electronic businesses have driven the Flexible Alternating Current Transmission System (FACTS) to progress the course of the electrical framework. FACTS can regulate dynamic and responsive control and improve the electrical framework for unexpected fluctuations in control necessities and ensure the superiority transfer of electrical imperativeness to the progressed clients. Redox flow battery (RFB) is additionally inside the framework of FACTS. It may well be a fast-acting essentialness capacity contraption that can give the capacity in development to the dynamic essentialness of generator rotors, which can share the unexpected fluctuations inside the control ask and successfully clammy out the electromechanical movements of the control framework [29-30].

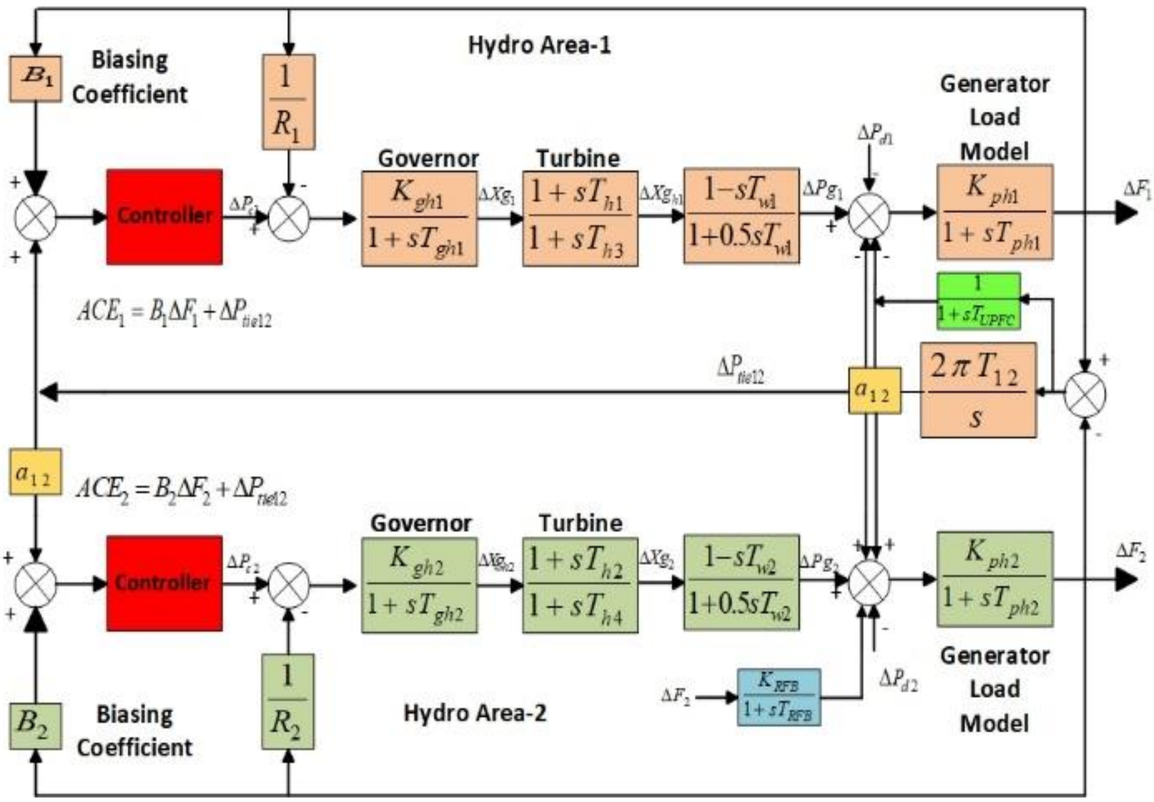


Figure 4.1: Transfer function model of a two-area power system including UPFC and RFB

At anything point, there is a sudden rise within the control ask. The put-away vitality in RFB is rapidly discharged complete control transformation framework, including an inverter/rectifier framework. Basically, it acclimatizes control in the midst of the sudden release of loads. Because it may not be conceivable to put RFB in each locale of interconnected control systems due to money-related reasons, subsequently, unified power flow control (UPFC) may demonstrate viable, exceptionally inexpensive, and can be presented in the course of action through tie-line to improve the execution of the electrical imperativeness system [35]. In this way, the encouraging response of RFB and UPFC is utilized to control the framework situations of overpowering hydro appearing in money-related and more rapidly.

4.2 Modelling of Fuzzy-PSO PID

The advanced control activity's construction is the sequence of a fuzzy PID. Also, PID picks up is determined by solid optimization preparation identified as particle swarm optimization (PSO), resulting in a Fuzzy-PSO PID. The performance of the Fuzzy-PSO PID depends on the yield of K_P, $K_{I,}$ and K_D. Hence, in arranging an absolute LFC activity, K_P, K_I, and KD pick-up must be taken suitably to attain extra beneficial energetic performance for the closed-loop framework. In this investigation, and as a new-made tuning methodology called PSO, actuate the foremost fantastic result of screen picks up to remove the Fuzzy-PSO PID screen LFC frameworks' better dynamic accomplishment. The numerical description of PID is as regards;

$$K(s) = K_P + \frac{K_I}{s} + K_D s \tag{4.1}$$

Where, K_P, $K_{I,}$ and K_D are the picks up of the control activity, and LFC's production exceedingly depends upon this amount. These amounts are chosen for the PSO optimization handle in this article. On another side, the FLC is composed of four leading mechanisms: the fuzzification, the fuzzy acceptance model, the run the showing up the range, and the defuzzification. Fuzzy-PSO PID has two input signals, i.e., Area Control Error (ACE) and derivative of Pro, and one output signal. The model of Fuzzy-PSO PID is given in Figure 4.2.

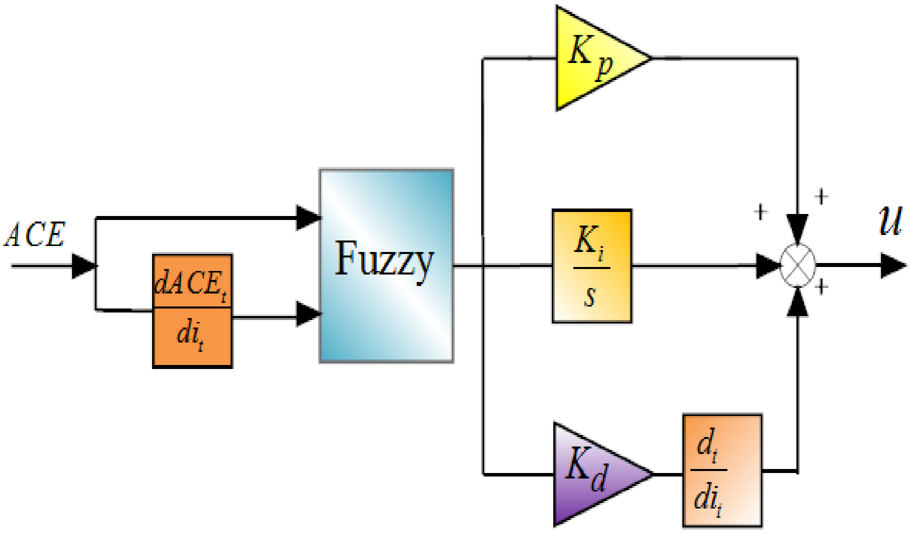


Figure 4.2: A schematic diagram of a fuzzy tuning

4.2.1. Fuzzification

Fuzzification is the component by which a crisp value of the results changes over transform fuzzy value by utilizing points of interest within the information base. Although different sorts of bends are broadly utilized within the fuzzification strategy within histories, such as Gaussian, triangle, and trapezoidal MFs. In any case, in show investigation, triangle MFs are preferred due to effortlessness and balance. The Fuzzy-PSO PID maintains two information signals, i.e., Area Control Error (ACE) and derivative of ACE and one production standard. Each information & production becomes five participations (all mf is triangular). The step middle way of mfs is applied likely, i.e., [–1 to 1].

4.2.2. Fuzzy inference system

The input mfs, the fuzzy in case next etymological laws, and the yield mf are formed of the mamdani fuzzy inference design (fis). The fis regulation is conducted in four steps. The fundamental level is to fuzzify the information data crisp factors, which are here ACE and subsidiary of ACE. It defines the grade to which those information data have a put to particular of the basic fuzzy positions by mfs. The specific action is the way the show-up estimation or inference. The fuzzified information data are performed on the heralds of the fuzzy laws. The min of the herald estimation is related to mf of the evolving approximately by cutting or cut the appearing practically mf in the level of the herald accuracy. The third level is the combination of the way the show-up yields or reproduction. The mfs of everything the covered the show-up consequents as of presently modified are combined commonly within a singular fuzzy position. The fourth level is the defuzzification of that accumulated individual fuzzy position as expressed within the catch behind the part.

4.2.3. Allocation of Regions of Inputs

The control laws feature may obtain extra difficulty than mfs, based on the producer's responsibility and approach to the particular natural framework. The rules are included so that they can be used to composing KP, KI, and KD. Because individually shifting of inputs and Output has 5 mfs, 25 laws are needed to create a fuzzy yield. The If-then laws are used so as: In situation ACE is NB and subsidiary of ACE is NB at this time yield is NB. In the situation, the portion is named as a forerunner. Moreover, subsequent that the part is a called as coming about. The complete law base is given in Table 4.1.

Table 4.1: Rule base for Fuzzy-PSO PID

ACE \ dACE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

4.2.4. Defuzzfying the Output Value

The crisp amount is defuzzified by the well-popular technique named the centroid. The procedure is also recognized as a property of a region or an adjusts of interest.

4.2.5. Objective function

Inside the technique of a now-day heuristic optimization performance established regulator, the real character is, to begin with, explained based on the demanded features of attracted and confinements. Achievement criteria ordinarily analyzed under control arrange are the Integral of Time Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE), and Integral of Absolute Error (IAE). ITAE degree decreases the settling period, which cannot be completed by IAE or ISE based tuning. ITAE type besides decreases the most excellent overshoot. ITSE based control provides a sweeping control product for an instantaneous variation into state problems, which isn't useful in case the control determines the condition of seeing. It necessity be point by point that ITAE may do a significant supportive, accurate work in LFC considers. Concurrently, ITAE is used as a real effort to optimize the measured value and analyze and pick up the Fuzzy-PSO PID [21]. The entrance into the ITAE intention performance is portrayed as [21]. The appearance of the ITAE objective work is shown in Eq. (4.2).

$$J = ITAE = \int_{0}^{t_{sim}} \left(|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie12}| \right) \cdot t \cdot dt \tag{4.2}$$

Under the over eq^n, ΔF_1 & ΔF_2 are the frameworks frequency differences; ΔP_{Tie} is the incremental adjustment in tie-line power; *tsim* is the period continue of diversion. The problem objectives continue these PID component boundaries. In this system, the organized problem can be established, such as catching subsequent optimization problems. Depend upon this performance record *J* optimization issue can be signified as: Reduction J restrained to:

$$K_P^{\min} \le K_P \le K_P^{\max} \quad (4.3)$$

$$K_I^{\min} \le K_I \le K_I^{\max} \quad (4.4)$$

$$K_D^{\min} \le K_D \le K_D^{\max} \quad (4.5)$$

4.2.6. PSO Algorithm

This advanced approach highlights various focuses of intrigued; it is fundamental, quick, and can be coded in many lines. Besides, its capacity need is negligible. Other than this, this methodology is beneficial over evolutionary and genetic algorithms in various methods. To start with, PSO has memory. That is, each particle recalls its best course of action (adjacent best) as well as the bunch best organization (around the world best). An additional improvement of PSO is that the beginning populace of the PSO is kept up. So there is no demand for applying supervisors to the state, a designation that's time and memory-storage-consuming. In extension, PSO is based upon "helpful cooperation" connecting particles, in differentiating with the genetic algorithms, which are founded on ‘‘the survival of the fittest.” PSO starts with a population of self-assertive organizations ‘‘particles” in a D-dimension space. The ith particle is defined by $X_i = (x_{i1}, x_{i2},...,x_{iD})$. Various particle keeps a record of its organizes in hyperspace, which is related to the most appropriate organization it has obtained so distantly. The esteem of the eligibility for particles(pbest) is additionally put away as $P_i = (p_{i1}, p_{i2},...,p_{iD})$. The around the world form of PSO keeps a record of the in common best esteem (gbest). Its region is received in this way distant by any particle inside the populace. PSO covers of, at each step, varying the speed of each particle approaching its pbest and gbest. The speed of particles talked to as $V_i = (v_{i1}, v_{i2},...,v_{iD})$. Advancing up is weighted by a changeable term, with limited subjective numbers being created for increasing speed toward pbest and gbest. The balanced speed and place of each particle can be determined to utilize the actual speed, and the separations from the $pbest_{j,g}$ to $gbest_g$ as showed up inside the taking after conditions [24]:

$$v_{j,g}^{(t+1)} = w \times v_{j,g}^{(t)} + c_1 \times r_1() \times (\text{pbest}_{j,g} - x_{j,g}^{(t)}) + c_2 \times r_2() \times (\text{gbest}_g - x_{j,g}^{(t)}) \quad (4.6)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad (4.7)$$

With j = 1, 2, ……, n and g = 1, 2, …., m. Where n is the value of particles inside the swarm, m the number of elements for the vectors v_j and x_j, t the value of times (generations), $v_{j,g}^{(t)}$ the *gth* element of the velocity of particle j at iteration t, $v_g^{\min} \leq v_{j,g}^{(t)} \leq v_g^{\max}$, w the inertia weight calculate, C_1; C_2 the cognitive and communicative speeding up factors independently, r_1; r_2 the irregular values reliably passed on inside the run (0, 1), $x_{j,g}^{(t)}$ the *gth* element of the situation of particle *j* at cycle *t*, *pbest*$_j$ = *pbest* of molecule *j, gbest* = *gbest* of the gather. The execution steps of the PSO is given in Figure 4.3.

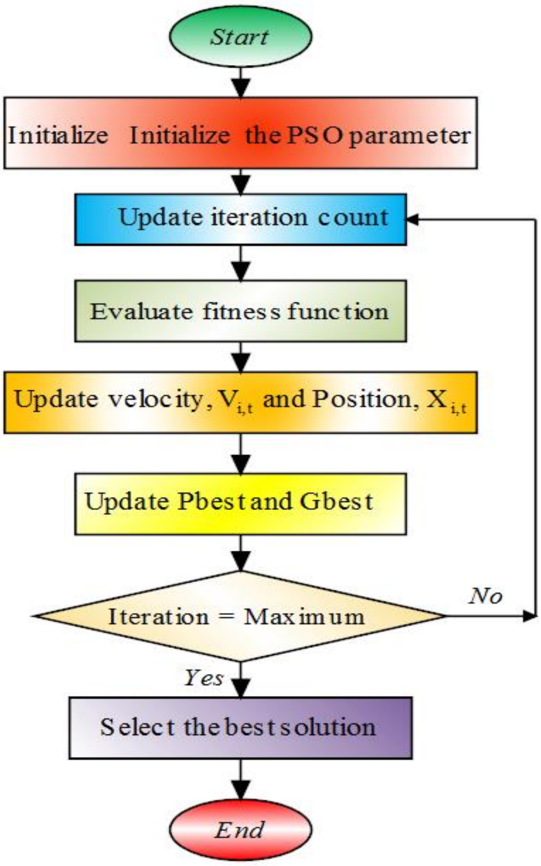


Figure 4.3: The execution steps of PSO

4.2.7 UC Modeling

Ultra-capacitor (UC), an electrochemical device named super-capacitor or electric double-layer capacitor, is the foremost as of late made imperativeness capacity contraption. It involves two permeable anodes, an ion-exchange layer confining them, and a potassium hydroxide electrolyte. The liquid electrolyte and porous terminals in UC offer a colossal surface locale separated from a standard capacitor. Following, the creation of a two-fold layer of slight thickness in UC progresses its specific capacitance. These two variables are reliable for high capacitance (100-1000 times) of a UC in comparison to a standard electrolytic capacitor. UC is compact in degree, shows up extraordinary vitality thickness, and can store extraordinary energy than a standard capacitor. UC offers high regard for power thickness than battery. UC's particular energy is 1-10 Wh/kg and the specific power energy is 1000-5000 W/kg. It can be charged/discharged millions of times faster than a regular battery or standard capacitor. Consequently, UC is around bolstered free and offers a longer generation. All these potentials of UC make it reasonable for an updated LFC. Dismissing nonlinearities and different suspicions, the final illustration of a UC can be shown through a first-order TF. The frequency deviation of the control zone will work as the input to UC and its TF is as [37-39];

$$\Delta P_{UC}(s) = \left\{ \frac{K_{UC}}{1 + sT_{UC}} \right\} \Delta F(s) \tag{4.8}$$

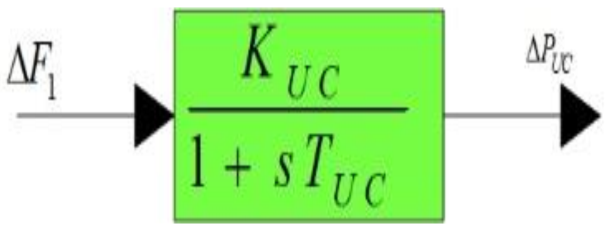


Figure 4.4: UC transfer function model

Figure 4.4 shows the model of UC. Here, UC is joined together in all ranges. T_{UC} is the time steady, and K_{UC} is the gain of UC. The regard K_{UC} is based on the state of charge (SOC). SOC is the circumstance at which UC is charged. Here, K_{UC} is kept consistent at −7/10 between 50% and 90% of the working SOC of UC.

4.3 Summary

This chapter presents the points of interest of the control techniques, which are actualized in the thesis. This comprehensively examines the Fuzzy logic based PSO-PID controller is another control design proposed for the arrangement of the load frequency control issue of a multi-area control framework in this work. All perspectives of the planning of the fuzzy logic controller are moreover performed. The following chapter comprises simulation results of two area frameworks with diverse framework restrictions on advanced controllers' usage.

CHAPTER 5

ANALYSIS AND RESULTS DISCUSSION

5.1 Analysis and Results of the LQR based system

The present research work aims to design the secondary control action for LFC of the interconnected system considering electric power generation through hydro turbines in area-1 & 2 of an interconnected system. The hydropower generation plants are linked via means of AC tie-line. Furthermore, hydro power is one of the clean and cheap electricity generation sources and will prove to be cost-effective for the rising electric power demand in the near future.

Though hydro turbines reply time to variable load demand is much more compared to thermal power plants, very few research work was reported in LFC literature with respect to all hydro generation. On the other side, most of the LFC research work was done considering the continuous time frame, and very few initiatives were taken to propose control design for LFC in discrete mode. However, in reality, the ACE samples were transmitted via means of a communication channel to the central regulator, and finally, the output is regulated in discrete steps in order to match the power generation to load demand on a minute by minute basis. Hence, this work aims to solve the model of hydro system's in transfer function as given in Figure 3.2 and then design the LFC control via optimal control theory in discrete form.

The LFC results are obtained via a 1% load disturbance in area-1 of an interconnected system, and the effect of various sampling time on LFC for optimal control in discrete form is analyzed. The discrete LFC analysis is carried out considering the sampling time of 0.05, 0.07, 0.09, 0.5, 0.7, and 0.9 seconds. The system eigenvalues and feedback gains are only shown for 0.05, 0.07, and 0.09 seconds, as the sampling time increases, the system loses its stability totally.

The discrete eigenvalues are given in Table 5.1. Feedback gains obtain via discrete LQR for different sampling time are shown in Table 5.2. The LFC results are given in Figure 5.1 (a-c). With eigenvalue analysis, it is perceived that the real part is reducing, and there is an increment in the imaginary part of eigenvalues as we move from sampling time of 0.05 to 0.07 and to 0.09 seconds and hence there is a reduction in the stability of the system as sample time is varied from 0.05 to 0.09 seconds.

Table 5.1: Eigenvalue for Discrete LQR

Ts=0.05	**Ts=0.07**	**Ts=0.09**
0.8091 + 0.0562i	0.7422 + 0.0725i	0.6801 + 0.0860i
0.8091 - 0.0562i	0.7422 - 0.0725i	0.6801 - 0.0860i
0.8060 + 0.0000i	0.7393 + 0.0000i	0.6780 + 0.0000i
0.8719 + 0.1025i	0.8221 + 0.1360i	0.7732 + 0.1657i
0.8719 - 0.1025i	0.8221 - 0.1360i	0.7732 - 0.1657i
0.9543 + 0.0032i	0.9366 + 0.0044i	0.9192 + 0.0056i
0.9543 - 0.0032i	0.9366 - 0.0044i	0.9192 - 0.0056i
0.9712 + 0.0000i	0.9599 + 0.0000i	0.9487 + 0.0000i
0.9846 + 0.0000i	0.9785 + 0.0000i	0.9725 + 0.0000i
0.9993 + 0.0000i	0.9990 + 0.0000i	0.9987 + 0.0000i
0.9993 + 0.0000i	0.9990 + 0.0000i	0.9987 + 0.0000i

The LFC responses of Figure 5.1 (a-c) show the effect of sample time on LFC results, and due to increasing sample time overshoot in frequency and tie-power deviation is increasing. However, there is no change observed on settling time on LFC at 0.05, 0.07 & 0.09 seconds, but there is a noticeable change observed in settling time if samples are collected at 0.5s and the system loses its stability totally when samples are collected at 0.7s. The study is extended to investigate the effect of UPFC by adding it to tie-line in series and by integrating RFB in area-2 of the hydro system. The LFC regulator based on optimal control theory is designed considering the sampling time of 0.05 seconds, and its response for LFC is check for step load disturbance in area-1.

The LFC responses for hydropower are also obtained under similar load disturbance and sampling time with UPFC and with the joint effect of UPFC and RFB. The results are shown in Table 5.3-5.4 & Figures 5.2 (a-c). The look at eigenvalues clearly reveals that system stability is ensured for all studies carried out in the present work. Further, as UPFC is included in the system model, there is an increase in the discrete LFC feedback gains, and as UPFC is included with RFB, there is a significant enhancement in feedback gains of area-1 and area-2 for all system states. Due to improvement in feedback gains with UPFC and with joint efforts of UPFC & RFB, there is an appreciable reduction in the first peak of responses for the hydropower system. Also, there is an enhancement in settling time for all LFC responses.

Table 5.2: Feedback Gains Obtained Through Discrete LQR

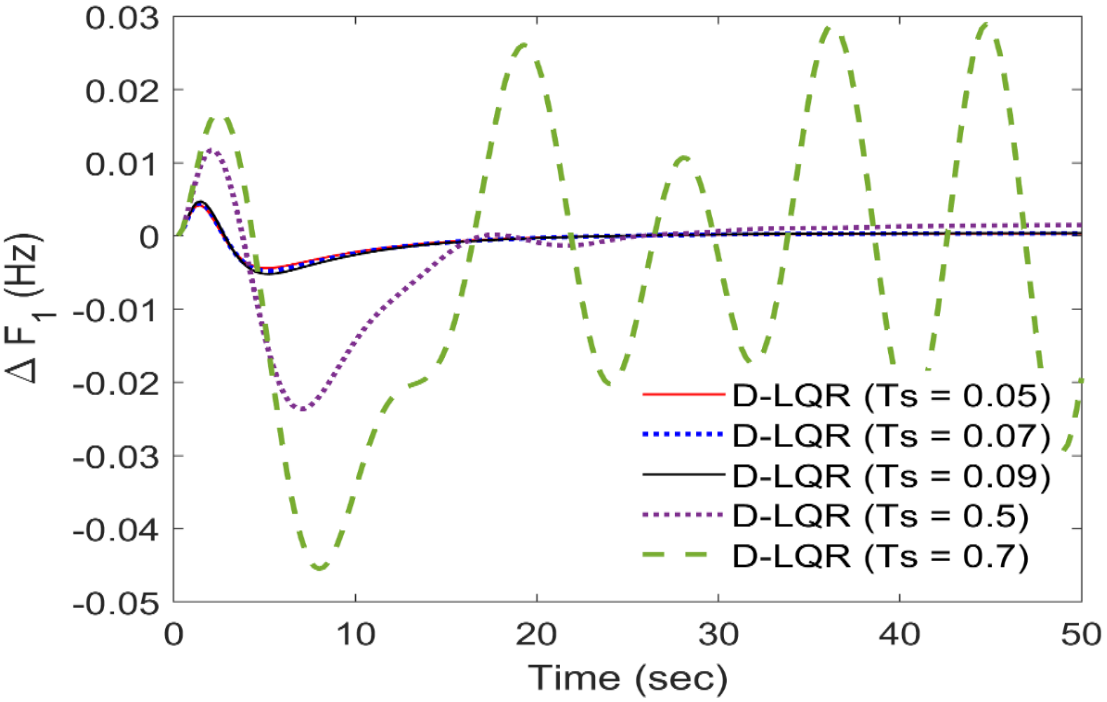
Ts=0.05	-0.9523 -0.1894 -7.7355 108.4258 0.2676 0.4117 -3.3291 39.9403 -0.8743 -0.8146 0.0016 0.1085 0.2292 3.5353 -30.5669 -1.0686 -0.8424 -2.5148 40.9996 -0.2763 -0.0073 -0.8336
Ts=0.07	-0.9189 -0.2303 -7.1255 99.9670 0.2447 0.3873 -3.0589 36.8977 -0.7390 -0.7520 0.0004 0.0986 0.2153 3.2826 -28.3417 -1.0123 -0.8330 -2.3635 38.2108 -0.3231 -0.0078 -0.7767
Ts=0.09	-0.8879 -0.2673 -6.5716 92.2634 0.2235 0.3646 -2.8128 34.1216 -0.6154 -0.6949 -0.0005 0.0893 0.2024 3.0515 -26.3090 -0.9598 -0.8233 -2.2253 35.6510 -0.3655 -0.0082 -0.7246

Table 5.3: Eigenvalues for Discrete LQR with UPFC & RFB

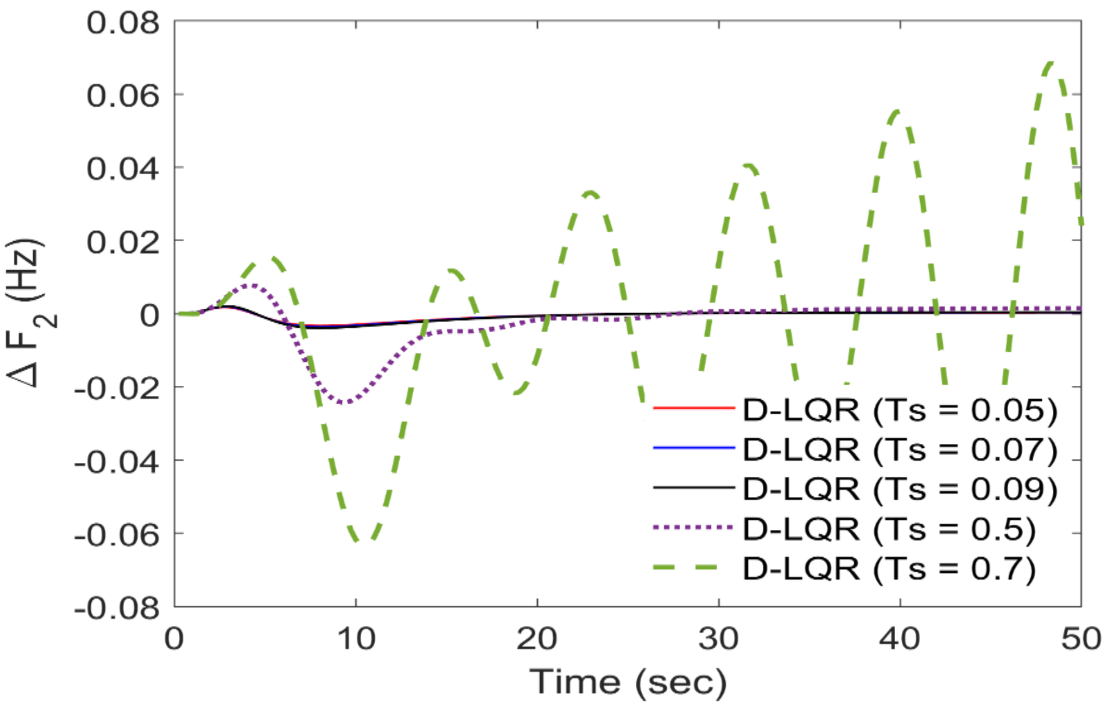
Ts=0.05	**Ts=0.05 (UPFC)**	**Ts=0.05 (UPFC+ RFB)**
0.8091 + 0.0562i	0.0067 + 0.0000i	0.0067 + 0.0000i
0.8091 - 0.0562i	0.7741 + 0.0972i	0.7735 + 0.0966i
0.8060 + 0.0000i	0.7741 - 0.0972i	0.7735 - 0.0966i
0.8719 + 0.1025i	0.8563 + 0.1022i	0.8348 + 0.0914i
0.8719 - 0.1025i	0.8563 - 0.1022i	0.8348 - 0.0914i
0.9543 + 0.0032i	0.8561 + 0.0000i	0.8861 + 0.0000i
0.9543 - 0.0032i	0.9598 + 0.0060i	0.9633 + 0.0098i
0.9712 + 0.0000i	0.9598 - 0.0060i	0.9633 - 0.0098i
0.9846 + 0.0000i	0.9694 + 0.0000i	0.9623 + 0.0000i
0.9993 + 0.0000i	0.9862 + 0.0000i	0.9730 + 0.0000i
0.9993 + 0.0000i	0.9993 + 0.0000i	0.9993 + 0.0000i
	0.9993 + 0.0000i	0.9989 + 0.0000i

Table 5.4: Feedback Gains obtained using UPFC & RFB

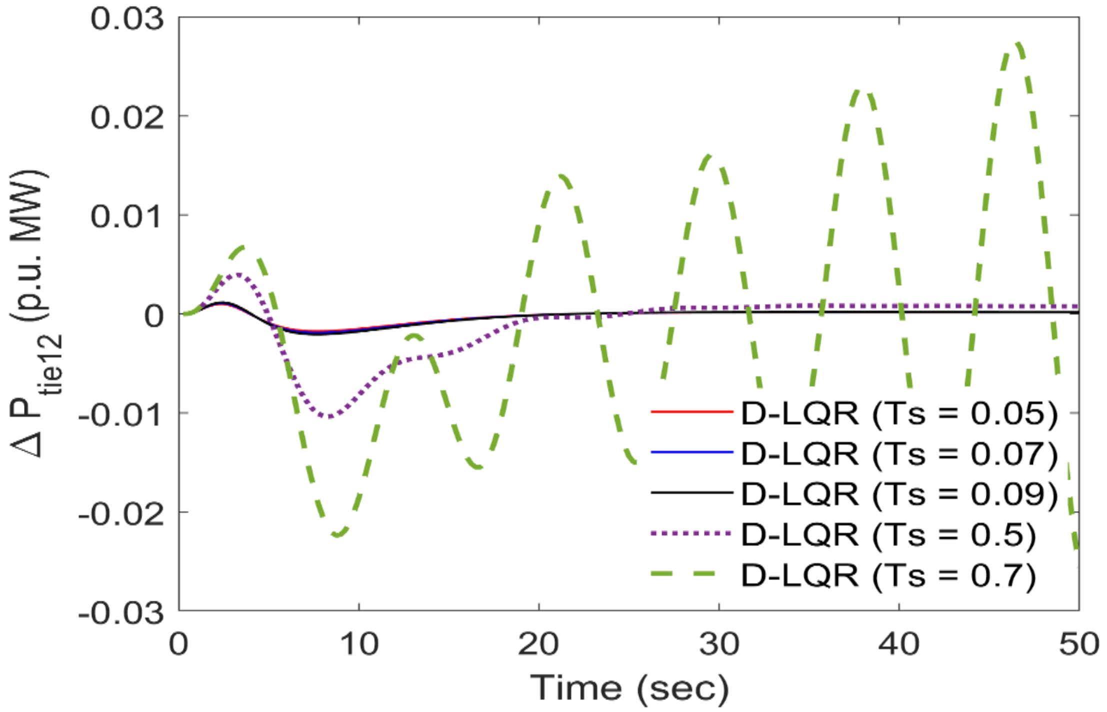
Ts=0.05	-0.9523 -0.1894 -7.7355 108.4258 0.2676 0.4117 -3.3291 39.9403 -0.8743 -0.8146 0.0016 0.1085 0.2292 3.5353 -30.5669 -1.0686 -0.8424 -2.5148 40.9996 -0.2763 -0.0073 -0.8336
Ts=0.05 **UPFC**	-1.0978 -0.0259 -6.4333 101.9551 0.3386 0.5975 -3.2484 42.8998 -1.2110 -0.7956 -0.0789 -0.0001 0.0866 0.1939 4.6535 -42.1043 -1.0811 -0.8058 -1.9347 36.4067 -0.2038 0.0773 -0.8284 -0.0000
Ts=0.05 **UPFC+ RFB**	2.9296 9.2679 32.8858 -99.2228 5.0280 11.1696 39.7525 -169.7919 3.6751 -0.7957 -0.0104 -0.0001 21.6934 6.2073 13.9508 54.2572 -256.8836 5.4031 14.7798 53.8293 -196.2140 7.6231 0.0085 -0.7977 -0.0000 28.9564


0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
D-LQR (Ts = 0.05)
D-LQR (Ts = 0.07)
D-LQR (Ts = 0.09)
D-LQR (Ts = 0.5)
D-LQR (Ts = 0.7)

(a)

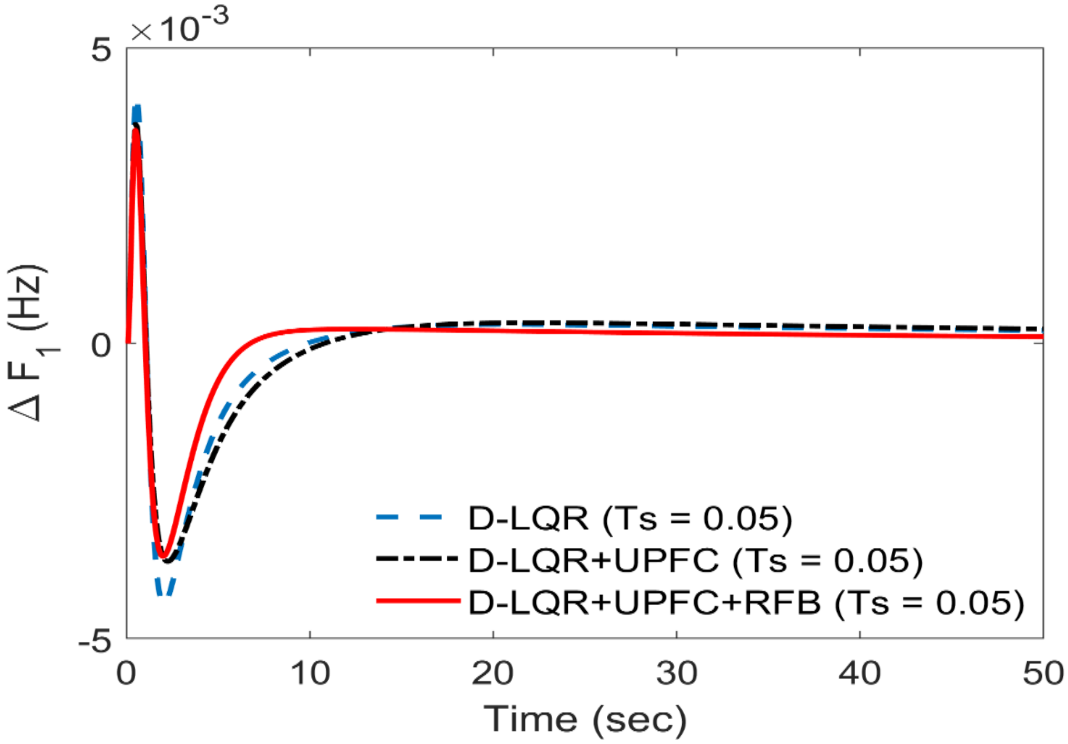

0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
D-LQR (Ts = 0.05)
D-LQR (Ts = 0.07)
D-LQR (Ts = 0.09)
D-LQR (Ts = 0.5)
D-LQR (Ts = 0.7)

(b)

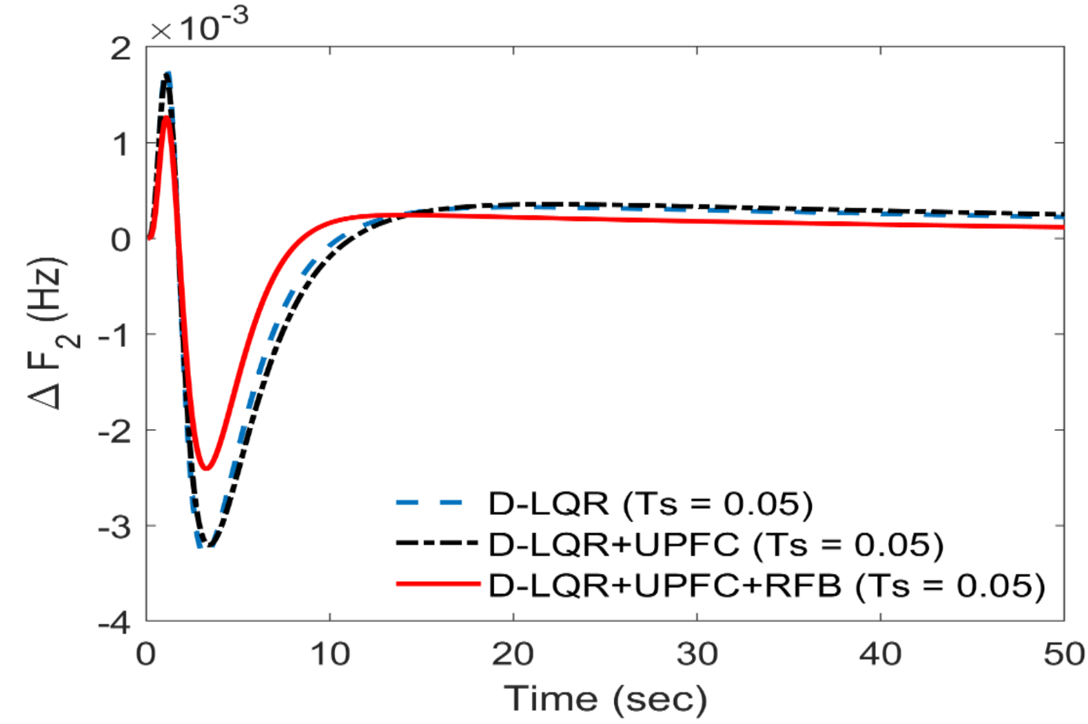


(c)

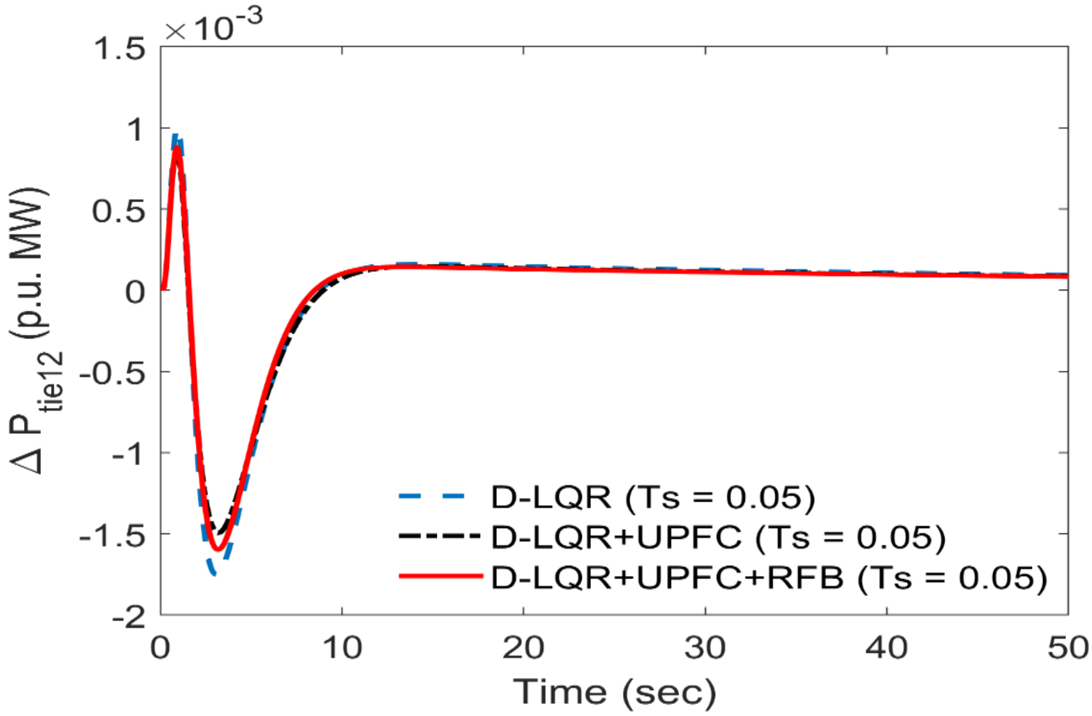
Figure 5.1: (a-c) LFC responses obtain via discrete LQR at various sampling times.



(a)



(b)



(c)

Figure 5.2: (a-c) LFC responses obtain via merging LQR with UPFC & UPFC + RFB at sample time of 0.05 seconds.

5.2 Analysis of Results of Fuzzy-PSO-PID with UPFC & UPFC-RFB

A two-region interconnected essentialness framework having hydro turbines in together of the control districts with equal capacity is utilized for the examination. The thought behind the ask almost work is to investigate the execution of such a hydro-ministered framework to illustrate and offer a compelling arrangement of Fuzzy-PSO-PID to estimate the execution of control for LFC underneath contrasting working situations. Outstandingly rare examinations were achieved, and nitty-gritty by the scientists on this appear for LFC as the hydro overseeing models are unstable due to great reacting time of hydro turbines in organizing to meet the unexpected variation of control demand. The Fuzzy-PSO-PID control is presented in individually of the control regions, and the output (u) gotten is associated with each control region to obtain the LFC standards.

At first, the fuzzy logic action is designed for the hydro system and the ACE & its derivative work as input to the fuzzy logic system. The fuzzy system's two inputs are scaled within the membership function's help to convert original values into crisp value. The fuzzy logic system's rule base for two input and one control output, i.e., u having a total of 25 rule sets, is given in Table 4.1. The output is defuzzified to get back the original value from crisp value and input to PID.

The gain value of PID is obtained through the PSO technique. The ITAE is selected to achieve the best PID value, considering the minimum value of ITAE. The gain value of PID is selected with respect to minimum and maximum limitations. The PSO technique is run for 100 iterations, and the best solution achieves after 100 iterations with respect to a minimum value of ITAE. gain values of PID are mentioned in Table 5.5, resulting in a Fuzzy-PSO PID for LFC. Fuzzy-PSO PID's outcome is assessed for standard load change in area-1, and the application outcomes match recent LFC outcomes.

From the look of Table 5.5 results, it is observed that ITAE is reduced to a good value, i.e., 0.002725, which shows financial aspects of LFC strategy implementation. It is also observed that the value of ITAE is quite less in comparison to Classical PID (41.1935015), Pessen PID (46.5603916), Some overshoot PID (38.0953828) & No overshoot PID (31.388228). Fuzzy-PSO PID's outcome is assessed for standard load alteration in area-1 and the application outcomes match recent LFC outcomes. The graphical LFC outcomes are given in Figure 5.3 (a-c), and it is revealed that frequency and tie-power deviations have a minimum value of the first peak and settling back to original value very quickly after load alteration.

The same outcome or near to Fuzzy-PSO PID outcomes for LFC is not achieved through other LFC techniques: Classical PID, Pessen PID, Some overshoot PID & No overshoot PID. It is also observed that LFC outcomes are completely free from oscillations, which is not possible via means of other LFC actions for the hydro ruling framework.

Still, there is a scope for further enhancement, and hence now UPFC links with tie-line in series connection and RFB connected in control region-2, and now the studies are extended to see the impact of these FACTS in LFC for a hydro ruling framework. The gain value of Fuzzy-PSO PID and the value of ITAE are matched with Fuzzy-PSO PID with UPFC & Fuzzy-PSO PID with UPFC-RFB. These results are tabulated in Table 5.6. It is observed that UPFC integration has resulted in a reduction of ITAE (i.e., 0.002471) and further reduction seen with joint efforts from UPFC-RFB (i.e., 0.001103).

To observe the same effect, the graphical LFC is shown in Figure 5.4 (a-c), and it is observed that the joining of UPFC and RFB has way better the LFC results to an incredible degree. At last, there is an advancement counting least, to begin with crest, upgrade settling to reference esteem, and wavering free LFC results calculated through Fuzzy-PSO PID with UPFC and RFB.

The considered appear to boot evaluated for random load pattern design over a period of 50 seconds, and the LFC results are revealed in Figures 5.5 (a-d). It realizes that Fuzzy-PSO PID with UPFC and RFB is continuously taking after the random load design and extinguishing the frequency and tie-power deviations successfully to zero esteem.

In addition, the affectability examination of the Fuzzy-PSO-PID with UPFC and RFB control in addition surveyed by changing the system factors like T_{12} (tie-line matching coefficient), and Tg (responding time of governor) over the great values from regular plant values and are showed up in Figure 5.6 (a-c).

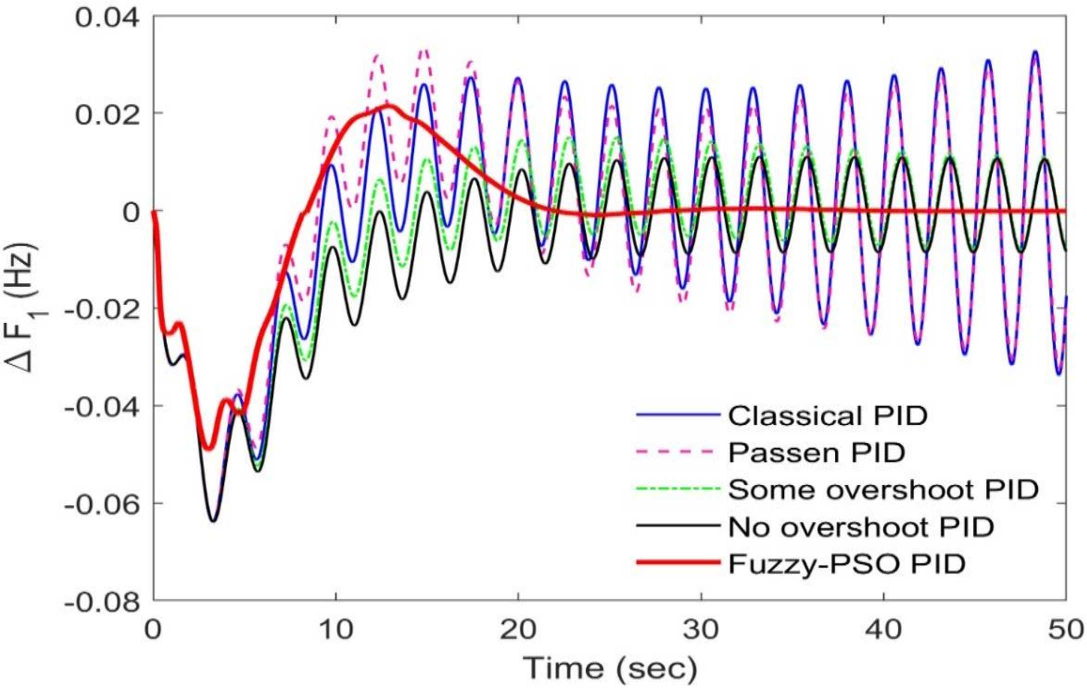
From the comes approximately fulfilled, it is perceived that the Fuzzy-PSO-PID with UPFC and RFB offers energetic execution in the instance of parametric assortments and scarcely any alter is taken note inside the dynamic reactions of the measured control framework. Hence, it can reveal that Fuzzy-PSO PID offers robust performance for all analysis and can be recognized for such kind of hydro administering system.

Table 5.5: Numerical outcomes of Fuzzy-PSO PID

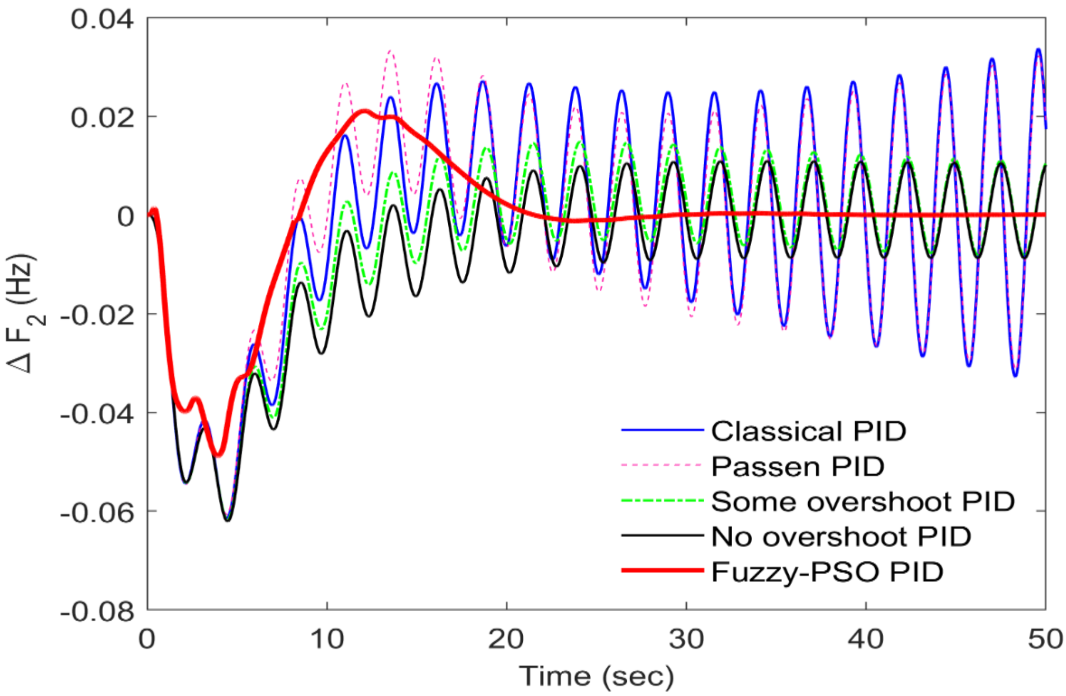
Methods	K_P	K_I	K_D	ITAE
Classical PID [25]	-0.12	-0.091603	0.0393	41.1935015
Pessen PID [25]	-0.14	-0.050381	0.05502	46.5603916
Some overshoot PID [25]	-0.066	-0.050381	0.05764	38.0953828
No overshoot PID[25]	-0.04	-0.030533	0.034933	31.388228
Fuzzy-PSO PID	-1.0684	-0.0591	-0.1305	0.002725

Table 5.6: Numerical outcomes of Fuzzy-PSO PID+UPFC+RFB

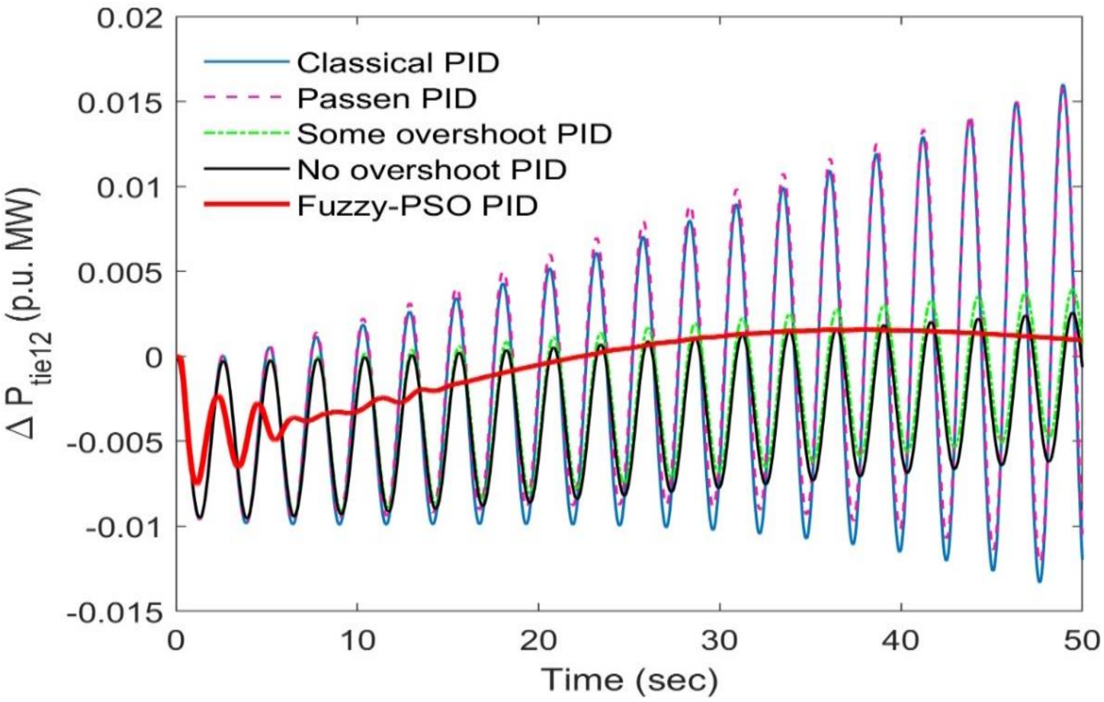
Models	K_P	K_I	K_D	ITAE
Fuzzy-PSO PID	-1.0684	-0.0591	-0.1305	0.002725
Fuzzy-PSO PID+UPFC	-1.0684	-0.0591	-0.1305	0.002471
Fuzzy-PSO PID+UPFC+RFB	-1.0684	-0.0591	-0.1305	0.001103


0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
Classical PID
Passen PID
Some overshoot PID
No overshoot PID
Fuzzy-PSO PID

(a)

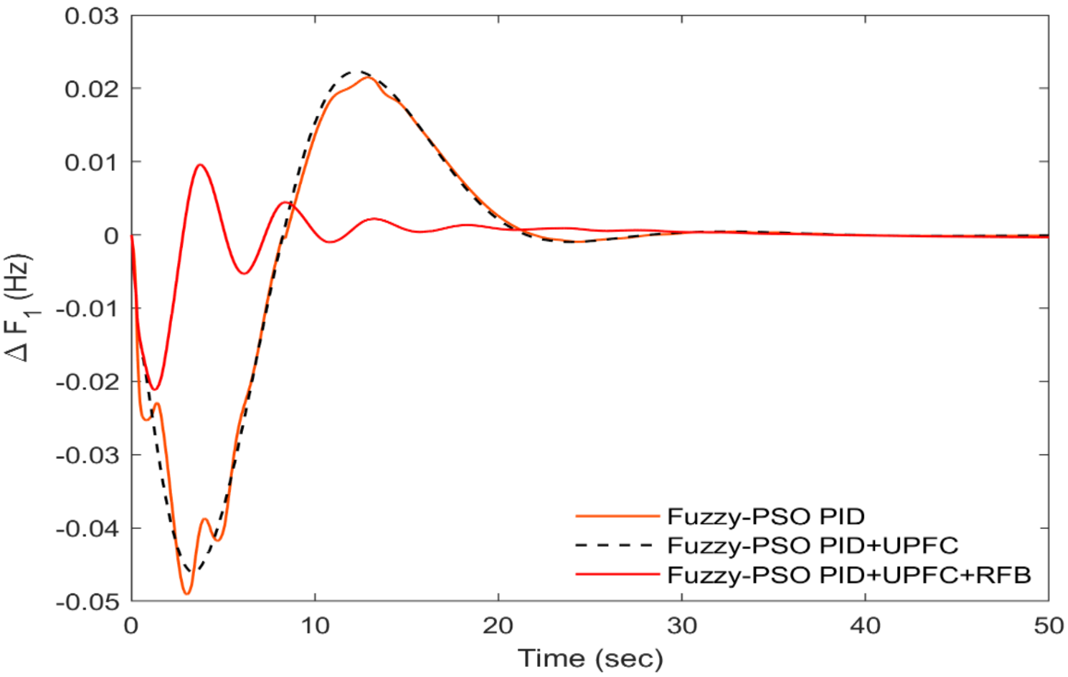

0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
Classical PID
Passen PID
Some overshoot PID
No overshoot PID
Fuzzy-PSO PID

(b)

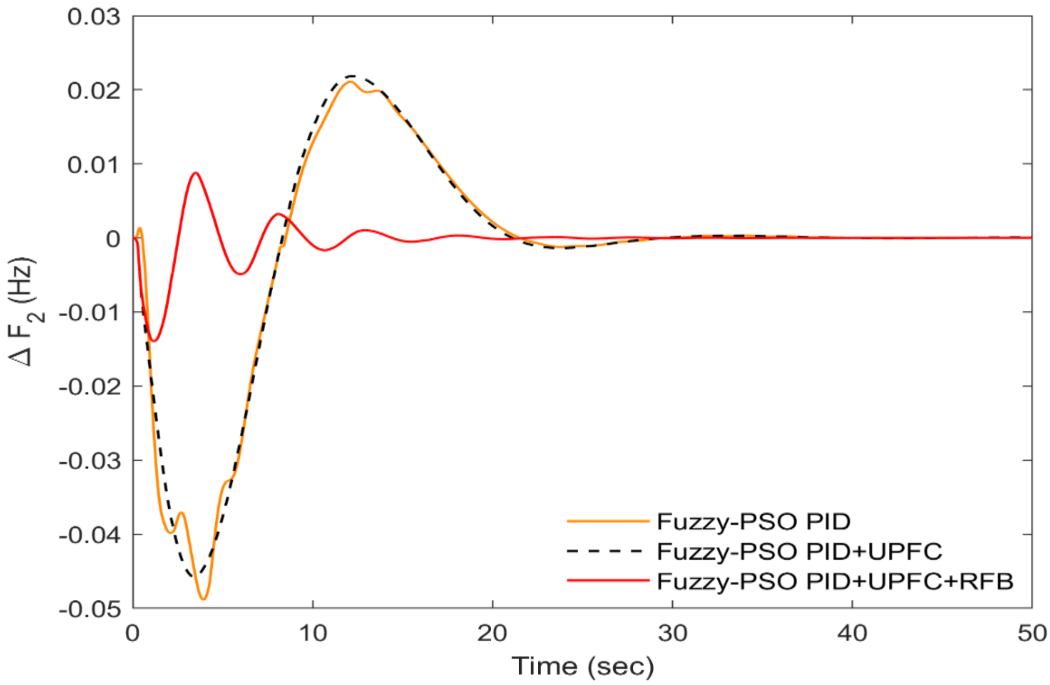


(c)

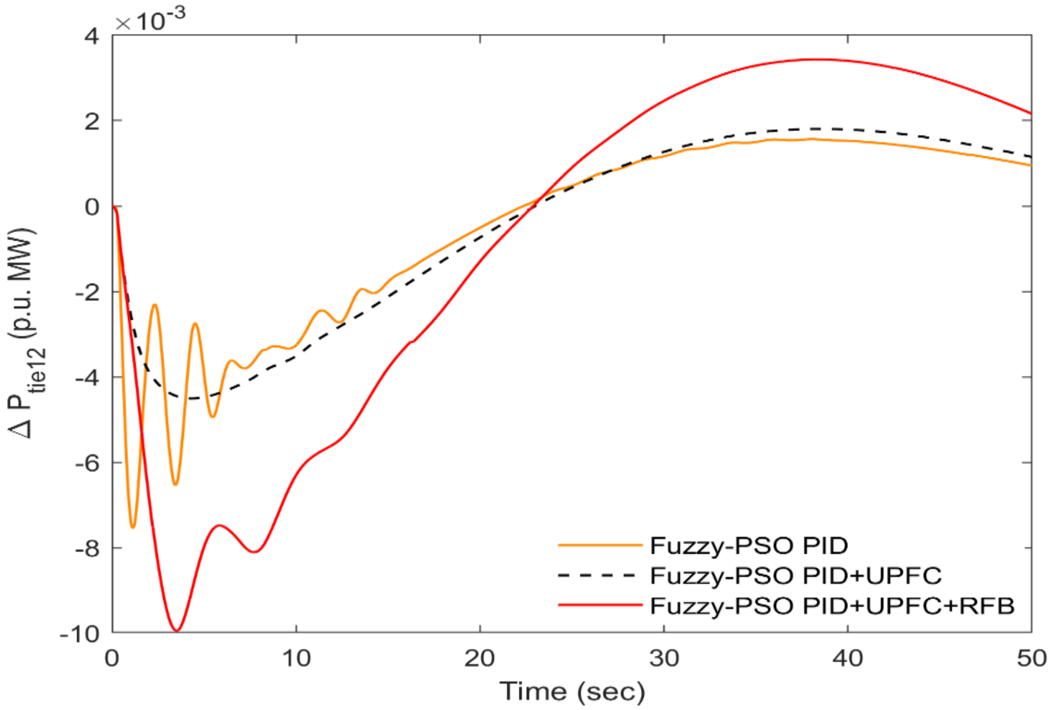
Figure 5.3: (a-c) LFC results for 1% load alteration in region one



(a)

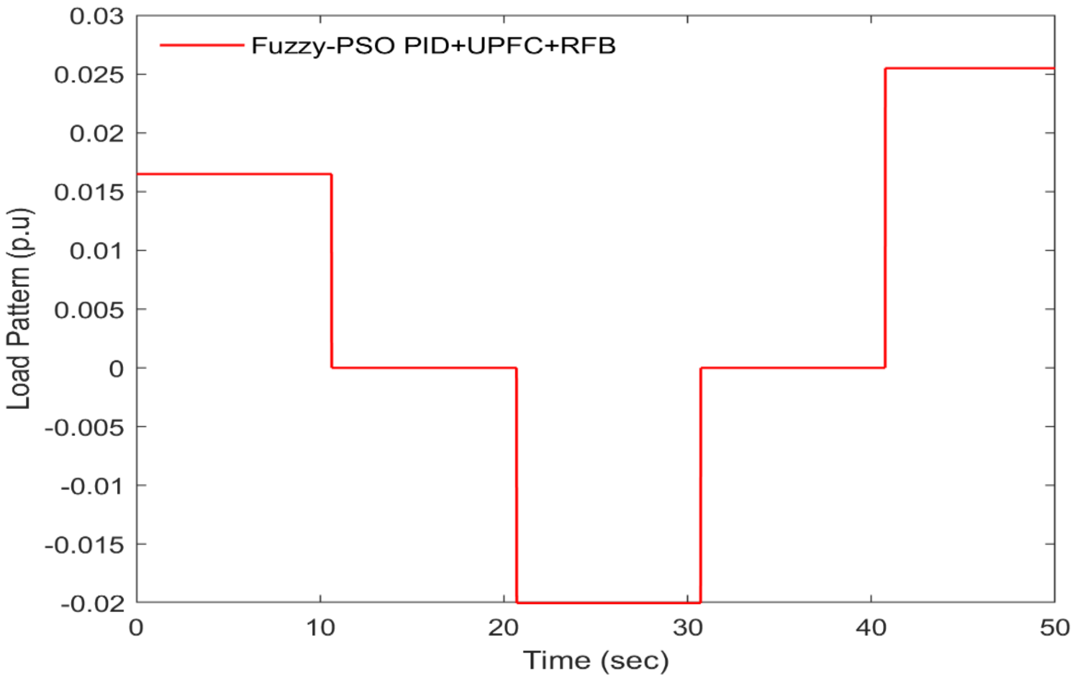


(b)

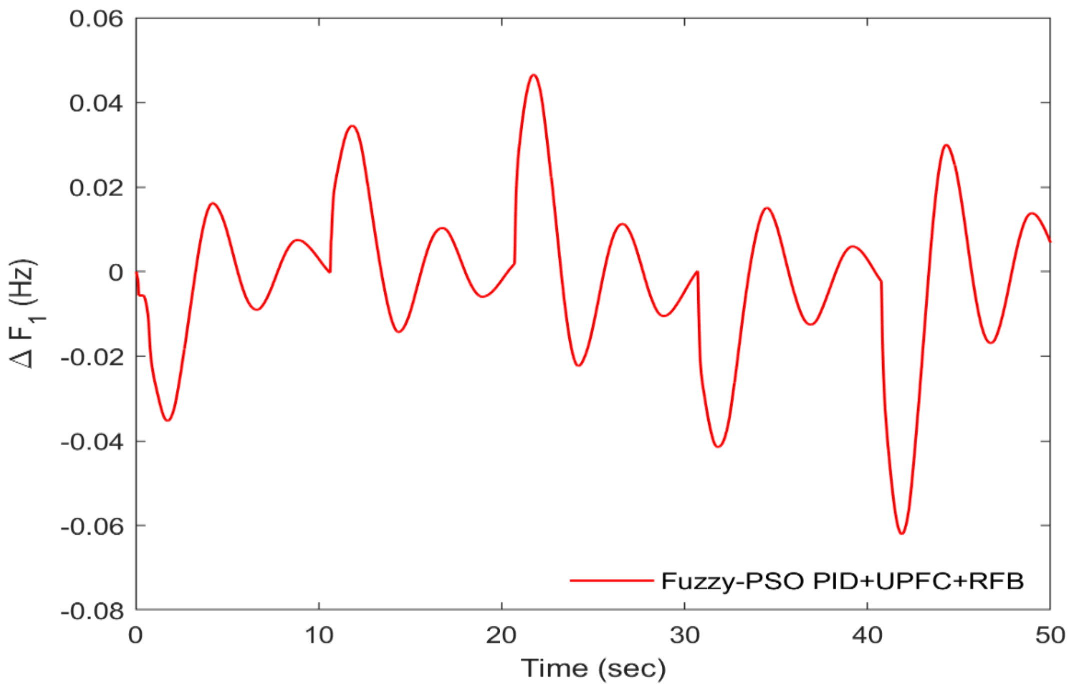


(c)

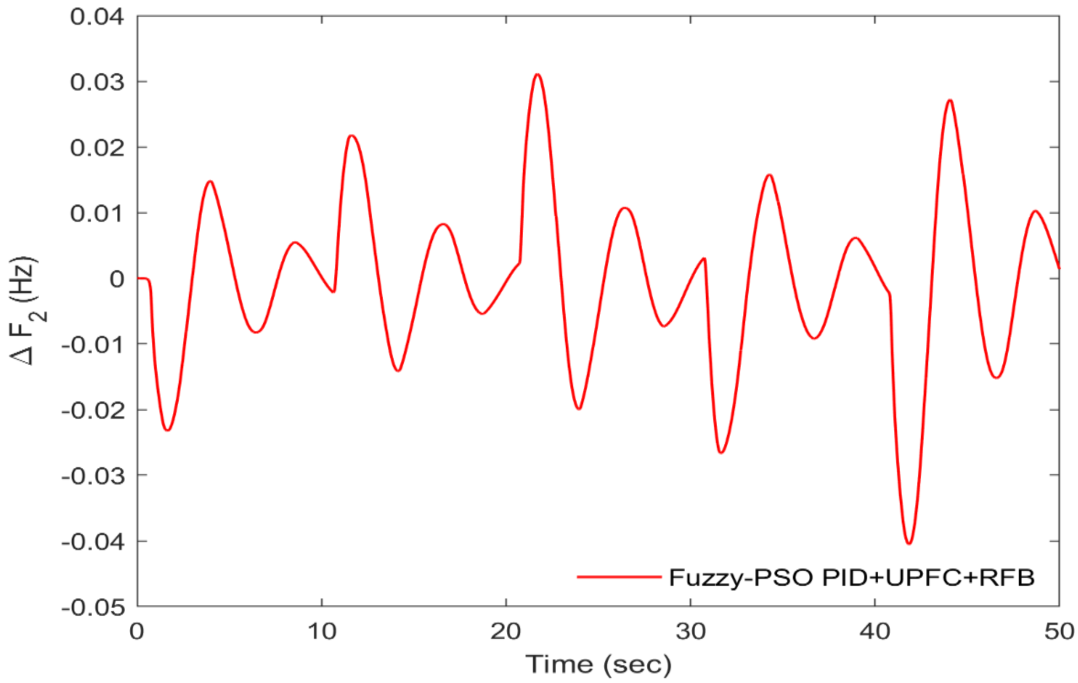
Figure 5.4: (a-c) LFC results for 1% load alteration in region one


Fuzzy-PSO PID+UPFC+RFB
Load Pattern (p.u)
Time (sec)
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
10
20
30
40
50

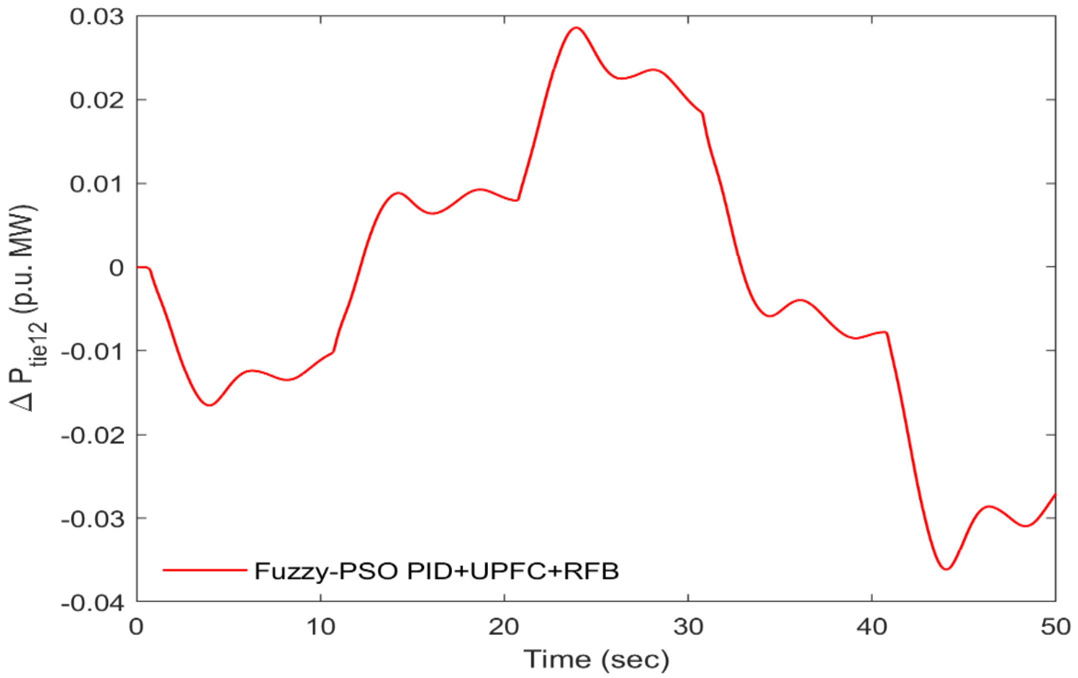
(a)


Δ F1 (Hz)
Time (sec)
Fuzzy-PSO PID+UPFC+RFB
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
10
20
30
40
50

(b)

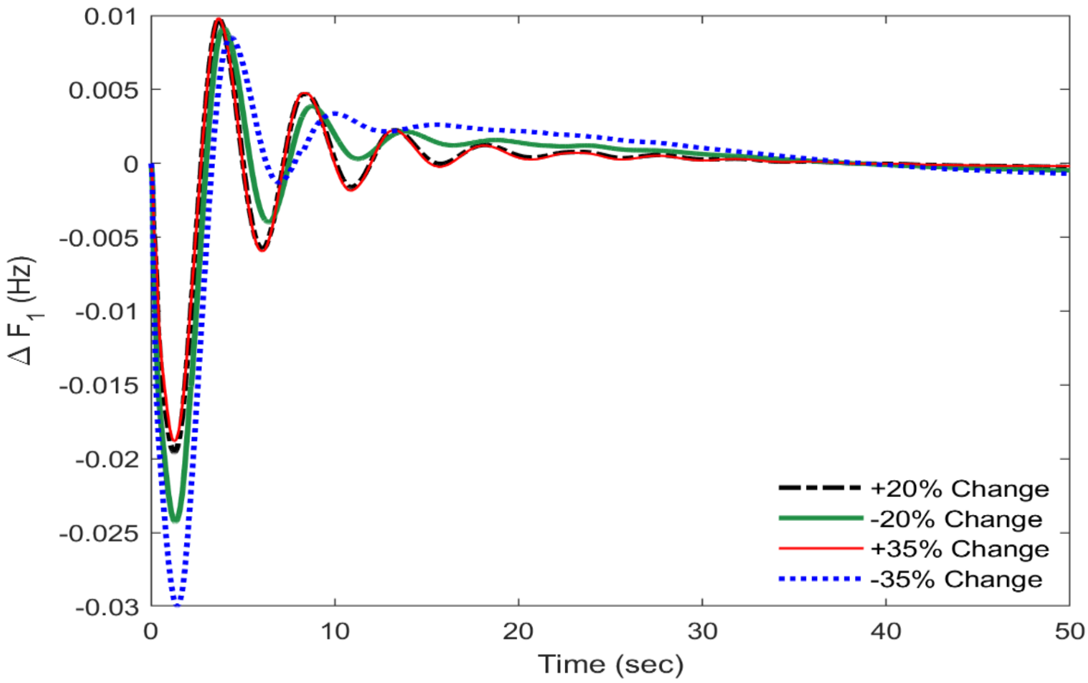


(c)



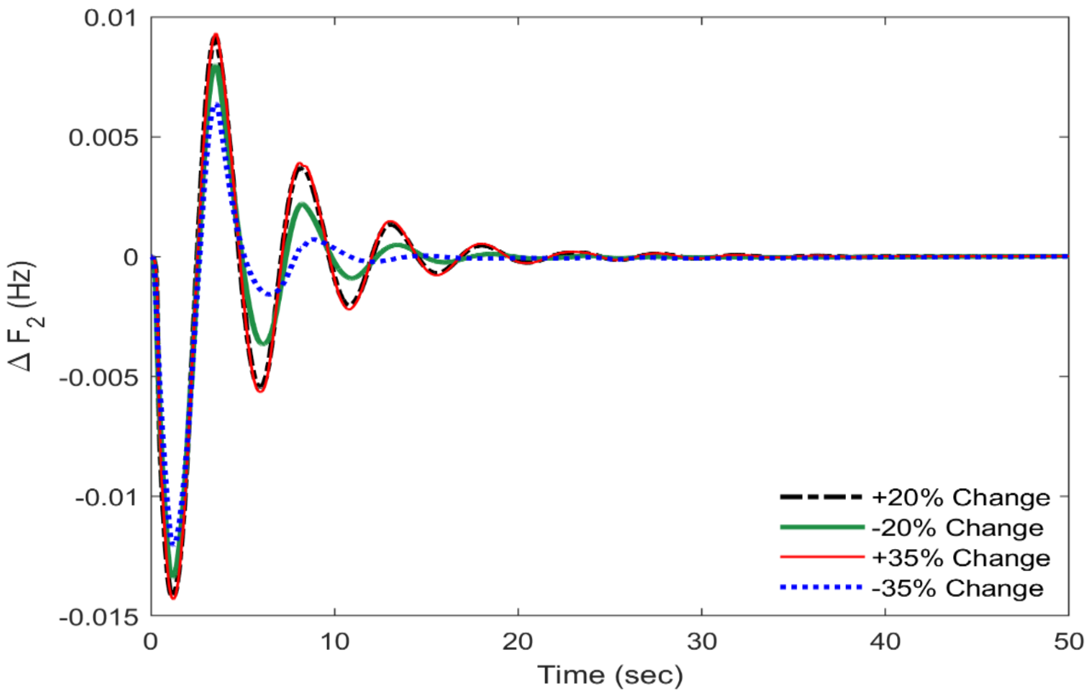
(d)

Figure 5.5: (a-d) LFC results for continuous random load pattern



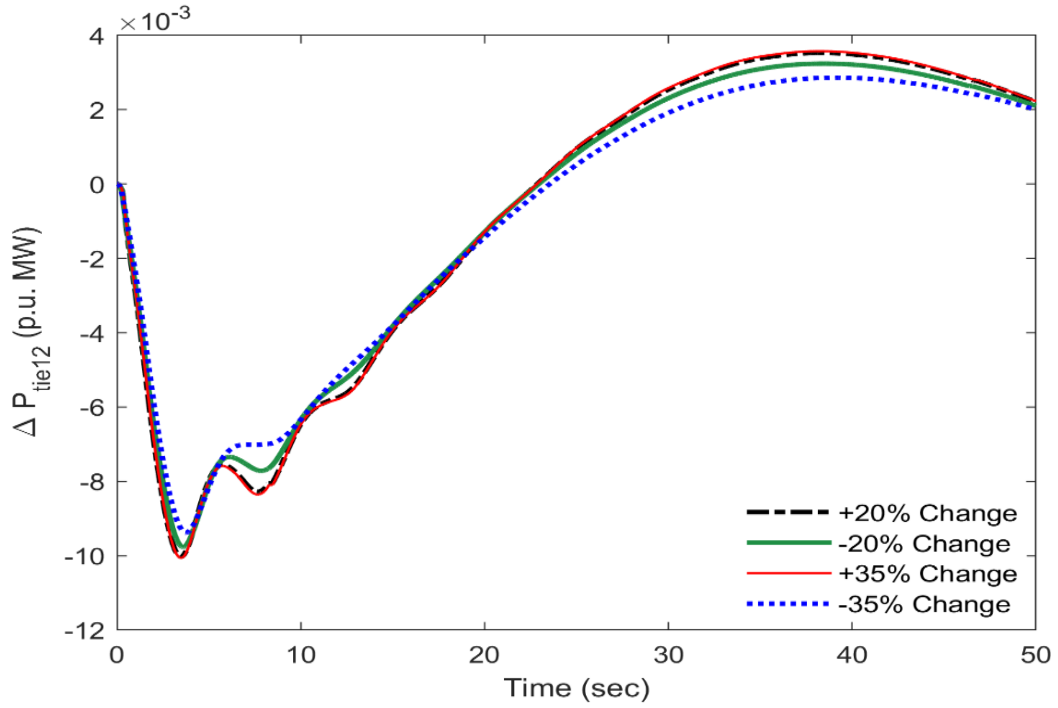
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
+20% Change
-20% Change
+35% Change
-35% Change

(a)



0.01
0.005
0
-0.005
-0.01
-0.015
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
+20% Change
-20% Change
+35% Change
-35% Change

(b)



(c)

Figure 5.6: (a-c) LFC results for wide parametric alteration

5.3 Analysis of Results of Fuzzy-PSO-PID with UC-UC & UC-RFB

A two-region interconnected essentialness framework with hydro turbines in the control locale equally with similar capability is utilized for the examination. The Fuzzy-PSO-PID control is displayed in individually of the control regions, and the abdicate (u) gotten are related to each control region to get the LFC measures. To begin with, the FL activity is a plan for the hydro framework, and the ACE & D-ACE work as input to the FL framework. The two inputs of the FL framework are scaled with the assistance of participation work in arrange to change over unique values into fresh esteem. They run the show base of FL framework for two inputs and one control yield, i.e., u having to add up to 25 run the show set is given in Table 4.1. The output is defuzzified to induce back the initial esteem from fresh esteem and input to PID.

The pickup value of PID are obtained through the PSO strategy. The ITAE & IAE is chosen to realize the most excellent choice up PID's esteem, considering the least appreciation of ITAE & IAE. The pickup esteem of PID is selected concerning the least and most significant limitations. The PSO procedure is run for 100 cycles, and the leading arrangement accomplishes after 100 periods in relation to the least esteem of ITAE & IAE, pickup values of PID say in Table 5.7, and consequently, it comes about into a Fuzzy-PSO-PID for LFC. Fuzzy-PSO-PID results are evaluated for step load alteration in region one, and the application results are coordinated with later LFC results [25].

Table 5.7: Numerical results of Fuzzy-PSO-PID

Techniques	**K_P**	**K_I**	**K_D**	**IAE**	**ITAE**
PSO-PID [25]	-0.49628	-0.11681	0.378604	0.2141	2.3314
BFO-PID [25]	-0.27106	-0.11900	0.615888	0.2321	2.3442
Hybrid BFO-PID [25]	-0.55962	-0.04598	0.876421	0.2768	3.269
Fuzzy-PSO-PID	-1.0684	-0.0591	-0.1305	0.2085	2.293

From the see of Table 5.7 comes about, it is watching that ITAE and IAE are decreased to great esteem, i.e., 2.293 and 0.2085, which appears budgetary angles of LFC methodology usage. It is additionally watch that esteem of ITAE is very less in comparison to PSO-PID (ITAE: 2.3314 & IAE: 0.2141), BFO-PID (ITAE: 2.3442 & IAE: 0.2321) and Hybrid BFO-PID (ITAE: 3.269 & IAE: 0.2768). The result of Fuzzy-PSO-PID are surveyed by applying load alteration in step in region one, and the application results are coordinate with later LFC results [25]. The graphical LFC outcomes are given in Figure 5.7 (a-c), and it is uncovered that all LFC deviations have the least esteem of, to begin with, top and settling back to unique esteem exceptionally rapidly after step load modification.

At next, considering step load alteration in region one seeing GRC non-linearity in each zone of linked hydro system and the outcome of Fuzzy-PSO-PID is evaluated by calculating the values of ITAE & IAE and on the basis of system results. The numerical values of ITAE and IAE are again matched with PSO-PID, BFO-PID, and Hybrid BFO-PID and reported in Table 5.8 and graphs in Figure 5.8 (a-c).

It is watching that ITAE and IAE values are minimal as attained via Fuzzy-PSO-PID and the same is not possible via PID evaluated via other optimization techniques. Further, the same result or close to Fuzzy-PSO-PID outcomes are not accomplished through other LFC strategies, which are PSO-PID, BFO-PID, and Hybrid BFO-PID. From the graphical results, it is watched that GRC has limited the LFC control efforts, and due to which, there is an increase in overshoot as well as for settling time is affected for all LFCs. However, the LFC outcomes of Fuzzy-PSO-PID have lesser overshoot with a shorter time to get back to original values after deviations.

Table 5.8: Outcomes of Fuzzy-PSO-PID with GRC

Techniques	IAE	ITAE
PSO-PID [26]	0.2634	2.087
BFO-PID [26]	0.3078	2.699
Hybrid BFO-PID [26]	0.3937	5.016
Fuzzy-PSO-PID	0.1763	1.889

Still, there's a scope for assist improvement of Fuzzy-PSO-PID, and consequently, presently, UC is located in each region of the hydro system. In addition to this, the UC is located in zone one and RFB in region two. And now, the outcomes of Fuzzy-PSO-PID are matched with Fuzzy-PSO-PID with UC-UC and Fuzzy-PSO-PID with UC-RFB. The esteem of ITAE and IAE are listed in Table 5.9 for step load modifications, and comparative deviations are shown in Figure 5.9 (a-c).

It is watched that UC and UC in each region have reduced the value of ITAE to 2.190 and IAE to 0.1367 in comparison to when no UC is seen in regions of hydro and hence UC-UC have shown enhance control efforts. As there is a reduction in ITAE and IAE, and hence the frequency deviation is limited to 0.02 Hz in region one and 0.015 Hz in region two. The tie-power deviation is also less. Further enhancement in the LFC of hydro is observed when the UC-RFB combination is tried in a linked hydro system with Fuzzy-PSO-PID. Now the ITAE finally reaches to 2.002 and IAE to 0.1253, which is not possible via Fuzzy-PSO-PID & Fuzzy-PSO-PID with UC-UC and hence present combination is superior with regards to cost and control efforts.

The look of frequency deviations reveals that deviation is 0.02 Hz as well as for settling in 10 seconds in region one with 0.015 Hz deviation in region two with the same settling time as seen in region one. The settling of tie-power to original value is also less when match with outcomes of Fuzzy-PSO-PID and Fuzzy-PSO-PID+UC-UC.

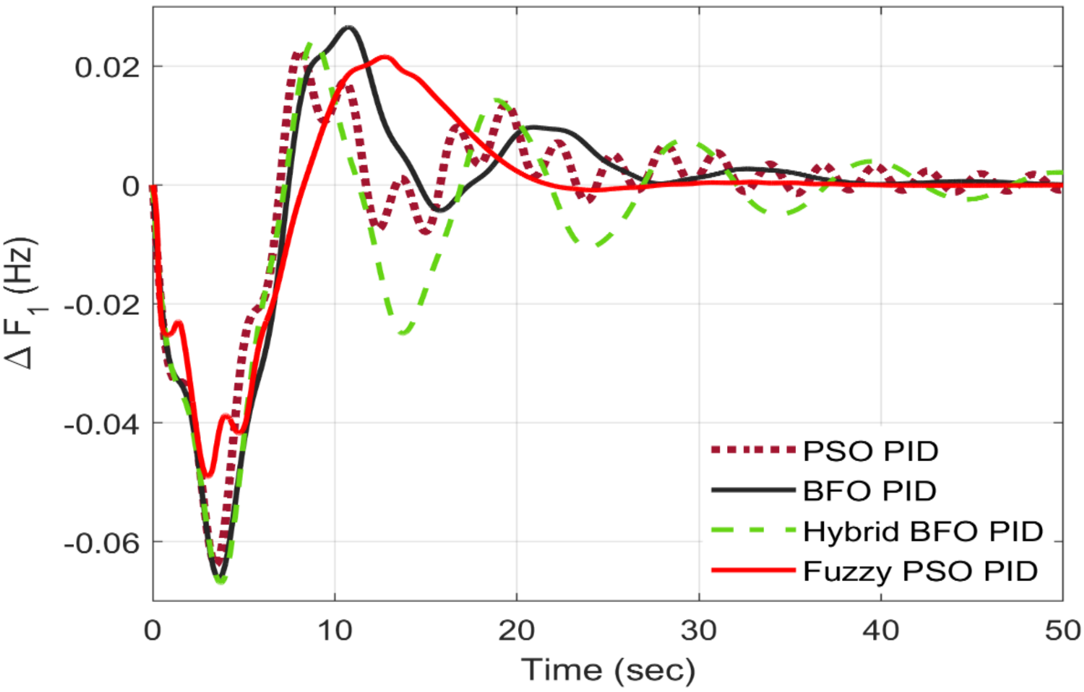
Table 5.9: Outcomes of Fuzzy-PSO-PID with UC-UC and UC-RFB

Models	**IAE**	**ITAE**
Fuzzy-PSO-PID	0.2085	2.293
Fuzzy-PSO-PID+UC+UC	0.1367	2.190
Fuzzy-PSO-PID+UC+RFB	0.1253	2.002

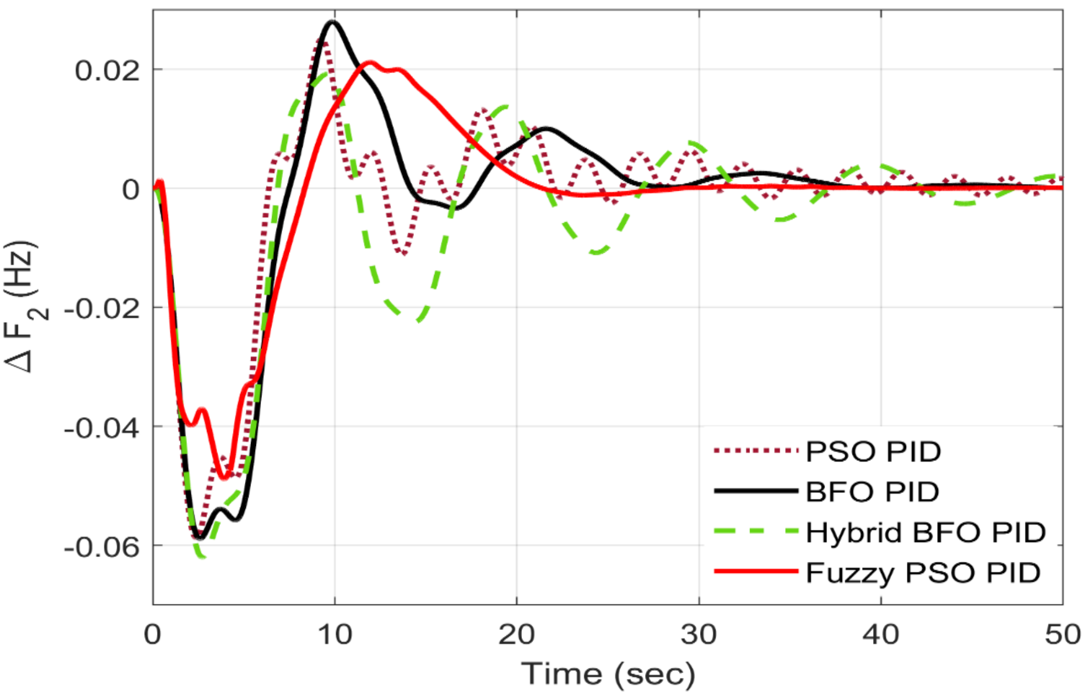
The considered show up to boot assessed for endless load modification over a period of 50 seconds, and the LFC comes about are uncovered in Figures 5.10 (a-d). It is realized that Fuzzy-PSO PID with UC and RFB is come full circle in taking after the endless load persistently and quenching the frequency and tie-power deviations effectively to zero regards.

In expansion, the affectability examination of the Fuzzy-PSO-PID with UC and RFB control in expansion studied by changing the framework parameters like T_{12} (tie-line synchronizing coefficient), and Tg (reacting time of governor) over the wide run from average plant values and are appeared up in Figure 5.11 (a-c).

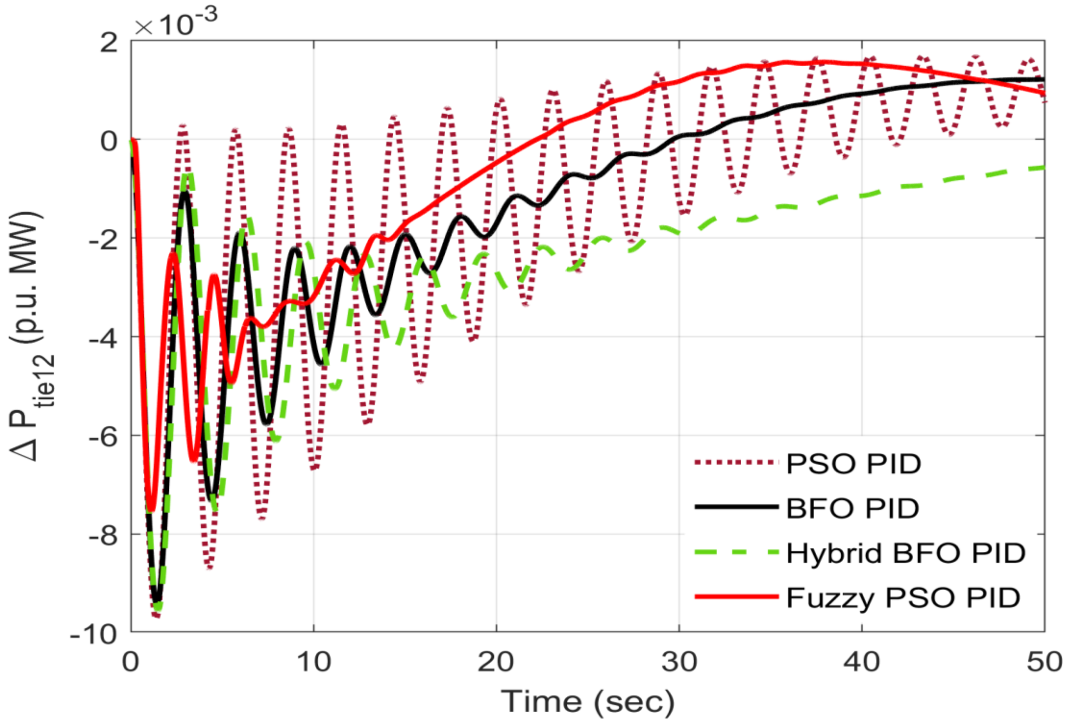
It is also noted from the framework outcomes that variation from original values shows higher peak overshoot and motions within LFC outcomes. However, all LFC deviations manage to effectively reach the original value after load modification with alteration in system values. Be that as it may, the framework reactions are inside worthy limits and in general, can be acknowledged for such kind of hydro-hydro overwhelming control framework.


0.02
0
-0.02
-0.04
-0.06
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
PSO PID
BFO PID
Hybrid BFO PID
Fuzzy PSO PID

(a)

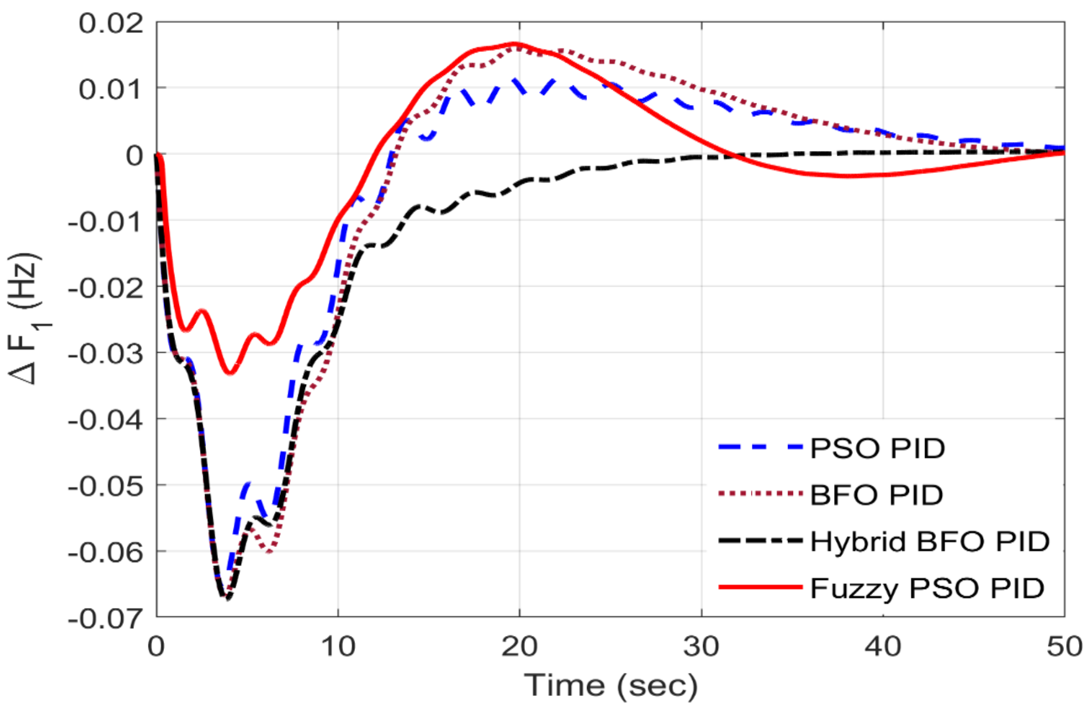

0.02
0
-0.02
-0.04
-0.06
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
PSO PID
BFO PID
Hybrid BFO PID
Fuzzy PSO PID

(b)

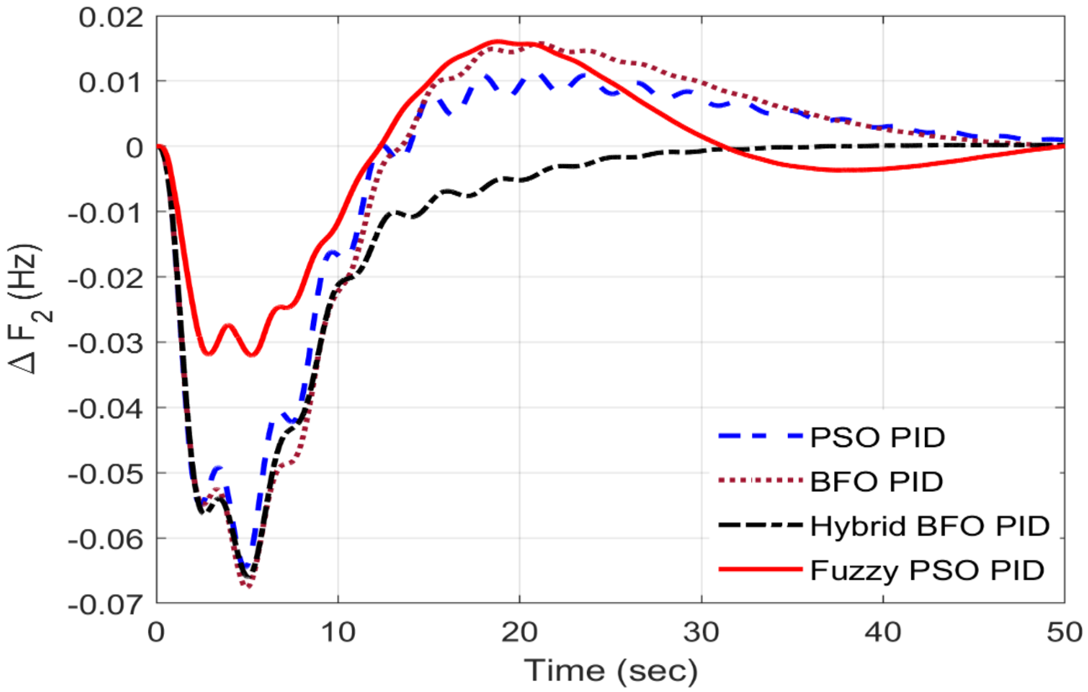


(c)

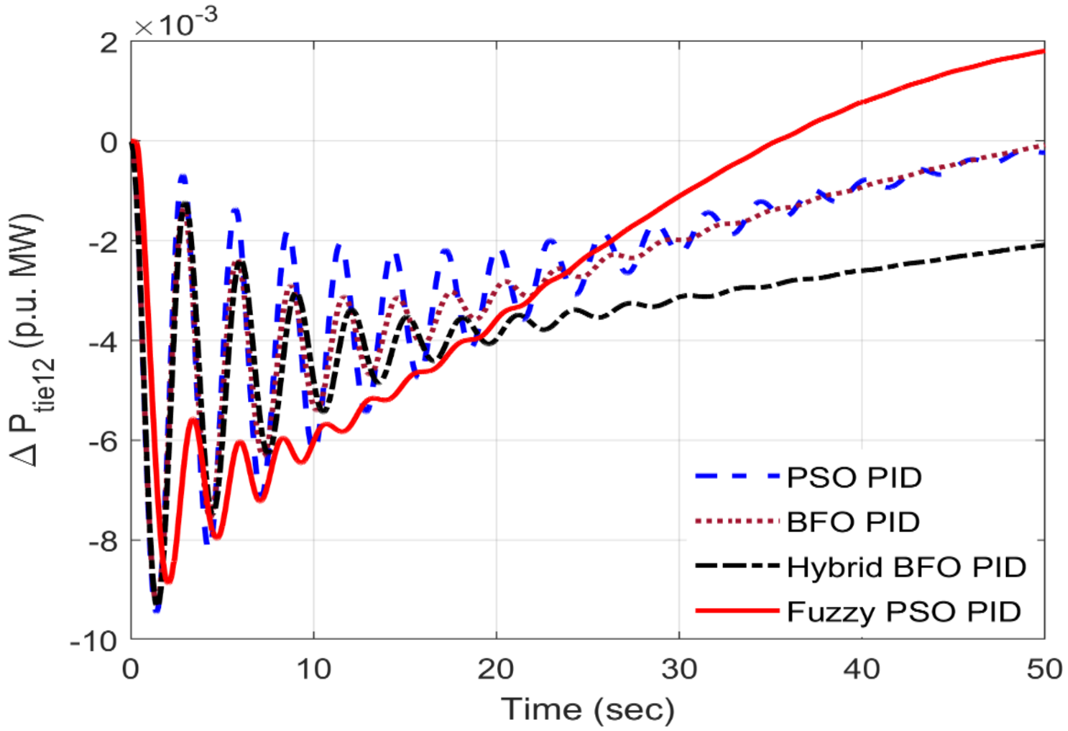
Figure 5.7: (a-c) Graphical outcomes for step load alteration in region one



(a)

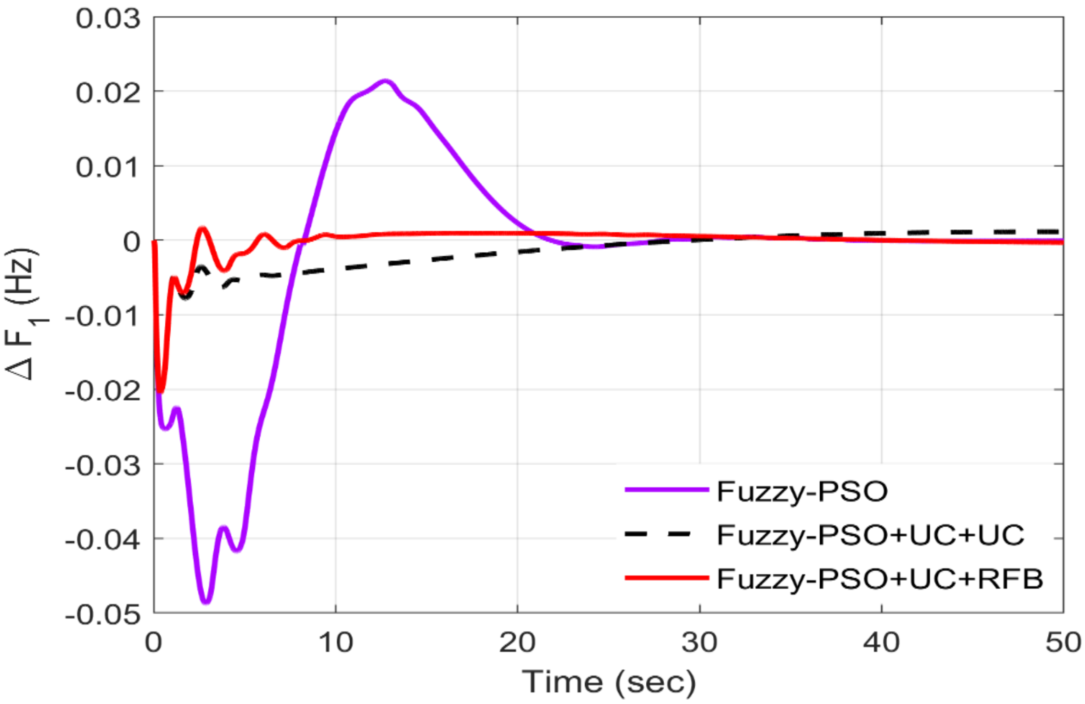


(b)

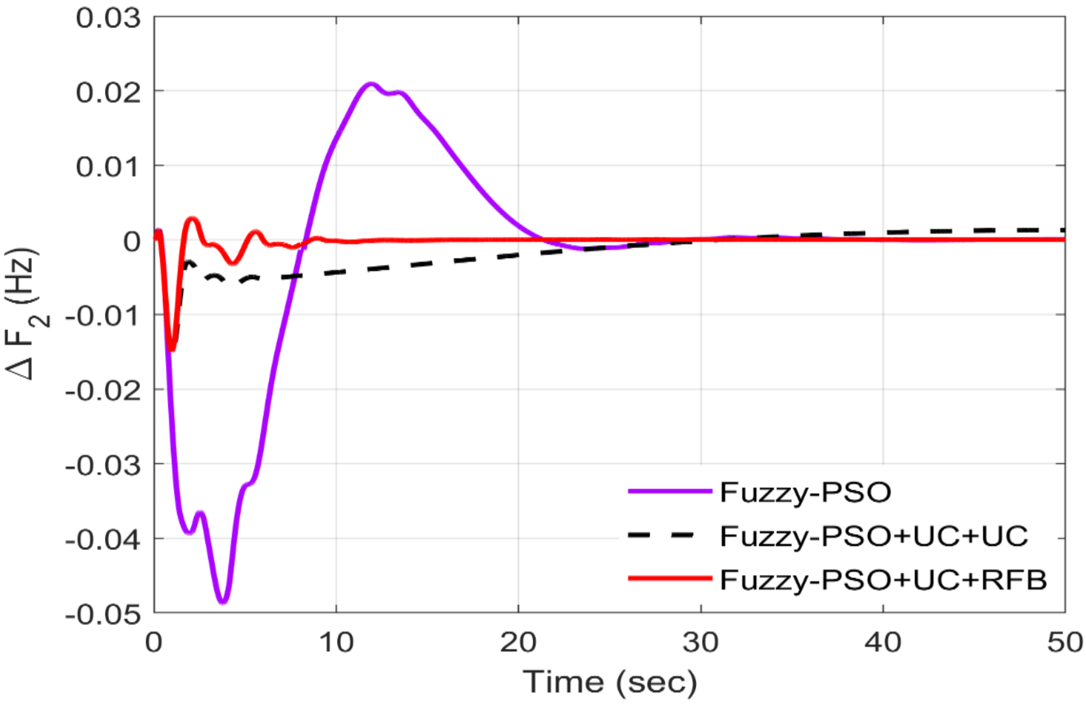


(c)

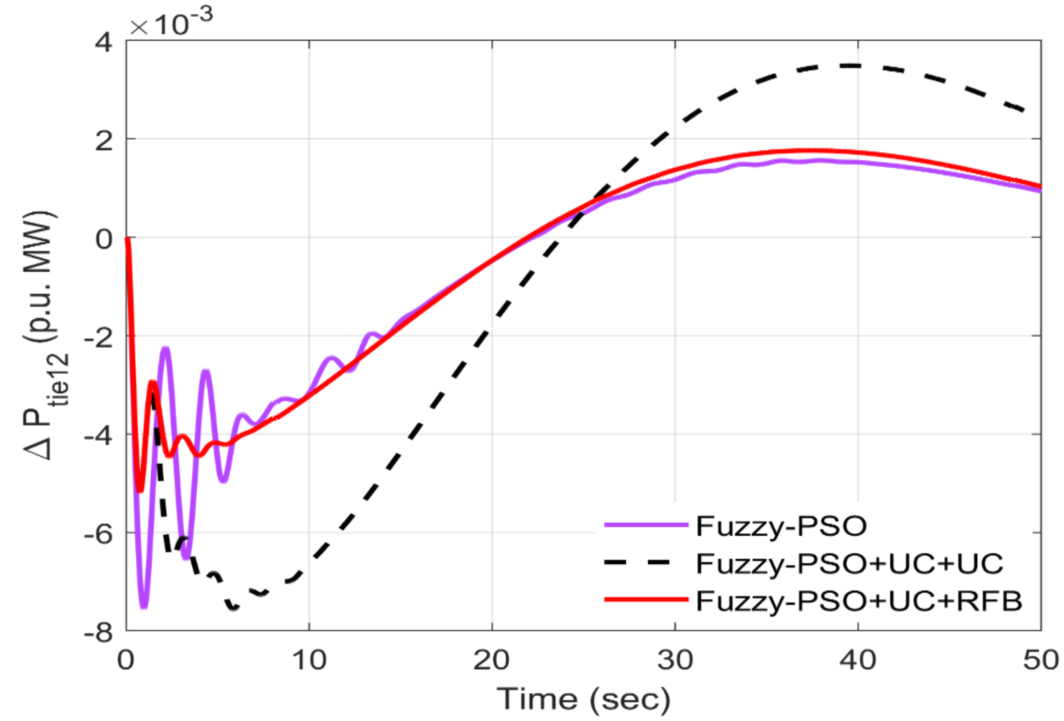
Figure 5.8: (a-c) Graphical outcomes for step load alteration in region one with non-linearity


0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
Fuzzy-PSO
Fuzzy-PSO+UC+UC
Fuzzy-PSO+UC+RFB

(a)

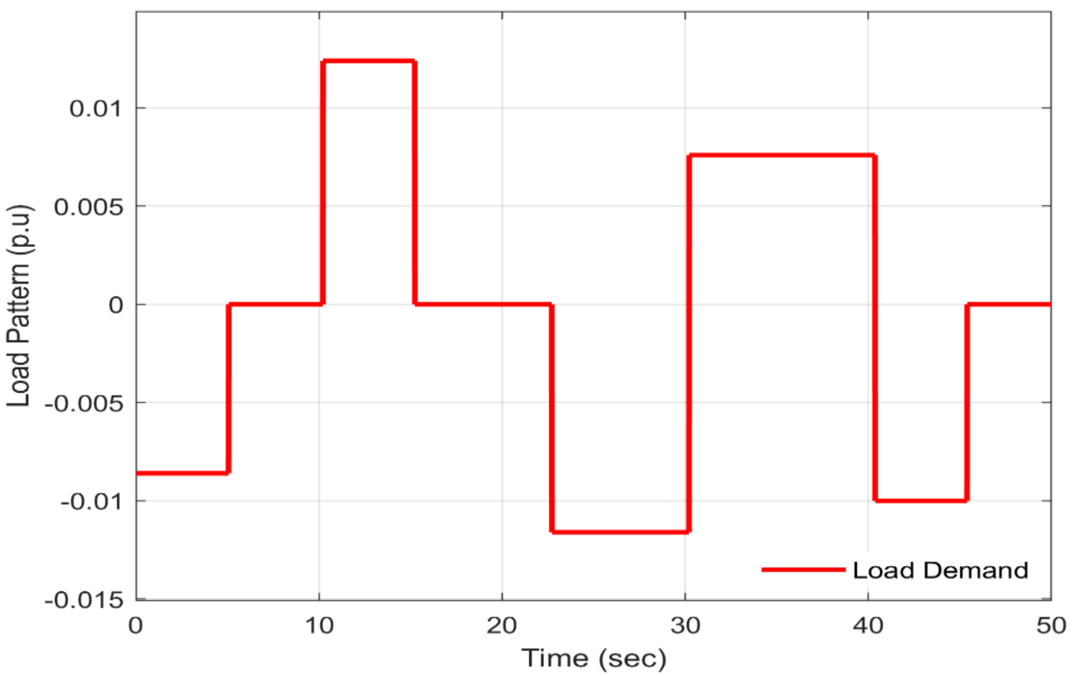

0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
Fuzzy-PSO
Fuzzy-PSO+UC+UC
Fuzzy-PSO+UC+RFB

(b)

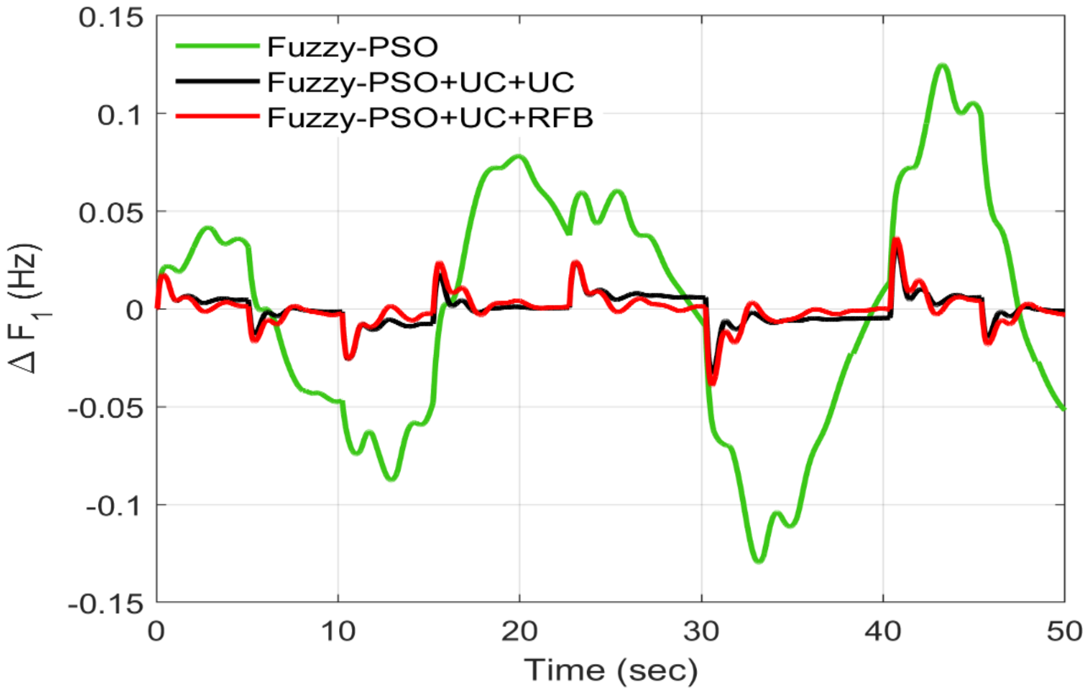


(c)

Figure 5.9: (a-c) Graphical outcomes of Fuzzy-PSO-PID with UC-UC & UC-RFB

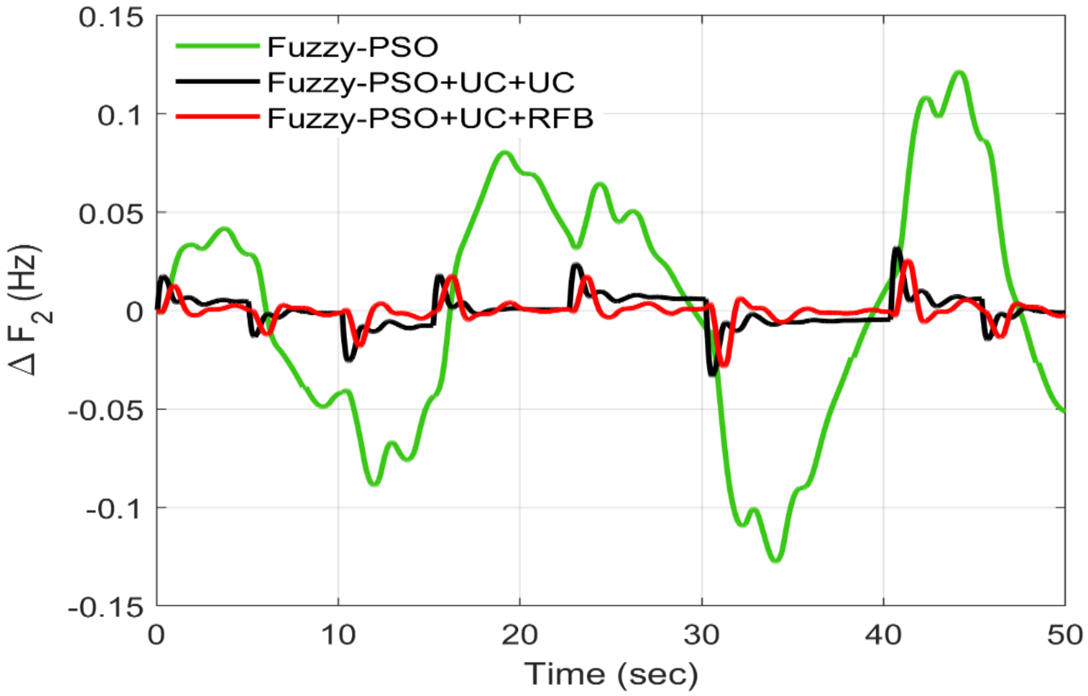


(a)



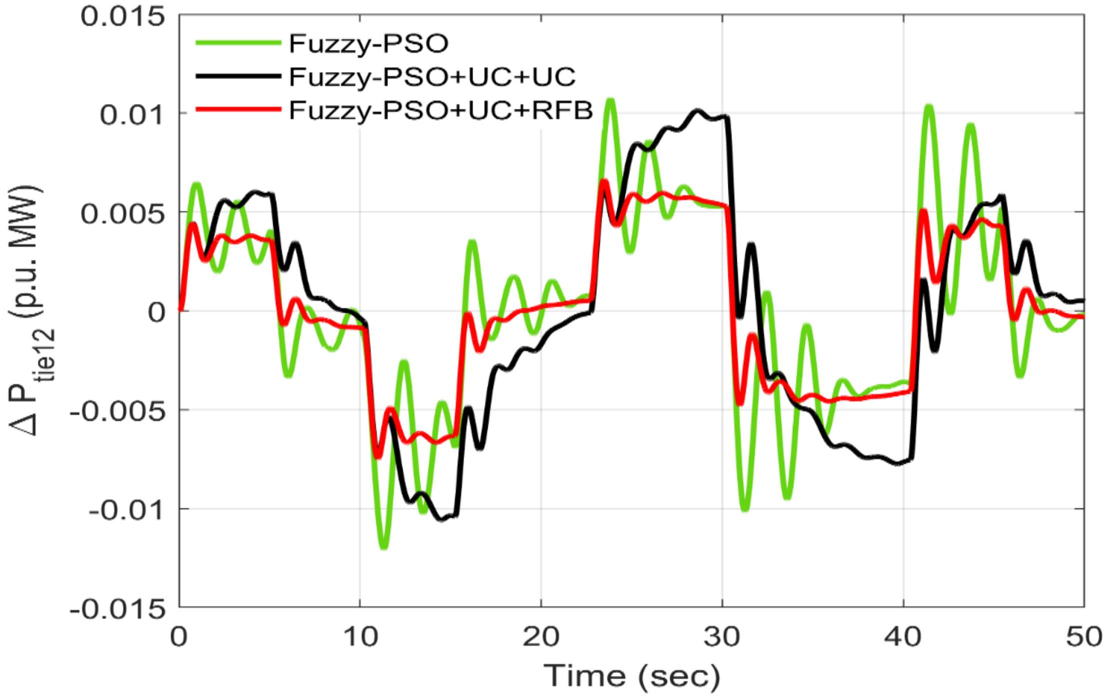
Fuzzy-PSO
Fuzzy-PSO+UC+UC
Fuzzy-PSO+UC+RFB
Δ F1 (Hz)
Time (sec)

(b)



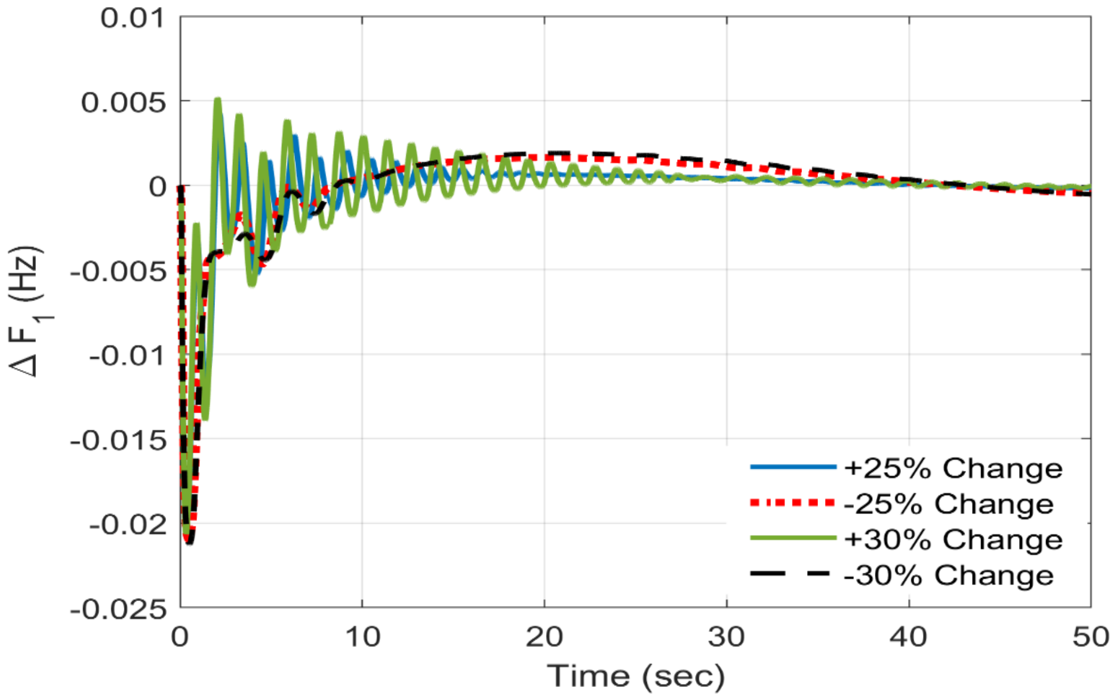
Fuzzy-PSO
Fuzzy-PSO+UC+UC
Fuzzy-PSO+UC+RFB
Δ F2 (Hz)
Time (sec)

(c)

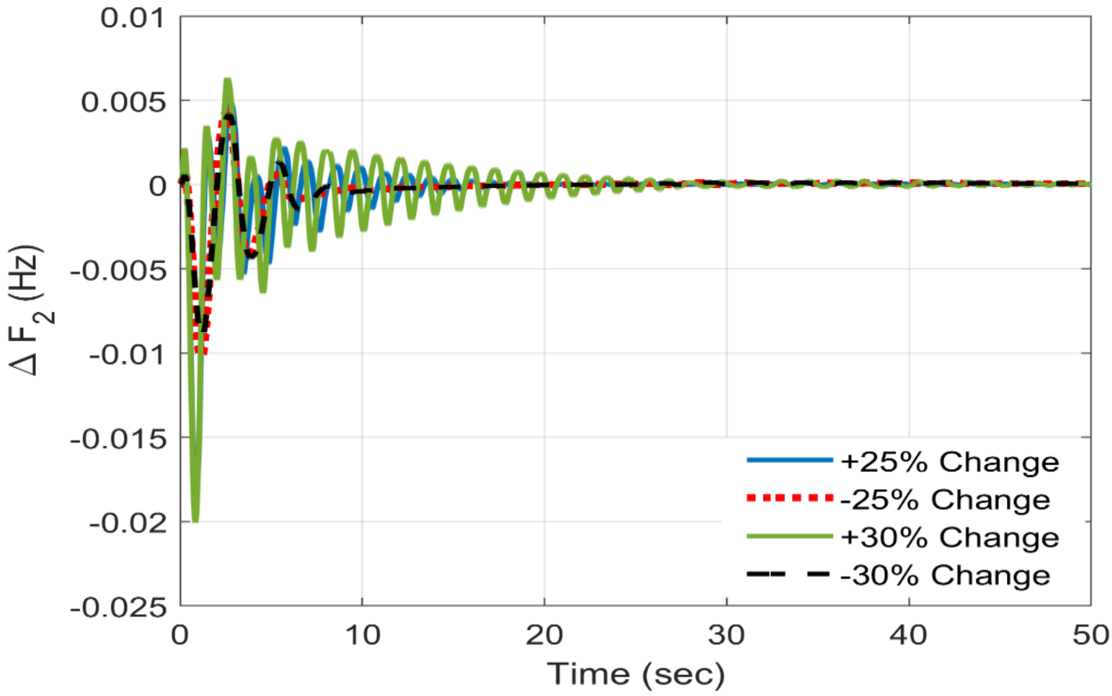


(d)

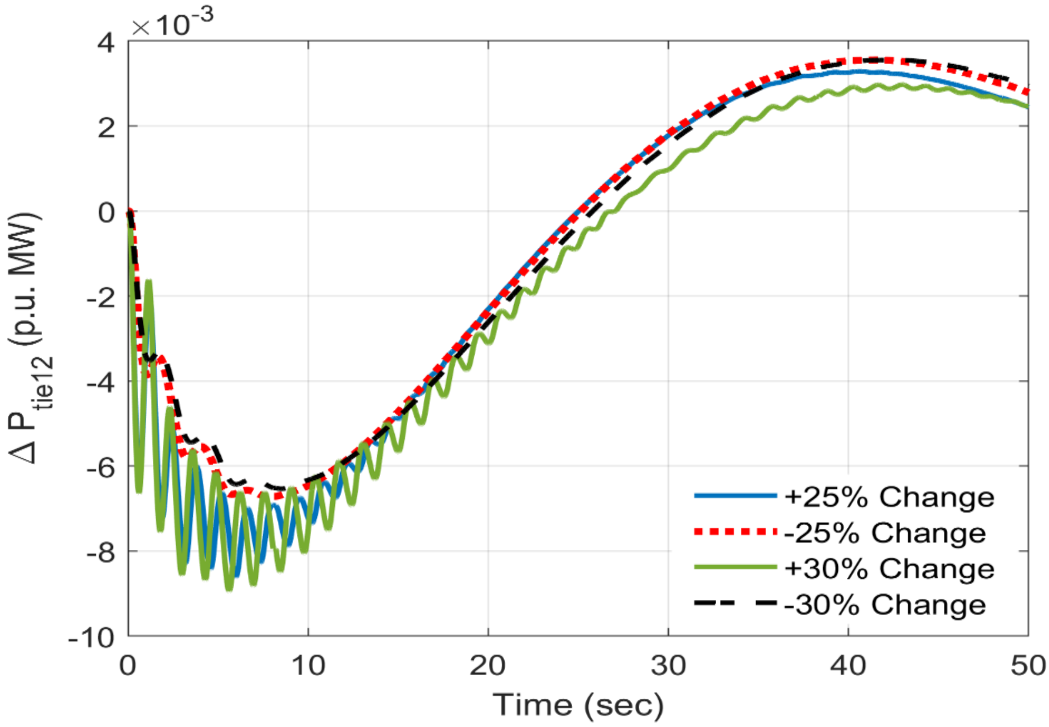
Figure 5.10: Endless load profile (a) LFC outcomes for load profile in (b-d)



(a)



(b)



(c)

Figure 5.11: (a-c) LFC outcomes in view of parametric alteration

5.4 Summary

Two regions interconnected frameworks with different choices and various control strategies are comprehensively considered, and results are analyzed with the earlier published work of other research. All the cases are considered for the 1% change in the load. LQR strategy used for load frequency control is beginning examined, and the next fuzzy-PSO-PID control methodology is actualized on different cases for linked two region frameworks. Responses gotten have appeared. UPFC link is connected in series to AC tie-line and RFB connected in area-2 to improve the framework response. Fuzzy-PSO-PID based control technique is utilized for this as well, and the achieved responses of hydro power are outstanding and are superior when matched with other results.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In electric-power generation, violence affected by load variations will affect differences within the craved frequency esteem and tie-line loadings. In this way, load frequency control is exceptionally imperative in power framework performance for providing adequate and secure electrical power of good quality. There are two targets of load frequency control. Firstly, the framework frequency is to be kept up at or exceptionally close to specified nominal esteem. Secondly, tie-line variations must moreover be provided region as quickly as useful.

Analysts have often executed many kinds of control methodologies to arrange to attain load frequency control targets, which is also respected as automatic generation control. A complete literature survey on load frequency control difficulty is given in chapter two, and various control strategies, i.e., a conventional approach to the brilliant strategies, are entirely discussed.

This thesis attempts to solve the energy system's LFC problem, having all hydro turbines and linked with the help of AC tie-lines. The main contributions and findings from this research are as follows:

1. The LQR is designed in discrete mode, and it is based on optimal control theory for the LFC problem. In addition to the above, the effect of diverse sampling time also checks for the same problem. The results clearly reveal that higher sampling time reduces the system's stability for the sudden load disturbance and drives the system towards instability.
2. It is also observed that UPFC addition in series to tie-line and RFB integration in one control area has improved all LFC results. To a great extent, in terms of higher stability margins, enhance feedback gains and

an appreciable reduction in overshoot and settling time for all LFC responses.

3. This work also shows up a novel control orchestrate for LFC of hydro-hydro imperativeness framework based on joint endeavors. The fuzzy logic with PID viably optimized through particle swarm optimization (PSO) is coming into a new and robust Fuzzy-PSO-PID to start with time to realize LFC's measures for complex and insecure structures such as linked hydro-hydro.
4. The Fuzzy-PSO PID is pleasant enough to meet the LFC rules of a hydro regulating framework concerning ITAE & IAE esteem, pickups of PID, and LFC reactions compared to other LFC activities utilized within the display consider. Still, it needs to empower alter in organize to have prevalent LFC action for such frameworks.
5. The integration of UC-UC in each region of the hydro system has shown enhancement in deviations of all LFC results, and the value of ITAE and IAE reduces to a significant less value.
6. Furthermore, the combination of UC installation in region one and RFB in region two has shown further improvement in achieving fewer deviations in frequency and tie-line power compared to results achieved via Fuzzy-PSO-PID with UC-UC and through Fuzzy-PSO-PID only.
7. Diminish in ITAE & IAE respect gotten through Fuzzy-PSO-PID with UC, and RFB appears to take a toll and control the proposed plan's reasonability.
8. The charging system parameters and endless load alterations were deployed in this work. Furthermore, the GRC non-linearity to boot evaluated with UC and RFB for Fuzzy-PSO-PID were also included. The ultimate examinations uncover that the Fuzzy-PSO-PID action is sensibly overpowering, clear, and adequately able for a linked hydro system's LFC movement.

6.2 Scope for Future Work

With respect to future research directions, the following problems can be examined, based on the research presented in this thesis:

1. The LQR is designed in discrete mode by considering the diverse sampling time. The structure of state cost weighting matrix (Q) and control cost matrix (R) is assumed to be an identity in the present research. However, the structure of Q and R influences the output of LQR to a great extent, and hence optimization algorithms can be used in the future to find the exact structure of these matrices.
2. The output of FL-PSO-PID can improve further by considering hybrid optimization algorithms and the parameters of energy storage devices that can be optimized further to have better LFC output.
3. The study can be extended to a multi-area energy system.
4. The present research work is based on a regulated energy system environment. However, this study can be extended to a deregulated environment considering various market transactions.

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Appendix A: Hydro Power Plant Data

Power Plant Data

Area-1	Area-2	Data\Value
B_1	B_2	0.425
R_1	R_2	3.0
K_{gh1}	K_{gh2}	1
T_{gh1}	T_{gh2}	0.6
T_{h1}	T_{h2}	5
T_{h3}	T_{h4}	32
T_{w1}	T_{w2}	1
K_{ph1}	K_{ph2}	20
T_{ph1}	T_{ph2}	3.76
$2\Pi T_{12}$	-	0.545
a_{12}	a_{12}	1

UPFC Facts Device

T_{UPFC}	0.02

RFB Device

K_{RFB}	0.67
T_{RFB}	0

UC Device

K_{UC}	-7\10
T_{UC}	0.9

PSO Parameters

Max. Generation	100
Population in swarm	50
C_1 & C_2	1.5 & 0.12
W_{max} & W_{min}	0.9 & 0.4