INVESTIGATION OF FIREFLY ALGORITHM AND CHAOS FIREFLY ALGORITHM FOR LOAD FREQUENCY CONTROL

ZAID BIN NAJID

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2015

INVESTIGATION OF FIREFLY ALGORITHM AND CHAOS FIREFLY ALGORITHM FOR LOAD FREQUENCY CONTROL

ZAID BIN NAJID

RESEARCH REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2015

UNIVERSITI MALAYA
ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: **ZAID BIN NAJID**

Registration/Matric No	:	**KMA110003**
Name of Degree	:	**Master of Engineering (Power System)**
Title Research Report ("this Work")	:	**INVESTIGATION OF FIREFLY ALGORITM AND CHAOS FIREFLY ALGORITHM FOR LOAD FREQUENCY CONTROL**
Field of Study	:	**Power System**

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

……………………………………………

Candidate's Signature　　　　　　　　　　Date:……………..

Subscribed and solemnly declared before,

……………………………………………

Witness's Signature　　　　　　　　　　Date:……………..
Name:…………………………………….
Designation:……………………………...

ABSTRACT

The changes of the structure of the power system, size, and complexity have increased the important of LFC. For this reason, this research studies the controller aspect of LFC by using the Fractional Order Integral-Derivative (FOID) controller or $I^{\lambda}D^{\mu}$ Controller. In order to obtain the best controller parameter values for LFC, Firefly Algorithm (FA) and Chaos Firefly Algorithm (CFA) are used. This project analyzes the performance of the algorithms based LFC in three power system area. The primary objectives of LFC are to maintain frequency and minimize power interchanges with neighboring control areas. These objectives are met by measuring a control error signal called the area control error (ACE), which calculates the real power difference between generation and load. In this project, the integral of time multiply squared error (ITSE) as the objective function is used on the ACE. The model of the system is designed using Matlab software to carry out simulation studies. Step input load deviation is injected to the system at designated location and the optimization of ramp rate, speed regulation and the $I^{\lambda}D^{\mu}$ parameters are carried out. The frequency deviation and tie line power changes characteristics are analyzed to observe the system performance. The maximum overshoot, settling time and ITSE value is also recorded and compared. Result shows that the CFA is the best optimization method due to its robustness and consistency. The project can be further improved by tuning the controller using other optimization techniques and including other physical constraints.

ABSTRAK

Perubahan stuktur pada sistem kuasa elektrik, saiz, dan kerumitanya meninggikan lagi keperluan untuk menaik taraf LFC. Oleh sebab itu, laporan ini menyiasat perbezaan antara teknik pampasan yang digunapakai iaitu algoritma api-api (FA) dan algoritma “Chaos” FA (CFA) meggunakan “Fractional Order Integral-Derivative” (FOID) atau $I^{\lambda}D^{\mu}$ di dalam LFC untuk mendapatkan parameter yang optimum. Projek ini menganalisa prestasi algoritma-algoritma tersebut yang digunapakai di dalam LFC untuk sistem kuasa tiga kawasan kawalan. Objektif utama LFC adalah untuk mengekalkan frekuensi dan mengurangkan pertukaran kuasa dengan kawasan kawalan yang bersebelahan. Objektif utama ini dapat dicapai dengan mengukur isyarat ralat kawalan ataupun dipanggil Ralat Kawasan Kawalan (ACE), yang mengira perbezaan kuasa sebenar antara penjanaan dan beban. Di dalam projek ini, “Integral Time weighted Squared Error (ITSE)” yang dilaksanakan di dalam ACE. Model bayangan menyerupai yang sebenar dibina menggunakan perisian Matalab untuk mensimulasi system tersebut. Input “step” beban sisihan disuntik kepada tempat-tempat terpilih dengan pengoptimuman parameter “ramp rate, speed regulation dan $I^{\lambda}D^{\mu}$. Kemudian tindak balas lajakan frekuensi dan perubahan kuasa pada pusat talian dianalisis. Nilai lonjakan maksima, masa selesai dan ITSE direkodkan dan dibandingkan. Keputusan menunjukkan CFA cara pengoptimuman yang terbaik kerana kestabilannya dan kekonsistansinya. Projek ini dapat ditambah baik dengan meggunakan cara pengoptimuman yang lain dan menambah kekangan fizikal yang lain.

ACKNOWLEDGEMENTS

In the name of Allah, The Most Gracious, Most Merciful and Him alone worthy of all praises.

First and foremost, I would like to express my gratitude to my supervisor, Assoc. Prof. Dr. Hazlie bin Mokhlis for his knowledge, time, guidance and support in guiding me to complete this research report. Appreciation is also extended to Mr. Kanendra, Mr. Nazmi Zulkifli and Department of Electrical Engineering, Faculty Engineering for their advice and support in completing this research report.

Thanks also to my parents *'Mek'* and *'Ayah'* and my family whom being so supportive throughout my postgraduate studies and completing this research report. May Allah reward them the best of gift. Not to be forgotten, I would like to thank my lovely wife Murni for her support and patience for me. To my daughter, *'Atikah*, you are my inspiration.

Last but not least, many thanks to those who have directly or indirectly have helped me throughout completing this course. Your kindness and consideration are greatly appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
ACE	Area Control Error
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
CFA	Chaos Firefly Algorithm
FA	Firefly Algorithm
FOID	Fractional Order Integral-Derivative
FOPID	Fractional Order Proportional-Integral-Derivative
ID	Integral-Derivative
ITSE	Integral of Time Multiply Squared Srror
kW	kilo-Watts
LFC	Load Frequency Control
PID	Proportional Integral Derivative

CHAPTER 1

INTRODUCTION

1.1 Overview

A power system is a non-linear and large-scale multi input multi output (MIMO) dynamic system with huge numbers of variable together with the protection devices, control loops with different dynamic responses and characteristic. Multiple numbers of generators will supply power into the interconnected system to be transmitted which will then be distributed to loads. However a successful operation of interconnected power system requires a balance of the total generation with the load demand with its losses. At any given time, the power system is possible to experience fault or sudden changes that may yield to undesirable effects.

In power system generation, it is important to consider the active and reactive power load demand. The power system controller should effectively compensate the load requirement as it is constantly changing. Two most important network parameters which are the voltage and frequency should be maintained at its specified limits because any deviation to both of it may compromise the system security and stability.

The changes in active power will affect the frequency while changes in the reactive power will affect the voltage. Thus both voltage and frequency are controlled separately. Load Frequency Control (LFC) is a mechanism to control frequency which will be reflected to the active power. Meanwhile, Automatic Voltage Regulator (AVR) is to control voltage and the reactive power.

1.2 Problem Statement

In the past, research work has been conducted which compares a new controller, named fractional order controller, $I^{\lambda}D^{\mu}$ with classical integer order (IO) such as I, PI, and PID controllers (Sanjoy Debbarma, Lalit Chandra Saikia, Nidul Sinha, 2013). The obtained results shown that $I^{\lambda}D^{\mu}$ controller provide improved dynamic response and outperform the classical IO controller. Thus for this research, $I^{\lambda}D^{\mu}$ controller is used. However to obtain the optimum parameters for $I^{\lambda}D^{\mu}$ controller is more tedious and time consuming because there are four parameters to be determined; I, D, λ and μ (fractional gains). Due to this complexity, meta-heuristic methods called Firefly Algorithm (FA) and Chaos Firefly Algorithm (CFA) are applied to get the optimum combination of the $I^{\lambda}D^{\mu}$ controller gains, to be used for the LFC in the interconnected reheat thermal power system.

1.3 Objectives of Research

The main objectives of this project are:

a) To model LFC for three area non-reheat thermal with multiple generator power system using Simulink function in Mathlab simulation software.

b) To integrate Firefly Algorithm (FA) and Chaos Firefly Algorithm (CFA) in the LFC model.

c) To compare the performance of FA and CFA in determining optimum combination of the $I^{\lambda}D^{\mu}$ controller gains.

1.4 Project Methodology

In order to achieve the above-mentioned objectives, these steps will be carried out:

a) Review of LFC, Automatic Generation Control (AGC), $I^{\lambda}D^{\mu}$ controller and FA optimization method.

b) From the review, suitable LFC and AGC model will be selected. For the system controller, two optimization techniques will be selected namely FA and Chaos Firefly Algorithm (CFA). Both FA based controller is investigated for this project.

c) Modeling of a three area interconnected thermal power system with multiple generators in LFC with AGC by using Simulink in Matlab.

d) Build the programming code for the proposed algorithm using Matlab.

e) Test proposed algorithm by a set of step input load injection at designated location and optimization of some physical constraints.

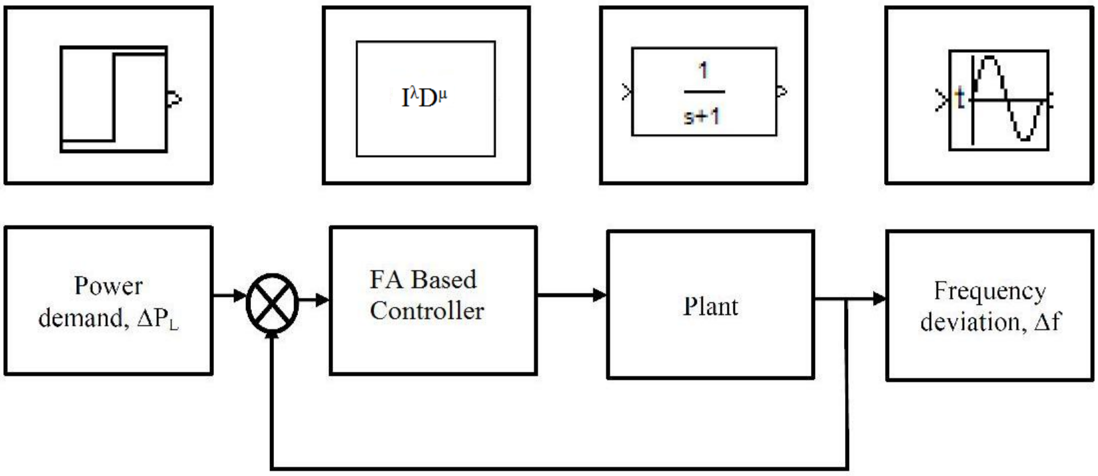


Figure 1.1 : General Overview of Project Block Diagram

The general overview of the project block diagram is shown in Figure 1.1. Real power demand as unit step function is the input of the system. The controller is a $I^{\lambda}D^{\mu}$ controller utilizing FA based optimization technique. The controller will perform calculation and compensate the plant in accordance to the error signal. The error signal is the difference of input signal with respect to the feedback of the plant. The plant is represented using transfer function which corresponds to the plant generation model and the time constants of the generator. The output of the system is the frequency deviation of the system. It also acts as the feedback of the system.

1.5 Research Report Organization

This research report is structured into five main chapters:

Chapter One includes the overview, problem statement, objective and research report organization.

Chapter Two discusses the literature review regarding generator control loop as a whole, LFC model, Automatic Generation Control (AGC), Feedback Control System method, the optimization algorithm which consists of the firefly algorithm and the fractional order controller.

Chapter Three discusses on the methodology of this research. LFC and AGC of three area system are modeled in this section.

Chapter Four shows the results obtained from Matlab simulation using FA based controller on LFC. All results are highlighted here.

Chapter Five covers the conclusion of this research and emphasizes the future work that can be extended.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

This research focuses on the investigation of FA based for LFC using $I^{\lambda}D^{\mu}$ controller. A literature review regarding this topic had been performed and presented in this chapter. All theoretical and conceptual frameworks are explained in this chapter to ensure the understanding of this project aligns with the objectives. This chapter describes the necessary models and algorithms used for the simulation.

2.2 Basic Generator Control Loop

Changes in real power affect mainly the system frequency while reactive power is less sensitive to changes in frequency and is mainly dependent on changes in voltage magnitude. Thus real power and reactive power are controlled separately. LFC controls the real power and Automatic Voltage Regulator (AVR) regulates the reactive power and voltage magnitude.

In any generation either an isolated or interconnected power system, LFC and automatic voltage regulator (AVR) equipment are installed at each generator. The schematic diagram of the LFC and AVR loops is represent in Figure 2.1. The controller is set of particular operating condition that has input of small changes in load demand to maintain the frequency and voltage magnitude within the specified limit. The excitation system time constant is much smaller than the prime mover time constant and its transient decay much faster and does not affect the LFC dynamic. Thus, the cross coupling between the LFC and AVR loops is negligible. The load frequency and excitation voltage control are also analyzed separately.

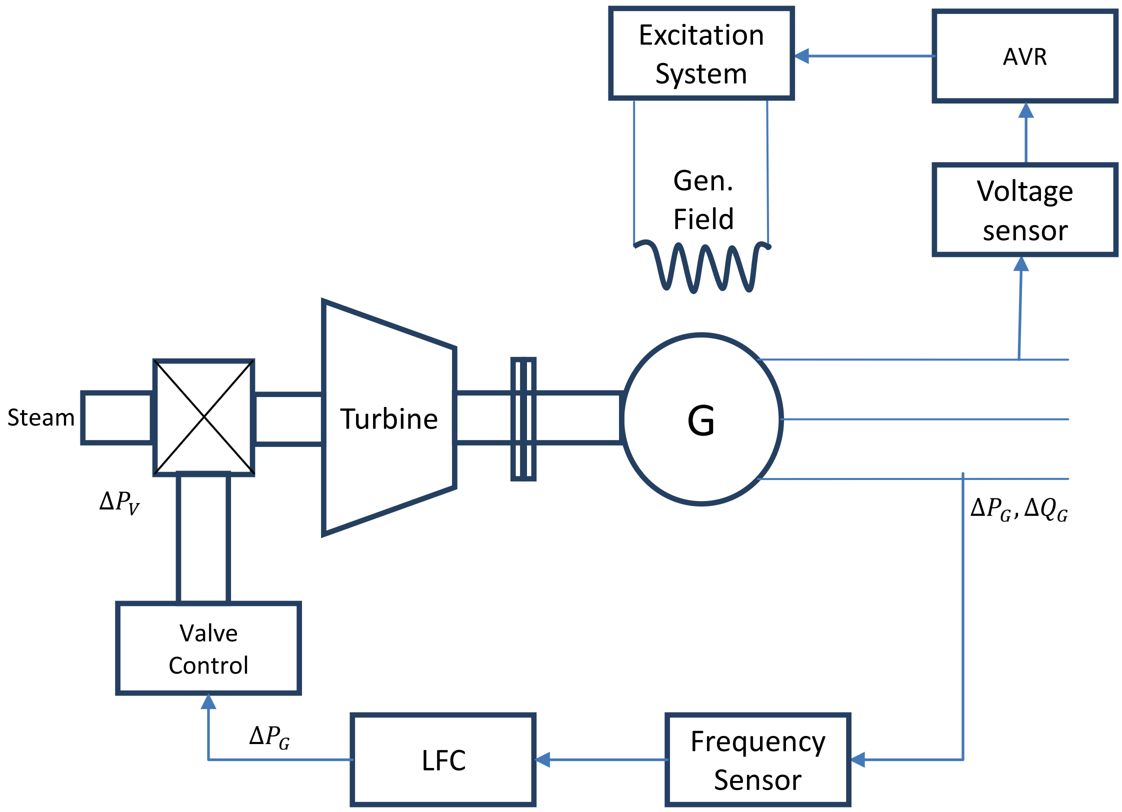


Figure 2.1: Schematic diagram of LFC and AVR of a synchronous generator (Hadi Saadat, 2004)

From the figure, which is assumed to be a steam turbine, LFC controls the valve opening which controls the steam amount. Then the steam will enter into the turbine to rotate it. AVR controls the excitation system voltage of the generator by supplying DC voltage to the rotor field winding.

2.3 Automatic Generation Control (AGC)

Generation scheduling and control is an important component of daily power system operation. The overall objective of AGC is to control the electrical output of generators while to regulate with the continuous changing load in an economical manner. AGC is a program containing much of the associated function. Power system operator or the dispatcher which buy power from Generation Company (GENCO) will sell it to consumer whom will interact most of the time with AGC to monitor its result and give input as to improvise current condition. In order to effectively maintain generation control within the power system, the AGC scheme is guided by the Area Control Error (ACE).

AGC can be defined as a system that represents the mechanism or the action that is taken to ensure maximum economy and optimum power flow in an interconnected power system network that comprises of generation, transmission and distribution. The objectives of AGC (Thomas M. Athay 1987):

a) Matching total system generation to total system load
b) Regulating system electrical frequency error to zero
c) Distributing system generation among control areas so that net area tie flows match net area tie flow scheduled
d) Distributing area generation among area generation sources so that area operating cost are minimized

AGC as it known can be analyzed for a single area system or multi areas system. The main objective of AGC in a single area system or an isolated system is to restore the system frequency to the nominal value because there are no other areas for power to flow. Figure 2.2 below shows the block diagram of an AGC for a single area or an isolated power system.

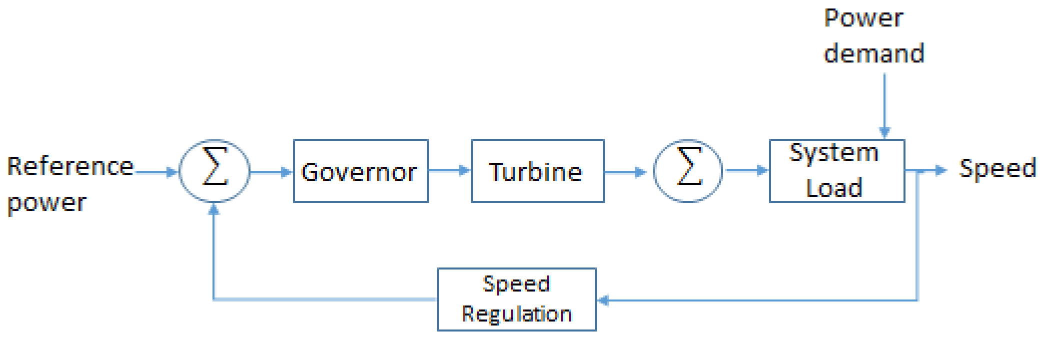


Figure 2.2: Single Area Power System

Figure 2.2 shows the basic diagram for an isolated system. The generator and the system load are connected to a series of connection in which the speed regulator plays a role in maintaining the system frequency.

While for multi area system AGC, the generators are closely looped or coupled together. This group of generators needs to be synchronized or exhibit coherent properties. This will enable the group generators to be termed or referred to as a control area. Figure 2.3 shows the diagram of three area control system. The interconnected system can contain two or more control areas.

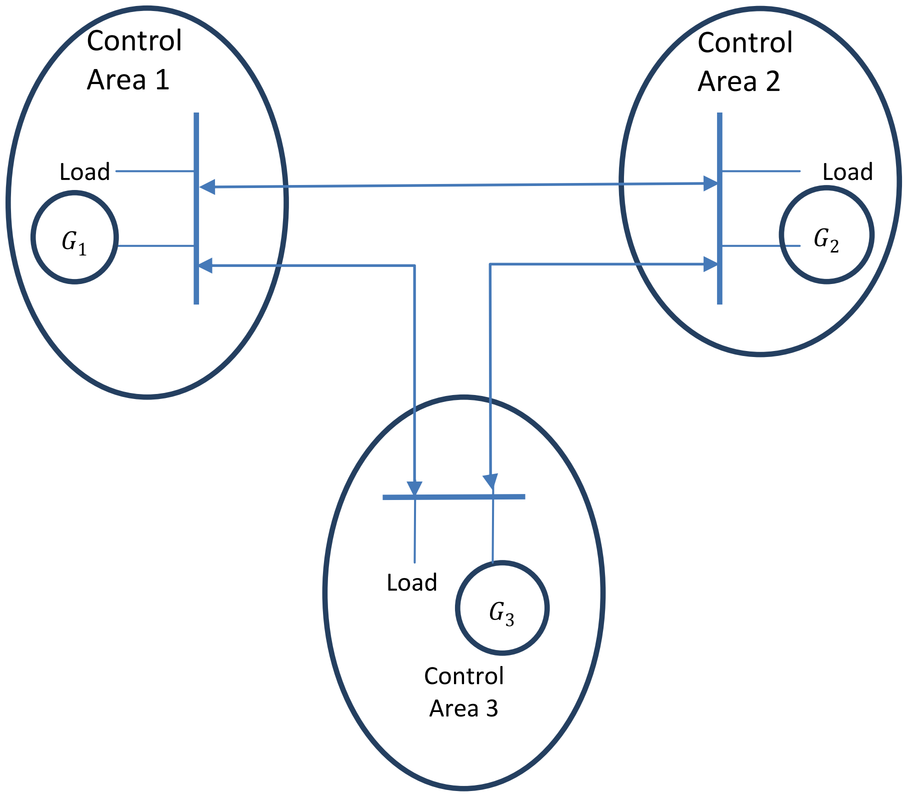


Figure 2.3: Three Area Power System

Each control area in Figure 2.3 shall capable of supplying to its own area at the first place. Meanwhile, power flows between the control areas through the tie-lines. This means, there is an effect to the entire system even there is changes at any point in the system.

2.4 Load Frequency Control (LFC)

It is still a common practice throughout the world especially on developing countries to practice monopoly in electricity business. It means generation, transmission and distribution of electricity are under control of a single body or entity. Thus, for an isolated power system, within monopoly strategy, imbalance of power and changes in loads does not a serious issue. Hence, referring to Figure 2.1, LFC task is limited to restore the system frequency to the specified nominal value. There are following possible ways to share the change in the load to maintain frequency:

i. Either of generating units caters the change in load (Flat Frequency Regulation).

ii. All units share the change in load (Parallel Frequency Regulation).

Within real system, generating units are large in numbers, with introduction of some Independent Power Producers (IPP) into the system, loads are more diverse through the transmitting lines and the system surely is more complex. In controlling this issue, frequently used technique is to divide the whole system into some relative controllable smaller systems which been called control areas or multi area control. Therefore, LFC that located in each of the control area within this multi area control need to regulate area frequency plus to control the supplementary power at scheduled values.

On the other hand, for region that practices the electricity industry deregulation, the operational of the power system structure itself do add the byzantine in controlling it. Before that, deregulation of electricity industry is reducing direct government involvement in, and to increase the economic efficiency through a change in the electricity industry. Deregulation do divides generation, transmission and distribution commonly called GENCO, TRANSCO and DISCO accordingly to end the monopoly whilst increase competition and maximizing profit.

Through this deregulated regime, the operational of the LFC is different such as Free LFC, Charged LFC, Bilateral LFC, Tender Market LFC, Auction Market LFC and Real Time Balancing LFC. All these type of LFC operations in deregulated regime are not been discussed here but it is to highlight the importance of performance of LFC.

2.5 Area Control Error (ACE)

The deviation of interchanged power flow and frequency in the multi area system is the derivation from ACE. F. Daneshfar et al. (2009), ACE is determined from main system parameters such as frequency deviation, power flow deviation and prime mover control. Hence, ACE is a quantity that represents the power mismatch between the generation and the load by taking into account the above mentioned system parameters. Transient analysis of the system provides valuable information on the stability of the system and the ACE has to be regulated to zero. But, to regulate ACE to zero is tough because load is always fluctuating. Thus, tie-line power and frequency shall always be maintained to its scheduled value. Formula for deviation of tie-line power flow and the frequency deviation is obtained from below (M.R.I Sheikh et. Al. 2009):

$$ACE_i = \sum_{j \neq 1}^{n} j = \Delta P_{tie,ij} + \beta_i \Delta f_i \tag{2.1}$$

- $\Delta P_{tie,ij}$ is the tie-line power flow
- β_i is frequency bias factor of the area
- Δf_i is frequency deviation

Frequency Bias Factor

The frequency bias factor of an area is given as:

$$\beta_i = D_i + \frac{1}{R_i} \tag{2.2}$$

- D_i is the load damping constant which is the percentage change in load
- R_i is the governor speed regulation

2.6 LFC Control Techniques

2.6.1 Classical Control Technique

Classically, AGC frequency deviation is minimized using flywheel type of governor of synchronous machine. But the LFC objective control is not achieved. Bode and Nyquist are the pioneering control engineers whom established links between the frequency response of a control system and its closed-loop transient performance in the time domain. However the response resulted into relatively large overshoot and transient frequency deviation. In addition, the settling time of the system frequency deviation of comparatively long and is of the order of 10s to 20s (D.R. Chaudury,2005).

Based on P. Kundur (1994) most of conventional LFC uses proportional integral controller. But the disadvantage is the integral gain limit the system performance. Increasing the gain will cause large oscillations thus taking long time to settle and create instability to the system. Hence desirable transient recovery and low overshoot in the dynamic response of the overall system shall be compromised from the integral gain setting. But then using this PI controller with the enlargement and improvement of modern power system risking the system oscillation propagate into wider area that can cause total black out. Therefore advanced control method were introduced in LFC such as optimal control, adaptive control and robust control.

2.6.2 Optimal Control

Modern optimal control theory which is one of the LFC regulator design techniques enable electric power engineers to design an optimal control system with respect to given performance criterion. Optimal control theory does create a new direction to solve large multivariable control problems in a simplified version. The state variable representation of the model is been considered in optimal control. Elgerd and Fosha who are the first addressed optimal control concept in LFC by using a state variable model and regulator problem of optimal control theory to develop new feedback control law for interconnected power system (Fosha and Olle, 1970).

2.6.3 Adaptive and Self-Tuning

The controller performance in a system may not be optimal as the operating point of a power system will keep changing throughout the day. Better approach to ensure the system performance at it optimum state is to track the operating point and using the updated parameters to compute the control. Perfect model following condition or explicit parameters identification are usually required by adaptive control. The objective of the adaptive control is to make the process under control less sensitive to changes in plant parameters and to un-modeled plant dynamics (H. Shayeghi et al.,2009).

2.6.4 Robust Control

In any power system control area, the uncertainties and disturbances are differing to one another. This is due to load variation, changing system parameters and characteristics, modeling error and environmental conditions. As per explain, randomly changes in load daily makes the operating points of the power system keep changing. That is the reason an optimal LFC based on nominal system is not suitable for LFC and may create inadequate to provide the desired system functioning. Hence later design of LFC controllers is using robust approach with the objectives to design load frequency controllers which guarantee robust stability and robust performance even though the parameters change verily (Wang Y, Zhou R, Wen C, 1993). In addition, robust approach design is capable to use the physical constraints of power system and considering the system uncertainties for the synthesis procedure. Nevertheless, the larger the model, the connection between subsystems will be uncertain, parameter variation will be broader, and the organizational structure of power systems will be elaborate bigger.

2.6.5 Fractional Order ID ($I^{\lambda}D^{\mu}$) Controller

In total, there are numerous techniques available in LFC but varying of parameters and rejection of disturbance always being the problem statement. Recently development of LFC is going to the direction of the fractional order controller's formulation. Based on the literature review on hand, fractional order controller is known to have an exceptional ability in handling varying parameters, in rejection of disturbance, robust to high frequency noise and reducing steady state errors while improving stability for nonlinear systems. All this characteristic of fractional order controller makes it flexible and desirable for control strategy.

Before we proceed, the term 'Fractional' or 'Fractional Order' is inaccurate and instead more accurate term is 'non-integer-order' since the order itself can be irrational. The reason is fractional order calculus is like a derivative or integral but with non-integer order. For example, the expressions of $\frac{dx}{dt}, \frac{dx^2}{dt^2}$ are usually found. But for fractional order, it can be any real number or it is a fractional of a derivative or integral like $\frac{dx^{\frac{1}{2}}}{dt^{\frac{1}{2}}}$.

For a start, the commonly used definition for fractional differential-integral by Reimann-Liouville (R-L) is explained.

The R-L definition for fractional derivative is given

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t (t-\tau)^{n-\alpha-1} f(\tau) d\tau \tag{2.3}$$

- $n-1 \leq \alpha < n$, n is an integer
- $\Gamma(.)$ is the Euler's gamma function.

The R-L definition for fractional integral is given

$$ {}_aD_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau) d\tau \tag{2.4}$$

- ${}_aD_t^{\alpha}$ is the fractional operator

The Laplace transformation of Riemann-Liouville definition for the fractional derivative of equation (2.3) is given by

$$ L\{ {}_aD_t^{\alpha} f(t)\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^k \, {}_aD_t^{\alpha-k-1} f(t)|_{t=0} \tag{2.5}$$

- $n-1 \leq \alpha \leq n$
- $L\{f(t)\}$ is the normal Laplace transformation

$PI^{\lambda}D^{\mu}$ is the most common form of fractional order controller while λ and π are non-integer order of integrator and differentiator and it can be any real numbers. The transfer function is given in the form

$$C(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{2.6}$$

If λ or μ value is equal to 1, then it will become normal PID. If λ equal 1 and μ value is equal to 0, fractional order PI is obtained and vice versa. Next, the differential equation for fractional order $PI^{\lambda}D^{\mu}$ is

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \tag{2.7}$$

For FOID, $I^{\lambda}D^{\mu}$ the transfer function is given by

$$C(s) = k_p \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{2.8}$$

FOID, $I^{\lambda}D^{\mu}$ the differential equation is given by

$$u(t) = K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \qquad (2.7)$$

2.7 Soft Computing / Artificial Intelligent Technique

2.7.1 Fuzzy Logic

Fuzzy logic based intelligent controller objective is to facilitate the smooth operation and fewer oscillate when system experience sudden load change. Fuzzy logic is the root of the fuzzy controller which is closer to human thinking and natural language than classical logical system which solves problem base on experience and knowledge about the system (Rahul U, Sanjeev K, Man M and D.K. Chaturvedi, 2012). Meanwhile, fuzzy controllers advantages are its robustness nad reliability make it versatile for vast of control problem. However the disadvantages are it is difficult to acquire knowledge and there no adaptability and hence for dynamic time varying system, it is unable to perform well due to change in system.

2.7.2 Artificial Neural Network (ANN)

ANN is unlike fuzzy controller. ANN does not require knowledge (Rule) but it will find and identify patterns given appropriate design and training. ANN is like a black box which compares non-linear connection between input and output. It is inspired from our brain which contains hundreds of billions of neurons that connect each other.

2.7.3 Firefly Algorithm

The Firefly Algorithm has been discovered by Xin-She Yang in 2007 which is inspired from the firefly behavior.

Firefly Algorithm

Objective function $f(\boldsymbol{x})$, $\quad \boldsymbol{x} = (x_1, ..., x_d)^T$
Generate initial population of fireflies $\boldsymbol{x}_i$ $(i = 1, 2, ..., n)$
Light intensity I_i *at* $\boldsymbol{x}_i$ *is determined by* $f(\boldsymbol{x}_i)$
Define light absorption coefficient γ
while $(t < MaxGeneration)$
for $i = 1 : n$ *all* n *fireflies*
  for $j = 1 : n$ *all* n *fireflies (inner loop)*
  if $(I_i < I_j)$, *Move firefly* i *towards* j; **end if**
    Vary attractiveness with distance r *via* $\exp[-\gamma r]$
    Evaluate new solutions and update light intensity
  end for j
end for i
Rank the fireflies and find the current global best $\boldsymbol{g}_*$
end while
Postprocess results and visualization

Figure 2.4 : Firefly Algorithm General Pseudo Code

The main objective for a firefly to flash its light is to create a signal system to draw other firefly. The FA is formulated by these three assumptions:

i. All fireflies are unisex, thus one firefly will be attracted by other firefly
ii. Attractiveness is proportional to their brightness, and for any two fireflies, the less bright one will be attracted by and move closer to the brighter one; however, the brightness can decrease as their distance increases;
iii. The firefly will move randomly if there are no fireflies brighter than a given firefly.

In FA, there are two vital features to be considered:

i. the variation of light intensity.
ii. formulation of attractiveness.

The relationship between light intensity and distance denotes by:

$$I(r) = I_0 e^{-\gamma r^2} \tag{2.9}$$

where I is the intensity, I_0 is the original light intensity and γ is the light absorption coefficient. For this research, the value of γ is 1.

If the light of a firefly is more intense, the brighter it is. Thus light density is proportional to brightness. Brightness can be defines as

$$\beta(r) = \beta_0 e^{-\gamma r^2} \tag{2.10}$$

- β_0 is a constant that denote the present attractiveness at r=0

For this research, the value of β_0 is 0.2. The distance of any two fireflies i and j at xi and xj, can be defined as the Cartesian distance

$$r_{ij} = \left| x_i - x_j \right| \tag{2.11}$$

The movement of a firefly i is attracted towards more attractive (brighter) firefly j can be calculated by

$$\Delta x_i = \beta_0 e^{-\gamma r^{2}{ij}} \left(x_j - x_i \right) + \alpha \varepsilon_i \tag{2.12}$$

- α is the randomization parameter
- ε_i is a vector of random numbers which drawn from Gaussian distribution

$$x_i^{t+1} = x_i^t + \Delta x_i \tag{2.13}$$

From Equation 2.19, two limiting cases will occur which is γ small and large. When γ is close to zero, a firefly can easily be seen by all other fireflies because the attractiveness and brightness become constant. But when γ is very large, the attractiveness (brightness) decreases dramatically, which maybe the environment the fireflies fly are in thick foggy where they cannot see each other or maybe the fireflies are short sighted; this means all fireflies move almost randomly, which corresponds to a random search technique. Thus, the firefly algorithm correlates to the situation between these two maximum.

CHAPTER 3

METHODOLOGY

3.1 Background

This chapter describes the methodology used in modeling the test system using Mathlab software. The modeling of overall generation system and the parameter feed in the model are explained. The method of the study was divided into four stages:

a. Study on knowledge related to LFC and AGC.

b. Model the system.

c. Capture all data required.

d. Analyze best data gathered.

3.2 LFC and AGC Modelling

Each LFC model consists of the generator model, load model, prime mover model, governor model and physical constraints (time delay and dead band). All these sub models is build and connected together to create the simulation block as shown in Figure 3.1:

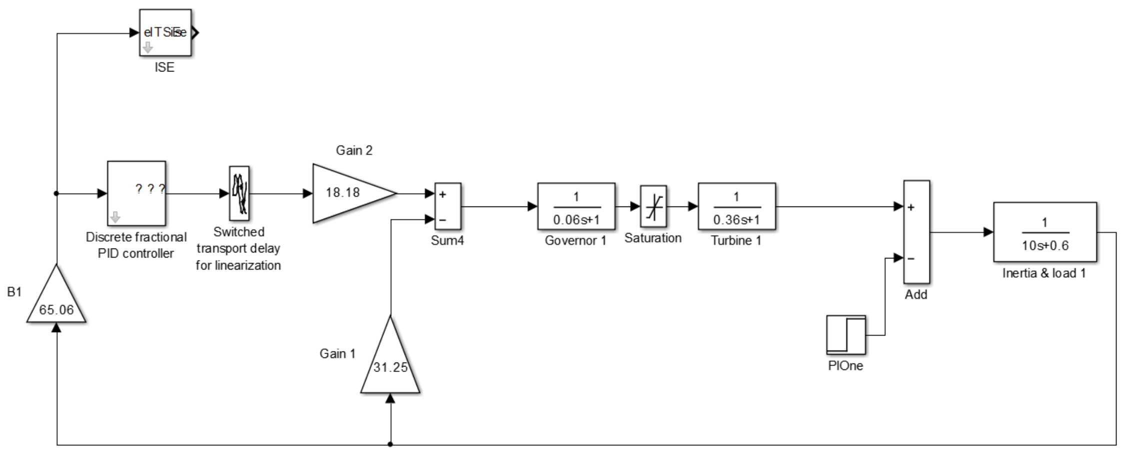


Figure 3.1 : Single Area Power System Model

Figure 3.1 shows a close loop of sinlge area LFC system. For generating the most accurate model as compared to real, some physical constraints have been included which are the time delay and ramping rate. In LFC system, any signal processing and filtering introduces delays that should be considered. Typical filters on tie-line metering and ACE signal (with the response characteristics of generator units) uses about 2 seconds or more for the data acquisition and decision cycles of the LFC systems. However the introduction of this time delay will reduce the effectiveness of the LFC performance.

For this project, two generators were included in each control area. Another one set of generator model were inserted as per Figure 3.2 below.

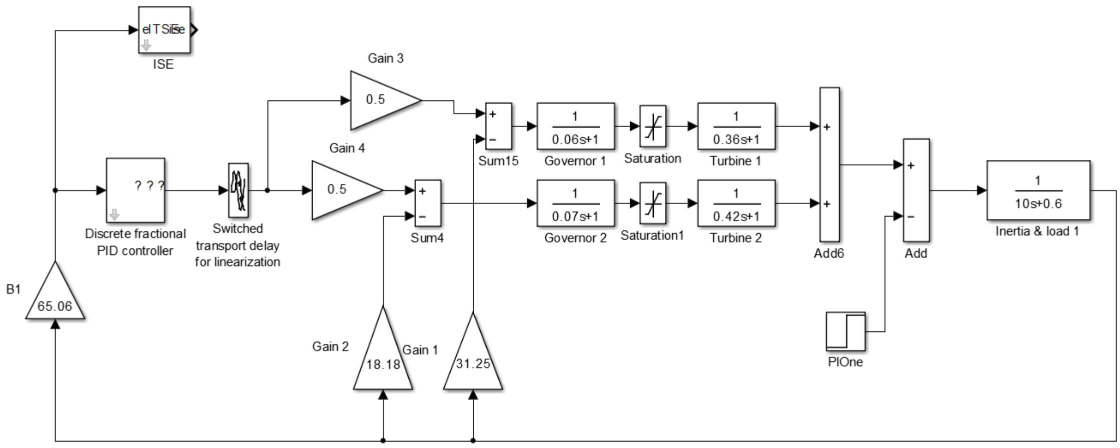


Figure 3.2 : Single Area Power System Model with Two Generators

3.3 Three Area System AGC

Single area control block diagram then is combined to form three area power system as shown in Figure 3.3. From this model, interconnected thermal power system with multiple generators is analyzed and implemented.

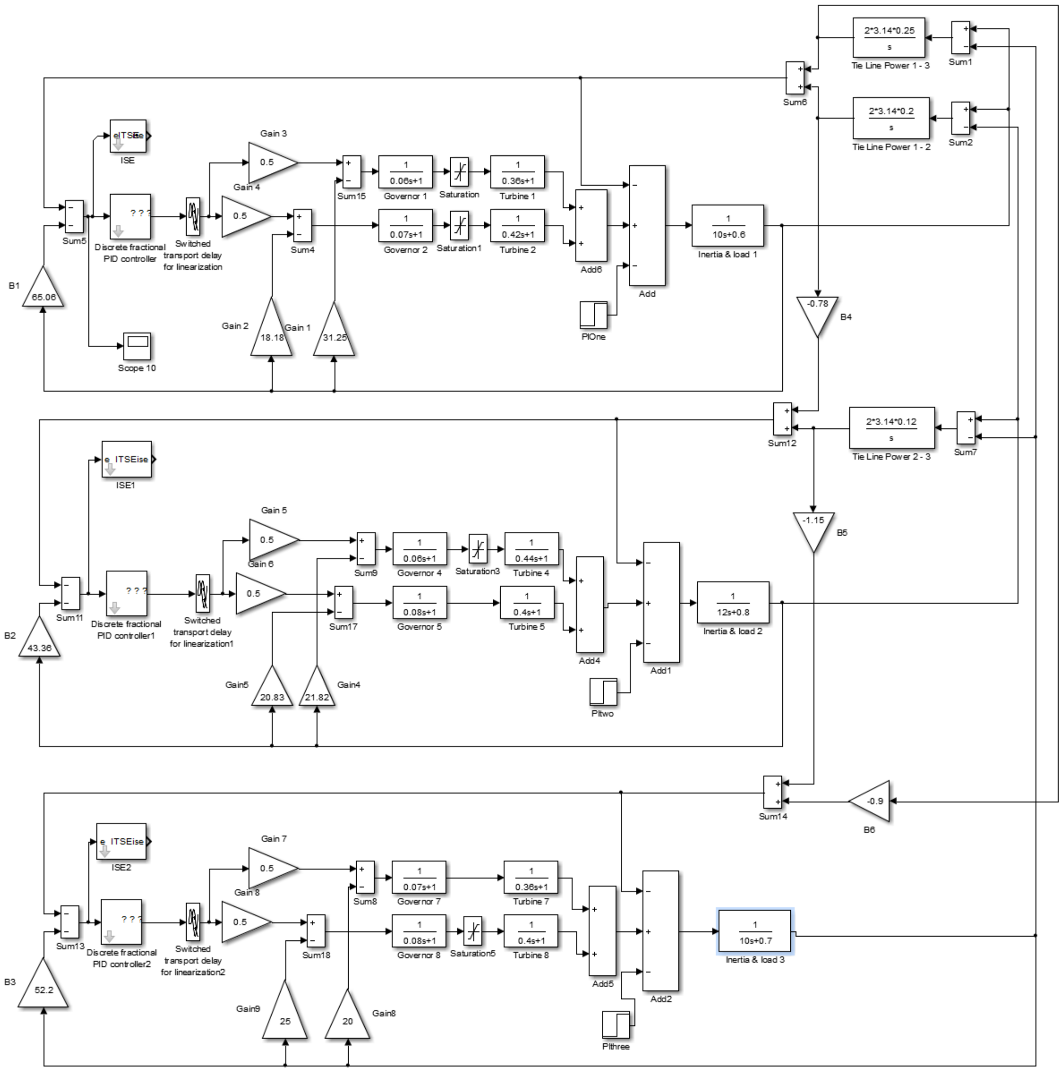


Figure 3.3 : Three Area Power System Model with 2 Generators

3.4 Modelling of ACE

Integral Time Weighted Squared Error (ITSE) is used as the objective function to calculate the system performance. The mathematical equation is as below.

$$ITSE = \int_0^t t.(ACE_i)^2 dt \tag{3.1}$$

Thus for this project, three area power system is used. Hence, sum operator is added

$$ITSE = \sum_{i=1,2,3} \int_0^t t.(ACE_i)^2 dt \tag{3.2}$$

Simplified block diagram is shown below in Figure 3.4.

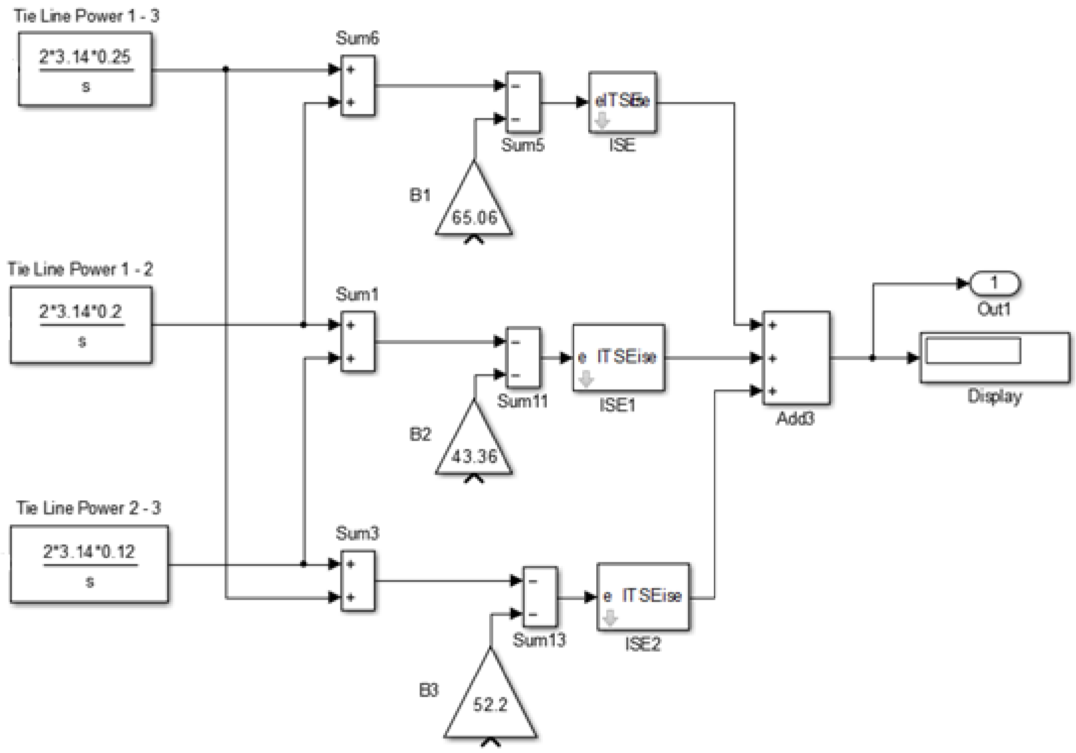


Figure 3.4 : Close Up ITSE Block Diagram

The adjacent tie line power of each area will be summed up and then will be fed into ITSE to calculate the integral value. Lower ITSE value means lower deviation between input and output and vice versa. As the objective function of this study, ITSE value acts as the firefly attractiveness. The lower the value of the error, the system performance is better.

3.5 Optimization of Firefly Algorithm

As per discussion, the model will cater for optimization of several parameters such as Ki, Kd, λ, μ, ramp rate and speed regulation. From the general FA pseudo code, it is then modified to employ FA into LFC and the corresponding implementation is in the flow chart below in Figure 3.5.

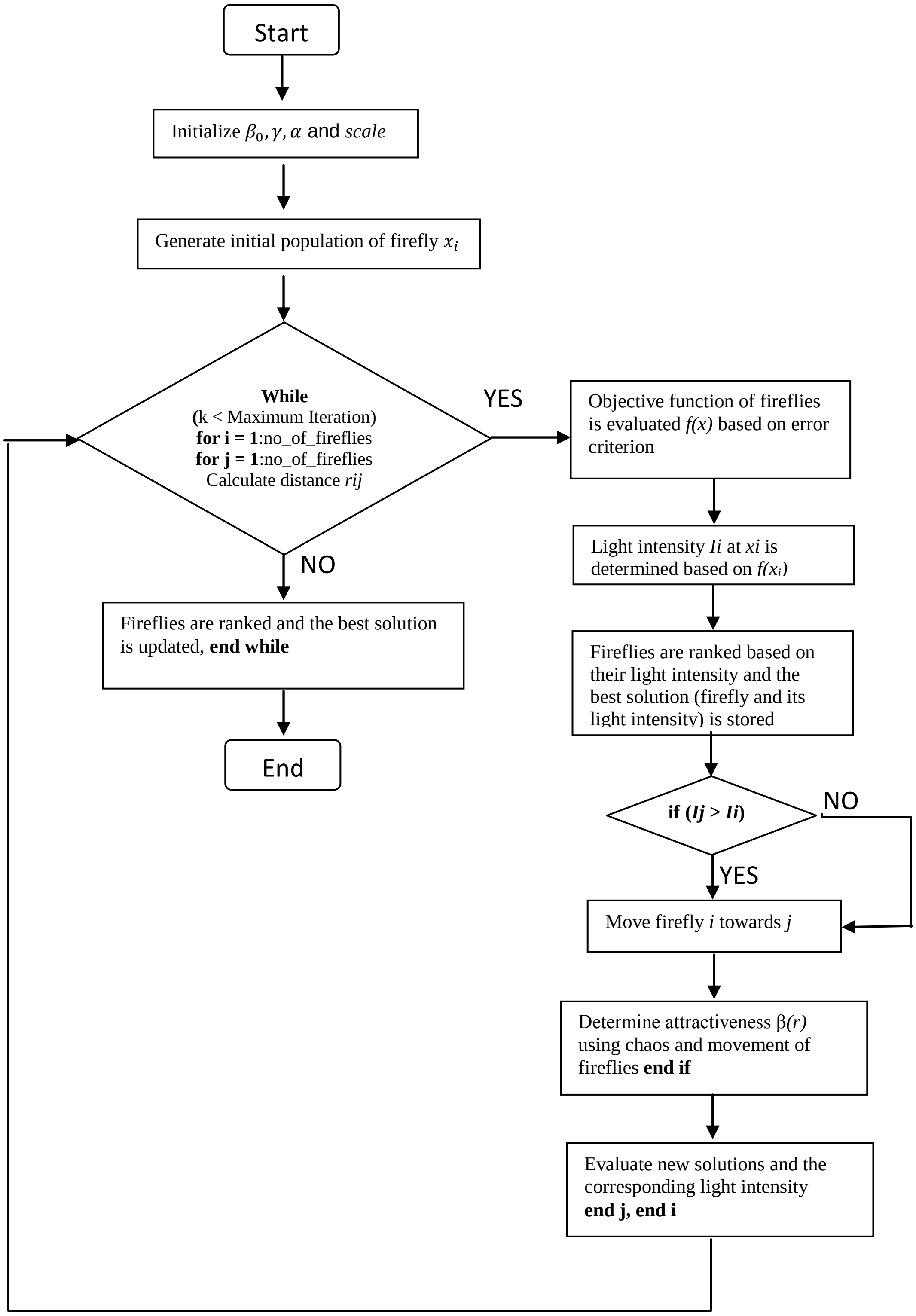


Figure 3.5 : Flow Chart for FA

3.6 Optimization of Chaos Firefly Algorithm

Chaos is introduced to existing FA by modifying the β. In this CFA algorithm, Chebyshev map (A.H. Gandomi, 2012) is being investigated. The difference between FA and CFA is the usage of Chebyshev map for movement of the new generated firefly. The equation is shown below:

$$x_{k+1} = \cos\left(k.cos^{-1}(x_k)\right) \tag{3.3}$$

From the basic equation of FA

$$\beta(r) = \beta_0 e^{-\gamma r^2} \tag{3.4}$$

Hence, replacing Equation 3.3 into Equation 3.4 for the firefly attractiveness,

$$\beta = \cos\left(j.cos^{-1}(x_j)\right) \qquad (3.4)$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Background

After the firefly based algorithm had been integrated in the fractional order controller for the three area power system using Simulink as per explained in previous chapter, the results obtained will be presented and analyzed in this chapter. Both FA and CFA had been tested and been compared.

The objective function of each case of the simulation is to get the lowest Area Control Error. The fractional order controller parameters achieved to get the best result are extracted as the output of the program.

4.2 System Parameter

The system parameters of Figure 3.4 are as per table below.

Table 4.1 : System Parameters for Three Area Power System

System Parameters	Area 1	Area 2	Area 3
Speed Regulation, $\frac{1}{Rii}$	$\frac{1}{R_1} = 20$	$\frac{1}{R_2} = 22$	$\frac{1}{R_3} = 21.25$
Frequency sensitive load coefficient, D_i	$D_1 = 0.9$	$D_2 = 1.0$	$D_1 = 0.9$
Inertia constant, H_i	$2H_1 = 10$	$2H_2 = 12$	$2H_3 = 7.5$
Governor time constant, τ_g	$\tau_{g1} = 0.08s$	$\tau_{g2} = 0.06s$	$\tau_{g3} = 0.07s$
Governor time constant, τ_T	$\tau_{T1} = 0.4s$	$\tau_{T2} = 0.44s$	$\tau_{T3} = 0.3s$
Synchronizing coefficient, $T_{i,j}$	$\tau_{1,2} = 0.2$	$\tau_{2,3} = 0.12$	$\tau_{1,3} = 0.25$

4.3 System Testing

The system has been tested for five cases. Table 4.2 below describes the configuration of each cases.

Table 4.2: System Test Configuration

Case	Load Demand Variation	Ramp Rate Optimization	Speed Regulation Optimization
1	ΔP_{L1}=0.1 p.u. ΔP_{L2}=0.1 p.u. ΔP_{L3}=0.1 p.u.	-	-
2	ΔP_{L1}=0.3 p.u. ΔP_{L2}=0.2 p.u. ΔP_{L3}=0.1 p.u.	-	-
3	ΔP_{L1}=0.1 p.u. ΔP_{L2}=0.1 p.u. ΔP_{L3}=0.1 p.u.	✓	
4	ΔP_{L1}=0.1 p.u. ΔP_{L2}=0.1 p.u. ΔP_{L3}=0.1 p.u..	-	✓
5	ΔP_{L1}=0.1 p.u. ΔP_{L2}=0.1 p.u. ΔP_{L3}=0.1 p.u.	✓	✓

The first case has been conducted to test the system when all parameters are set constant with the condition that nominal load demand of 0.1 p.u. had been injected at each area. The second case has been conducted to analyze the performance of the system when the simultaneously injected load demand is varied at each area. For the third case, the system has been conducted to optimize the Ramp Rate gain while the forth case has been tested to optimize the Speed Regulation gain. Lastly, the fifth case, the system has been tested with both optimization of Ramp Rate and Speed Regulation.

The investigation of the system includes the following criteria:

i. Integral Time Weighted Squared Error, ITSE

ii. Settling Time (s) – Time required for the output to settle with respect to the step input.

iii. Peak Frequency Overshoot (%) – The peak value of the frequency overshoot value (in percentage) with respect to the nominal frequency.

4.4 Result and Discussion

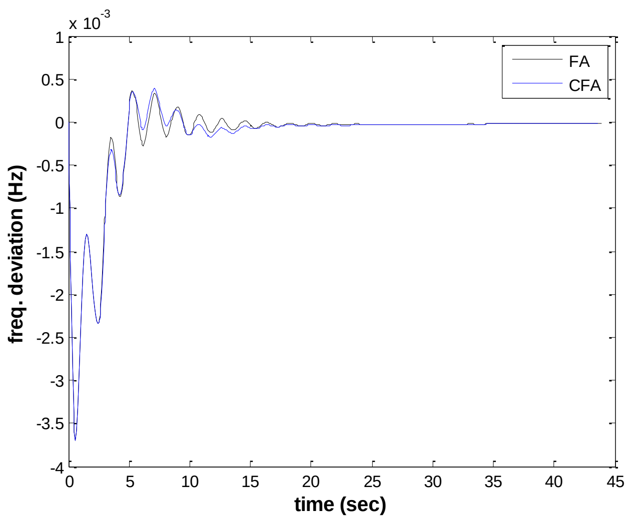
4.4.1 Case 1 Simultaneous Loading in All Areas

Table 4.3 shows the result of the system performance when it is being tested for the Case 1. The objective for this case is to investigate the performance of both FA and CFA under all parameters are set constant.

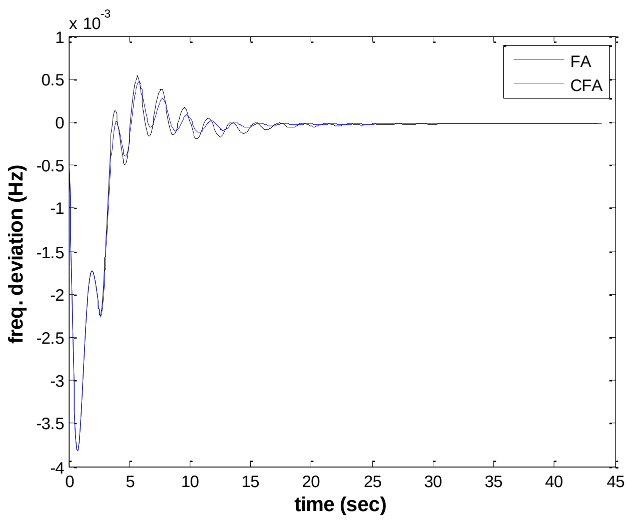
Table 4.3: System Performance for Case 1

Method	Area 1		Area 2		Area 3		ITSE
	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	
FA	13.7987	3.66%	16.5518	5.34%	14.5119	3.72%	0.2414
CFA	14.0805	3.91%	12.9642	4.71%	14.2734	4.76%	0.2411

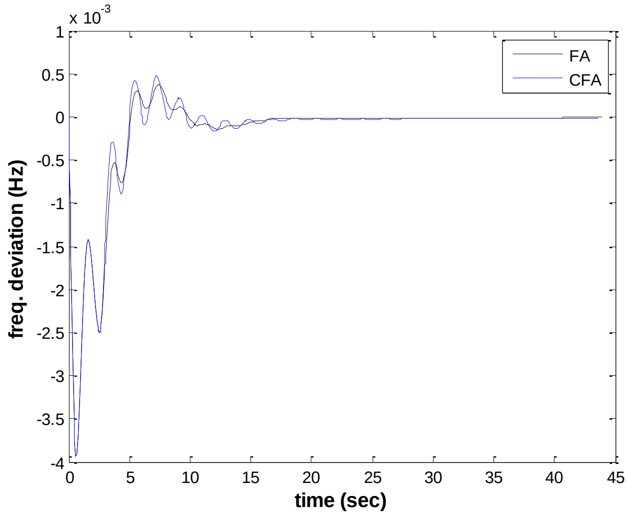
Figure 4.1 shows the frequency deviation step response comparison for FA and CFA. While Figure 4.2 shows tie line power changes.



(a) Frequency deviations in Area 1

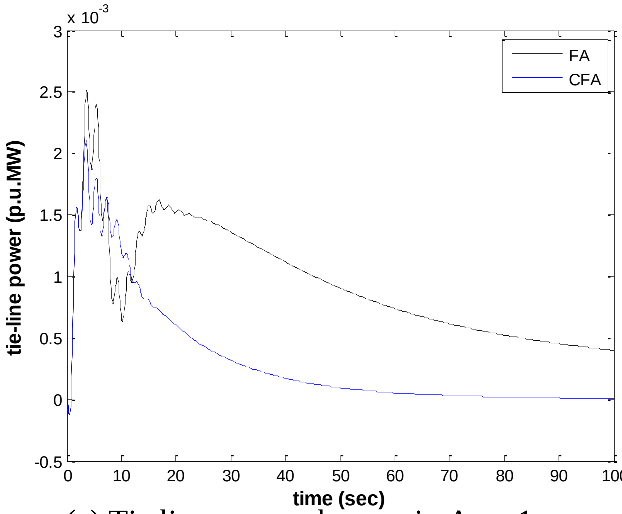


(b) Frequency deviations in Area 2

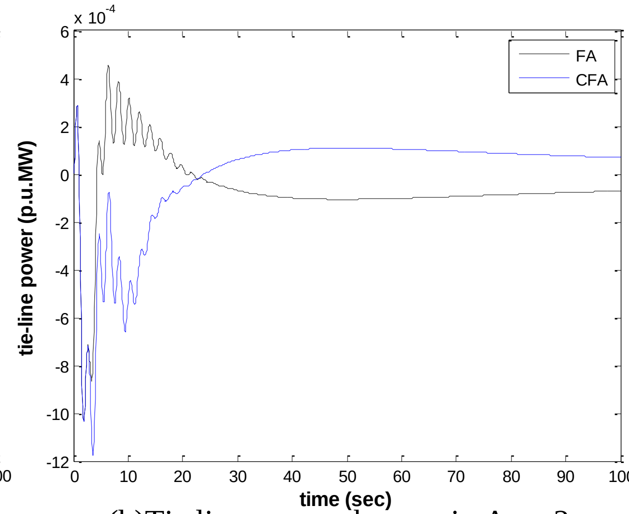


(c) Frequency deviations in Area 3

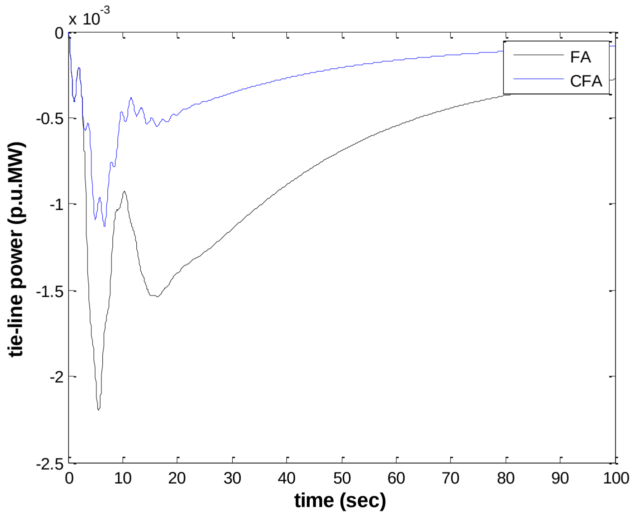
Figure 4.1: Frequency Deviation Step Response Comparison for Case 1



(a) Tie line power changes in Area 1



(b)Tie line power changes in Area 2



(c) Tie line power changes in Area 3

Figure 4.2: Tie line power changes for Case 1

A nominal load demand of 0.1 p.u. had been injected simultaneously for this case at each area. For Area 1 and Area 3, CFA showed the highest frequency overshoot, while for Area 2, the FA frequency overshoot is higher. However for settling time, for Area 1 and Area 3, FA settled faster while for Area 2, CFA settled faster. From Figure 4.2, after 100 seconds, tie-line power of CFA is closer to zero for Area 1 and Area 3. Comparing the ITSE value, CFA give better value than FA. Table 4.4 indicate the optimal FOID parameters for Case 1.

Table 4.4: Optimal FOID parameters Case 1

Method	Area	FOID parameters			
		K_i	K_d	λ	μ
FA	Area 1	0.2415	0.1782	0.9800	0.0908
	Area 2	0.4076	0.3325	0.9142	0.4031
	Area 3	0.3144	0.0953	0.9002	0.3790
CFA	Area 1	0.2852	0.1356	0.9176	0.2988
	Area 2	0.3683	0.2786	0.9352	0.2617
	Area 3	0.3234	0.1619	0.9127	0.3898

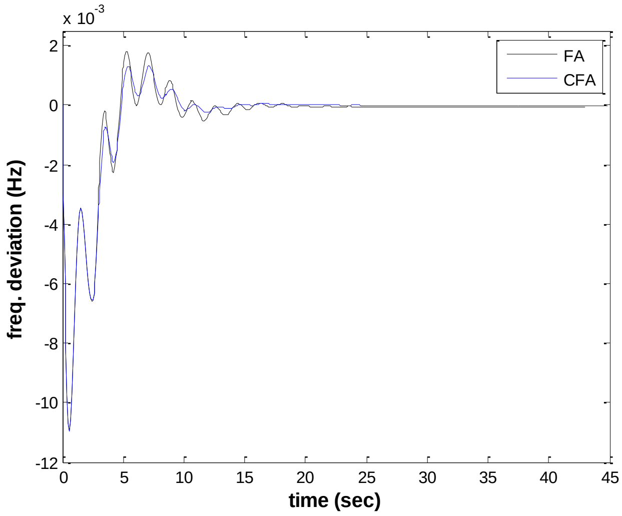
4.4.2 Case 2 Different Load Demand Injected at Each Area

For Case 2, the simultaneously load demand applied at Area 1, Area 2 and Area 3 are 0.3 p.u., 0.2 p.u. and 0.1 p.u. accordingly. Table 4.5 shows the result of the system performance.

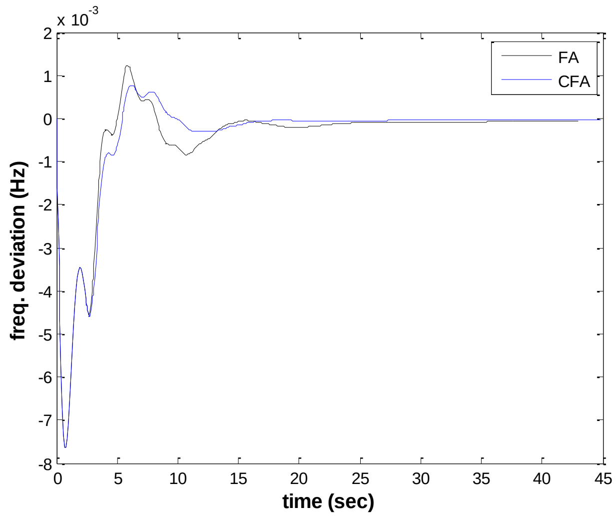
Table 4.5: System Performance for Case 2

Method	Area 1		Area 2		Area 3		ITSE
	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	
FA	13.7271	1.79%	20.9272	1.24%	41.6626	6.82%	1.4147
CFA	11.9939	1.47%	16.4823	8.69%	38.9543	3.44%	1.3248

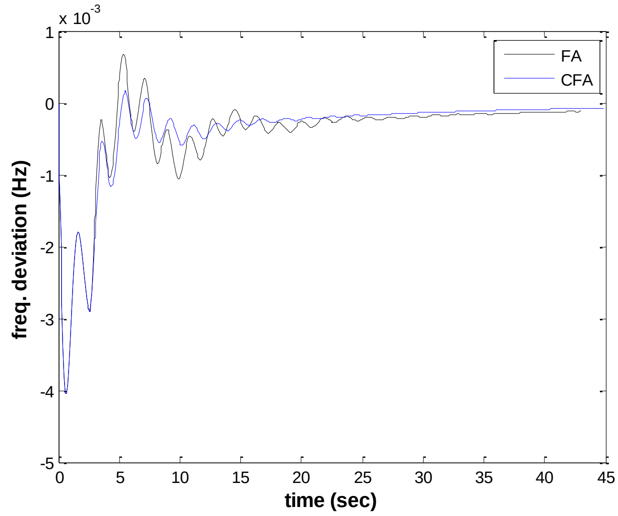
Figure 4.3 shows the frequency deviation step response comparison for FA and CFA while Figure 4.4 shows tie line power changes.



(a) Frequency deviations in Area 1

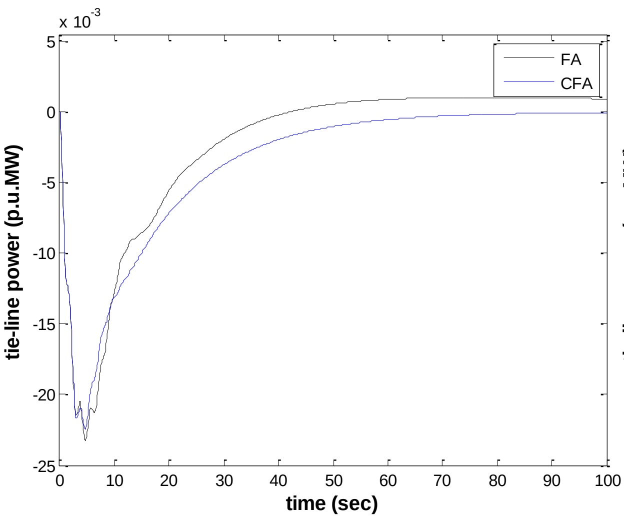


(b) Frequency deviations in Area 2

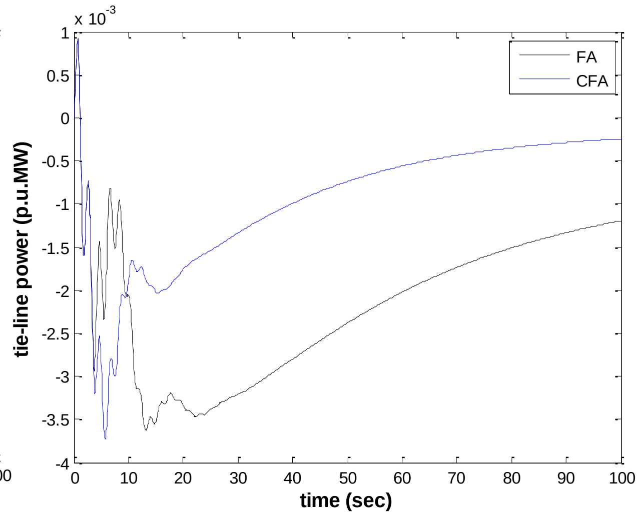


(c) Frequency deviations in Area 3

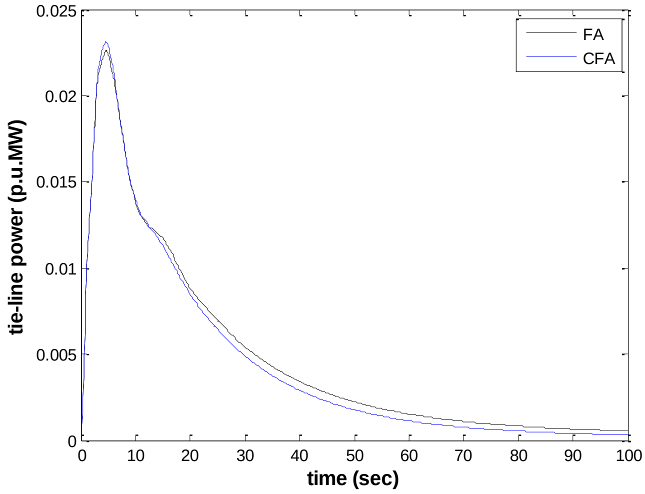
Figure 4.3: Frequency Deviation Step Response Comparison for Case 2



(a) Tie line power changes in Area 1



(b) Tie line power changes in Area 2



(c) Tie line power changes in Area 3

Figure 4.4: Tie line power changes for Case 2

For Area 1 and Area 3, FA illustrated higher frequency maximum overshoot, while for Area 2, the CFA frequency overshoot is higher. However for settling time, CFA settled faster at all three area. From Figure 4.4, tie-line power of CFA is closer to zero for all three area. Comparing the ITSE value, CFA give better value than FA. Table 4.6 indicate the optimal FOID parameters for Case 2.

Table 4.6 : Optimal FOID parameters for Case2

Method	**Area**	**FOID parameters**			
		K_i	K_d	λ	μ
FA	Area 1	0.3063	0.1485	0.8983	0.3946
	Area 2	0.4890	0.1662	0.7866	0.6064
	Area 3	0.5138	0.2029	0.7531	0.7360
CFA	Area 1	0.2742	0.1058	0.9266	0.1831
	Area 2	0.3628	0.1217	0.8983	0.3386
	Area 3	0.3596	0.1758	0.8648	0.3529

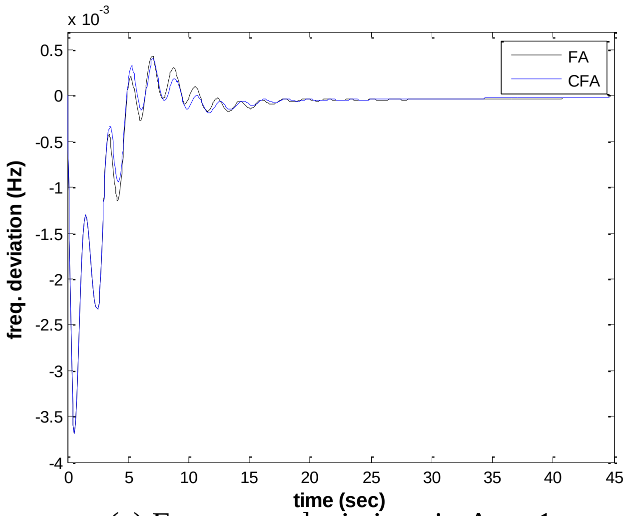
4.4.3 Case 3 Optimization of Ramp Rate

For Case 3, the simultaneously load demand applied at all area is same which is 0.1 p.u. However for this case, the optimization is not only on the FOID parameters, but also on the Ramp Rate gain. Table 4.7 shows the result of the system performance.

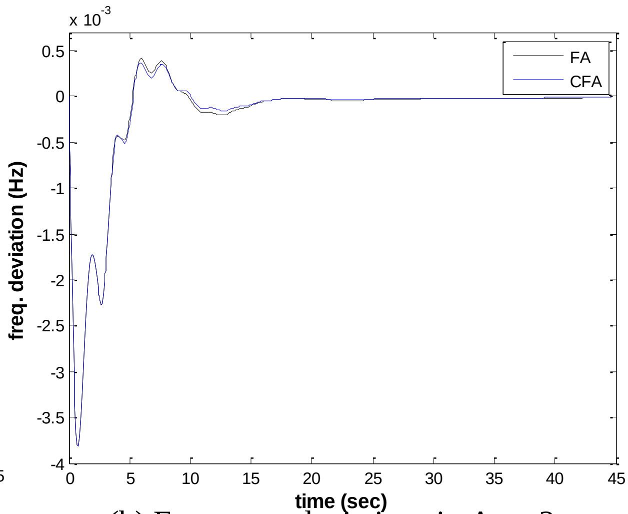
Table 4.7: System Performance for Case 3

Method	Area 1		Area 2		Area 3		ITSE
	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	
FA	17.1185	4.34%	15.2491	4.18%	14.4002	5.38%	0.2646
CFA	15.6414	4.07%	15.1290	3.70%	14.1772	4.19%	0.2492

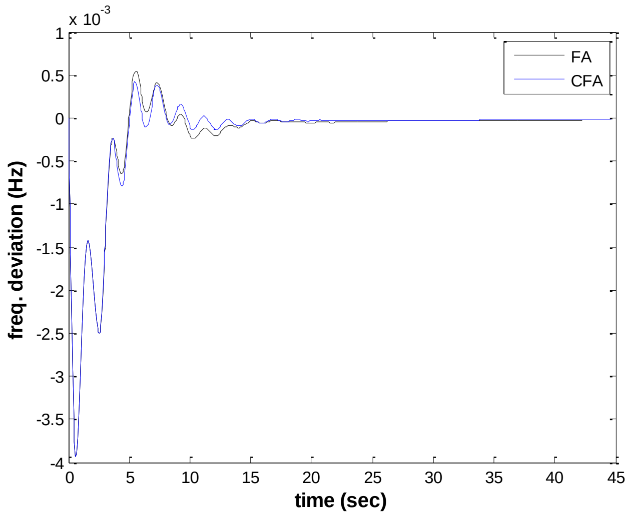
Figure 4.5 shows the frequency deviation step response comparison for FA and CFA. While Figure 4.6 shows tie line power changes.



(a) Frequency deviations in Area 1

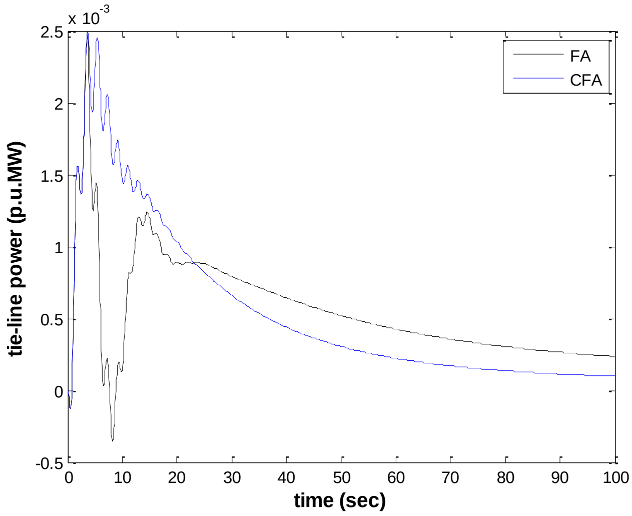


(b) Frequency deviations in Area 2

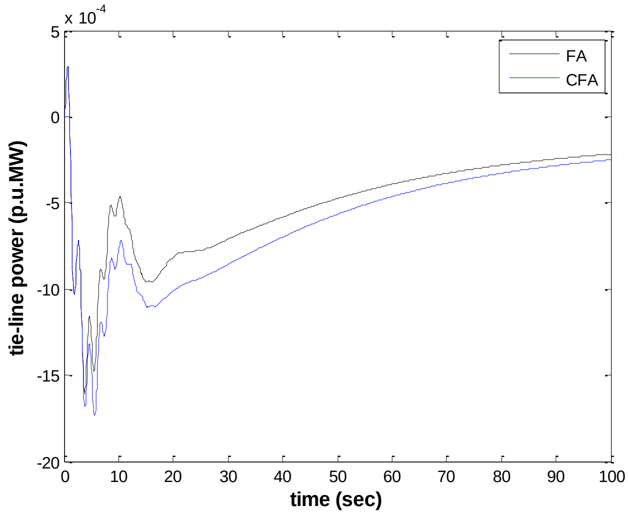


Frequency deviations in Area 3

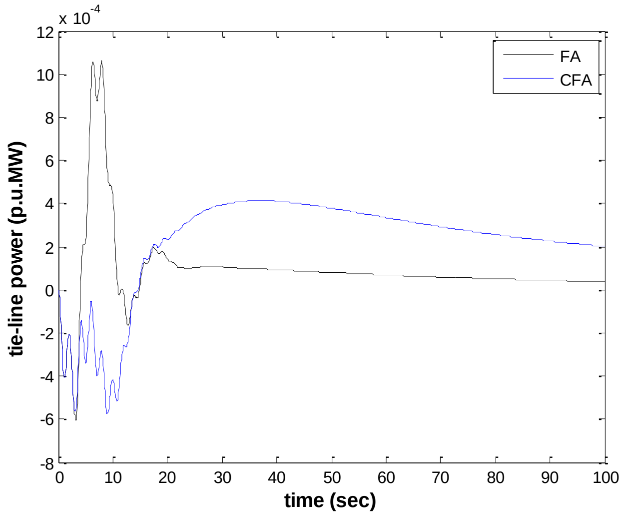
Figure 4.5: Frequency Deviation Step Response Comparison for Case 3



(a) Tie line power changes in Area 1



(b) Tie line power changes in Area 2



(c) Tie line power changes in Area 3

Figure 4.6: Tie line power changes for Case 3

FA display higher frequency maximum overshoot at all area. Hence CFA settled faster at all area. From Figure 4.6, tie-line power of CFA is closer to zero for all three area. However for this Case 3, the different between CFA and FA is significant. Comparing the ITSE value, CFA give better value than FA. Table 4.8 indicates the optimal FOID parameters and Ramp Rate for Case 3.

Table 4.8 : Optimal Ramp Rate and FOID parameters for Scenario 3

Method	Area	FOID parameters					
		K_i	K_d	λ	μ	α_{gen1}	α_{gen2}
FA	Area 1	0.6712	0.3538	0.9139	0.4857	0.2480	0.1604
	Area 2	0.7923	0.3361	0.8718	0.5459	0.3250	0.1857
	Area 3	0.3369	0.1215	0.8963	0.2737	0.7109	0.3125
CFA	Area 1	0.2994	0.1481	0.9163	0.3531	0.5803	0.3737
	Area 2	0.4521	0.2070	0.8858	0.4903	0.3953	0.4580
	Area 3	0.5144	0.2712	0.9419	0.1827	0.3683	0.2115

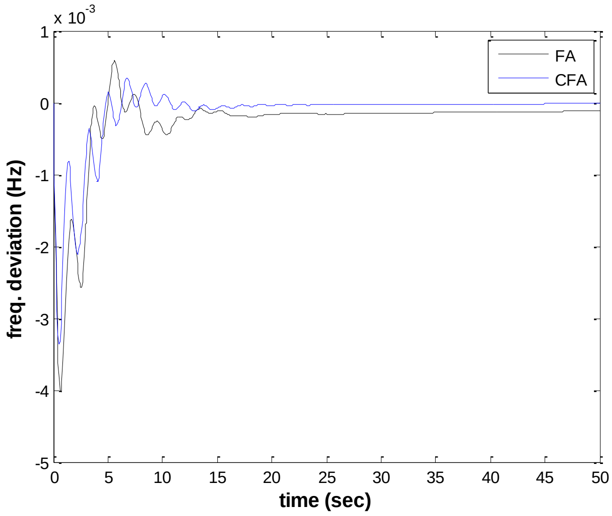
4.4.4 Case 4 Optimization of Speed Regulation

For Case 4, the simultaneously load demand applied at all area is same which is 0.1 p.u. However for this case, the optimization is on the FOID parameters and the Speed Regulation. Table 4.9 shows the result of the system performance.

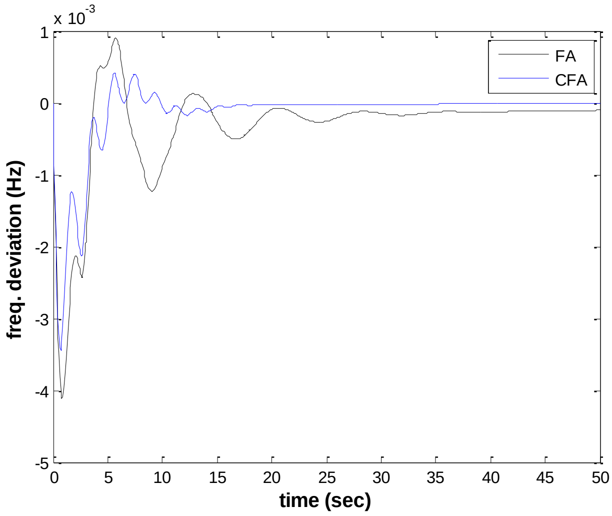
Table 4.9: System Performance for Case 4

Method	Area 1		Area 2		Area 3		ITSE
	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	
FA	26.9156	5.81%	33.8952	8.97%	33.5528	8.03%	0.6704
CFA	16.5123	3.37%	14.7319	4.10%	15.3709	4.60%	0.1945

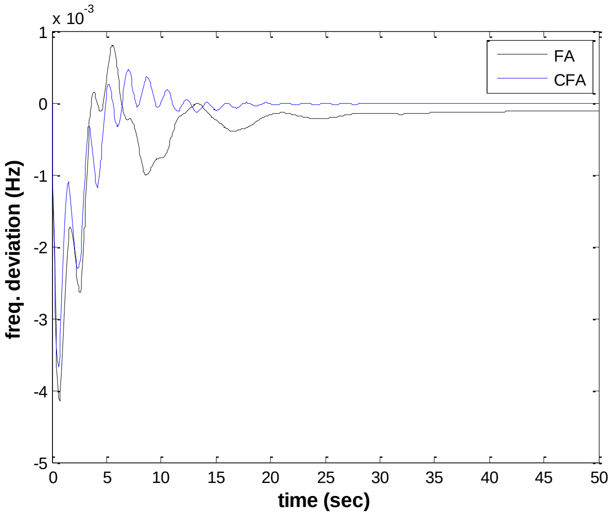
Figure 4.7 shows the frequency deviation step response comparison for FA and CFA. While Figure 4.8 shows tie line power changes.



(a) Frequency deviations in Area 1

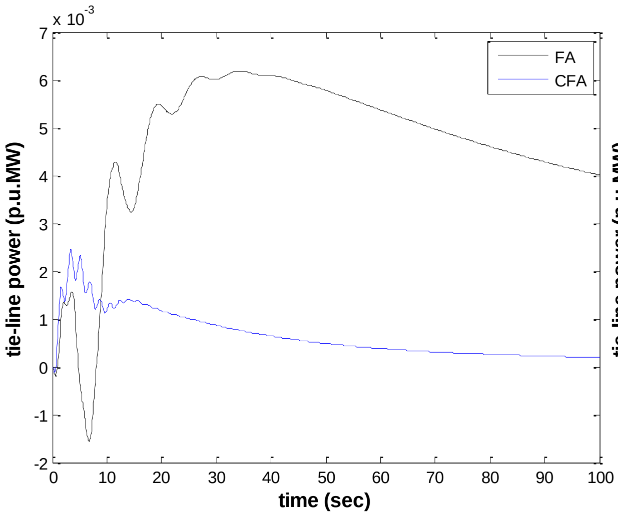


(b) Frequency deviations in Area 2

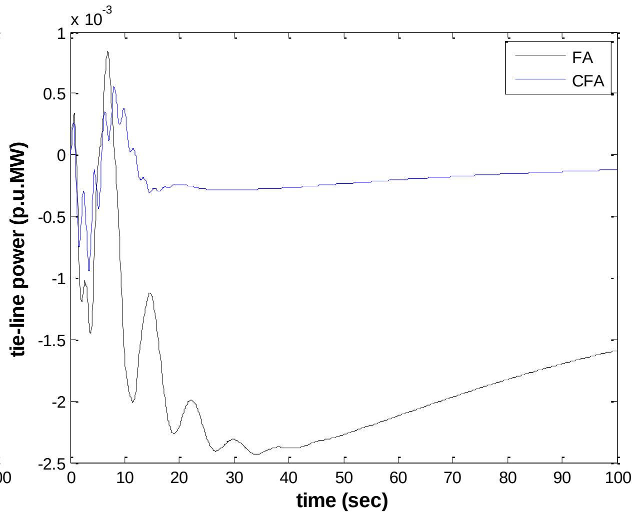


Frequency deviations in Area 3

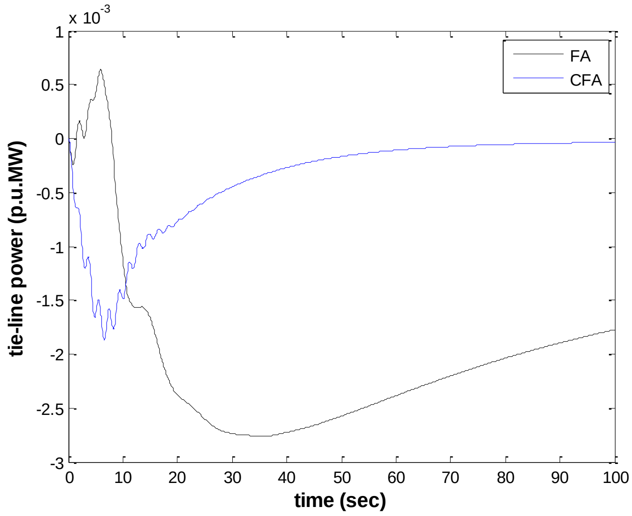
Figure 4.7: Frequency Deviation Step Response Comparison for Case 4



(a) Tie line power changes in Area 1



(b) Tie line power changes in Area 2



(c) Tie line power changes in Area 3

Figure 4.8: Tie line power changes for Case 4

For the Case 4, FA display higher frequency maximum overshoot at all area. Hence CFA settled faster at all area. From Figure 4.8, tie-line power of CFA is closer to zero for all three area compared to FA. However, FA performance for tie line power changes looks like it will take much longer time. Comparing the ITSE value, CFA give better value than FA. Table 4.10 indicate the optimal FOID parameters and Speed Regulation for Case 4.

Table 4.10 : Optimal FOID parameters and Speed Regulation for Scenario 4

Method	Area	FOID parameters					
		K_i	K_d	λ	μ	R_{gen1}	R_{gen2}
FA	Area 1	0.2430	0.1199	0.8785	0.0019	15.0213	28.0287
	Area 2	0.6069	0.1714	0.6137	0.7829	8.2762	28.8542
	Area 3	0.5109	0.1080	0.6144	0.8384	17.8979	22.8067
CFA	Area 1	0.3098	0.1414	0.9414	0.3879	29.9952	29.9745
	Area 2	0.4690	0.2216	0.8980	0.4692	29.9920	21.7403
	Area 3	0.3389	0.1716	0.9206	0.4887	29.5696	21.4688

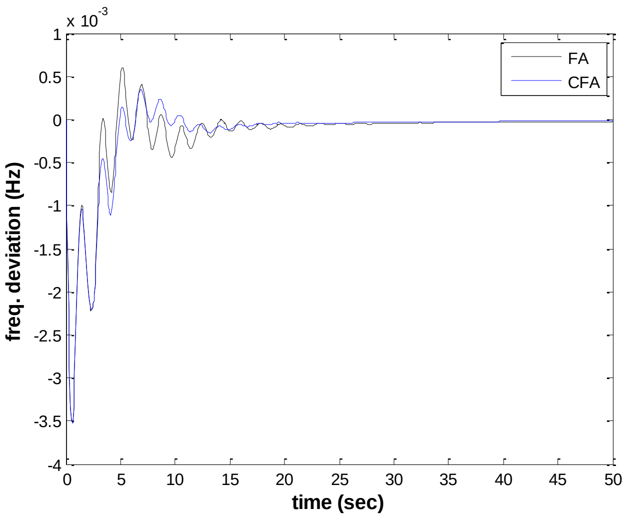
4.4.5 Case 5 Optimization of Ramp Rate and Speed Regulation

For Case 5, the simultaneously load demand applied at all area is same which is 0.1 p.u. However for this case, the optimization are on the FOID parameters, the Ramp Rate and the Speed Regulation. Table 4.11 shows the result of the system performance.

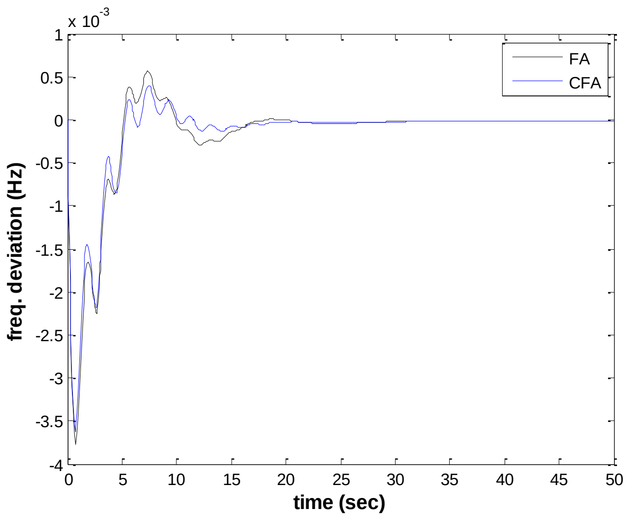
Table 4.11: System Performance for Case 5

Method	**Area 1**		**Area 2**		**Area 3**		**ITSE**
	Settling Time (s)	**Peak Δf (Hz)**	**Settling Time (s)**	**Peak Δf (Hz)**	**Settling Time (s)**	**Peak Δf (Hz)**	
FA	20.8527	6.04%	16.1305	5.62%	14.4070	3.92%	0.2543
CFA	16.8636	3.42%	16.3315	3.92%	17.0528	4.57%	0.2306

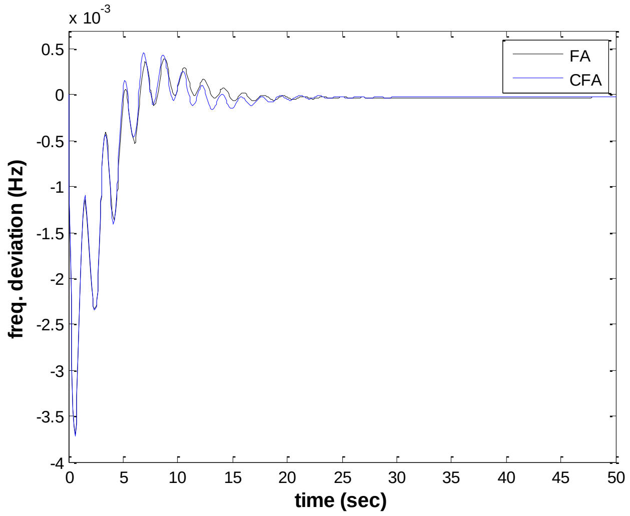
Figure 4.9 shows the frequency deviation step response comparison for FA and CFA. While Figure 4.10 shows tie line power changes.



(a) Frequency deviations in Area 1

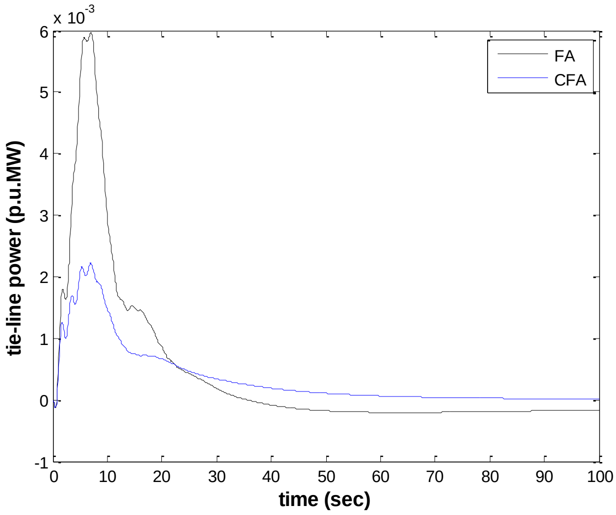


(b) Frequency deviations in Area 2

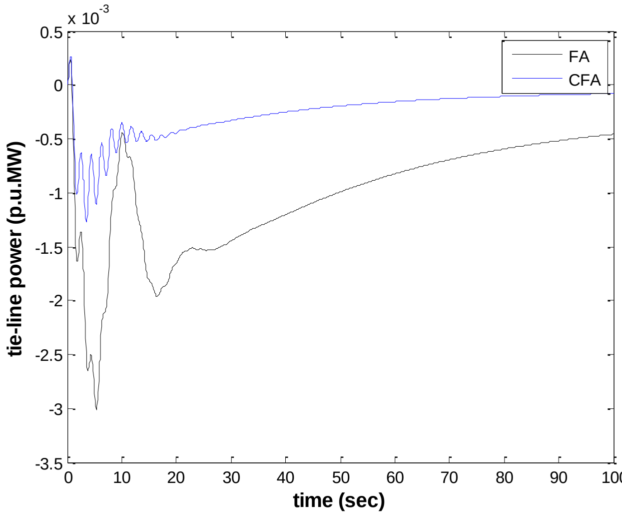


Frequency deviations in Area 3

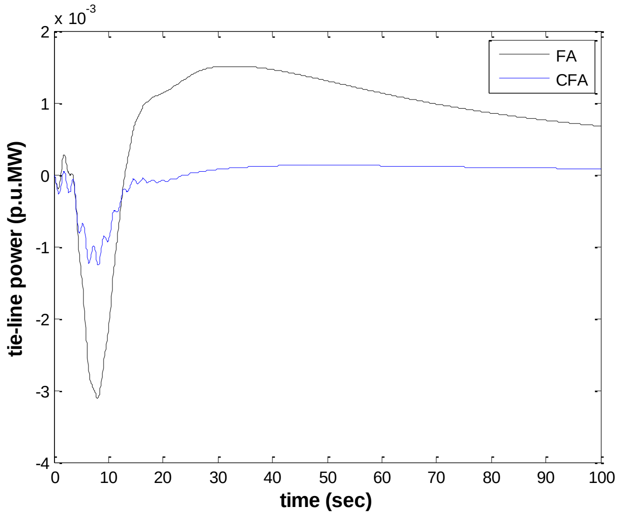
Figure 4.9: Frequency Deviation Step Response Comparison for Case 5



(a) Tie line power changes in Area 1



(b) Tie line power changes in Area 2



(c) Tie line power changes in Area 3

Figure 4.10: Tie line power changes for Case 5

Finally, for Case 5, FA display higher frequency maximum overshoot at Area 1 and Area 2. At Area 3, CFA frequency overshoot is higher. For the settling time, at Area 1 and Area 2, CFA settled faster while at Area 3, FA settled faster. From Figure 4.10, tie-line power of CFA is closer to zero for all three area compared to FA. Comparing the ITSE value, CFA give better value than FA. Table 4.10 indicate the optimal FOID parameters, Ramp Rate and Speed Regulation for Case 4.

Table 4:12 : Optimal FOID parameters and system performance for Scenario 5

Method	Area	FOID parameters							
		K_i	**K_d**	**λ**	**μ**	**R_{gen1}**	**R_{gen2}**	**α_{gen1}**	**α_{gen2}**
FA	Area 1	0.5704	0.2217	0.8442	0.4030	25.4801	29.7432	0.3830	0.3029
	Area 2	0.5397	0.2456	0.8399	0.8844	16.3297	27.1575	0.3891	0.4164
	Area 3	0.4293	0.2966	0.9837	0.4079	28.2332	22.3602	0.1956	0.4397
CFA	Area 1	0.2897	0.1199	0.9036	0.5234	29.5721	24.8882	0.4659	0.5781
	Area 2	0.4859	0.2807	0.9003	0.5900	24.8167	22.3897	0.4747	0.3544
	Area 3	0.8781	0.4418	0.9222	0.6481	20.8010	30.0000	0.2188	0.1485

4.4.5 Comparison of All Cases

Looking on overall for all cases, CFA give a smaller value for ITSE for all cases. For Area 1, CFA frequency overshoot is lower at all cases except for Case 1. For Area 2, CFA frequency overshoot is lower at all cases. For Area 3, CFA overshoot is lower for Case 2, 3 and 4. For Area 1, the CFA settling time is shorter for all cases except than Case 1. For Area 2, the CFA settling time is shorter for all cases except than Case 5. For Area 3, CFA settling time is shorter for all cases except than Case 5 also. Table 4.13 below is detailed out the performance for every case.

Table 4:13: System Performance for All Cases

Case	Method	Area 1		Area 2		Area 3		ITSE
		Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	Settling Time (s)	Peak Δf (Hz)	
1	FA	13.7987	3.66%	16.5518	5.34%	14.5119	3.72%	0.2414
	CFA	14.0805	3.91%	12.9642	4.71%	14.2734	4.76%	0.2411
2	FA	13.7271	1.79%	20.9272	1.24%	41.6626	6.82%	1.4147
	CFA	11.9939	1.47%	16.4823	8.69%	38.9543	3.44%	1.3248
3	FA	17.1185	4.34%	15.2491	4.18%	14.4002	5.38%	0.2646
	CFA	15.6414	4.07%	15.1290	3.70%	14.1772	4.19%	0.2492
4	FA	26.9156	5.81%	33.8952	8.97%	33.5528	8.03%	0.6704
	CFA	16.5123	3.37%	14.7319	4.10%	15.3709	4.60%	0.1945
5	FA	20.8527	6.04%	16.1305	5.62%	14.4070	3.92%	0.2543
	CFA	16.8636	3.42%	16.3315	3.92%	17.0528	4.57%	0.2306

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusion

Interconnected three area non-reheat thermal power system with multiple generators of LFC has been modeled using Matlab Simulink. To achieve that, the sub-systems such as the generator, governor, non-reheat steam turbine, load model and physical constraint have been reviewed. Fractional Order Integral-Derivative (FOID) or $I^{\lambda}D^{\mu}$ controller has been implemented into the LFC model. Fractional order concept has been explained in Section 2.6.5. Self computing methods which include artificial intelligent techniques have been looked into including the Firefly Algorithm which has been chosen as the basis for the LFC optimization. In getting the optimum configuration of $I^{\lambda}D^{\mu}$ controller, FA and CFA have been integrated into the LFC model.

Investigation of the performance of the CFA and FA based LFC controller have been conducted. Simultaneous load demand has been injected at each area with different value. Despite of the optimization on getting the optimum of $I^{\lambda}D^{\mu}$ controller parameter, optimizations on the ramp rate and speed regulation gain have also been conducted. ITSE has been selected as the objective function of this study which is used as the performance indicator for the LFC.

From the result shown in Section 4.4, CFA based controller outperform FA based controller in LFC non-reheat thermal power system with multiple generators. CFA based controller shown lower ITSE value for the entire test and having better settling time in most of the test. Tie-line power changes for CFA controller are all settled to zero. All in all, both FA and CFA can be used as LFC controller optimization method for $I^{\lambda}D^{\mu}$ controller with system remains stable.

5.2 Future Work

Some improvements can be done in order to achieve better performance LFC :

1. To include other physical constraints such as Governor Rate Constraints (GRC) and uncertainties.
2. To investigate and apply $I^{\lambda}D^{\mu}$ controller into hyro-thermal generation model.
3. To increase the initial value of firefly and increase the iteration.
4. To vary the γ and β_0 value in the simulation.

REFERENCES

Bakken B. H., & Grande O. S. (November 1998). Automatic Generation Control in a Deregulated Power System. *IEEE Transactions on Power Systems, Vol. 13, No. 4, November 1998.*

Cam E., & Kocaarsalan I. (2004). Load frequency control in two area power system using fuzzy logic controller. *Energy Conversion and Management 45 (2005) 233-243.*

Chang C. S., & Fu W. (1998). Load frequency control using genetic-algorithm based fuzzy gain scheduling of PI controllers. *Electric Machines and Power System Research (1998) 26:39-52.*

Chang C. S., & Fu W. (1997). Area load frequency control using fuzzy gain scheduling of PI controllers. *Electric Power System Research 42 (1997). 145-152.*

Concepcion Alicia Monje, YangQuan Chen, Blas Manueal Vinagre, Dingyu Xue, Vicente Feliu. (2010). Fractional Order Systems and Controls. Springer

Demiroren, Zeynelgil H. L, & Sengor N. S. (September 2001). The Application of ANN Technique to Load-frequency Control For Three-area Power System. *2001 IEEE Porto Power Tech Conference. 66*

Dong L., Member, IEEE, & Zhang Y. (June 2010). On Design of a Robust Load Frequency Controller for Interconnected Power Systems. American Control Conference Marriott Waterfront, Baltimore, MD, USA

Douglas L. D., Green T. A., & Kramer R. A. (1993). New Approaches to the AGC non- conforming load problem. IEEE Transaction on Power System.

Dy Liacco T. E. (1967). The Adaptive Reliability Control System. *IEEE Transactions On Power Apparatus And Systems Vol. Pas-86, No. 5 May 1967*

F. Daneshfar, & H. Bevrani (2009). Load–frequency control: A GA-based multi-agent reinforcement learning. *IET Generation Transmission Distribution, 2010, Vol. 4, Iss. 1, pp. 13–26. doi: 10.1049/iet-gtd.2009.0168*

Farahani S. M., Abshouri A. A., Nasiri B., & Meybodi M. R. (2011). A Gaussian Firefly Algorithm. *International Journal of Machine Learning and Computing, Vol. 1, No. 5, December 2011. 67*

Farook S., P. Sangameswara, Raju. (2012). Feasible AGC Controllers to Optimize LFC Regulation in Deregulated Power System Using Evolutionary Hybrid Genetic Firefly Algoroithm. *J. Electrical System 8-4 (2012) 459-471*

Farook S., & Sangameswara Raju P. (2012). Feasible AGC Controllers to Optimize LFC Regulation in Deregulated Power System Using Evolutionary Hybrid Genetic Firefly Algorithm. *Regular paper - Journal of Electrical Systems 8-4 (2012): 459- 471.*

Farahani M., Ganjefar S., & Alizadeh M. (2012). PID Controller Adjustment Using Chaotic Optimization Algorithm For Multi-Area Load Frequency Control. *IET Control Theory and Applications (2012).*

Gandomi A. H., Yang X. S., Talatahari S., & Alavi A. H. (2012). Firefly Algorithm With Chaos. *2012 Elsevier Commun Nonlinear Sci Numer Simulat 18 (2013) 89–98.*

H. Shayeghi, H.A. Shayanfar, A. Jalili. (Nov 2008). Load Frequency Control Strategies: A State-of-the-Art Survey for the Researcher. *Energy Conversion and Management 50 (2009) 344-353*

Hassan Bevrani (2009). Robust Power System Frequency Control, Springer.

Hadi Saadat (2004). Power System Analysis. *McGraw-Hill, Inc.*

Kanendra. N., Hazlie. M., & Abdul .Halim. A. B. (2013). Application Of Firefly Algorithm (FA) Based Optimization In Load Frequency Control For Interconnected Reheat Thermal Power System. *2013 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT).*

Kundur P. (1994). Power System Stability and Control. *McGraw-Hill,Inc. 68*

Lukasik S., & Zak S. (2009). Firefly Algorithm for Continuous Constrained Optimization Tasks. *Springer-Verlag Berlin Heidelberg 2009.*

Sanjoy Debbarma, Lalit Chandra Saikia, Nidul Sinha. (Oct 2013). Solution to Automatic Generation Control Prolem Using Firefly Algorith Optimized $I^{\lambda}D^{\mu}$ Controller. *ISA Transactions 53 (2014) 358-366*

Sheikh M. R. I, Muyeen S. M., Member IEEE, Takahashi R., Member IEEE, Muraa T., & Tamura J., Senior Member IEEE (2009). Application of Self Tuning FPIC to AGC for Load Frequency Control in Multi Area Power System. *IEEE Bucharest Power Tech Conference.*

Sachin k. Jain, S. Chakrabarti, S. N. Singh. (2013). Review of Load Frequency Control Methods. *2013 International Conference on COntrol, Automation, Robotics and EMbedded Systems (CARE)*

Shashi kant Pandeu, Soumya R. Mohanty, Nand Kishor. (Apr 2013). A Literature Survey on Load-Frequency Control for Conventional and Distribution Generation Power System. *Renewable and Sustainable Energy Reviews 25 (2013) 318-334.*

Swati Sondhi, Yogesh V. Hote. (June 2014). Fractional Order PID Controller for Load Frequency Control. *Energy Conversion and Management 85 (2014) 343-353*

Thomas M. Athay. (Dec 1987). Generation Scheduling and Control. *Proceedings of the IEEE, VOl. 75, No. 12.*

Yen J, Senior Member, IEEE (January/February 1999). Fuzzy Logic - A Modern Perspective. *IEEE Transactions On Knowledge And Data Engineering, Vol. 11, No. [1]*

Yang X. S. Firefly Algorithm, Stochastic Test Functions and Design Optimization.

Yang X. S (2010). Nature-Inspired Metaheuristic Algorithms. *Luniver Press. 72*

APPENDIX

MATHLAB CODE

FIREFLY ALGORITHM (FA)

```
%FireflyPID
% clear all


no_fireflies  = 20;
MaxGeneration = 100;
D=9;        %/*The number of parameters of the problem to be
optimized*/
ub=1 ;     %/*lower bounds of the parameters. */
lb=0.2;     %/*upper bound of the parameters.*/
Range = ub-lb;

D2 = 6;
ub2 = 1;
lb2 = 0.001;
Range2 = ub2-lb2;

% -------------------------------------------------

gamma=1.0;      % Absorption coefficient
delta=0.97;     % Randomness reduction (similar to an annealing
schedule)
alpha = 0.8;    % Randomness 0--1 (highly random)
betamin = 0.2;

% -------------------------------------------------

%Initialization
runtime = 1;

runner = 1;
for r=1:runtime


firefly = rand(no_fireflies,D) .* Range + lb;
firefly2 = rand(no_fireflies,D2) .* Range2 + lb2;
firefly = [firefly firefly2];
ObjVal   = FFtracklsq89(firefly, no_fireflies)';
Fitness  = calculateFitness(ObjVal);

for k=1:MaxGeneration    %%%%% start iterations
k

    %-------------------------------------------------
    % This line of reducing alpha is optional
    % alpha=alpha_new(alpha,MaxGeneration);
    % alpha_n=alpha_0(1-delta)^NGen=10^(-4);
    % alpha_0=0.9

    delta=1-(10^(-4)/0.9)^(1/MaxGeneration);
    alpha=(1-delta)*alpha;
```

```
    %-------------------------------------------------

    % Evaluate new solutions (for all n fireflies)
    for i=1:no_fireflies
       %ObjVal(i) = (firefly(i).^2+firefly(i)).*cos(firefly(i));
       ObjVal(i)   = FFtracklsq89(firefly(i,:), 1)';
       Lightn(i)=ObjVal(i);
    end

    % Ranking fireflies by their light intensity/objectives
    [Lightn,Index]=sort(ObjVal);
    ns_tmp=firefly;
    for i=1:no_fireflies
    firefly(i,:)=ns_tmp(Index(i),:);
    end

    % Find the current best
    fireflyo=firefly;
    Lighto=Lightn;
    Firelfybest=firefly(1,:);
    Lightbest=Lightn(1);

    % For output only
    fbest(k,:)=Lightbest;

    % Scaling of the system
    scale  = abs(ub - lb);
    scale2 = abs(ub2 - lb2);

    fireflyc = firefly;
    firefly = firefly(:,1:9);
    fireflyo1 = firefly(:,1:9);
    % Updating fireflies
    for i=1:no_fireflies
    % The attractiveness parameter beta=exp(-gamma*r)
       for j=1:no_fireflies
          r=sqrt(sum((firefly(i,:)-firefly(j,:)).^2));
          % Update moves
            if Lightn(i)>Lighto(j), % Brighter and more attractive
            beta0=1;
            beta=(beta0-betamin)*exp(-gamma*r.^2)+betamin;
            tmpf=alpha.*(rand(1,D)-0.5).*scale;
            firefly(i,:)=firefly(i,:).*(1-
beta)+fireflyo1(j,:).*beta+tmpf;
            end
       end % end for j
    end % end for i

   firefly2 = fireflyc(:,10:15);
   fireflyo2 = fireflyc(:,10:15);
   for i=1:no_fireflies
    % The attractiveness parameter beta=exp(-gamma*r)
       for j=1:no_fireflies
          r=sqrt(sum((firefly2(i,:)-firefly2(j,:)).^2));
          % Update moves
            if Lightn(i)>Lighto(j), % Brighter and more attractive
            beta0=1;
            beta=(beta0-betamin)*exp(-gamma*r.^2)+betamin;
            tmpf2=alpha.*(rand(1,D2)-0.5).*scale2;
```

```
            firefly2(i,:)=firefly2(i,:).*(1-
beta)+fireflyo2(j,:).*beta+tmpf2;
            end
        end % end for j
    end % end for i



    fireflyb = [firefly firefly2];
    firefly = fireflyb;

    %Limits

    for i2=1:no_fireflies


        if (firefly(i2,1)<lb)
         firefly(i2,1) = lb;
        end
        if (firefly(i2,2)<lb)
         firefly(i2,2) = lb;
        end
        if (firefly(i2,3)<lb)
         firefly(i2,3) = lb;
        end
        if (firefly(i2,4)<lb)
         firefly(i2,4) = lb;
        end
        if (firefly(i2,5)<lb)
         firefly(i2,5) = lb;
        end
        if (firefly(i2,6)<lb)
         firefly(i2,6) = lb;
        end
        if (firefly(i2,7)<lb)
         firefly(i2,7) = lb;
        end
        if (firefly(i2,8)<lb)
         firefly(i2,8) = lb;
        end
        if (firefly(i2,9)<lb)
         firefly(i2,9) = lb;
        end

        if (firefly(i2,10)<lb2)
         firefly(i2,10) = lb2;
        end
        if (firefly(i2,11)<lb2)
         firefly(i2,11) = lb2;
        end
        if (firefly(i2,12)<lb2)
         firefly(i2,12) = lb2;
        end
        if (firefly(i2,13)<lb2)
         firefly(i2,13) = lb2;
        end
        if (firefly(i2,14)<lb2)
         firefly(i2,14) = lb2;
        end
        if (firefly(i2,15)<lb2)
         firefly(i2,15) = lb2;
```

```
        end


        if (firefly(i2,1)>ub)
         firefly(i2,1) = ub;
        end
        if (firefly(i2,2)>ub)
         firefly(i2,2) = ub;
        end
        if (firefly(i2,3)>ub)
         firefly(i2,3) = ub;
        end
        if (firefly(i2,4)>ub)
         firefly(i2,4) = ub;
        end
        if (firefly(i2,5)>ub)
         firefly(i2,5) = ub;
        end
        if (firefly(i2,6)>ub)
         firefly(i2,6) = ub;
        end
        if (firefly(i2,7)>ub)
         firefly(i2,7) = ub;
        end
        if (firefly(i2,8)>ub)
         firefly(i2,8) = ub;
        end
        if (firefly(i2,9)>ub)
         firefly(i2,9) = ub;
        end

        if (firefly(i2,10)>ub2)
         firefly(i2,10) = ub2;
        end
        if (firefly(i2,11)>ub2)
         firefly(i2,11) = ub2;
        end
        if (firefly(i2,12)>ub2)
         firefly(i2,12) = ub2;
        end
        if (firefly(i2,13)>ub2)
         firefly(i2,13) = ub2;
        end
        if (firefly(i2,14)>ub2)
         firefly(i2,14) = ub2;
        end
        if (firefly(i2,15)>ub2)
         firefly(i2,15) = ub2;
        end

    end

pp(k,:) = Lightbest;
% cc(k,:) = firefly;
% cc2(k,:) = firefly2;
Lightbest
end

GlobalParams = Firelfybest;
GlobalMin = Lightbest;
Kp = GlobalParams(:,1)
Ki = Kp/GlobalParams(:,2)
```

```
Kd = Kp*GlobalParams(:,3)

Kp2 = GlobalParams(:,4)
Ki2 = Kp2/GlobalParams(:,5)
Kd2 = Kp2*GlobalParams(:,6)

Kp3 = GlobalParams(:,7)
Ki3 = Kp3/GlobalParams(:,8)
Kd3 = Kp3*GlobalParams(:,9)

lambda = GlobalParams(:,10)
mu = GlobalParams(:,11)

lambda2 = GlobalParams(:,12)
mu2 = GlobalParams(:,13)

lambda3 = GlobalParams(:,14)
mu3 = GlobalParams(:,15)

list(runner,:) = [Kp Ki Kd Kp2 Ki2 Kd2 Kp3 Ki3 Kd3 lambda mu lambda2
mu2 lambda3 mu3 GlobalMin]

end
lambda_a = lambda;
mu_a = mu;
sim('FOC8')
sysval1 = stepinfo(b1.signals.values,b1.time);
sysper1 = [sysval1.SettlingTime sysval1.SettlingMin
sysval1.SettlingMax]
sysval2 = stepinfo(b2.signals.values,b2.time);
sysper2 = [sysval2.SettlingTime sysval2.SettlingMin
sysval2.SettlingMax]
sysval3 = stepinfo(b3.signals.values,b3.time);
sysper3 = [sysval3.SettlingTime sysval3.SettlingMin
sysval3.SettlingMax]

pastez = [list; sysper1 sysper2 sysper3 zeros(1,7)]

ddd = polxxx
```

CHAOS FIREFLY ALGORITHM (CFA)

```
%FireflyPID
clear all


no_fireflies  = 40;
MaxGeneration = 150;
D=9;        %/*The number of parameters of the problem to be
optimized*/
ub=1 ;      %/*lower bounds of the parameters. */
lb=0.2;     %/*upper bound of the parameters.*/
Range = ub-lb;

D2 = 6;
ub2 = 1;
lb2 = 0.001;
Range2 = ub2-lb2;

% -------------------------------------------------

gamma=1.0;      % Absorption coefficient
delta=0.97;     % Randomness reduction (similar to an annealing
schedule)
alpha = 0.8;    % Randomness 0--1 (highly random)
betamin = 0.2;

% -------------------------------------------------

%Initialization
runtime = 1;

runner = 1;
for r=1:runtime


firefly = rand(no_fireflies,D) .* Range + lb;
firefly2 = rand(no_fireflies,D2) .* Range2 + lb2;
firefly = [firefly firefly2];
ObjVal   = FFtracklsq89(firefly, no_fireflies)';
Fitness  = calculateFitness(ObjVal);

for k=1:MaxGeneration    %%%%% start iterations
k

    %-------------------------------------------------
    % This line of reducing alpha is optional
    % alpha=alpha_new(alpha,MaxGeneration);
    % alpha_n=alpha_0(1-delta)^NGen=10^(-4);
    % alpha_0=0.9

    delta=1-(10^(-4)/0.9)^(1/MaxGeneration);
    alpha=(1-delta)*alpha;

    %-------------------------------------------------


    % Evaluate new solutions (for all n fireflies)
    for i=1:no_fireflies
```

```
        %ObjVal(i) = (firefly(i).^2+firefly(i)).*cos(firefly(i));
        ObjVal(i)   = FFtracklsq89(firefly(i,:), 1)';
        Lightn(i)=ObjVal(i);
    end

    % Ranking fireflies by their light intensity/objectives
    [Lightn,Index]=sort(ObjVal);
    ns_tmp=firefly;
    for i=1:no_fireflies
    firefly(i,:)=ns_tmp(Index(i),:);
    end

    % Find the current best
    fireflyo=firefly;
    Lighto=Lightn;
    Firelfybest=firefly(1,:);
    Lightbest=Lightn(1);

    % For output only
    fbest(k,:)=Lightbest;

    % Scaling of the system
    scale  = abs(ub - lb);
    scale2 = abs(ub2 - lb2);

    fireflyc = firefly;
    firefly = firefly(:,1:9);
    fireflyo1 = firefly(:,1:9);
    % Updating fireflies
    for i=1:no_fireflies
    % The attractiveness parameter beta=exp(-gamma*r)
       for j=1:no_fireflies
          r=sqrt(sum((firefly(i,:)-firefly(j,:)).^2));
          % Update moves
            if Lightn(i)>Lighto(j), % Brighter and more attractive
            beta0=1;

            tmpf=alpha.*(rand(1,D)-0.5).*scale;

              beta = abs(cos(j*abs(acosd(firefly(j,:)))));
            firefly(i,:)=firefly(i,:).*(1-
beta)+fireflyo1(j,:).*beta+tmpf;
            end
       end % end for j
    end % end for i

   firefly2 = fireflyc(:,10:15);
   fireflyo2 = fireflyc(:,10:15);
   for i=1:no_fireflies
    % The attractiveness parameter beta=exp(-gamma*r)
       for j=1:no_fireflies
          r=sqrt(sum((firefly2(i,:)-firefly2(j,:)).^2));
          % Update moves
            if Lightn(i)>Lighto(j), % Brighter and more attractive
            beta0=1;

            tmpf2=alpha.*(rand(1,D2)-0.5).*scale2;
            beta2 = abs(cos(j*abs(acosd(firefly2(j,:)))));
            firefly2(i,:)=firefly2(i,:).*(1-
beta2)+fireflyo2(j,:).*beta2+tmpf2;
            end
```

```
   end % end for j
end % end for i



fireflyb = [firefly firefly2];
firefly = fireflyb;

%Limits

for i2=1:no_fireflies


   if (firefly(i2,1)<lb)
    firefly(i2,1) = lb;
   end
   if (firefly(i2,2)<lb)
    firefly(i2,2) = lb;
   end
   if (firefly(i2,3)<lb)
    firefly(i2,3) = lb;
   end
   if (firefly(i2,4)<lb)
    firefly(i2,4) = lb;
   end
   if (firefly(i2,5)<lb)
    firefly(i2,5) = lb;
   end
   if (firefly(i2,6)<lb)
    firefly(i2,6) = lb;
   end
   if (firefly(i2,7)<lb)
    firefly(i2,7) = lb;
   end
   if (firefly(i2,8)<lb)
    firefly(i2,8) = lb;
   end
   if (firefly(i2,9)<lb)
    firefly(i2,9) = lb;
   end

   if (firefly(i2,10)<lb2)
    firefly(i2,10) = lb2;
   end
   if (firefly(i2,11)<lb2)
    firefly(i2,11) = lb2;
   end
   if (firefly(i2,12)<lb2)
    firefly(i2,12) = lb2;
   end
   if (firefly(i2,13)<lb2)
    firefly(i2,13) = lb2;
   end
   if (firefly(i2,14)<lb2)
    firefly(i2,14) = lb2;
   end
   if (firefly(i2,15)<lb2)
    firefly(i2,15) = lb2;
   end
```

```
        if (firefly(i2,1)>ub)
         firefly(i2,1) = ub;
        end
        if (firefly(i2,2)>ub)
         firefly(i2,2) = ub;
        end
        if (firefly(i2,3)>ub)
         firefly(i2,3) = ub;
        end
        if (firefly(i2,4)>ub)
         firefly(i2,4) = ub;
        end
        if (firefly(i2,5)>ub)
         firefly(i2,5) = ub;
        end
        if (firefly(i2,6)>ub)
         firefly(i2,6) = ub;
        end
        if (firefly(i2,7)>ub)
         firefly(i2,7) = ub;
        end
        if (firefly(i2,8)>ub)
         firefly(i2,8) = ub;
        end
        if (firefly(i2,9)>ub)
         firefly(i2,9) = ub;
        end

        if (firefly(i2,10)>ub2)
         firefly(i2,10) = ub2;
        end
        if (firefly(i2,11)>ub2)
         firefly(i2,11) = ub2;
        end
        if (firefly(i2,12)>ub2)
         firefly(i2,12) = ub2;
        end
        if (firefly(i2,13)>ub2)
         firefly(i2,13) = ub2;
        end
        if (firefly(i2,14)>ub2)
         firefly(i2,14) = ub2;
        end
        if (firefly(i2,15)>ub2)
         firefly(i2,15) = ub2;
        end

    end

pp(k,:) = Lightbest;
% cc(k,:) = firefly;
% cc2(k,:) = firefly2;
Lightbest
end

GlobalParams = Firelfybest;
GlobalMin = Lightbest;
Kp = GlobalParams(:,1)
Ki = Kp/GlobalParams(:,2)
```

```
Kd = Kp*GlobalParams(:,3)

Kp2 = GlobalParams(:,4)
Ki2 = Kp2/GlobalParams(:,5)
Kd2 = Kp2*GlobalParams(:,6)

Kp3 = GlobalParams(:,7)
Ki3 = Kp3/GlobalParams(:,8)
Kd3 = Kp3*GlobalParams(:,9)

lambda = GlobalParams(:,10)
mu = GlobalParams(:,11)

lambda2 = GlobalParams(:,12)
mu2 = GlobalParams(:,13)

lambda3 = GlobalParams(:,14)
mu3 = GlobalParams(:,15)

list(runner,:) = [Kp Ki Kd Kp2 Ki2 Kd2 Kp3 Ki3 Kd3 lambda mu lambda2
mu2 lambda3 mu3 GlobalMin]

end
lambda_a = lambda;
mu_a = mu;
sim('FOC8')
sysval1 = stepinfo(b1.signals.values,b1.time);
sysper1 = [sysval1.SettlingTime sysval1.SettlingMin
sysval1.SettlingMax]
sysval2 = stepinfo(b2.signals.values,b2.time);
sysper2 = [sysval2.SettlingTime sysval2.SettlingMin
sysval2.SettlingMax]
sysval3 = stepinfo(b3.signals.values,b3.time);
sysper3 = [sysval3.SettlingTime sysval3.SettlingMin
sysval3.SettlingMax]

pastez = [list; sysper1 sysper2 sysper3 zeros(1,7)]

ddd = polxxx
```