OPTIMIZATION OF LOAD FREQUENCY CONTROL PERFORMANCE IN TWO-AREA POWER SYSTEM WITH PID CONTROLLER USING ICA AND GSA ALGORITHMS

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FACULTY OF ENGINEERING
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ORIGINAL LITERARY WORK DECLARATION

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Name of Degree: Master of Engineering (Power System)

Title of Project Thesis: Optimization of load frequency control performance in two-area power system with PID controller using ICA and GSA algorithms

Field of Study: Power System

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OPTIMIZATION OF LOAD FREQUENCY CONTROL PERFORMANCE IN TWO-AREA POWER SYSTEM WITH PID CONTROLLER USING ICA AND GSA ALGORITHMS

ABSTRACT

The importance of load frequency control (LFC) in the field of power system cannot be denied due to the necessity in the demand of a reliable and stable power supply. LFC in power systems is used to stabilize and regulate the electrical power supply in a nested area power system. The change in the system is signified by the change in the system frequency and tie-line (T-L) load. The performance of LFC has to be tuned properly so that the response can be optimized with a selected controller and algorithm for optimization. Hence, in this project, imperialist competitive algorithm (ICA) and gravitational search algorithm (GSA) are proposed in a LFC of two-area power system to optimize the performance of PID controllers using MATLAB and Simulink. The PID controller is used as a control unit to improve the performance of the LFC in the presence of perturbation in the system. A comparative study performed based on the proposed algorithms clearly shows that the performance of GSA-PID is superior over ICA-PID controller in terms of the rise time and the settling time during perturbation or disturbance in the system.

Keywords: Load Frequency Control (LFC), Gravitational Search Algorithm (GSA), Imperialistic Competitive Algorithm (ICA), Tie-Line (T-L).

OPTIMISASI PENCAPAIAN KAWALAN FREKUENSI BEBAN DALAM SISTEM KUASA DUA KAWASAN DENGAN PENGAWAL PID MENGGUNAKAN ALGORITM ICA DAN GSA

ABSTRAK

Kepentingan Kawalan Kekerapan Beban (LFC) dalam bidang sistem kuasa tidak dapat dinafikan kerana wujudnya keperluan dalam permintaan bekalan kuasa yang boleh dipercayai dan stabil. Sistem kuasa LFC digunakan untuk menstabilkan dan mengawal bekalan kuasa elektrik dalam sistem kuasa kawasan bersarang (nested area). Perubahan dalam sistem ini ditandakan oleh perubahan frekuensi sistem dan beban talian tali (T-L). Prestasi LFC perlu ditala dengan betul supaya suatu respon dapat dioptimumkan dengan pengawal dan algoritma yang dipilih untuk pengoptimuman. Oleh itu, dalam projek ini, algoritma daya saing imperialis (ICA) dan algoritma carian graviti (GSA) dicadangkan untuk disertakan dalam sistem kuasa LFC dua lokasi (two-area power system) untuk mengoptimumkan prestasi pengawal PID melalui penggunaan MATLAB dan Simulink. Pengawal PID digunakan sebagai unit kawalan untuk meningkatkan prestasi LFC apabila mempunyai gangguan dalam sistem. Kajian komparatif yang dilakukan berdasarkan algoritma yang dicadangkan dengan jelas menunjukkan bahawa prestasi GSA-PID lebih baik berbanding dengan pengawal ICA-PID dari segi waktu naik (rise time) dan waktu ketenangan (settling time) semasa berlakunya gangguan (perturbation) atau gangguan dalam sistem.

Kata kunci: Kawalan Frekuensi Beban (LFC), Algoritma Carian Gravitasi (GSA), Algoritma Kompetitif Imperialistik (ICA), Tie-Line (T-L).

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LIST OF SYMBOLS AND ABBREVIATIONS

AGC	:	Area Generation Control
LFC	:	Load Frequency Control
T-L	:	Tie-Line Power
H∞	:	H-infinity
FACTS	:	Flexible AC Transmission System
HVDC	:	High Voltage Direct Current
ITAE	:	Integral of Time and Absolute Error
ISE	:	Integral Square Error
PID	:	Proportion Integral Derivative
ABC	:	Bee Colony Algorithm
BFOA	:	Bacteria Foraging Optimization Algorithm
ADRC	:	Active Disturbance Rejection Control
ECS	:	Energy Control System
SDBR	:	Series Dynamic Breaking Resistor
GRC	:	Generation Rate Constraint
GDR	:	Geographically Dispersed Resiliency
CLPSO	:	Comprehensive Learning Particle Swarm Optimizer.

CHAPTER 1: INTRODUCTION

1.1 Overview

The significance of load frequency control (LFC) in electrical power system is vital for uninterrupted subordinate services. An LFC of an interconnected area maintain frequency at a desired limit and keep the tie-line (T-L) power flow at certain pre-stated threshold. This is visible by changing output power from the generator in order to compensate for any slight deviation in the load demand (Pandey, Mohanty, & Kishor, 2013). The power grid is composed of interconnected electric generators. Any failure due to disturbances or change in the load consumption can be instantly sensed by LFC between power consumption and production, preventing power outage (Balaji & Neelan, 2015).

However, an AC interconnected generator, known as synchronous area, synchronism between the generators must be kept at uniform frequency and network frequency is kept constant, for example at 50Hz in Nigeria and 60Hz in Saudi Arabia. The stability in in a power system calls for balance or a constant set-point in generation, demand and losses in the power grid at all time. It must regain balance within a few seconds in case of any deviation (Aho et al., 2012). Within a very short period, the consumers of power supply are obliged to controlling system balance with a suitable control in order to ensure the stability i.e. a very small deviation is allowed as shown in the Figure 1.1, which the entire system is affected and can cause power outage.

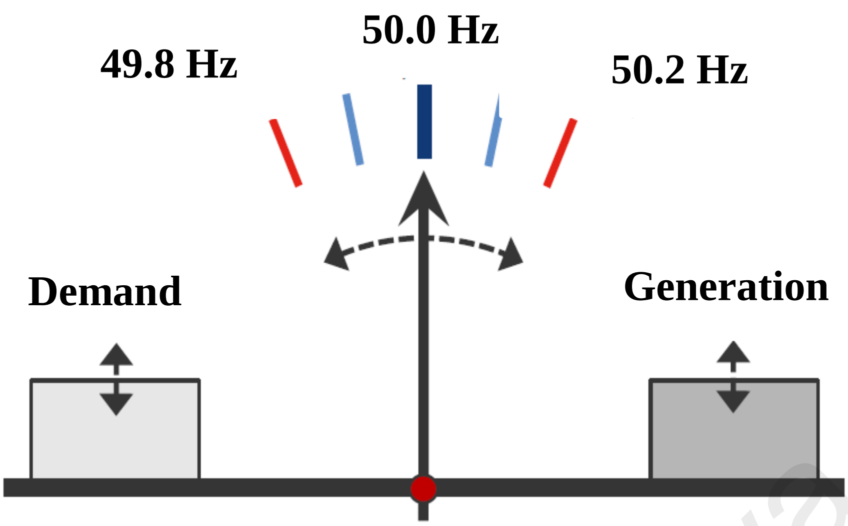

Figure 1.1: Frequency Set point

The deviation in the power system frequency is enhanced by an increase or decrease in the load in a particular area, hence the name load frequency control (LFC) (Elsisi, Aboelela, Soliman, & Mansour, 2015). It is important to note that the study of LFC is far beyond technical complexity but due to cost relevance. Having known the importance of maintaining a constant frequency in a power grid, the study of its control is of great importance in order to maintain the system frequency within pre-set limit at all times. A well-designed system should be fit to withstand any change in load and power interchange between connected area and disturbances in the system. The problem of frequency deviation is more complicated in an interconnected area than a single area system, which is discussed in detail in Chapter 2.

In this regard, numerous studies on LFC has been carried out by various researchers that shows the complexity in advance power system. Distribution of disturbances can spread to a wide range in the power system, leading to blackout (Ali & Abd-Elazim, 2011). In this context, innovative regulator procedure such as best control, inconsistence structure control, control that are flexible to changes, self-optimized control, active/strong and intelligent control were applied in LFC problem.

LFC is considered as a part of automatic generation control (AGC) and an important aspect of focus under research. The frequency and T-L power are good indicator signal that shows the consistency of the connected generators. The mentioned indicators tell the condition of operation in terms of reliability and stability of the power system which is more complicated in an interconnected system or area. The consistency of speed and T-L power within desired set-point are the main primary objectives to keep the system in synchronism. These objectives can be achieved by measuring the relation error signal, called the area control error (ACE), which is the difference between generation and demand.

1.2 Problem Statement

Load Frequency Control (LFC) is one of the most important aspect in power system operation and becomes more pronounced recently by growing the size, configuration and intricacy of change in the recovery, especially in two-area power system. Normally, for large-scale power systems of interconnected subsystems or multi area power control, the connection between control areas is done by using a tie-line. Each region has its own generator or it is responsible for interchange power with neighboring areas. To ensure the quality of supply, load frequency controller is required to maintain the system frequency at nominal value.

Objectives

i. To construct a load frequency control (LFC) of two-area power system with PID controller

ii. To propose optimization of load frequency control (LFC) using ICA and GSA algorithms

iii. To compare the performance of the LFC with optimized PID controller parameters between ICA, GSA and other algorithms

1.3 Project Methodology

This project presents a comparative study of two optimization techniques, Imperialistic Competitive Algorithm (ICA) and Gravitational Search Algorithm (GSA) in order to test for effectiveness and robustness of each proposed technique. The modeling of a two-area power system was designed in Simulink with a T-L connecting the two area together. The detailed design of the model is explained in Chapter 3 of this report.

1.4 Thesis Outline

This thesis report is subdivided into 5 chapters; Chapter 1 explains the overview of the LFC problem on the power system and a brief background of study, chapter 2 reviews the previous study in the literature relating to the previous solution presented by researchers and their point of views regarding the LFC problem and T-L power deviation during discrepancies on the power system. Chapter 3 covers the method of study in this proposed technique. Chapter 4 presents the results of studies and finally, Chapter 5 is about conclusions and recommendations for future work.

CHAPTER 2: LOAD FREQUENCY CONTROL (LFC) IN ONE AND TWO AREA POWER SYSTEMS

2.1 Introduction

The importance of load–frequency control (LFC) can never be overemphasized in the present day because power system networks and consumers expand daily. The demand of the power needed daily changes over time and the consumers will not pre-informed the utility before connecting home appliances to the grid. Hence, the need for stable frequency and power exchange across the T-L arises no matter the change in load or demand. The deviation in the power can simply be adjusted by increasing or decreasing the mechanical input into the turbine, thus compensating for the electrical output of the generator in order to feed the load. A power system should be able to withstand any disturbances or change in load in that area and providing quality power supply by maintaining the system set frequency and voltage.

Over decade, system instability due to LFC problem has called the attention of researchers focusing on AGC controller, excitation controller scheme and control performance with respect to factor variation/reservations and different load characteristics. However, the demand for power supply is proportional to intricacy of the advanced power system network. Hence, the undulation of the nominal settings of the power system is apparent due to disturbance and consistence change in load might lead to blackout. In this regards, a reliable control strategy is needed such as optimization technique, variable configuration, adaptive, self-tuning, robust and intelligent control were developed as a solution to the LFC problem. The study of literature has shown various intelligent soft computing techniques such as artificial neural network (ANN), fuzzy logic, fusion neuro-fuzzy, neuro-genetic etc. to provide a lasting solution to the non-linearity problem in respective interconnected areas in the power system.

The controller parameters play a vital role for its performance, thus it should be tuned properly with suitable optimization techniques. Different optimization techniques, such as genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA) etc., were used to present the application of the optimization objectives. Due to oscillation and uncertainty in the component in power system parameter, various robust control techniques such as Riccati equation, $H\infty$, m synthesis, robust pole assignment, loop shaping, linear matrix inequality (LMI) have been adopted to tackle the LFC problems.

Nowadays, there is rapid momentum in the progress of the research to tackle the LFC in the deregulated environment, LFC with communication delay and LFC with new energy systems, FACTS devices and HVDC links. This literature survey intensively detailed the LFC problems in customary and dispersal generation-based power systems. An extensive analysis of traditional power system of single area, multi-area connections, HVDC power system and control problem in the deregulation atmosphere is presented in this chapter. Furthermore, LFC issues relating to renewable energy systems and its incorporation with the grid is also discussed. In addition to this, the latest trends in LFC such as communication delays, wide area monitoring, phase measurement unit and penetration of different renewable energy sources impact on the LFC is also discussed.

2.2 Previous Work

The power system structure in the early age used to be very simple and limited. Hydro and thermal were the major basis of generation and able to meet the demand in a particular area. However, as time passes by, the increase in the electricity demand results in the restructure of the power system structure in order to meet the increase in demand and call the attention of the researchers to the oscillation. In (Jadhav, Toppo, & Vadirajacharya, 2012), the study of load frequency control in high, medium and low head hydro single area power system using PSO optimization technique was presented to select optimal value of the

PID controller parameter with integral squared error (ISE) and integral time absolute error (ITAE) as the fitness function. The simulation results show that the ITAE presented a promising result with less settling time over ISE. In (Farahani, Ganjefar, & Alizadeh, 2012), LFC problem was examined in two connected area as a case study using lozi map-based chaotic algorithm to select optimum value for the PID parameters. The simulation result and a comparative study with other optimization technique show the robustness of the proposed optimization technique.

PID is a major controller used in LFC control, hence in (Sahu, Panda, & Padhan, 2014), the impact of PID/PIDF controller parameter optimization using GSA was investigated to monitor the Area Generation Control (AGC) of an interconnected power system. The proposed tuning of the parameter of the GSA technique were found to be a=20, G0=100, NP=20 and T=100 respectively. The area/region of study was first optimized in the absence of physical constraint using traditional objective function and Integral Time Absolute Error (ITAE) objective function. ITAE was found to be more effective when used to minimize damping ratio, settling time and peak overshoots of the frequency and tie-line power deviation compared to IAE, ISTE and ISE objective function.

A new objective function was investigated and the parameters of PI/PIDF controller were optimized by GSA (Sahu et al., 2014). The authors were able to reveal the robustness and effectiveness of the proposed technique by comparing the proposed technique with the conventional optimization algorithm. The proposed technique considered real power system model by putting the physical constraints into considerations. It was observed that the variation of the performance index is more prominent when the constraints were introduced in the studies.

There are more factors to be considered in LFC study in the power system than what the former authors have presented. The most difficult part to model in the power system is the load, which shows uncertainty due to its constant variation. Hence, more aspects need to be discovered about the load variation and some uncertainty in the power system. In (Balaji & Neelan, 2015), an optimization based methodology using PSO to control the PID parameters considering a unique objective function in a two area with governor dead band was proposed. The results show better steady-state response for frequency and tie-line during disturbances.

In (Jamadar & Reddy, 2015), the study with more effective way of controlling and maintaining the power system frequency and tie-line power exchange between two area using PI controller based on Artificial Neural Network optimization (ANN) technique to select suitable PI parameter values at a lower and optimum cost was considered. The proposed method was found to be more effective against parametric uncertainties, parameter changes and load compared to the traditional control. However, the study presented by Jamadar and Reddy did not consider uncertainties or load change to proof the stability of the power system under study.

The PID has been a common controller for decades in this regard. Hence, comparison of the effectiveness of Model Predictive Control (MPC) controller and PI controlled by ICA an optimization technique on a two-Area power system was proposed (Elsisi, Aboelela, et al., 2015). The authors were able to show the superiority of MPC over PI. The MPC controller provides a viable solution, which can be tested on a real world of multi-connected power systems. A further study in (Elsisi, Soliman, Aboelela, & Mansour, 2015) proposed ABC optimization technique to control or select optimal PID parameters in a two-area non-reheat power plant for the non-linear LFC problem in the power system. The simulation results show the robustness of the proposed algorithm and damping oscillation compared to GA and BFOA for tuning PID controller.

In (Liu, Li, Cao, She, & Wu, 2016), a study considering load variation and uncertainty was presented. The authors revealed that the proposed method has a capability of rejecting the effects of random load variations, parameter uncertainties and guaranteeing high dynamic performance. The state-space model of LFC system is established and showed that ADRC (Active Disturbance Rejection Control) method could be applicable to improve LFC control with EID (Equivalent Input Disturbances) to provide correction to any imbalances of frequency and the scheduled tie-line power in an interconnected area. This method has proven to be more effective than the conventional single ADRC.

A sector-bounded H∞ control approach was used for compensating the nonlinearities based on a minimum order dynamic LFC model to avoid the complexity of a high-order model. In (Chuang, 2016), a novel sector-bounded H∞ approach of solving problem related to frequency deviation and power transmission through interconnected area (Tie-Line) was studied by using a robust H-controller and was able to prove its reliability over conventional PI and PID using online tuning based try and error method to setting the controller parameters.

Renewable energy contributes immensely to the fluctuation in the power system; thus in (Okedu, 2017), the implementation of ECS and SDBR for the control of the deviation in the set point of the system frequency and scheduled tie-line power in an interconnected system was investigated by observing the variation in the time constant of a low pass filter in DC chopper in an energy capacitor system. The synergy of the ECS and SDBR results in a faster and reliable damping in the oscillation of the system variable during disturbances.

The authors in (Baydokhty, Zeynal, & Zare, 2016) proposed a Hierarchical Takagi Sugeno Kang Fuzzy (OHTSKF) controller optimization technique for the load frequency control where the Cuckoo Optimization Algorithm (COA) was employed in the model in other to ameliorate the feedback error. The result of this studies shows that the proposed technique provides a better feasible solution and compared to Fuzzy Mamdani and TSKF controllers.

GSA algorithm is a powerful heuristic algorithm and one of the latest optimization technique under study, which was developed by Rashedi et al. (2009). The authors in (Duman, Yorukeren, & Altas, 2012) presented their studies using the former algorithm GSA to control LF and interconnected TL power deviation during perturbation. The simulation results show that GSA provides a promising solution when used to control the parameters of the PI and PID controller compared to the traditional PI tuning technique such as Ziegler Nichols and Karl-Astrom.

Investigation on grey wolf optimization (GWO), a new meta-heuristic algorithm developed by Mirjalili et al. in solving LFC control problem in the power system with the aid of PI/PID controller was presented (Guha, Roy, & Banerjee, 2016a). The extensive study of the proposed technique was tested on two-area; integrated non-reheat thermal-thermal, multi-units hydrothermal, multi-sources power system embedded with thermal, hydro and gas power plants and three-unequal-area. It was done to show the efficiency of the proposed algorithm putting into consideration of the relevant uncertainties modeled into the system such as GRC, GDB and time delay of the transmission system. An intensive comparison with conventional techniques such as CLPSO, EPSDE, hFA–PS, FA, hPSO–PS, PSO, DE, hBFOA–PSO, GA, ZN, etc reveals a promising result that feasible in a real world environment.

In (Guha, Roy, & Banerjee, 2016b), an improved technique of GWO, robust and promising solution using quasi-oppositional grey wolf optimization algorithm (QOGWO) was investigated to set the optimum value of the PID controller parameter. Using two-area hydro-thermal and four-area hydro-thermal power plant as the system case study, uncertainty condition and integral time absolute error (ITAE) based fitness function was measured to show feasibility of the proposed technique. The efficiency and robustness of the proposed technique is evident when compared to the GWO and other intelligent optimization techniques. The authors were able to prove that the proposed technique provides a better dynamic output in terms of fitness, overshoot, undershoot, settling time of system oscillations and under uncertainty.

2.3 Load Frequency Control (LFC)

The main role of LFC in the power system is to ensure that the frequency is kept constant within a reasonable standard limit, divide the load to the generators and to maintain scheduled real power interchange on the T-L. The rotor angle is an important indicator of the change in frequency and T-L on the power system, the deviation is sensed and send to the prime mover in the form of a command signal, which is used for the increase in the mechanical input into the turbine mainly by adjusting the governor. Hence, it changes the generator electrical output by an amount, which in turn changes the value of the frequency and T-L active power interchange between the connected area with in an acceptable range or limit.

A mathematical modelling is an essential step used in the analysis of the aforementioned control. Two popular models are transfer function and state space variable technique. The state space is relevant to portray linear and nonlinear system. In order to use the transfer function and linear state equation, the system must first be linearized. Proper assumption and approximations are made to linearize the mathematical equations describing the system and a transfer function model is obtained.

2.4 Load Frequency Control (LFC) in one area power system

Considering an LFC loop, the speed of the generator is altered by external disturbance such as line disconnection for maintenance or change in the load driven by the machine an equivalent change in the system frequency. When this occurs, the governor set point is adjusted to compensate for the observed frequency change either by increasing or decreasing the mechanical input into the turbine. A reset activity is expected to mitigate the frequency deviation to zero. The reset activity is accomplished by introducing an integral controller acting on the load reference setting to alter the speed set point.

2.5 Design of one area power system

2.5.1 Generator

With the use of swing equation of a synchronous machine to small perturbation,

$$\frac{2H}{W}\frac{d^2\Delta\delta}{dt^2} = \Delta Pm - \Delta Pe \tag{2.1}$$

Or in terms of small change in speed,

$$\frac{d\Delta\frac{\omega}{\omega_s}}{dt} = \frac{1}{2H}(\Delta Pm - \Delta Pe) \tag{2.2}$$

Laplace Transformation gives,

$$\Delta\Omega(\mathrm{s}) = \frac{1}{2Hs}[\Delta Pm(s) - \Delta Pe(s)] \tag{2.3}$$

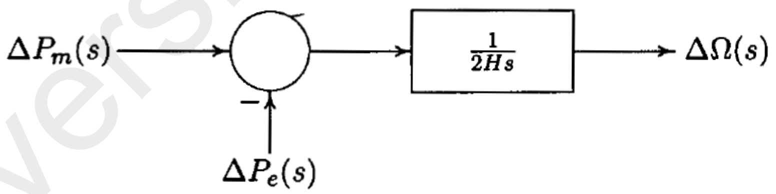

Figure 2.1: Frequency Set point (Saadat, 1999)

2.5.2 Governor

An increase in load slows down the generator speed which results in an equivalent increase in the electrical torque greater than the mechanical torque. This difference in torque decreases the power required to drive the load. There is a need to compensate for the differences in the torque. The governor sends signal to open up the valve for more water or gas as the case may be to balance the torque which tends to increase the speed of the prime mover to bridge the deficiency in speed. The opening and closing of the valve makes it possible to adjust the mechanical output during system operation shift. However, the governor uses an electronic mean to adjust the speed during any undesirable situation. Figure 2.2 shows a simple speed governing system.

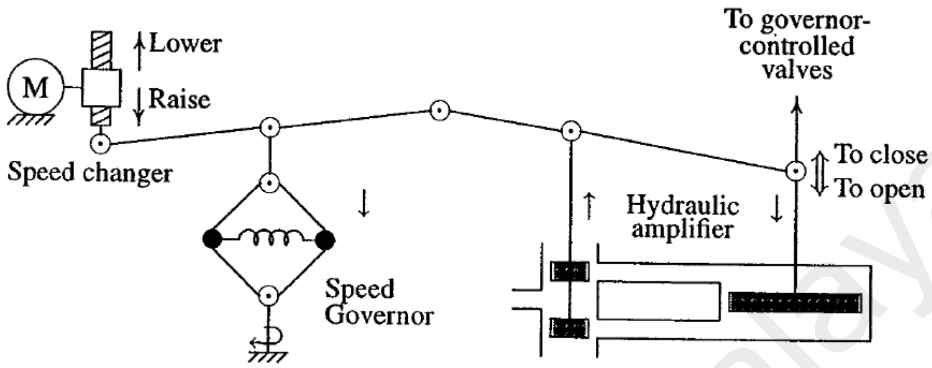

Figure 2.2: Frequency Set point(Saadat, 1999)

The governor is designed in such a way that they can withstand any load change in the system or simply are used as a correction tool. When there is an increase in load, the governor adjusts the speed simultaneously. The Figure 2.3 below represent the governor under the state of equilibrium.

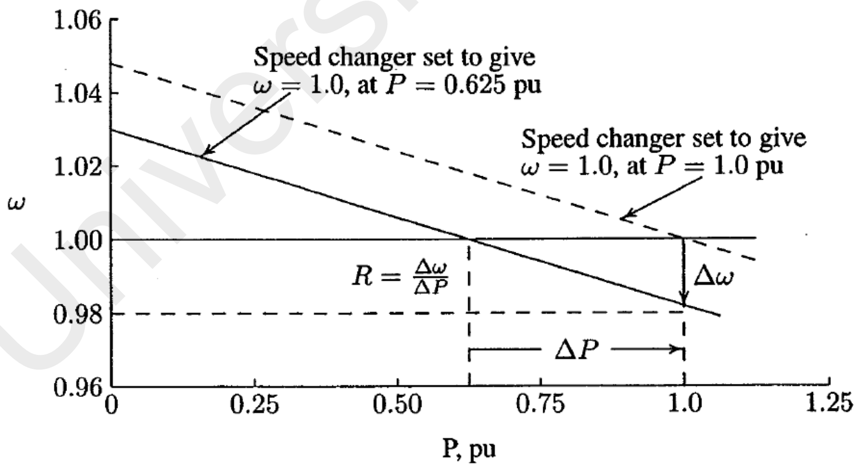

Figure 2.3: Governor Characteristic speed steady state(Saadat, 1999)

$$\Delta Pg = \Delta Pref - \frac{1}{R}\Delta\omega \tag{2.4}$$

OR in s domain

$$\Delta Pg(s) = \Delta Pref(s) - \frac{1}{R}\Delta\Omega(s)$$

The command ΔP_g is transformed through the hydraulic amplifier to the steam valve position command ΔPv. Assuming a linear relationship and considering a simple time constant τ_g, the following s-domain relation is obtained:

$$\Delta Pv(s) = \frac{1}{1+\tau_g}\Delta P_g(s) \tag{2.5}$$

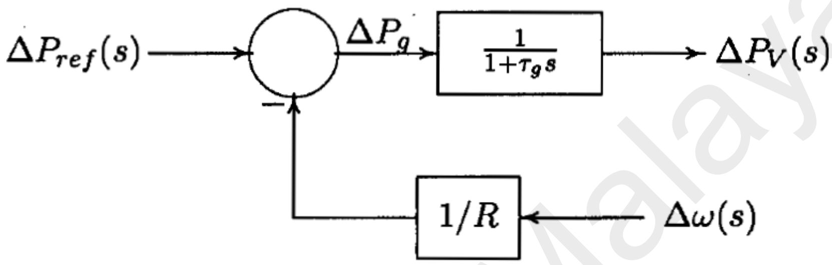

Figure 2.4: Steam turbine speed governing system(Saadat, 1999)

2.5.3 Load

The power generated is used to drive different type of load such as resistive, capacitive and inductive load. The inductive load such as induction machine, motor or devices that stores energy in form of magnetic field are considered to be more sensitive to change in frequency on the power system. The sensitivity is based on the characteristic of the connected devices and the speed-load, which can be approximated as:

$$\Delta P_e = \Delta P_L - D\Delta\omega \tag{2.6}$$

Where:

P_L = the none-frequency sensitive load

$D\Delta\omega$ = the frequency sensitive load change

D = the percentage load change to the percentage change in frequency i.e. $\frac{\%\Delta L}{\%\Delta f}$ Consider a load change of 2% with a frequency change of 1.2% hence the D will be 2%/1.2% which is equal to 1.67.

Connecting the load model to the generator model gives the block diagram in Figure 2.5:

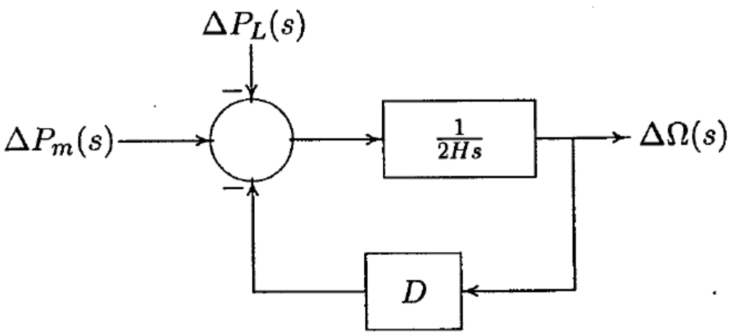

Figure 2.5: Frequency Set point(Saadat, 1999)

Eliminating the feedback D results Figure 2.6.

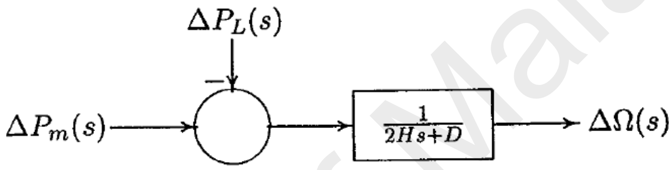

Figure 2.6: Frequency Set point(Saadat, 1999)

2.5.4 Prime Mover

The prime mover is considered as the main point of mechanical power generation in to the system such as hydraulic turbine, gas turbine and steam turbine. In order to model the turbine, the mechanical power change can be related to the change of steam valve position. A non-reheat steam turbine can be simplified with a time constant which ranges from 0.2 to 2.0 seconds as shown by:

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1 + \tau_T s} \tag{2.7}$$

Its equivalent block diagram is as shown:

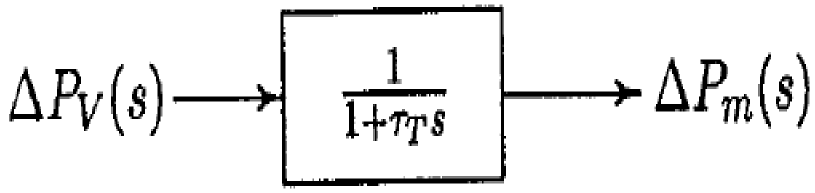

Figure 2.7: Block diagram non-reheat steam turbine(Saadat, 1999)

2.5.5 Overall one area system model

The block diagram in Figure 2.5 shows the combination of all aforementioned system component, which results in a complete LFC of an isolated power station.

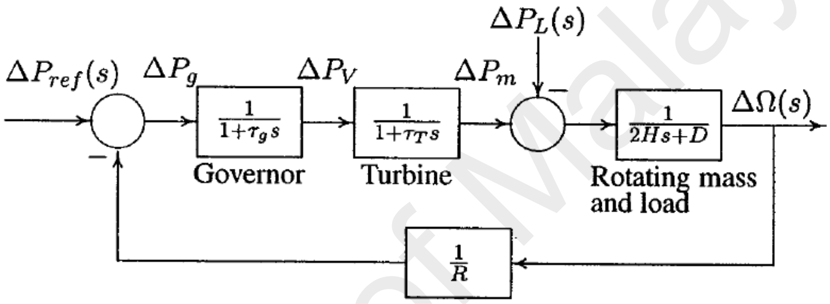

Figure 2.8: Block diagram(Saadat, 1999)

The system is modelled with a load change $-\Delta P_L(s)$ as system input and $\Delta\Omega \quad (s)$ as the system output from the diagram in Figure 2.5. The open-loop transfer function of the model is:

$$KG_sH_s = \frac{1}{R}\frac{1}{(2H_s + D)(1 + \tau_g s)(1 + \tau_T s)} \tag{2.8}$$

The close-loop relating to the system load and frequency deviation is

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = \frac{(1 + \tau_g s)(1 + \tau_T s)}{(2H_s + D)\big(1 + \tau_g s\big)(1 + \tau_T s) + 1/R} \tag{2.9}$$

$$\Omega(s) = -\Delta P_L(s)T_{(s)}$$

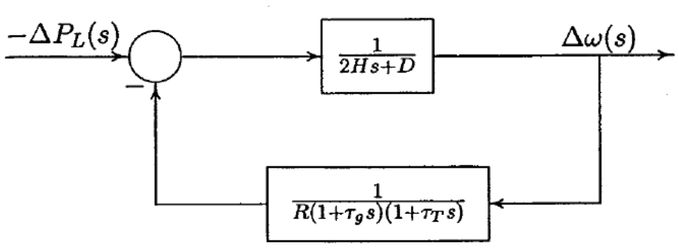

Figure 2.9: LFC Block diagram with input and output(Saadat, 1999)

The input is selected as unit step with the application of final value theory, the steady state of $\Delta\omega$ is therefore

$$\Delta\omega_{ss} = \lim_{n\to\infty} s\Delta\Omega(s) = -\Delta P_L\left(\frac{1}{D + {}^{1}/_{R}}\right) \tag{2.10}$$

The governor speed adjustment determines the steady state deviation in frequency with the value of D set to zero under no frequency sensitive load, which is

$$\Delta\omega_{ss} = (-\Delta P_L)R \tag{2.11}$$

In a situation when there are large number of generators with governor speed adjustment, $R1, R2\ , R3\ \dots\dots\dots\dots, Rn$ are connected to the power system the frequency alteration from the steady state and is given by:

$$\Delta\omega_{ss} = -\Delta P_L \frac{1}{D + {}^{1}/_{R1} + {}^{1}/_{R2} + \cdots . {}^{1}/_{Rn}} \tag{2.12}$$

2.6 Design of two-area power system

A two-area power system is select as an instance of study to show the response of the simulation system to the proposed technique.

2.6.1 Introduction

In a real life, a group of generators in a power system is commonly internally connected swinging in synchronism. The coherence operation of the generators tends to possess the same response characteristics. A two-area study is chosen in order to have a better view of multiple system, where the areas are connected through a lossless T-L with reactance X_{tie} . The T-L acts as a sensor, which provides signal or information about the connected area, the change in the T-L scheduled power signifies the need for compensation in either area. Under normal operation of the system, power is exchanged through the T-L, which can be represented by:

$$P_{12} = \frac{|E1||E2|}{X_{12}} sin\delta_{12} \tag{2.13}$$

Where:

$X_{12} = X_1 + X_{tie} + X_2$

And $\delta_{12} = \delta_1 - \delta_2$

The T-L power can therefore be linearized for a slight change in the T-L power from the nominal set value by:

$$P_{12} = \frac{dP_{12}}{d\delta_{12}}|_{\delta_{12_0}} \Delta\delta_{12} = P_s \Delta\delta_{12} \tag{2.14}$$

At the early stage of working angle $\delta_{12_0} = \delta_{1_0} - \delta_{2_0}$, the measured value of P_s represents the slope of the power angle curve. Therefore,

$$P_{12} = \frac{dP_{12}}{d\delta_{12}}|_{\delta_{12_0}} = \frac{|E1||E2|}{X_{12}} cos\Delta\delta_{12_0} \tag{2.15}$$

The T-L power can therefore be represented as

$\Delta P_{12} = \quad = P_s\,(\Delta\delta_1 - \Delta\delta_2)$

The T-L power becomes apparent due to an increase or decrease in load in a particular area, which relies on the channel of the flow. The deviation in the phase angle is the major determinant of the direction of flow, for example $> \Delta\delta_2$ signifies that the power flows from area1 to area2 and vice versa.

2.6.2 Block diagram of two-area power system.

The LFC with a primary loop can be modeled as shown in Figure 2.10.

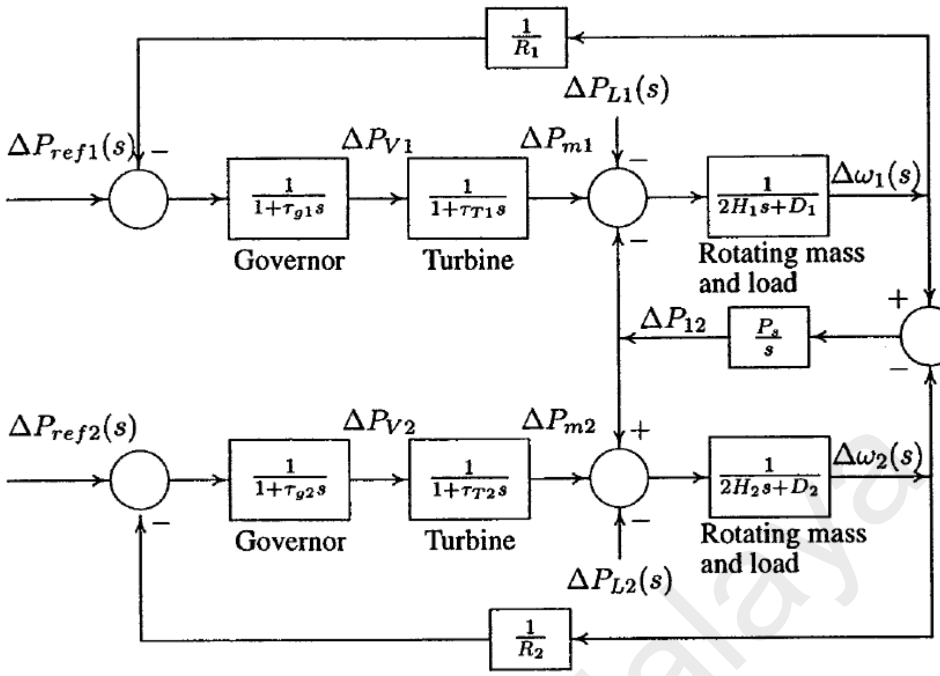

Figure 2.10: Two Area Power System (Saadat, 1999)

Observing a change in the load in one area as shown in the block diagram in Figure 2.10, the two areas will operate in steady state frequency deviation of

$$\Delta\omega = \Delta\omega_1 = \Delta\omega_2$$

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{L1} = \Delta\omega D_1 \quad (2.16)$$

$$\Delta P_{m2} + \Delta P_{12} = \Delta\omega D_2$$

2.6.3 Mathematical modeling of two-area power system

The feature of the governor speed determines the deviation in mechanical power and given by.

$$\Delta P_{m1} = \frac{-\Delta\omega}{R_1} \quad (2.17)$$

$$\Delta P_{m2} = \frac{-\Delta\omega}{R_2}$$

Where R stands for speed droop or regulation. A 4% droop mean that a 4% change in frequency will lead 100% change in power output or valve opening.

Substituting (2.17) into (2.16) and making $\Delta\omega$ the subject of the equation:

$$= \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + (\frac{1}{R_2} + D_2)} \tag{2.18}$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + (\frac{1}{R_2} + D_2)}$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{(B_1) + B_2}$$

And

$$B_1 = \frac{1}{R_1} + D_1$$

$$B_2 = \frac{1}{R_2} + D_2$$

Where B1 and B2 are known as the frequency biased factors. The T-L power deviation is:

$$\Delta P_{12} = \frac{(\frac{1}{R_2} + D_2) - \Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + (\frac{1}{R_2} + D_2)} \tag{2.19}$$

$$= \frac{B_2}{(B_1) + B_2}(-\Delta P_{L1})$$

2.7 PID controller

PID is an acronym with three coefficients, which stands for Proportional, Integral and Derivative controller.

2.7.1 Introduction

The PID controller is known for its simplicity of use and robustness in vast application in control engineering field. In industries where complex machines are operated, the need for an automatic control can never be overestimated. The controller is operated by simply connecting the output from a sensor as the input into the controller and then the input is calculated by the summation of the proportional, integral and derivative responses in order to give a desired output as:

Output = Proportional + Integral + Derivative

2.7.2 Structure of PID controller

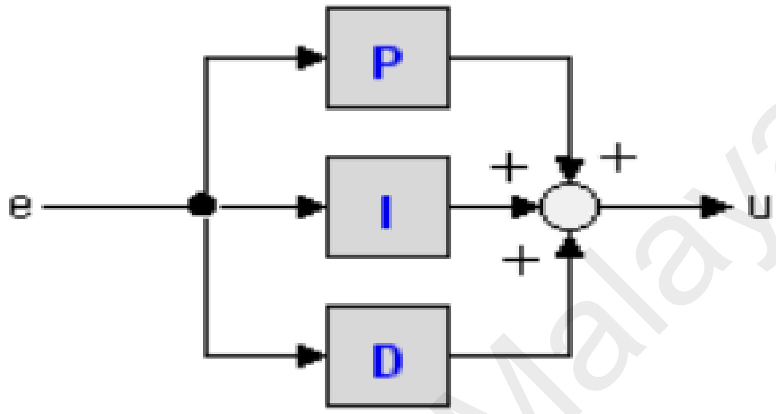

Figure 2.11: PID structure

The mathematical structure of PID controller as shown in Figure 2.11 is:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d(t) + K_d \frac{de(t)}{dt} \quad (2.20)$$

In an industrial controller, there are combination of two controllers. The proportional controller can be represented as:

$\boldsymbol{Output = Gain * Error}$ While $\boldsymbol{Error = Setpoint - ProcessValue}$

The amount of error determines the amount of proportional control needed. This control method has a setback of introducing an offset into the system, which can cause a continuous oscillation if the proportional control is increased further. Thus, proportional controller cannot be used on its own due to oscillation.

$$u(t) = K_p e(t) \quad (2.21)$$

2.7.3 Integral part

The integral control provides an improvement technique, which considers the track of the past position or sum of all previous errors. The error causes an increase in the integral response overtime. The integral response comes into picture in order to eliminate the offset generated by the proportional control. The integral increases overtime unlike the proportional response that remains constant. Hence, integral controller cannot be used on its own due to very slow response.

$$u(t) = K_i \int_0^t e(t)d(t) \tag{2.22}$$

2.7.4 Derivative part

The derivative response looks into the future of the system error before applying a corrective force. It causes the decrease or increase in the output depending on the state of process variable. Its response acts in proportional to the variable deviation.

$$u(t) = K_d \frac{de(t)}{dt} \tag{2.23}$$

CHAPTER 3: OPTIMIZATION OF LOAD FREQUENCY CONTROL

3.1 Introduction

LFC is a mean of setting control limit of system frequency and the line connecting the two or more areas known as T-L. The T-L is a passage through which power exchange takes place, making sure it is within desired set value or close as scheduled. Hence, this method of control of frequency and the T-L power is popularly known as Load Frequency Control (LFC). Studies clearly shows the dependency of frequency on the balance of active power on the tie-line. However, in two or more connected areas, the power generated in each of the area should be able to withstand its connected load and control the power interchange as close as possible to the scheduled power on the tie-line(Yesil, Savran, & Guzay, 2014).

Frequency in a power system can be controlled or maintained effectively within a certain limited value while keeping tie-line power as scheduled. Frequency control is a very powerful factor of consideration on power system. However, the importance of Area Generation Control (AGC) in this case cannot be overemphasized due to its great ability to keep the frequency and T-L power at a scheduled value during normal and slight perturbation(Juang & Lu, 2004). Nowadays, the integration of smart grid improves the reliability of the power supply. Hence, the scheduled frequency can be achieved by controlling the connected loads and the governor at the generating station. There are two major control techniques in LFC namely:

(i) Primary Control

(ii) Secondary Control

The rule of thumb is that the load is proportional to the speed; the change in one affects the other proportionally. The primary control is responsible for the adjustment of the frequency and T-L power by adjusting the governor, which tries to reduce the T-L and frequency deviation to zero by increasing or decreasing the input of the turbine(Mu, Tang,

& He, 2017). The initial re-adjustment of the frequency and tie-line power of governor was done by primary speed control. The governor will try to reduce the speed and T-L power alteration to zero by manipulating the input mechanical power from the turbine(Shayeghi & Ghasemi, 2016). On the other hand, supplementary control adjusts the speed deviation to zero by the use of integral action.

3.2 Design of LFC for two area power systems

In an interconnected two areas system, the yardstick is to keep the frequency at nominal or as close as possible to the nominal value and also to ensure evenly distribution of load among the generators while keeping the power exchange at scheduled value(Jadhav et al., 2012). It is apparent that load changes without any preformation by the consumers causes a constant change in connection of load on the grid which the system should be able to cater for. Considering a connected two-area A and B through a T-L, it is noticed that a change in load in area A will be sensed by area B due to the change in the scheduled T-L value between the two areas(Jamadar & Reddy, 2015). A drop or an increase in the nominal frequency this deviation will trigger the generation in area B in order to keep the frequency and T-L power at set-point value. However, each area is monitored through a module called Area Control Error (ACE), which is responsible for the minimization ACE value to zero by

ACE= Frequency Error + T-L Error

3.3 Imperialist competitive algorithm (ICA)

Imperialistic competitive algorithm is a very powerful evolutionary algorithm for the purpose of optimization technique. Evolutionary Algorithm is a random search commonly used to solve complex problems and multidimensional function of which actual value is unknown (Cheng-Hung Chen & Chen, 2016). The functionality of EA's depends on certain number of individuals or agent populations with certain biological characteristics. There are numbers of EA aside ICA a good example is PSO, GA and GSA. Literarily optimization is the process of making something better putting a low cost as the factor of consideration. Considering a function f(x), in this case, the value of argument *x* can be found at an optimum cost, hence the bone of contention ICA is cost optimism (Esmaeil Atasphaz-Gargari & lucas, 2007).

The principle of operation of imperialistic competitive algorithm is based on countries with respective population. The countries are divided into a group called empire. The strength and power of countries in a region is incomparable. Hence, this factor of power variation is used to select the most powerful countries called imperialist while the less powerful ones are colonies. After the selection of the imperialist empires, the colonies are distributed among the imperialists based on their power and strength. The competition begins after among the imperialists fighting for weaker colonies. The stronger the strength of an empires and its colonies, the easier it is to overcome the weak empires at the long run. The competition ended up with one and strongest empire which possess all other empires and their respective colonies as a single colony. The algorithm is as follows:

(i) Initialization of the imperialist by selecting some random points on the function

(ii) Assimilation by moving the colonies to the imperialist that deserve it.

(iii) Whenever there is a colony in an empire with lower cost than that of the imperialist, exchange the position of the imperialist with the colony.

(iv) Compute the total cost of all the empire.

(v) Select the weakest colonies from the weakest empires and allocate it to the empire or imperialist that deserve to possess it.

(vi) Eradicate the powerless or weak empire

(vii) Stop the iteration if there is only one empire and if not start over from 2

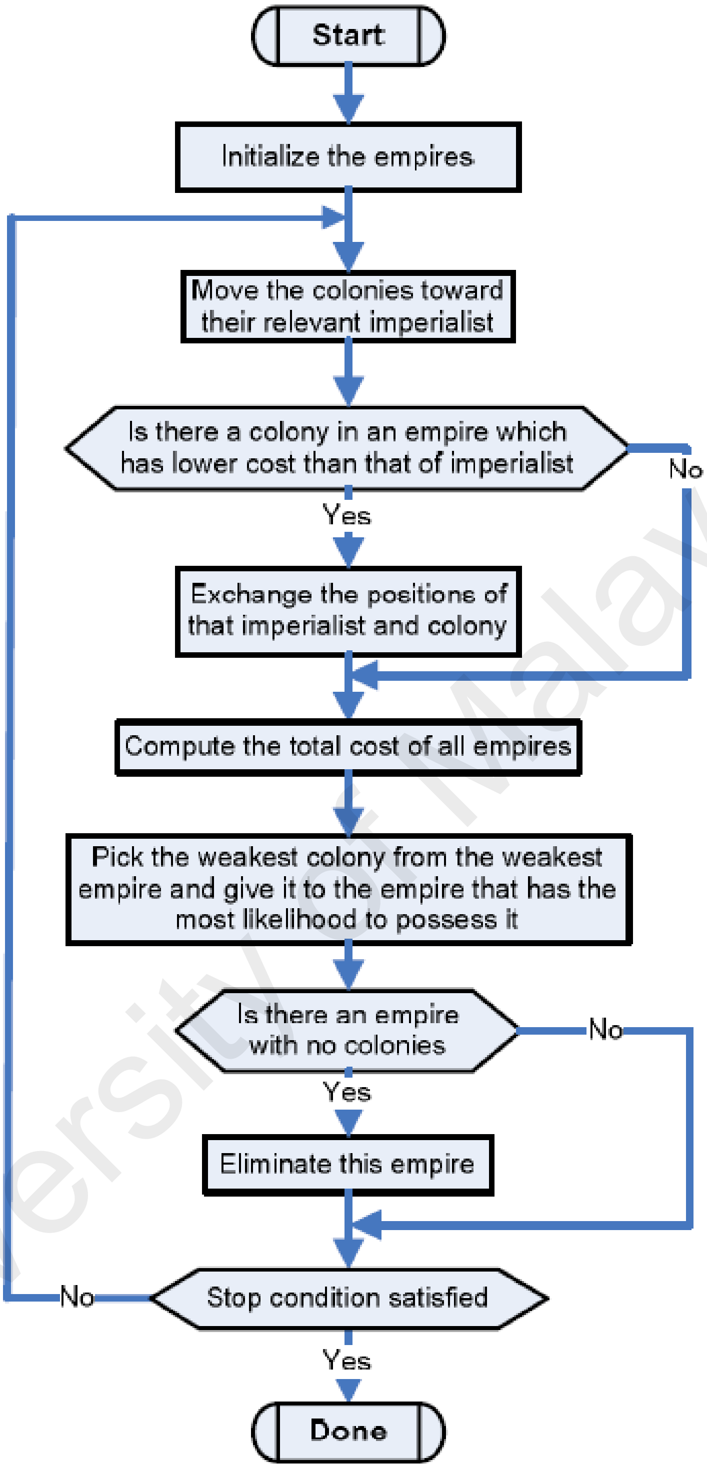

Figure 3.1: Flow Chat of IC Algorithm

3.4 Gravitational search algorithm (GSA)

GSA provides a room for wide dimension search space in solving optimization problems. The exponential increase in the search space with regards to the optimization problem size makes GSA an outstanding algorithm among the traditional optimization technique. It has been shown by researchers for years the need of an algorithm that imitates the natural phenomena (Eldos & Al Qasim, 2013; J.D. Farmer, N.H. Packard, & Perelson., 1986; Marco Dorigo, Vittorio Maniezzo, & Colorni., 1996). However, complex computational problems are best solved using this algorithm such as the optimization of control objectives, image processing, pattern recognition and objective functions (Du & Li, 2008; Yao, Liu, & Lin, 1999). Studies in (Dorigo, Maniezzo, & Colorni, 1996; Kennedy, 2011; Tang, Man, Kwong, & He, 1996) in different area through analysis have shown the existence of different heuristic method such as Genetic, Colony search, PSO, Ant colony Algorithm etc.

However, the robustness and effectiveness of a particular algorithm in solving optimization problems varies with area of application i.e. some provide better or promising solution to problems in a particular area than others (Wolpert & Macready, 1997). One of the proposed techniques in this work is GSA, which is based on the study of gravitational force. The Newton law of gravity is used to explain the working principle of the proposed algorithm. "***Newton's law of universal gravitation states** that a particle attracts every other particle in the universe using a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers*".

The GSA algorithm presents the agents with mass as objects. Objects in the search field with a gravitational force attraction between them, which in turn causes the displacement of an objects with small mass toward the larger mass object. The study of GSA has shown the effect of heavier object over object with lesser weight i.e. massive object provide a better solution. The agents are known with four basic characteristics; position, inertial mass, active gravitational mass, and passive gravitational mass and this are determined using fitness function. However, the mass an agent present a solution, after a few search through the agents in a stated dimension, the heavier agent is expected to have attracted all the lighter agent with less mass. This algorithm can be considered as an artificial world embedded with masses of objects.

3.5 Selection of ICA and GSA parameters

3.5.1 ICA parameters

Let N_{var} be the dimension of the optimization problem which is represented as an array of countries.

$$country = [p_1, p_2, p_3 \ldots . p_{N_{var}}] \tag{3.1}$$

The cost of a country is found as:

$$cost = f(country) = f(p_1, p_2, p_3 \ldots . p_{N_{var}}) \tag{3.2}$$

The population N_{pop} size is needed to start the optimization algorithm from which powerful country is selected as the imperialist N_{imp} while the remaining less powerful countries are the colonies N_{col} each of which are shared among the imperialist or the powerful empires based on their power. Hence there are two set of countries involve in the imperialistic competition which are $imperialist\ and\ the\ colonies$. The normalized cost of an imperialist can be stated mathematically by

$$C_n = c_n - max_i\{c_i\} \tag{3.3}$$

This can be used to deduce the normalized power of each imperialist as

$$p_n = \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \tag{3.4}$$

Then, the number of colonies that needs to be allocated to an imperialist is given as

$$N.C_i = round\{p_n . N_{col}\} \tag{3.5}$$

These colonies along with the imperialist form the empire.

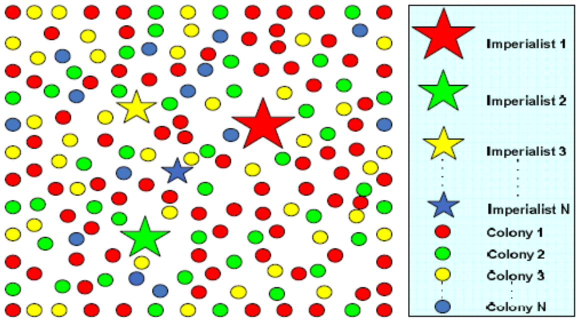

Figure 3.2: Initialization of imperialist

Next is the moving of the colonies to their respective imperialist which they are allocated to. The movement of a particular colony at a distance x toward imperialist as shown in Figure 3.3, while x is a random variable with uniform distribution.

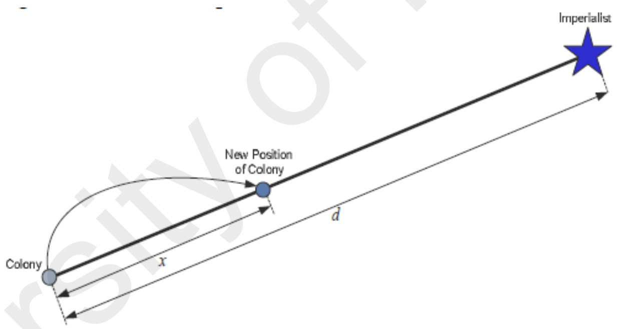

Figure 3.3: Initialization of imperialist

From $x{\sim}U(0, \beta * d)$, with β being greater than 1 causes the colony to move closer to the imperialist from either side. In order to make an effective search around the imperialist, a randomize deviation from the direction of movement is introduced as $\theta{\sim}U(-\gamma, \gamma)$ where γ is the parameter that causes the deviation movement. Research has shown that setting $\beta = 2$ and $\gamma = 0.7854\ rad$ gives a better convergence of the countries to the global minimum.

In a situation where a colony encounter a lesser cost than the imperialist, the colony and the imperialist tend to swap position.

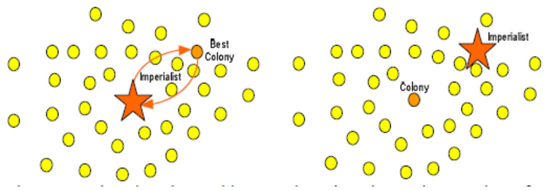

Figure 3.4: Exchange colonies and imperialist position

Next is the evaluation of power of an empire which is mostly affected by the power of the imperialist country while the power of a colony has a negligible effect on the empire. This can be modelled by stating the total cost of an nth empire.

$$TC_n = cost(imperialist_n) + \xi mean\{(colonies\ of\ empire)\} \tag{3.6}$$

Where:

TC_n is the total cost of nth empire.

If ξ is set less than 1, the total power is determined by imperialist and if is greater than 1, the total power is determined by the colonies. Hence, the imperialistic competition commences when the powerful empire conquers the weakest empire and taking over their colonies and controlling them and their territories. This leads to the increase of the strength of powerful empires and an equivalent decrease in the weaker ones. A pictorial display of the imperialistic competition is as shown Figure 3.5.

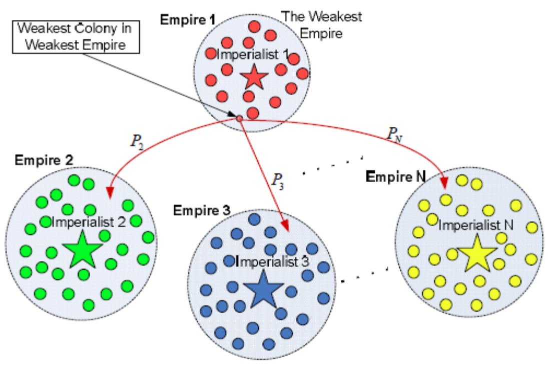

Figure 3.5: Imperialist competition

First empire deserves to possess the weak colonies or empire is found by evaluating its total power. The normalized total cost is obtained by:

$$N.T.C_n = T.C_n - max_i\{T.C_i\} \tag{3.7}$$

Where $T.C_n$ is the total cost while $N.T.C_n$ is the normalized total cost of nth empire. Hence, the probability of an empire taking over a colony or a weak empire as whole is

$$p_{p_n} = \frac{N.T.C_n}{\sum_{i=1}^{N_{imp}} N.T.C_i} \tag{3.8}$$

A vector P $P = [p_{p_1}, p_{p_2}, p_{p_3}, \dots \dots . p_{p_{N_{imp}}}]$ with the probability list of empires with their possibility or capability of taken over a colony and also form another vector with the same size as P and random number uniformly distributed,

$$R = [r_1, r_2, r_3, \dots \dots . r_{N_{imp}}] \tag{3.9}$$

Finally, a vector $D = P - R$ i.e. is created by subtracting R from P, which results in the allocation of the colonies to the empire whose relevant index in D is maximum. The powerless empire will lose in the competition while their colonies are divided among the powerful empire. Finally, when a convergence is reached, all the empire collapses except one with the largest mass will remain and put an end to the algorithm.

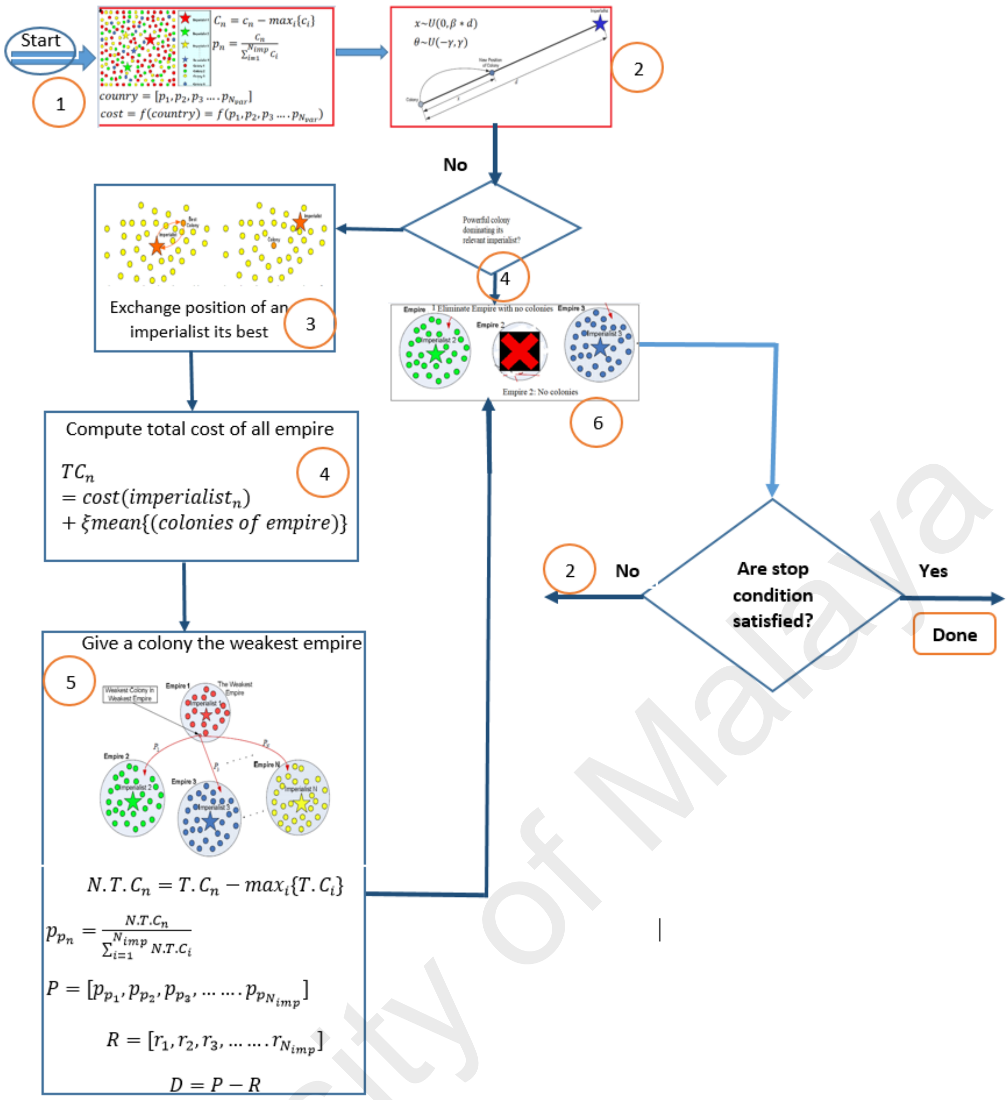

Figure 3.6: Imperialist competition

3.5.2 GSA parameters

Let N be the number of agents with masses with their respective positions as

$$X_i = x_i^1 + x_i^d + \cdots + x_i^n \tag{3.10}$$

where x_i^d Is the position of ith agent in dth dimension.

At a time "t" the force exacted on "i" by "j" is

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t) * M_{aj}(t)}{R_{ij}(t) + \varepsilon}(x_j^d(t) - x_i^d(t)) \tag{3.11}$$

where

M_{pi} → Passive gravitation mass related to agent i.

M_{aj} → Passive gravitation mass related to agent j.

G → Gravitational constant at time "t" which is firstly initialized and reduce with time to control the accuracy of the search and is given as

$G(t) = G(G_0, t)$

ε → A small constant.

R_{ij} → Euclidian distance between agent I & j.

$$R_{ij}(t) = ||x_i(t), x_j(t)||2 \quad (3.12)$$

In other to show the random characteristic to this algorithm, let the force acting on agent i in dimension s is the sum of all other agent exerting force on it,

$$F_i^d(\mathrm{t}) = \sum_{j=1, j\neq i}^{N} rand_j F_{ij}(t) \quad (3.13)$$

$rand_j$ → Random number in interval [0,1].

Thus acceleration of agent i at time t from the law of Motion at dimension d^{th} is

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \quad (3.14)$$

M_{ii} → Initial mass of i^{th} agent.

The next position and velocity of an agent can be calculated by adding he agent present velocity to its acceleration,

$$v_i^d(t+1) = rand_i + v_i^d(t) + a_i^d(t) \tag{3.15}$$

$$x(t+1) = x_i^d(t) + v_i^d(t+1) \tag{3.16}$$

The gravitational and inertia mass of an agent are best calculated by searching for the agent with minimum fitness in case of minimization problem while the reverse is the case in maximization problem,

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \tag{3.17}$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \tag{3.18}$$

$$best(t) = fit_i(t)$$

The performance of GSA algorithm can be improved by allowing the K_{best} only attracts all other weaker agents and this is made possible by monitoring the exploration and exploitation. Recall that the K_{best} is a function of time with an initial K_0 at the beginning which reduce with time,

$$\sum_{j \in K_{best} j \neq i} rand_j F_{ij}^d(t) \tag{3.19}$$

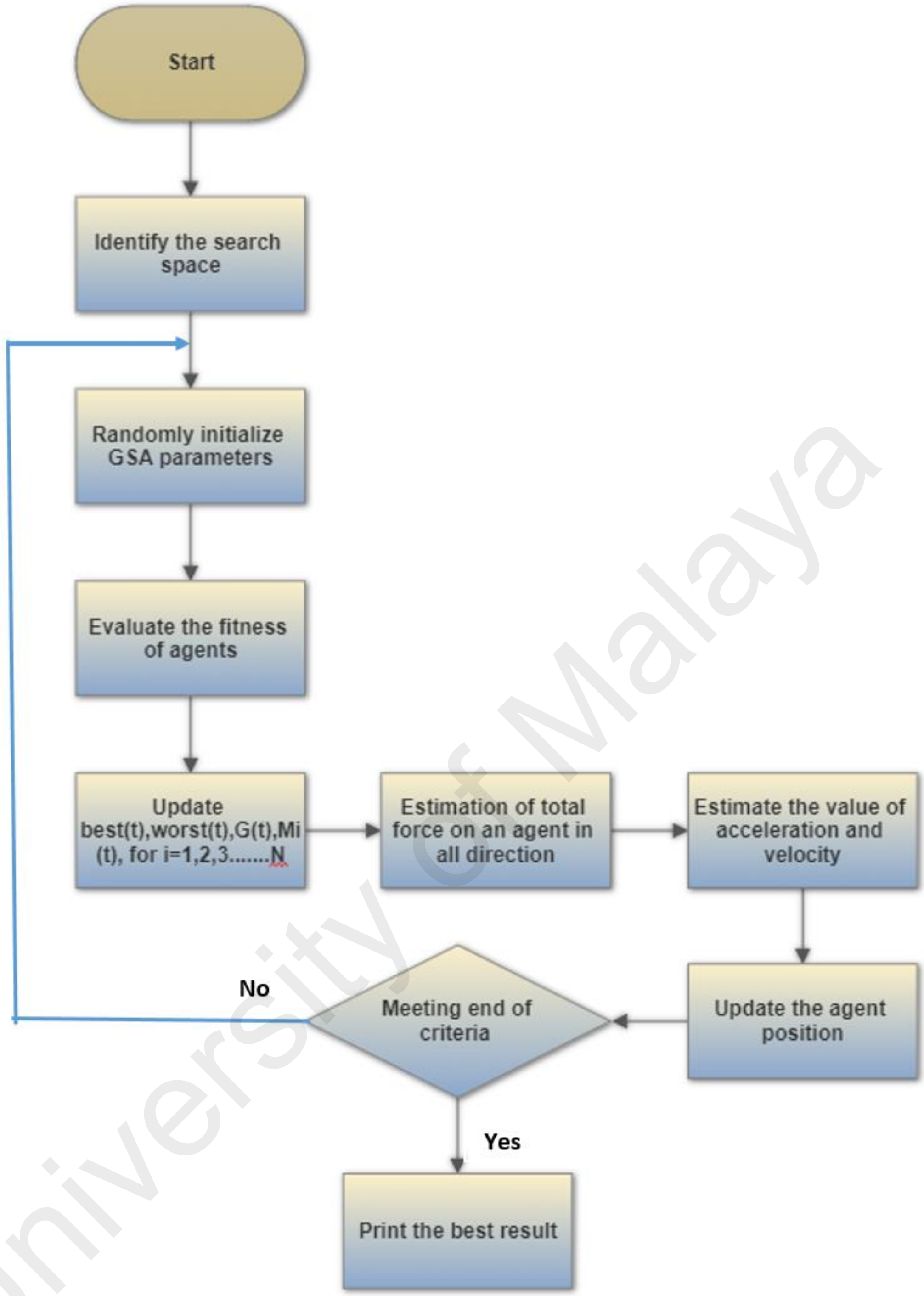

Figure 3.7: GSA Flowchart

The entire steps of GSA can be summarized as follows:

(i) Identify the search space

(ii) Initialize randomly

(iii) Evaluate the fitness of the agents

(iv) Update $best(t), worst(t), G(t), M_i(t)\ for\ i = 1,2,3 \ldots.. N$

(v) Estimation of the total force on an agent in all direction

(vi) Estimate the value of acceleration and velocity

(vii) Update the agent position

(viii) Reiterate from step 3 to step 7 until the stop criteria is reached.

(ix) End

3.6 Tie-line bias control

The need for constant frequency and T-L power is obvious. In order to keep the power system in a normal state of operation to provide the need of connected areas satisfied at nominal frequency, a simplified secondary control (AGC) was introduced. However, the AGC is needed to maintain the frequency and T-L power at the desired value 60Hz or 50Hz. The power system is accustomed to T-L bias control, where each area monitors the area control error (ACE) as it goes to zero. The ACE can be represented mathematically by

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + K_i \Delta\omega \tag{3.20}$$

A favorable performance can be achieved by setting K_i equal to the frequency bias factorB_i. Hence for two area:

$$ACE_1 = \Delta P_{12} + B_1 \Delta\omega_1 \tag{3.21}$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta\omega_2$$

Where ΔP_{12} & ΔP_{21} are deviation from the set-point power, where ACE serves as a sensing mechanism to actuate any deviation from the scheduled power. ΔP_{12} &$\Delta\omega$ are thus set to zero at steady-state. Figure 3.6 shows a simple two area AGC and can be extended to any number of n-areas.

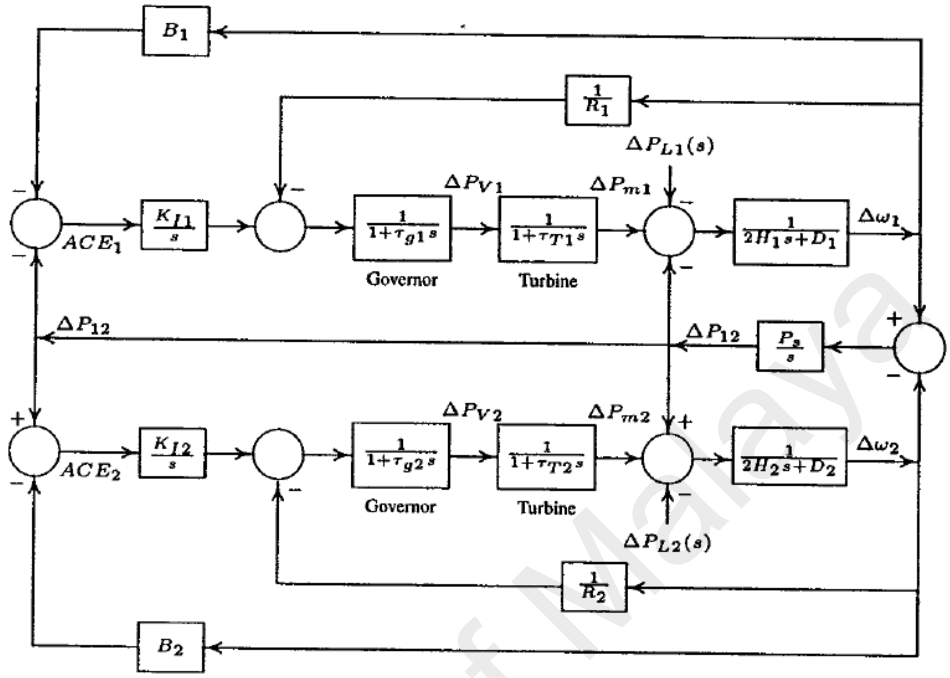

Figure 3.8: Two area system AGC Block Diagram(Saadat, 1999)

3.7 Frequency Deviation

The frequency plays a major role in the power system as a load control. A constant or steady frequency power supply is needed in order to keep the interconnected generators on the power system in synchronism. However, the frequency estimates the difference between the load demand and generation, i.e. an increase or decrease in frequency signal or the change in the load such as overload caused by tripping, generator and transmission line failure. This happens when AGC is needed to restore and maintain the frequency and interchange power as scheduled. Figures 3.9 and 3.10 show the two-area power system with one PID controller and two PID controllers that has been developed in MATLAB Simulink software.

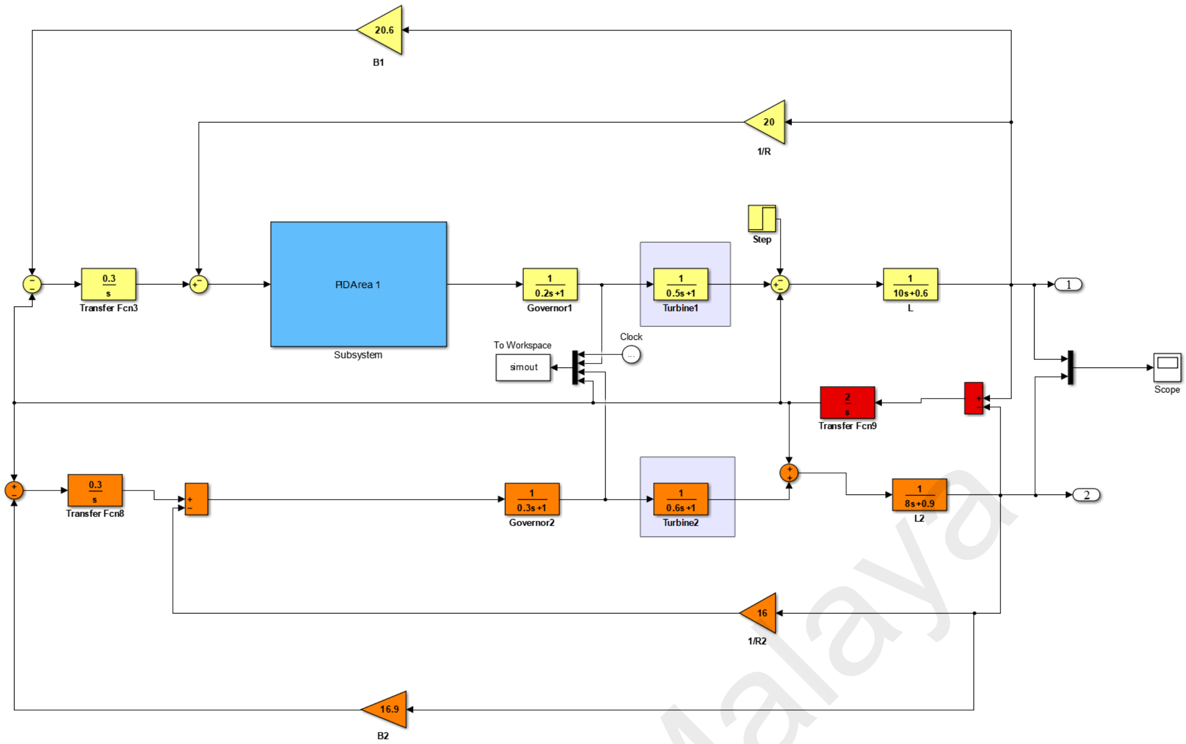

Figure 3.9: Two Area Power System with one PID

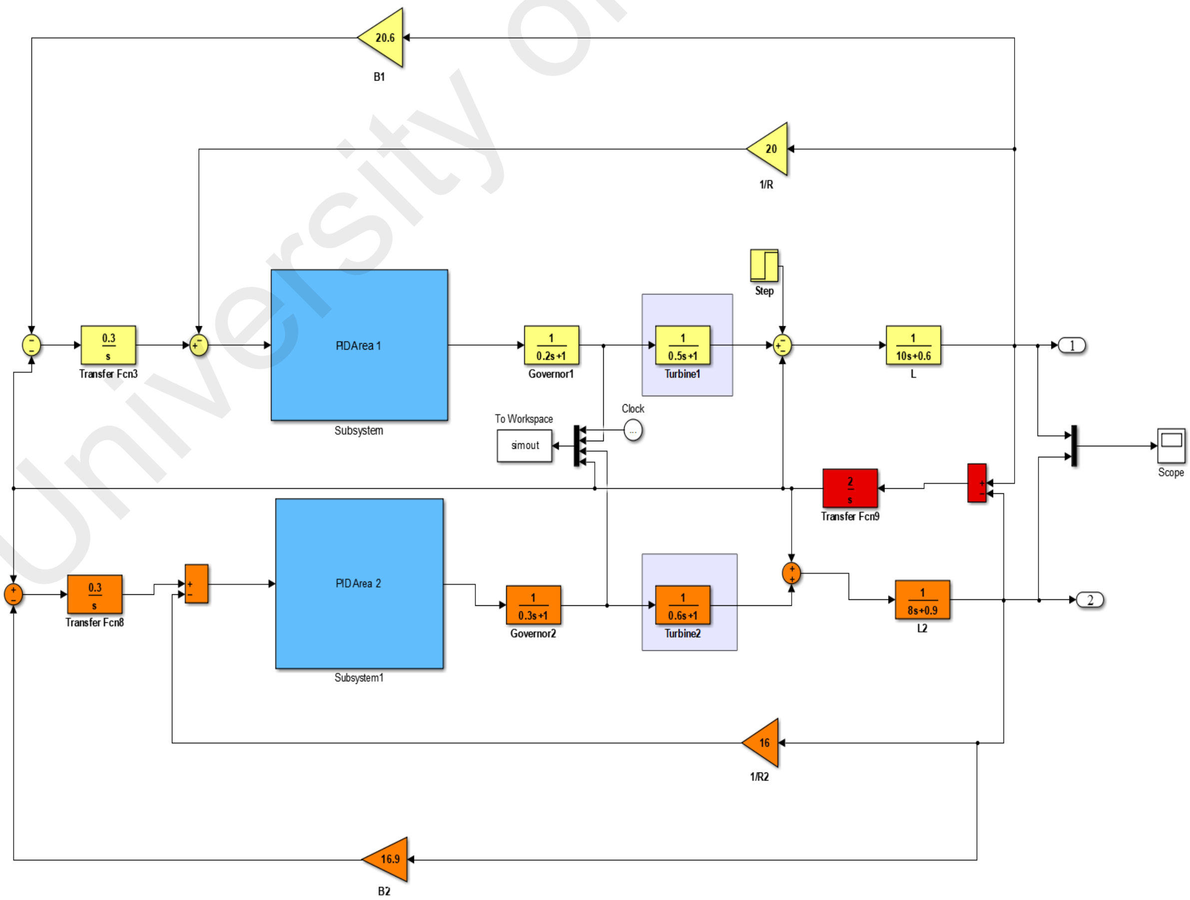

Figure 3.10: Two Area Power System with Two PID

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This section presents the results that been obtained from this work. A comparative study of system responses to perturbation of step load increase of 2% in Area-1 as the baseline of study is presented. The effectiveness of the proposed algorithms (ICA and GSA) to optimize the selection of the PID parameters and how fast their respective response to the perturbation are evaluated. The two interconnected areas are modelled in SIMULINK while the optimization code for the respective algorithm is written in MATLAB editor file. The system was studied with PID in Area-1 and with PID in both areas.

4.2 LFC with one PID controller

The figure 4.1 shows the response of a two-area system under study with only one PID controller connected to Area-1 under a step load change as stated (Area-1). This leads to an undesirable response, which has high rise time and settling time in area one while area two keeps oscillation until it finally comes to a steady state after 50 seconds.

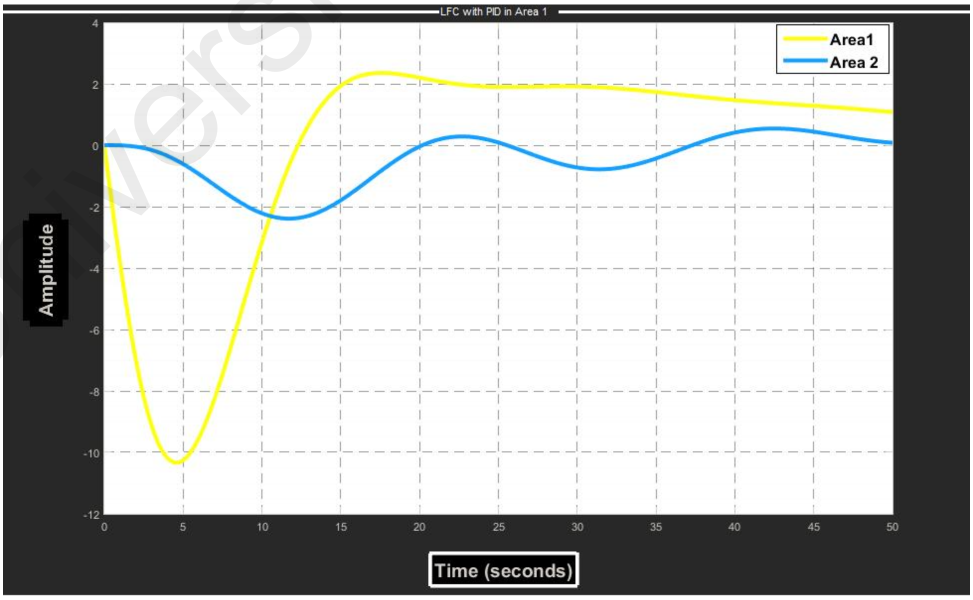

Figure 4.1: Frequency in Area-1 with 1 PID controller without optimization

4.3 LFC with two PID controllers

The response of two interconnected areas with two PIDs is shown in Figure 4.2. It can be seen that a better response than with only 1 PID controller is obtained in term of the settling time in Area-2 and with less ripple or oscillation:

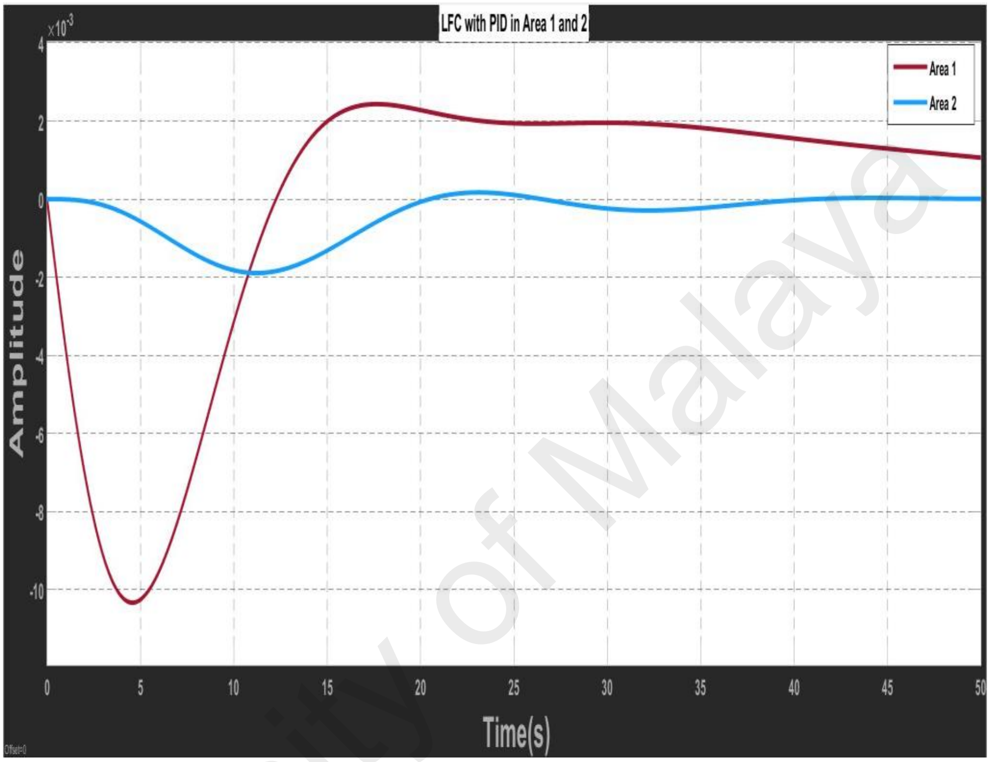

Figure 4.2: The frequency deviation in Area 1 and 2 with 2PID controller without optimization

4.4 Optimization of LFC with one PID controller

The PID controller parameters (Kp, Ki, Kd) were selected with the proposed optimization techniques, ICA and GSA. The respective results for each algorithm are presented in Table 1 and 2 below. Each technique was run 30 times with 30 iterations under the same condition of step input load change of 2% in Area1. Figure 4.3 shows the response of the system to the load change while Figure 4.4 shows the fitness of the ICA under this condition. Figures 4.5 to 4.8 shows the responses and fitness by using GSA.

Table 4.1: Optimization using ICA with one PID controller in Area 1

Runs	Kp1	Ki1	Kd1	RT_A1	ST_A1	RT_A2	ST_A2	Fitness
1	2.6798	1.3075	1.5198	0.0026	16.2318	0.0195	26.8266	4.3897
2	0.2492	0.3321	1.6629	0.0026	16.2318	0.0195	26.8266	4.3897
3	3.4388	0.2908	1.0291	0.0026	16.2318	0.0195	26.8266	4.3897
4	0.5235	1.9938	0.7244	0.0026	16.2318	0.0195	26.8266	4.3897
5	4.0892	0.3555	1.3555	0.0026	16.2318	0.0195	26.8266	4.3897
6	3.6963	0.7516	0.9120	0.0026	16.2318	0.0195	26.8266	4.3897
7	1.8628	0.1376	0.8925	0.0026	16.2318	0.0195	26.8266	4.3897
8	4.6608	0.2492	1.2177	0.0026	16.2318	0.0195	26.8266	4.3897
9	1.5705	0.2241	1.3922	0.0026	16.2318	0.0195	26.8266	4.3897
10	3.7684	1.6061	0.8884	0.0026	16.2318	0.0195	26.8266	4.3897
11	0.8901	0.7509	1.9736	0.0026	16.2318	0.0195	26.8266	4.3897
12	0.1556	1.1099	1.281	0.0026	16.2318	0.0195	26.8266	4.3897
13	2.6798	1.3075	1.5198	0.0026	16.2318	0.0195	26.8266	4.3897
14	0.2493	0.3321	1.6629	0.0026	16.2318	0.0195	26.8266	4.3897
15	2.1996	0.1680	0.8213	0.0026	16.2318	0.0195	26.8266	4.3897
16	0.1144	1.9776	0.1828	0.0026	16.2318	0.0195	26.8266	4.3897
17	3.7704	0.40966	1.7742	0.0026	16.2318	0.0195	26.8266	4.3897
18	4.4586	1.7571	0.3793	0.0026	16.2318	0.0195	26.8266	4.3897
19	1.1896	1.2354	0.6296	0.0026	16.2318	0.0195	26.8266	4.3897
20	0.1933	1.6089	0.6806	0.0026	16.2318	0.0195	26.8266	4.3897
21	4.5833	1.7907	1.0413	0.0026	16.2318	0.0195	26.8266	4.3897
22	0.8619	0.44248	0.8896	0.0026	16.2318	0.0195	26.8266	4.3897
23	3.7375	1.5832	1.8632	0.0026	16.2318	0.0195	26.8266	4.3897
24	4.6091	1.9671	1.3424	0.0026	16.2318	0.0195	26.8266	4.3897
25	3.0589	0.52434	1.4267	0.0026	16.2318	0.0195	26.8266	4.3897
26	2.6915	1.205	0.2774	0.0026	16.2318	0.0195	26.8266	4.3897
27	4.783	1.6335	0.8327	0.0026	16.2318	0.0195	26.8266	4.3897
28	0.5871	0.06454	0.3727	0.0026	16.2318	0.0195	26.8266	4.3897
29	2.314	1.6641	1.244	0.0026	16.2318	0.0195	26.8266	4.3897
30	1.6503	1.6801	1.0604	0.0026	16.2318	0.0195	26.8266	4.3897
				0.0026	**16.2318**	**0.0195**	**26.8266**	**4.3897**

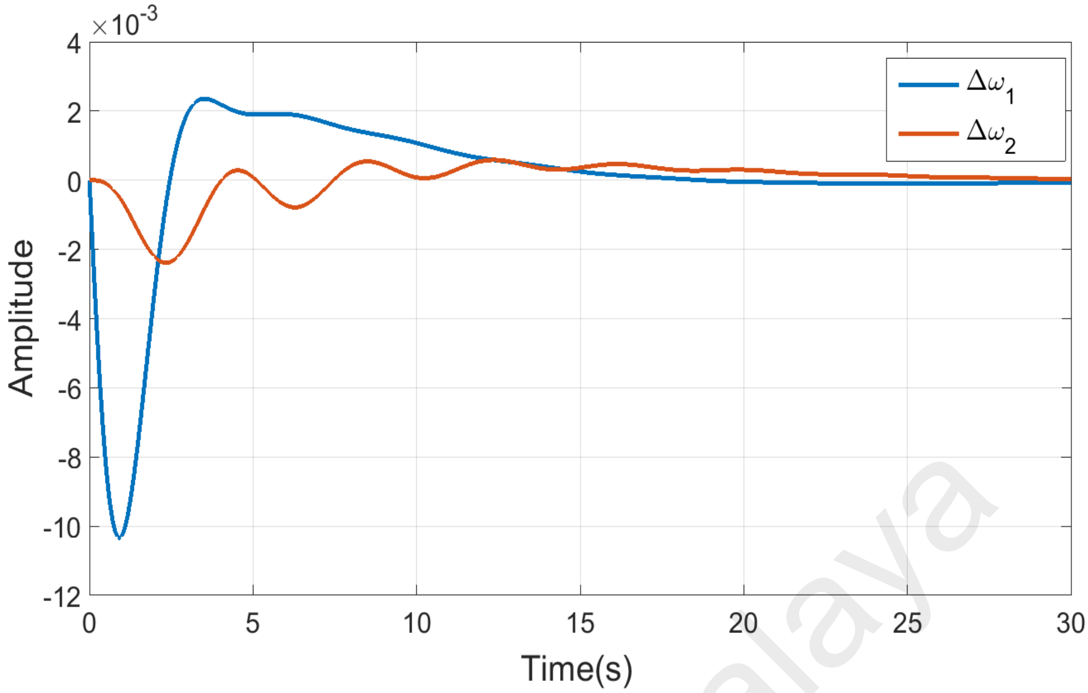

Figure 4.3: Frequency response with one PID controller using ICA

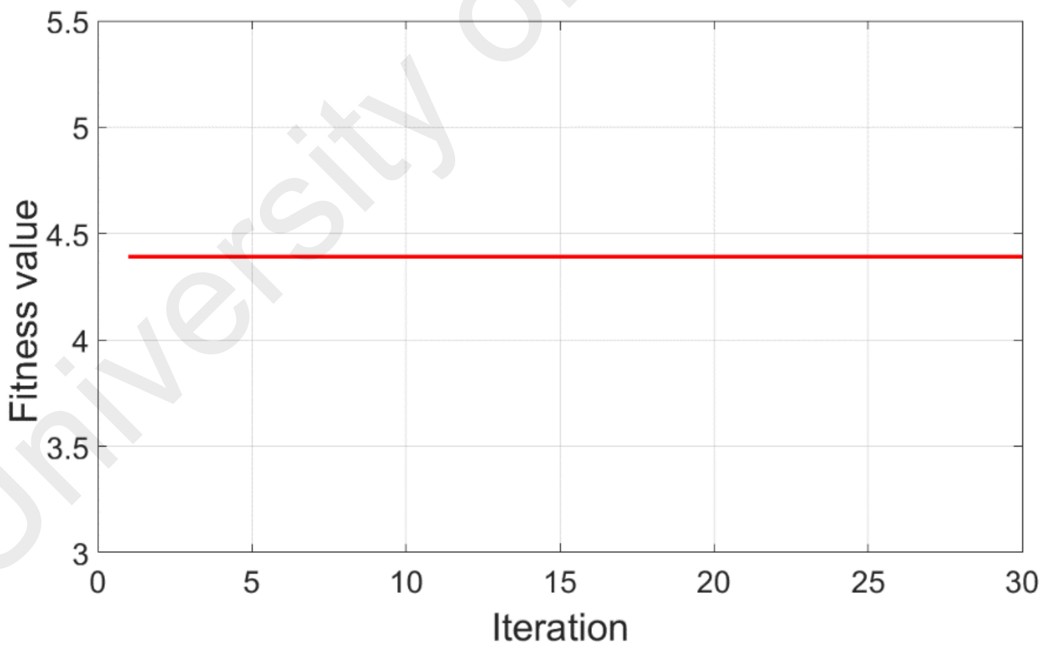

Figure 4.4: Convergence curve for ICA for 1 PID controller

Table 4.2: Optimization using GSA with one PID controller in Area 1

Run	Kp1	Ki1	Kd1	RT_A1	ST_A1	RT_A2	ST_A2	Fitness
1	1.0396	1.4967	0.6548	1.41E-04	15.5302	0.1084	21.4762	1.2048
2	0.9955	1.0624	1.0596	1.04E-04	15.8064	0.0934	21.2052	1.2179
3	0.7947	1.5415	1.8419	0.0049	28.533	0.1333	28.9914	1.2559
4	1.2211	1.9647	0.0571	6.3997	29.989	6.4107	29.9772	1.2567
5	1.3389	1.5002	0.153	0.1073	29.9898	0.5223	29.9889	1.1919
6	1.6586	1.7528	0.8722	6.24E-05	8.8497	0.0893	20.8427	1.2375
7	1.6103	1.6802	1.7138	5.42E-05	11.6369	0.078	21.141	1.2258
8	1.9471	1.519	0.7158	9.90E-05	9.2508	0.0835	20.7616	1.2444
9	1.3024	0.6823	0.7566	4.22E-04	11.3865	0.0996	24.4253	1.2103
10	1.0896	1.5314	1.3937	9.18E-04	15.0691	0.075	20.4991	1.2727
11	1.0939	1.9799	1.3667	1.18E-04	18.3959	0.0941	21.636	1.2221
12	1.9475	1.9608	1.3092	0.0108	29.4569	0.1581	29.6113	1.2574
13	1.8449	1.9886	1.5034	26.2537	29.9481	26.3102	29.9261	1.2705
14	1.8763	1.8459	1.8419	0.0236	29.8033	0.3601	29.5042	1.2558
15	1.9711	1.9436	1.3638	8.5393	29.9742	8.6177	29.9802	1.2405
16	1.9998	1.8334	1.6446	1.39E-04	14.7798	0.0934	21.0048	1.2148
17	1.9448	1.8757	1.5677	0.0016	27.3716	0.1001	23.1049	1.2331
18	1.91	1.7982	1.7208	1.22E-04	9.843	0.091	21.1116	1.2522
19	1.9599	1.9155	1.5289	2.15E-04	10.7549	0.085	24.1581	1.224
20	1.9881	1.9653	1.3935	4.00E-05	11.5202	0.1081	24.575	1.2244
21	1.9083	1.8933	1.4569	0.0016	17.136	0.069	27.8415	1.2588
22	1.7929	1.9028	1.9148	9.57E-05	15.3594	0.0891	21.2366	1.2936
23	1.9326	1.77	1.9536	0.0017	19.182	0.3251	28.394	1.2412
24	1.9685	1.9282	1.8782	0.0015	16.1063	0.0486	27.3713	1.1926
25	1.9316	1.9319	1.7987	9.16E-04	12.4558	0.0979	25.4254	1.2128
26	1.9514	1.8811	1.774	0.0019	27.899	0.081	22.0494	1.2133
27	**1.9821**	**1.9262**	**1.5656**	**3.98E-05**	**16.9466**	**0.1058**	**21.2223**	**1.2089**
28	1.9393	1.9709	1.5944	2.72E-04	23.6625	0.0454	23.7559	1.2148
29	1.9791	1.9559	1.8269	8.92E-05	14.2056	0.1168	25.0459	1.1845
30	1.9754	1.8382	1.6291	9.75E-04	17.6629	0.0273	27.186	1.2235
	Average Fitness			1.38E+00	18.95018	1.49058	24.7816	1.23189

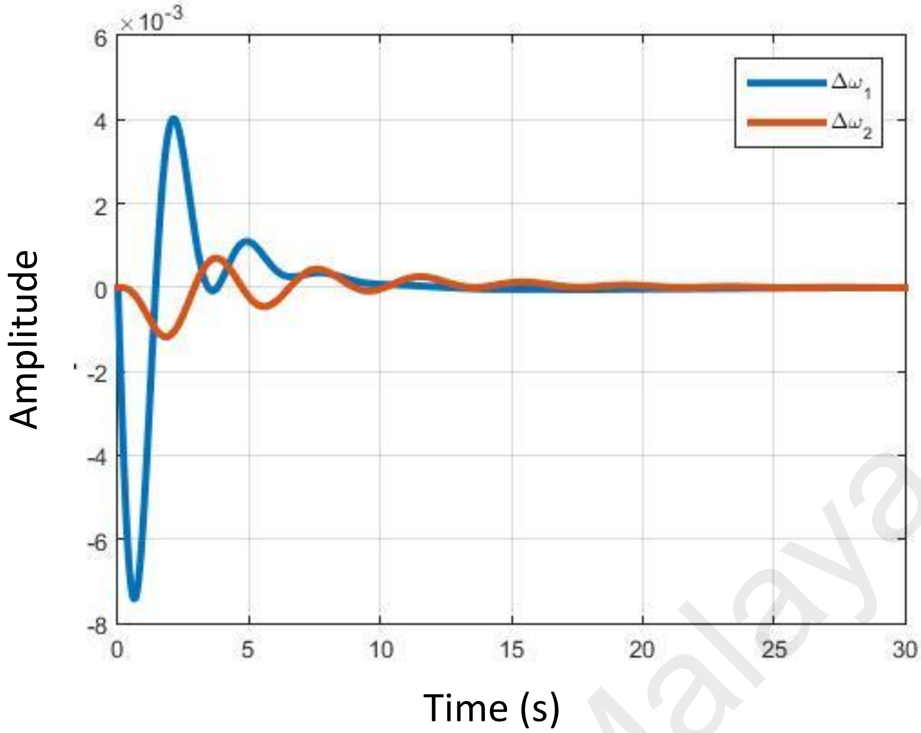

Figure 4.5: Frequency response with one PID controller using GSA

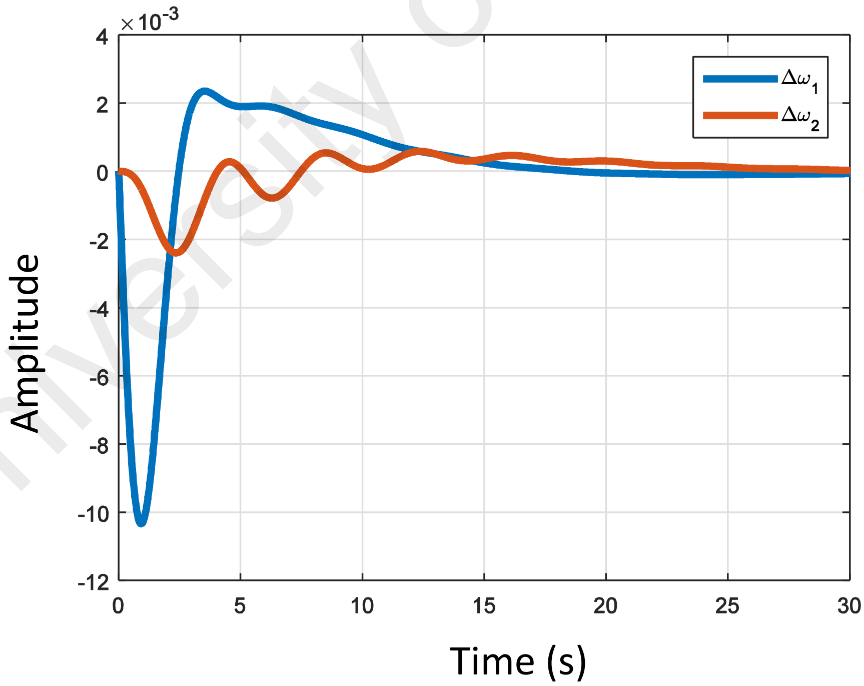

Figure 4.6: Frequency response with one PID controller using GSA

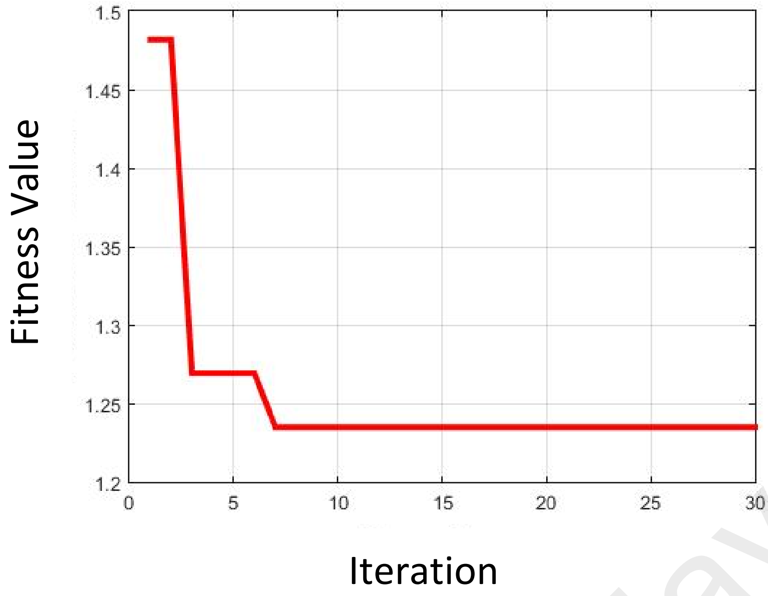

Figure 4.7: Convergence curve for GSA for 1 PID controller

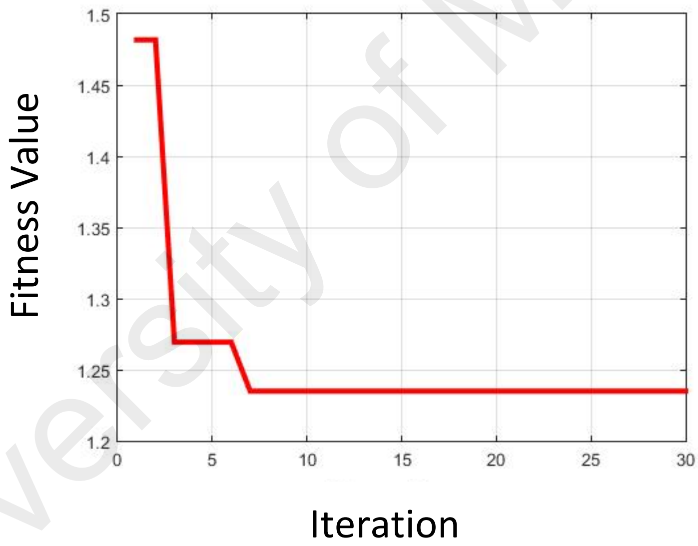

Figure 4.8: Convergence curve for GSA for 1 PID controller

4.5 Optimization of LFC with two PID controllers

In this case connection of PID controller to both areas were considered with the optimization technique i.e. ICA and GSA being applied to the selection of the controller parameters (Kp, Ki, Kd). Hence the respective result for each algorithm are presented in the table (4.3 and 4.4) below for each technique respectively for total 30 runs each with total 30 number of iteration with consideration of a step input load change of 2% in Area1. The ICA response graph and fitness is as shown in Figure (4.9 and 4.10) below while figure (4.11 and 4.12) reveals the system response with GSA with the fitness in Figure 4.13

Table 4.3: PID controller parameters in Area 1 and 2 using ICA

Run	Kp1	Ki1	Kd1	Kp2	Ki2	Kd2	RT_A1	ST_A1	RT_A2	ST_A2	Fitness
1	1.818	1.241	0.621	0.378	1.261	1.745	0.003	15.8056	0.161	28.2086	4.1229
2	2.461	0.427	1.790	2.129	1.701	0.365	0.003	15.8056	0.161	28.2086	4.1229
3	1.668	1.211	1.709	2.761	0.248	1.927	0.003	15.8056	0.161	28.2086	4.1229
4	3.629	0.519	0.216	2.867	0.505	1.213	0.003	15.8056	0.161	28.2086	4.1229
5	4.215	0.847	1.219	3.440	0.788	1.521	0.003	15.8056	0.161	28.2086	4.1229
6	4.777	0.457	0.251	3.997	0.285	1.757	0.003	15.8056	0.161	28.2086	4.1229
7	0.283	1.313	0.973	2.553	1.585	1.051	0.003	15.8056	0.161	28.2086	4.1229
8	2.588	0.736	1.232	1.446	0.217	1.410	0.003	15.8056	0.161	28.2086	4.1229
9	2.032	0.779	1.319	0.208	0.500	1.662	0.003	15.8056	0.161	28.2086	4.1229
10	2.902	0.175	1.817	4.288	0.895	1.666	0.003	15.8056	0.161	28.2086	4.1229
11	4.499	0.737	0.885	0.765	1.077	1.726	0.003	15.8056	0.161	28.2086	4.1229
12	3.181	0.825	1.117	0.052	1.793	1.926	0.003	15.8056	0.161	28.2086	4.1229
13	4.513	0.838	0.047	2.876	1.217	0.190	0.003	15.8056	0.161	28.2086	4.1229
14	4.719	1.073	0.995	2.499	0.201	1.419	0.003	15.8056	0.161	28.2086	4.1229
15	0.873	1.130	0.805	0.394	1.554	1.784	0.003	15.8056	0.161	28.2086	4.1229
16	3.339	0.476	0.883	1.880	1.985	1.421	0.003	15.8056	0.161	28.2086	4.1229
17	0.881	1.928	0.028	3.239	0.220	1.501	0.003	15.8056	0.161	28.2086	4.1229
18	4.319	1.887	1.060	0.614	1.347	1.120	0.003	15.8056	0.161	28.2086	4.1229
19	0.057	1.314	0.078	2.970	1.849	0.664	0.003	15.8056	0.161	28.2086	4.1229
20	2.468	0.153	0.661	3.42	1.372	1.723	0.003	15.8056	0.161	28.2086	4.1229
21	2.583	0.722	1.014	2.330	1.298	1.689	0.003	15.8056	0.161	28.2086	4.1229
22	4.363	0.791	0.488	3.747	1.636	1.110	0.003	15.8056	0.161	28.2086	4.1229
23	1.668	1.211	1.709	2.760	0.248	1.926	0.003	15.8056	0.161	28.2086	4.1229
24	2.032	0.779	1.319	0.208	0.500	1.662	0.003	15.8056	0.161	28.2086	4.1229
25	0.873	1.130	0.805	0.394	1.554	1.784	0.003	15.8056	0.161	28.2086	4.1229
26	1.668	1.211	1.709	2.761	0.248	1.926	0.003	15.8056	0.161	28.2086	4.1229
27	4.309	1.426	1.747	4.691	0.288	0.794	0.003	15.8056	0.161	28.2086	4.1229
28	0.607	1.774	1.940	4.713	1.279	0.190	0.003	15.8056	0.161	28.2086	4.1229
29	2.468	0.154	0.661	3.42	1.372	1.724	0.003	15.8056	0.161	28.2086	4.1229
30							**0.003**	**15.8056**	**0.161**	**28.2086**	**4.1229**

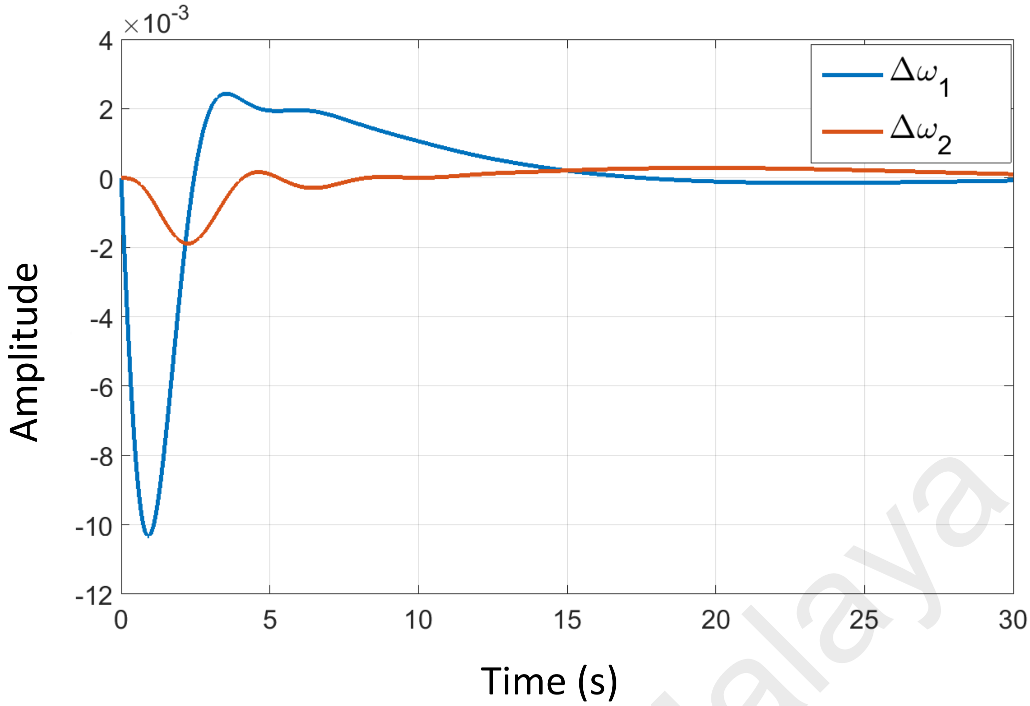

Figure 4.9: Frequency deviation with 2 PID controller in Area 1 & 2 using ICA

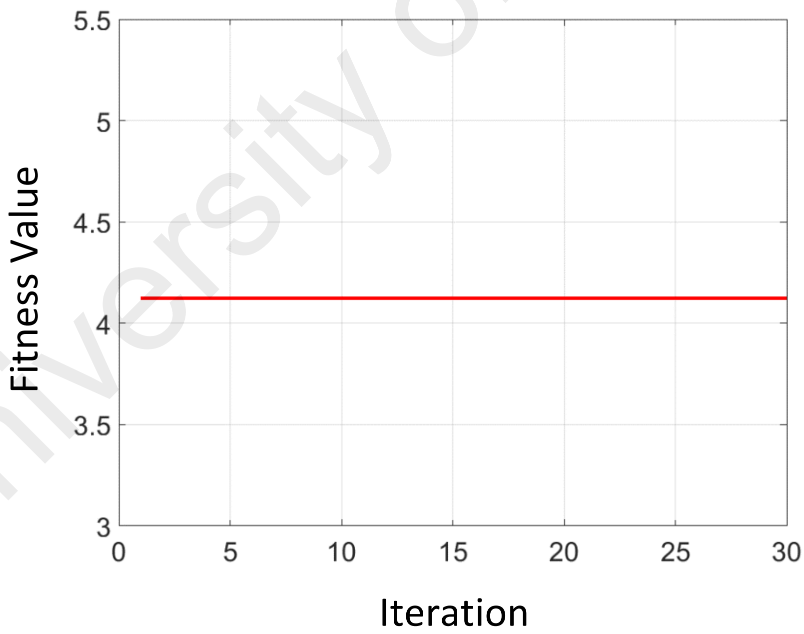

Figure 4.10: Convergence curve for ICA for 2 PID controllers

Table 4.4: PID controller parameters in Area 1 and 2 using GSA

Run	Kp1	Ki1	Kd1	Kp2	Ki2	Kd2	RT_A1	ST_A1	RT_A2	ST_A2	Fitness
1	1.956	1.942	1.743	1.088	1.189	1.605	0.002	15.922	0.146	26.416	1.164
2	1.965	1.803	1.401	1.253	1.894	0.823	0.004	27.337	0.159	28.049	1.243
3	1.998	1.869	1.772	1.018	0.997	1.325	0.004	27.439	0.319	29.936	1.176
4	1.957	1.959	1.272	1.560	0.713	0.796	0.947	29.905	8.142	29.782	1.140
5	1.954	1.730	1.570	1.626	0.925	0.863	0.002	9.919	0.131	25.915	1.185
6	1.972	1.856	1.021	1.848	0.843	1.964	6.07E-04	10.363	0.030	29.887	1.194
7	1.633	1.961	1.332	1.951	0.136	1.964	29.186	29.906	9.077	29.987	1.301
8	1.866	1.756	1.820	1.421	1.862	0.814	0.0045	21.548	0.142	26.492	1.241
9	1.844	1.656	1.972	1.714	0.410	0.659	0.0107	28.163	0.078	27.944	1.236
10	1.838	1.920	1.904	1.915	1.211	0.493	0.0012	18.345	0.346	29.653	1.194
11	1.953	1.899	0.679	1.498	1.224	1.484	0.0021	19.075	0.120	26.879	1.348
12	1.773	1.716	1.196	1.847	0.091	1.627	0.0042	22.055	0.169	29.859	1.287
13	1.788	1.735	1.206	1.569	1.377	1.562	0.0017	28.454	0.071	23.789	1.292
14	1.986	1.919	1.276	1.394	0.123	0.224	0.2409	29.939	17.793	29.599	1.154
15	1.989	1.592	1.692	1.568	0.593	1.937	1.3099	29.927	0.4181	29.884	1.222
16	1.920	1.784	1.503	1.566	1.423	0.511	15.034	29.518	1.5506	29.937	1.231
17	1.905	1.780	1.736	1.489	0.909	1.903	0.9355	29.655	0.8091	29.618	1.182
18	1.839	1.558	1.575	1.809	1.356	1.231	0.013	26.633	0.3145	29.478	1.302
19	1.983	1.925	1.009	1.984	1.471	0.975	0.0005	7.7153	0.1786	28.522	1.205
20	1.750	1.955	1.910	1.572	0.139	0.644	0.0012	8.5732	0.2934	29.754	1.228
21	1.750	1.955	1.91	1.573	0.139	0.644	0.0012	8.5732	0.2934	29.754	1.229
22	1.750	1.954	1.91	1.572	1.573	0.644	0.0012	8.5732	0.2934	29.754	1.229
23	1.977	1.697	1.114	1.597	0.062	0.612	0.0079	26.903	0.1518	29.879	1.224
24	1.916	1.749	1.195	1.122	0.283	1.852	6.07E-05	10.148	0.0038	23.049	1.243
25	1.837	1.925	0.975	1.947	0.804	0.558	0.0016	26.822	0.1649	27.601	1.261
26	1.926	1.777	1.625	1.693	1.490	0.823	0.001	18.835	0.117	25.896	1.195
27	1.953	1.788	1.813	1.305	1.399	1.033	0.0016	9.2346	0.1233	26.068	1.194
28	1.871	1.958	1.329	1.108	1.422	1.809	0.0107	27.447	0.0751	28.333	1.211
29	1.844	1.656	1.972	1.714	0.410	0.659	0.0107	28.163	0.078	27.944	1.236
30	1.956	1.942	1.743	1.088	1.189	1.605	0.002	15.922	0.146	26.416	1.164

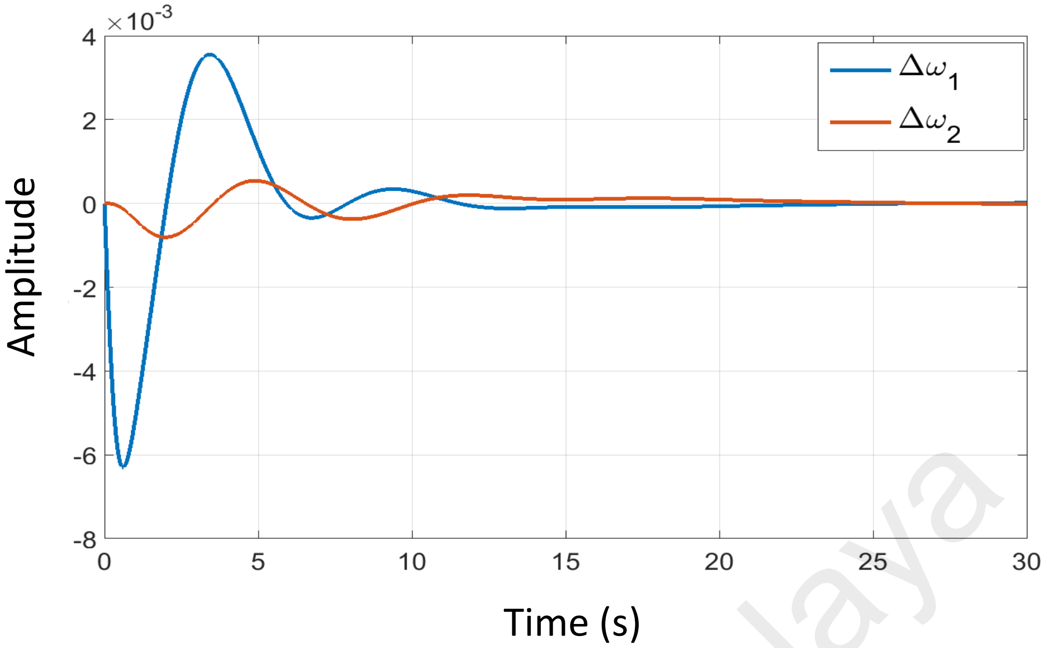

Figure 4.11: Frequency deviation with 2 PID controller in Area 1 & 2 using GSA

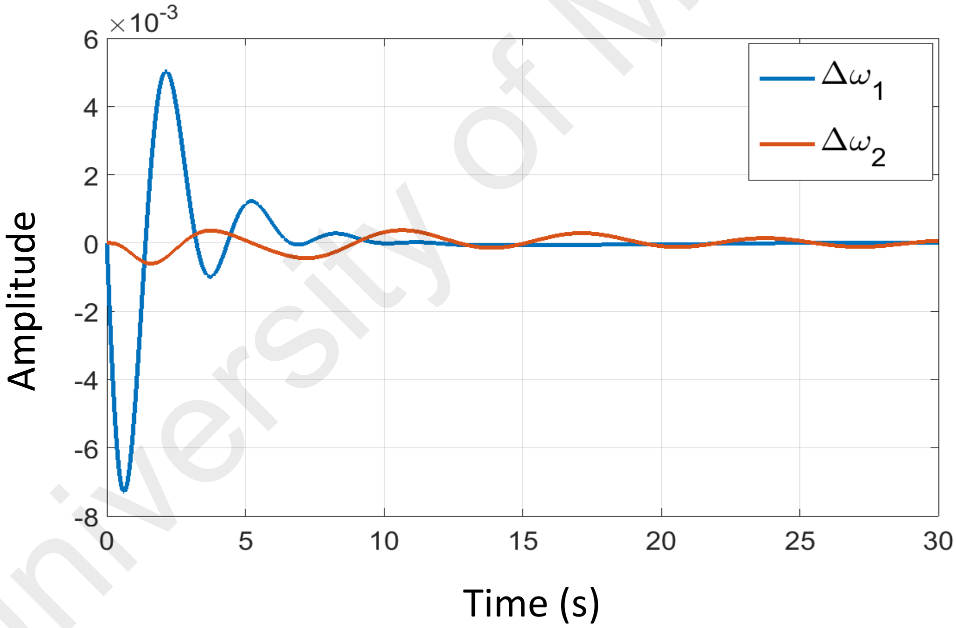

Figure 4.12: Frequency deviation with 2 PID controller in Area 1 & 2 using GSA

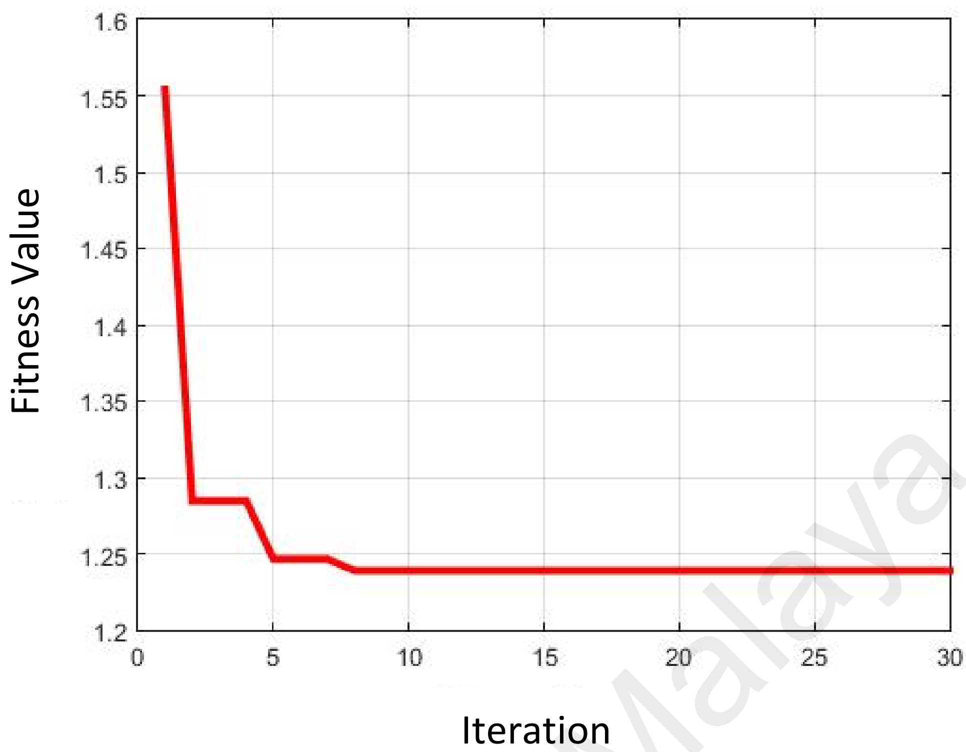

Figure 4.13: Convergence curve for GSA for 2 PID controllers

4.6 Comparison between using one and two PID controllers

This section presents a comparative study of the research work. Table 4.5 shows the selected best results from the pool of results obtained with and without optimization.

Table 4.5: Best Results

	Optimization Technique	Rise Time Area 1	Rise Time Area 2	Settling Time Area 1	Settling Time Area 2
1 PID Controller	N/A	11	0	∞	50
1 PID Controller	ICA	0.0026	0.0195	16.2318	26.8266
1 PID Controller	GSA	0.000039	0.0273	8.8497	20.4991
2 PID Controller	N/A	11	0	∞	38
2 PID Controller	ICA	0.003	0.161	15.8056	28.2086
2 PID Controller	GSA	0.000061	0.0038	7.7153	23.0493

4.7 Discussion

At this instance, a slight change in load or in the presence of disturbance in any area will lead to undesirable change in power system parameters such as the frequency and power exchange across the T-L. Figures 4.1 and 4.2 show the possible response that may arise when there is a change or an increase in the load demand, which can lead to deviation of the frequency reference point. The observation from the graph shows the level at which the conventional PID can contribute to the adjustment of the deviance in the system frequency back to the set-point 50/60 Hz as the case may be. The weakness of the conventional PID controller is obvious in both cases with undesirable high response rise time and continuous oscillation, which is more apparent with only PID in one area only. Hence, two PID controllers can be considered to provide a better solution though with its own downside response and cannot be implemented or use in real life situation. This is where the need for optimization arises.

Consider a two-area power system network with a 2% step increase in the demand in power demand in Area-1 and with a time delay of 2 seconds. The change in the power system can never be overemphasized in a second. Hence a change in power system is considered to be normal. This unavoidable situation calls for continuous research for fast and optimum solution to withstand the change on the system at any instance of time. This instance however presents an optimization technique on a two-area system with PID controller connected to Area-1. The selected optimization techniques, ICA and GSA algorithm, have helped to enhance a proper selection of the PID controller parameters for fast and optimum response. After several studies using both optimization techniques, the best of the results is as shown in Table 4.1 and 4.2 and it shows that GSA yields a better response compared to ICA in terms of the rise time and settling time areas. ICA was observed to provide a constant response (settling and rise time in both area) in the entire run of the simulation while GSA provides various promising results at different convergence time to a solution with lesser settling time and rise time as shown in Figure 4.14.

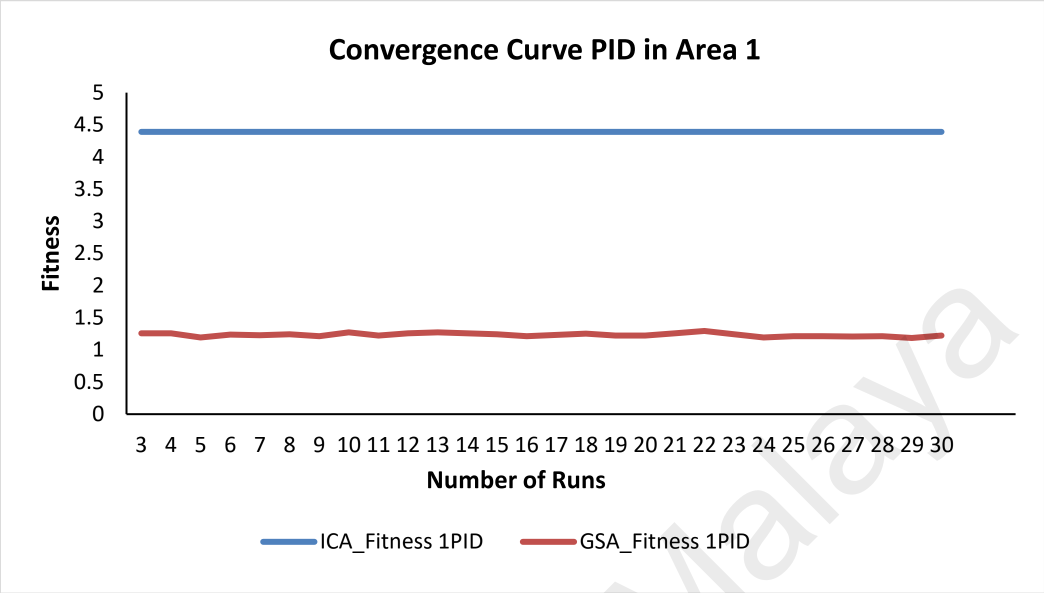

Figure 4.14: Fitness vs. number of runs for LFC in two-area system with 1 PID controller connected to Area-1

Furthermore, this section presents a study using two PID controllers connected in Area-1 and-2 with all other connections unaltered. The two-area system was modelled as interconnected power system with a 2% rise in the power demand in Area-1 with a time delay of 2 seconds. The selected optimization techniques, ICA and GSA algorithms, have helped to enhance a proper selection of the PID controller parameters for fast and optimum response. After several studies of both optimization techniques under this condition, GSA still retains its effectiveness and robustness over ICA as presented in the convergence curve as shown in Figure 4.15. Observing closely from the selected best results for both optimization as shown in Table 4.5 and Figure 4.15, the fast response of GSA makes it a preferable solution compared to ICA.

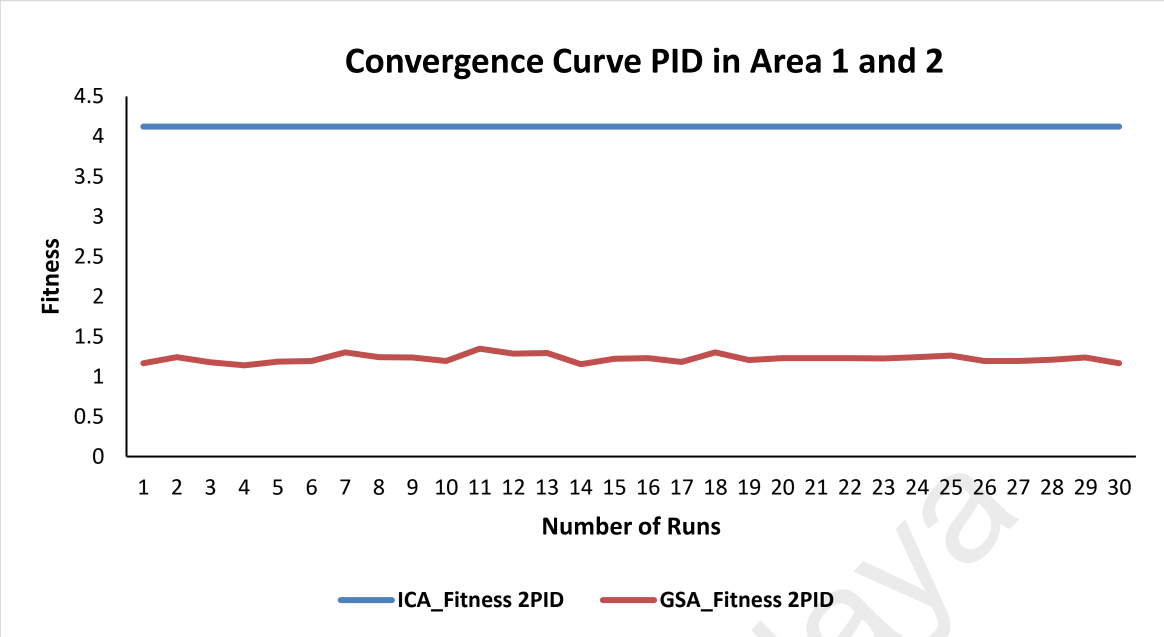

Figure 4.15: Fitness vs. number of runs for LFC in two-area system with 1 PID controller connected to Area-1 and Area-2

Based on analysis of the result in this report with other algorithms used for LFC study in the literature, the effectiveness and robustness of the GS-Algorithm over Craziness-PSO (CPSO) has been made apparent by using PI and PID controllers. ITAE and ISE were used as the response measurement criteria for automatic generation control in a two-area power system, as presented in Table 4.6. The model used in this report was tested under same condition with (Mohapatra, 2017) as:

$G_0 = 100;\ \alpha = 20; \Delta load = 10\%; number\ of\ iteration = 20$ with two-area networks:

The settling time and the rising time of the model with PID in Area1 and both Area1 and 2 respectively when compared with the result in literature show that GSA is a promising optimization technique for LFC. Table 4.7 presents the output of GSA results under the stated condition. The proposed algorithm using GSA with PID controller provides fast settling time when subjected to 10% step change disturbance compared to the CPSO as shown in Table 4.6.

Table 4.6: Comparison of the results with literature

Parameters		CPSO Optimized PI Controller	GSA optimized PI controller	GSA optimized PID controller
ITSE				
T_S Sec	$\Delta f1$	26.27	23.75	7.86
	$\Delta f2$	18.01	15.98	5.45
	ΔP_{tie}	26.27	25.66	6.32
ISE				
T_S Sec	Δf_1	23.84	22.45	6.56
	Δf_2	17.57	17.21	5.87
	ΔP_{tie}	23.83	22.89	5.98

Table 4.7: Output using GSA with 1 and 2 PID controllers

	Optimization Technique	**Rise Time Area 1**	**Rise Time Area 2**	**Settling Time Area 1**	**Settling Time Area 2**
1 PID Controller	GSA	0.0000056	0.0222	9.9787	8.4991
2 PID Controller	GSA	0.000071	0.0031	10.7153	11.0439

CHAPTER 5: CONCLUSIONS

5.1 Conclusion

In this project, imperialist competitive algorithm (ICA) and gravitational search algorithm (GSA) have been successfully proposed in a load frequency control (LFC) of two-area power system to optimize the performance of PID controllers using MATLAB and Simulink. The PID controller was used as a control unit to improve the performance of the LFC in the presence of perturbation in the system. A comparative study performed based on the proposed algorithms clearly shows that the performance of GSA with 2 PID controllers is superior over ICA with 2 PID controllers in terms of the rise time and settling time during perturbation or disturbance in the system. Hence, GSA can be proposed to be used in the tuning of actual PID controllers for a load frequency control of two-area power systems.

5.2 Recommendation for future works

- Testing the two-area network in consideration with external constraints such as fault and disconnection of large generators using the proposed algorithm.
- Verifying the effect of different load change in a multi-connected power system network
- Testing the proposed algorithm with some other controllers

REFERENCES

Aho, J., Buckspan, A., Laks, J., Fleming, P., Jeong, Y., Dunne, F., . . . Johnson, K. (2012). *A tutorial of wind turbine control for supporting grid frequency through active power control.* Paper presented at the American Control Conference (ACC), 2012.

Ali, E., & Abd-Elazim, S. (2011). Bacteria foraging optimization algorithm based load frequency controller for interconnected power system. *International Journal of Electrical Power & Energy Systems, 33*(3), 633-638.

Balaji, K., & Neelan, S. (2015). OPTIMIZATION OF LOAD FREQUENCY CONTROL FOR TWO AREA SYSTEM USING PARTICLE SWARM OPTIMIZATION.

Baydokhty, M. E., Zeynal, H., & Zare, A. (2016). *Nonlinear load-frequency control: An approach using optimized hierarchical fuzzy systems.* Paper presented at the Electrical Engineering (ICEE), 2016 24th Iranian Conference on.

Cheng-Hung Chen, & Chen, W.-H. (2016). United-Based Imperialist Competitive Algorithm for Compensatory Neural Fuzzy Systems *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS, VOL. 46, NO. 9*, 1180-1188.

Chuang, N. (2016). Robust H∞ load-frequency control in interconnected power systems. *IET Control Theory & Applications, 10*(1), 67-75.

Dorigo, M., Maniezzo, V., & Colorni, A. (1996). The ant system: Optimization by a colony of cooperative agents.

Du, W., & Li, B. (2008). Multi-strategy ensemble particle swarm optimization for dynamic optimization. *Information Sciences, 178*(15), 3096-3109. doi: https://doi.org/10.1016/j.ins.2008.01.020

Duman, S., Yorukeren, N., & Altas, I. H. (2012). *Load frequency control of a single area power system using Gravitational Search Algorithm.* Paper presented at the

Innovations in Intelligent Systems and Applications (INISTA), 2012 International Symposium on.

Eldos, T., & Al Qasim, R. (2013). On the performance of the gravitational search algorithm. *Int J Adv Comput Sci Appl, 4*(8), 74-78.

Elsisi, M., Aboelela, M., Soliman, M., & Mansour, W. (2015). Model Predictive Control of Two-Area Load Frequency Control Based Imperialist Competitive Algorithm. *Indonesian Journal of Electrical Engineering and Computer Science, 16*(1), 75-82.

Elsisi, M., Soliman, M., Aboelela, M., & Mansour, W. (2015). ABC Based Design of PID Controller for Two Area Load Frequency Control with Nonlinearities. *Indonesian Journal of Electrical Engineering and Computer Science, 16*(1), 58-64.

Esmaeil Atasphaz-Gargari, & lucas, C. (2007). Imperialistic Competitive Algorithm: An Algorithm for Optimization Inspired by Imperialistic Competition. *Compress on Evolutionary Computation*, 4661-4667.

Farahani, M., Ganjefar, S., & Alizadeh, M. (2012). PID controller adjustment using chaotic optimisation algorithm for multi-area load frequency control. *IET Control Theory & Applications, 6*(13), 1984-1992.

Guha, D., Roy, P. K., & Banerjee, S. (2016a). Load frequency control of interconnected power system using grey wolf optimization. *Swarm and Evolutionary Computation, 27*, 97-115.

Guha, D., Roy, P. K., & Banerjee, S. (2016b). Load frequency control of large scale power system using quasi-oppositional grey wolf optimization algorithm. *Engineering Science and Technology, an International Journal, 19*(4), 1693-1713.

J.D. Farmer, N.H. Packard, & Perelson., A. S. (1986). The immune system, adaptation and machine learning. *Physica D 2*, 187-204.

Jadhav, A. M., Toppo, E. T., & Vadirajacharya, K. (2012). *Load frequency control based on Particle Swarm Optimization in a single area hydro power system under various heads.* Paper presented at the Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on.

Jamadar, M. N. M., & Reddy, M. A. R. (2015). Load Frequency Control for Two Area Deregulated Power System Using ANN Control.

Juang, C.-F., & Lu, C.-F. (2004). *Power system load frequency control by evolutionary fuzzy PI controller.* Paper presented at the Fuzzy Systems, 2004. Proceedings. 2004 IEEE International Conference on.

Kennedy, J. (2011). Particle swarm optimization *Encyclopedia of machine learning* (pp. 760-766): Springer.

Liu, F., Li, Y., Cao, Y., She, J., & Wu, M. (2016). A two-layer active disturbance rejection controller design for load frequency control of interconnected power system. *IEEE Transactions on Power Systems, 31*(4), 3320-3321.

Marco Dorigo, Vittorio Maniezzo, & Colorni., A. (1996). The Ant System: Optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics–Part B, 26*(1), 1-13.

Mu, C., Tang, Y., & He, H. (2017). Improved Sliding Mode Design for Load Frequency Control of Power System Integrated an Adaptive Learning Strategy. *IEEE Transactions on Industrial Electronics*.

Okedu, K. E. (2017). Effect of ECS low-pass filter timing on grid frequency dynamics of a power network considering wind energy penetration. *IET Renewable Power Generation*.

Pandey, S. K., Mohanty, S. R., & Kishor, N. (2013). A literature survey on load–frequency control for conventional and distribution generation power systems. *Renewable and Sustainable Energy Reviews, 25,* 318-334.

Saadat, H. (1999). *Power system analysis*: McGraw-Hill.

Sahu, R. K., Panda, S., & Padhan, S. (2014). Optimal gravitational search algorithm for automatic generation control of interconnected power systems. *Ain Shams Engineering Journal, 5*(3), 721-733.

Shayeghi, H., & Ghasemi, A. (2016). Improvement of Frequency Fluctuations in Microgrids Using an Optimized Fuzzy P-PID Controller by Modified Multi Objective Gravitational Search Algorithm. *Iranian Journal of Electrical and Electronic Engineering, 12*(4), 241-256.

Tang, K.-S., Man, K.-F., Kwong, S., & He, Q. (1996). Genetic algorithms and their applications. *IEEE signal processing magazine, 13*(6), 22-37.

Wolpert, D. H., & Macready, W. G. (1997). No free lunch theorems for optimization. *IEEE Transactions on Evolutionary computation, 1*(1), 67-82.

Yao, X., Liu, Y., & Lin, G. (1999). Evolutionary programming made faster. *IEEE Transactions on Evolutionary computation, 3*(2), 82-102.

Yesil, E., Savran, A. I., & Guzay, C. (2014). *Load frequency controller design using new Big Bang-Big Crunch 2 algorithm.* Paper presented at the Innovations in Intelligent Systems and Applications (INISTA) Proceedings, 2014 IEEE International Symposium on.