Comparative Analysis of Different Controllers on Two Area Interconnected Power System Model using Gravitational Search Algorithm

This Dissertation is submitted in partial fulfillment of the
requirements for the award of degree of

Master of Technology
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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the Dissertation entitled **"Comparative Analysis of Different Controllers on Two Area Interconnected Power System Model using Gravitational Search Algorithm",** in partial fulfillment of the requirements for the award of the **Degree of Master of Technology** and submitted in the **Department of Electrical Engineering**, Malaviya National Institute of Technology Jaipur, is an authentic record of my own work under the supervision of Dr. Vikas Gupta, Associate Professor, Department of Electrical Engineering, Malaviya National Institute of Technology Jaipur.

The matter presented in this dissertation embodies the results of own work and studies carried out by me and have not been submitted for the award of any other degree of this institute or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Date:

(Dr. Vikas Gupta)
Supervisor

ABSTRACT

Power systems are heterogeneous electrical networks which are a combination of generation, transmission and distribution systems. These systems distributed over a wide geographical area, which circulated throughout the globe. The system load is always uncertain in the power system network, which keeps wavering according to the needs of the consumers from time to time. Hence, to preserve the stability of the electrical system, well-designed controllers are recommended. Controllers regulate the system deviation as well as guarantee its reliable operation. In an interconnected system load fluctuations causes frequency deviation in each area and also power fluctuations in tie-line. Load Frequency Control (LFC) technique is preferred to eliminate these variations. Small power mismatches cause smaller deviation of frequency which can be handled easily. Significant frequency deviations can be a problematic and may lead to damage of equipment and even blackouts.

In this research work; the effect of different controllers is analyzed on the dynamic performance of LFC in a two area interconnected thermal power system. Initially, different standard error criteria considered as objective function. Their performance is compared to choose an appropriate objective function for the optimization problem.

The Controller gain setting; proportional (P), integral (I) and derivative (D) constants are optimized using Gravitational Search Optimization Algorithm (GSA). Integral of Time multiplied with Absolute value of Error (ITAE) is used as objective function. Time domain simulations are performed to investigate the performance of the system with and without Generation Rate Constraint (GRC). The proposed GSA based PID controller gives the best dynamic performance compared to I and PI controller. It also keeps the frequency and tie-line power within the permissible limit. Hence, it proves the effectiveness of proposed approach in two area interconnected thermal system.

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ABBREVIATIONS

ACE	: Area Control Error
APF	: Area Participation Factor
GRC	: Generation Rate Constraint
GSA	: Gravitational Search Algorithm
I	: Integral Controller
IAE	: Integral of Absolute Value of Error
ISE	: Integral of Squared Value of Error
ITAE	: Integral of Time Multiplied With Absolute Value of Error
ITSE	: Integral of Time Multiplied With Squared Value of Error
LFC	: Load Frequency Control
PI	: Proportional plus Integral Controller
PID	: Proportional, Integral and Derivative Controller

NOMENCLATURE

B_1, B_2 : Frequency Bias Parameters

ACE_1, ACE_2 : Area Control Errors

u_1, u_2 : Control Outputs from the Controller

R_1, R_2 : Governor Speed Regulation Parameters

T_{g1}, T_{g2} : Governor Time Constants

ΔP_{g1} , ΔP_{g2} : Change in Governor Valve Positions

T_{t1} , T_{t1} : Turbine Time Constants

K_r : Reheat Time Constant

T_r : Reheat Gain

ΔP_{t1} , ΔP_{t2} : Change in Turbine Output Powers

ΔP_{D1} , ΔP_{D2} : Load Demand Changes

ΔP_{Tie} : Incremental change in Tie-Line Power

K_{PS1} , K_{PS2} : Power System Gains

T_{PS1}, T_{PS2} : Power System Time Constants

T_{12} : Synchronizing Coefficient

ΔF_1 , ΔF_2 : System Frequency Deviations

CHAPTER 1

INTRODUCTION

1.1 Overview

The Power systems i.e. combination of generation, transmission and distribution networks are the interconnection of more than one control areas connected through tie-lines. The system load keeps wavering due to its uncertain nature. Our work is to maintain continuous power supply in all circumstances. To achieve this, we require properly designed controllers to regulate the frequency and voltage. Thus the system stability is sustained [1]. The system equilibrium is preserved by the balance between power demand and generated power.

The hasty ramification of the industries has further lead to the increase in the complexity of the systems. Frequency and voltage rely on the active – and reactive – power respectively and results in two control difficulties i.e. regulation of the active – and reactive – power. The control of active power i.e. frequency regulation is called Load Frequency Control (LFC) [2]. As long as there is a counterbalance between load and power generated, system stability is sustained. Tie-line power interchange is also an important task of LFC. Power systems are the composition of several generating units. For enhancing fault toughness, these units are connected through tie-line.

When there is a swift change in load appearing in an area; there is an energy transfer from the adjacent area through tie-line to fulfill that demand. The area go through a change in load demand will either balance it without any exterior backing or there will be economic competition between them. Therefore, it is preferred to use an independent load frequency controller for each area to monitor the tie-line power. Each area of an interconnect power systems should set their set point individually. Thus, LFC ensures regulation of frequency as well as tie-line power.

The controller takes charge of minor variation in load demand to manage the frequency and tie-line power change within prescribed limits. With a small increment of demand in any area, the operating frequency of that area will set to a new value to eliminate mismatch between load and generation. Initially, the imbalance is fulfilled by the extraction of kinetic energy from the system which results in frequency deviation. With the increment in demand, frequencies will decrease and vice-versa.

In an interconnected system, if the load changes, there is a change in active power demand and frequency will change. Power also flows from tie-line to the interconnected areas. Therefore, the system becomes unstable. LFC loop eliminates the disturbance and maintains the stability at the time of the load fluctuation. To achieve this, we have to minimize transient variation of tie-line power along with frequency change and keeping the steady state error to zero. The frequency needs to be maintained within the scheduled values. Otherwise, it may cause tripping of the lines and system may collapse.

To maintain the frequency within specified limit for slow and regular load changes are the primary objective of LFC. If output variations are significant, then frequency cannot stay within specified range. As a result, emergency control is required to maintain the stability. Our objective is to preserve continuous power supply without any delay or voltage drop while keeping uninterrupted and abundance power supply to the consumer. Power exchange needs to keep within limits in tie-line.

1.2 Objectives of the Power Systems

- Rated voltage and frequency has to be provided to the consumer
- The faulty section isolated at a faster rate keeping other section healthy.
- The generator must be stable under disturbance and fault conditions.
- The flexible power supply has to be available.
- The cost of electrical energy per KWhr is to be minimum.

The power plants are delivering power to a large number of consumers. As we know power plants located at the remote location and electricity must supply to all the consumers. To provide energy to far end consumers; we have to transmit power to long distances. In this transmission losses will affect power quality. Thus; the superiority of power supply depends upon some of the factors as follows

a) The system frequency must be to its nominal value.

b) Bus voltage magnitude is also maintained within specified limit under normal range.

So frequency and voltage regulations are the significant measures of a power system. This guarantees the sustainability of the scheme.

1.3 Need to Grip Frequency Constant

The intimidating challenge for a power engineer is to keep frequency within specified limits. Power must be supplied to the consumer with constant frequency and constant voltage. The switching on and off the load are the deciding factor of power consumption which results in an imbalance between generation and demand. We have to deal with it in a short period; otherwise frequency deviates from its nominal value. High divergence in the frequency may cause a severe threat to power system stability and surveillance of the scheme. Also, it may result in the damage of equipment and shut down of the entire system. Hence, the normally operated system must possess constant frequency and keep the balance between generation and load.

Understanding to keep frequency constant is [3, 35]:

i. The speed at which most types of AC motors run is directly related to the frequency. The majority of the loads driven by AC motors may not be sensitive to larger frequency fluctuations (frequency is kept within ±0.05 Hz of nominal-value).

ii. Let nominal-frequency be 50Hz; if running speeds of turbine analogous to ±2.5 Hz frequency variation then most likely turbine blades will get damage.

iii. The synchronous motors drive the electrically operated clocks and accurateness of those clocks relying on the incidence together with the integral of this frequency error.

iv. In thermal power plant the turbine used are designed to run nearly at synchronous speed. The velocity of expanding steam is uncontrollable and for higher turbine efficiency it is mandatory to have the synchronism of speed.

v. An emergency frequency control i.e. under frequency load shedding disconnects a large group of customers (loads) to protect the generator from damage at the time of extremely large frequency imbalance.

So, the frequency must be maintained constant. Interconnection of the power systems is made feasible by tie-lines.

1.4 Classification of Frequency Responses

Frequency response is defined as the automatic actions provided by the system or elements of the system for balancing demand and power supply at the time of frequency deviation [4].

The term-frequency response is traditionally used by the industries to-describe how an interconnected-system behaves on stabilizing the frequency after the sudden loss of generation. Frequency responses can classified into three categories on the basis of time frame.

Table 1.1 Frequency Response Classifications

Response	Time
Primary	10-60 seconds
Secondary	1-10 minutes
Tertiary	10 minutes – hours

1.4.1 Primary Response

It provides by governor against load disturbance. This response is generally delivered entirely within 10 to 14 seconds. It only stabilizes the frequency to a new value to fulfill the demand. The primary response of the governor compensated by the inertia of generator and frequency depended load response. Governor adjusts the turbine speed by regulating steam input so; frequency will change.

Droop characteristic is the key factor to make a change in frequency by the governor. The droop curve decides generator’s power output. The gain of the feedback loop of the primary frequency controller is known as speed droop (R). It’s value is determined as

$$R = -\frac{\frac{\partial F}{F_0}}{\frac{\partial P_D}{P_D}} \tag{1.1}$$

Where F_0 is the nominal frequency and P_D is the power generated.

1.4.2 Secondary Response

Primary frequency response limits the frequency deviations but not capable of bringing back the frequency to its nominal value. Typically governor control controls in case of single generator unit. On the other side, the secondary control is automatic control and it does that i.e. set the frequency to its nominal value. The Load Frequency control implements it.

The LFC controller installed in each and every area of an interconnected system recovers the frequency to its nominal value. It will take few minutes to restore the frequency. It monitors the total demand, total generation, frequency inside that area and figures out area control error (ACE). The net scheduled and the actual interchange is the ACE and if its value is not zero, then LFC loop drive ACE to zero.

1.4.3 Tertiary Response

It is the manual action preceded by the system operator to avoid the current and future contingencies. It operates from few minutes to hours which are a long duration. It has the motive to restore primary and secondary reserve but when secondary control fails to restore system frequency at desired level.

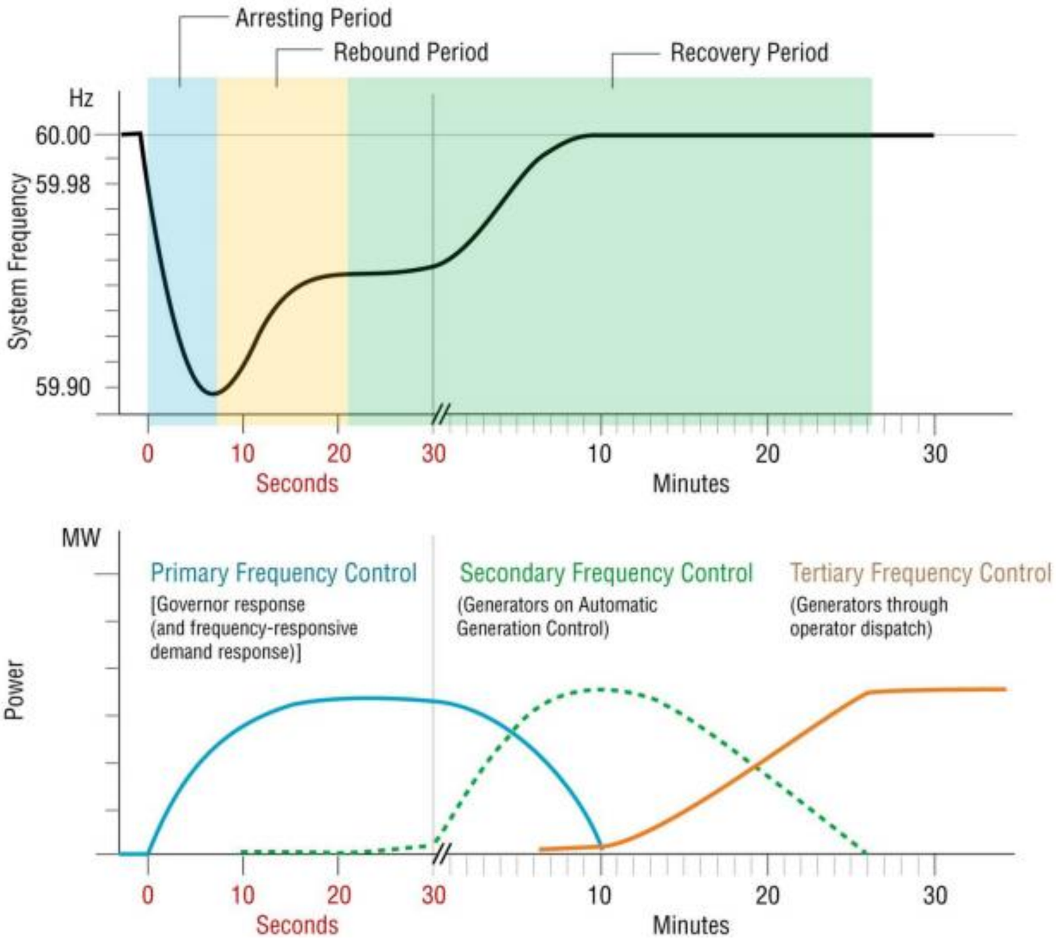


Figure 1.1 Impact on System Frequency When the Sudden Loss of-Generation and Action of different Frequency Control [4]

As a result, it responds to the subsequent loss of generating units. It also calls for coordinated changes in generating unit loading and commitment e.g. to restore its reserve capacity, dispatch one generator down. Simultaneously to replace the power provided by the first generator, dispatch another generator up. Thus, system frequency maintained. The final stage of the recovery period is the deployment of tertiary frequency control as indicated in fig. 1.1.

1.5 Research Motivation

From the literature survey, it is evident that Gravitational Search Algorithm (GSA) is a spontaneous approach providing persistent results. Hence, it is practiced for two-area inter-connected thermal power systems for tuning different controllers in LFC, to select the best one. As we already know, load diversity is a primary source of frequency fluctuations. The load is relying on the consumers i.e. we do not have any authority on consumer wish and cannot be predicted sooner so that disciplinary steps are taken.

For light performance, the error function is obtained with the help of tie-line power – and frequency – variation, which is termed as Area Control Error (ACE). There are four standard error functions used generally. We have a comparison to select the suitable error function for our problem. Then to overcome the value of ACE; we optimize the error function using controllers. These controllers gain values are calculated via GSA algorithm is the prime endeavor of this work.

1.6 Thesis Objectives

Standard operating frequency in India is 50 Hertz, and if the fluctuation is ± 2.5 hertz, then it will have a substantial effect on the interconnected system. For example turbine, blades will get damaged in this condition.

The objectives are

- Objective function effects on the system performance
- To find efficient or optimum GSA control parameters
- Comparative analysis of different controllers and design a controller whose parameters are optimized using GSA algorithm for regulating the value of frequency to nominal value during all load variations.

- Tie-line power flow between areas is also maintained within its pre-specified value
- Consider the physical constraint GRC, which makes system nonlinear than analyze the system performance. Also design the controllers for this conditions.
- Sensitivity analysis to study the robustness of the system.

1.7 Thesis Layout

Chapter 1 Discuss the basics of power system problem i.e. load variation and review the load frequency problem. Highlight the frequency change and its effect on system performance. A brief description of research motivation and objective of the work also presented.

Chapter 2 Brief literature survey presented. A short review of some of the algorithms and different types of controllers used in LFC problems discussed. Different approaches, different objective functions and different controllers help to understand the issue in detail.

Chapter 3 Deals with the LFC of two area thermal interconnected system. A mathematical modeling of a unit area of scrutiny system drawn and then explained each component briefly. Drawn two areas interconnect power system model.

Chapter 4 Discusses the tie-line – and frequency – problem; the importance of the optimization problem over the estimation problem. Selection of controller and the proposed performance indices also discussed. Then the simulations models are presented with and without physical constraints.

Chapter 5 Gravitational Search Algorithm is presented with complete mathematical manipulation. Flowchart is also drawn to execute it step by step. Later choice of GSA over other algorithms described.

Chapter 6 Covers the applications of GSA and then its parameter tuning for successful implementation of the algorithm. Afterwards, results are analyzed for different cases and compared with other techniques. At last sensitivity analysis with - and without - physical constraints is to validate it is potential.

Chapter 7 Finally a conclusion is drawn with the future scope of work.

CHAPTER 2

LITERATURE SURVEY

2.1 Overview

The purpose of the power system is maintaining uninterrupted and consistent power supply which must be fed to all consumers with rated voltage and frequency. The LFC problem is the most significant issue of concern in the interconnected system. In this type of problem frequency to be regulated by using governor’s but their response is not satisfactory for system stability. Thus; a supplementary technique has been required to the governor which regulates the frequency.

C. Concordia and L. K. Kirchmayer et. al. [3] have done much work in the field of LFC. Significant work on LFC of power systems has been done by Olle I. Elgerd [2, 39, 43, 46].

M. Y. Akhtar et. al. [5] focused on the significance of passive load characteristics and proposes a method to represent such load w. r. t. frequency changes ± 5%. They stated that with the rise in operating frequency active power fall linearly. Also divides the load into components such as dynamic load containing induction motor, passive frequency dependent load and resistive load.

D. P. Kothari et. al. [6] considered reheat thermal interconnected system and discussed that new control area using P-I compensator provides better results compared to conventional and integral control.

D. Das et. al. [7] used a variable structure controller (VSC) based on sliding mode concept analyses two areas reheat thermal system using the integral squared error (ISE) technique. They investigated that this controller has tremendous advancement in the dynamic responses of the system over integral compensator and also stable over wide fluctuations.

Louis S.V. et. al. [8] has tried to understand the automatic generation control. They observed that the involvement of physical constraint limits the AGC and also presented their characteristics. AGC acts slowly; no precise control mechanism suggested to speed it up. There is much scope to utilize this to make the power system more stable and reliable.

C.S. Chang et. al. [9] studied LFC using PI controller tuned with Fuzzy techniques. They also formulated the control area that always guarantees the zero steady state error. This approach is extended to four area interconnected power systems.

Fernando G. Martins et. al. [10] found that ITAE is good tuning criteria to calculate PID controller parameters. They also explained that this approach (ITAE) not typically referred due to its computational toughness but suggested that MATLAB is providing us a platform to use it smoothly to tune controller parameters.

Rajesh Joseph Abraham et. al. [11] considered a Phase Shifter with Thyristor Control (TCPS) in sequence with the tie-Line in a hydro-thermal inter-connected system. Suggest that frequency stabilization is possible by controlling the thyristor angle. Integral controller gain parameter is tuned using ISE performance index and reveals that TCPS suppressed the frequency and tie-line deviations when sudden load disturbance takes place compare to without TCPS.

Kamel Sabahi et. al. [12] proposed a modified feedback learning approach (FEL) based on the new adaptive controller for LFC problems. This method consists conventional and intelligent controller. Classical feedback controller (CFL) i.e. PID controller fails to supply significant control performance and stability over a vast range of fluctuations thus supervised controller used to tune the PID controller parameters under all abnormal conditions. To improve overall performance Fuzzy neural network is employed in INFC over the conventional neural network and finally compared with CFEL and PID for different performance indices.

J. Nanda et. al. [13] made a first attempt to apply a compelling intelligence technique i.e. Bacteria Foraging (BF) to optimize several parameters simultaneously such as K_{Ii}, R_i and B_i on a three different interconnected thermal systems with reheat turbine and GRC; compared the results with Genetic Algorithm (GA) and conventional techniques. These simultaneous optimizations also allow us to use the value of R more than practically used. Thus; made the governor cheaper and best dynamic performance under wide fluctuations in the load is achieved.

H. Golpira et al. [14] focused on AGC problem for an interconnected power system considering three physical constraints i.e. GRC, dead band, and time delay. Tune the integral controller using GA in different scenarios Firstly the system without physical constraint are tuned. Then the model is tuned using constraint one by one. System deviations are plotted for each area and compared.

E.S. Ali et. al. [15] developed a novel algorithm Bacteria Foraging Optimization Algorithm (BFOA) used in a non-reheat thermal interconnected power system for load flow studies to snuff out the oscillations. PI controller parameters are tuned using this algorithm and time domain simulations are performed, it results in superior performance over GA with a PI controller with the same system.

Reza Farhangi et. al. [16] proposed an approach based on emotional learning for the betterment of LFC problem of two areas interconnect power system considering GRC constraint. A new controller has neuro-fuzzy with power error. Its derivative used as input. The present situation evaluated by a fuzzy critic to calculate stress signal. To reduce critic stress, the controller makes changes in its characteristics. With the absence and presence; presentation of the controller is correlated with PI, Fuzzy logic (FL) and HNF controller to show its faster response.

Adil Usman et al. [17] have studied the simulation of LFC for the unit and two area systems and tried to manage frequency and voltage in the specific limit under load variations. Also states the importance of secondary loop which governors the dynamic responses. They found that the tie-line help in damping out the oscillations.

R. Arivoli et. al. [18] investigated two-area thermal systems with nonlinearity (GDB and GRC) are connected through TCPS, which is connected in series with tie-line. It is also considered Superconducting Magnetic Energy Storage (SMES) unit in each field. It is capable of controlling system variations simultaneously and quickly. Craziness Particle Swarm Optimization (CPSO) used to tune the PI compensator. It Concluded that multi-objective PSO controller provides better results than controller based on CPSOISE for 1% load disturbance in area one.

Rabindra Kumar Sahu et. al. [19] proposed a parallel 2-degree Freedom of PID compensator for LFC in interconnected system considering GRC physical constraint. Differential evolution algorithm optimized the controller parameters with ISE, ITSE, and ITAE performance Indices. Results prove its superiority over CPSO for same interconnect system.

K. Naidu et. al. [20] implemented the multi-objective optimization Artificial Bee Colony (ABC) optimization for LFC. It has capability for local and global search both. PID controller optimizes using weighted function approach.

Surya Prakash et. al. [21] proposed a hybrid neuro-fuzzy (HNF) in four-area interconnected systems for LFC. Area- 1 and -2 have thermal reheat control system whereas area - 3 and - 4 have a hydro power plant. Time domain simulations are performed using ANFIS, Fuzzy, ANN, conventional PI and PID compensators. Simulation result clears that intelligent HNF has better dynamic performance than others.

Seyed Abbas Taher et. al. [22] designed fractional order PID (FOPID) controller in three area system for LFC problem. Different generating units are considered. Controller's parameters are tuned with ICA algorithm and observed FOPID. It provides better dynamic performance than conventional PID.

A.Y. Abdelaziz et. al. [23] used three-area system with nonlinearity and analyzed a cuckoo search (CS) algorithm to tune the controller gains to maintain system stability in case of load fluctuations. The results are proving its superiority over GA, PSO and conventional integral compensator.

Initially, numerous conventional error criterions are studied. The PI compensator parameters are tuned by GSA technique for a two-area system. The performance index analyzes the system performance. Further tuning of the result obtained from GSA is done by Pattern Search (PS) technique. R. K. Sahu et. al. has made a maiden attempt to apply an hGSA-PS technique. Further results are compared with FA, BFOA, DE, hBFOA-PSO, PSO and GA algorithms have been done to prove its effectiveness [24].

U. K. Rout et. al. [25] investigated that PI controller based on the differential evolution algorithmic program used for AGC of the interconnected thermal power system provided better results when correlated with other optimization techniques such as GA and BFOA optimized PI controller. Pandey et. al. [26] has presented a captious literature survey on LFC problems.

PI and PID controller are tuned using NSGA-II i.e. Multi-objective Non-Dominated Shorting Genetic Algorithm-II technique. To find the best-conciliated result; a fuzzy-based membership value assignment method is exercised and further correlated with the results with some modern heuristic optimization approaches such as BFOA, GA and CPSO (Craziness based Particle Swarm Optimization) tuned controllers for the similarly interconnected power systems [27].

H. Shabani et. al. [28] has demonstrated that parameters of the compensator are tuned using an imperialist competitive algorithm (ICA), provides better performance when compared with GA and Neural Network Optimized PI controllers.

L. Hari et. al. [30] deals with the AGC to select a value of speed governor regulation parameter (R) considering physical constraint GRC. They found that it is not necessary to consider low value of R, High value also acceptable and it provides better dynamic performance. Sensitivity analysis is also performed to check the robustness of the system.

Nanda et. al. [30] have tested that controller parameters are tuned using BFOA provide better results than that of controllers based on GA and conventional methods for an interconnected power system.

In this research work, GSA, a recently developed heuristic optimization method is used. It is more competent regarding central processing unit time; gives correct and higher persistent results [31]. It is a global optimizing method used to explore the search space. It is giving better results nearer to optimum value solution. Initially, a comparison is made between different objective functions. To chose the suitable objective function for our problem. Then the superior objective function further employed to obtain the optimized value of controller gains. Many controllers are proposed in the literature, each of them has their significance. Different compensators used i.e. I, PI & PID and the system performance is analyzed. Optimization of these compensators done with GSA and results further compared with I, PI and PID compensators. Simulations are done in MATLAB SIMULINK to prove its effectiveness.

CHAPTER 3

LOAD FREQUENCY CONTROL

3.1 Introduction

Generation of electrical energy from naturally available renewable and the non-renewable source of energy terms as a power system. Automatic generation control work is to adjust the power output of the different generators in an interconnected system with the change in load. A sustainable balance between production and demand is the fundamental requirement of the power grid. The balance is judged by the variation in frequency if it goes high that means more power is to be generated to fulfill consumer demand and vice versa. AGC deals with both frequency and voltage control, but LFC only deals with frequency control i.e. active power [3]. It is a loop that maintains: frequency constant and regulates stable active power output in all circumstances.

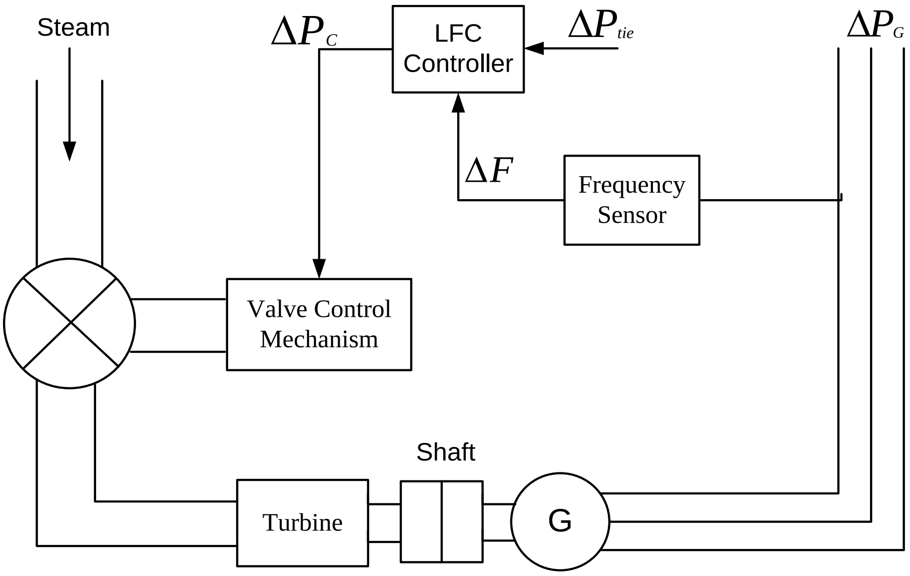


Figure 3.1 Schematic Diagram of LFC

It consists two loops; as we already know due to variation in demand, system frequency will change. Frequency is direct function of the speed of the rotor. Then the speed will also change. The governor senses a speed variation and it will open or close the valve to increase or decrease the generation respectively. This will result in an automatic change in mechanical output power to maintain balance. It is performed by the primary loop. This set to the frequency to a new value. Reference point must be adjusted to bring frequency to its nominal value. It does by load frequency control loop i.e. secondary regulation. It goes without saying that with load variations; frequency will also vary and in first few cycle's governance is done by governor response, and afterward, the LFC will take off.

Fig. 3.1 shows the schematic arrangement for LFC loop. Small changes in active power decided by rotor angle; results in frequency deviations also. Frequency sensor senses the change in frequency and then LFC controller regulates the governor valve reference point and according to that valve opened and closed to generate power. Therefore; the continuous power supply is maintained.

In today's scenario frequency regulation problem for the interconnected power system is more important than single area because power plants are interconnected and performance of one plant affects others so; sustainable power supply required.

Interconnection of the power systems is made feasible by tie-lines. Electric power flows between two regions through tie-line. It also introduces a power exchange error in an inter-connected system.

Figure 3.2 Two Areas Connected by Tie-Line

Whenever load demand increases in a zone; energy supplied by neighboring area through Tie-line to help fulfill demand in this field. These exchange energies are scheduled i.e. area_i can provide a particular amount of energy to area_j while accepting another specific amount of energy from N_{th} area. Therefore, this Tie-line exchange power also regulated by LFC loop [45].

The prime objectives of LFC are

1. To maintain frequency constant with load variation
2. Tie-line exchange power is also managed within its specified limit in each area.

The main objective of this study is to control both frequency and tie-line interchanged power within the specified range. When the load is increased then governor will change the steam input accordingly after that frequency set to a new value. To bring back to the frequency to its normal value and to maintain tie-line power within a permissible range; the controller is used [47].

3.2 Mathematical Modeling of Unit Area

The mathematical model of the unit area of an inter-connected thermal power system is presented in this section. This model is shown in fig. 3.3 consists of mentioned blocks [4].

1. Generator–load model which is responsible initially for fulfilling the increased load demand by its rotor inertia;
2. Turbine which reduces its speed when there is reduction in frequency;
3. Governor is used to increasing the speed by changing the steam input;
4. The controller is used to regulate the frequency.

All these blocks represented in the time-constant form shown in fig. 3.3. Each unit described as its transfer function. Each input block is responsible for their output.

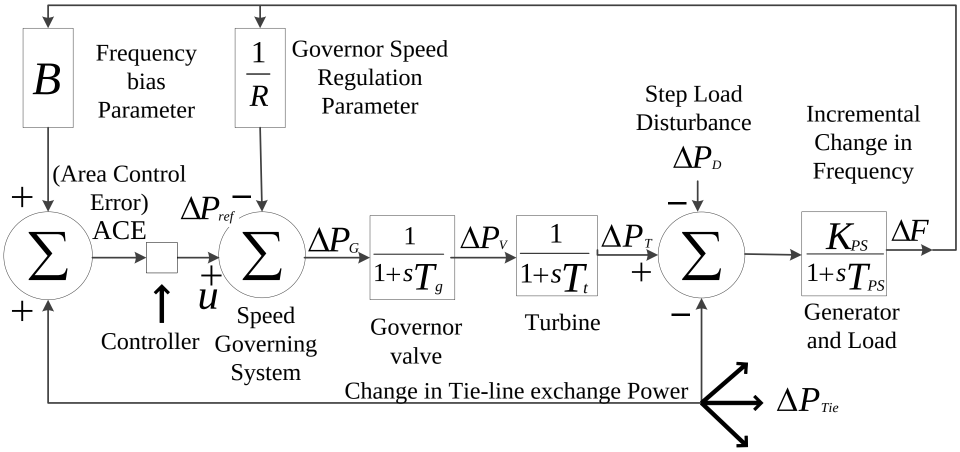


Figure 3.3 Block Diagram of Unit Area of Interconnected System

Now each block is explained in detailed below and also expanded to two area interconnected model.

3.2.1 Turbine

It is spinning mechanical accessory which takes energy from steam or water; converts it into mechanical power ΔP_m. This power further converted to electrical energy by a generator which is fed to the utilities. Turbine and generator are connected through shaft. Turbine drives the generator. Normally turbines are of non-reheat, reheat and hydraulic type. Non-reheat turbine is simplest among all. Initially in this work non-reheat turbine considered and later both reheat – and non-reheat – turbine are used.

The transfer functions of governor valve, Non-reheat and Reheat turbine and generator-load model are given below

$$\mathrm{G_T(s)} = \frac{\Delta \mathrm{P_T(s)}}{\Delta \mathrm{P_V(s)}} = \frac{1}{1 + \mathrm{sT_t}} \tag{3.1}$$

$$\mathrm{G_T} = \frac{\Delta \mathrm{P_T(s)}}{\Delta \mathrm{P_V(s)}} = \left(\frac{1 + \mathrm{sK_r T_r}}{1 + \mathrm{sT_r}}\right)\left(\frac{1}{1 + \mathrm{sT_t}}\right) \tag{3.2}$$

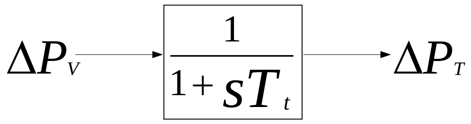


Figure 3.4 Non-reheat Turbine model

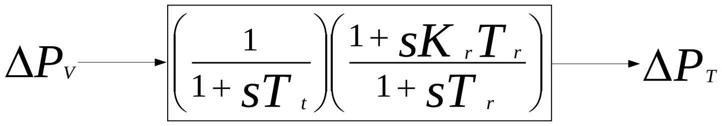


Figure 3.5 Reheat turbine model

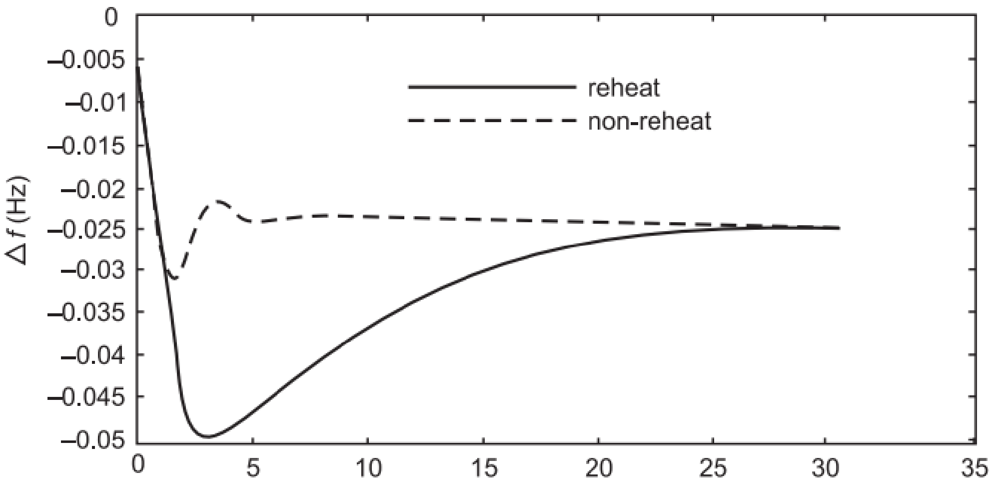


Figure 3.6 Dynamic Responses for Single Area Non-Reheat and Reheat Turbine.

Fig. 3.4 is the linear-transfer function model representation of the non-reheat turbine. In literature, non-reheat turbine model is mostly used. Fig. 3.5 shows the reheat turbine model. Both turbine models have governor valve as input and turbine output fed to the generator. In first Simulink model; we have considered only non-reheat turbine in both the areas and analyses the performance. In model two we have reheat turbine in area one and non-reheat turbine in area two.

Fig. 3.6 represents the dynamic responses for reheat and non-reheat turbine for unit step disturbance considering same steady state error. It clears a significant difference in their transient response.

3.2.2 Generator-Load Model

Mechanical power i.e. the output of the turbine is converted into electrical power by a generator which fed to the consumer. Load fluctuation creates unbalance between demand and generation. In mechanical to electric power transformation; energy conversion is not having much importance but preference given to rotor speed that is a factor of frequency. Power plants have an enormous amount of generation and it is not easy to store that large amount of power. This balance ensures the reliability of power systems. The load is uncertain in nature and the demand is varying every second of time which creates a problem in plants. If variations are small that will be supplied by rotor inertia, but significant changes in load create problems for us.

A large number of electrical appliances are used by consumers. A few of them are resistive and others are motor driven loads. These are the leading part of the burden. With advancement of power electronics converters which lead to the inductive nature. This requires more reactive power but in this work main focus on active power. Power increment($\Delta \mathrm{P_G}$) in generator output is depend on the variation in load ($\Delta \mathrm{P_D}$). To meet the power demand, generator always adjusts its output. Therefore,

$$\Delta \mathrm{P_G} = \Delta \mathrm{P_D} \tag{3.3}$$

Some assumptions made for interconnected areas of power systems

1. In normal operating condition in a system, there is a balance between generation and demand. The nominal value of frequency is $\mathrm{F_0}$.
2. With rising in load demand; there is increment in generator power output i.e. $\Delta \mathrm{P_G} = \Delta \mathrm{P_D}$.
3. From the dynamics we know kinetic energy (K.E.) is directly proportional to the square of speed thus K.E. for an area.

$$W_{kin} = W_{kin}^{0}\left(\frac{F}{F_0}\right)^2 \tag{3.4}$$

4. The change in motor load is the function of frequency because it is sensitive to change in speed.

For minor variation in system frequency ΔF, percentage change of the load with frequency can be treated as constant; that written as

$$\left(\frac{\partial P_D}{\partial F}\right)\Delta F = D.\Delta F \tag{3.5}$$

Where

$$D = \frac{\partial P_D}{\partial F} = \text{constant} \tag{3.6}$$

Thus, balance equation of power

$$\Delta P_T = \Delta P_D + \frac{d}{dt}(W_{kin}) + D.\Delta F \tag{3.7}$$

Let F=$F_0 + \Delta F$

$$W_{kin} = W_{kin}^{0}\left(\frac{F_0 + \Delta F}{F_0}\right)^2$$

$$= W_{kin}^{0}\left[1 + \frac{2\Delta F}{F_0} + \left(\frac{\Delta F}{F_0}\right)^2 + \cdots\right]$$

$$\approx W_{kin}^{0}\left[1 + \frac{2\Delta F}{F_0}\right] \tag{3.8}$$

Now from K.E. equation

By substituting this equation into power balance equation

$$\Delta P_T = \Delta P_D + \frac{W_{kin}^{0}}{F_0}\frac{d}{dt}(\Delta F) + D.\Delta F \tag{3.9}$$

At scheduled frequency the K.E. is

$$W_{kin}^{0} = H \times P_r \tag{3.10}$$

Where H is inertia constant which is independent of system size.

From power balance equation:

$$\Delta P_T = \Delta P_D + 2HP_r \frac{d}{dt}\left(\frac{\Delta F}{F_0}\right) + D.\Delta F \tag{3.11}$$

$$\frac{\Delta P_T}{P_r} = \frac{\Delta P_D}{P_r} + 2H\frac{d}{dt}\left(\frac{\Delta F}{F_0}\right) + \frac{D.\Delta F}{P_r} \tag{3.12}$$

$$\Delta P_T(p.u.) = \Delta P_D(p.u.) + 2H\frac{d}{dt}\left(\frac{\Delta F}{F_0}\right) + D(p.u.).\Delta F \tag{3.13}$$

Taking Laplace transform

$$\Delta P_T(s) = \Delta P_D(s) + \frac{2H}{F_0}s\Delta F(s) + B.\Delta F(s) \tag{3.14}$$

$$\Rightarrow \Delta F(s) = \frac{\Delta P_T(s) - \Delta P_D(s)}{D + \frac{2H}{F_0}s}$$

$$= G_P(s)[\Delta P_T(s) - \Delta P_D(s)] \tag{3.15}$$

Where

$$G_P(s) = \frac{K_{PS}}{1 + sT_{PS}} \tag{3.16}$$

$$T_P = \frac{2H}{F_0 D} \tag{3.17}$$

$$K_P = \frac{1}{D} \tag{3.18}$$

Fig. 3.7 presents a linear transfer model of generator load model and summation point is to create disturbance in the system. Modeling already discussed with the help of mathematical equations.

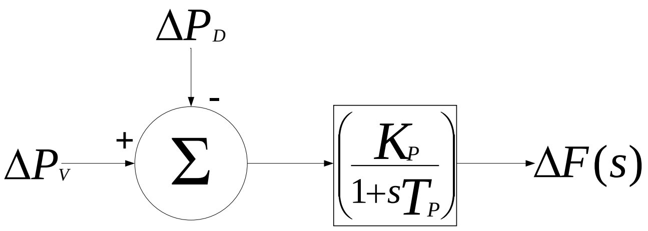


Figure 3.7 Block Diagram Representation of Generator-Load Model

3.2.3 Governor

It is also termed as speed limiter. It senses the change in turbine speed and brings back the speed to its nominal value by changing the steam input. Speed is a direct function of frequency so we have to regulate the frequency. It is also helpful in turbine protection under operating conditions which cause damages. The load is always varying in nature and depends on the consumer demand. This variability in load creates a mismatch between generation and demand [33].

Governor work is to provide significant arrangement i.e. open or close the steam valve on load demand. Normally preferred governor is isochronous governor. The isochronous mean constant speed and its work are to get back the frequency value to its normal value. It performs very well with an isolated load, only single generator in the multi-generator system is wished to supply that burden.

$$\Delta \mathrm{P_g} = \Delta \mathrm{P_{ref}} - \frac{1}{\mathrm{R}} \Delta \mathrm{F} \tag{3.19}$$

$$\frac{\Delta \mathrm{P_V}}{\Delta \mathrm{P_g}} = \frac{1}{1 + s\mathrm{T_g}} \tag{3.20}$$

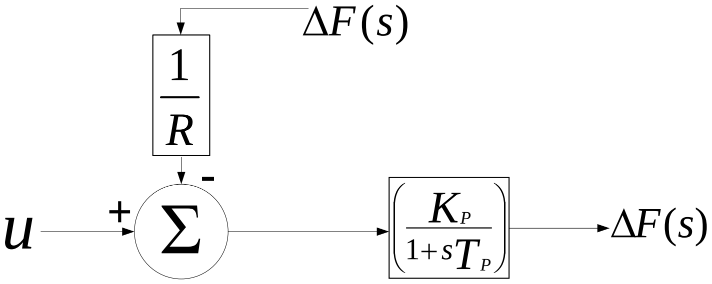


Figure 3.8 Block Diagram Representation of Governor

Fig. 3.8 represents the linear transfer function model of the governor. Input u is the load reference point which is important factor in regulation of the load frequency relationship. The load reference point accomplishes by using speed change motor. For an example of speed-load characteristics have 4% droop; it means 4% droop i.e. 2 Hz cause 100% change in power output.

3.2.4 Two Area Interconnected Power System

Tie-lines made it possible to interconnect different generating power station [34]. They also help inflow of power between areas. So the control of tie-line power between different areas must be monitored by LFC. This exchange power is the integral of the difference of frequency in connected areas.

This Tie-line exchange power expressed as

$$P_{12}^0 = \frac{|V_1^0||V_2^0|}{X}\sin(\delta_1^0 - \delta_2^0) \tag{3.21}$$

Here δ_1^0, δ_2^0 are power angle of area-1 and -2 respectively.

With minor variations in demand the power becomes

$$\Delta P_{12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) \tag{3.22}$$

Where T_{12} is synchronizing coefficient i.e.

$$T_{12} = \frac{|V_1^0||V_2^0|}{X}\cos(\delta_1^0 - \delta_2^0) \tag{3.23}$$

ΔF is related to reference angle by

$$\Delta F = \frac{1}{2\pi}\frac{d}{dt}(\delta^0 + \Delta\delta) \tag{3.24}$$

$$= \frac{1}{2\pi}\frac{d}{dt}(\Delta\delta) \tag{3.25}$$

Since

$$\Delta\delta = 2\pi \int \Delta F dt \tag{3.26}$$

Therefore

$$\Delta P_{12} = 2\pi T_{12}\left(\int \Delta F_1 dt - \int \Delta F_2 dt\right) \tag{3.27}$$

Taking Laplace transform, we get

$$\Delta P_{12}(s) = \frac{2\pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) \tag{3.28}$$

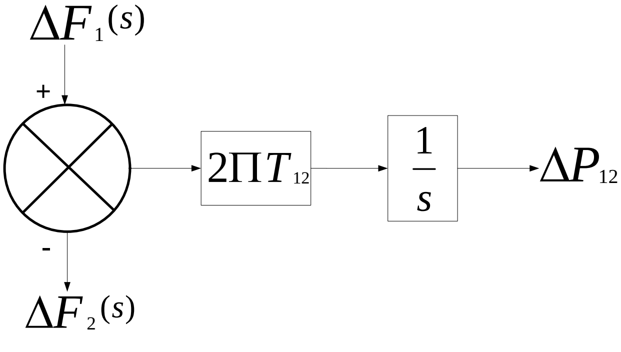


Figure 3.9 Linear Representation of Tie-line

Fig. 3.9 shows the linear transfer function for tie-line in the inter-connected power system.

Alike T_{21} also be write concerning T_{12}

$$\mathrm{T}_{21} = \mathrm{a}_{12}\mathrm{T}_{12} \tag{3.29}$$

So, for area-2

$$\Delta \mathrm{P}_{21}(\mathrm{s}) = \frac{-2\pi \mathrm{a}_{12}\mathrm{T}_{12}}{\mathrm{s}}\left(\Delta \mathrm{F}_1(\mathrm{s}) - \Delta \mathrm{F}_2(\mathrm{s})\right) \tag{3.30}$$

Now we can easily draw the two-area interconnected power system model as shown in fig. 3.10.

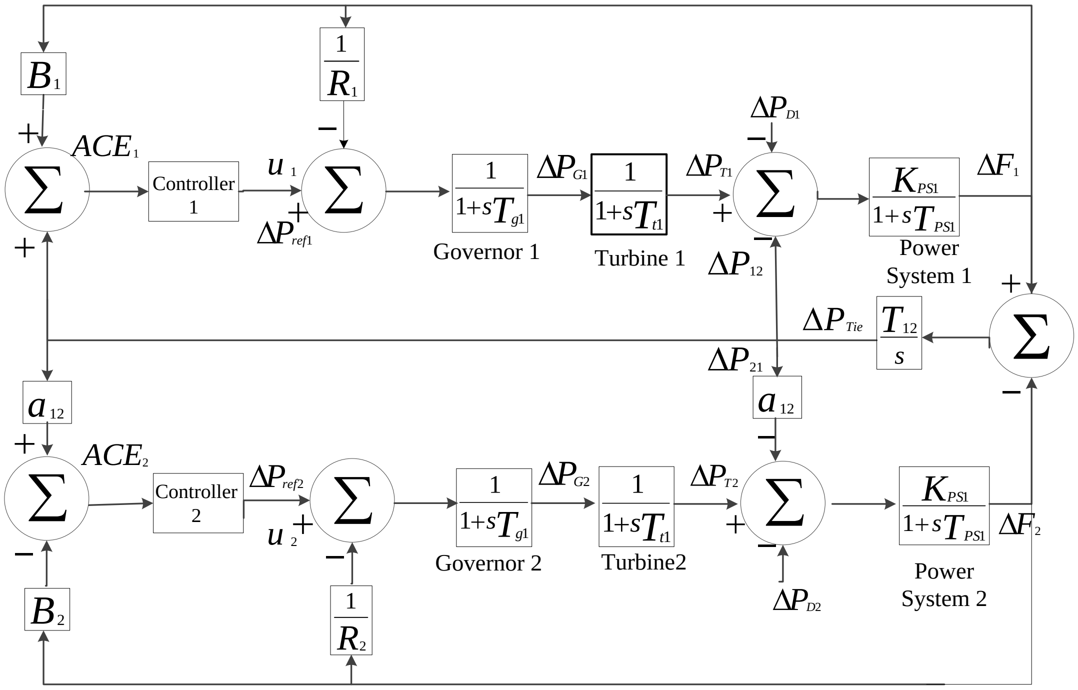


Figure 3.10 Block Diagram of Two-Area Interconnected System

3.2.5 Area Control Error

From fig. 3.10 the block diagram of power system model; ACE have an essential role in the elimination of system deviations. In each area, ACE consists of a linear connection of frequency – and tie-line power – change. It also stands for the inequality between domain generation and demand. LFC objective is to eliminate the error in frequency in each area likewise to maintain tie-line power error to specified values [34]. That is not so easy because the load is changing every second of time. If we success to bring back to frequency error to zero. Then it will results in tie-line power error also to zero because it is the integral of the frequency deviations between adjacent control areas. Thus, it is helpful to consider tie-line power variation in control input. Now ACE can be written as

$$\mathrm{ACE_i} = \sum_{j=1}^{n} \Delta \mathrm{P_{tie,ij}} + \mathrm{B_i} \Delta \mathrm{F_i} \tag{3.31}$$

Here,

$\mathrm{ACE_i}$ is control error of the i^th^ area.

$\Delta \mathrm{f_i}$ is frequency error of the $\mathrm{i^{th}}$ area.

$\Delta \mathrm{P_{tie,ij}}$ is tie-line power flows between the $\mathrm{i^{th}}$ and $\mathrm{j^{th}}$ areas.

$\mathrm{B_i}$ is frequency bias coefficient of the $\mathrm{i^{th}}$ area.

3.2.7 Generation Rate Constraint

Generator'always alters its output to fulfil load demand. Generally in a system, power production is kept underneath maximal limits. In our case, we have to regulate the steam governing valve and the power plant generation rate can be supervised. GRC typical value is normally 3% per minutes [35].

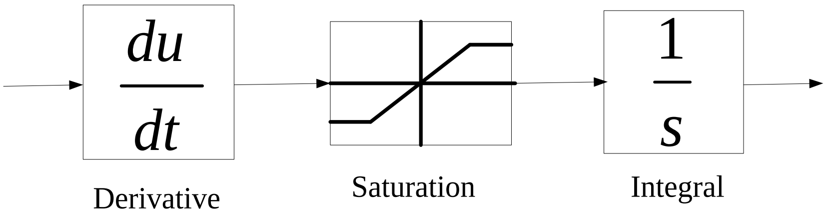


Figure 3.11 GRC Block Diagram

CHAPTER 4

PROBLEM FORMULATION

4.1 Load Frequency Problem

Due to uncertain nature of load; it is fluctuating every second of time. It has got the serious effect on frequency. In India, rated frequency is 50 Hertz and shall regularly be supervised within the limits as per Indian Electricity Rules, 1956 as altered time to time. ±1% variation in frequency is not having any serious effect on the system. If it goes beyond that, there are so many severe effects on power systems.

4.2 Tie-Line Power Problem

Consider interconnected power system. There is load change in both the area that taken care of by the respective area generating units in addition to power also flows from tie-line to help to supply that load demand. Tie-line power flow either keeps within the limits or reduces it to zero value to sustain the system stability.

4.3 How Estimation Problem Becomes Optimization Problem

Estimation problem is nothing but an approximation of the values of the unknown parameters; by a set of measured data. Apart from that optimization problem; it is totally depending on the technique of going over finest solution among the reasonable solution on a distinct goal. This is the achieved through the course of several steps; solution termed as the optimal solution. In this research work, an algorithm is used to calculate optimal assessment of controller parameters and they maintain the system stability. Also minimize the objective function value. The objective function constitutes the errors which are due to load fluctuations.

4.4 Proposed Controller

Modern Power system utilization engages with several types of controllers such as Integral (I), proportional (P), derivative (D) and the combination of these compensators i.e. PI, PD, and PID. Control objective of these compensators is to minimize the initial response i.e. transient response which consists peak overshoot and damping as well as final response i.e. steady-state error includes settling time and tolerance band.

The Integral controller does not exhibit steady-state error but is relatively slow responding. PI controller Remove offset and provide much faster response than integral controller widely used in industries like controlling variables like level, flow and pressure [40]. It utilized who have a lesser time-constant system. PID finds universal applications, but proper tuning is difficult. PID controller preferred due to its structural integrity, accuracy and the performance and cost are in equal ratio.

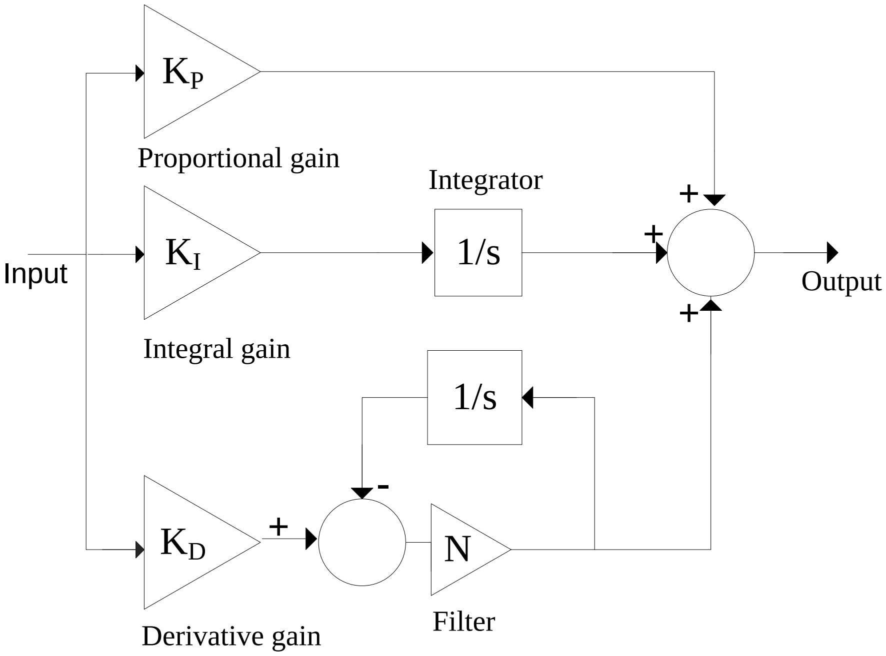


Figure 4.1 Structure of PID Controller With Derivative Filter

Apart from these assets, these controllers also offer minor user-expertise concerns, uncomplicated dynamic modeling and minimal improvement effort; which are most common problems to engineering practice. PID controllers used where the fast response recommended and it also improves the system stability [41]. There is also an increment in the proportional - and decrement in integral - gain with a derivative mode which also enhances the speed of response.

Fig. 4.1 shows the block diagram of PID controller with a filter. If we are using PI controller, the filter is removed. Inputs to the compensators i.e. the error, are the respective ACE is given by

$$e_1(t) = ACE_1 = B_1\Delta F_1 + \Delta P_{Tie} \tag{4.1}$$

$$e_2(t) = ACE_2 = B_2\Delta F_2 - \Delta P_{Tie} \tag{4.2}$$

The controllers output u_1 and u_2 are acts as the control inputs. Controller transfer function represented as

$$\mathrm{TF_{PID}} = \left[\mathrm{K_P} + \mathrm{K_I}\left(\frac{1}{\mathrm{s}}\right) + \mathrm{K_D}\left(\frac{\mathrm{Ns}}{\mathrm{s+N}}\right)\right] \tag{4.3}$$

Here N represents a filter coefficient.

4.5 Objective Function

To determine the optimum values of controller parameters the objective functions considered given below:

$$\mathrm{J_1} = \mathrm{IAE} = \int_0^{\mathrm{t_{sim}}} (|\Delta \mathrm{F_1}| + |\Delta \mathrm{F_2}| + |\Delta \mathrm{P_{Tie}}|)\, \mathrm{dt} \tag{4.4}$$

$$\mathrm{J_2} = \mathrm{ITAE} = \int_0^{\mathrm{t_{sim}}} (|\Delta \mathrm{F_1}| + |\Delta \mathrm{F_2}| + |\Delta \mathrm{P_{Tie}}|)\, \mathrm{tdt} \tag{4.5}$$

$$\mathrm{J_3} = \mathrm{ISE} = \int_0^{\mathrm{t_{sim}}} (|\Delta \mathrm{F_1}| + |\Delta \mathrm{F_2}| + |\Delta \mathrm{P_{Tie}}|)^2\, \mathrm{dt} \tag{4.6}$$

$$\mathrm{J_4} = \mathrm{ITSE} = \int_0^{\mathrm{t_{sim}}} (|\Delta \mathrm{F_1}| + |\Delta \mathrm{F_2}| + |\Delta \mathrm{P_{Tie}}|)^2\, \mathrm{tdt} \tag{4.7}$$

The problematic constraints are the parameters of LFC regulator which contains P, I and D are optimized and bound with their limits. Hence, the design problem can be formulated as Minimize J

$$\mathrm{K_{Pmin}} \le \mathrm{K_P} \le \mathrm{K_{Pmax}} \tag{4.8}$$

$$\mathrm{K_{Imin}} \le \mathrm{K_I} \le \mathrm{K_{Imax}} \tag{4.9}$$

$$\mathrm{K_{Dmin}} \le \mathrm{K_D} \le \mathrm{K_{Dmax}} \tag{4.10}$$

Where $\mathrm{K_P}$, $\mathrm{K_I}$ and $\mathrm{K_D}$ are the proportional, integral and derivative compensator gains, have limits between -2 to 2 [10,12,19,20,21,37,38,42].

4.6 System under Study

A two-area non-reheat thermal interconnected power system is considered as shown in fig. 4.2. Each area has a rating of 2000 MW with a nominal load of 1000 MW. The system extensively used in literature. So for LFC problem; we designed this model and further analyses the results.

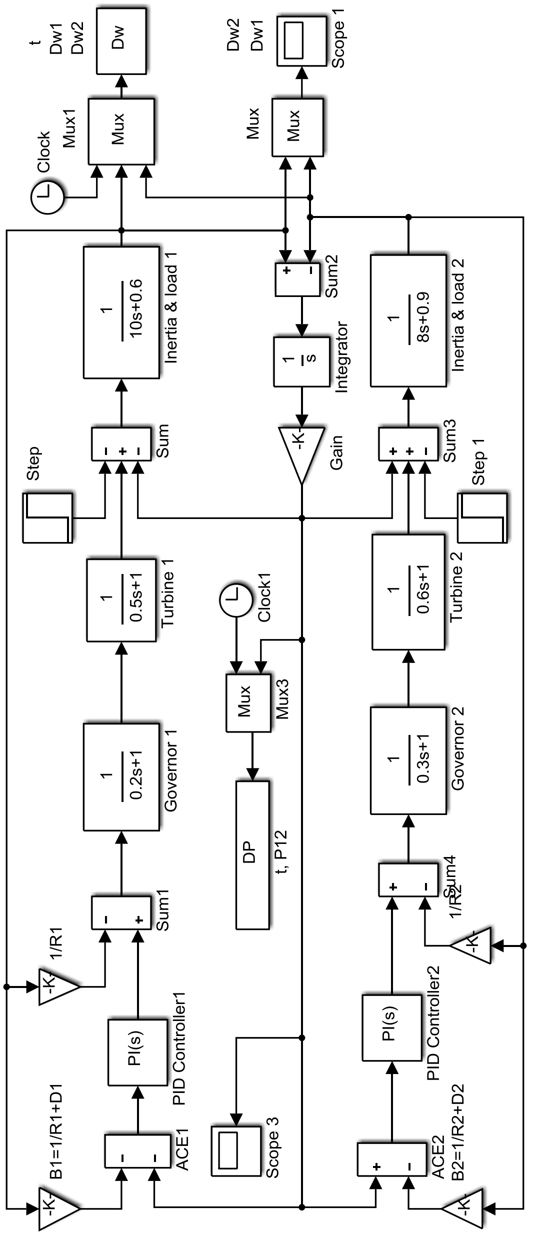


Figure 4.2 MATLAB SIMULINK Model of Two-Area Non-Reheat Thermal System

Now we considered physical constraint and redesign the model for two-area interconnected power system as shown in fig. 4.3. In which both area have two generation units which are participating equally in a generation. Area - one and - two has reheat – and non-reheat – turbine respectively. They have GRC value as 3% and 10% per minute respectively. Mostly; power generation kept under a utmost limit. The production rate of the power plant can be regulated by monitoring the steam valve of the governor [44].

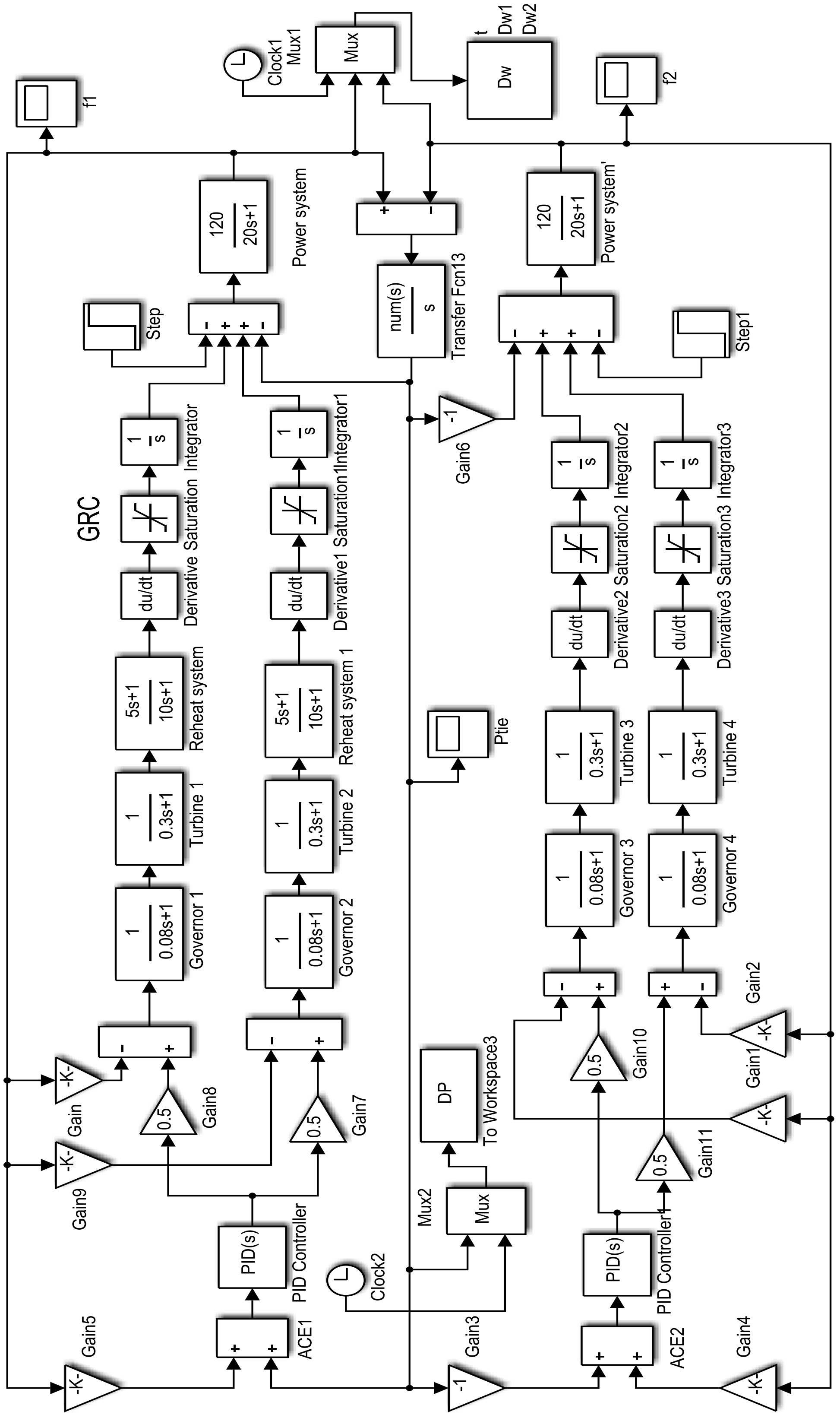


Figure 4.3 MATLAB SIMULINK Model of Two Area Thermal System

CHAPTER 5

PROPOSED METHODOLOGY

5.1 Gravitational Search Algorithm

It is one of the recent heuristic algorithms influenced by gravity – and motion – law proposed by Newton. “Heuristic” is a Greek word which means to “to find,” “to discover” or “to disclosed” [31]. These are the techniques which pursue an optimal solution at a likely computational cost but does not guarantees. Literature states that either we get optimal, or close the optimal solution. Agents act as objects, and their respective masses do their performance measurement.

The gravitational force states that there is a force of attraction between these objects. In search space there is a movement of all objects towards the objects with a heavier mass is the result of this effect. Hence, masses communicate with each other by using this attraction force i.e. direct in nature. The heavier masses attract more the mass that is light weight. So from this, it can be suggested that the heavier mass will provide the best solution. Exploration and exploitation are the backbones of any algorithm. Initially global search space i.e. exploration take place. As the time bypass there is a short search space and it comes to the exploitations. At the end, one mass is there that is proving us an optimizing solution. Each agent has four parameters i.e. position, inertial mass, active – and passive – gravitational mass of an agent.

The position of agent gives us a solution. The inertial mass is the property to resist change in position. The active gravitational mass(M_a) is defined as gravitational field strength in the presence of an object. The passive gravitational mass (M_P) of agent is termed as object strength in the presence of a gravitational field. Lesser gravitational field offered by an agent with small active gravitational mass than that of an agent with high gravitational mass. A Light force is experienced by an object with smaller passive gravitational mass than an object with a large passive gravitational mass but within the same gravitational field. When a force is experienced by an agent; it’s resistance to change its state of motion is a measure of inertial mass (M_i).

An object has slow change in motion with large – compared to low – inertial mass. Inertia masses, Active, and Passive gravitational mass is evaluated by a fitness function. The solution is represented by proper adjustment of masses and is helpful in the navigation of algorithm. Without delay, it is expected that heavier masses will be attracting other masses. This heavier mass presents an optimum solution.

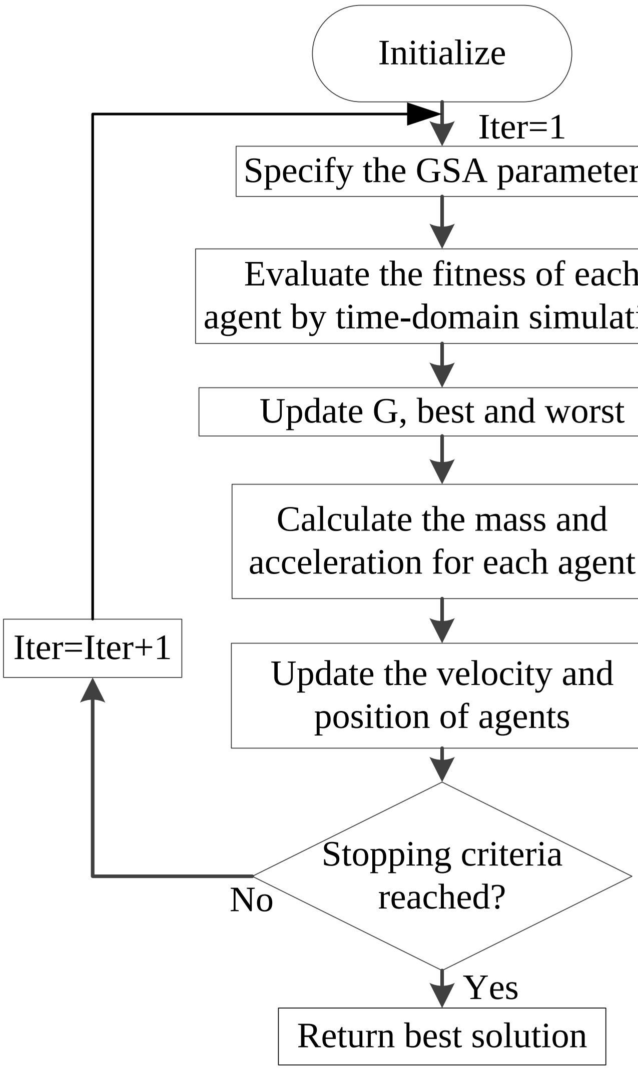


Figure 5.1 Flow Chart of Gravitational Search Algorithm Optimization Approach

Law of Gravity: In this universe each particle attracts every other particle. The two particles experiences a force between them that is directly proportional to the product of their masses and inversely proportional to the distance between them R.

Law of Motion: It states that the summation of the fraction of its earlier speed and the deviation in the speed gives the present velocity of any mass. Acceleration or distinction in the velocity of any mass is equal to the force acted on the system divided by the weight of inertia.

Let n agents (masses) in a system and the i^{th} position of an agent is distinct as

$$X_i = \left(X_i^1 \ldots\ldots\ldots\ldots\ldots . X_i^d \ldots\ldots\ldots\ldots\ldots\ldots\ldots X_i^n\right) \text{ for"} i = 1,2 \ldots\ldots\ldots . . n \tag{5.1}$$

Where X_i^n is the position of ith agent in the n dimension.

At time t, mass j applies a force to mass i written below as

$$F_{ij}^d(t) = G(t)\frac{M_{Pi}(t) * M_{aj}(t)}{R_{ij} + \in}\left(X_j^d(t) - X_i^d(t)\right) \tag{5.2}$$

Where

M_{aj} is the active gravitational mass of agent j.

$M_{Pi}(t)$ is passive gravitational mass of agent i.

$G(t)$ is gravitational constant at time t.

$\in$ is small constant.

R_{ij} is the Euclidian distance between agents i and j can be represented as

$$R_{ij}(t) = \left\|X_i(t), X_j(t)\right\|_2 \tag{5.3}$$

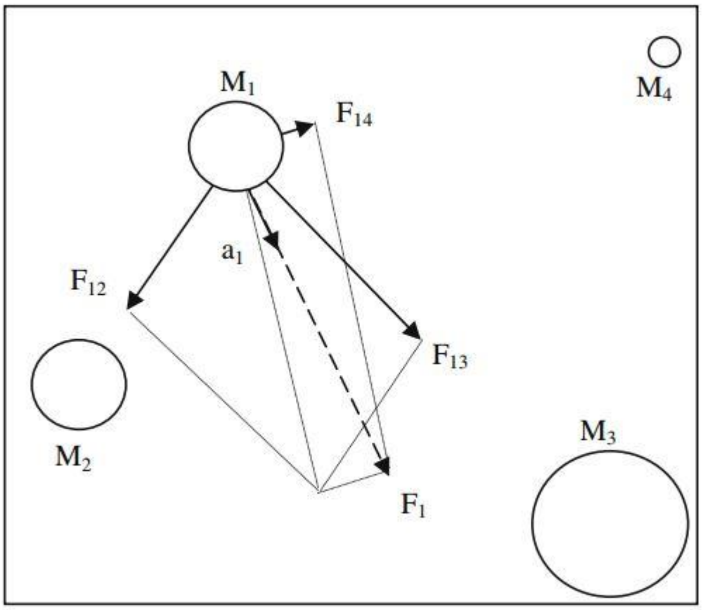


Figure 5.2 Every Mass Accelerate toward the Resulting Force that Acts it from the Other Masses

As we know GSA is stochastic in nature, so estimate its integrity; an agent i in a dimension d experiences total force is an arbitrarily biased sum of the forced exercise from another agent in d dimension as

$$F_i^d(t) = \sum_{j=1, j\neq i}^{n} \text{rand}_j F_{ij}^d(t) \tag{5.4}$$

Here rand_j varies from 0 to 1.

By the law of motion; at time t, acceleration is given by

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{5.5}$$

Where $M_{ii}(t)$ is the inertial mass of i^{th} agent.

Current speed and acceleration are responsible for the next position of the agent; thus, the speed and position can be updated as

$$v_i^d(t+1) = \text{rand}_j * v_i^d(t) + a_i^d(t) \tag{5.6}$$

$$X_i^d(t+1) = X_i^d(t) + v_i^d(t+1) \tag{5.7}$$

Here the arbitrary number is used to give heuristic characteristics to the search progression. At start, we initialize the gravitational constant initial value i.e. G_0. With time it decreases and is given by

$$G(t) = G_0 e^{\frac{-\alpha t}{T}} \tag{5.8}$$

Where α is a constant and T is no of iteration.

The inertial mass and active – or passive – gravitational masses are calculated using fitness function. Agents with heavier masses are efficient in this optimization. At the start we consider inertial and gravitational mass equal and their values are computed with the map of fitness. These masses are reorganized as

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1,2 \dots\dots\dots\dots n \tag{5.9}$$

$$m_i(t) = \frac{\text{fit}_i(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)} \tag{5.10}$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{n} m_j(t)} \tag{5.11}$$

Where $\text{fit}_i(t)$ is the agent fitness value at time t.

For minimization problem $\text{best}(t)$ can be defined as

$$\mathrm{Best}(t) = \min \mathrm{fit}_j(t), \quad j \in (1,2,\ldots\ldots\ldots n) \tag{5.12}$$

$$\mathrm{Worst}(t) = \max \mathrm{fit}_j(t), \quad j \in (1,2,\ldots\ldots\ldots n) \tag{5.13}$$

Equation 5.4 shows the reduction of the no of agents as the time elapse. A force is applied by the agents with heavier mass to others. The performance will improve if a balance is maintained between exploration and exploitation. Exploration is associated with global search and exploitation is linked with local search. In case of the first one; our objective is exploring the search space and find a good solution but in the case of second; the aim is to refine the solution to get a better result and also eliminate the big jump in search space.

In GSA explore the search space at start. With the lapse of iteration, this must be faded and exploitation will come in action. At the beginning force is applied by all agents on others but as time passes, as agents decrease linearly. In the end only one agent is there who applying force to other indicated as Kbest.

So equation 5.4 can be customized as

$$F_i^d(t) = \sum_{j=\mathrm{kbest}, j\neq i} \mathrm{rand}_j F_{ij}^d(t) \tag{5.14}$$

Here Kbest has biggest mass k and a set of first k agents with best fitness values.

GSA represents a straightforward approach. It is easier to apply and to compete effectively. Flexible and balanced mechanism nature is helpful to boost the exploration and exploitation effectiveness. By assuming a higher inertia mass, precise search is achieved. It also results in the search space, a slower motion of agents. By considering a greater gravitational mass, faster convergence is obtained which motivates a huge attraction of objects. It is a memory-less algorithm but also works powerfully and gives better result. Literature reviews that GSA has a higher convergence and provides global optimum solution, faster than other algorithms [31].

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 Applications of GSA

Initially, physical constraints such as reheat turbine, GRC and area participation factor are neglected [25, 30]. Two-Area Non-Reheat Thermal System model is prepared in MATLAB SIMULINK as shown in fig. 3.4. GSA program is done. Firstly, there is four type standard error criteria are considered and a comparison between them by tuning PI controller parameters for each area. A 10% step change in area one is made and algorithm is run. LFC Model is simulated for each new controller value. For every run the objective function is calculated in the .m file.

GSA parameters are specified i.e. population size NP = 20; maximum iteration T = 100; gravitational constant G_0 = 100 and α = 20 used at first instant. These simulations are conducted on Core i3 of 1.9 GHz and 4 GB RAM computer in the MATLAB R2015b environment. Theses simulations are repeated 50 times and the finest one among these runs is selected as the final solution.

Table 6.1 Optimized Controller Parameters and Performance Analysis for Each Objective Function

Objective function	**Controller parameters**		**Settling Time (s)**			**Peak overshoot**			ξ
	Proportional gain (K_P)	**Integral gain (K_I)**	F_1	F_2	P_{Tie}	F_1	F_2	P_{Tie}	
J1: ISE	0.4969 0.3865	0.4376 0.1747	17.14	23.07	23.85	0.0057	0.0011	0.0152	0.1173
J2: IAE	0.4978 0.0940	0.4611 0.3233	17.19	24.41	23.38	0.0057	0.0011	0.0119	0.1124
J3: ITSE	0.3340 0.4952	0.4932 0.3440	15.21	25.60	21.71	0.006	0.0012	0.0131	0.1234
J4: ITAE	0.3609 0.3865	0.4935 0.1747	**15.04**	**21.31**	**21.20**	**0.006**	**0.0012**	**0.0125**	**0.1266**

The solutions obtained for each objective function are shown in Table 6.1. The Bold values are showing the best results. To look into the effect of the different compensator on systems responses; settling time (t_s), damping ratio (ξ) and peak overshoot are calculated for each objective function.

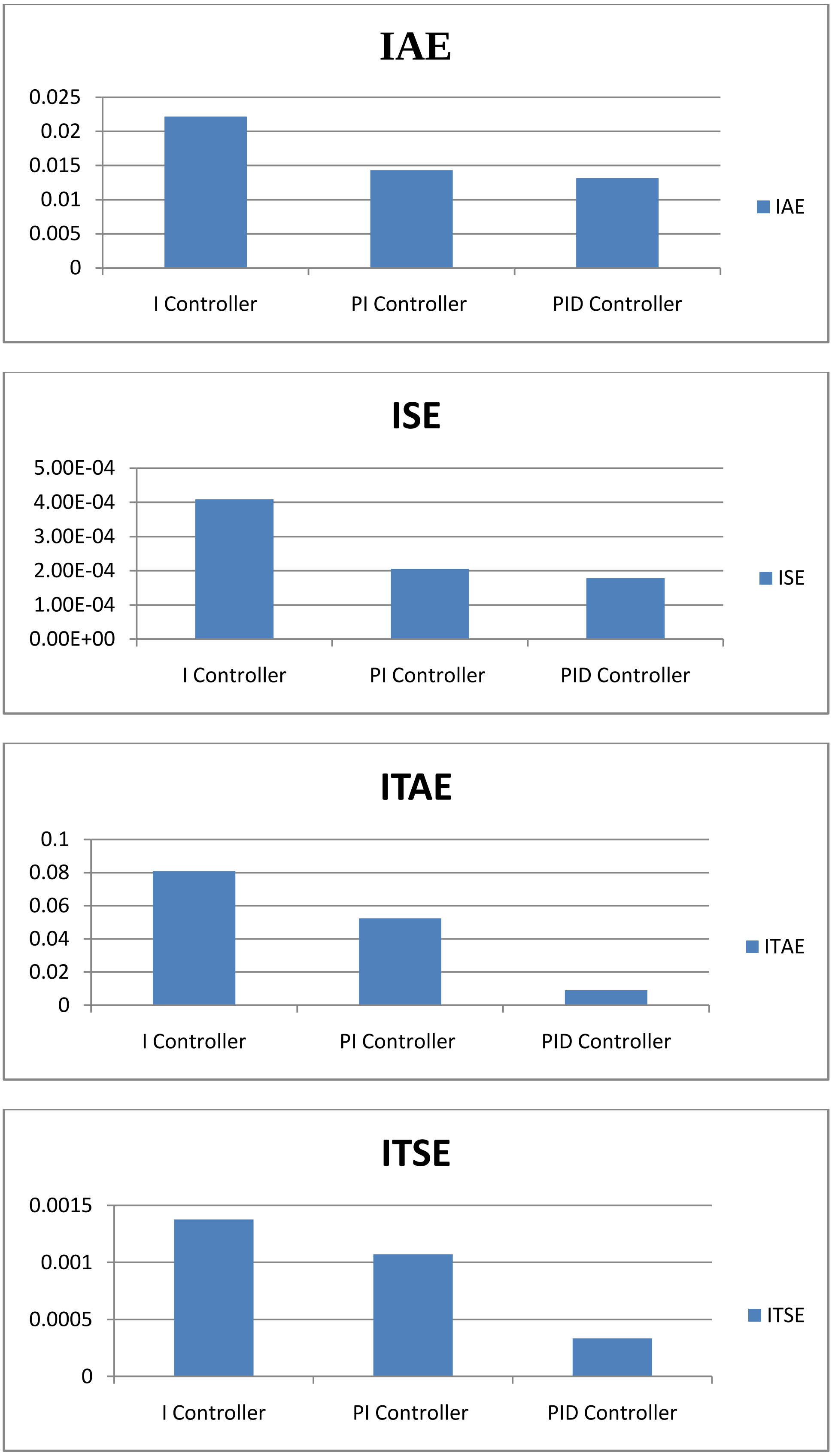


Figure 6.1 Comparison of Different Fitness Function for Each Controller

A comparison is made to prove the superiority of the objective function for this problem. t_s is the time required for the response to reach steady within precise range of 2 % to 5 % of its final value. Peak overshoots in frequency are unwanted spikes. Lower the spikes, stable the system is. Most of the systems are underdamped. It is desirable to have damping factor near to one.

Table 6.1 clears that ITAE objective function provides the best system performance regarding minimum t_s, minimum peak overshoot and maximum ξ; which are desired characteristics.

To further analyze this objective function for its robustness each performance indices value is evaluated for each controller for the problem and carefully observing the alteration in the fitness value as we change the controller. The second comparison is shown in fig. 6.1 also proving the dominance of ITAE objective function. From the graph it is clear that there is higher decrement in the value of ITAE as compared to others controller I, PI and PID respectively. It is concluded that ITAE is the best among them and used further for work.

6.2 GSA Parameters Tuning

Proper selection of control parameter is a key to the success of an algorithm. As GSA is applied for the optimization problem, control parameters should be chosen carefully for the successful accomplishment of the algorithm. Thus; a successful practice of algorithm is decided by these parameters.

For proper tuning of GSA parameters, a series of experiments were conducted to tune the PI compensator gain parameters considering ITAE performance indices. GSA outcomes is shown in table 6.2. 50 independent runs were executed to quantify the results, for each parameter variation. Table 6.2 clears that constant α, gravitational constant (G_0), population size (NP) and number of iterations (T) values for the best settings are $\alpha = 20$, $G_0 = 100$, NP = 20, and T = 100, respectively.

Now tuning the controller parameters for different cases (i.e. load disturbances in the interconnected areas) are validate the controller for all undesirable conditions. Good tuning of parameters results in better performance. Therefore, advised to tune GSA parameters very carefully.

Table 6.2 Tuning of GSA Parameters

Parameter	Mean	Max.	St. Dev.	Other Parameters
α=10	0.0262	0.0439	0.0126	NP=20, T=50, G_0=100
α=15	0.0260	0.0418	0.0116	
α=20	**0.0258**	**0.0438**	**0.0126**	
α=25	0.0259	0.0444	0.0134	
α=30	0.0245	0.0428	0.0123	
G_0=30	0.0263	0.0489	0.0129	α=20, NP=20, T=50
G_0=70	0.0252	0.0452	0.0127	
G_0=100	**0.0258**	**0.0439**	**0.0126**	
G_0=130	0.0263	0.0453	0.0135	
G_0=150	0.0274	0.0482	0.0121	
NP=10	0.0272	0.0460	0.0137	α =20, T=50, G_0=100
NP=15	0.0254	0.0443	0.0131	
NP=20	**0.0258**	**0.0438**	**0.0126**	
NP=25	0.0244	0.0472	0.0121	
NP=30	0.0247	0.0453	0.0118	
T=30	0.0242	0.0441	0.0121	α=20, NP=20, G_0=100
T=50	0.0251	0.0439	0.0125	
T=100	**0.0258**	**0.0437**	**0.0125**	
T=200	0.0267	0.0443	0.0128	

6.3 Analysis of Result Without Physical Constraint

Two-area non-reheat thermal system is considered in both the areas. The parameters of I, PI and PID compensators are optimized with ITAE objective functions by employing GSA. The system responses obtained though optimized controllers which are used to observe the system performance.

6.3.1 Case 1: Change in Area-1 only

Fig. 6.2 shows the frequency variation in area 1, area 2 and tie-line power deviations. A 10% load disturbance is applied in area-1 and time domain simulations are plotted [48].

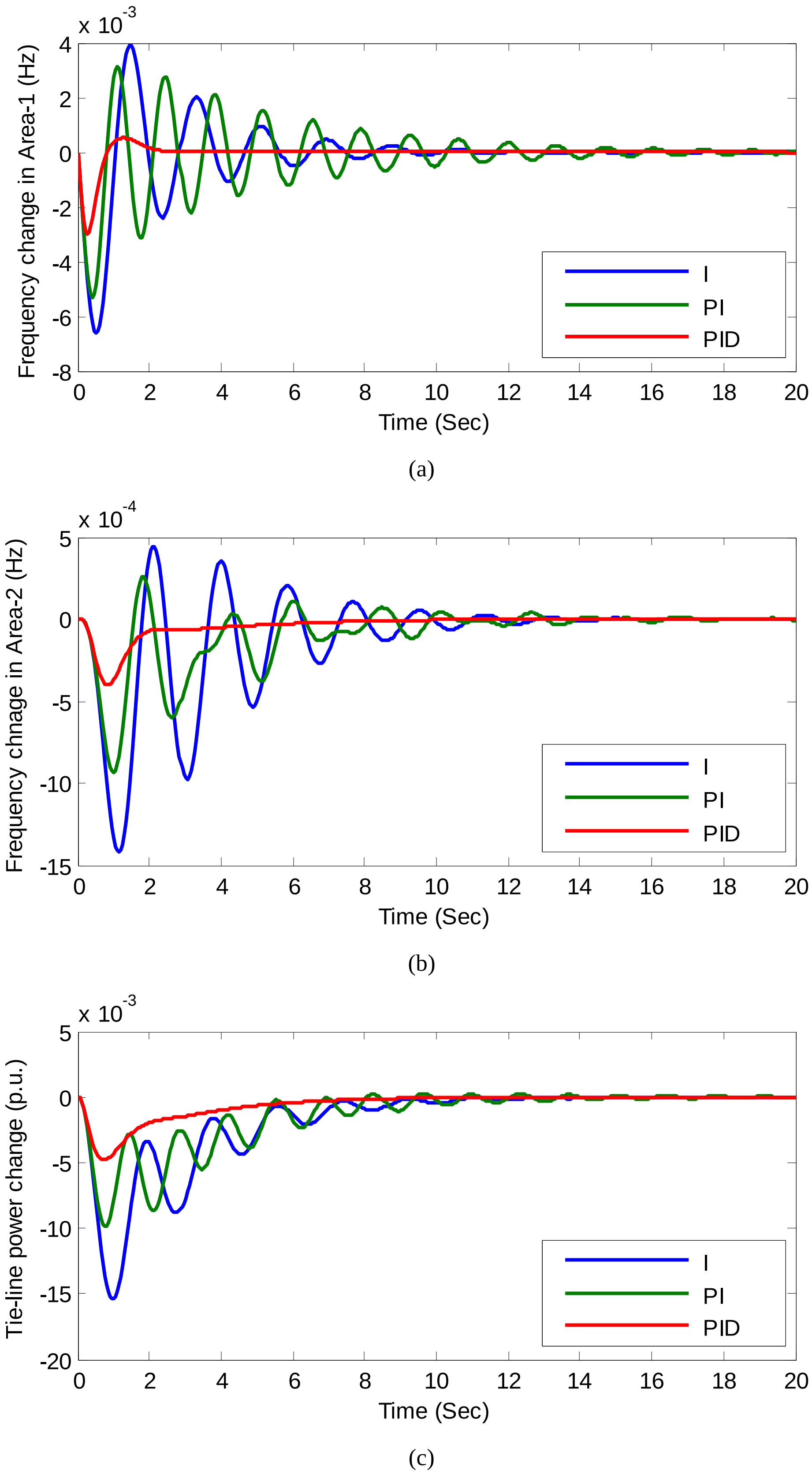


Figure 6.2 Transient Responses for 10% Load Disturbance in Area-1

(a) Frequency Change in Area-1

(b) Frequency Change in Area-2

(c) Tie-Line Power Change

From these responses table 6.3 is prepared to compare the controller responses regarding time-domain simulation characteristics. It is observed from the table that PID controller provides better results than other controllers.

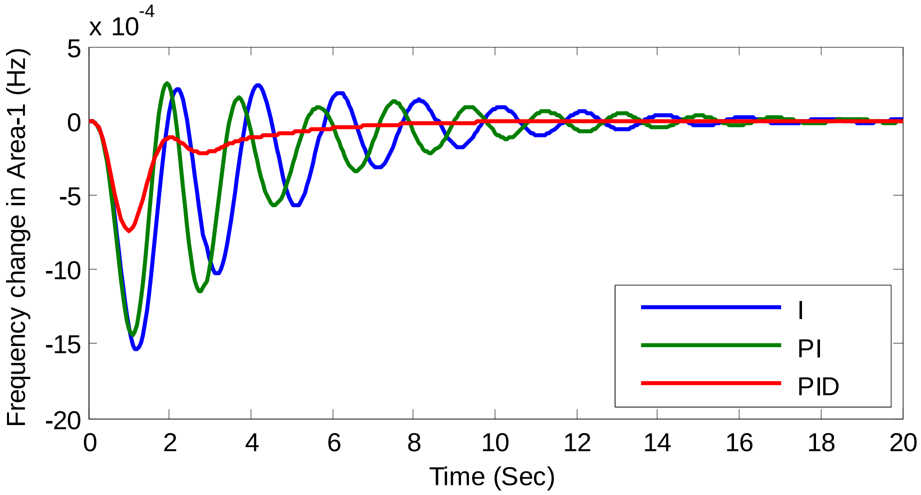
Table 6.3 Optimized Controller Parameters and Performance Analysis for Each Controller

Cont-roller	**Controller parameters**				**Settling Time (s)**			**Peak overshoot**			ξ
	$\mathbf{K_P}$	$\mathbf{K_I}$	$\mathbf{K_D}$	**N**	$\mathbf{F_1}$	$\mathbf{F_2}$	$\mathbf{P_{Tie}}$	$\mathbf{F_1}$	$\mathbf{F_2}$	$\mathbf{P_{Tie}}$	
I	-	0.4931 0.0122	-	-	10.27	18.35	18.54	0.0066	0.0014	0.0155	0.2128
PI	0.4213 0.0581	0.4922 0.0964	-	-	17.41	17.56	13.45	0.0053	0.00093	0.0098	0.3854
PID	0.3761 0.5577	0.9992 0.2536	0.4949 0.2709	37.55 53.32	**3.61**	**8.95**	**9.08**	**0.0030**	**0.00004**	**0.0048**	**0.6385**

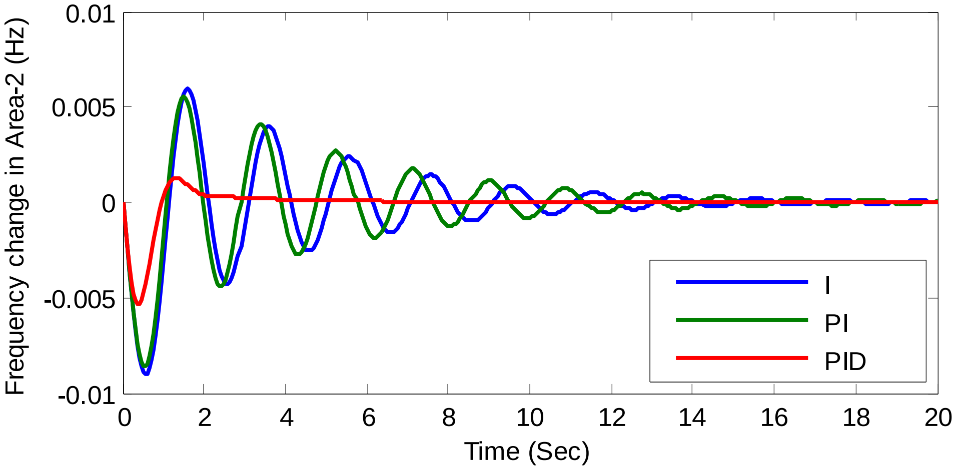
6.3.2 Case 2: Change in Area-2 only

A 10% load disturbance is applied in area-2 and time domain simulations are plotted, fig. 6.3 shows frequency variation in area-1, area-2 and tie-line power deviations.

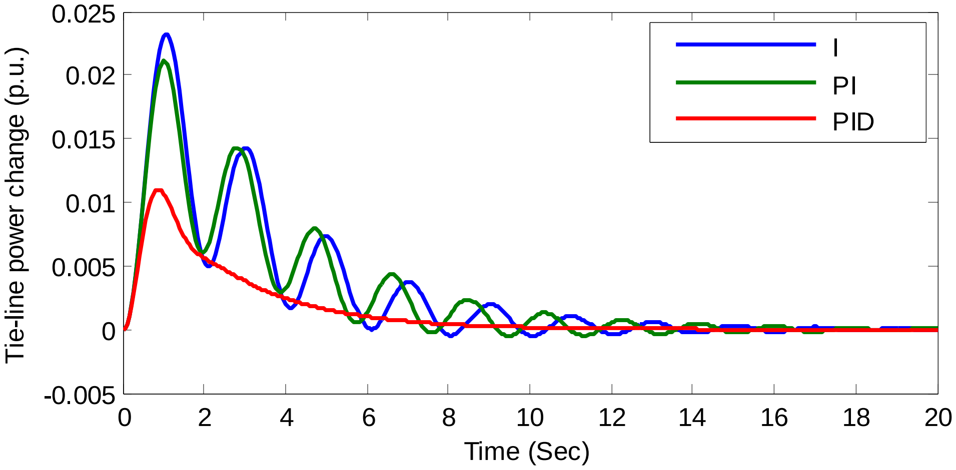
Similar to case one a comparison is made between controller performances regarding time-domain simulation characteristics. These responses clearly show that PID compensator gives better response as compared to others compensators.



(a)



(b)



(c)

Figure 6.3 Transient Responses for 10% Load Disturbance in Area-2

(a) Frequency Change in Area-1

(b) Frequency Change in Area-2

(c) Tie-Line Power Change

6.3.2 Case 3: Change in Area-1 and Area-2 Simultaneously

A 20% load disturbance is applied in area-1 and 10% in Area-2. Time domain simulations for variation in frequency in area-1, area-2 and tie-line power deviations are plotted in fig. 6.4.

In this case, PID controller provides good response as compare to another controller. To check its superiority, GSA-PID controller is compared with another technique based controllers as shown in table 6.4.

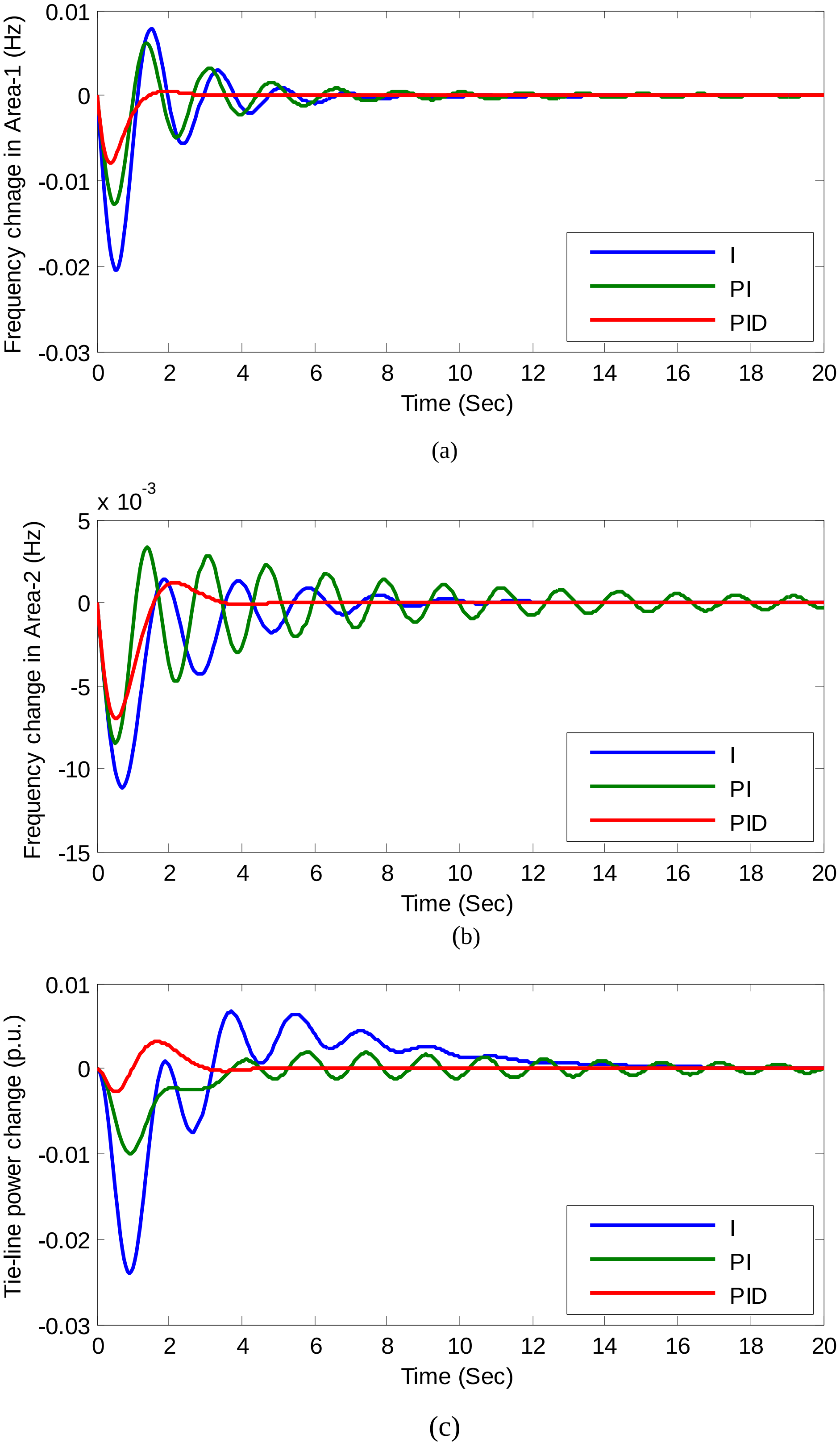


Figure 6.4 Transient Responses for 20% Load Disturbance in Area-1 and 10% in Area-2

(a) Frequency Change in Area-1

(b) Frequency Change in Area-2

(c) Tie-Line Power Change

It is evident from Table 6.4 that GSA based PI controller provides a minimum value of the objective function (considered ITAE error criteria in all concerned system) is minimum compared with FA, DE, hybrid BFOA-PSO, PSO, NSGA-II, BFOA, GA and conventional techniques. Further, GSA-PID provides much lower value and better time-domain simulation performance.

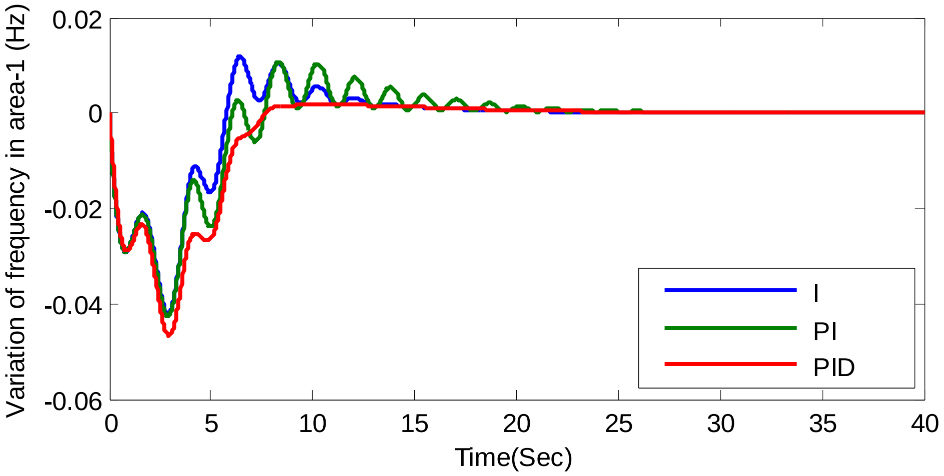
Table 6.4 Optimized Controller Parameter and Corresponds Performance Indices Value

Technique	Tuned controller parameter			ITAE
	K_P	K_I	K_D	
Conventional PI [13]	−0.3317	0.4741	-	3.7568
GA PI [13]	−0.2346	0.2662	-	2.7474
BFOA PI [13]	−0.4207	0.2795	-	1.8270
DE PI [4]	−0.2146	0.4335	-	0.9911
FA PI [15]	−0.3267	0.4296	-	0.8695
PSO tuned PI [16]	−0.3597	0.4756	-	1.2142
hBFOA-PSO tuned PI [16]	−0.3317	0.4741	-	1.1865
NSGA-II [14]	−0.4287	0.2967	-	1.6764
GSA PI	−0.3145	0.4628	-	**0.0457**
GSA PID	-0.3762	0.9011	0.6743	**0.0107**

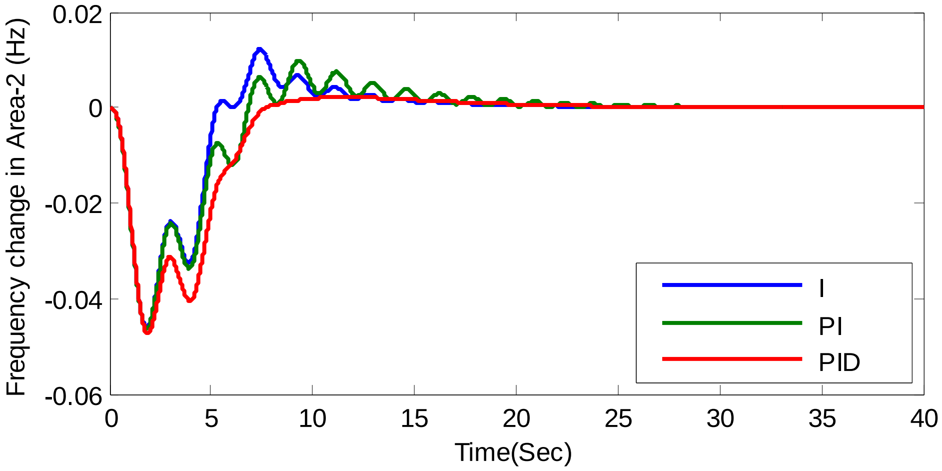
6.4 Analysis of Result With Physical Constraint

Reheat and non-reheat i.e. two-area thermal interconnected system is considered with GRC and area participation factor. Two generating units are considered in each area whose participation in a generation is equal to 50%.

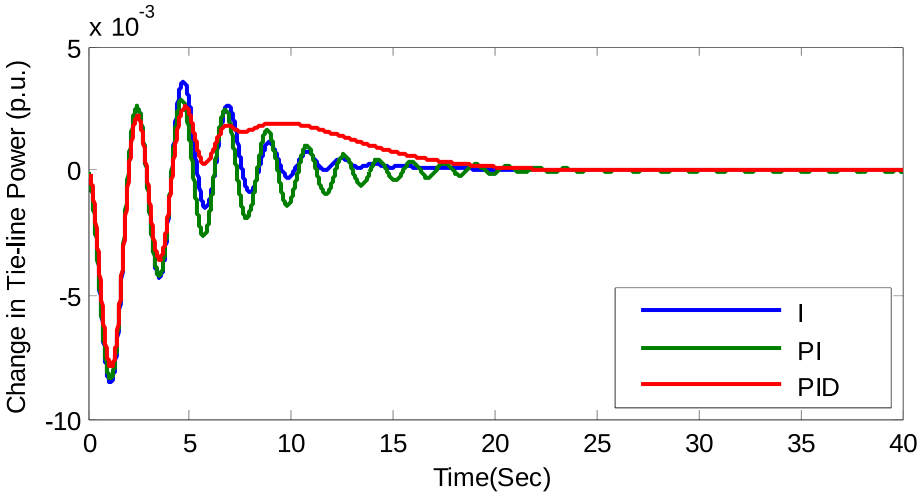
6.4.1 Case 1: Change in Area-1 only



(a)



(b)



(c)

Figure 6.5 Transient Responses for 1% Load Disturbance in Area-1 Considering Physical Constrain

(a) Frequency Change in Area-1

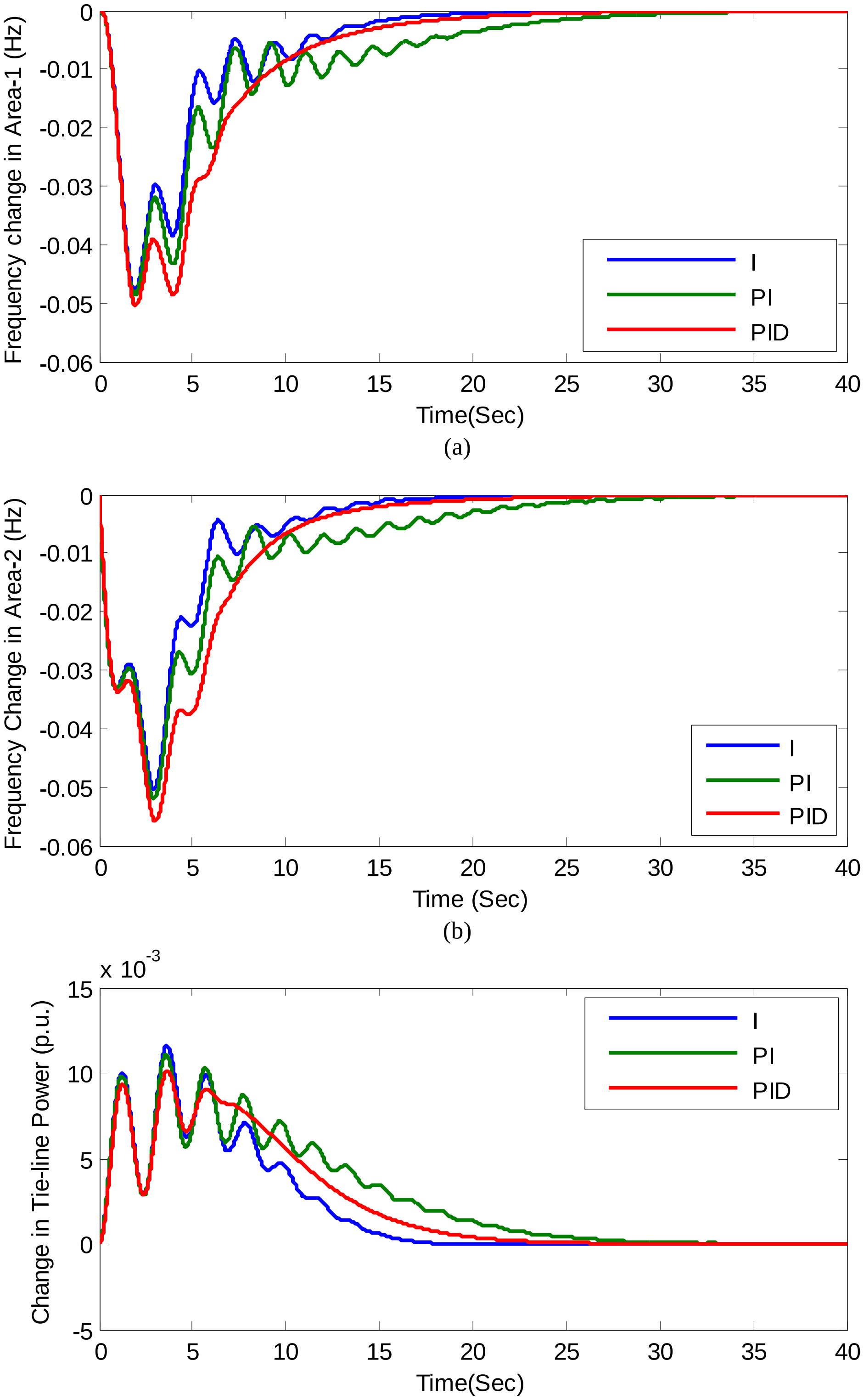
(b) Frequency Change in Area-2

(c) Tie-Line Power Change

A 1% load disturbance is applied in area-1. Time domain simulations results are plotted as shown in fig. 6.5 for variation in frequency in area-1, area-2 and tie-line power.

6.4.2 Case 2: Change in Area-2 only

A 1% load disturbance is applied in area-2. Time domain simulations results are plotted as shown in fig. 6.6 for variation in frequency in both area and tie-line interchange power.



(a)

(b)

(c)

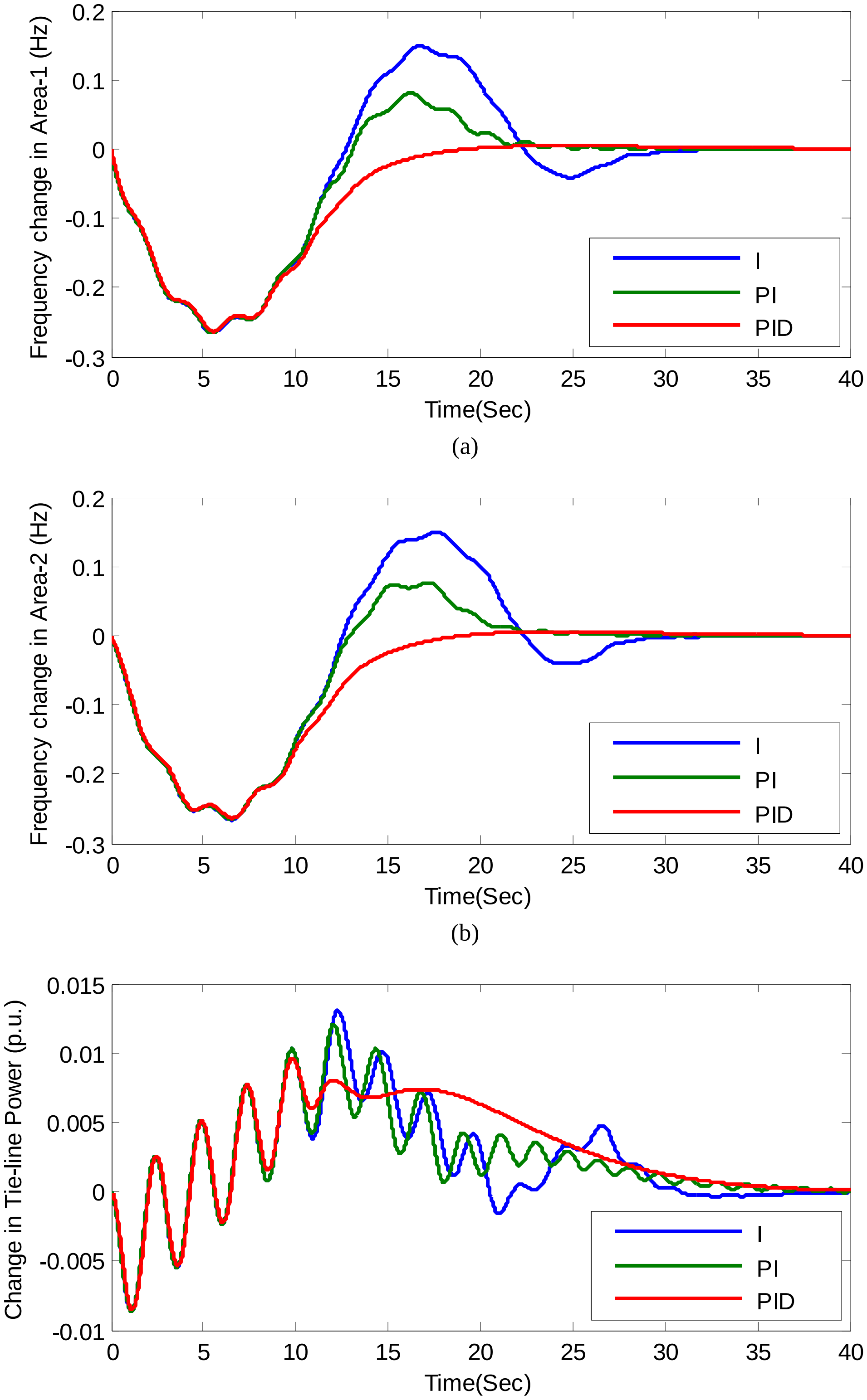
Figure 6.6 Transient Responses for 1% Load Disturbance in Area-2 Considering Physical Constraint

(a) Frequency Change in Area-1

(b) Frequency Change in Area-2

(c) Tie-Line Power Change

6.4.3 Case 3: Change in Area-1 and Area-2 Simultaneously



(a)

(b)

(c)

Figure 6.7 Transient Responses for 2% Load Disturbance in Area-1 and 1% in Area-2 Considering Physical Constraint

(a) Frequency Change in Area-1

(b) Frequency Change in Area-2

(c) Tie-Line Power Change

A 2% load disturbance is applied in area one and 1% in Area two. Time domain simulations results are plotted in fig. 6.7 for variation in frequency in both area and tie-line power.

We observe from case -1 to -3 that PID controller provides good responses compared to other controller in all the cases.

6.5 Sensitivity analysis

To study the robustness of the system sensitivity analysis is performed [49]. Varying speed governor (T_{g}) -, turbine (T_t) -, and tie line power interchange (T_{12}) - time constants respectively; one at a time from their nominal values in the range of +50% to –50% in steps of 25%.

6.5.1 Without Physical Constraint

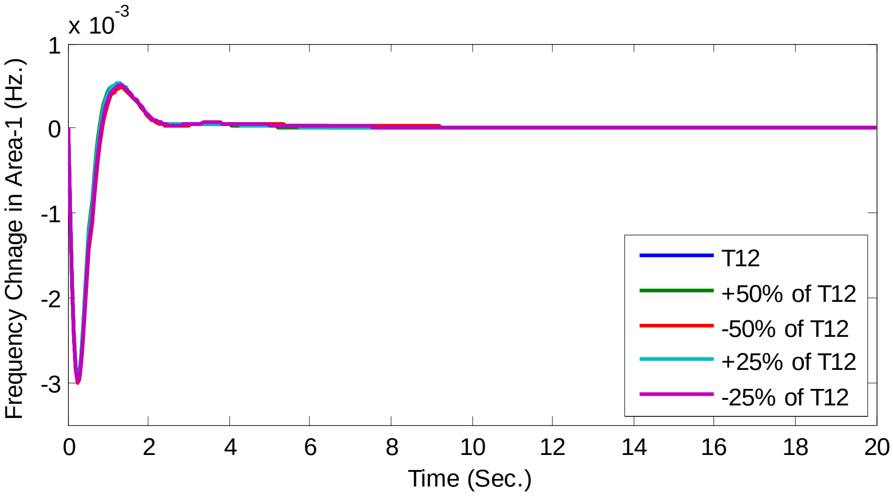


Figure 6.8 ΔF_1 for Change in T_{12} for PID Controller With 10% Change in Area-1

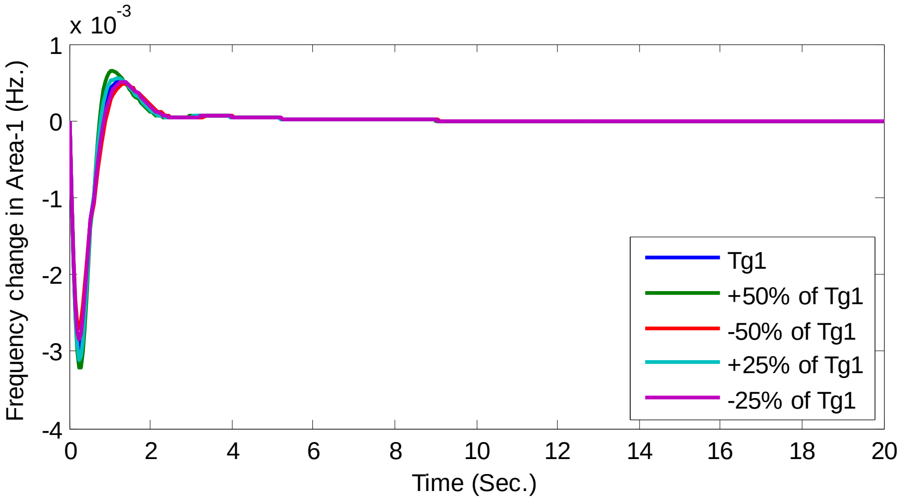


Figure 6.9 ΔF_1 for Change in T_{g1} for PID Controller With 10% Change in Area-1

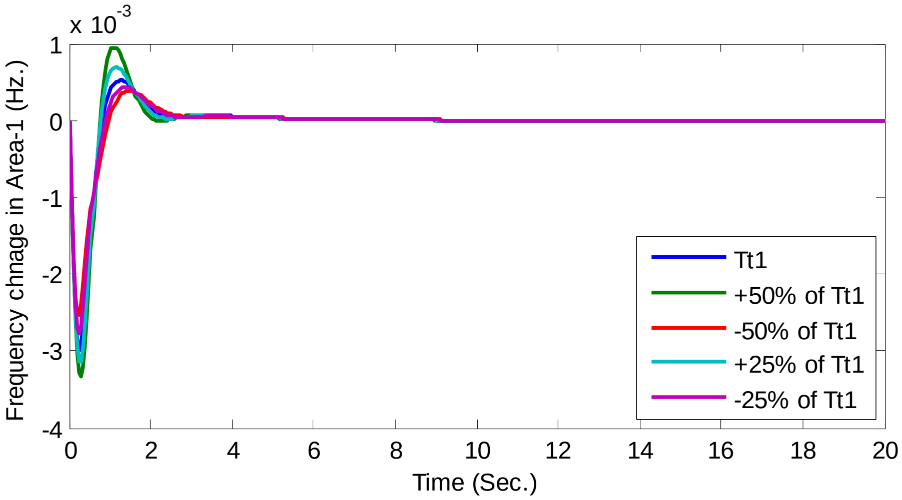


Figure 6.10 ΔF_1 for Change in T_{t1} for PID Controller With 10% Change in Area-1

Frequency change in area one with 10% load disturbance responses with above mentioned varied conditions are shown in figs. 6.8 - 6.10.

6.5.2 With Physical constraint

Frequency variation in area one with 1% load disturbance responses with above mentioned varied conditions are shown in figs. 6.11 - 6.13.

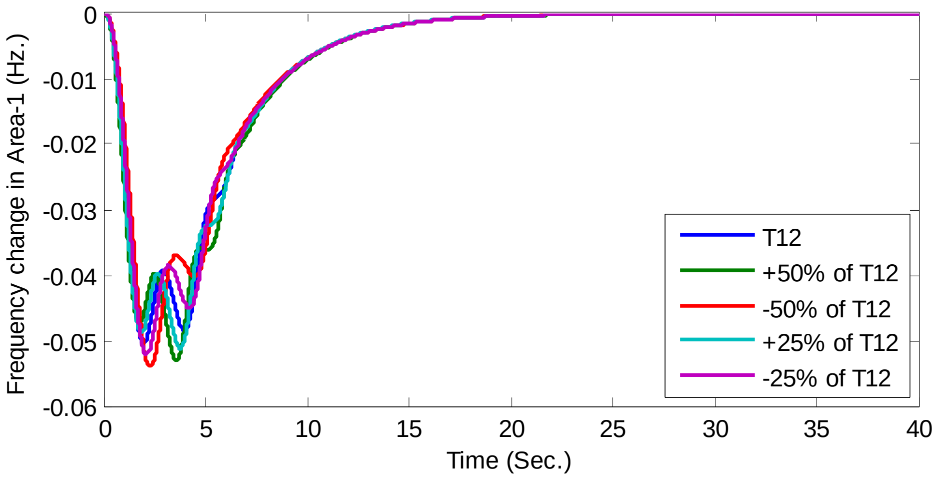


Figure 6.11 ΔF_1 for Change in T_{12} for PID Controller With 1% Change in Area-1

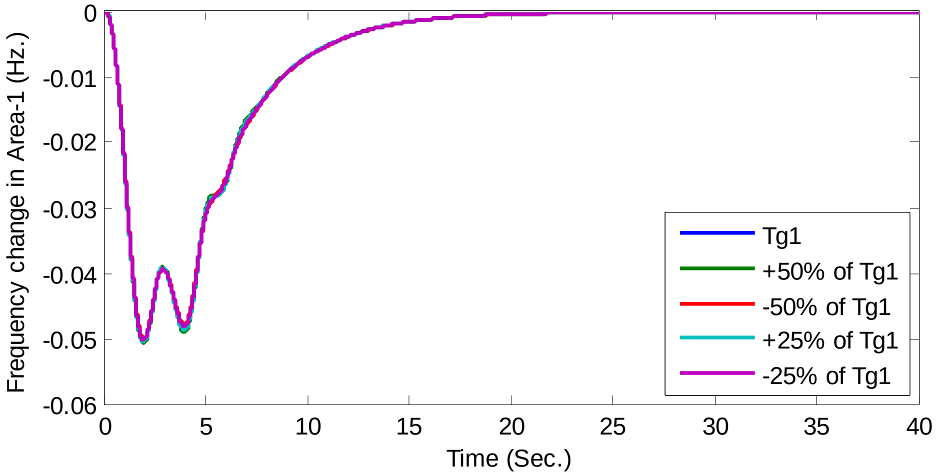


Figure 6.12 ΔF_1 for Change in T_{g1} for PID Controller With 1% Change in Area-1

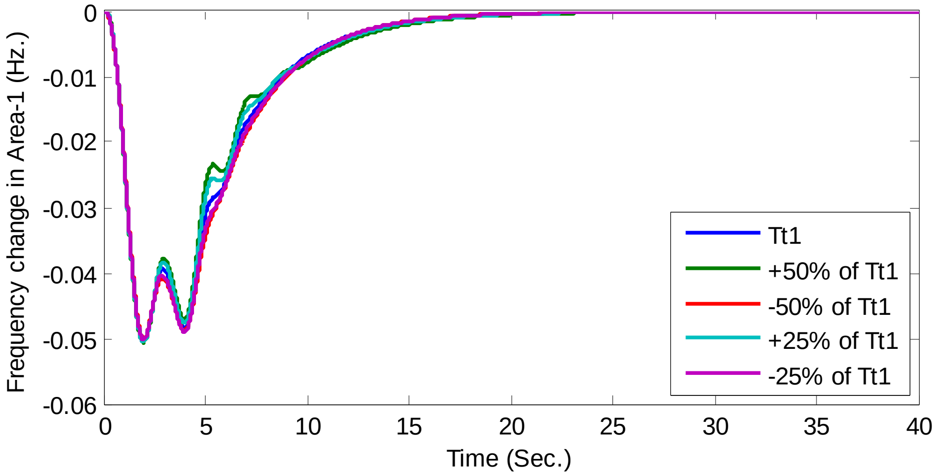


Figure 6.13 ΔF_1 for Change in T_{t1} for PID Controller With 1% Change in Area-1

It is clear from the fig. 6.9-6.13 that there is a minor variation in the frequency response when time constant of governor, turbine and tie-line interchange coefficient are varied respectively. It proves the robustness of the system.

6.6 Convergence Curve

Different controllers for an interconnected power system with same objective function are used. Minimum value is desired. It is clear from fig. 6.14 that with PID controller minimum value of objective function is achieved. Thus; all the results prove that PID is superior over other controllers.

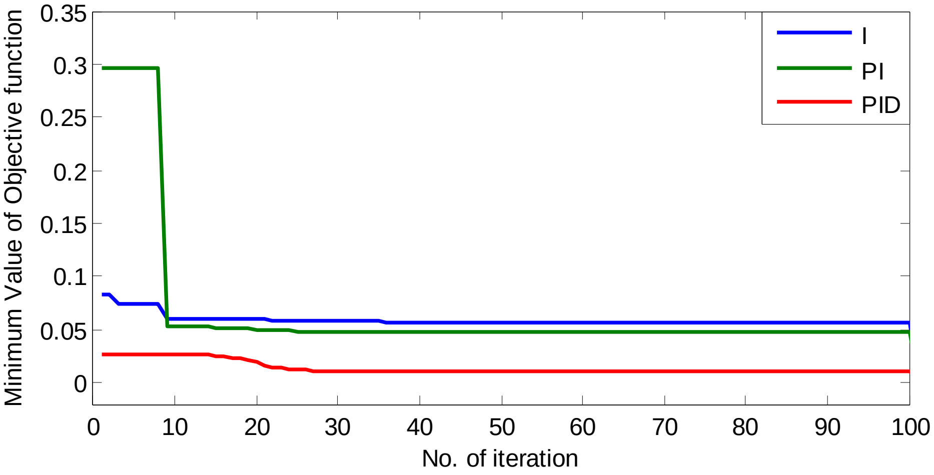


Figure 6.14 Convergence Curve

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

To meet the changing power demand of the consumer is a challenging task for the power engineers. It motivates to develop an intelligent controller to maintain operations of Load frequency control (LFC). The work is an effort to contribute towards the composition of an intelligent controller for LFC of different types of modern interconnected power systems. This controller should be able to overcome the frequency – and tie line power – deviation quickly.

In this thesis; GSA is used to optimize the different controller parameters for two-area non-reheat thermal interconnected system initially; followed by reheat and non-reheat two-area thermal power systems are considered with generation rate constraint and two generating units in each area. The objective function ITAE is used; which provides better result than other error criteria. Frequency and tie-line power variations are plotted by varying load demand in both the areas. The results justify the superiority of GSA based PID controller over other controllers.

7.2 Future Scope

1. It can be implemented for the muti-area system. Interconnection of thermal, hydro and nuclear power plant.
2. Various other algorithms can also be applied to tune the controller.
3. The generation rate constraints of diesel power generation units can be a consideration in future works.

PUBLICATION

- Dev Kumar, B.P. Soni, Vikas Gupta, “Comparative Analysis of Different Controllers on Two Area Interconnected Power System Model using Gravitational Search Algorithm”, 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), DTU, New Delhi, India.(**Accepted**)

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50. MATLAB

APPENDIX

TABLE A.1

PARAMETERS OF TWO-AREA NON-REHEAT THERMAL SYSTEM

P_R=2000MW (RATING), P_L=1000MW (NOMINAL VALUE)

Area-1		**Area-2**	
Parameters	**Values**	**Parameters**	**Values**
B_1	20.9	B_2	18.6
R_1	0.05hz/p.u.	R_2	0.055Hz/p.u.
T_{g1}	0.2sec.	T_{g2}	0.3sec.
T_{t1}	0.5sec.	T_{t2}	0.6sec.
K_{PS1}	1.67Hz./p.u.	K_{PS2}	1.11Hz./p.u.
T_{PS1}	16.67sec.	T_{PS2}	8.89sec.
T_{12}	0.746	T_{21}	-0.746
a_{12}	-1	a_{21}	1

TABLE A.2

PARAMETERS OF TWO-AREA THERMAL PLANT WITH AREA PARTICIPATION FACTOR AND GENERATION RATE CONSTRAINT

Area-1		**Area-2**	
Parameters	**Values**	**Parameters**	**Values**
B_1	0.045p.u.	B_2	0.045p.u.
R_1	2.4Hz./p.u.	R_2	2.4Hz./p.u.
T_{g1}	0.08sec.	T_{g2}	0.08sec.
T_{t1}	0.3sec.	T_{t2}	0.3sec.
K_{PS1}	120Hz./p.u.	K_{PS2}	120Hz./p.u.
T_{PS1}	20sec.	T_{PS2}	20sec.
T_{12}	0.545p.u.	T_{21}	-0.545p.u.
a_{12}	-1	a_{21}	1
K_{r1}	0.5	-	-
T_{r2}	10	-	-