DESIGN OF ROBUST CONTROLLER FOR THE LOAD FREQUENCY CONTROL OF INTERCONNECTED POWER SYSTEM

A project submitted in the partial fulfilment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY

IN

ELECTRICAL & ELECTRONICS ENGINEERING

By

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VASIREDDY VENKATADRI INSTITUTE OF TECHNOLOGY

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Accredited by NBA (B.Tech program), Approved by AICTE,
Permanently Affiliated to JNTUK, NAAC Accredited with ‘A’ Grade,
ISO 9001:2015 Certified

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CERTIFICATE

This is to certify that the project entitled **"DESIGN OF ROBUST CONTROLLER FOR THE LOAD FREQUENCY CONTROL OF INTERCONNECTED POWER SYSTEM"** is being submitted by **MACHARLA RAJESWARI** (20BQ1A0276), **KALLEVARAPU BHAVANA** (20BQ1A0255),**MAILAVARAPU LAKSHMI PRASANNA** (20BQ1A0280), **KONDA LIKHITHA** (20BQ1A0264) in partial fulfillment for the award of **Bachelor of Technology in Electrical & Electronics Engineering** to the Vasireddy Venkatadri Institute of Technology (Autonomous) affiliated to Jawaharlal Nehru Technological University Kakinada in the academic year 2023-24, is a record of bona-fide work carried out by the them under our guidance & supervision. The results embodied in this project have not been submitted to any other University or Institute for the award of any other diploma or degree.

Signature of the Guide	**Head of the Department**
Dr. Ch. Naga Sai Kalyan,	Dr. A. V. Naresh Babu,
Associate Professor	Professor & HOD
Department of EEE	Department of EEE

Examiner

DECLARATION

The Project entitled **"DESIGN OF ROBUST CONTROLLER FOR THE LOAD FREQUENCY CONTROL OF INTERCONNECTED POWER SYSTEM"** is a record of bona fide work carried out by us and submitted in partial fulfillment for the award of **Bachelor of Technology** in **Electrical & Electronics Engineering** to Vasireddy Venkatadri Institute of Technology (Autonomous) affiliated to the Jawaharlal Nehru Technological University Kakinada

The results embodied in this project have not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

This project aims to develop a robust controller of (1+PD)-PID cascade controller for the frequency stabilization of multi-area interconnected power system. The operational performance of the proposed controller is studied by laying the step load disturbance of 10% in the area-1 of the considered power system model. For the fine tuning of the proposed controller, Butterfly optimization algorithm is considered. However, the superiority performance of the proposed controller is validated with other controllers available in the literature. Further, to obtain the improvement in the power system performance the high voltage DC line is implemented with the test system model. The simulation results confirmed the improvement in the system performance with the incorporation of the HVDC line. To check the robustness of the proposed controller, the sensitivity test is conducted and validated the robustness.

Keywords: (1+PD)-PID cascade controller, Butterfly optimization algorithm, Frequency stabilization, Interconnected power system, 10% step load disturbance.

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CHAPTER-1

1. Introduction

Load Frequency Control (LFC) is a crucial aspect of power system operation that involves maintaining the balance between the electric power generation and consumption in real-time. The primary goal of LFC is to keep the system frequency within acceptable limits by adjusting the power output of generating units in response to changes in load demand.
Here's a brief introduction to the key concepts of Load Frequency Control:

Basic Principle:
Power systems operate on the principle of supply and demand. The total power generated must match the total power consumed to maintain a stable system frequency.
LFC ensures that any mismatch between power generation and load demand is corrected promptly to prevent frequency deviations.
Frequency Deviation:
System frequency is a critical parameter that needs to be maintained within a narrow range (e.g., 50 Hz or 60 Hz) for the proper functioning of electrical devices.
Deviations from the nominal frequency can lead to undesirable consequences, affecting the performance and lifespan of equipment.
Control Area and Control Zones:
Power systems are divided into control areas, each responsible for maintaining its own load-generation balance.
Within a control area, there might be several control zones, each with its set of generating units and load centers.
Control Actions:
LFC relies on control actions to adjust the power output of generating units. These actions are based on signals and feedback from the system.

- Primary control (automatic generation control) involves rapid adjustments to address sudden load changes.
- Secondary control (automatic voltage control) involves slower adjustments to restore the system to its scheduled operating point.

Communication and Control Signals:
Communication between control centers and generating units is crucial for effective LFC. Control signals are sent to generators based on real-time measurements of system frequency and tie-line power flow.

Advances in technology have enabled the use of sophisticated control algorithms and communication systems to enhance the efficiency of load frequency control.

Challenges:

LFC faces challenges such as uncertainties in load demand, unpredictable renewable energy sources, and variations in generation capacity.

The integration of renewable energy introduces additional complexities, as these sources often have variable and intermittent power output.

Modern Techniques:

Advanced control techniques, such as model predictive control and advanced optimization algorithms, are being increasingly employed to enhance the performance of load frequency control in modern power systems.

In summary, Load Frequency Control plays a vital role in maintaining the stability and reliability of power systems by ensuring a balance between generation and load, thereby keeping the system frequency within acceptable limits. Advanced control strategies and technologies continue to evolve to meet the challenges posed by the changing landscape of power generation and consumption.

1.1 Literature Survey

- In [1] the authors focus on Load Frequency Control (LFC) in power systems using a robust backstepping sliding mode controller. The study incorporates a combination of backstepping control and sliding mode control to achieve robust performance in regulating the load frequency. They highlight the challenges posed by varying loads and disturbances and emphasize the need for robust control strategies to ensure stable and efficient power system operation.
- In [2] by presenting on Hierarchical Bi-Level Load Frequency Control in the context of multi-area interconnected power systems. It explores the significance of load frequency control in the efficient and stable operation of power systems, particularly in interconnected multi-area setups.
- The work implemented in [3] a data-driven predictive-based load frequency control addresses the challenge of load frequency control in

power systems with a significant presence of renewable energy sources on load frequency control strategies, specifically focusing on those designed for power systems with a high penetration of renewable energy. Traditional control methods are examined in the context of their limitations in handling the variability introduced by renewable sources.

- In this [4] the two-area by presenting an intelligent load frequency control to enhance the penetration of wind power in power systems. They explored intelligent control strategies in power systems, highlighting the potential advantages of leveraging intelligent techniques for load frequency control. The survey emphasizes the need for adaptive and intelligent approaches to cope with the dynamic and uncertain behavior of wind power.
- In this [5] the author focuses on load frequency control in isolated microgrids using a novel cascade-loop controller and the Dandelion Optimizer algorithm. The challenges and importance of load frequency control in microgrid environments, emphasizing the unique characteristics of isolated systems.
- In this sixth reference [6] the dual-area for power grid load frequency control in power grids utilizing a Fractional Order PID controller along with pumped storage and battery energy storage systems. The need for advanced control techniques to address the dynamic and uncertain nature of modern power grids. Traditional PID controllers and their limitations are discussed in the context of load frequency control.
- In [7] a novel approach to Load Frequency Control (LFC) for a 2-area interconnected power system. The literature survey begins by exploring the importance of LFC in power systems, particularly in interconnected setups, and the challenges associated with achieving stability and efficiency.
- In this [8] the four-area presents a dual-loop IMC structure for addressing load frequency control issues in multi-area multi-sources power systems. The literature survey begins by exploring the challenges associated with load frequency control in power systems, specifically focusing on the complexities introduced by multiple areas and diverse power sources. Particularly focusing on the limitations of traditional controllers in handling the complexities of interconnected power systems. The survey explores the utilization of fractional-order

controllers and two-input-three-DOF feedback controllers in power system control applications.

- The work implemented in [9] the two-area for improving load frequency control performance in interconnected power systems addresses load frequency control in power systems with energy storage, utilizing a disturbance observer-based control strategy. They focus on the limitations of conventional controllers in handling the dynamics introduced by energy storage systems.
- In this tenth reference [10] they addresses load frequency control in power systems with energy storage, utilizing a disturbance observer-based control strategy. Load frequency control strategies, with a focus on the limitations of conventional controllers in handling the dynamics introduced by energy storage systems. The authors demonstrate the effectiveness of their proposed approach, providing insights for further research in the field of power system control and energy storage integration.
- In [11] the author introduces the use of the Marine Predators Algorithm for load frequency control in modern interconnected power systems with renewable energy sources and energy storage units. The literature survey begins by exploring the challenges associated with load frequency control in modern power systems, emphasizing the unique characteristics introduced by renewable energy integration and energy storage.
- The work implemented in [12] mainly focus on the application of the Backtracking Search Algorithm in load frequency control for a multi-area interconnected power system. By exploring the challenges associated with load frequency control in multi-area power systems and the need for advanced control strategies.
- The work implemented in [13] a novel load frequency control scheme for an interconnected multi-area power system with wind turbine generation and a redox flow battery. The literature survey begins by exploring the challenges associated with load frequency control in interconnected power systems, especially with the integration of renewable energy sources and energy storage.
- In [14] the three-area for optimized fuzzy self-tuning PID controller design based on Tribe-DE optimization algorithm and rule weight adjustment method. Load frequency control strategies, emphasizing the

limitations of conventional controllers in handling the dynamic and uncertain nature of interconnected power systems. The survey delves into the application of fuzzy self-tuning PID controllers and the advantages they offer in adapting to system variations

- The work implemented in [15] addresses load frequency regulation in multi-area power systems with renewable sources using active disturbance rejection control. The prior research efforts that have incorporated renewable energy sources into load frequency control strategies, specifically focusing on the utilization of active disturbance rejection control.
- The researchers established the 3-degree-of-freedom (DOF) proportional-integral-derivative(3DOFPID) using seagull optimization in [16]. The technique is tested on two area step load disturbance (SLD) of 10%. More over the authors compared the proposed controller performance with MAIPS dynamical behaviour and it is slightly more deviated up on considering CTDs of the system.
- In [17] the authors proposed the Dynamically adaptive control using the Adaptive super twisting sliding mode load. The approach is tested on multi area Nonlinear coupling between control area. Further, the authors compared the controller performance with frequency deviations with typical nonlinearities in power systems were also found within acceptable limits.
- The work implemented in [18] the authors Fault-tolerant control using the FTC algorithm. The approach is tested on four area hybrid energy storage system. More over the authors proposed the better frequency stabilization effect and early warning function.
- In [19] the authors proposed Adaptive high-order sliding mode control using the Super twisting (ST) algorithm. The technique is tested on three area interconnected power system with nonlinearities. Further, the authors proposed the frequency deviation and ACE (area control error) converge to zero when using the proposed method.
- In [20] the authors proposed Model predictive control (MPC) using Quasi-oppositional harmony search algorithm (QOHSA). the approach is tested on single area hybrid power system (HPS). moreover, the authors handle different variances of the disturbance signals or noise entering the system as well as the model mismatch.

- The work implemented in [21] the authors proposed FOPID controller using PSO algorithm. the technique is tested on multi area large scale power system. Further, the authors proposed the integrated control strategy for electrolytic aluminium load participation in frequency modulation showed that the FOPID controller optimized by the PSO algorithm has stronger Robustness in the LFC.
- In [22] the authors proposed Synthetic Inertia Control (SIC) using PSO algorithm. the technique is tested on multi area Low-inertia power systems. Moreover, the authors proposed that it is observed that there is an 87 % improvement in the system frequency dynamics performance for various disturbances and loading conditions as compared to the cases with no FSIC provision.
- The work implemented in [23] the authors proposed LS control using Cooperative reinforcement learning algorithm, traversal mode of the algorithm. The approach is tested on three-area Microgrid system modified into 13 bus system. Further, the authors proposed that the LS control technology is a key technology to ensure the safe and stable operation of an islanded microgrid. The results show that the proposed coordinated LS control scheme has significant performance in frequency regulation and the uninterrupted power supply of critical loads.
- The researchers established LQG-based auxiliary controller using Genetic algorithm (GA) in [24]. The technique is tested on multi-area Two robust LFC schemes using conventional linear quadratic gaussian (LQG). Moreover, the authors proposed that the conventional and modified LQG-based BESS auxiliary control techniques are proposed for non-linear islanded microgrid LFC system with measurement noise in the secondary and auxiliary measurement channels.
- In [25] the authors proposed Renewable energy sources, interconnected hybrid power systems, LFC, robust controllers using Advanced control algorithm, fuzzy logic, neural network, genetic algorithm. The technique is tested on multi-area Hybrid power system. Further, the authors proposed methodology represents a first attempt to systematically define the control requirements to be imposed on CIG to ensure frequency stability as its penetration in power systems increases.

- The work implemented in [26] the authors proposed PI (Proportional-Integral) controllers using Dual SRF filtering-based PLL (DSRF-PLL). The technique is tested on four-area Converter -interfaced generation (CIG). Moreover the authors proposed methodology represents a first attempt to systematically define the control requirements to be imposed on CIG to ensure frequency stability as its penetration in power systems increases.
- In [27] the authors proposed LQR based controller using the algorithm is simulated in MATLAB R2018a. The technique is tested on single-area Power system. Further, the author's proposed Simulations are carried out in a single-area power system in MATLAB/SIMULINK, in which the observer implemented as a separate MATLAB code is plugged into the system to sample the output from the power system and inject the control back.
- The researchers established A fractional-order proportional integral derivative (FOPID) controller for load frequency control (LFC) using Runge Kutta optimizer (RUN) algorithm in [28]. The technique is tested on Two area Interconnected power system. More over the authors proposed The results showed that EPS in the 2035 future scenario has high-frequency stability even with the increased penetration of renewable energy sources. Additionally, the FOPID controller optimized by Runge Kutta optimizer (RUN) gives a better performance than PID, PI, and I controllers at different operation scenarios and different power system disturbances.
- The work implemented in [29] the authors proposed Fuzzy model predictive control using A spider monkey optimization (SMO) Algorithm. the technique is tested on Multi-area frequency control systems. More over the authors proposed that the simulation results have been concluded from four various scenarios and indicated that the proposed control strategy provides better performance than the previous controller. As an illustration, the proposed controller error (IAE) is one-fourth and one eighth of the AOMPC and H _infinity controllers during normal situation.
- In [30] the authors proposed Parallel combination of tiltintegral-derivative with filter (TIDF) and hybrid fractional-order (HybFO) using Marine predator optimization algorithm (MPA) and in this the technique is tested on Two-area Robust frequency regulation in

interconnected power systems. Moreover, the authors proposed that the controller combines TIDF and HybFO controllers to improve power system stability during frequency and tie-line power fluctuations.

- In [31] the author's proposed the (GAC-LFC) using an EE-MADDPG algorithm. The suggested control approach is tested on four area power system with solar and wind generation. Moreover, the algorithm introduces effective exploration strategies, agents operating on various principles, and artificial intelligence functions based on imitation learning and curriculum learning, which altogether constitute a more robust strategy.
- The research established in [32] the authors proposed the GPC controller, FOPID controller using (GPC) algorithm, FOPID algorithm. The proposed control technique is tested on single area system, hydropower plants with the load and transmission line. The proposed approach enhances stability and consequently avoids operational failures of hydropower plants in contingent islanding mode.
- In [33] the author's proposed the PI and PID controllers, PID + D^2 controller using the COOT algorithm. The suggested control technique is tested on dual area power system, Renewable energy sources such as wind plants, solar PV plants, and geothermal power plants are considered. The COOT algorithm shows better convergence and figure of demerit characteristics compared with particle swarm optimization and firefly algorithms. The obtained simulation results are also tested successfully through OPAL-RT OP4500 RT-LAB-RCP/HIL system for their real-time validation.
- The work implemented in [34] is a PI controller is proposed by the author's using FLOC algorithm, MOMVO algorithm. The proposed control approach is tested on single area power system with seismic and wind load. More over the author compared the proposed control performance with the existence of various techniques for predicting and quantifying uncertainties in environmental loads, the accuracy of these methods is not always guaranteed, as they can be influenced by factors such as the availability and quality of data and the size of the sample.
- In [35] the author's proposed a FR controller using the SIRL algorithm. The suggested control approach is tested on one area power system, intermittent renewable energy sources Moreover, the author's compared the proposed control performance with an optimal

output feedback controller using only output state variables and demonstrated that it possesses better performance relative to the full-state feedback controller response.

- The research established in [36] a 2DOF-TIDμ controller, 2DOF-PID and 2DOF-TID controllers are proposed by the author's using Coot Optimization Algorithm (COA). The suggested control technique is tested on two area power system, interconnected microgrids including Bio renewable generation, RES, HESS, PSS and UPFC. Moreover, the author's compared the proposed control performance with deviations from the nominal values within the Power system have the potency to damage the equipment or diminish the quality of the electrical energy being generated.
- In [37] the author's proposed PI controller, FPI-MRAC using CHIO optimizer, Whales Optimization Algorithm, Grey Wolf Optimization Algorithm, Antlions Optimization Algorithm, and Moth Flame Optimization Algorithm. The proposed control techniques are tested on single area power system. Moreover, the author's compared the proposal control performance with all applied scenarios, the FPI-MRAC offers a much superior dynamic response than PI controller. Using super-capacitors also improves the system frequency when there are disruptions.
- The work implemented in [38] a PI controller is proposed by the author's using Kalman smoother algorithm. The suggested control approach is tested on one area wind power-integrated power system. Moreover, the proposed method can identify required parameters accurately with only local measurement and optimize the frequency trajectory to eliminate the nadir and second dip, thus improving the frequency stability of power system.
- In [39] the author's proposed Multiple-Model Linear Optimal Control (MMLOC), linear optimal controller (LOC) using Polynomial Combination Algorithm (PCA). The suggested control techniques are tested on one area Flexible AC Transmission Systems (FACTS). The proposed control strategy is evaluated, this strategy not only maintains stability but also reduces LFO effectively. Furthermore, steady state error of rotor speed and rotor angle tend to zero favorably.
- The research established in [40] the author's proposed (FOPIDN) controller, proportional-integral controller using Sparrow search

algorithm. The suggested control techniques are tested on single area systems and MG voltage and frequency control based power system. More over the author's proposed control outperforms the traditional proportional-integral controller in efficacy and resilience. The proposed controller was shown an excellent transient response for load variation and the induction motor loading condition.

SI.NO	TITLE	AREA	TEST SYSTEM	CONTROLLER	ALGORITHM	REMARKS
1	Load Frequency Control in Power Systems by a Robust Backstepping Sliding Mode Controller Design	Two-area	Thermal power system with non-reheat turbines	Robust Backstepping Sliding Mode Controller	Backstepping Control combined with Sliding Mode Control	The proposed controller is designed to enhance the load frequency control in power systems by utilizing a robust backstepping sliding mode control strategy
2	Hierarchical Bi-Level Load Frequency Control for Multi-Area Interconnected Power Systems	Multi-area	Multi-Area Interconnected Power Systems	Hierarchical Bi-Level Load Frequency Control	Moth flame optimization (MFO) algorithm	The proposed hierarchical bi-level control strategy aims to enhance load frequency control in multi-area interconnected power systems, offering a structured approach to address the challenges associated with system dynamics and interactions.
3	Data-Driven Predictive-Based Load Frequency Robust Control of Power System with Renewables	Two-area	Power System with Renewables	Data-Driven Predictive-Based Load Frequency Robust Control	Matrix zonotope	The study proposes a data-driven predictive-based control strategy for load frequency control in power systems integrating renewable energy sources. The focus is on developing a robust control approach that considers the uncertainties and variability associated

						with renewable energy generation
4	Intelligent Load Frequency Control for Improving Wind Power Penetration in Power Systems	Two-area	Power System with wind power Integration	Intelligent Load Frequency Control	Intelligent optimization algorithms, fuzzy algorithms, artificial neural networks and other intelligent algorithms to be introduced into the LFC control strategy design and solution	An intelligent load frequency control strategy tailored to enhance the integration of wind power in power systems. The aim is to address the challenges associated with the variability and uncertainty of wind power generation, ultimately improving the overall stability and performance of the power system.
5	A Novel Cascade-Loop Controller for Load Frequency Control of Isolated Microgrid via Dandelion Optimizer	Single-area	Isolated Microgrid	Cascade-Loop Controller	Dandelion Optimizer	A unique cascade-loop controller for load frequency control in an isolated microgrid, leveraging the Dandelion Optimizer algorithm. The proposed controller aims to enhance the frequency regulation in microgrid scenarios, contributing to the stability and reliability of isolated power systems.
6	Power Grid Load Frequency Control Based on Fractional	Two-area	Power Grid	Fractional Order PID Controller	Pumped Storage and Battery Energy Storage	A load frequency control strategy for power grids using a Fractional Order PID

	Order PID Combined with Pumped Storage and Battery Energy Storage					controller in conjunction with both pumped storage and battery energy storage systems. The combination of these control elements aims to enhance the overall frequency regulation in the power grid.
7	Linear Quadratic Differential Games-based MIMO-PID Design for Load Frequency Control of a 2-Area Interconnected Power System: An Iterative LMI Approach	Two-area	2-Area Interconnected Power System	MIMO-PID (Multiple-Input Multiple-Output Proportional-Integral-Derivative) Controller	Iterative algorithm	The load disturbances as well as provide improved transient response specifications
8	Dual Loop IMC Structure for Load Frequency Control Issue of Multi-Area Multi-Sources Power Systems	Four area	Multi-Area Multi-Sources Power Systems	Dual Loop IMC (Internal Model Control) Structure	FOPID	Renewable power sources such as wind power generator, solar power generator, fuel cell and aqua-electrolyzer to show the effectiveness of the proposed approach.

9	Improving Load Frequency Control Performance in Interconnected Power Systems with a New Optimal High Degree of Freedom Cascaded FOTPID-TIDF Controller	Two-area	Interconnected Power Systems	Cascaded FOTPID-TIDF (Fractional Order Two-DOF Proportional-Integral-Derivative - Two-Input-Three-DOF Feedback) Controller	Optimization algorithm	The characteristics and uncertainties of renewable sources, interconnected loads, and grid inertia
10	Load Frequency Control of Power System with Energy Storage Based on Disturbance Observer	Four-area	Power System with Energy Storage	Disturbance Observer-based Load Frequency Control	Lyapunov principle is used to analyze the stability	Effectively ameliorate the robustness and operational stability of power systems with energy storage
11	Marine Predators Algorithm for Load Frequency Control of Modern Interconnected Power Systems Including Renewable Energy Sources and Energy Storage Units	Two-area	Modern Interconnected Power Systems	Proportional-integral-derivative (PID) controllers	Marine Predators Algorithm (MPA)	The role of ES units in enhancing the time-domain transient responses
12	Application of Backtracking Search Algorithm in Load Frequency Control of Multi-Area Interconnected Power System	Two-area	Multi-Area Interconnected Power System	PI/PID controllers	Backtracking search algorithm	The comparative analysis of the performances indicates that the proposed controller gives better results than other techniques available in the literature

13	Novel Load Frequency Control Scheme for an Interconnected Two-Area Power System Including Wind Turbine Generation and Redox Flow Battery	Two-area	Interconnected thermal power system	Novel Load Frequency Control Scheme	Modified sine–cosine algorithm (MSCA)	LFC scheme provides better dynamic performance compared to other ones
14	Optimized Fuzzy Self-Tuning PID Controller Design Based on Tribe-DE Optimization Algorithm and Rule Weight Adjustment Method for Load Frequency Control of Interconnected Multi-Area Power Systems	Three-area	Interconnected Multi-Area Power Systems	Fuzzy Self-Tuning PID Controller	Tribe-DE (TDE) algorithm	Good transient behaviour, disturbance rejection capability and insensitivity to parameter changes are advantages of the proposed controller
15	Load Frequency Regulation for Multi-Area Power Systems with Renewable Sources via Active Disturbance Rejection Control	Multi-area	Load frequency regulation for multi-area power system with renewable sources	Proportional–integral–derivative (PID) controller	ADRC principle	Multi-area power system indicates a promising potential of the proposed cascaded ADRC in the power industry

16	Higher Order Degree of Freedom Controller for Load Frequency Control of Multi Area Interconnected Power System with Time Delays	Two-area	Multi-Area Power Systems with Renewable Sources	Active Disturbance Rejection Control	Seagull optimization algorithm (SOA)	MAIPS dynamical behaviour is slightly more deviated up on considering CTDs and is justified
17	Adaptive Super Twisting Sliding Mode Load Frequency Control for an Interconnected Power Network with Nonlinear Coupling Between Control Areas	Two-area	Nonlinear coupling between control area	Dynamically adaptive control	Adaptive Super Twisting Sliding Mode Load	Frequency deviations with typical nonlinearities in power systems were also found to be within acceptable limits
18	Actuator fault-tolerant load frequency control for interconnected power systems with hybrid energy storage system	Four-area	Hybrid energy storage system	Fault-tolerant control	FTC algorithm	Better frequency stabilization effect and early warning function
19	The Load Frequency Control by Adaptive High Order Sliding Mode Control Strategy	Three-area	Interconnected power system with nonlinearities	Adaptive high-order sliding mode control	Super twisting (ST) algorithm	The frequency deviation and ACE (area control error) converge to zero when using the proposed method

20	Load Frequency Control of Distributed Generators Assisted Hybrid Power System Using QOHSA Tuned Model Predictive Control	Single-area	Hybrid power system (HPS)	Model predictive control (MPC)	Quasi-oppositional harmony search algorithm (QOHSA)	Handle different variances of the disturbance signals or noise entering the system as well as the model mismatch
21	Integrated control strategy for electrolytic aluminium load participation in frequency modulation	Two-area	Large scale power system	FOPID controller	PSO algorithm	The integrated control strategy for electrolytic aluminium load participation in frequency modulation show that the FOPID controller optimized by the PSO algorithm has stronger Robustness in the LFC
22	Adaptive Synthetic Inertia Control Framework for Distributed Energy Resources in Low-Inertia Microgrid	Multi-area	Low-inertia power systems	Synthetic Inertia Control (SIC)	PSO algorithm	It is observed that there is an 87% improvement in the system frequency dynamics performance for various disturbances and loading conditions as compared to the cases with no FSIC provision.
23	Coordinated load shedding control scheme for recovering frequency in islanded Microgrids	Three-area	Microgrid system modified into 13 bus system	LS control	Cooperative reinforcement learning algorithm, traversal mode of the algorithm	LS control technology is a key technology to ensure the safe and stable operation of an islanded microgrid. The results show that the proposed coordinated LS control scheme has

						significant performance in frequency regulation and the uninterrupted power supply of critical loads
24	LQG-Based Virtual Inertial Control of Islanded Microgrid Load Frequency Control and DoS Attack Vulnerability Analysis	Multi-area	Two robust LFC schemes using conventional linear quadratic gaussian (LQG)	LQG-based auxiliary controller	Genetic algorithm (GA)	The conventional and modified LQG-based BESS auxiliary control techniques are proposed for non-linear islanded microgrid LFC system with measurement noise in the secondary and auxiliary measurement channels. The performance of proposed controllers are also compared with several other control schemes and the vulnerability to DoS attack is analysed for microgrid LFC system with and without auxiliary control loop.
25	EID-Based load frequency control for interconnected Hybrid power system integrated with RESs	Multi - area	Hybrid power system	Renewable energy sources, interconnected hybrid power systems, LFC, robust controllers	Advanced control algorithm, fuzzy logic, neural network, genetic algorithm	The LFC model is set up and experiment results indicate the validity and superiority of the proposed controller

26	Determination of Control Requirements to Impose on CIG for Ensuring Frequency Stability of Low Inertia Power Systems	Four-area	Converter-interfaced generation (CIG)	PI (Proportional-Integral) controllers	Dual SRF filtering-based PLL (DSRF-PLL)	The proposed methodology represents a first attempt to systematically define the control requirements to be imposed on CIG to ensure frequency stability as its penetration in power systems increases. From the economic viewpoint, said methodology can also be used by system operators or energy regulators as a support tool in the design of grid code requirements related to frequency control capability in CIGs.
27	Optimal load frequency control through combined state and control gain estimation for noisy measurements	Single-area	Power system	LQR based controller	The algorithm is simulated in MATLAB R2018a	Simulations are carried out in a single-area power system in MATLAB/SIMULINK, in which the observer implemented as a separate MATLAB code is plugged into the system to sample the output from the power system and inject the control back. The performance of the implemented LFC is tested by injecting a sudden

						change in demand lasting for 30 s.
28	Automatic Generation Control of a Future Multisource Power System Considering High Renewables Penetration and Electric Vehicles	Two-area	Interconnected power system	A fractional-order proportional integral derivative (FOPID) controller for load frequency control (LFC)	Runge Kutta optimizer (RUN)	The results showed that EPS in the 2035 future scenario has high-frequency stability even with the increased penetration of renewable energy sources. Additionally, the FOPID controller optimized by Runge Kutta optimizer (RUN) gives a better performance than PID, PI, and I controllers at different operation scenarios and different power system disturbances
29	A Novel Control Strategy Based on an Adaptive Fuzzy Model Predictive Control for Frequency Regulation of a Microgrid With Uncertain and Time-Varying Parameters	Multi-area	Multi area frequency control systems	Fuzzy model predictive control	A spider monkey optimization (SMO) algorithm	The simulation results have been concluded from four various scenarios and indicated that the proposed control strategy provides better performance than the previous controller. As an illustration, The proposed controller error (IAE) is one-fourth and one eighth of the AOMPC and H infinity controllers during normal situation

30	Frequency Regulation of Electric Vehicle-Penetrated Power System Using MPA-Tuned New Combined Fractional Order Controllers	Two-area	Robust frequency regulation in interconnected power systems	Parallel combination of tiltintegral-derivative with filter (TIDF) and hybrid fractional-order (HybFO)	Marine predator optimization algorithm (MPA)	The proposed controller combines TIDF and HybFO controllers to improve power system stability during frequency and tie-line power fluctuations. Compared to traditional TIDF controllers, the proposed controller and design algorithm achieve 15.52%, and 38.35% of the ISE and IAE values
31	Grid-area coordinated load frequency control strategy using large-scale multi-agent deep reinforcement learning	Four-area	Power system with solar and wind generation	(GAC-LFC)	An EE-MADDPG algorithm is proposed	
32	Enhanced stability and failure avoidance of hydropower plant in contingent island operation by model predictive frequency control	Single-area	Hydropower plants with the load and transmission line	GPC controller, FOPID controller	(GPC) algorithm, FOPID algorithm	
33	Application of COOT algorithm optimized PID plus D^2 controller for combined control of frequency and voltage	Two-area	Renewable energy sources such as wind plants, solar PV plants, and geothermal power	PI and PID controllers, PID + D^2 controller	COOT algorithm	

	considering renewable energy sources		plants are considered.			
34	Fuzzy logic based adaptive vibration control system for structures subjected to seismic and wind loads	Single-area	Seismic and wind load	PI controller	FLOC algorithm, MOMVO algorithm	Despite the existence of various techniques for predicting and quantifying uncertainties in environmental loads, the accuracy of these methods is not always guaranteed, as they can be influenced by factors such as the availability and quality of data and the size of the sample
35	Cooperative grid frequency control under asymmetric V2G capacity via switched integral reinforcement learning	Single area	Intermittent renewable energy sources	FR controller	SIRL algorithm	
36	Combined frequency and voltage control of two-area multi-source interconnected microgrids via the 2DOF-TIDμ controller	Two-area	Interconnected micro grids including bio renewable generation, RES, HESS, PSS and UPFC.	2DOF-TID^{μ} controller, 2DOF-PID and 2DOF-TID controllers.	Coot Optimization Algorithm (COA)	Any deviations from the nominal values within the Power system have the potency to damage the equipment or diminish the quality of the electrical energy being generated.

37	Adaptive nonlinear controllers based approach to improve the frequency control of multi islanded interconnected microgrids	Single-area	Microgrids	PI controller, FPI-MRAC	CHIO optimizer, Whales Optimization Algorithm, Grey Wolf Optimization Algorithm, Antlions Optimization Algorithm, and Moth Flame Optimization Algorithm	
38	Optimal frequency control for wind power-integrated power system based on parameter identification	Single-area	Wind power-integrated power system	PI controller	Kalman smoother algorithm	The proposed method can identify required parameters accurately with only local measurement
39	Improving power system low-frequency oscillations damping based on multiple-model optimal control strategy using polynomial combination algorithm	Single-area	Flexible AC Transmission Systems (FACTS)	Multiple-Model Linear Optimal Control (MMLOC), linear optimal controller (LOC)	Polynomial Combination Algorithm (PCA)	
40	A Novel Decentralized FO Voltage and Current Control Scheme for Voltage and Frequency Regulation in Inverter Dominated Islanded Microgrids Using Improved Droop Control	Single-area	MG voltage and frequency control based power system	(FOPIDN) controller, proportional-integral controller	Sparrow search algorithm	

1.2 Research Gap Identified

The following research gap is identified after completing the expensive literature survey

1) Numerous controllers are proposed by the researches and their corresponding robustness is yet to be demonstrated.
2) Several optimization algorithms are applied to the LFC in the literature; the drawbacks many of the algorithms are identified.
3) The test system models with more than 3 types of generation units in each control area of the multi area systems are not available in the literature.

1.3 Thesis Contributions

The contributions of this thesis are

a) The LFC of two-area four source model of the IPS is investigated and the power system model is developed in MATLAB/SIMULINK (R2019a) domain.
b) The investigation is conducted, subjected to 10% SLD on area-1.
c) The BFOA tuned cascade (1+PD)-PID controller is suggested as the secondary controller.
d) The efficacy of the suggested controller is validated with PID and FOPID controllers available in the literature.
e) Later, the HVDC line is enacted as the tie-line and the simulation analysis confirmed the improvement in the system performance.
f) The robustness of the proposed control approach is validated from the sensitivity test.

1.4 Organization of the Thesis

1. Introduction
    - Literature Survey
    - Research Gap Identified
    - Thesis Contributions
    - Organization of the Thesis
2. Power System Model
    - Linear System Model
    - Territory HVDC
3. Controller & Objective Function
    - PID Controller
    - FOPID Controller
    - (1+PD)-PID Controller
4. Butterfly Optimization Algorithm
    - BOA Pseudo-Code
5. Simulation Results
    - **Case 1:** Analysis of Two-area four source system under various controllers
    - **Case 2:** Performance of TAFS system using cascade (1+PD)-PID controller and HVDC line
    - **Case 3:** Sensitivity test $\pm$50% from nominal loading
6. Conclusion & Future Scope
    - Conclusion
    - Future Scope

CHAPTER-2

2. Power System Model

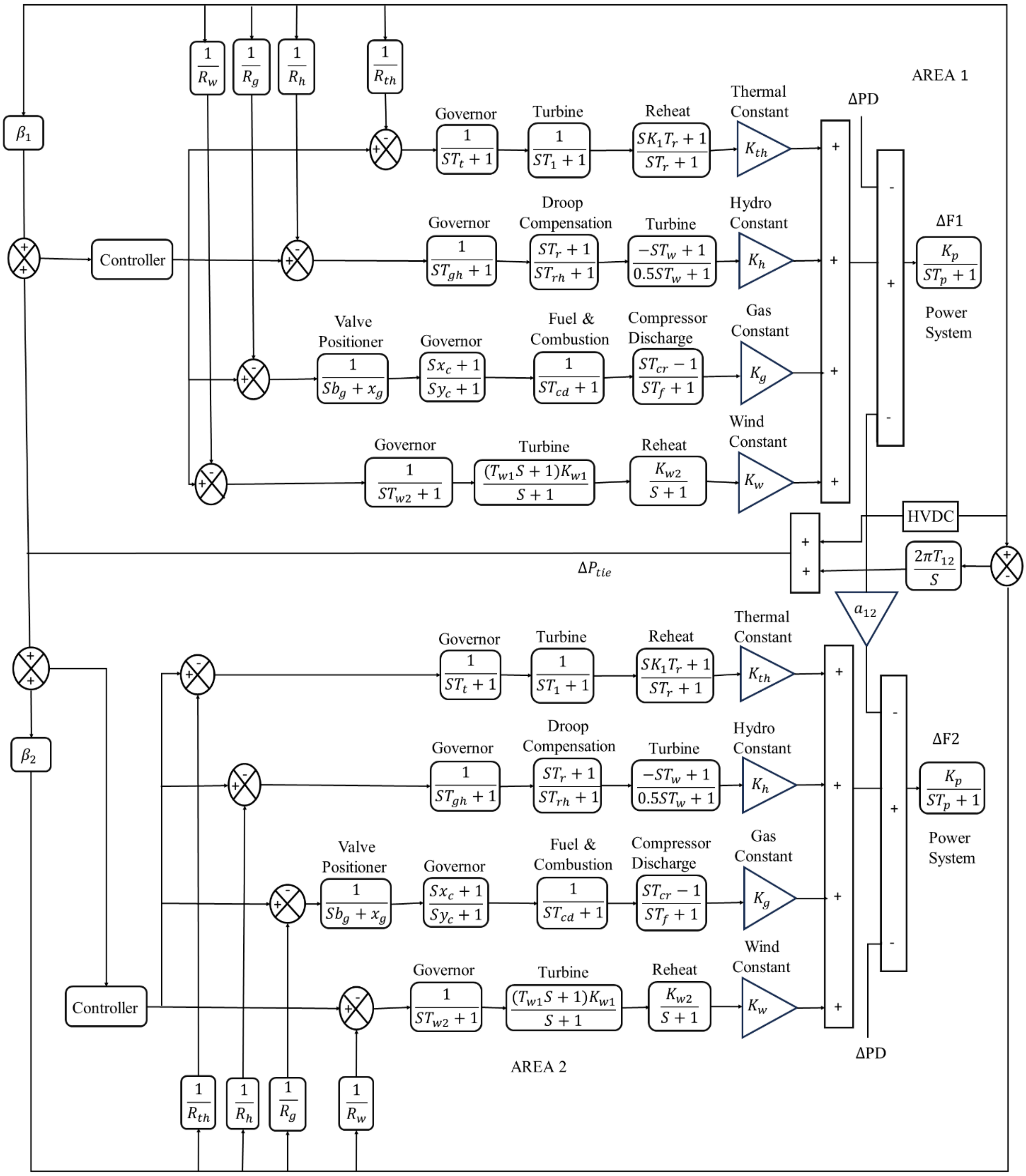

Fig-2.1 Two- area four source system 10% SLD on area-1

LINEAR SYSTEM MODEL:

A two-area four source interconnected power system is considered in Figure 1 that has a combination of thermal, hydro, wind and gas power units, where the two areas are connected via tie line. In Figure 1, β1 and β2 represent the frequency bias constants of Area-1 and Area-2, respectively. ΔF1 and ΔF2 denote the change in frequency for Area 1 and Area 2 respectively.

While R_{th}, Rg, R_w and R_h while R_{th}, R_g, R_w and R_h represent droop constant of Area 1 and Area 2, respectively for thermal, gas and hydro power system. On the other hand R_{th}, R_g, R_w and R_h denote the constant for gas, hydro, wind and thermal power system respectively.

- Thermal unit is composed of governor, reheat and turbine with Transfer Function (TF) $\frac{1}{ST_t+1}$, $\frac{SK_1T_r+1}{ST_r+1}$ and $\frac{1}{ST_1+1}$ respectively.
- While the hydropower system is comprised of governor, droop compensation and penstock turbine with TF of $\frac{1}{ST_{gh}+1}$, $\frac{ST_r+1}{ST_{rh}+1}$ and $\frac{-ST_w+1}{0.5ST_w+1}$ respectively.
- While the gas power system is composed of valve position, governor, fuel combustion reaction and compressor discharge with TF of $\frac{1}{Sb_g+x_g}$, $\frac{Sx_c+1}{Sy_c+1}$, $\frac{1}{ST_{cd}+1}$ and $\frac{ST_{cr}-1}{ST_f+1}$ respectively.
- On the other hand, the wind power system is composed of governor, turbine and reheat with TF of $\frac{1}{ST_{w2}+1}$, $\frac{(T_{w1}S+1)K_{w1}}{S+1}$ and $\frac{K_{w2}}{S+1}$ respectively.
- while the TF for the proposed power system model is $\frac{K_p}{ST_p+1}$.

Territory HVDC

HVDC, which stands for High Voltage Direct Current, is a crucial technology in modern electrical power systems. Unlike traditional AC (Alternating Current) transmission, which oscillates between positive and negative voltage cycles, HVDC carries electrical power in a continuous, unidirectional flow. This technology has several advantages, making it an essential component in the transmission and integration of renewable energy sources, long-distance power transmission, and interconnection of asynchronous AC grids.

One of the primary benefits of HVDC transmission is its ability to efficiently transmit large amounts of electrical power over long distances with lower losses compared to AC transmission. This is particularly valuable for transmitting power from remote renewable energy sources, such as offshore wind farms or remote hydroelectric plants, to urban centers where electricity demand is high. Additionally, HVDC systems offer better control over power flow, enabling operators to manage grid stability and optimize system performance.

HVDC technology also facilitates the interconnection of different AC grids, even if they operate at different frequencies or are not synchronized. By converting AC to DC and then back to AC at the receiving end, HVDC systems allow for the exchange of power between grids that would otherwise be incompatible. This interconnection enhances grid reliability, facilitates electricity trading between regions, and supports the integration of diverse energy resources into the grid.

Furthermore, HVDC transmission is less susceptible to voltage stability issues and can provide better control of power flow compared to AC transmission. This makes it particularly useful for enhancing grid resilience and mitigating the impact of disturbances, such as faults or fluctuations in demand or generation.

In summary, HVDC technology plays a critical role in modern power systems by enabling efficient long-distance transmission, interconnection of AC grids, integration of renewable energy sources, and enhancing grid stability and control. Its versatility and advantages make it a vital territory in the ongoing development and optimization of electrical power networks worldwide.

$$G_{HVDC} = \frac{K_{HVDC}}{1 + sT_{HVDC}}$$

CHAPTER-3

3. Controller & Objective Function

3.1 PID Controller

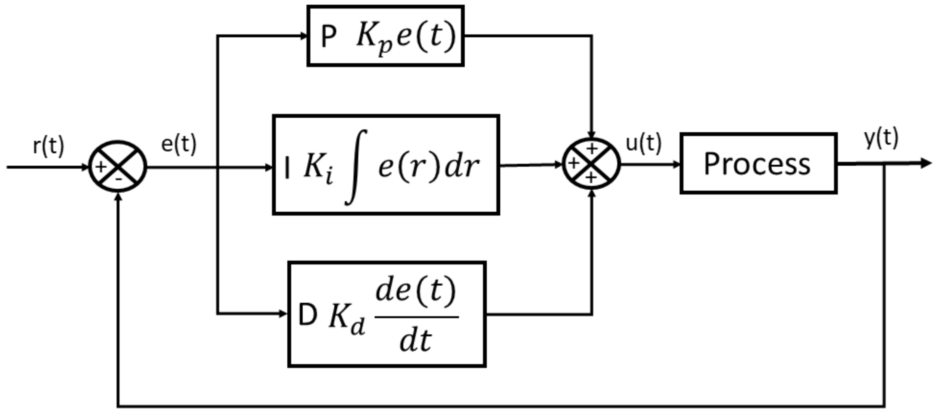

Fig 3.1 – Structure of PID Controller

Where r(t) = System Setpoint, e(t) = Error Signal, u(t) = Control Signal, y(t) = System Output.

PID controllers are a type of feedback control system that uses feedback to control a process or system. They are widely used in industrial applications such as manufacturing, robotics, and process control.

PID controllers work by continuously measuring the difference between the desired setpoint and the actual process variable, then using that information to adjust the control output. The three components of the PID controller, proportional, integral, and derivative, are used to calculate the control output.

PID controllers use three components to calculate the control output: proportional, integral, and derivative. Each of these components works together to adjust the control output to reach the desired setpoint.

Proportional Control: Proportional control is based on the error between the setpoint and the actual process variable. The proportional gain is multiplied by this error to produce the control output. This component provides a linear response, which means that the control output is directly proportional to the error.

Integral Control: Integral control is based on the integral of the error between the setpoint and the actual process variable. This component provides a way to eliminate steady-state error in the system. The integral gain is multiplied by the sum of the errors over time to produce the control output.

Derivative Control: Derivative control is based on the rate of change of the error between the setpoint and the actual process variable. This component provides a way to respond to changes in the system quickly. The derivative gain is multiplied by the rate of change of the error to produce the control output.

3.2 FOPID Controller

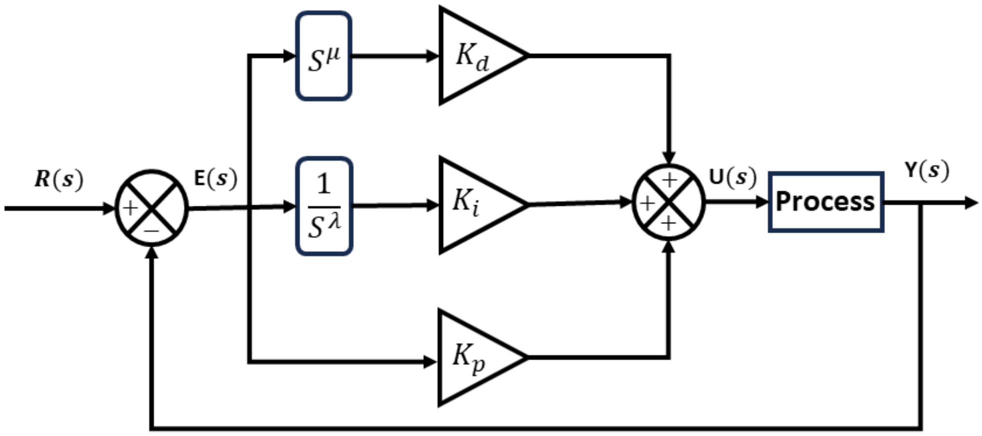

Fig 3.2 – Structure of FOPID Controller

A Fractional Order Proportional Integral Derivative (FOPID) controller is a type of controller that incorporates fractional calculus elements in its proportional, integral, and derivative actions. Unlike traditional PID controller, which use integer-order calculus, FOPID controllers utilize fractional-order calculus to provide more flexibility in modelling and controlling complex systems.

The fractional-order components allow for a more nuanced representation of system dynamics, which can be beneficial in handling processes with non-integer order characteristics. This can lead to improved performance, stability, and adaptability in controlling a wide range of systems, including those with long memory or anomalous behaviour.

The objective function of a Fractional Order Proportional-Integral-Derivative (FO-PID) controller is to minimize the difference between the desired setpoint and the actual output while considering fractional-order differentiation and integration terms. It typically involves terms related to proportional, integral, and derivative actions with fractional orders, aiming to achieve stable and accurate control in various systems.

3.2 Cascade (1+PD)-PID Controller

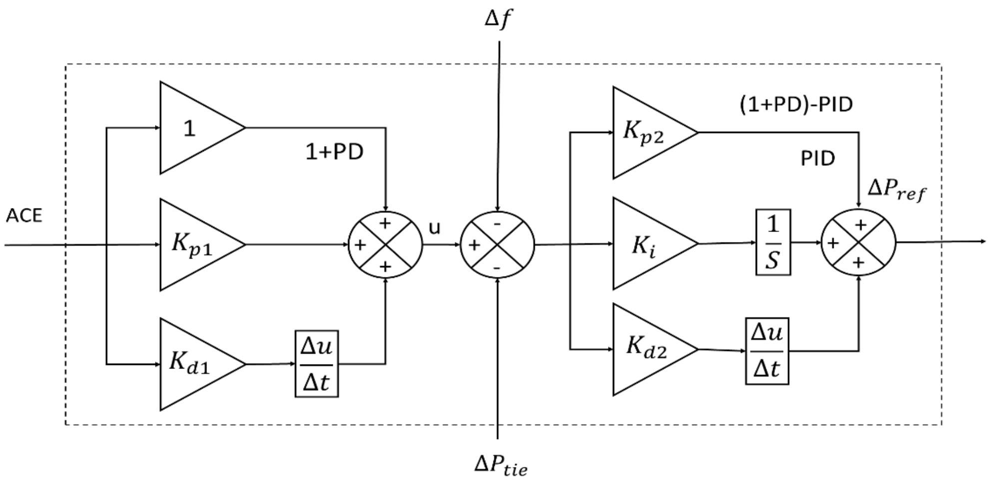

Fig 3.3 – Structure of Cascade (1+PD)-PID Controller

The expression (1 + PD) - PID seems to represent a Proportional-Integral-Derivative (PID) controller with an additional derivative term, often denoted as D, in the form of (1 + PD).

The objective function for this controller is similar to a standard PID controller, with the additional term (1 + PD) influencing the control action. The objective is to minimize the error signal, which is the difference between the desired setpoint and the actual output, by adjusting the proportional, integral, and derivative terms.

The expression (1 + PD) suggests that there is an additional derivative term with a factor of D. This could provide enhanced control capabilities, such as improved damping or responsiveness, depending on the specific requirements of the controlled system.

The tuning of the PID parameters, including the additional (1 + PD) term, is crucial to achieving optimal control performance, balancing the trade-off between fast response, minimal overshoot, and stability.

To improve generation-load balance through LFC, the (1+PD)-PID cascade controller acting as a secondary controller must be designed appropriately. The number of parameters to be tuned for the proposed (1+PD)-PID cascade controller is 5. Setting these parameters by trial may import control performance far lower than the controller is capable when designed optimally. That is why, we take the design problem as an optimization problem by minimizing an objective function J_s. There are different error integrating objective functions like Integral Squared Error (ISE), Integral Absolute Error (IAE), Integral Time weighted Absolute Error (ITAE), and Integral Time weighted Squared Error (ITSE). Since the ISE objective function yield controlled response with less settling time and damped oscillation, it is employed in LFC studies more frequently than its other alternatives. Expression of ISE for two-area PS is given below

$$J_{ISE} = ISE = \int_0^{t_{sim}} |\Delta f|^2 . dt \qquad - 3.31$$

$$J_{ISE} = ISE = \int_0^{t_{sim}} \left|\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie12}^2\right| . dt \qquad - 3.32$$

where t_{sim} is simulation time that is set to a value long enough for the responses to settle. $\Delta f(\Delta f_1$ and Δf_2 in a two-area PS) and Δf_{pie} stand for the area frequency and tie line power deviations, respectively. The main focus of the present work is to minimize J_s via DSA because the minimum value of J_s corresponds to minimum oscillations and accordingly less settling time with no or small peak undershoot/overshoot in Δf_1, Δf_2 and Δf_{tie12} responses against a given step load perturbation (SLP).

CHAPTER-4

4. Butterfly Optimization Algorithm

The butterfly optimization algorithm (BOA) is a metaheuristic algorithm that simulates the foraging and mating behaviors of butterflies. The algorithm is based on the foraging strategies of butterflies, which use their sense of smell to determine: Environment coverage, Near-optimal path generation, Avoiding collision, and Reducing energy consumption.

Butterflies have more the 18,000 species around the world. These species can interact with each other using five senses that let them smell, sight, taste, touch, and hear. In addition, these senses can help them change home, reproduce, and find food.

The smell sense is essential due to its effect on finding food and nectar from long-distance. The butterflies have sense receptors scattered over the butterfly’s body used to smell. These receptors contain nerve cells, called chemoreceptors, which are also used to find the best mating partner.

The fragrance intensity is mathematically modelled as follows:

$$Pf_i = cI^a \qquad - (4.1)$$

Where Pf_i denotes the fragrance strength of i^{th}butterfly, I represents the stimulus intensity, c denotes the sensory modality, and a is the power exponent depending on modality, which presents a varying absorption degree. Each butterfly’s location is presented as a vector of particular problem values. Such a location can be updated in attempting to find a better location using the following formula:

$$x_i^{t+1} = x_i^t + F_i^{t+1} \qquad - (4.2)$$

where x_i^t denotes the current position of butterfy i in iteration t, x_i^{t+1} is the next position of butterfly i and F_i^{t+1} denotes fragrance that utilized by x_i to update its position during iterations.

As mentioned previously, the updating mechanism can be in two phases, including local and global searches. In the global search, the butterfly i moves toward the fittest butterfly g∗, which can be represented as:

$$F_i^{t+1} = (r^2 \times g^* - x_i^t) \times pf_i \qquad - (4.3)$$

where r is a random number in [0, 1]. In local search, the updating movement can be formulated as follows:

$$F_i^{t+1} = \left(r^2 \times x_j^t - x_k^t\right) \times pf_i \qquad -(4.4)$$

where x_j^t and x_k^t denote the positions of j^{th} and k^{th} butterflies in the search space. A new parameter, called switch probability p, is utilized in BOA to switch the algorithm's behaviour between local and global search to get the best balance between exploration and exploitation.

Step 1: BOA and the problem parameters initialization.

In this step, all BOA and the problem parameters are initialized. BOA has five parameters, including population size (N), number of iterations (Itr), c, a, and p.

Step 2: Population initialization.

All solutions are generated randomly by the BOA in this step. The solutions are presented as vectors of length equal to the problem dimension d. All solutions are located in a matrix to create the population, as shown in below.

$$\text{Population} = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_d^1 \\ x_1^2 & x_2^2 & \cdots & x_d^2 \\ \vdots & \vdots & \cdots & \vdots \\ x_1^N & x_2^N & \cdots & x_d^N \end{bmatrix} \qquad \text{---(4.5)}$$

Step 3: Fitness value calculation.

In this step, all solutions are evaluated based on the objective function of the optimization problem. Subsequently, the best solution is assigned to g∗ .

Step 4: Update the population.

In this step, all solutions are updated using the BOA to find better solutions based on the fitness values obtained in Step 3. In the BOA, a random number r is generated and compared with p to lead the searching behaviour locally or globally. In case r is less than p, the butterfly moves globally using Eq. 3; otherwise, it moves locally using Eq. 4. Subsequently, if the new solution is better than the old one, it replaces the old solution. Finally, g* will be updated.

Step 5: Check the stop condition

Steps 3 and 4 are reproduced until the maximum number of iterations is reached.

BOA Pseudo-Code

```
Step 1
Initialize the problem parameters
Initialize the BOA parameters (Itr, N, c, a, p)
Step 2
Initialize population matrix
Step 3
while(itr ≤ Itr) do
  for each solution do
      Calculate the solution's fitness value
      g* = the best solution
  end for
  Step 4
  for each solution do
       Generator r (random numbers in [0,1])
       if r<p then
          Update the solution using eq.3
        else
           Update the solution using eq.4
        end if
        if the solution is better, update the population.
        Update c
  end for
  Step 5
  if Itr is not reached then
      itr = itr+1
   end if
 end while
 return g*
```

CHAPTER-5

5. Simulation Results

Case 1: Analysis of Two-area four source system under various controllers

In this subsection, the dynamic behaviour of the two-area four source system model considered for investigation is analysed for 10% SLD on area-1. The controllers like PID, FOPID, cascade (1+PD)-PID are individually enacted as the secondary controller in both the areas of the considered system. To get the comparative analysis and to reveal the dominance of the suggested control technique, all the controllers are fine-tuned with the BFOA. The dynamic behaviour of the system under these controllers is compared in Fig.5.1 and is numerically assessed in terms of settling time in seconds as well as the peak under shoots (PUS) as placed in Table 1. After thorough analysis of the responses shown in Fig.5.1 and the interpretation of the numerical results shown in the Table 5.1, it is clear that the suggested cascade (1+PD)-PID controller outperforms the PID and FOPID in diminishing the PUS and the oscillations in the responses. Moreover, with the suggested controller the deviations in the responses are very quickly settled down and reached the stable position. Further, the cascade (1+PD)-PID controller effectively regularised the ISE index value and is enhanced by 80.17% and 71.26% with the PID and FOPID controllers. The optimal gains of cascade (1+PD)-PID, FOPID and PID controllers are given in Table 5.2.

Table 5.1: Numerical results for the test system responses under various control approaches

Numerical Results		PID	FOPID	(1+PD)-PID	HVDC line
Settling time (Seconds)	Δf_1	15.08	9.42	6.53	5.35
	ΔP_{tie12}	16.19	11.35	8.28	6.52
	Δf_2	16.16	10.89	8.32	5.35
Peak under shoot	Δf_1	0.0069	0.0041	0.0024	0.0018
	ΔP_{tie12}	0.0018	0.00095	0.00047	0.00021
	Δf_2	0.00435	0.00256	0.00173	0.00122
ISE*10^{-3}		65.314	45.055	12.948	-

Table 5.2: Controller Optimal Parameters

Parameters	Area-1			Area-2		
	PID	FOPID	(1+PD)-PID	PID	FOPID	(1+PD)-PID
K_P	2.539	1.379	1.513	2.655	1.336	1.390
K_I	1.189	0.618	0.096	1.264	0.094	0.157
K_D	1.202	1.036	0.834	1.319	0.627	0.474
K_{P2}	-	-	1.461	-	-	0.699
K_{D2}	-	-	0.428	-	-	0.478
λ	-	0.051	-	-	0.037	-
μ	-	0.150	-	-	0.096	-

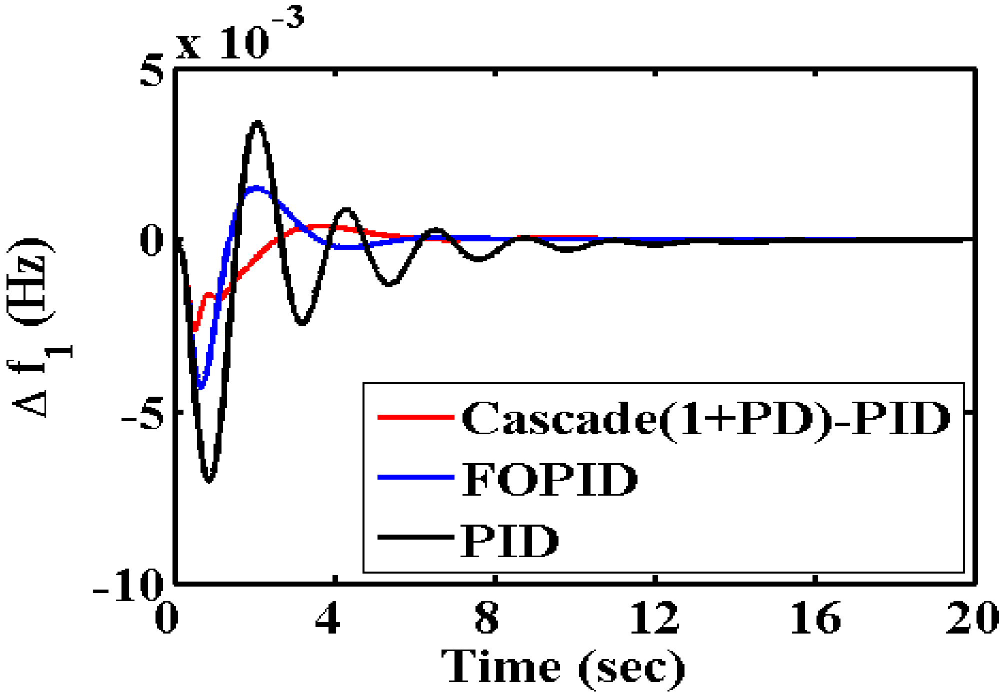

Fig 5.1(a)

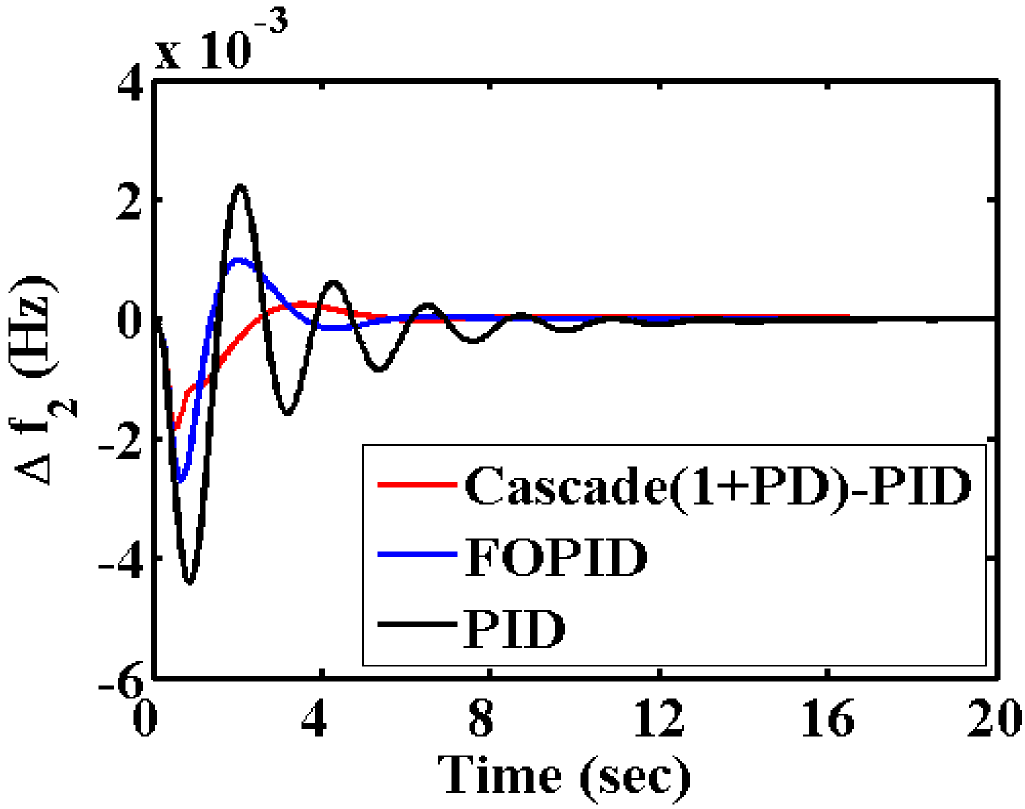

Fig 5.1(b)

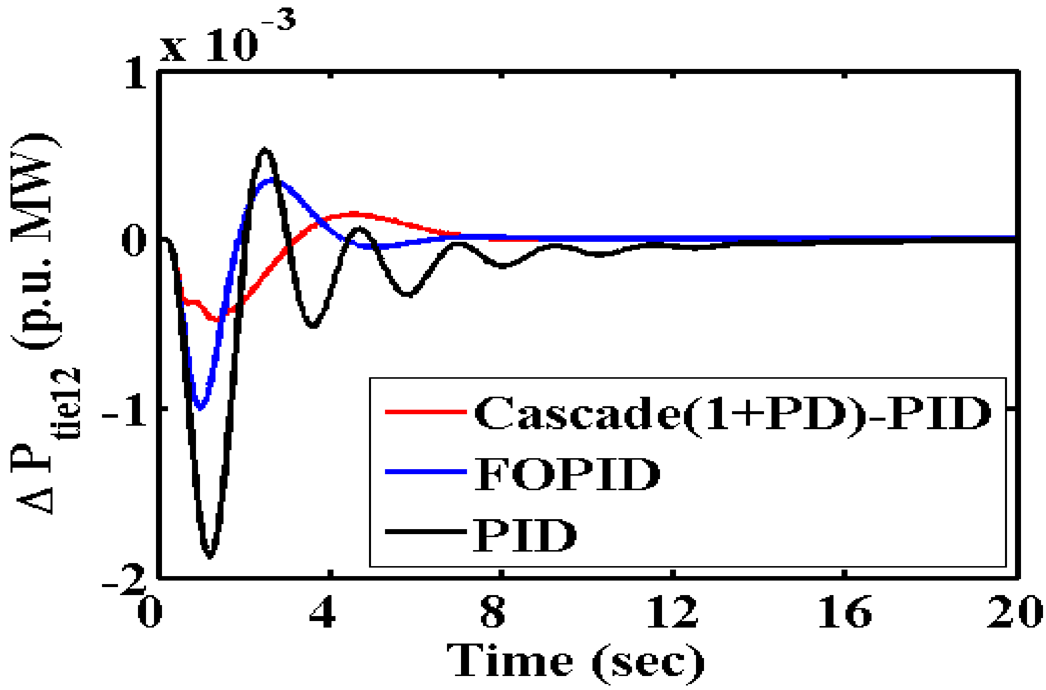

Fig 5.1(c)

Fig 5.1 Case – 1 responses. a. Δf_1 b. Δf_2 c. ΔP_{tie12}

Case 2: Performance of TAFS system using cascade (1+PD)-PID controller and HVDC line.

In order to improve the dynamic performance of the two-area four source model of the IPS further, it is incorporated with the HVDC as the tie-line under the secondary regulation of the BFOA based cascade (1+PD)-PID controller. The performance efficacy of the cascade (1+PD)-PID controller is validated in the above subsection and hence the further investigations are continued under the regulation of this controller. The behaviour of the IPS with and without enacting the HVDC line as the tie-line is shown in Fig.5.2 and is clear that the PUS are very much shrunken and with the vey less settling time the deviations are driven to the steady state position. The HVDC line is having the capability in dealing with the bulk power transfer and hence the exchange of power between the control regions can be performed in a much better way even under the large load perturbations. The responses settling time is indicated in the Fig.5.3 as the bar chart to get the clear inference regarding the efficacy of the proposed controller and the employment of the HVDC as the tie-line.

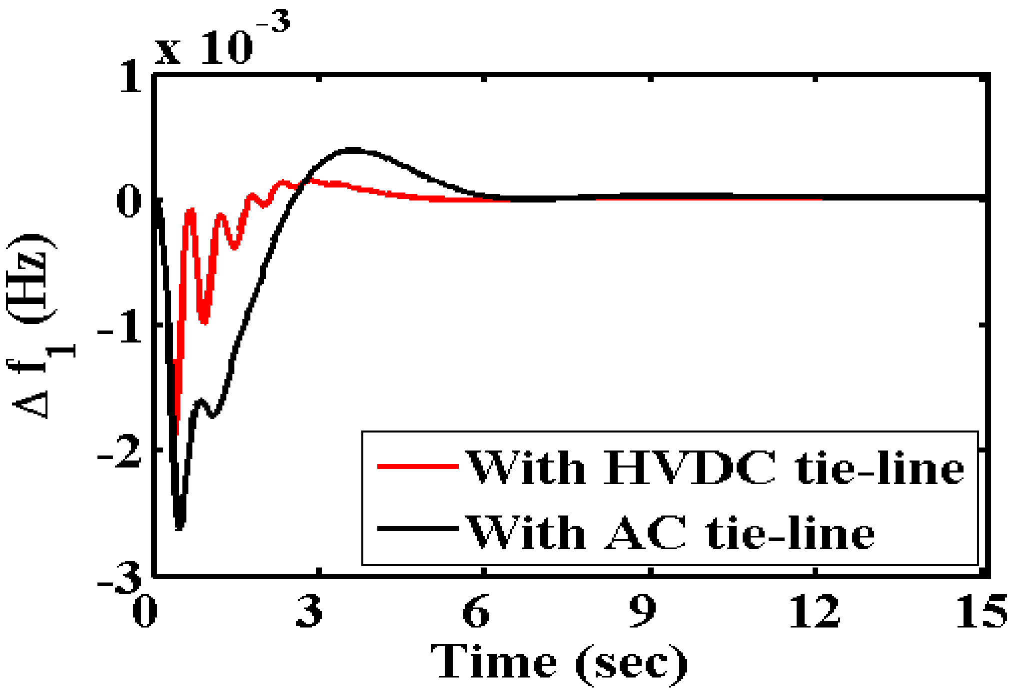

Fig 5.2(a)

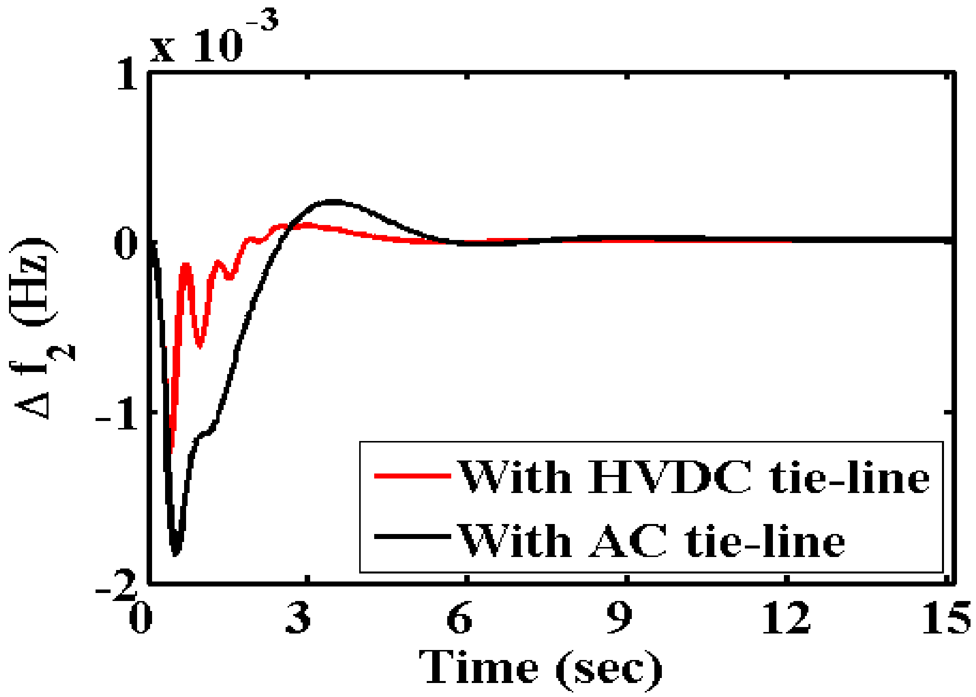

Fig 5.2(b)

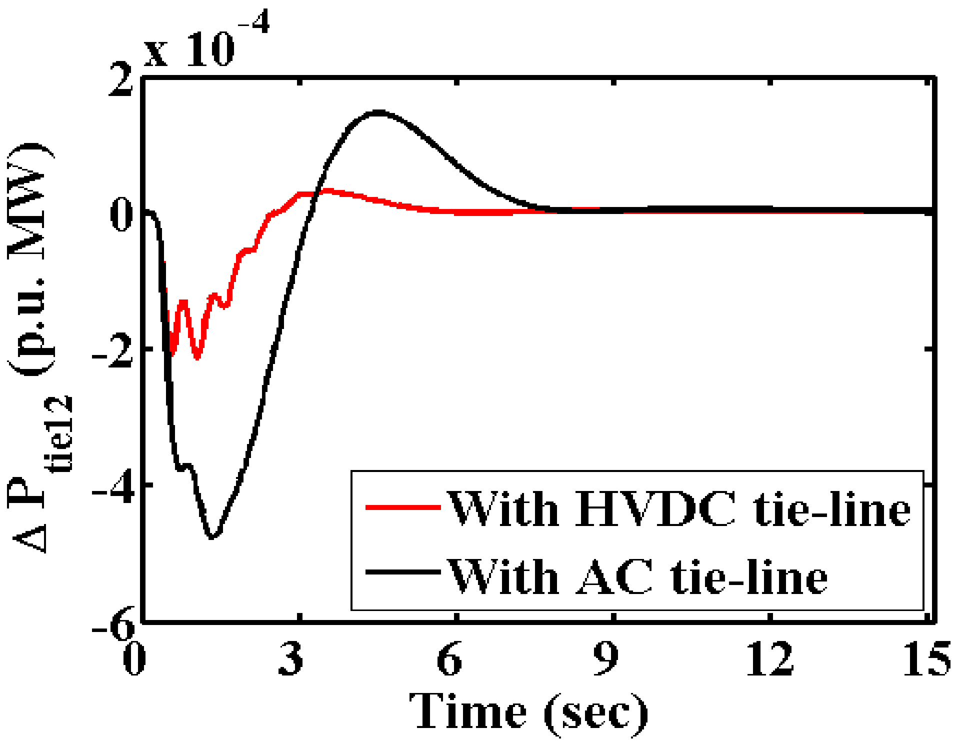

Fig 5.2(c)

Fig 5.2 Case – 2 responses. a. Δf_1 b. Δf_2 c. ΔP_{tie12}

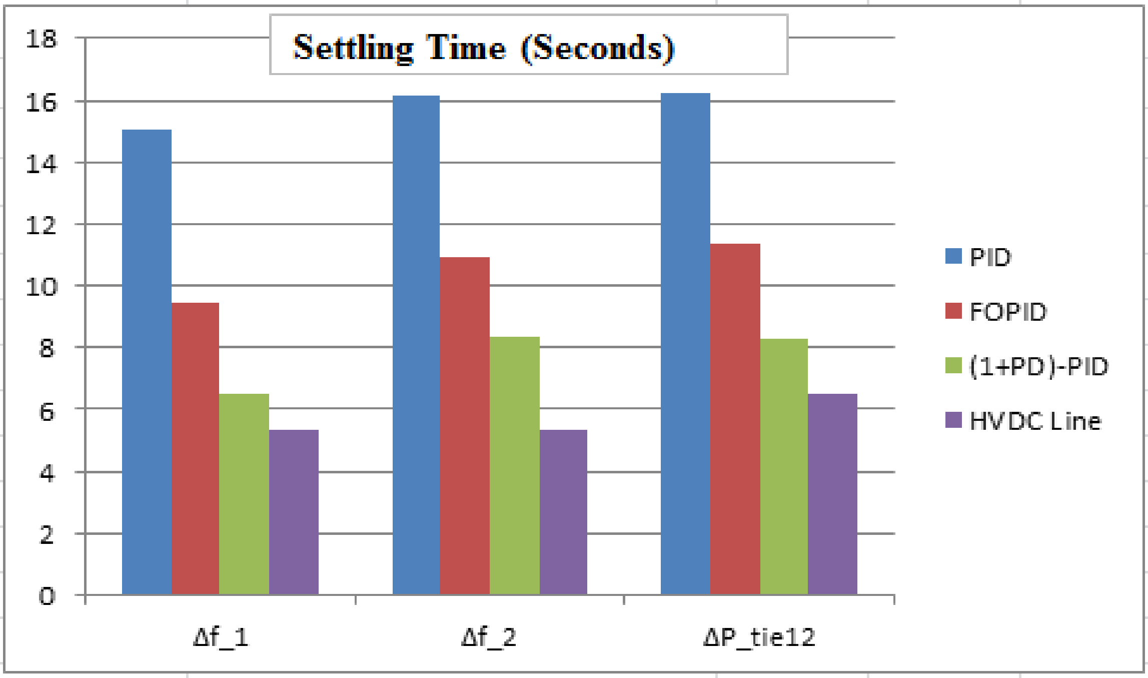

Fig. 5.3 Comparison of responses settling time under various controllers

Case 3: Sensitivity test ±50% from nominal loading

Finally, the sensitivity test is conducted by laying the investigated IPS with the ±50% from the nominal load. The sensitivity test is conducted on the system under the cascade (1+PD)-PID controller enacting as the secondary controller and the HVDC line as the tie-line to validate the robustness of the suggested control technique. The responses of the system for this subsection are shown in Fig.5.4 and is observed that the system responses are hardly deviated from the case of the responses that of the nominal loading. This means the suggested controller and the enacting of the HVDC line is exhibiting the robust control performance and hence it is declared that the suggested control technique in this work is robust.

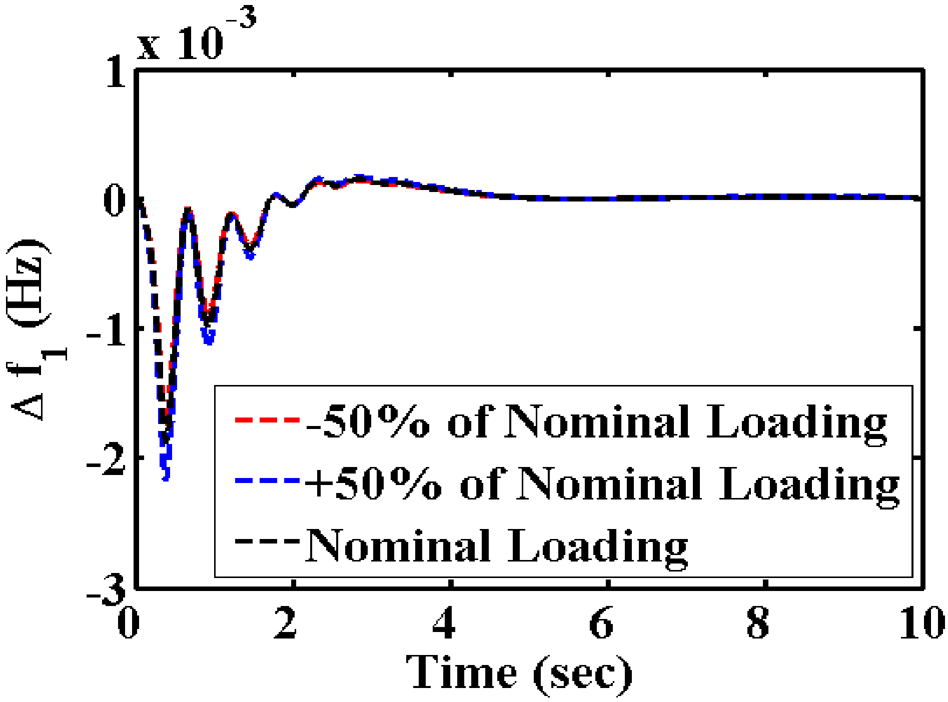

Fig 5.4(a)

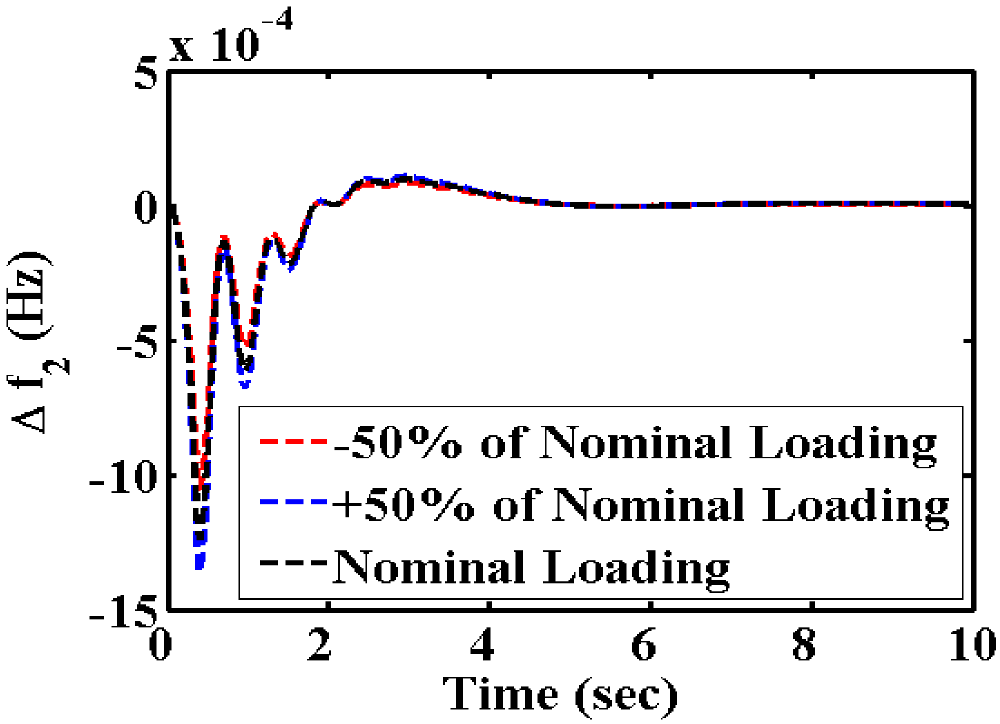

Fig 5.4(b)

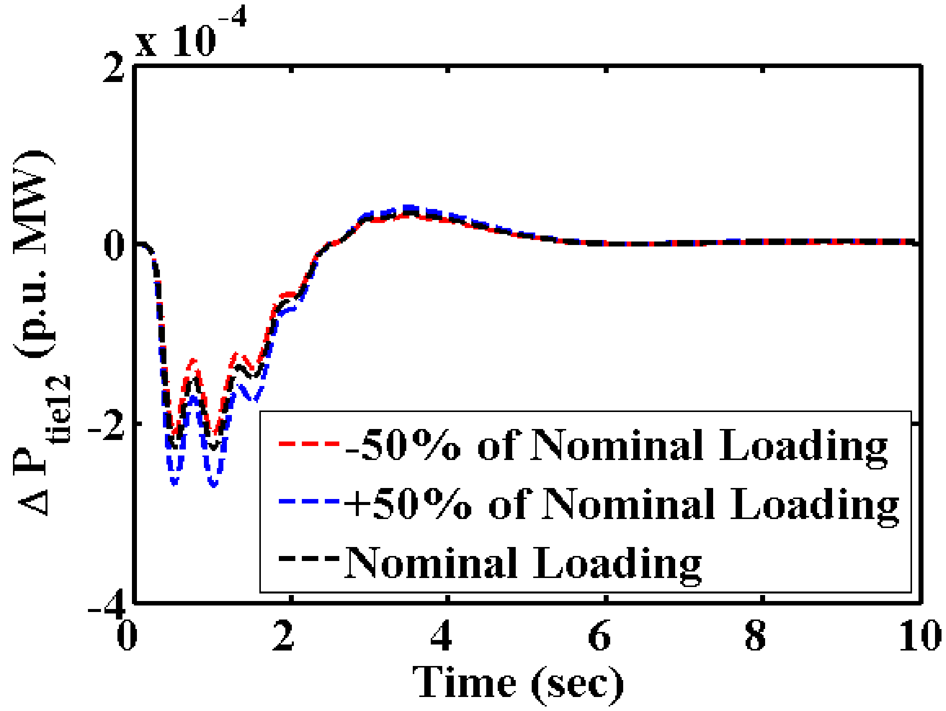

Fig 5.4(c)

Fig 5.4 Case − 3 responses. a. Δf_1 **b.** Δf_2 **c.** ΔP_{tie12}

CHAPTER-6

6. Conclusion & Future Scope

6.1 Conclusion

This work proposed the cascade (1+PD)-PID controller based on the BFOA technique as the frequency regulator for the IPS networks. The performance of the cascade (1+PD)-PID controller is tested on the two-area four source model of the IPS subjected to the perturbations of 10% SLD on area-1. However, the performance efficacy of the cascade (1+PD)-PID controller is validated with the performance of the PID and FOPID controllers available in the literature. Further, to get the enhancement in the system dynamic behaviour under the load disturbance the HVDC line is enacted as the tie-line instead of the AC line. The simulation analysis confirmed the improvement in the considered IPS network dynamic behaviour with the employment of the HVDC tie-line. Finally, the robustness of the suggested control approach is validated by conducting the sensitivity test in terms of applying the variations in load of ±50% from the nominal loadings.

6.2 Future Scope

In future, this work can be extended to the incorporation of the energy storage devices and the FACTS devices and further can be extended to the implementation of the fuzzy logic and some other intelligent controller

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