

# **Load Frequency Controller Tuning using Chaotic Firefly Algorithm**

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## DECLARATION

I hereby certify that the work which is being presented in this report entitled, "Load Frequency Controller Tuning using Chaotic firefly algorithm" as a part of curriculum during Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried under the Guidance of Mr. Souvik Ganguli, EIED.

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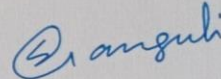
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## LIST OF ABBREVIATIONS

<b>AFA</b>	Adaptive Firefly Algorithm
<b>ACE</b>	Area Control Error
<b>AI</b>	Artificial Intelligence
<b>AFRC</b>	Area Frequency Response Characteristics
<b>AGC</b>	Automatic Generation Control
<b>ACO</b>	Ant Colony Optimization
<b>ABC</b>	Artificial Bee Colony
<b>BFOA</b>	Bacteria Foraging Optimization Algorithm
<b>CFA</b>	Chaotic Firefly Algorithm
<b>COA</b>	Chaotic Optimization Algorithm
<b>DE</b>	Differential Algorithm
<b>FA</b>	Firefly Algorithm
<b>FDM</b>	Fixed Dimension Multimodal
<b>GA</b>	Genetic Algorithm
<b>GRC</b>	Generation Rate Constraints
<b>IMC</b>	Internal Model Control
<b>ISE</b>	Integral of Square Error
<b>ITAE</b>	Integral of Time Absolute Error
<b>ITSE</b>	Integral of Time Square Error
<b><math>K_D</math></b>	Derivative Constant
<b><math>K_I</math></b>	Integral Constant
<b><math>K_P</math></b>	Proportionality Constant
<b>LFC</b>	Load Frequency Control
<b>PID</b>	Proportional Integral Derivative

<b>PI</b>	Proportional Integral
<b>PSO</b>	Particle Swarm Intelligence
<b>SI</b>	Swarm Intelligence
<b>SSE</b>	Sum of Square Error
<b>ZN</b>	Ziegler Nichols
$\Delta P_D$	Load disturbance
$\Delta F$	Frequency deviation
<b>U</b>	Reference Load
<b>T<sub>P</sub></b>	Time constant of the electric system
<b>T<sub>T</sub></b>	Time constant of the turbine
<b>T<sub>G</sub></b>	Time constant of the governor
<b>R</b>	Speed regulation due to the governor
$\Delta P_G$	Change in the generator input
$\Delta X_G$	Change in the valve position of the governor

## **ABSTRACT**

In this work, chaotic firefly has been applied to tune parameters of load frequency controller for multi-area and single area power systems using approximate model matching technique in frequency domain. The error function is minimized by using firefly with chaos by comparing the bode response of actual system model and reference system model. The algorithm was initially validated using 15 unconstrained benchmark functions. After the validation, the algorithm was applied to two single area problems and a two-area problem. The examples were performed for four objective functions with variations in light absorption coefficient and attraction coefficient. The results were performed for five chaotic maps. The results obtained were satisfactory with respect to both single and multi-area power system and convergence characteristics were obtained.

# CHAPTER 1: INTRODUCTION

## 1.1. OVERVIEW

### 1.1.1. LOAD FREQUENCY CONTROL PROBLEM

Load frequency control problem (LFC) in a power system has been one of the important topics of research of interconnected power systems. LFC plays a fundamental role in power systems. It makes the system reliable by maintaining the frequency and power in the system. A power system is an interconnection of more than one area via tie lines. For maintaining the frequency and power to a preset value both in dynamic and steady conditions the generators present in the control areas vary their speed accordingly. A sudden change in load brings a sudden change in the control area of the power system which leads to deviation in the frequency and tie line power.

In an electrical grid all the generators run in synchronism with each other and hence deliver the output power. On increase of load, the synchronous generator slows down thus resulting in a drop in the grid frequency. The frequency of the entire system will be brought back to normal by the governors that are connected with the generators. This action of frequency control by the governors linked with turbine and generators is known as “Primary Frequency Control”. Basically the control of frequency by the action of governors for any variation in load is called as primary frequency control. As energy cannot be stored in massive amounts therefore the output of the generators should be equal to the load demand. This means that the generator output should increase with the increase in the load and vice versa i.e. if the demand suddenly falls due to any disturbance in the tie line linked to heavy load, the generator should reduce the output to meet the load demand. The amount of load a plant should have is directed by the grid control authority. To shun hunting effect after the sudden change, the governors are designed in such a way that they continue to maintain stability at a speed corresponding to the new steady state level which mostly varies from the former speed. Hence primary control of frequency by the governor action only may not return frequency to required 50 Hz.

Frequency is controlled by the governors by putting more quantity of steam or water into the turbine. A secondary frequency control is needed at times when control of frequency by the governors is not adequate. When loading of plants is changed by the load dispatcher’s instructions, it is called “Secondary Frequency Control”. This control is done to bring the

frequency of the generating station back to specified value by transferring load among different areas. This control is an added control to the primary control. In primary frequency control the turbine control settings determine the power to be shared by generator whereas in secondary frequency control the load dispatch centers determine the load shared by the group of generating stations. The secondary control includes all the cost effective processes of the entire system with many interconnected generating stations.

In two area power system, the two areas are connected through tie lines; power exchange between these two areas is done through tie lines. The output frequency of each area tells information about its own area and the power deviation in the tie line gives information about other areas. The combination of the above information is referred as Area Control Error (ACE), which is the input to the controller.

### **1.1.2. INTERCONNECTED POWER SYSTEMS**

Generally the power systems are connected together to the neighboring areas. So the study of problems of load frequency control of interconnected power systems is significant and complex than single area power system.

There are some basic working principles of multi area power systems:

Under normal working conditions the load should be supported by its own area. Each area should adapt, regulate control schemes which are useful in both normal and abnormal working conditions. There are various advantages of the interconnection. The frequency drop in an interconnected power system is less than in single area power system for the same amount of change in load. This is because there is more availability of energy for larger systems so in comparison to single area system the static frequency drop is also less. Another advantage is that interconnected power systems require less reserve capacity due to the arrangement of interchanging energy. For large power systems the ratio of peak load to average load is quite less as compared to smaller power systems.

### **1.1.3. DRAWBACKS OF CONVENTIONAL INTEGRAL CONTROLLER**

The drawbacks can be summed up as:

- i. Their operating time is slow.

- ii. The integral controller does not care for some non-linear nature of various components of power system.
- iii. There are continuous load changes in the power system, due to this the operating point also keep changing. For best results the value of gain of the controller should also change with the change in operating point. To achieve this practically is difficult as an integral controller is a fixed type controller i.e. for a single condition it is optimal but unsuitable for another condition.

#### **1.1.4. NEED OF ADVANCE CONTROL TECHNIQUES**

Nowadays power systems have become more complex and vast therefore there is need for more improved, innovative and reliable control techniques. The new techniques developed should be secure, economic and fit for stable operation. Advance control techniques have the ability to adapt faster to the varying conditions. Examples of advances control techniques are optimal control pole placement, linear quadratic regulator, robust control, sliding mode control, internal model control etc. Further, nature inspired algorithms have also evolved and have been applied by various researchers for PID controller tuning to handle complex power system problems. The firefly algorithm (FA) appeared in 2008, and its application has extended intensely with miscellaneous applications [34].

#### **1.1.5. THE FIREFLY ALGORITHM**

FA was introduced by Xin-She Yang in the year 2007 and published in 2008[33]. FA was based on the flashing patterns and behavior of fireflies (light emitting flies). The flashing characteristics of fireflies were idealized so as to develop firefly-inspired algorithms. The light emitted by fireflies is an astonishing view in the night sky of the tropical and temperate regions. There are almost around 2000 species of fireflies in the world, and almost every firefly emits short, rhythmic flashes. There is a unique pattern of flashes for a certain species. Bioluminescence is the cause of flashing light. The correct functions of these signaling systems of the fireflies are still being questioned. However, the fundamental function of the light flashes emitted by the firefly help to attract breeding partners and prey. The rhythmic flashing of the firefly, the flashing rate, and difference in time between flashes form the signal system that helps to bring fireflies of both sexes together. In some species the female's respond to a unique flashing pattern of the male firefly whereas in some species the female firefly may even mimic the flashing

pattern of other species just to trap and then eat the male firefly who by the pattern of flashes think the female firefly as a suitable match.

As we all know that the intensity of light at a distance  $x$  from the source of light obeys inverse square law i.e. the intensity of light increases with decrease in  $x$ . Another fact is, light is absorbed by air and as distance increases it becomes weaker and weaker. By these two facts the fireflies are visible to a limited distance. Therefore, the flashing light of a firefly can be made the objective function to be optimized for various new optimization algorithms.

### **1.1.6. CHAOTIC FIREFLY ALGORITHM**

Recent advancement in concepts, theories and applications of non-linear dynamics, chaos etc. has expanded its applications in various fields. A sense of competition of FA with other meta-heuristic techniques has led to the development of various variants of FA. One of such variant is chaotic firefly algorithm. The theory of chaos offers deterministic time series of diverse characteristics. One of the applications of chaos is in the field of optimization techniques. The method of using chaotic variables in place of random variables in random based algorithms is called as Chaotic Optimization Algorithm [13,32]. Due of periodicity and non-repetition of chaos in these algorithms, they can carry out searches at higher speeds compared to stochastic searches. To generate chaotic sets one-dimensional, non-invertible maps like circle map, singer map, sine map, gauss map etc. are used.

### **1.2. OBJECTIVE OF WORK**

The analysis of the power systems have shown that LFC provide necessary support to the primary activities or operation of a power system. Therefore, LFC has become a very important topic of research and analysis. Many researchers have researched in this area using various systems, various types of controllers and different combinations of controllers. All the control methods quoted in literature have some advantages and disadvantages.

In the last decade there have been many changes in the control methods. Introduction of meta-heuristic techniques are one of them. Various nature based optimization algorithms have come up to optimize various variables of a power system.

The main objective of the work was to use firefly algorithm and chaotic firefly algorithm for unconstrained optimization problem of a power system. Further, Chaotic firefly is used for error

minimization in single area and multi area power system and tuning of PID controller parameters.

### **1.3. CONTRIBUTION OF THE AUTHOR**

Although load frequency control problems have been widely addressed in the literature but due to changes in the environment and power systems domain still there is a lot of scope of work. Earlier the tuning of PID controller has been carried out using various conventional methods, meta-heuristic techniques, which were less efficient. In this dissertation various systems have been taken and different types of errors have been minimized using chaotic firefly. The results have been compared to standard firefly algorithms and to the results already present in the literature. The chaotic FA optimization algorithm has been applied to the various objective functions of single area and multi area problems. Hence, it is concluded that the algorithm determines the best optimal solution globally than the conventional techniques.

### **1.4. ORGANIZATION OF THESIS**

The dissertation is organized in six chapters as follow:

Chapter 1 gives general introduction to load frequency control problem, firefly algorithm and chaotic firefly algorithm and author's contribution to the proposed work.

Chapter 2 discusses the past achievements in the literature of LFC.

Chapter 3 presents the unconstrained optimization problem on standard test functions using CFA.

Chapter 4 discusses the basics of FA and CFA, their structure and the variations used for single area power systems.

Chapter 5 gives details of the results pertaining to multi area power system using chaotic firefly algorithm. The results have been compared to different methods.

Chapter 6 summarizes the dissertation work and also discusses the future scope of work.

## CHAPTER 2: LITERATURE SURVEY

### 2.1. LITERATURE REVIEW OF FA

In this segment, a review on firefly algorithms and its various applications in engineering field has been carried out. Many researchers have used firefly algorithm because of its accuracy, superiority and faster convergence. Some publications tackling FA and its applications have been mentioned in Table 2.1. The applications using firefly algorithm has also been compared to other optimization techniques also and it has been proved its flexibility of use. Some of them are mentioned below:

Xin-She Yang [1] developed firefly algorithm to solve non-linear design problems using FA. Few new test functions were also proposed with stochastic components along with their global optima to validate new optimization problems. Pressure vessel design problem was also solved using FA to find an optimal solution.

Gandomi *et al.* [2] discussed the method of solving mixed discrete or continuous structural optimization problems using firefly algorithm (FA). Firefly algorithm was applied on six classical problems of structures and the validity of the algorithm was verified by the results. The exclusive search features executed in FA were properly analyzed in the paper.

Fister *et al.* [3] focused on how to avoid premature convergence in FA algorithm by introducing the quaternion operator in FA. The applications of quaternions have been explained and have been applied with firefly algorithm to enhance the performance. Convergence plots of the proposed method and standard FA was clearly depicted.

Xin-She Yang [4] provided a thorough explanation of Firefly algorithm (FA) for multimodal optimization applications. A comparison was drawn between firefly algorithm and other optimization techniques like particle swarm optimization (PSO) and genetic algorithm (GA). Various results and simulations results for finding the global optima of various test functions indicated that firefly performed better than other existing metaheuristic techniques.

Naidu *et al.* [5] implemented firefly algorithm on automatic generation control model with three unequal area reheat power system having an online wavelet filter. Wavelet transform was

introduced with FA to remove noise in the system. The results show that FA performed better than PSO for the noise minimization problem based in Integral of square error (ITSE).

Cheung *et al.* [6] carried out a parameter analysis using adaptive firefly algorithm. The analysis has been carried out over five different adaptive strategies. The performance of the five proposed adaptive firefly variants has been compared to three PSO based algorithms. The results validated that the adaptive firefly variants were better than the PSO based strategies.

Subotic *et al.* [7] proposed parallelized FA on standard unconstrained benchmark functions. A comparison was drawn by the authors between the proposed version and the classical methods. The results obtained show that the results of the proposed algorithm were much better and the execution time was also less.

Hui Wang *et al.* [8] discussed various firefly variants given in the literature and also proposed a new variant using firefly called neighborhood search-firefly algorithm. The proposed algorithm has a random attraction model and three search strategies to obtain a relation between its abilities to explore and exploit. The algorithm provides a dynamic adjustment technique for automatic adjustment of control parameters.

**Table 2.1:** Modification of FA

<b>Author</b>	<b>Topic</b>	<b>References</b>
Gandomi <i>et al.</i>	Solution to discrete or structural optimization problems	[2]
Fister <i>et al.</i>	Quaternion FA	[3]
Naidu <i>et al.</i>	Noise minimization problem in power systems	[5]
Cheung <i>et al.</i>	Adaptive FA	[6]
Subotic <i>et al.</i>	Parallelized FA	[7]
Hui Wang <i>et al.</i>	Randomly Attracted FA	[8]

## 2.2. LITERATURE REVIEW OF CFA

Papers tackling chaotic firefly algorithms have been presented in Table 2.2. The aim of this article is to study the various works covered with CFA in literature. After a detail analysis,

taxonomy of chaos based FA was projected. It also tells about the variation in parameters they used and whether they solved an engineering problem or found out the global optimum solution of a problem.

Xin-She Yang [9] performed to develop Chaos based firefly in 2011. In this paper logistic map was applied to the attraction and absorption coefficient in place of Gaussian distributed random variables. A global optimization problem was solved in the using this algorithm in the paper.

Coelho *et al.* [10] discussed solving of reliability-redundancy allocation problem using chaotic firefly algorithm. The chaotic map used as the absorption coefficient and randomization coefficient was logistic map. The proposed modified firefly algorithm performed better than other optimization methods used earlier like integer programming, dynamic programming. An example of over speed protection of gas turbine was also evaluated by proposed algorithm and mixed integer programming.

In 2012, in continuation to this Coelho *et al.* [11] also applied chaotic Tinkerbell map while tuning the parameters of PID controller. The results were compared to GA, PSO and standard FA.

Arul *et al.* [12] projected economic load dispatch problem using chaotic firefly algorithm. Tent map was used to generate chaotic variables in the proposed method. The algorithm's effectiveness was tested on 30 bus systems with different constraints and conditions. Optimal results attained by the proposed method were better than that of FA and other soft computing techniques reported in the literature.

Gandomi *et al.* [13] discussed 12 different chaotic maps to generate attraction coefficient and absorption coefficient. All these variations were applied to global optimization problem. Results showed that some chaotic maps performed well than the normal FA.

Abdel *et al.* [14] used chaotic firefly algorithm for solving definite integral. Sinusoidal chaotic map is used in the modified algorithm to calculate the results. Simulations shoe high rate of convergence and accuracy of the proposed algorithm.

Fister *et al.* [15] established randomized firefly algorithm with Gaussian distributions, levy flights, logistic chaotic maps and Kent chaotic maps. The randomization coefficient was improved using chaotic maps and probability distribution. Results confirmed that integration of FA with chaotic maps performed better.

Mishra *et al.* [16] solved the RSA public-key crypto system problem using chaotic firefly algorithm. The absorption and randomized coefficient were enhanced by using logistic chaotic map. The results show that CFA has been an effective tool to solve the problem.

Baykasoglu *et al.* [17] demonstrated adaptive firefly with chaos to solve mechanical design optimization problems. Various benchmark problems were considered and results of adaptive firefly algorithm (AFA) were compared to various chaotic maps applied to AFA. The results show chaotic AFA outperforms AFA.

**Table 2.2:** Recent Applications of CFA

Authors	Parameter Variation	Type of Problem	References
Yang	$\beta, \gamma$	Global	[9]
Coelho <i>et al.</i>	$\alpha, \gamma$	Engineering	[10]
Coelho et Mariani	$\alpha, \gamma$	Engineering	[11]
Arul <i>et al.</i>	$\alpha, \beta$	Engineering	[12]
Gandomi <i>et al.</i>	$\beta, \gamma$	Global	[13]
Abdel <i>et al.</i>	$\beta, \gamma$	Engineering	[14]
Fister <i>et al.</i>	$\alpha$	Global	[15]
Mishra <i>et al.</i>	$\alpha, \gamma$	Engineering	[16]
Baykasoglu <i>et al.</i>	$\alpha$	Engineering	[17]

### 2.3. LITERATURE REVIEW OF LFC

Concordia *et al.* [18] and Cohn [19] described the classical approach for load frequency control of a power system. The importance of tie line power, frequency and tie line bias control is described for interconnected power system. The dynamic performance of automatic tie line power and control of frequency has been analyzed.

Elgerd *et al.* [20] stated the concept of optimal control of load frequency control. NAPSIC i.e. North American Power Systems Interconnection Committee recommended that each and every area should have its fixed frequency bias coefficient which is equal to the AFRC (Area frequency Response Characteristic).

Fosha and Elgerd [21] proved that on the basis of optimal control method a state variable model can be made which will improve the stability margins and dynamic response of the system. Development of a state variable model of LFC control for a multi area system has been recorded. Feasible ways were studied to improve the dynamic response and stability of the system.

Ray *et al* [22] designed a robust LFC for large scale power systems. A combination of Lyapunov stability theory and matching conditions were used for the implementation of robust controller. Stability analysis was done for closed loop interconnected systems while including all the uncertainties. The proposed controller was applied on two-area power system model and simulation studies had been carried out.

Shayeghi *et al.* [23] designed a PSO based multi stage fuzzy controller for load frequency control problem. The membership functions of the fuzzy system were designed automatically using particle swarm optimization (PSO) technique. These techniques reduced the fuzzy system and large uncertainties of the system could be taken into account. Results of a three area power system were reported and are found to be better than genetic algorithm based multi stage fuzzy controller.

Tan [24] discussed tuning of load frequency controllers on the basis of two-degree-of-freedom internal model control (IMC) method. The controller performance is related to two tuning parameters which could be detuned very easily when necessary. To overcome generation rate constraints an anti-GRC was also proposed. Simulation results of two area power systems show that the proposed method was effective.

In continuation to this research, Tan published work in 2010 [25], where a unified tuning of PID load frequency control for multi area power systems. It was based on IMC design model and PID

approximation procedure. The time domain analysis was carried out and results prove that the proposed system improve the damping of the power system and can be applicable to reheat, non-reheat and hydro turbines systems.

Parmar *et al.* [26] designed a load frequency controller for multi area power system using optimal output feedback system. The proposed optimal output feedback system method uses measurable state variables. The optimal output control is determined by reducing the performance index under the proposed feedback conditions. The results show that the controller demonstrates better performance and robust behavior.

Padhan *et al.* [27] describes a new control method to tune a PID load frequency controller for single and multi-area power systems. Laurent series has been used to obtain the controller parameter. The proposed method confirms that the system remains asymptotically stable for uncertainties and for oscillations in the system. Simulations have been carried out on various examples and results reveal that this method improves the load disturbance rejection performance even when uncertainties are present in the plant.

Rout *et al.* [28] presented design of a PI controller for automatic generation control (AGC) of power systems based on differential evolution technique. Optimal controller parameters were found out using three different objective functions and results were compared to modern heuristic optimization techniques like bacteria foraging algorithm and genetic algorithm for interconnected power systems.

Padhan *et al.* [29] proposed load frequency control for multi-area power systems using firefly algorithm. Two area and three area power systems were considered and gains of PI and PID controller were optimized using firefly algorithm. The simulation results were compared to already existing techniques such as genetic algorithm, bacteria foraging optimization algorithm, differential evolution, particle swarm optimization, hybrid bacteria foraging optimization algorithm, particle swarm optimization and Ziegler–Nichols based controllers. Results show that FA performed better than other techniques.

Sahu *et al.* [30] proposed a hybrid PSO and pattern search based fuzzy PI controller for automatic generation control of interconnected power systems. A two area non-reheat system and a multi-source multi-area hydro thermal power system were studied using this algorithm. The advantage of the proposed fuzzy PI controller has been shown by comparing the results with Bacteria Foraging Optimization Algorithm (BFOA), Genetic Algorithm (GA), conventional Ziegler Nichols (ZN), Differential Evolution (DE), hybrid BFOA and PSO based PI controllers for the same interconnected power system. Further, sensitivity analysis was carried out which validates the capability of the proposed method to varied variations in system parameters, size and location of step load perturbation.

Further Sahu *et al.* [31] proposed another optimization technique of fuzzy PI controller based on hybrid FA and pattern search. Again this technique was applied to two area and three area systems. Simulation results depicted that it outperformed the hybrid PSO and pattern search based technique.

## CHAPTER 3: FIREFLY ALGORITHM

### 3.1. INTRODUCTION

Swarm Intelligence (SI) is a branch of artificial intelligence (AI) that has become very popular over the last few years. It has derived its inspiration from the behavior of swarm of bees, worms, flies and ants etc. These swarms exhibit a particular and coordinated behavior that helps them reach to their desired aims. This way the entire system possess a self-organizing behavior, and self-organization is the essence of swarm intelligence. The interaction between the individuals gives rise to this coordinated behavior, example, ants and bees move in a collective manner in search of food or builds their nests. Normally, with the help of chemical pheromone trails ants work together to discover the shortest route between their nest and the food. Likewise in a bee colony, there is an informer called scouts i.e. the bees who are in charge for searching new food sources. The communication among bees is called as 'waggle dance', by this communication technique only the bee colony is instructed by the scouts.

The swarms perform a tradeoff between exploitation (i.e. use of present data) and exploration (i.e. gathering of new data) during its search for new source of food. Therefore the swarms should be aware how and when to exploit its present source of food and look for new sources of food such that it maximizes the overall food intake while minimizing the efforts. The swarms show united behavior while performing various activities like where to feed, when and where to breed, find place to live and how to work as team to perform a task.

Swarm intelligence is a field of research that is based on the putting this coordinated behavior of swarms in organized and decentralized systems. Beni [40] used this term for the very first time in reference to cellular robotic systems which had agents that used to organize themselves by interaction of the neighbors. Lately, swarm intelligence algorithms are used in optimization, robotic controls, routing, mobile telecommunication networks and where robustness and flexibility is demanded. Some famous swarm-intelligence optimization approaches are ant colony optimization (ACO) [35], particle swarm optimization (PSO) [36], firefly algorithm [33, 34], bat algorithm [38] and artificial bee colony (ABC) [37].

One of the famous swarm intelligence methods is Firefly Algorithm, which was developed by Yang [39] in 2008. It is a nature-inspired, stochastic method that can be used to solve complex optimization problems. It is stochastic because it searches randomly to find a set of solutions. It has derived its inspiration from flashing light of the fireflies. It is a meta-heuristic technique because heuristic means ‘to find solutions using hit and trial [39]. There is no assurance that the best optimized solution will be found in a reasonable amount of time. Finally, meta-heuristic algorithm means ‘higher level’ algorithm, in which the process of search in algorithm is influenced by trade-off between randomization factor and local search [39]. Whereas in firefly algorithm, the ‘lower level’ algorithm (heuristic algorithm) ponders on the generation of new solutions within a specified search space and thus a best solution is selected.

### **3.2. FIREFLY ALGORITHM**

Firefly Algorithm was developed by Xin-She Yang in late 2007 and was published in 2008 [1, 9, 39]. The algorithm was based on the flashing patterns of the fireflies and their behavior.

#### **3.2.1. BIOLOGICAL FOUNDATION OF FA**

Fireflies are one of the most alluring of all insects due to their different light flashing patterns, and their charm has attracted various poets and scientists [41]. There are more than two thousand species present worldwide. Usually, fireflies are found in warm, temperate areas and produce unique pattern of light flashes in the night dark sky. Many scholars have studied this phenomenon of fireflies and have published their works on fireflies, for example, [1, 2, 5, 6, 42, and 43]. The flashing light in fireflies is produced by a biochemical process called bioluminescence. These light flashes serve two main purposes, the primary function is to send signals to the partner for mating and other is to attract a prey. There exist adults in some firefly species who are not capable of bioluminescence. In such species attraction to their mates is due to pheromone, similar to the way ants do. In fireflies there are special organ called lantern which helps a firefly to create light. The adults in many species of firefly are capable to regulate bioluminescence which helps them to emit high/low and discrete light flashes. Most of the species of firefly depend on bioluminescent signals to mate. The flying males are typically the first ones to give signals and try to attract female fireflies on the ground. The female fireflies emit light flashes in response to the signals given by male fireflies. Both the sexes produce unique light patterns that are properly timed and help them to understand the specie, sex of the

partner. Typically, a firefly is attracted to a firefly emitting brighter light flashes. It is well-known that the intensity of the light flashes change as the distance increases or decreases from the source. In some species of fireflies, they cannot differentiate between a closer light flash by a weak source of light and a bright source of light at a distance. In the process of natural selection, it is the survival of the fittest, therefore signals from the light flashes work as a mechanism of defense against predators. Self-organization and taking decentralized decisions are two characteristic features of swarm intelligence. Here, every independent individual live in groups in a common area for example ants live in anthills, bats in in cave colonies and bees live in hives. They live in groups with harmony, every individual in a group has to work as a team and adapt to the goals within the group. Socially the fireflies are more dedicated to reproduce than to foraging. These collective decisions are thoroughly associated with the light emitting behavior of the fireflies which is the main biological foundation for the firefly algorithm (FA) to evolve.

### **3.2.2. STANDARD FIREFLY ALGORITHM**

Scientist Xin-She Yang developed Firefly algorithm in 2007 and published his research in 2008. Firefly Algorithm is built on the flashing patterns of the fireflies and behavior of their movement [9, 39]. The algorithm is based on intensity of light that increases with decrease of the square of the distance. As the distance from the source of light tends to increase, the absorption of light becomes weaker. This phenomenon in the fireflies is considered as the objective function that needs to be optimized.

In simple words we can describe FA by the following conventions:

- A firefly is attracted towards another firefly despite of their sex; all fireflies are unisex.
- In Fireflies the degree of attraction depends on the firefly's brightness. Thus a firefly which is less bright will tend to move toward a brighter firefly. The degree of attraction is relative to the brightness of the firefly. The attraction and brightness of a fireflies decreases as the distance between them increases. It will move randomly if there exit no brighter firefly than a specific firefly.
- The landscape of the objective function is also a factor on which the brightness of a firefly is affected.

Based on these above conventions the firefly algorithm can be expressed as illustrated in Figure 3.1:

### Firefly Algorithm

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Define Objective Function,  $F(s)$ ,  $s_p = (s_1, s_2, \dots, s_d)^T$ , where  $p = 1, 2, \dots, n$ . . .

Initialize population of  $n$  fireflies.

Intensity of light  $I_p$  at  $s_p$  is defined by  $F(s_p)$ .

Initialize light absorption coefficient  $\gamma$ .

**while**  $t < \text{maximum\_generation}$ ,

**for**  $p = 1$  to  $n$  ,

**for**  $q = 1$  to  $n$  ,

**if**  $I_p < I_q$

Move Firefly  $p$  towards Firefly  $q$ .

**end if**

vary attractiveness accordingly with distance  $R$  via  $e^{-\gamma R^2}$ .

Calculate new solution and update intensity of light.

**end for q**

**end for p**

Give ranking to the fireflies and find optimal solution.

**end while**

Display results.

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**Figure 3.1** Pseudo Code for Firefly Algorithm.

There are two main issues in firefly algorithm:

- i. Light intensity variation
- ii. Calculation of the attractiveness coefficient.

To make it simple we assume that the coefficient of attraction is determined by the brightness of a firefly which is associated with the objective function formulated.

Taking simple example of a maximization problem, the degree of brightness  $I$  of a firefly at a point  $p$  can be represented directly proportional to objective function i.e.  $I(p) \propto F(p)$ . The

coefficient of attraction is relatively chosen. It varies with the distance  $R_{pq}$  between firefly  $p$  and  $q$ . As distance from light source increases the intensity of light decreases and the media also absorb some light, which means the degree of attractiveness vary with the degree of absorption.

The intensity of light can be expressed according to the inverse square law as,

$$I(R) = \frac{I_s}{R^2} \quad (3.1)$$

where  $I_s$  is the intensity of light at the source. For a particular medium the light absorption coefficient  $\gamma$  is fixed, therefore the intensity of light  $I$  vary with the distance  $R$ . The intensity of light  $I(R)$  varies with the distance  $R$  monotonically and exponentially as:

$$I = I_0 e^{-\gamma R} \quad (3.2)$$

where  $I_0$  is the original intensity of light and  $\gamma$  is the coefficient of light absorption. As a firefly's attractiveness is proportional to the intensity of light noticed by other adjacent fireflies, the attractiveness coefficient  $\beta$  of a firefly is defined a

$$\beta = \beta_0 e^{-\gamma r R^2} \quad (3.3)$$

Here  $\beta_0$  is known as attractiveness at  $R=0$ . It is worth pointing out that the exponent  $\gamma R^2$  can be replaced by other functions such as  $\gamma R^m$  when  $m > 0$ . The distance between fireflies  $p$  and  $q$  at location  $x_p$  and  $x_q$  respectively, is the Cartesian distance and is calculated as:

$$r_{pq} = \|\underline{x}_p - \underline{x}_q\| = \sqrt{\sum_{d=1}^n (\underline{x}_{pd} - \underline{x}_{qd})^2} \quad (3.4)$$

where  $\underline{x}_{p,d}$  is the  $d^{\text{th}}$  component of the spatial coordinate  $\underline{x}_p$  of  $i^{\text{th}}$  firefly. The movement of a firefly  $p$  towards a more attractive (brighter) firefly  $q$  is calculated by

$$\underline{x}_i = \underline{x}_j + \beta_0 e^{-\gamma r^2} (\underline{x}_i - \underline{x}_j) + \alpha (\text{rand} - 0.5) \quad (3.5)$$

The basic firefly is efficient but we have still seen the change in solutions as we approach towards optima. It is possible to improve the solution by using chaotic variables in place of parameters basic firefly algorithm.

### 3.3. CHAOTIC FIREFLY ALGORITHM

In terms of mathematics, chaos indicates a perfect ordered system with an essence of randomness[46]. This behavior with chaos returns random values in every iteration. In swarm intelligence based algorithms randomness plays an important role in the search processes by exploring the new results. Therefore, over the years a lot work has been done to find novel randomized methods. Recently, a theory of chaos has been successful in replacing the existing random variables in many applications because of the increasing power in exploration of the stochastic search processes. The algorithm that uses chaotic variables instead of random variables is known as chaotic optimization algorithm (COA). In this algorithm because of its aperiodic nature and ergodicity of chaos, the overall searches can be carried out at higher speeds than stochastic techniques. To fulfill this various non-invertible, one-dimensional maps are used to create chaotic sets. These methods are capable of easily adapting to fitness landscapes therefore can be used to solve different problems. These chaotic maps are also known as orbits [32], in which the values of input are mapped onto a set of values of output.

#### 3.3.1. REVIEW OF CHAOTIC MAPS

The basic firefly algorithm has two type of enhancement with chaos. First one is, the performance is improved by replacing randomly distributed parameters of firefly algorithm by chaotic maps [13, 45]. And the other is, the firefly structure is directly applied for tuning of parameters using chaotic maps [44].

Let us review some known one-dimensional chaotic maps used further [13]:

##### 3.3.1.1 Iterative Map

The iterative chaotic map can be expressed as:

$$x_{n+1} = \sin\left(\frac{\dot{a}\pi}{x_n}\right) \quad (3.6)$$

Where  $\dot{a} \in (0, 1)$  is a suitable parameter.

##### 3.3.1.2 Logistic Map

The equation for logistic map appears in non-linear dynamics of a population with chaotic nature. It is represented as:

$$x_{n+1} = \dot{a} x_n (1 - x_n) \quad (3.7)$$

Where  $x_n$  the nth chaotic number and n is denotes the no. of iteration. For experiments,  $\dot{a} = 4$  and  $x \in (0, 1)$ .

### 3.3.1.3 Sine Map

It is a unimodal map and expressed as:

$$x_{n+1} = \frac{\ddot{a}}{4} \sin(\pi x_n) \quad (3.8)$$

Where  $0 < \ddot{a} \leq 4$ .

### 3.3.1.4 Singer Map

One-dimensional singer map can be written as:

$$x_{n+1} = \dot{\mu} (7.86x_n - 23.31 x_n^2 + 28.75 x_n^3 - 13.3028 x_n^4) \quad (3.9)$$

The parameter  $\dot{\mu}$  lies between 0.9 and 1.08.

### 3.3.1.5 Sinusoidal Map

The expression for sinusoidal map is given below:

$$x_{n+1} = \dot{a} x_n^2 \sin(\pi x_n) \quad (3.10)$$

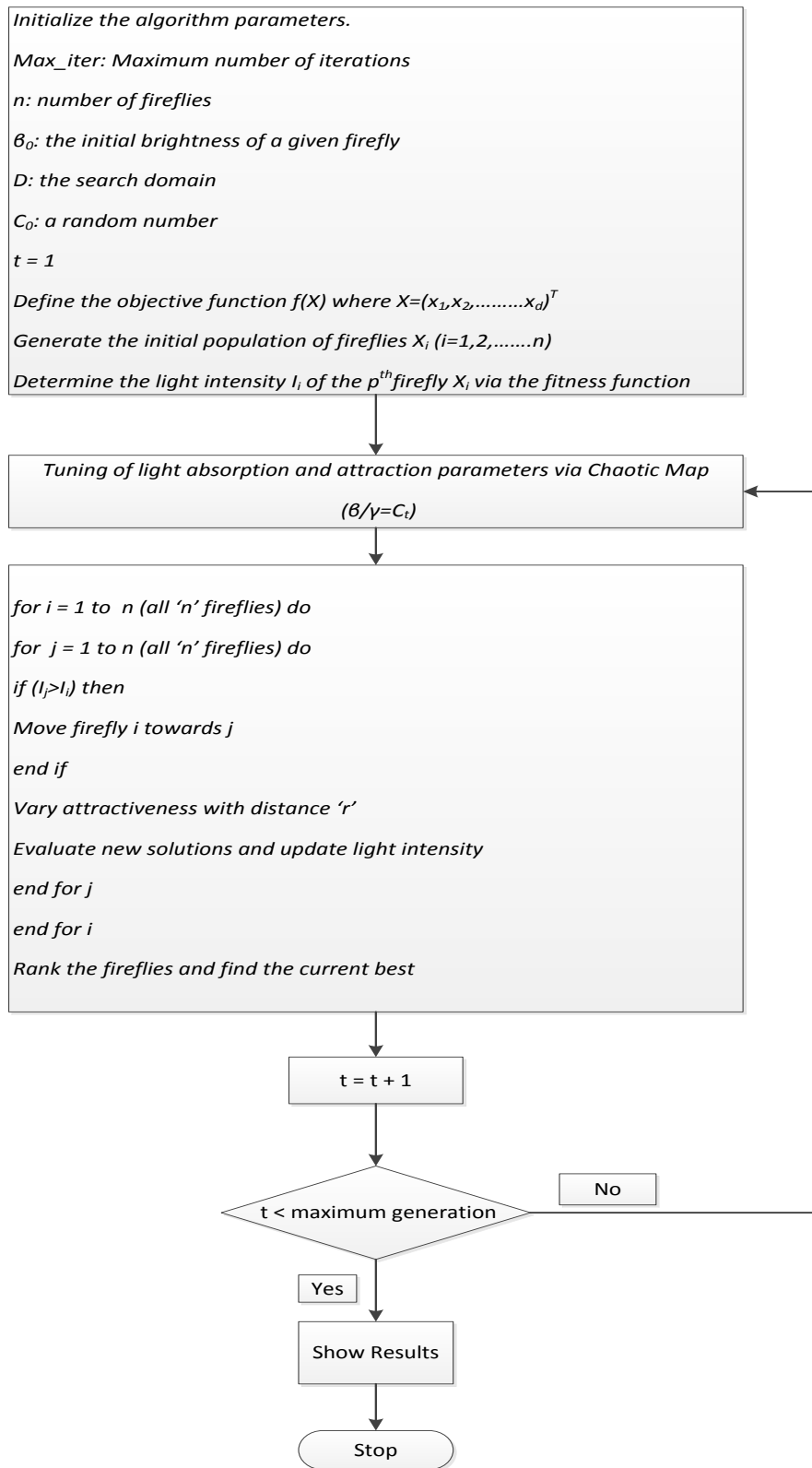
When  $\dot{a} = 2.3$  and  $x_0 = 0.7$ , the equation can be simplified as:

$$x_{n+1} = \sin(\pi x_n) \quad (3.11)$$

From the literature studied regarding chaotic firefly algorithms (CFA) it can be concluded that it has the following advantages over firefly algorithm (FA):

- Higher rate of convergence
- Higher accuracy levels
- Robustness increases

The algorithm has been applied to validate benchmark unconstrained optimization problems, single area power systems and multi area power systems problems. The algorithm of CFA is explained below in Figure 3.2.



**Figure 3.2** Block diagram of Chaotic Firefly Algorithm

### 3.4. VALIDATION OF FA AND CFA

In order to prove a new optimization technique/algorithm valid, it has to be used for some standard test functions. The results of the new algorithms when applied to the standard tests functions are then compared to the existing techniques to prove is better. Over the years many such standard test functions have been reported by various researchers, so there is no specific list of these functions. To test a new algorithm's validity it should be applied to a subset of test functions with different properties just to see the types of optimization problems the new algorithm can tackle like unimodal, multimodal, multi-dimensional, regular, irregular, separable and non-separable problems[2][13][47].

In this part various test functions have been reviewed and further a comparison has been drawn between standard FA and CFA using various test functions for unconstrained optimization problems[47]. Unconstrained optimization problem can be classified as: standard test functions and real world problems. Test functions are referred to as artificial problems; they are used to check the behavior of an algorithm in challenging and diverse situations. They may contain single global minimum, also multiple global minima even when many local minima are present. While testing an algorithm in diverse situations these artificial problems can be easily modified. Whereas, the origin of real world problems is from various fields of engineering, physics, mathematics, chemistry etc. These problems aren't easy to solve as they may have complex algebraic or differential equations therefore they cannot be manipulated easily; significant amount of information is required to compile them.

For this purpose, a set of 15 benchmark functions with diverse nature in terms of valley landscape, modality and separability for unconstrained optimization problems have been reviewed and applied to FA and CFA[47]. The function is represented by  $f(y)$ , dimension of the problem by  $d$ ,  $L_b \leq y_i \leq U_b$  denote domain size(i.e. the upper and lower bounds) and the optimal solution is represented by  $f(y^*) = f(y_1, \dots, y_n)$ . The functions can be classified as: Unimodal, multimodal and fixed dimensional multimodal functions.

#### 3.4.1. UNIMODAL FUNCTION

##### 3.4.1.1 Sphere Function:

$$f(y) = \sum_{i=1}^d y_i^2 \tag{3.12}$$

Subjected to,  $L_b < y_i < U_b = -5.12 \leq y_i \leq 5.12$

The global minimum:  $\mathbf{y}^* = (0, \dots, 0), f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

3.4.1.2 Sum Squares Function:

$$f(y) = \sum_{i=1}^d i y_i^2 \quad (3.13)$$

Subjected to,  $L_b < y_i < U_b = -10 \leq y_i \leq 10$

The global minimum:  $\mathbf{y}^* = (0, \dots, 0), f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

3.4.1.3 Rosenbrock Function:

$$f(y) = [100 (y_{i+1} - y_i^2)^2 + (y_i - 1)^2] \quad (3.14)$$

Subjected to,  $L_b < y_i < U_b = -5 \leq y_i \leq 10$

The global minimum:  $\mathbf{y}^* = (1, \dots, 1), f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

3.4.1.4 Beale Function:

$$f(y) = (1.5 - y_1 + y_1 y_2)^2 + (2.25 - y_1 - y_1 y_2^2)^2 + (2.625 - y_1 - y_1 y_2^3)^2 \quad (3.15)$$

Subjected to,  $L_b < y_i < U_b = -4.5 \leq y_i \leq 4.5$

The global minimum:  $\mathbf{y}^* = (3, 0.5), f(\mathbf{y}^*) = 0$ .

Number of variables:  $n = 2$ .

3.4.1.5 Dixon & Price Function:

$$f(y) = (y_1 - 1)^2 + \sum_{i=2}^d i (2y_i^2 - y_{i-1})^2 \quad (3.16)$$

Subjected to,  $L_b < y_i < U_b = -10 \leq y_i \leq 10$

The global minimum:  $\mathbf{y}^* = (2(\frac{2^i-2}{2^i})), f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

## 3.4.2. MULTIMODAL FUNCTION

3.4.2.1 Ackley Function:

$$f(\mathbf{y}) = -20e^{-0.02\sqrt{\frac{1}{d}\sum_{i=1}^d y_i^2}} - e^{d^{-1}\sum_{i=1}^d \cos(2\pi y_i)} + 20 + e \quad (3.17)$$

Subjected to,  $L_b < y_i < U_b = -15 \leq y_i \leq 30$

The global minimum:  $\mathbf{y}^* = (0, \dots, 0)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

#### 3.4.2.2 Griewank Function:

$$f(\mathbf{y}) = \sum_{i=1}^d \frac{y_i^2}{4000} - \prod \cos\left(\frac{y_i}{\sqrt{d}}\right) + 1 \quad (3.18)$$

Subjected to,  $L_b < y_i < U_b = -600 \leq y_i \leq 600$

The global minimum:  $\mathbf{y}^* = (0, \dots, 0)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

#### 3.4.2.3 Schwefel Function:

$$f(\mathbf{y}) = 418.9820 d - \sum_{i=1}^d y_i \sin(\sqrt{|y_i|}) \quad (3.19)$$

Subjected to,  $L_b < y_i < U_b = -500 \leq y_i \leq 500$

The global minimum:  $\mathbf{y}^* = (1, \dots, 1)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n$  variables

#### 3.4.2.4 Bohachevsky Function:

$$f(\mathbf{y}) = y_1^2 + 2y_2^2 - 0.3 \cos(3\pi y_1) - 0.4 \cos(4\pi y_2) + 0.7 \quad (3.20)$$

Subjected to,  $L_b < y_i < U_b = -100 \leq y_i \leq 100$

The global minimum:  $\mathbf{y}^* = (0, \dots, 0)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n = 2$ .

#### 3.4.2.5 Colville Function:

$$f(\mathbf{y}) = 100(y_1 - y_2^2)^2 + (1 - y_1)^2 + 90(y_4 - y_3^2)^2 + (1 - y_3)^2 + 0.1((y_2 - 1)^2 + (y_4 - 1)^2) + 19.8(y_2 - 1)(y_4 - 1) \quad (3.21)$$

Subjected to,  $L_b < y_i < U_b = -10 \leq y_i \leq 10$

The global minimum:  $\mathbf{y}^* = (1, \dots, 1)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n = 4$ .

### 3.4.3. FIXED DIMENSIONAL MULTIMODAL FUNCTIONS

3.4.3.1 Goldstein Price Function:

$$f(y) = [1 + (y_1 + y_2 + 1)^2 + (19 - 14y_1 + 3y_1^2 - 14y_2 + 6y_1y_2 + 3y_2^2)] \times [30 + (2y_1 - 3y_2)^2(18 - 32y_1 + 12y_1^2 + 48y_2 - 36y_1y_2 + 27y_2^2)]$$

(3.22)

Subjected to,  $L_b < y_i < U_b = -2 \leq y_i \leq 2$

The global minimum:  $\mathbf{y}^* = (0,1)$ ,  $f(\mathbf{y}^*) = 3$ .

Number of variables:  $n = 2$ .

3.4.3.2 Easom Function:

$$f(y) = -\cos(y_1) \cos(y_2) \exp[-(y_1 - \pi)^2 - (y_2 - \pi)^2] \quad (3.23)$$

Subjected to,  $L_b < y_i < U_b = -100 \leq y_i \leq 100$

The global minimum:  $\mathbf{y}^* = (\pi, \pi)$ ,  $f(\mathbf{y}^*) = -1$ .

Number of variables:  $n = 2$ .

3.4.3.3 Camel Function – Six Hump:

$$f(y) = \left(4 - 2.1y_1^2 + \frac{1}{3}y_1^4\right)y_1^2 + y_1y_2 + (4y_2^2 - 4)y_2^2 \quad (3.24)$$

Subjected to,  $L_b < y_i < U_b = -5 \leq y_i \leq 5$

The global minimum:  $\mathbf{y}^* = (0.0898, -0.7126)$ ,  $(-0.0898, 0.7126)$ ,  $f(\mathbf{y}^*) = 0$ .

Number of variables:  $n = 2$ .

3.4.3.4 Shekel Function:

$$f(y) = -\sum_{i=1}^7 [\sum_{j=1}^4 (y_i - a_{ij})^2 + c_i] \quad (3.25)$$

$$\text{Where } a = [a_{ij}] = \begin{bmatrix} 4 & 4 & 4 & 4 \\ 1 & 1 & 1 & 1 \\ 8 & 8 & 8 & 8 \\ 6 & 6 & 6 & 6 \\ 3 & 7 & 3 & 7 \\ 2 & 9 & 2 & 9 \\ 5 & 5 & 3 & 3 \end{bmatrix} \text{ and } c = [c_{ij}] = \begin{bmatrix} 0.1 \\ 0.2 \\ 0.2 \\ 0.4 \\ 0.4 \\ 0.6 \\ 0.3 \end{bmatrix}$$

Subjected to,  $L_b < y_i < U_b = 0 \leq y_i \leq 10$

The global minimum:  $\mathbf{y}^* = (4,4,4,4)$ ,  $f(\mathbf{y}^*) = -10.4029$ .

Number of variables: 4 variables.

#### 3.4.3.5 Hartman Function:

$$f(y) = -\sum_{i=1}^4 c_i \exp[-\sum_{j=1}^3 a_{ij}(y_j - p_{ij})^2] \quad (3.26)$$

Subject to  $0 \leq y_j \leq 1, j \in \{1, 2, 3\}$  with constants  $a_{ij}$ ,  $p_{ij}$  and  $c_j$  are given as

$$a = [a_{ij}] = \begin{bmatrix} 3 & 10 & 30 \\ 0.1 & 10 & 35 \\ 3 & 10 & 30 \\ 0.1 & 10 & 35 \end{bmatrix}, c = [c_j] = \begin{bmatrix} 1 \\ 1.2 \\ 3 \\ 3.2 \end{bmatrix},$$

$$p = [p_{ij}] = \begin{bmatrix} 0.3689 & 0.1170 & 0.2673 \\ 0.4699 & 0.4837 & 0.7470 \\ 0.1091 & 0.8732 & 0.5547 \\ 0.03815 & 0.5734 & 0.8828 \end{bmatrix}$$

The global minimum:  $\mathbf{y}^* = (0.1140, 0.556, 0.852)$ ,  $f(\mathbf{y}^*) = -3.862782$ .

Number of variables:  $n = 3$ .

Table 2.1 represents the validation results of the above explained functions using firefly algorithm (FA) and chaotic firefly algorithm (CFA). The CFA has been carried out using Iterative map with variation in both light absorption coefficient and attractiveness.

Simulations were conducted on Intel(R), core i-5 CPU @ 2.50GHz and 8GB RAM computer in Matlab R2014a environment. The best result was obtained in 20 test runs.

**Table 3.1.** Values of algorithm parameters

Algorithm Parameters	Value
Alpha	0.2
Beta	0.25
Gamma	1

Maximum Iterations	300
Population Size	30

**Table 3.2.** Validation Results

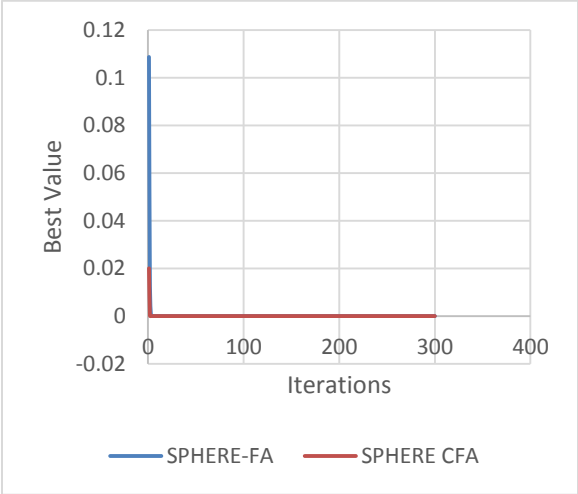
Function	Algorithm	FA	CFA
Sphere	Best Value	6.3550e-08	8.4266e-08
	Worst Value	1.1353e-07	1.3050e-07
	Average Value	8.8541e-08	1.0738e-07
	Standard Deviation	3.5343e-08	3.2691e-08
Sum Square	Best Value	4.4780e-07	9.4292e-09
	Worst Value	5.9963e-07	2.8444e-07
	Average Value	5.2371e-07	1.4694e-07
	Standard Deviation	1.0736e-07	1.9446e-07
Rosenbrock	Best Value	6.6376e-07	1.2639e-08
	Worst Value	3.2270e-06	1.0548e-06
	Average Value	1.9454e-06	5.3372e-07
	Standard Deviation	1.8125e-06	7.3693e-07
Beale	Best Value	2.0923e-07	1.1187e-08
	Worst Value	2.4073e-07	2.7753e-07
	Average Value	2.2498e-07	1.4436e-07
	Standard Deviation	2.2272e-08	1.8833e-07
Dixon & Price	Best Value	2.2910e-06	4.9356e-07
	Worst Value	2.0294e-05	2.4296e-06
	Average Value	1.1292e-05	1.4616e-06
	Standard Deviation	1.2730e-05	1.3690e-06
Griewank	Best Value	0.0016	2.8182e-04
	Worst Value	0.0023	6.6703e-04
	Average Value	0.0020	4.7443e-04
	Standard Deviation	4.7172e-04	2.7239e-04
Ackley	Best Value	0.0034	9.0298e-04

	Worst Value	0.0053	0.0022
	Average Value	0.0044	0.0016
	Standard Deviation	0.0014	9.1577e-04
Schwefel	Best Value	3.5593e-04	5.8816e-05
	Worst Value	118.4387	1.4257e-04
	Average Value	59.2196	1.0069e-04
	Standard Deviation	83.7486	5.9223e-05
Bohachevsky	Best Value	1.4813e-04	2.2002e-04
	Worst Value	0.0012	2.6095e-04
	Average Value	6.5556e-04	2.4049e-04
	Standard Deviation	7.1762e-04	2.8948e-05
Colville	Best Value	0.0035	3.8878e-04
	Worst Value	0.0086	3.9620e-04
	Average Value	0.0060	3.9249e-04
	Standard Deviation	0.0036	5.2498e-06
Goldstein Price	Best Value	3.0000	3.0000
	Worst Value	3.0000	3.0000
	Average Value	3.0000	3.0000
	Standard Deviation	3.0167e-06	1.2373e-06
Easom	Best Value	-0.9999	-1
	Worst Value	-0.9995	-1
	Average Value	-0.9997	-1
	Standard Deviation	3.1741e-04	4.2571e-05
Camel	Best Value	1.1193e-06	1.4323e-07
	Worst Value	3.8384e-06	2.0468e-07
	Average Value	2.4788e-06	1.7396e-07
	Standard Deviation	1.9227e-06	4.3454e-08
Shekel	Best Value	-10.4002	-10.4028
	Worst Value	-10.3990	-10.4007
	Average Value	-10.3996	-10.4017
	Standard Deviation	8.8674e-04	0.0015

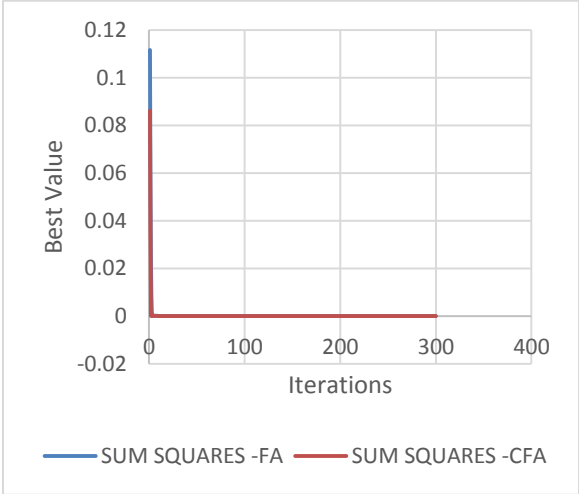
Hartman	Best Value	-3.8628	-3.8628
	Worst Value	-3.8628	-3.8628
	Average Value	-3.8628	-3.8628
	Standard Deviation	6.8020e-07	1.9547e-07

The validation results show that chaotic firefly algorithm perform better for most of the test functions. Therefore, chaotic firefly algorithm has been further used in load frequency control of single area and multi area problems.

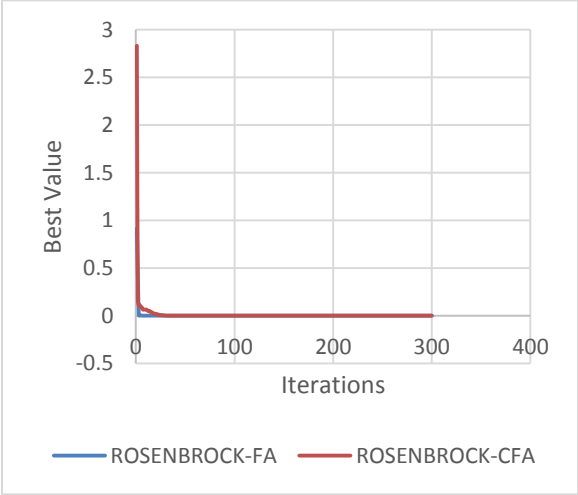
**3.5. CONVERGENCE CHARACTERISTIC OF THE TEST FUNCTIONS**



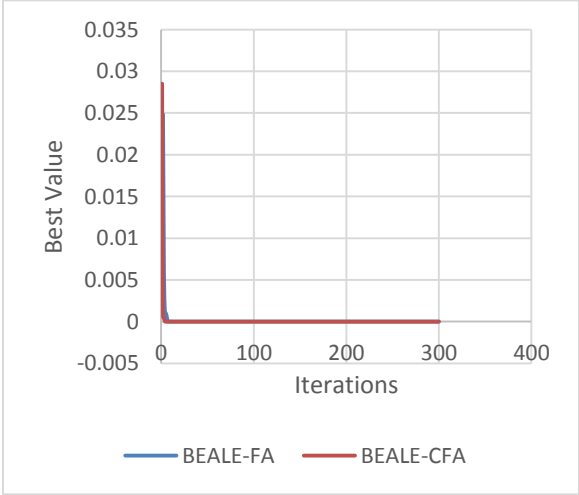
(a)



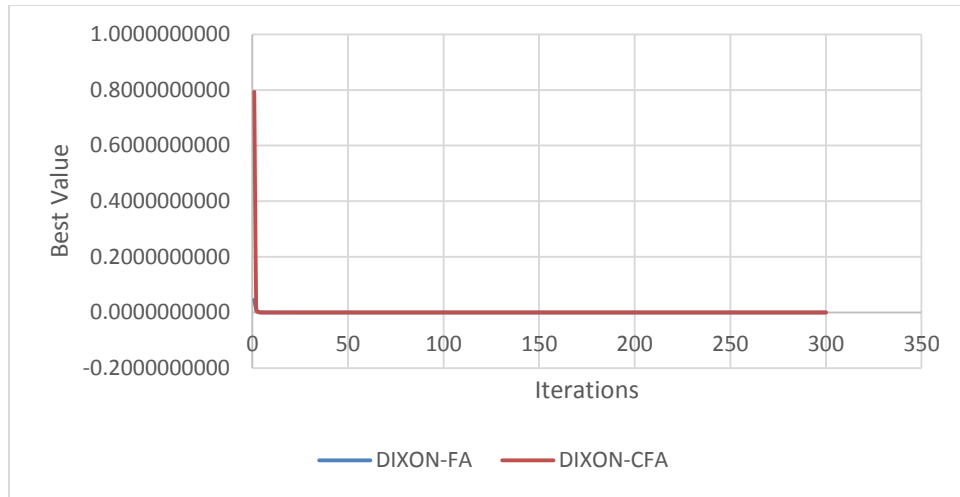
(b)



(c)

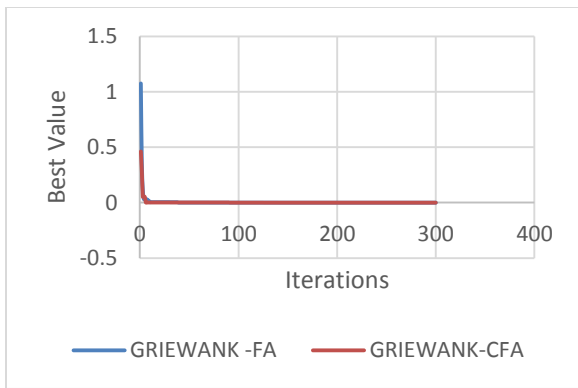


(d)

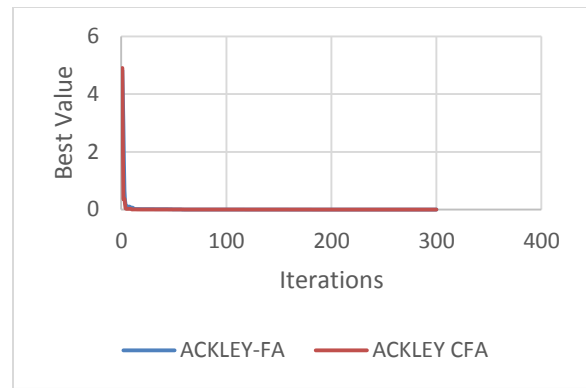


(e)

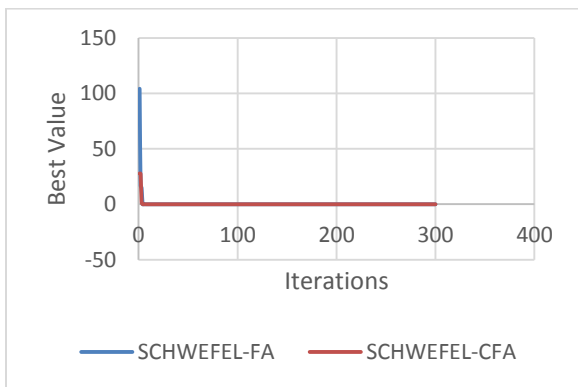
**Figure 3.3.** (a)-(e) Convergence characteristics of various unimodal test functions.



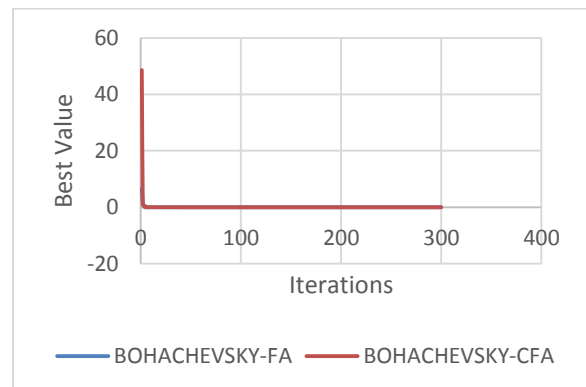
(a)



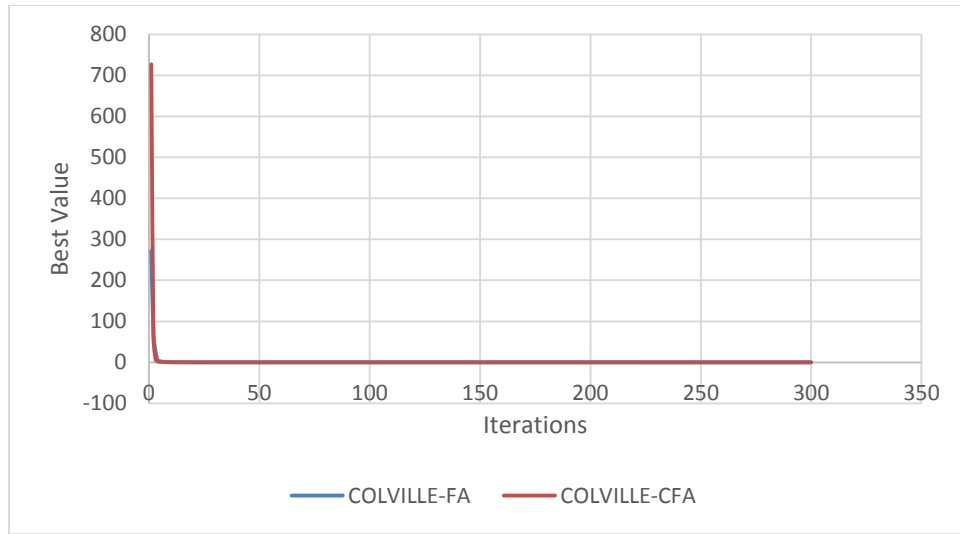
(b)



(c)

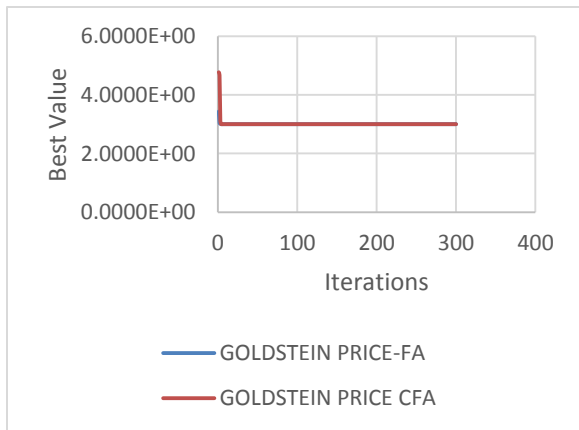


(d)

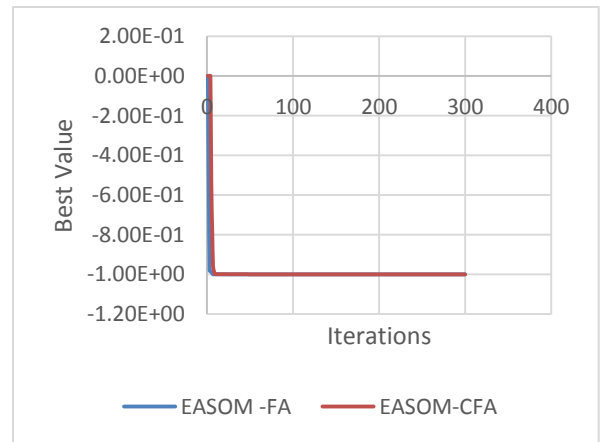


(e)

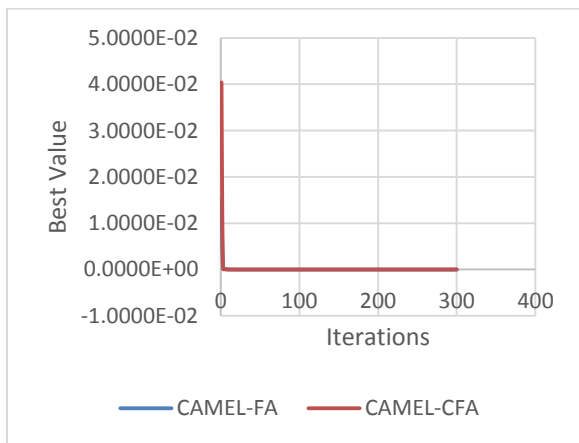
**Figure 3.4.** (a)-(e) Convergence characteristics of various multimodal test functions.



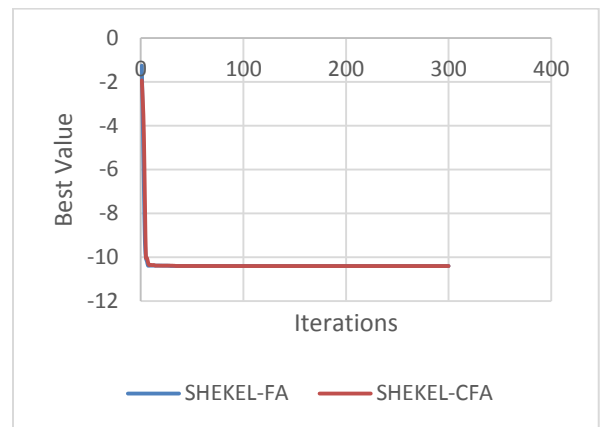
(a)



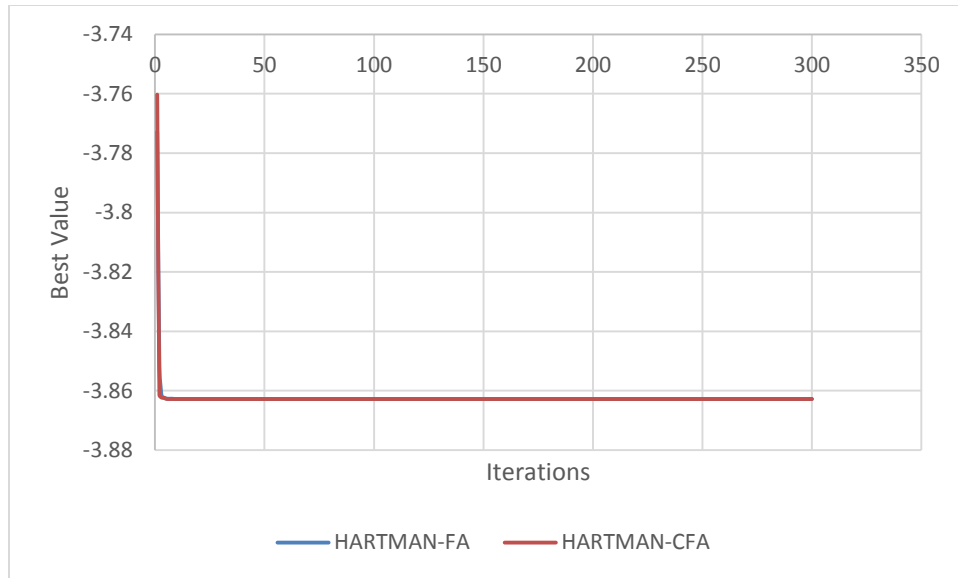
(b)



(c)



(d)



(e)

**Figure 3.5.** (a)-(e) Convergence characteristics of various fixed dimensional multimodal test functions

### 3.6. CONCLUSIONS

In this chapter, the basics of firefly algorithm and chaotic firefly algorithm were thoroughly discussed. Apart from studying the algorithms for FA and CFA, the algorithms were tested on various test functions for unconstrained optimization. The convergence characteristics of test functions show that CFA yields minimum function values as compared to FA on most of the occasions. In next chapters, controller parameter tuning is done using chaotic firefly algorithm for single and multi-area power systems.

## CHAPTER 4: LFC OF SINGLE AREA POWER SYSTEM

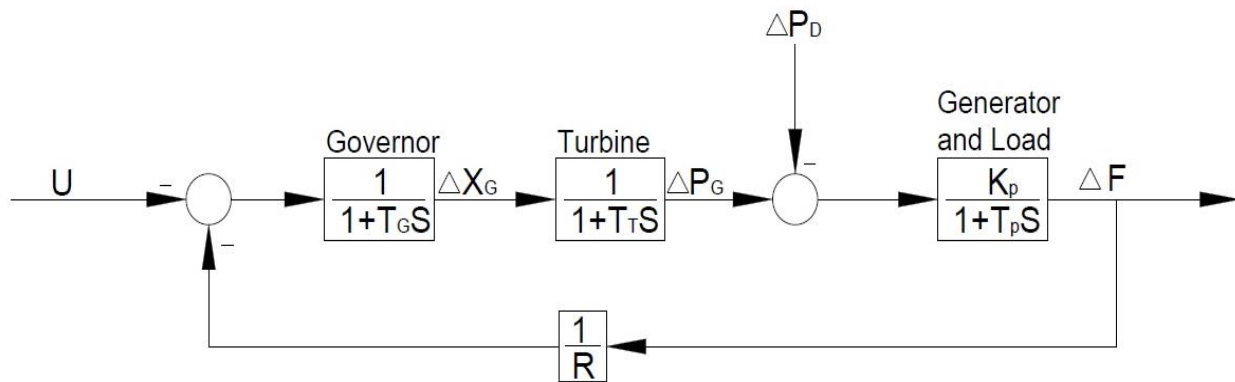
### 4.1. INTRODUCTION

In the previous chapter CFA and FA were validated on various unconstrained benchmark functions and it was observed CFA outperformed on most of the occasions.

Nowadays with the increasing complexity of power systems the need to study different control schemes is essential. Various control schemes and controllers have also been studied by various researchers [48-51]. Recently, various metaheuristic algorithms have also been introduced and have been also applied for the optimization of controller parameters.

In this chapter, a single area power system model has been described and tuning of the load frequency controller is carried out using firefly algorithm (FA) and chaotic firefly algorithm (CFA). Two examples from single area power system network to prove the superiority of CFA over conventional FA. Approximate model matching technique has been used to make a suitable reference model to develop an objective function.

### 4.2. SYSTEM MODEL



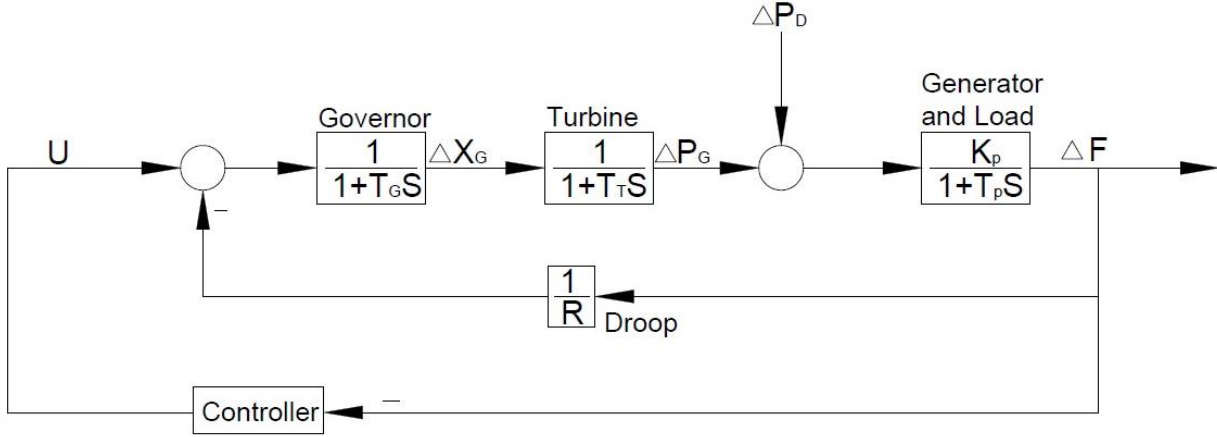
**Figure 4.1.** Block diagram of a single area power system

The above figure shows a block diagram of a single area isolated power system with a single supply U. The basic components of a single area power system are governor, turbine, generator and load. The transfer function from U to  $\Delta F$  as in Fig. 1 may be written as

$$G(s) = \frac{G_G G_T G_P}{1 + G_G G_T G_P / R} \tag{4.1}$$

Suppose  $G_1(s)$  is the closed-loop transfer function from  $\Delta P_D$  to  $\Delta F$  with a controller  $M(s)$  as in Figure 4.2 and is given by:

$$G_1(s) = \frac{K_P / (1+sT_P)}{1 + \left[ \frac{K_P}{(1+sT_P)} \times \frac{1}{(1+sT_G)} \times \frac{1}{(1+sT_T)} \right] (M(s) + \frac{1}{R})} \quad (4.2)$$



**Figure 4.2.** Unity negative output feedback configuration of single area power system.

A suitable reference model from  $\Delta P_D$  to  $\Delta F$  is made using approximate model matching technique[49]. The reference model transfer function  $H(s)$  is constructed for a desired closed-loop load–frequency control as given by,

$$H(S) = \frac{a_1s+a_0}{s^2+b_1s+b_0s} \quad (4.3)$$

The PID controller parameters obtained after using the optimization technique is given as

$$M(s) = K_P + \frac{K_I}{s} + K_Ds \quad (4.4)$$

Chaotic firefly algorithm has been applied to tune controller parameters for load frequency control in single area power system using approximate model matching technique in frequency domain using bode response technique. The difference between the magnitude and phase of the actual and reference model has been considered as the error function to be minimized with the help of the above mentioned algorithm and for the minimum value of error the controller parameters are obtained. Controller parameter tuning has also been performed with basic FA.

Examples of single area network from the literature have been taken to prove the effectiveness of CFA over FA. Integral square error (ISE), Sum of square error (SSE), Integral of time-weighted absolute error (ITAE) and Integral of time multiply squared error (ITSE) have been considered as objective functions which are minimized using FA and CFA respectively.

The FA parameters values and their notation in the algorithm are shown in Table 4.1.

**Table 4.1.** Values of FA parameters

Name of the algorithm	Algorithm Parameters	Value
CFA,FA	Randomization coefficient( $\alpha$ )	0.2
FA	Attraction Coefficient( $\beta$ )	0.25
FA	Light Absorption Coefficient( $\gamma$ )	1
CFA,FA	Maximum Iterations	50
CFA,FA	Population Size	20

Simulations were conducted on Intel(R), core i-5 CPU @ 2.50GHz and 8GB RAM computer in Matlab R2014a environment. The best result was obtained in 20 test runs.

#### 4.2.1. SIMULATION RESULTS

Two examples have been taken from literature to carry out load frequency control in single area power system [48].

**Example 1.** A single area power system with non-reheat turbine[50] is considered as:

System parameters are given as,

$$K_P = 1.25, T_P = 12.5, T_T = 0.5, T_G = 0.2, R = 0.05$$

The open loop transfer function of the system is given by:

$$\frac{1.25(0.5s+1)(0.2s+1)}{((12.5s+1)(0.5s+1)(0.2s+1)+1.25/0.05)} \quad (4.5)$$

The reference model for load frequency control is given as:

$$H(s) = \frac{0.01s}{s+1} \quad (4.6)$$

The performance comparison is done in Tables 4.2 - 4.4 where best value, worst value, average value, standard deviation, average CPU time and PID parameters are reported for 20 test runs. The convergence characteristics are shown in figures 4.3-4.6.

**Example 2.** A single area power system with the following specifications is considered from[54].

System parameters are given as,

$$K_P = 1, T_P = 10, T_T = 7, T_G = 0.2, R = 0.05$$

The open loop transfer function of the given system is

$$\frac{(7s+1)(0.2s+1)}{(10s+1)(7s+1)(0.2s+1)+\frac{1}{0.05}} \quad (4.7)$$

The reference model selected is given as,

$$M(s) = \frac{0.4s}{1.3s+1} \quad (4.8)$$

The performance comparison between CFA and FA is done in Table 4.5.-4.7 where best value, worst value, average value, standard deviation, average CPU time and PID parameters are reported for 20 test runs with introduction of chaos in light absorption coefficient, attraction coefficient or both at the same time. The convergence characteristics are shown in figures 4.7-4.10.

In the below tables CFA1 denotes the results for chaotic maps with different light absorption coefficient, CFA2 denotes results for chaotic maps with different attraction coefficient and CFA3 denotes results for chaotic maps when both attraction coefficient and light absorption coefficient are changing.

**Table 4.2.** Results for Example 1 with CFA1

Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	10.799	15.979	19.961	8.9000E-03	8.9900E-03	8.9400E-03	2.4549E-05	156.5202
	ISE	0.2421	19.9202	19.9351	4.74E-06	4.78E-06	4.76E-06	2.18E-08	<b>128.3024</b>
	ITAE	5.4146	19.945	19.976	<b>8.9638E-08</b>	8.9912E-08	8.9775E-08	<b>1.9336E-10</b>	151.9863
	ITSE	12.967	2.1774	18.9	1.33E-07	2.67E-07	<b>2.00E-08</b>	9.51E-09	187.0353
<b>Iterative Map</b>	SSE	0.04467	19.866	19.859	8.6350E-05	8.9635E-05	8.7350E-05	3.1680E-07	134.7625
	ISE	0.1003	19.7843	19.9783	4.67E-08	4.67E-07	8.87E-07	2.02E-09	<b>100.3264</b>
	ITAE	0.56035	18.947	19.951	<b>8.9635E-10</b>	9.1635E-10	9.0264E-04	<b>2.5538E-12</b>	147.5747
	ITSE	17.0611	15.9128	1.64	3.07E-09	3.92E-09	<b>3.50E-09</b>	6.03E-10	103.2808
<b>Logistic Map</b>	SSE	9.0498	19.104	19.909	8.9600E-04	9.1000E-04	9.0000E-04	2.5490E-06	136.8617
	ISE	4.9907	19.5515	19.8251	5.32E-07	5.55E-07	5.55E-07	5.34E-09	118.5437
	ITAE	5.2623	11.627	18.572	<b>9.6350E-10</b>	9.8400E-10	8.9635E-10	3.9638E-12	129.9785
	ITSE	19.9215	19.3472	1.46	3.66E-11	3.92E-11	<b>3.79E-11</b>	<b>1.89E-12</b>	<b>108.8537</b>
<b>Sine Map</b>	SSE	1.8629	20.00	19.8261	8.9635E-04	9.6350E-04	9.4356E-04	8.4828E-06	140.9784
	ISE	0.2123	20	19.8939	5.45E-07	5.64E-07	5.53E-07	2.39E-09	122.7683
	ITAE	1.0168	2.3689	19.8562	8.6350E-09	8.7000E-09	8.7350E-09	4.1550E-11	123.2317
	ITSE	19.7949	19.3792	1.5396	<b>3.90E-11</b>	3.93E-11	<b>3.91E-11</b>	<b>2.55E-13</b>	<b>118.3207</b>

<b>Singer Map</b>	SSE	7.6570	14.591	17.380	8.3635E-04	8.8635E-04	8.5350E-04	3.8580E-06	147.3648
	ISE	6.8853	19.8827	16.4792	5.57E-07	5.72E-07	5.68E-07	6.53E-09	<b>118.5358</b>
	ITAE	15.856	16.269	16.533	8.1350E-09	8.3500E-09	8.2130E-09	2.8230E-10	123.8767
	ITSE	19.7332	19.4368	1.5113	<b>3.93E-11</b>	<b>3.95E-11</b>	<b>3.94E-11</b>	<b>1.53E-13</b>	120.2367
<b>Sinusoidal Map</b>	SSE	7.2450	1.7365	18.913	8.9496E-06	8.9960E-06	8.7496E-06	1.7560E-09	131.1367
	ISE	2.1140	20	19.934	5.55E-07	5.93E-07	5.71E-07	3.55E-09	126.3068
	ITAE	1.9207	19.973	19.935	8.6635E-09	8.8650E-09	8.7600E-09	5.8210E-11	130.2546
	ITSE	17.463	16.8013	1.7053	<b>3.27E-11</b>	<b>3.92E-11</b>	<b>3.59E-11</b>	<b>4.65E-12</b>	<b>127.8635</b>

**Table 4.3.** Results for example 1 with CFA2

Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	10.799	15.979	19.961	8.9000E-03	8.9900E-03	8.9400E-03	2.4549E-05	156.5202
	ISE	0.2421	19.9202	19.9351	4.74E-06	4.78E-06	4.76E-06	2.18E-08	<b>128.3024</b>
	ITAE	5.4146	19.945	19.976	<b>8.9638E-08</b>	8.9912E-08	8.9775E-08	<b>1.9336E-10</b>	151.9863
	ITSE	12.967	2.1774	18.9	1.33E-07	2.67E-07	<b>2.00E-08</b>	9.51E-09	187.0353
<b>Iterative Map</b>	SSE	14.180	19.9941	19.9310	8.9716E-05	8.9830E-05	8.9773E-05	8.0595E-07	135.3806
	ISE	4.1114	3.6106	18.6871	4.72E-07	4.78E-07	4.75E-07	4.73E-09	<b>104.0937</b>
	ITAE	6.2845	19.8442	19.9060	<b>8.5760E-10</b>	<b>8.7800E-10</b>	<b>8.6835E-10</b>	<b>5.9150E-12</b>	145.2557
	ITSE	11.7959	10.4787	1.4940	8.03E-09	2.17E-09	1.49E-09	9.68E-10	110.7996

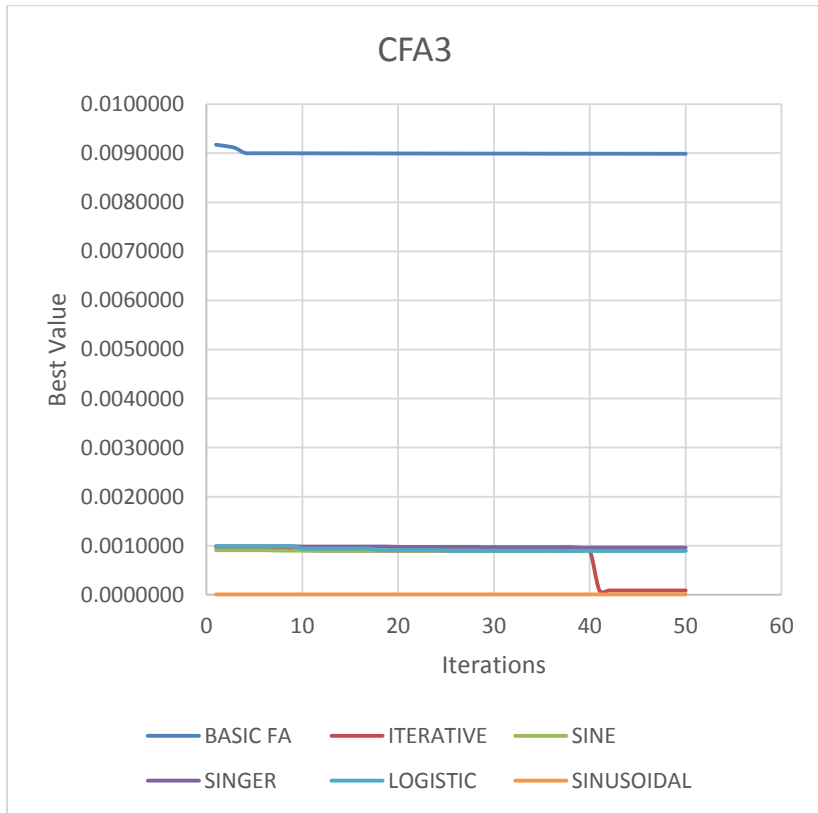
<b>Logistic Map</b>	SSE	3.8009	19.7518	19.9891	8.1635E-04	8.9635E-04	8.4635E-04	5.4900E-06	139.7878
	ISE	9.3738	16.3253	19.8057	5.55E-07	5.75E-07	5.55E-07	5.49E-09	<b>119.7556</b>
	ITAE	4.0822	18.7809	19.9451	9.5350E-10	9.7240E-10	8.9635E-10	<b>5.2460E-12</b>	130.3536
	ITSE	19.0304	18.5067	1.53347	<b>2.61E-11</b>	<b>3.69E-11</b>	<b>3.15E-11</b>	7.69E-12	129.1157
<b>Sine Map</b>	SSE	10.372	19.8876	19.3992	8.7790E-04	8.9840E-04	8.8810E-04	1.2816E-07	138.3546
	ISE	1.7729	10.4321	19.9657	5.64E-07	5.68E-07	5.66E-07	3.05E-09	123.8375
	ITAE	16.046	11.5410	19.9647	8.9780E-09	9.0076E-09	8.9928E-09	<b>2.0886E-11</b>	122.7153
	ITSE	14.69	13.3622	1.67627	<b>2.24E-11</b>	<b>7.52E-10</b>	<b>3.87E-10</b>	5.16E-10	<b>118.7813</b>
<b>Singer Map</b>	SSE	12.377	199.8533	20.000	7.9635E-04	8.5635E-04	8.3350E-04	7.8100E-06	149.9124
	ISE	13.7723	18.5069	17.5342	5.55E-07	5.93E-07	5.76E-07	6.85E-09	<b>117.8209</b>
	ITAE	1.1864	20.0000	19.967	7.8635E-09	8.9635E-09	8.5400E-09	2.5300E-10	124.5883
	ITSE	18.412	19.7737	2.8775	<b>3.88E-11</b>	<b>3.96E-11</b>	<b>3.92E-11</b>	<b>6.11E-13</b>	118.1134
<b>Sinusoidal Map</b>	SSE	11.292	13.8723	19.9998	8.9928E-05	8.9955E-05	8.9942E-05	1.8756E-08	135.9675
	ISE	8.155	14.8047	19.9373	5.62E-07	5.65E-07	5.63E-07	1.25E-09	<b>124.8089</b>
	ITAE	5.3182	12.3801	19.9981	8.9864E-09	8.9903E-09	8.9883E-09	2.7778E-11	129.5775
	ITSE	12.3326	10.7942	1.5177	<b>1.02E-11</b>	2.37E-11	<b>1.69E-11</b>	<b>9.55E-12</b>	143.3577

**Table 4.4.** Results for example 1 with CFA3

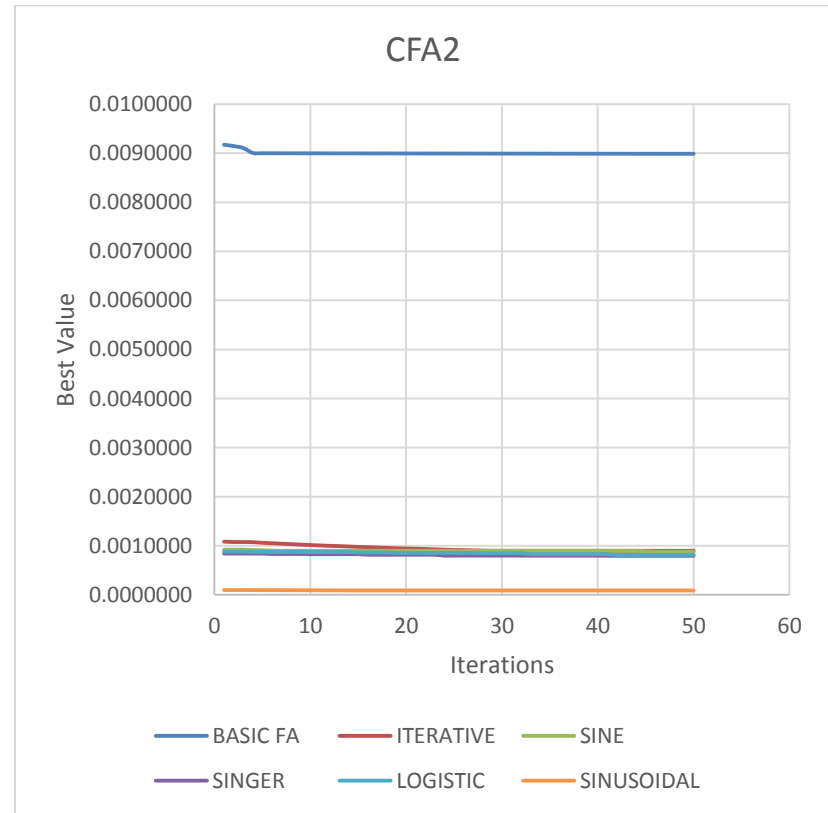
Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
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<b>Basic FA</b>	SSE	10.799	15.979	19.961	8.9000E-03	8.9900E-03	8.9400E-03	2.4549E-05	156.5202
	ISE	0.2421	19.9202	19.9351	4.74E-06	4.78E-06	4.76E-06	2.18E-08	<b>128.3024</b>
	ITAE	5.4146	19.945	19.976	<b>8.9638E-08</b>	8.9912E-08	8.9775E-08	<b>1.9336E-10</b>	151.9863
	ITSE	12.967	2.1774	18.9	1.33E-07	2.67E-07	<b>2.00E-08</b>	9.51E-09	187.0353
<b>Iterative Map</b>	SSE	10.070	13.115	19.956	8.8800E-05	8.9945E-05	8.9914E-05	4.3168E-07	136.5657
	ISE	1.3473	19.938	19.9292	4.67E-08	4.70E-07	9.13E-07	1.90E-09	<b>103.2746</b>
	ITAE	6.5258	12.921	19.975	<b>8.9698E-10</b>	8.9908E-10	<b>8.9803E-10</b>	<b>1.4915E-12</b>	142.8431
	ITSE	17.0928	1.67203	16.0636	3.02E-08	3.66E-08	3.34E-08	4.49E-09	111.2058
<b>Logistic Map</b>	SSE	1.7976	14.058	19.814	8.9635E-04	9.6350E-04	9.2350E-04	3.5490E-06	132.9622
	ISE	0.367452	19.9208	19.8285	5.28E-07	5.48E-07	5.55E-07	5.88E-09	<b>120.9632</b>
	ITAE	8.1395	19.874	19.962	9.1635E-10	9.3635E-10	9.2650E-10	<b>4.2892E-12</b>	131.9414
	ITSE	13.781	12.3126	1.57903	<b>1.79E-11</b>	3.76E-11	<b>2.78E-11</b>	1.39E-11	122.0652
<b>Sine Map</b>	SSE	12.9024	1.2784	1.9951	8.9798E-04	8.9994E-04	8.9896E-04	1.3858E-06	139.0527
	ISE	12.0626	12.9449	19.9266	5.59E-07	5.67E-07	5.63E-07	5.82E-09	123.4274
	ITAE	13.1128	1.3155	1.9987	8.9871E-09	8.9993E-09	8.9932E-09	8.6723E-11	124.4906
	ITSE	14.5592	13.0837	1.68631	<b>2.04E-11</b>	3.08E-10	<b>1.64E-10</b>	<b>2.03E-11</b>	<b>120.7267</b>
<b>Singer Map</b>	SSE	9.5749	13.411	12.3660	9.6350E-04	9.9635E-04	9.7635E-04	8.6800E-06	148.0775
	ISE	1.1504	19.9352	19.9405	5.56E-07	5.78E-07	5.67E-07	6.25E-09	<b>115.0616</b>
	ITAE	3.6216	20	19.9445	7.9635E-09	8.1350E-09	8.0150E-09	3.4730E-10	122.0699
	ITSE	19.9538	19.5271	1.4769	<b>3.91E-11</b>	<b>3.95E-11</b>	<b>3.93E-11</b>	<b>2.57E-13</b>	118.2433

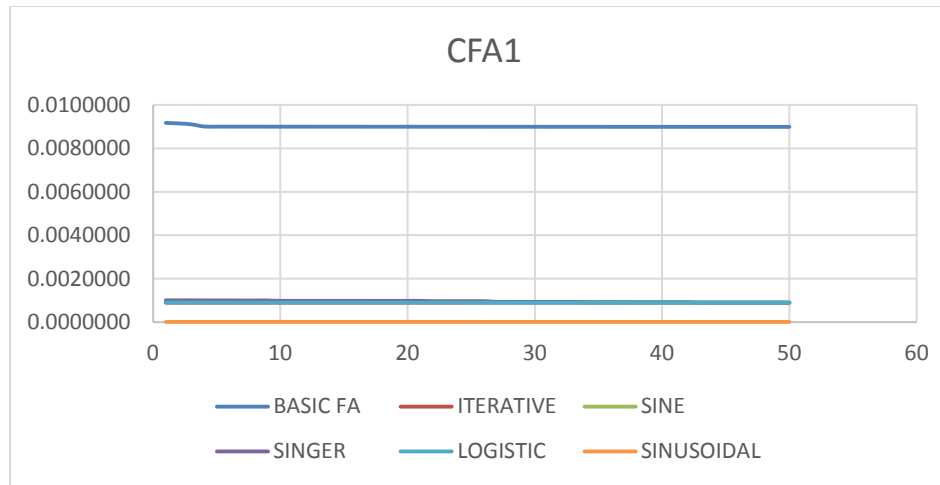
<b>Sinusoidal</b>	SSE	6.8709	17.6883	19.9261	8.9788E-06	8.9987E-06	8.9888E-06	1.4086E-08	132.5718
<b>Map</b>	ISE	8.50822	7.61695	19.9532	5.61E-07	5.70E-07	5.65E-07	3.69E-09	<b>123.0522</b>
	ITAE	11.8409	17.7138	19.9617	8.9866E-10	9.0064E-10	8.9965E-10	1.4031E-12	128.0676
	ITSE	13.5165	11.9421	1.60	<b>1.58E-11</b>	1.68E-11	<b>1.63E-11</b>	<b>7.54E-13</b>	137.0632



(a)

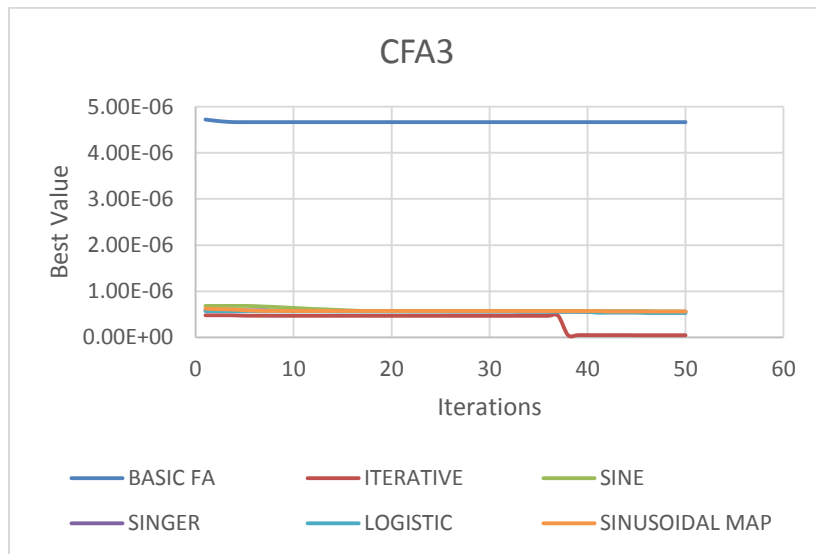


(b)

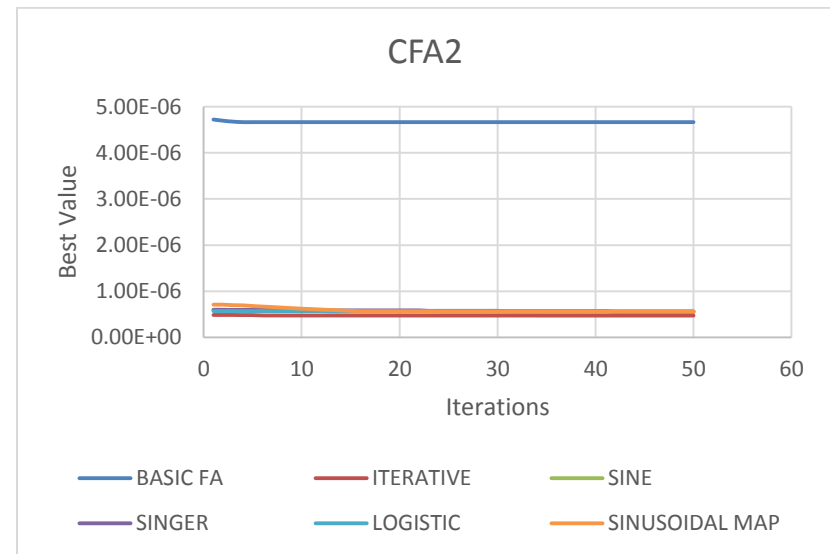


(c)

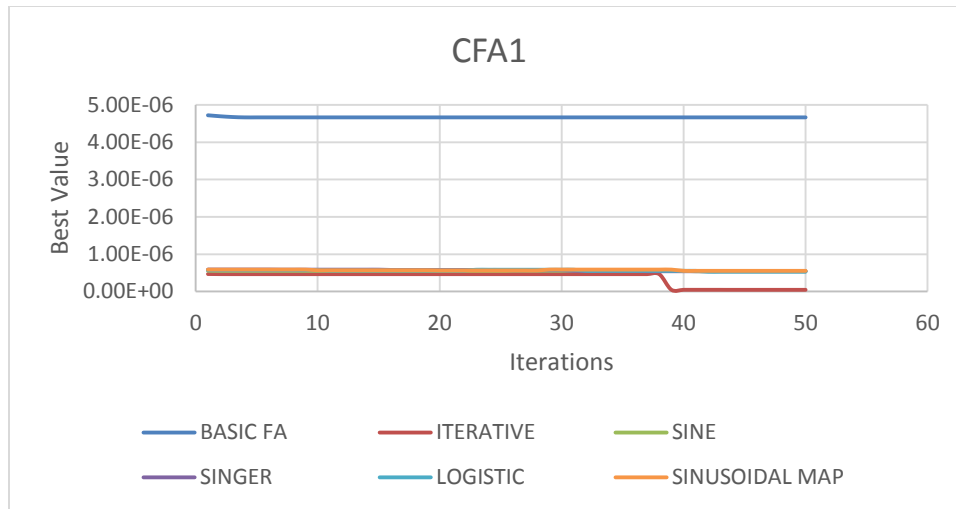
**Figure 4.3:** (a)-(c) Convergence characteristics for SSE(example 1)



(a)

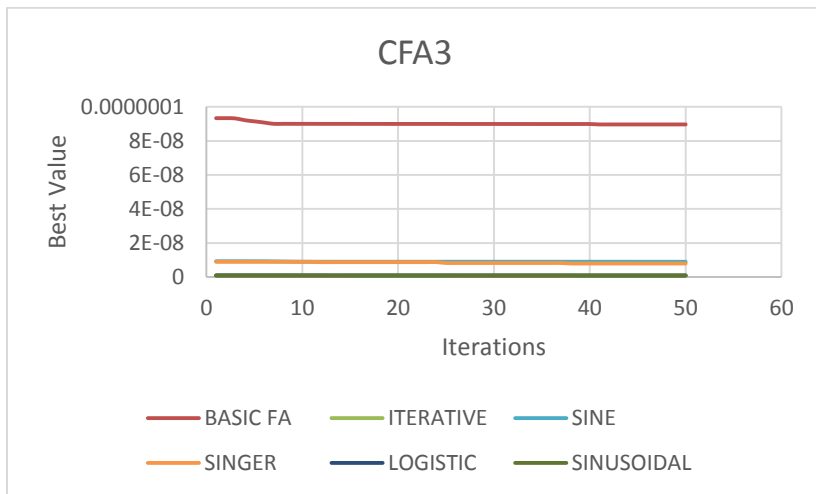


(b)

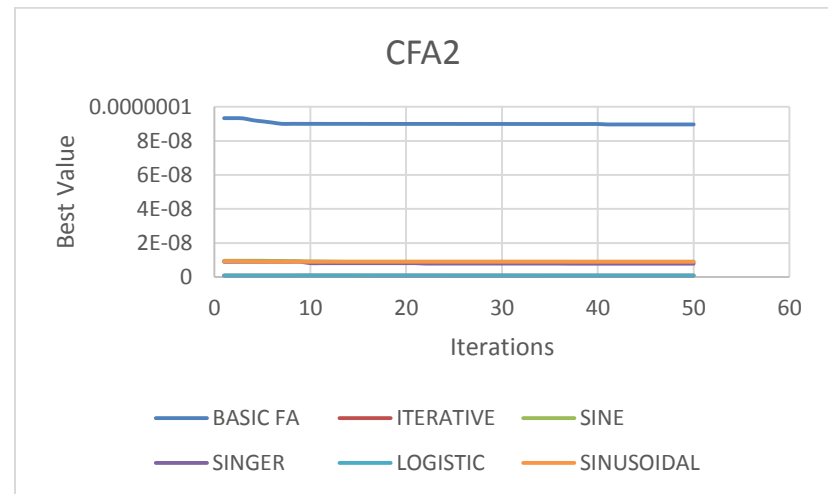


(c)

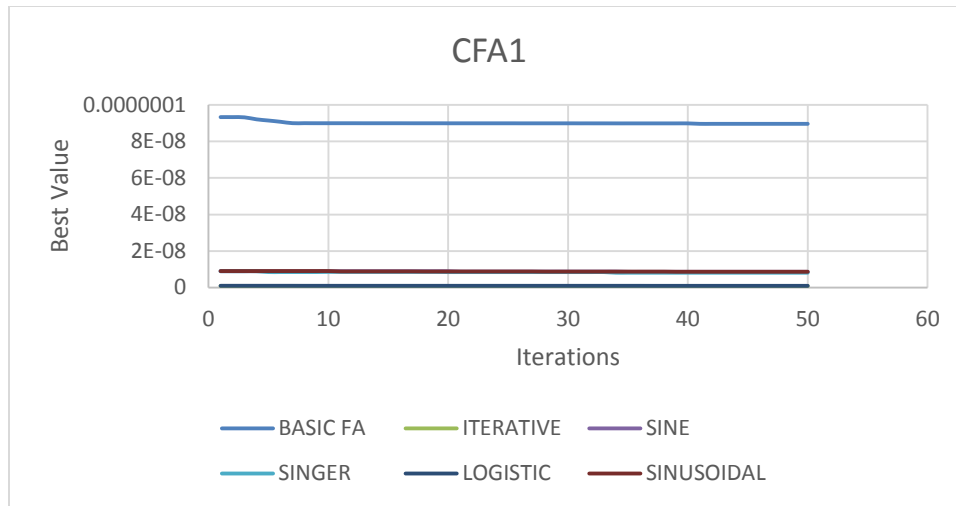
**Figure 4.4:** (a)-(c) Convergence characteristics for ISE(example 1)



(a)

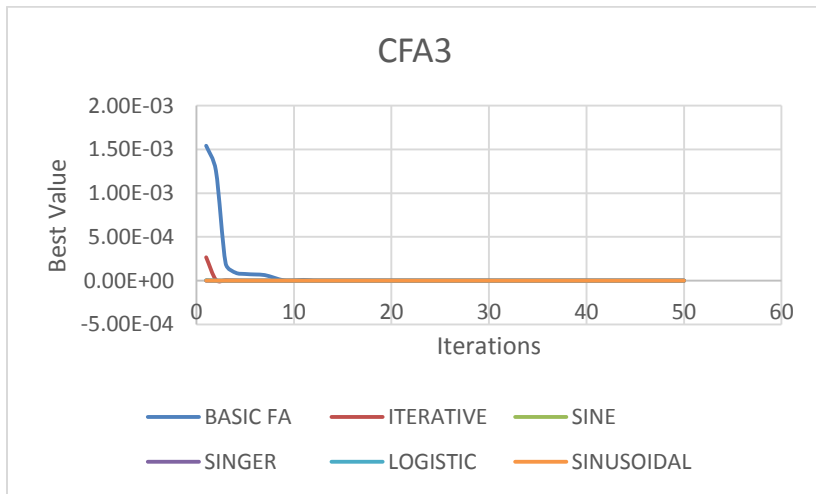


(b)

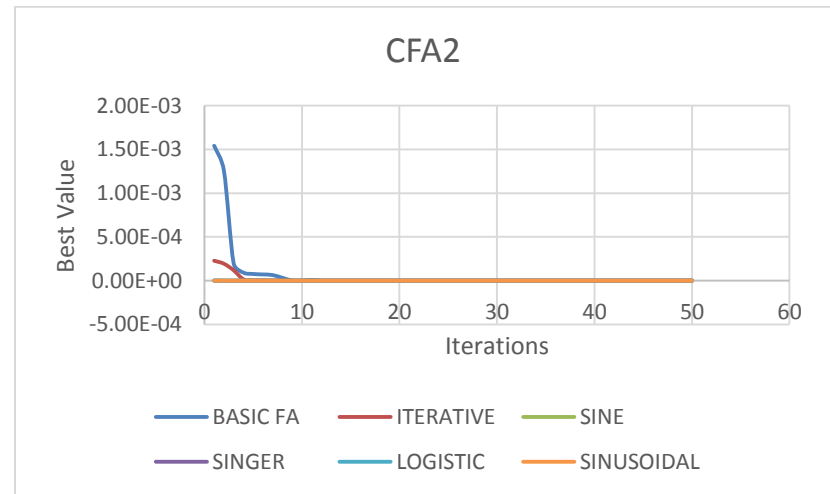


(c)

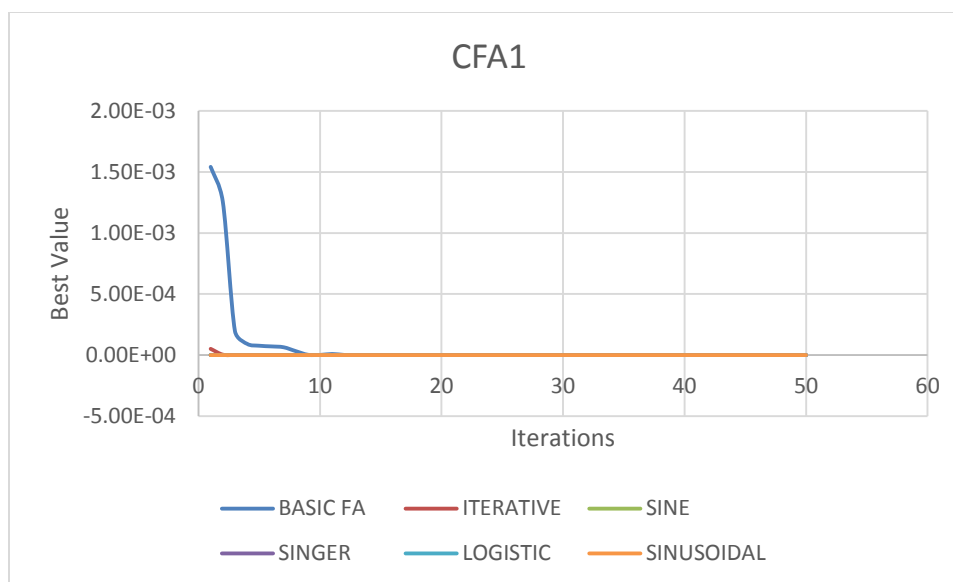
**Figure 4.5:** (a)-(c) Convergence characteristic of ITAE (example 1)



(a)



(b)



(c)

**Figure 4.6:** (a)-(c) Convergence characteristic of ITSE(example 1)

**Table 4.5.** Results for Example 2 with CFA1

Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	14.1114	1.2194	2.5435	3.27E-08	4.44E-08	3.86E-08	8.30E-09	167.0993
	ISE	16.1974	0.6036	2.5355	3.74E-10	1.15E-11	7.64E-10	5.51E-12	124.8458
	ITAE	0.3902	0.6128	2.4777	<b>1.26E-11</b>	1.28E-11	<b>1.27E-11</b>	<b>6.59E-15</b>	125.0547
	ITSE	0.3055	0.4038	1.9109	7.40E-04	7.40E-04	7.40E-04	2.67E-09	<b>124.2791</b>

<b>Iterative Map</b>	SSE	8.1715	0.1681	2.4942	7.50E-13	2.05E-12	1.40E-12	9.20E-13	137.4392
	ISE	10.4814	0.1103	2.531	5 1.09E-15	1.31E-15	1.20E-15	1.51E-16	<b>112.1456</b>
	ITAE	0.3322	0.6154	2.3945	<b>1.26E-17</b>	1.26E-17	<b>1.26E-17</b>	<b>3.03E-20</b>	113.1384
	ITSE	0.2850	0.3265	2.0583	7.40E-16	8.60E-16	8.00E-16	6.41E-18	115.8292
<b>Logistic Map</b>	SSE	8.8532	0.4303	2.5044	5.27E-13	1.89E-12	1.21E-12	9.66E-13	110.2690
	ISE	16.9786	0.8597	2.5196	3.61E-16	2.21E-15	1.29E-15	1.31E-15	118.6832
	ITAE	0.3295	0.5686	2.4211	<b>1.26E-19</b>	1.31E-19	<b>1.29E-19</b>	<b>2.20E-20</b>	116.3789
	ITSE	0.2717	0.4203	1.9514	7.41E-14	7.47E-14	7.44E-14	5.45E-18	<b>113.4780</b>
<b>Sine Map</b>	SSE	9.4833	1.0442	2.5542	8.99E-14	1.16E-12	6.24E-13	7.55E-13	134.1365
	ISE	3.1592	0.0631	2.5508	2.52E-16	1.61E-15	9.30E-16	9.58E-16	110.0742
	ITAE	0.3450	0.5412	2.3603	<b>1.25E-15</b>	1.26E-15	<b>1.26E-15</b>	<b>2.41E-18</b>	<b>109.4689</b>
	ITSE	0.3064	0.3597	2.0393	7.40E-14	7.40E-14	7.40E-14	4.20E-18	115.2618
<b>Singer Map</b>	SSE	0.7351	0.6769	2.4775	3.78E-13	1.58E-12	9.81E-13	8.53E-13	148.0642
	ISE	5.9597	0.7162	2.4727	8.18E-16	4.17E-15	2.50E-15	2.37E-15	111.3568
	ITAE	0.4311	0.6494	2.4321	<b>1.26E-16</b>	1.28E-16	<b>1.27E-16</b>	<b>9.47E-20</b>	<b>111.2290</b>
	ITSE	0.3787	0.4552	1.9399	7.40E-14	7.45E-14	7.43E-14	2.35E-17	120.0653
<b>Sinusoidal Map</b>	SSE	14.2614	0.0719	2.5140	1.70E-13	2.07E-13	1.88E-13	2.59E-14	<b>105.4579</b>
	ISE	19.8216	1.8659	2.5478	6.65E-17	4.52E-16	2.59E-16	2.72E-16	119.1689
	ITAE	0.4529	0.6254	2.4506	<b>1.26E-20</b>	1.34E-20	<b>1.30E-21</b>	<b>8.91E-21</b>	111.0874
	ITSE	2.4932	1.8849	7.1917	4.53E-17	4.73E-17	4.63E-17	1.40E-19	111.1578

**Table 4.6.** Results for Example 2 with CFA2.

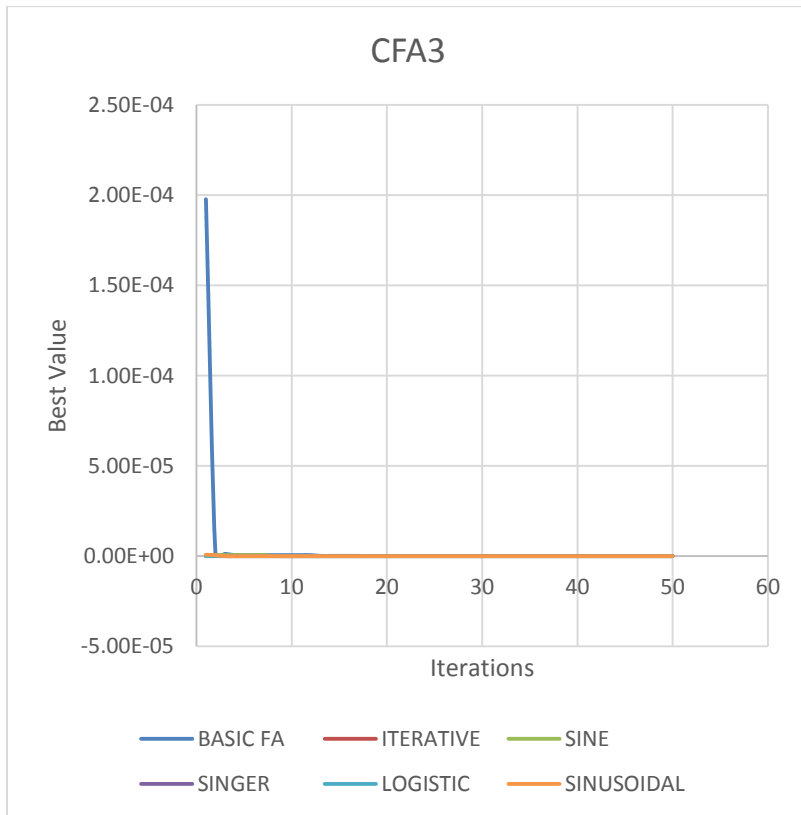
Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
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<b>Basic FA</b>	SSE	14.1114	1.2194	2.5435	3.27E-08	4.44E-08	3.86E-08	8.30E-09	167.0993
	ISE	16.1974	0.6036	2.5355	3.74E-10	1.15E-11	7.64E-10	5.51E-12	124.8458
	ITAE	0.3902	0.6128	2.4777	<b>1.26E-11</b>	1.28E-11	<b>1.27E-11</b>	<b>6.59E-15</b>	125.0547
	ITSE	0.3055	0.4038	1.9109	7.40E-04	7.40E-04	7.40E-04	2.67E-09	<b>124.2791</b>
<b>Iterative Map</b>	SSE	7.0738	1.9542	2.448	1.93E-10	4.97E-09	2.58E-09	3.37E-09	137.0736
	ISE	8.2947	6.0825	2.5306	1.65E-12	1.53E-11	8.48E-12	9.66E-12	115.2670
	ITAE	0.2107	2.0435	6.5101	7.64E-15	1.18E-14	9.71E-15	2.93E-15	112.1579
	ITSE	0.2661	0.4714	2.1567	<b>1.08E-16</b>	1.06E-15	<b>5.84E-16</b>	<b>6.72E-18</b>	<b>122.0478</b>
<b>Logistic Map</b>	SSE	11.5788	0.58137	2.5575	7.14E-14	1.64E-13	1.18E-13	6.57E-14	<b>108.0637</b>
	ISE	12.8454	1.42033	2.45567	1.06E-17	1.26E-17	1.16E-17	1.70E-17	116.0742
	ITAE	0.3293	0.5296	2.4103	<b>1.24E-19</b>	1.29E-19	<b>1.27E-19</b>	<b>1.29E-20</b>	116.2678
	ITSE	0.3883	0.3757	1.9908	7.40E-14	7.40E-14	7.40E-14	3.85E-18	114.9426
<b>Sine Map</b>	SSE	8.1143	6.1975	2.5387	1.57E-09	6.47E-09	4.02E-09	3.46E-09	<b>107.6904</b>
	ISE	10.9669	9.3044	2.5365	2.40E-12	8.68E-12	5.54E-12	4.44E-12	110.0426
	ITAE	0.1104	1.4274	4.957	<b>4.85E-15</b>	1.38E-14	<b>9.30E-15</b>	<b>6.29E-15</b>	119.2718
	ITSE	0.2620	2.3141	8.0618	2.67E-12	5.82E-12	4.25E-12	2.23E-12	116.0536
<b>Singer Map</b>	SSE	7.0738	1.9542	2.4489	1.3325E-12	2.7958E-12	2.0641E-12	1.0347E-12	146.4787
	ISE	2.3425	7.0595	5.5482	6.6839E-15	1.7873E-14	1.2278E-14	7.9118E-15	<b>111.8759</b>
	ITAE	0.3227	0.5732	2.3581	<b>1.2500E-16</b>	<b>1.2687E-16</b>	<b>1.2625E-16</b>	<b>8.7636E-19</b>	121.0637
	ITSE	0.3855	0.4661	2.5101	7.3904E-14	7.4072E-14	7.0056E-14	2.2186E-17	118.9592
<b>Sinusoidal Map</b>	SSE	12.9223	3.5951	2.4324	3.71E-10	2.08E-09	1.22E-09	1.21E-09	110.6893
	ISE	10.9702	2.3260	2.4959	1.07E-13	2.15E-13	1.61E-13	7.61E-14	117.2578
	ITAE	0.1840	1.9982	6.2727	<b>7.30E-19</b>	1.26E-18	<b>9.96E-19</b>	<b>3.76E-21</b>	111.9426
	ITSE	0.3267	0.3619	2.0234	7.40E-19	4.53E-17	2.30E-17	3.15E-19	<b>109.1579</b>

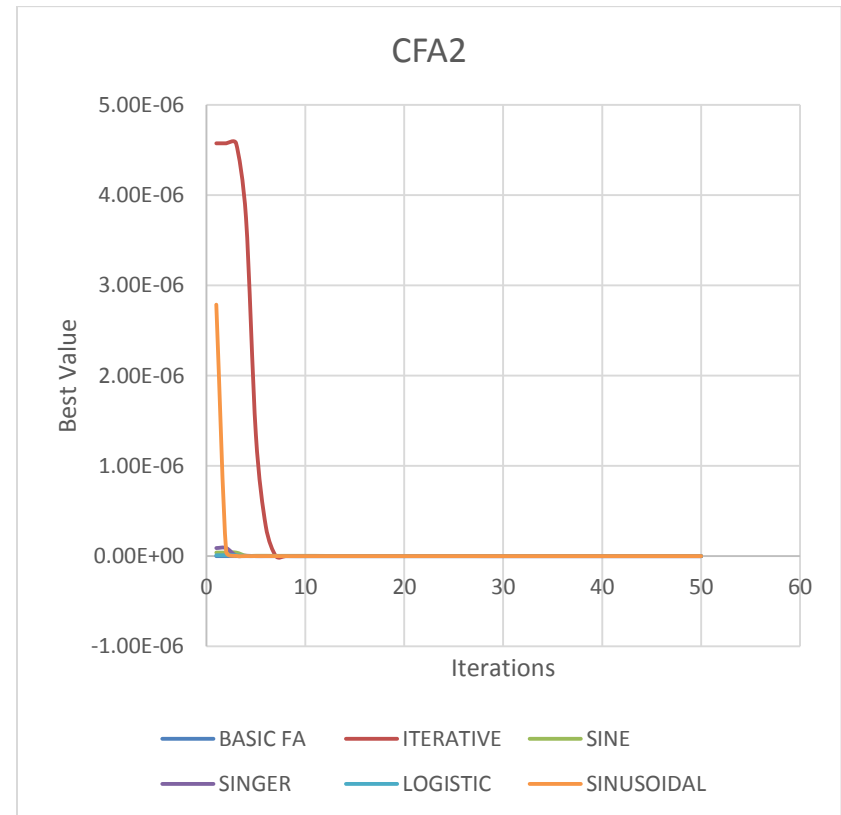
**Table 4.7.** Results for Example 2 with CFA3

Chaotic Map/Basic FA	Type of Error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	14.1114	1.2194	2.5435	3.27E-08	4.44E-08	3.86E-08	8.30E-09	167.0993
	ISE	16.1974	0.6036	2.5355	3.74E-10	1.15E-11	7.64E-10	5.51E-12	124.8458
	ITAE	0.3902	0.6128	2.4777	<b>1.26E-11</b>	1.28E-11	<b>1.27E-11</b>	<b>6.59E-15</b>	125.0547
	ITSE	0.3055	0.4038	1.9109	7.40E-04	7.40E-04	7.40E-04	2.67E-09	<b>124.2791</b>
<b>Iterative Map</b>	SSE	6.5232	1.9618	2.554	7.31E-11	1.57E-10	1.15E-10	5.92E-11	135.1780
	ISE	19.0636	2.1335	2.5010	6.35E-15	3.26E-13	1.66E-13	2.26E-13	114.5317
	ITAE	0.4397	0.5035	2.4491	1.26E-15	5.92E-15	3.59E-15	3.30E-15	<b>112.9526</b>
	ITSE	0.3298	0.4125	2.0433	<b>7.40E-18</b>	4.40E-16	<b>2.24E-16</b>	<b>3.00E-19</b>	121.3571
<b>Logistic Map</b>	SSE	10.5266	0.4966	2.4631	8.35E-13	1.46E-12	1.15E-12	4.43E-13	<b>111.0897</b>
	ISE	12.1854	1.2805	2.4930	6.44E-16	1.57E-15	1.10E-15	6.51E-16	118.7658
	ITAE	0.3418	0.5300	2.3991	<b>1.25E-19</b>	1.30E-16	<b>1.27E-16</b>	<b>1.53E-20</b>	117.0783
	ITSE	0.3330	0.3715	1.9321	7.33E-14	7.40E-14	7.36E-14	5.23E-16	113.1679
<b>Sine Map</b>	SSE	8.5560	1.0715	2.4196	6.64E-09	1.24E-08	9.54E-09	4.10E-09	132.1589
	ISE	15.9965	1.9034	2.5626	1.92E-14	6.93E-14	4.42E-14	3.54E-14	<b>109.0753</b>
	ITAE	0.4291	2.8833	8.5673	<b>1.05E-14</b>	1.13E-14	<b>1.09E-14</b>	<b>5.66E-16</b>	117.1589
	ITSE	0.2979	2.1144	7.4687	2.30E-12	4.68E-12	3.49E-12	1.68E-12	116.2679
<b>Singer Map</b>	SSE	0.7029	0.0404	2.4998	2.53E-12	8.25E-12	5.39E-12	4.05E-12	148.0135
	ISE	3.4752	0.3190	2.4737	1.44E-15	1.43E-14	7.89E-15	9.12E-15	<b>110.2567</b>
	ITAE	0.2640	0.6776	2.8264	<b>1.26E-15</b>	1.28E-15	<b>1.27E-15</b>	<b>2.46E-18</b>	122.8663
	ITSE	0.6212	0.3671	1.8606	7.40E-13	7.41E-13	7.41E-13	4.08E-16	119.9763
<b>Sinusoidal Map</b>	SSE	7.3571	4.2577	2.5618	7.36E-10	1.34E-09	1.04E-09	4.26E-10	<b>107.0754</b>
	ISE	9.1388	8.5202	2.5276	3.75E-12	6.92E-12	5.33E-12	2.24E-12	118.2568

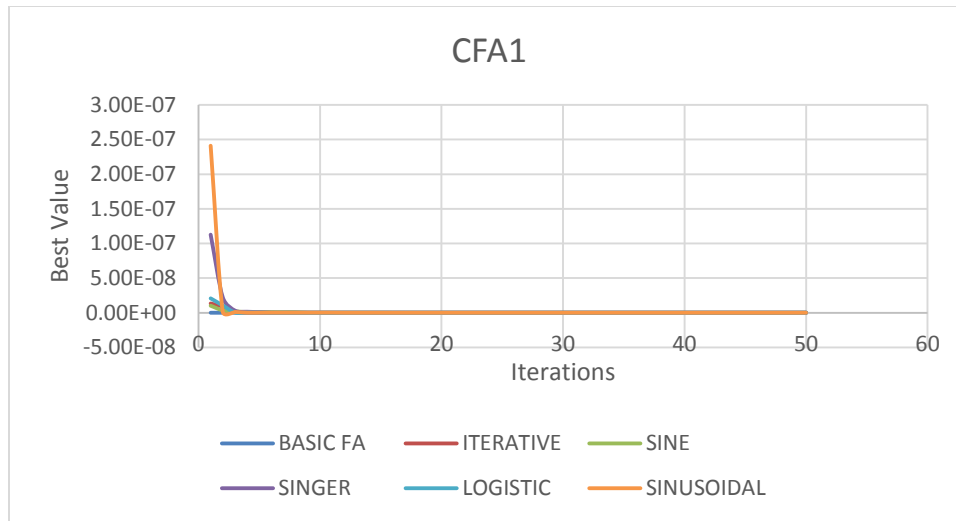
ITAE	0.0256	1.8783	6.0811	<b>7.06E-20</b>	7.26E-20	<b>7.16E-20</b>	<b>4.99E-22</b>	113.0763
ITSE	0.2642	0.4721	2.4664	9.33E-19	4.09E-17	2.09E-17	2.83E-20	108.1358



(a)

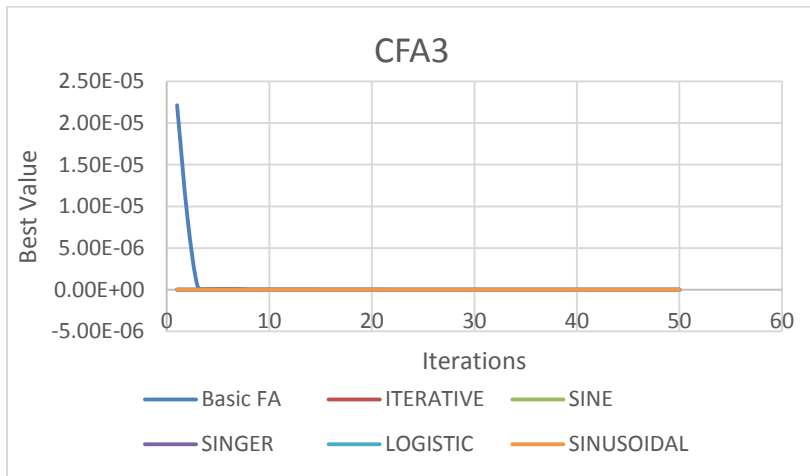


(b)

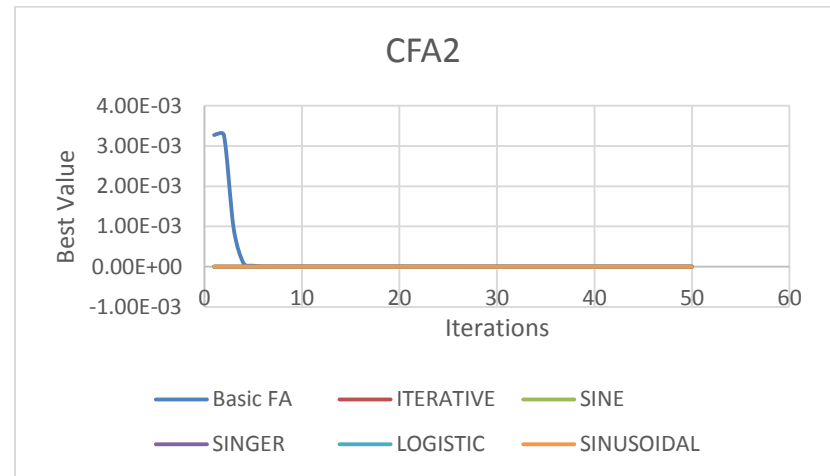


(c)

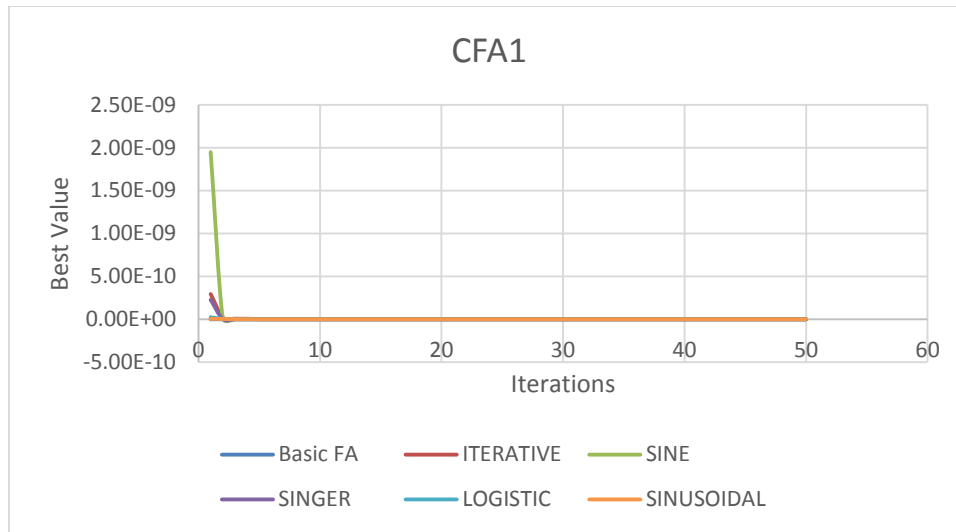
**Figure 4.7 : (a)-(c) Convergence characteristic of SSE(example 2)**



(a)

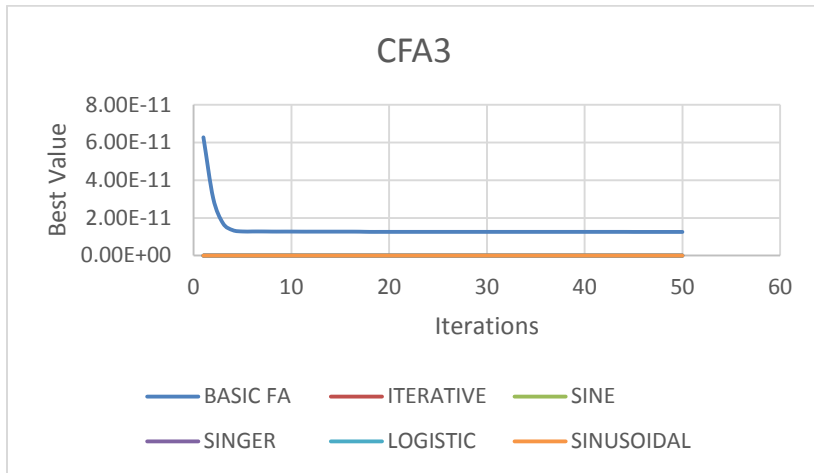


(b)

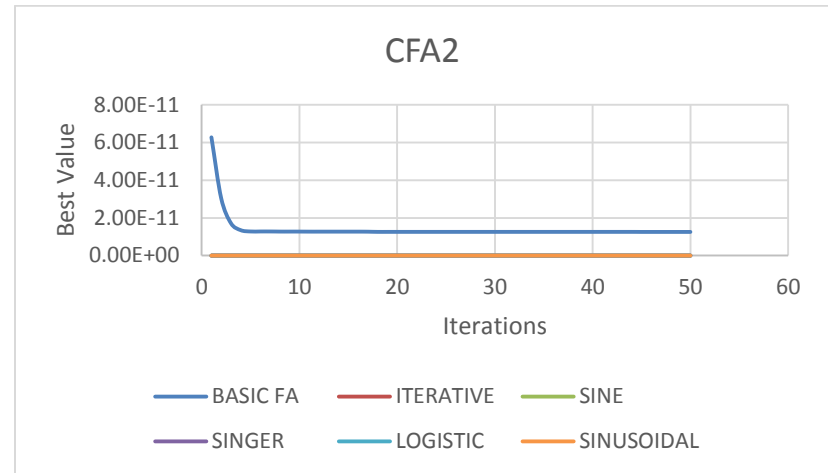


(c)

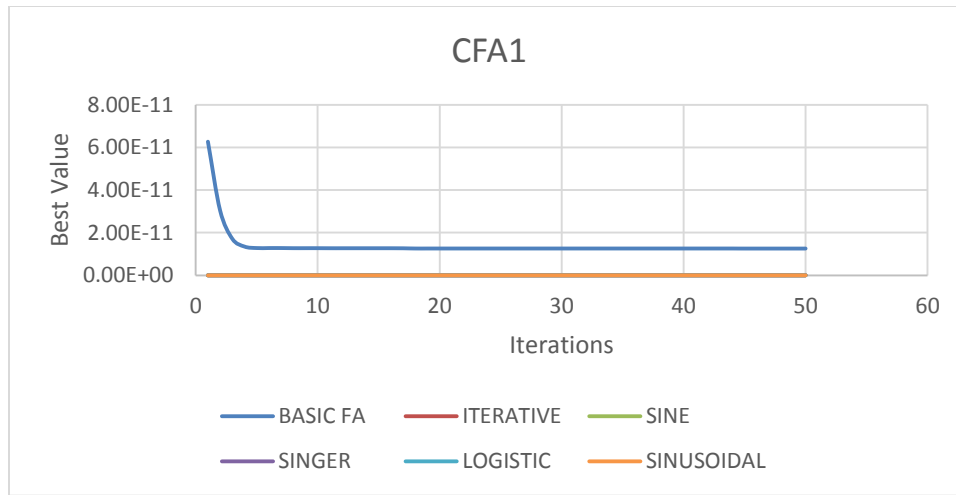
**Figure 4.8:**(a)-(c) Convergence characteristic of ISE(example 2)



(a)

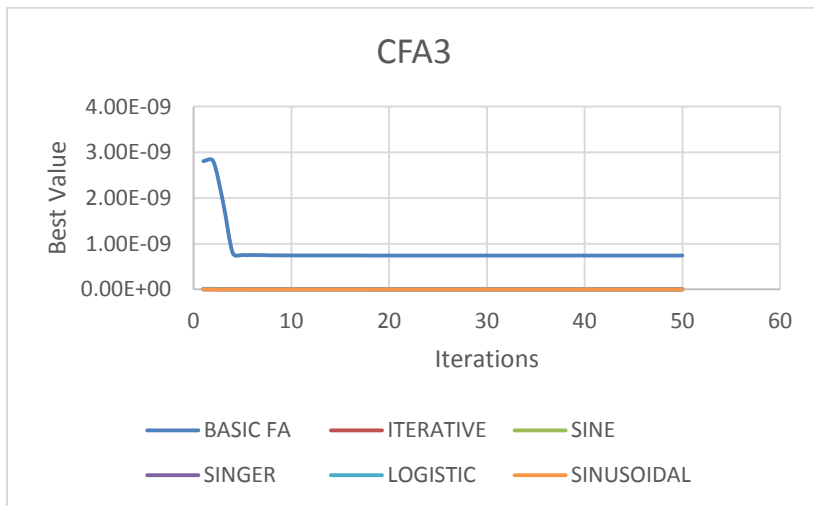


(b)

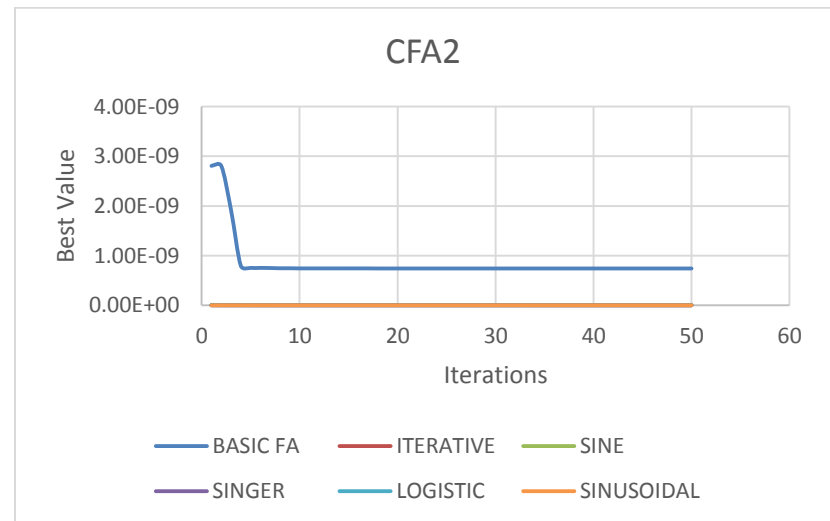


(c)

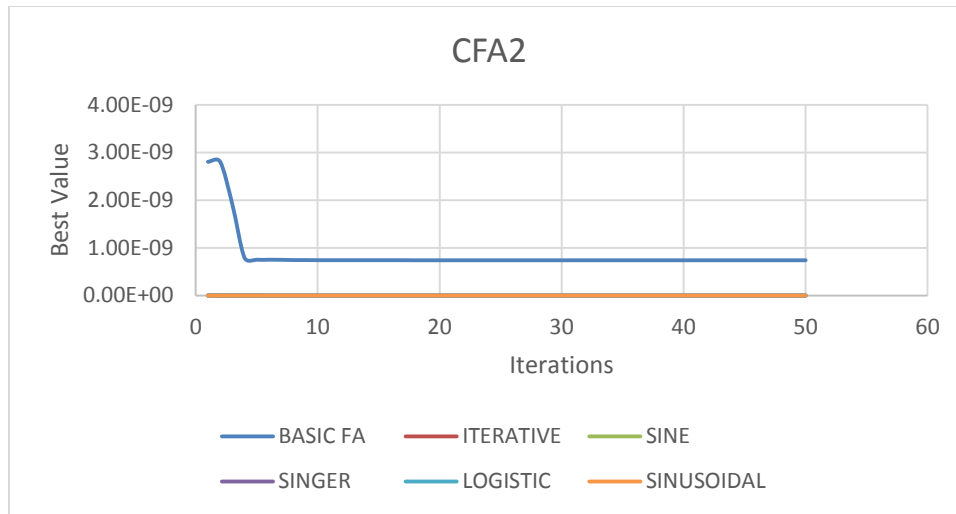
**Figure 4.9** :(a)-(c) Convergence characteristic of ITAE(example 2)



(a)



(b)



(c)

**Figure 4.10 :** (a)-(c) Convergence characteristic of ITSE(example 2)

### **4.3. CONCLUSIONS**

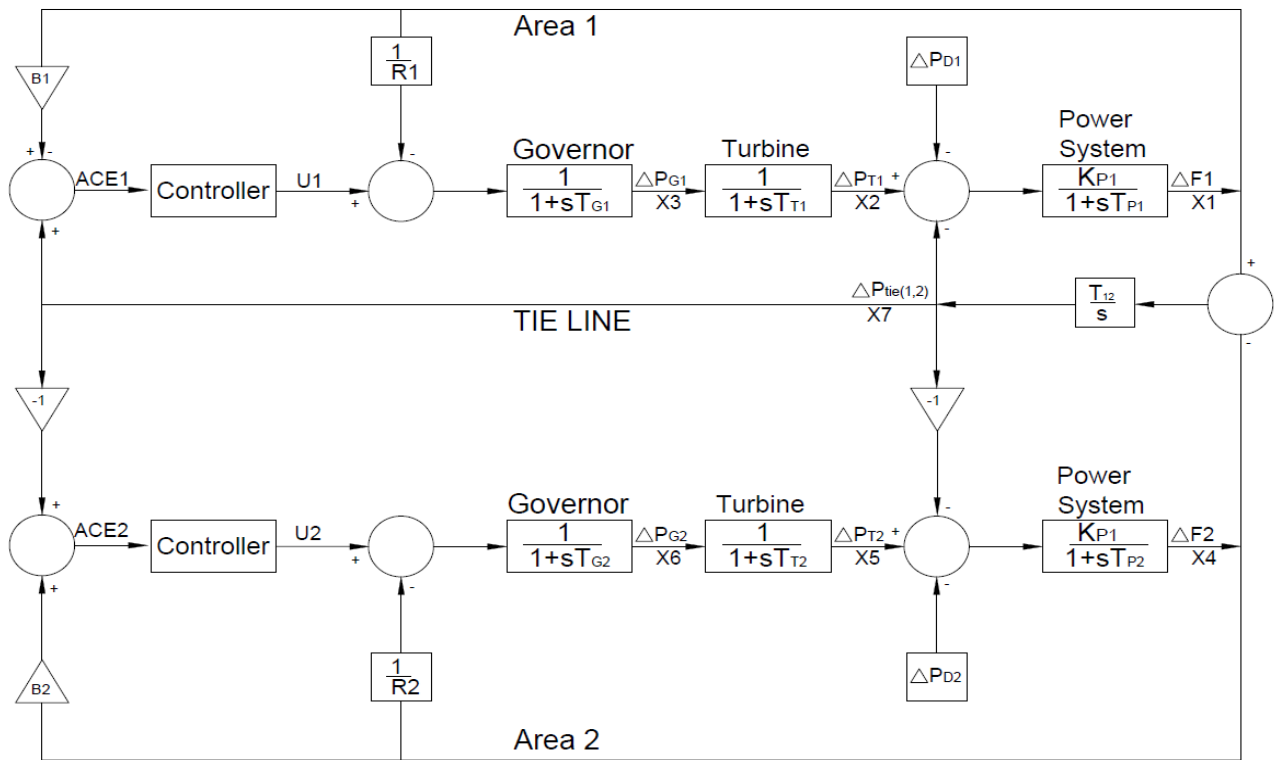
The convergence characteristics for various errors show that errors are optimized better using chaos based FA than standard firefly algorithm. The results depict that the algorithm converges faster when chaotic maps are applied to the algorithm for single area problems but the real time problems are mostly multi area connected systems. Hence, the next chapter shows the application of CFA and FA to a two area network.

## CHAPTER 5: LFC OF MULTI AREA POWER SYSTEM

### 5.1. INTRODUCTION

In the last chapter load frequency control of single area system was carried out for four objective functions and the results prove that CFA performs better than FA. In this chapter, a problem of two area power system will be solved using CFA. In a multi area system, load frequency control is a mechanism that helps to maintain a balance between generation of power and the power demand regardless of the fluctuations in load to maintain the deviation of frequency in acceptable limits[51].

A Multi area power system is an interconnection of various single area power systems. Each system in the power system has three main components i.e. a speed governing system, turbine system and generator system[20]. Each area in the system has three inputs i.e.  $\Delta P_{ref}$  which is denoted by  $U$ ,  $\Delta P_D$  which is the load disturbance in the system and  $\Delta P_{tie}$  which is the tie line power error. The outputs of the system are change in generator frequency  $\Delta F$  and area control error(ACE). The block diagram of two area system is shown below.



**Figure 5.1.** Block diagram of two area power system.

To study frequency domain analysis of the system, transfer functions of each component is used to model the system. The governor can be represented in form of a transfer function as:

$$G_G(s) = \frac{1}{1+sT_G} \quad (4.1)$$

The transfer function of the turbine is given as:

$$G_T(s) = \frac{1}{1+sT_T} \quad (4.2)$$

The generator and load block in the system is represented as,

$$G_P(s) = \frac{K_P}{1+sT_P} \quad (4.3)$$

The two outputs of the system  $\Delta F$  and ACE are represented as,

$$\Delta F(s) = G_P(s)[\Delta P_T(s) - \Delta P_D(s)] \quad (4.4)$$

$$ACE = B\Delta F + \Delta P_{tie} \quad (4.5)$$

To control the change in frequency controllers are used in each area. Here we have used a PID controller for load frequency control. The area control error is the input to the controller and the inputs are given by

$$ACE1 = B\Delta F + \Delta P_{tie} \quad (4.6)$$

$$ACE2 = B\Delta F + \Delta P_{tie} \quad (4.7)$$

Where B is the frequency bias constant and  $\Delta P_{tie}$  is the tie line power.

In this dissertation the controller has been designed using chaotic firefly algorithm. The objective function is designed by considering the desired specifications of the system. The performance criteria or objective function considered here are SSE, ISE, ITSE, ITAE. The problem is formulated for minimization of the objective function which means controller parameters are chosen based on the minimum value of the frequency error.

## 5.2. CONTROLLER DESIGN

The model of a power system can be generalized in state space form[20][24]. Modern control theory says that the inputs to the system (U1 and U2 in figure 5.1) are formed by the linear combination of system states.

The state space form of a power system can be described as:

$$\dot{x} = Ax + Bu \quad (4.8)$$

With  $x(0) = x_0$

$$y = Cx \quad (4.9)$$

Where,  $x$  is a state vector with dimension  $p \times 1$ ,  $p$  = number of state variables,

$u$  is a control vector of dimension  $q \times 1$ ,  $q$  = number of control variables,

$y$  is an output vector of  $m \times 1$  dimension,  $m$  = number of output variables,

$A, B$  and  $C$  are constant matrices with dimensions  $p \times p$ ,  $q \times p$  and  $m \times p$  respectively.

A multi area system can be represented as a form of transfer function using these  $A, B$  and  $C$  matrices. Another matrix  $D$  i.e disturbance matrix also comes into the picture while converting state space model into a transfer function. The transfer function is given by

$$\text{Transfer Function} = C(sI - A)^{-1}B + D \quad (4.10)$$

After finding the transfer function for the system, a model reduction technique is applied to get a lower order transfer function, to make modelling and analysis easy and to make the controller feasible. The model order reduction was done using FA with SSE as objective function.

$$SSE = \sum_{i=1}^N (y - y_r)^2 \quad (4.11)$$

Where  $N$  = number of samples,  $y$  = higher order system,  $y_r$  = lower order system.

By the method of approximate model matching[49], reference models for the reduced transfer functions are formed. In this chapter, chaotic firefly algorithm has been applied to minimize the error between reference model and reduced model using approximate model matching technique in frequency domain using bode plots.

### 5.3. REFERENCE MODEL SELECTION

In this thesis approximate model matching type of controller design is used. The approximate model matching technique designs a controller by approximately matching a pre-specified model i.e. the reference model. Therefore the structure and simplicity of the controller depends on the selection of a reference model. The reference model to be chosen should have rapid response,

should be robust and should satisfy design specifications like frequency domain, time domain, complex domain specifications.

The model selection procedure briefly described below[49]:

Let a reference model transfer function may be given by:

$$H(s) = \frac{h_1s+h_0}{s^2+g_1s+g_0} \quad (4.12)$$

For steady state matching  $h_0 = g_0$  . Then (4.11) can be rewritten as

$$H(s) = \frac{h_1s+g_0}{s^2+g_1s+g_0} \quad (4.13)$$

Let the desired closed-loop specifications that  $K(s)$  has to satisfy are

Velocity error constant =  $k_v$ , Crossover frequency =  $\omega_c$  and damping ratio =  $\xi$ .

A second order model  $H(s)$  has to be selected that satisfies the above specifications, for that the parameters  $g_0, g_1$  and  $h_1$  in equation 4.12 can be determined using equations [49]:

$$\omega_c^2 g_1^2 - 2\omega_c^2 g_1 h_1 - g_0^2 = -\omega_c^4 \quad (4.14)$$

$$g_1 - \frac{g_0}{k_v} - h_1 = 0 \quad (4.15)$$

$$g_1^2 - 4g_0\xi^2 = 0 \quad (4.16)$$

#### 5.4. SYSTEM UNDER STUDY

A two area power system is considered with the system parameters for each area is as follows:

**Table 5.1:** System Parameters for Area1 and Area2

Parameters	Area1	Area2
Speed Regulation	0.05	0.0625
Frequency sensitive load coefficient	0.6	0.9
Inertia constant	5.5	5
Governor time constant	0.25	0.3
Turbine time constant	0.5	0.5

From the state space matrices given for the system and obtain the response for an increase in load of area 1 by 0.1pu. Design a Load Frequency Controller (LFC) for the two-area system

when the above mentioned change in load occurs. Initially whole system is running at a nominal frequency of 50Hz. The two area power system connected through a tie-line given on a base value of 1000MVA.

The state space matrices of a two area system can be formed as per standard formation is given below where A, B and C are the constant matrices and D is the disturbance matrix.

$$A = \begin{bmatrix} -\frac{1}{T_{ps1}} & \frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 & 0 & -\frac{K_{ps1}}{T_{ps1}} & 0 & 0 \\ 0 & -\frac{1}{T_{T1}} & \frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1 T_{SG1}} & 0 & -\frac{1}{T_{SG1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{PS2}} & \frac{K_{ps2}}{T_{ps2}} & 0 & -a_{12} \frac{K_{ps2}}{T_{ps2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{T2}} & \frac{1}{T_{T2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_2 T_{SG2}} & 0 & -\frac{1}{T_{SG2}} & 0 & 0 & 0 \\ 2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & a_{12} & 0 & 0 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{1}{T_{SG1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{SG2}} & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The state space model has been converted to transfer function using matlab programming. Four transfer functions of tenth order have been obtained. Model reduction technique was applied to it using chaotic firefly algorithm in order to convert the transfer function of tenth order to a third order transfer function. Further, second order reference models were generated and errors (SSE,ISE,ITAE,ITSE) were optimized using CFA and FA.

The algorithms were run for a population size of 20 and 50 iterations. The PID parameters were obtained for four objective functions i.e. SSE, ISE, ITSE and ITAE along with the best value,

worst value, average value, standard deviation and average CPU time. All the results were carried out for 5 chaotic maps namely iterative map, sine map, singer map, logistic map and sinusoidal map for 20 test runs.

Results are shown in tables 5.2-5.4.

## **5.5. CONCLUSIONS**

The results for multi area system show that FA with chaos is superior to basic FA. The convergence graphs show that for almost every chaotic map the convergence is less as compared to standard FA. The result tables show best value, average value, standard deviation and the computation time is less for CFA than FA. This clearly proves that results have vastly improved with introduction to chaos.

**Table 5.2.** Results with CFA1.

Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	0.0731	7.9733	9.6514	0.0125	0.0185	0.0155	0.0089	476.2941
	ISE	0.0020	0.1909	0.0271	0.0013	0.0017	0.0015	<b>0.0001</b>	489.1562
	ITAE	0.0831	8.2533	9.6277	0.0224	0.0224	0.0224	0.0224	462.4941
	ITSE	0.0273	0.9072	7.0718	<b>1.0945E-03</b>	1.0995E-03	<b>1.0965E-03</b>	1.5385E-04	<b>460.0183</b>
<b>Iterative Map</b>	SSE	1.4822	6.8204	5.9822	1.7505E-03	1.9518E-03	1.8482E-03	0.0007	<b>444.5393</b>
	ISE	0.0109	6.3825	7.5815	0.0012	0.0014	0.0013	0.0002	456.0293
	ITAE	1.4322	7.0892	15.9284	1.8760E-03	1.9314E-03	1.9063E-03	8.6260E-04	460.2031
	ITSE	1.0034	7.0325	10.8125	<b>1.5050E-04</b>	1.7182E-04	<b>1.6283E-04</b>	<b>4.0183E-05</b>	458.0482
<b>Logistic Map</b>	SSE	0.1321	15.9801	19.1396	1.3300E-02	1.3320E-02	1.3310E-02	1.0395E-02	458.2357
	ISE	0.0184	8.9681	10.893	<b>4.8511E-08</b>	1.3000E-03	<b>6.3457E-04</b>	<b>6.2638E-10</b>	428.0796
	ITAE	0.6728	15.0271	19.2846	1.1110E-03	1.3336E-03	1.2221E-03	2.5791E-04	432.1031
	ITSE	0.0192	8.9452	12.9043	7.9720E-03	7.9992E-03	7.9861E-03	3.3920E-04	438.0823
<b>Sine Map</b>	SSE	0.0114	0.1075	0.0805	4.0938E-08	4.4843E-08	4.2416E-08	1.6147E-08	457.4513
	ISE	0.0029	9.0128	10.1091	6.1682E-08	9.4128E-08	7.8460E-08	2.3726E-10	488.7518
	ITAE	0.9354	10.0955	0.0823	2.8712E-08	2.9319E-08	2.9037E-08	1.7523E-09	<b>443.0128</b>
	ITSE	0.0489	14.8872	18.1184	<b>8.1915E-09</b>	8.2575E-09	<b>8.2210E-09</b>	<b>1.2936E-09</b>	455.0384
<b>Singer Map</b>	SSE	0.0606	0.171	0.0201	6.7948E-07	6.8714E-07	6.8339E-07	3.4863E-08	461.0758
	ISE	10.4278	16.5814	9.4228	1.3000E-03	1.3200E-03	1.3100E-03	1.9714E-05	<b>430.1279</b>

	ITAE	0.3956	6.7148	0.1094	<b>6.1873E-07</b>	6.3806E-07	<b>6.2853E-07</b>	<b>3.2790E-08</b>	458.0384
	ITSE	5.9348	18.8144	6.8341	6.6610E-07	6.7014E-07	6.6802E-07	3.8293E-08	451.6342
<b>Sinusoidal Map</b>	SSE	0.0731	0.1325	0.0200	9.52E-07	1.04E-02	5.200E-03	0.0074	464.8537
	ISE	0.0686	6.1481	9.0390	4.2080E-08	1.2000E-03	5.779E-04	8.17E-09	451.7551
	ITAE	0.2841	0.2528	10.091	<b>3.4139E-09</b>	3.5983E-09	<b>3.5094E-09</b>	<b>1.6840E-10</b>	439.0274
	ITSE	0.8636	7.1163	9.0365	1.2617E-05	1.3419E-05	1.3093E-05	1.2617E-06	<b>428.0284</b>

**Table 5.3.** Results with CFA2.

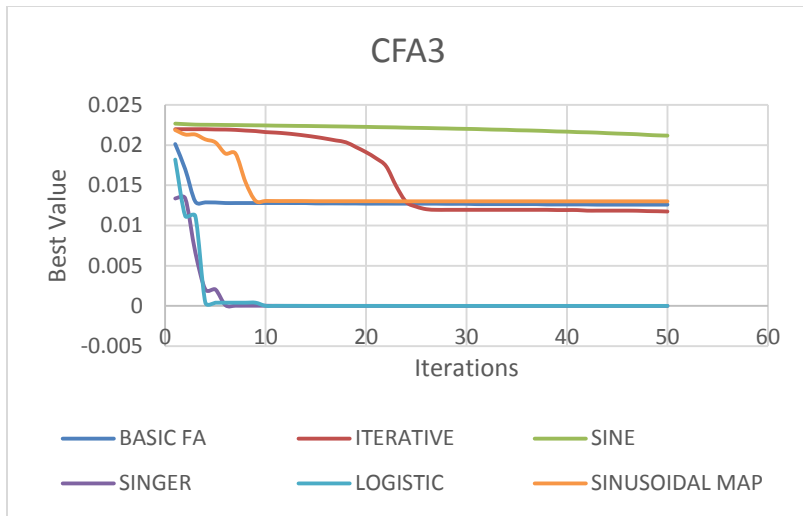
Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	0.0731	7.9733	9.6514	0.0125	0.0185	0.0155	0.0089	476.2941
	ISE	0.0020	0.1909	0.0271	0.0013	0.0017	0.0015	<b>0.0001</b>	489.1562
	ITAE	0.0831	8.2533	9.6277	0.0224	0.0224	0.0224	0.0224	462.4941
	ITSE	0.0273	0.9072	7.0718	<b>1.0945E-03</b>	1.0995E-03	<b>1.0965E-03</b>	1.5385E-04	<b>460.0183</b>
<b>Iterative Map</b>	SSE	9.7240	7.8245	6.9723	3.4607E-07	1.2500E-02	6.300E-03	1.7547E-08	<b>451.6444</b>
	ISE	0.0879	1.0892	1.2159	6.1852E-04	1.2000E-03	9.195E-04	4.2568E-04	447.9690
	ITAE	1.9345	7.8583	16.738	7.6102E-08	7.6725E-08	7.6493E-08	3.7920E-09	456.0283
	ITSE	0.0369	9.8239	11.6159	<b>2.2083E-08</b>	2.8206E-08	<b>2.5180E-08</b>	<b>1.9273E-09</b>	448.9072
<b>Logistic Map</b>	SSE	0.0254	6.6346	7.9423	1.2200E-02	1.2614E-02	1.2407E-02	3.8670E-03	437.1732
	ISE	0.0929	0.1397	0.1391	0.0012	0.0013	0.0012	8.9735E-04	438.9786
	ITAE	1.0839	7.6205	17.2833	9.1740E-04	9.1942E-04	9.1841E-04	1.4800E-05	<b>429.7244</b>
	ITSE	.0385	7.4139	11.9127	<b>6.1100E-04</b>	6.1120E-04	<b>6.1110E-04</b>	<b>1.1024E-05</b>	439.793

<b>Sine Map</b>	SSE	1.5741	5.2847	2.7509	2.1800E-02	2.2618E-02	2.2171E-02	0.004748	450.9062
	ISE	4.5199	15.0467	8.2229	<b>9.5237E-08</b>	9.9304E-08	<b>9.6159E-08</b>	<b>1.2865E-09</b>	474.1685
	ITAE	1.5741	12.8935	2.9284	1.9646E-03	1.9842E-03	1.9716E-03	1.4256E-04	<b>445.1283</b>
	ITSE	1.9839	15.7823	17.9892	7.7601E-05	7.9673E-05	7.8658E-05	1.7239E-07	456.7243
<b>Singer Map</b>	SSE	0.0415	0.1960	0.0198	8.3487E-08	9.7158E-08	9.7158E-08	<b>2.5821E-09</b>	447.2693
	ISE	9.137	17.1946	6.0283	1.3279E-03	1.4015E-03	1.3640E-03	1.7826E-05	<b>439.7506</b>
	ITAE	0.0927	6.4805	0.8983	<b>5.4304E-08</b>	5.5717E-08	<b>5.5054E-08</b>	4.3960E-09	459.2841
	ITSE	6.3847	17.1936	8.8334	6.2627E-08	6.7692E-08	6.5083E-08	5.1027E-09	450.8293
<b>Sinusoidal Map</b>	SSE	0.0537	10.0022	12.2301	1.2900E-02	1.3200E-02	1.3019E-02	2.24E-04	452.1579
	ISE	0.0822	7.2918	8.844	<b>1.1558E-03</b>	1.1996E-03	<b>1.1751E-03</b>	2.3593E-04	439.0268
	ITAE	0.2849	10.0026	12.2381	9.8010E-03	9.8825E-03	9.8416E-03	<b>1.8010E-04</b>	427.9241
	ITSE	2.3494	9.2824	11.634	1.2367E-03	1.2594E-03	1.2414E-03	5.1782E-04	<b>427.0183</b>

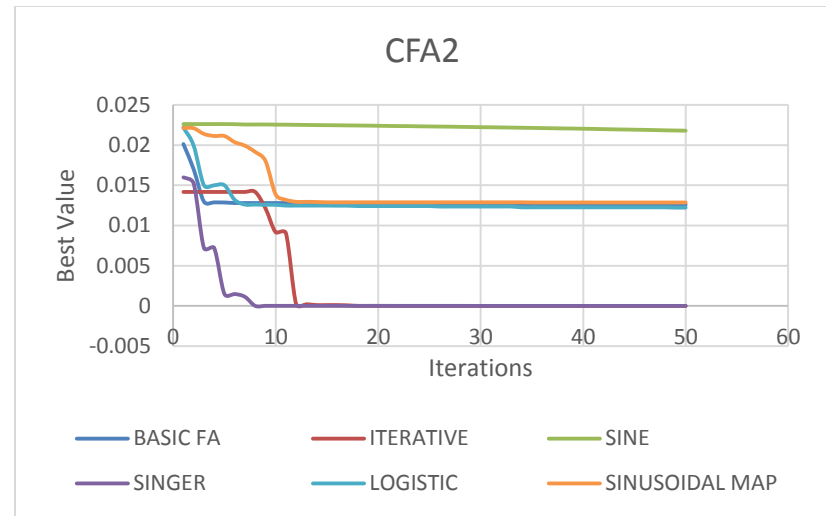
**Table 5.4.** Results with CFA3.

Chaotic Map/Basic FA	Type of error	$K_d$	$K_p$	$K_i$	Best Value	Worst Value	Average Value	Standard Deviation	Average CPU Time
<b>Basic FA</b>	SSE	0.0731	7.9733	9.6514	0.0125	0.0185	0.0155	0.0089	476.2941
	ISE	0.0020	0.1909	0.0271	0.0013	0.0017	0.0015	<b>0.0001</b>	489.1562
	ITAE	0.0831	8.2533	9.6277	0.0224	0.0224	0.0224	0.0224	462.4941
	ITSE	0.0273	0.9072	7.0718	<b>1.0945E-03</b>	1.0995E-03	<b>1.0965E-03</b>	1.5385E-04	<b>460.0183</b>
<b>Iterative Map</b>	SSE	0.0556	5.1185	6.0808	0.01170	0.01291	0.01232	0.00086	<b>439.9715</b>
	ISE	0.0297	12.1611	14.7839	<b>5.160E-08</b>	1.2640E-07	<b>8.9000E-08</b>	<b>5.29E-09</b>	441.4881
	ITAE	2.3847	8.1035	16.0649	3.7570E-03	3.7716E-03	3.7619E-03	2.4890E-04	458.2934
	ITSE	2.0700	11.1831	13.9429	7.4100E-04	7.4100E-04	7.4100E-04	7.4100E-04	443.9272

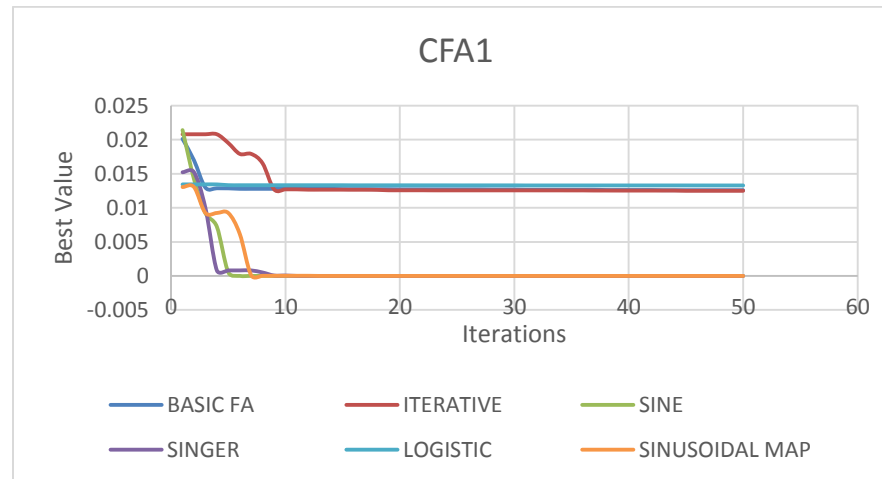
<b>Logistic Map</b>	SSE	0.1357	8.4855	12.8088	9.6309E-08	9.6917E-08	9.6642E-08	<b>1.9320E-09</b>	440.8620
	ISE	0.0639	9.1060	11.3611	9.5238E-08	9.9219E-08	9.7203E-08	2.0633E-09	444.2693
	ITAE	0.1594	8.4873	16.7888	<b>1.2508E-08</b>	1.2510E-08	<b>1.2509E-08</b>	3.5918E-09	<b>428.0283</b>
	ITSE	0.3325	8.1240	11.3125	8.2803E-08	8.3283E-08	8.3001E-08	3.0318E-08	440.2983
<b>Sine Map</b>	SSE	0.3649	11.6341	11.9212	1.3200E-02	2.1200E-02	1.7200E-02	0.0056	454.0792
	ISE	4.962	18.8452	3.24506	1.3000E-03	1.5000E-03	1.4000E-03	9.0520E-04	772.0797
	ITAE	0.3477	11.4281	1.24962	4.0240E-03	4.0543E-03	4.0407E-03	2.3740E-04	<b>449.2034</b>
	ITSE	4.9342	13.052	17.7923	<b>1.1294E-04</b>	1.1311E-04	<b>1.1304E-04</b>	<b>1.3723E-05</b>	450.0274
<b>Singer Map</b>	SSE	0.0483	0.0955	0.019208	3.6350E-07	3.6540E-07	3.6415E-07	1.8864E-08	458.7619
	ISE	0.1117	11.7117	19.1893	2.5088E-08	2.7081E-08	2.6102E-08	1.0720E-09	<b>432.2819</b>
	ITAE	0.0496	5.8305	0.08839	<b>3.4696E-09</b>	3.5418E-09	<b>3.5075E-09</b>	<b>1.4866E-10</b>	457.2093
	ITSE	4.9284	15.5147	9.1033	4.4497E-07	4.4633E-07	4.4510E-07	3.2927E-08	449.2038
<b>Sinusoidal Map</b>	SSE	0.0782	11.2636	13.5761	1.0700E-02	1.300E-02	1.1800E-02	0.0017	459.5832
	ISE	0.0746	8.3357	10.1157	<b>1.2652E-03</b>	1.4694E-03	<b>1.3620E-03</b>	3.0183E-04	442.7022
	ITAE	0.3264	11.3627	13.6491	1.1461E-02	1.1695E-02	1.1526E-02	5.6371E-04	<b>426.1845</b>
	ITSE	3.2354	10.2477	9.5467	9.3640E-03	9.4439E-03	9.4017E-03	<b>7.3364E-05</b>	427.0234



(a)

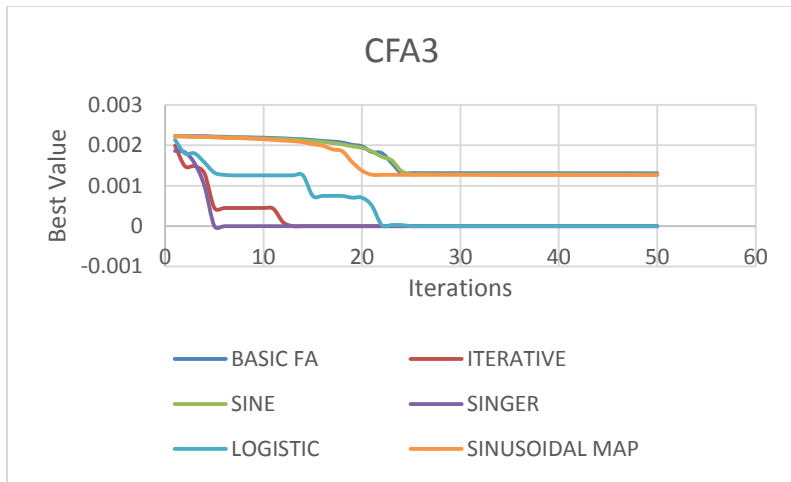


(b)

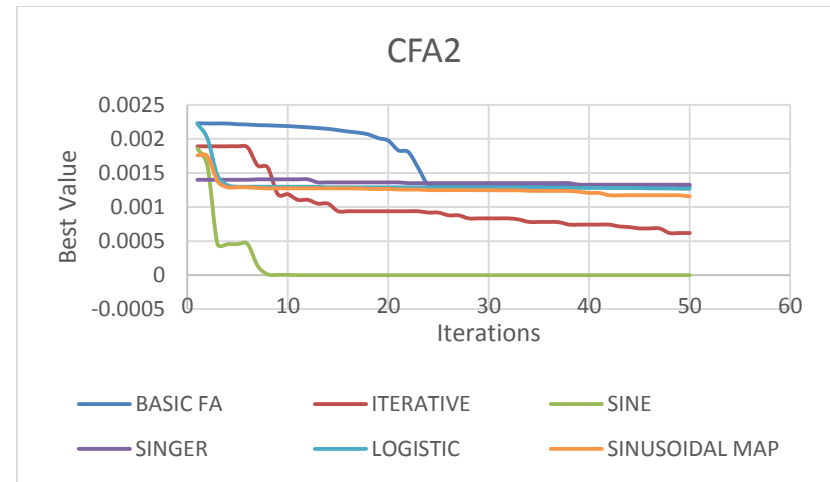


(c)

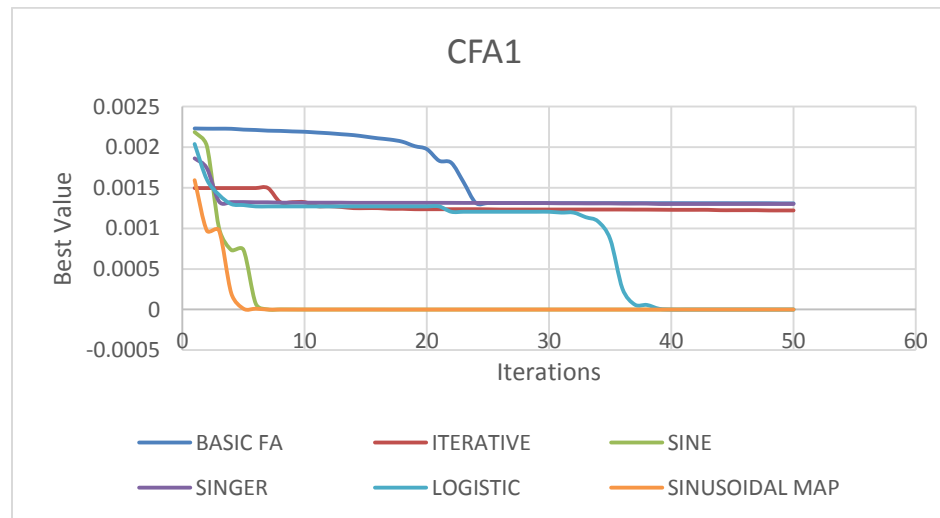
**Figure 5.2:** (a)-(c) Convergence Characteristics for SSE



(a)

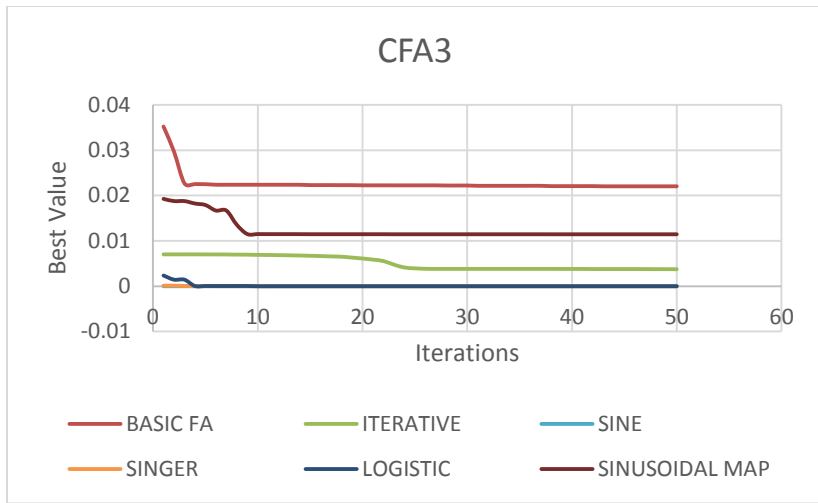


(b)

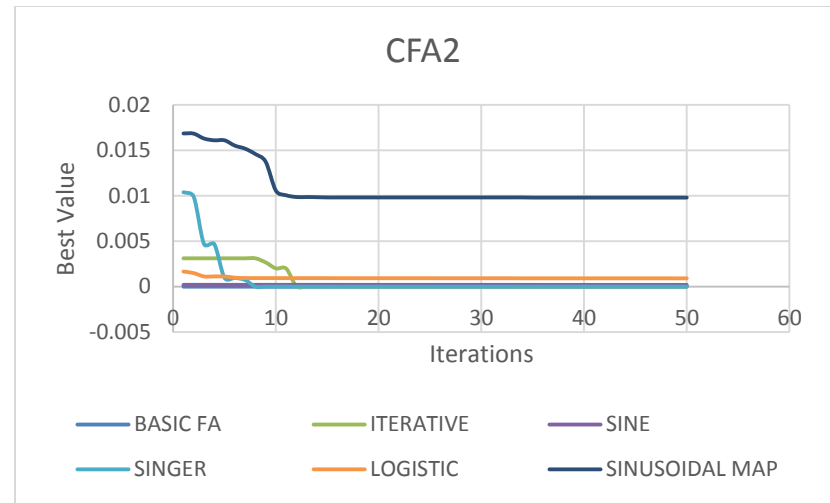


(c)

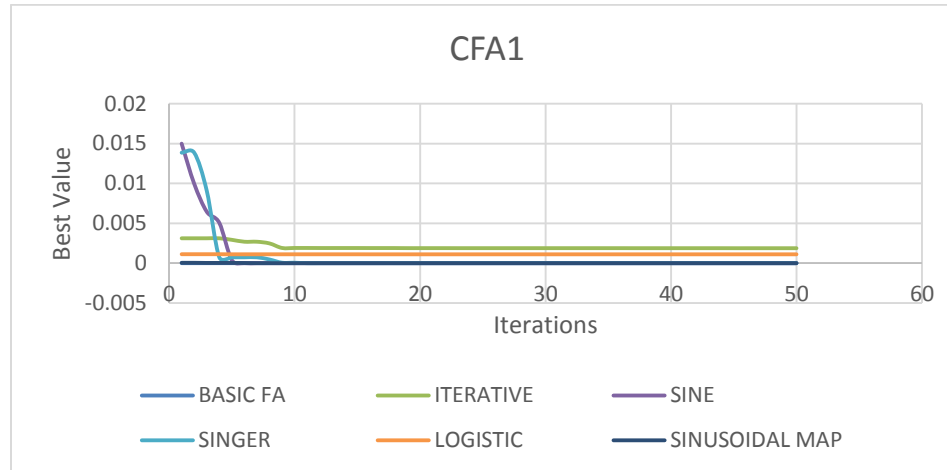
**Figure 5.3:** (a)-(c) Convergence characteristic for ISE



(a)

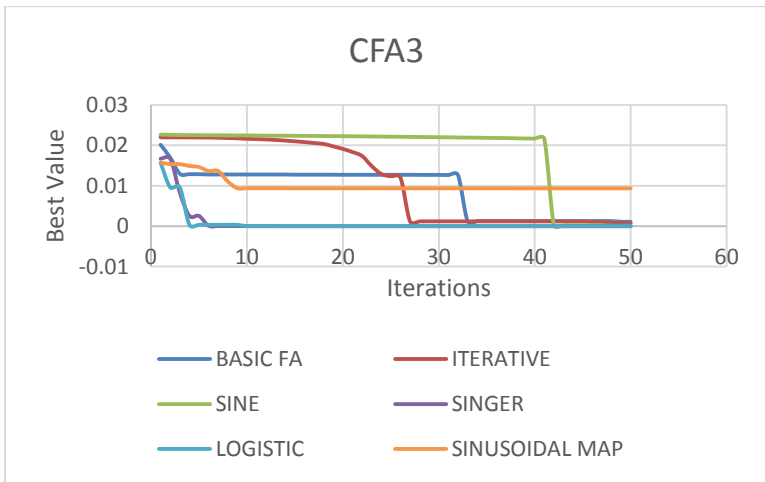


(b)

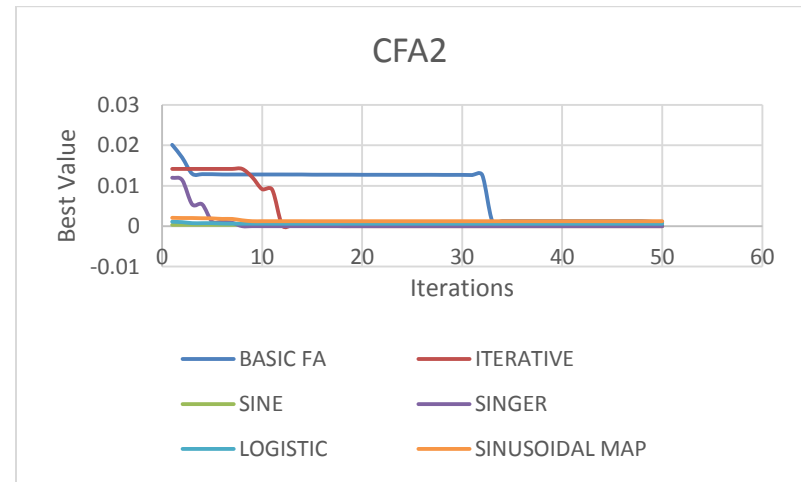


(c)

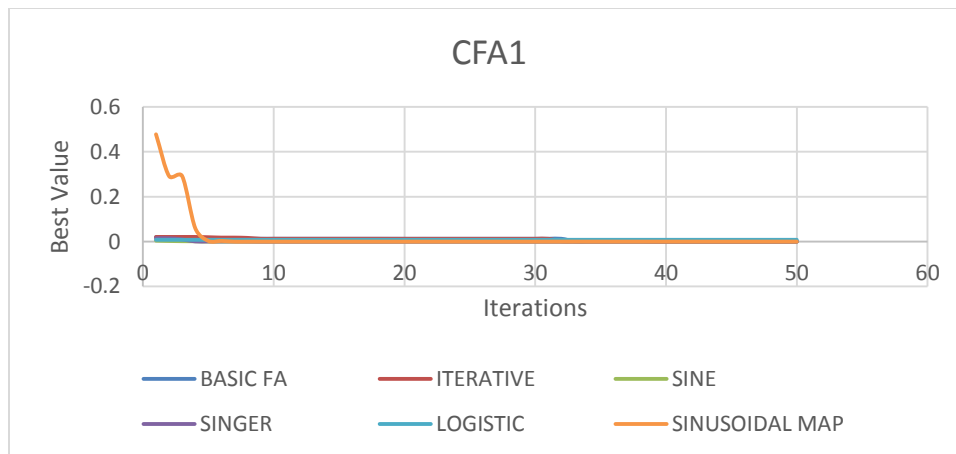
**Figure 5.4:** (a)-(c) Convergence characteristics for ITAE



(a)



(b)



(c)

**Figure 5.5:** (a)-(c) Convergence characteristics for ITSE

## CHAPTER 6: CONCLUSION AND FUTURE WORK

### 6.1. CONCLUSION

Firefly algorithm is a meta-heuristic technique developed by Xin-She Yang in 2008 based on the flashing patterns and behavior of light emitting fireflies. It has been used to solve various optimization problems like continuous, multimodal, unimodal, unconstrained, constrained and also real-world problems. Over the years many researchers have developed various variants of FA.

Here FA and Chaotic FA have been validated using some standard test functions of diverse nature for unconstrained optimization problems. On the basis of their characteristic the standard benchmark functions are classified as unimodal functions, multimodal functions and fixed dimensional multimodal functions. The results of FA and CFA show that the algorithms converge at the optimal

Further, CFA and FA were used to minimize the frequency error in a single area power system. In a power system whenever the demand in load changes there occurs a change in the frequency so using the algorithm this change in the frequency was minimized using bode response. The error to be minimized is the difference of bode response of given system and reference system. The results were carried out for four different objective function(i.e. errors) and a comparison was drawn between CFA and FA. From the convergence characteristics it was clear that CFA performed better than FA.

After studying the single area power system problem, a two area power system problem was studied. A multi area power system has two outputs i.e. frequency deviation and tie line power which as a whole are known as area control error(ACE). In the two area power system problem CFA was used to minimize the ACE. The state space model of the two area power system was converted to a transfer function and model order reduction technique was applied to it using firefly algorithm. Reference models of the reduced order system were generated using approximate model matching technique. The difference reduced order transfer function and reference model transfer function was optimized using bode response. The results of CFA were

compared to basic FA, standard deviation is less for CFA which means the system is more stable and computational time is also less as compared to FA.

## **6.2. SCOPE OF FUTURE WORK**

Future considerations of work as follows:

- Expansion of further chaotic maps to devise new algorithms.
- More variations can be inculcated in the variables like introduction of chaos in  $\gamma, \beta, \alpha$  or  $\alpha, \beta$  or  $\alpha, \gamma$ .
- Two area power system problem can be further expanded to analyze more complicated systems like 3-area, 4-area systems.
- CFA can be hybridized with any other meta-heuristic algorithm to obtain better results.





## LIST OF PUBLICATIONS

---

[1] T. Chaudhary and S. Ganguli, "Chaotic firefly algorithm for optimal tuning of PID controller parameters in single area power systems, "Journal of Basic and Applied Engineering Research, vol. 4, pp.288-291, 2017.

## REFERENCES

---

- [1] X.-S. Yang, "Firefly algorithm, stochastic test functions and design optimisation," *International Journal of Bio-Inspired Computation*, vol. 2, no. 2, pp. 78–84, 2010.
- [2] A. H. Gandomi, X.-S. Yang, and A. H. Alavi, "Mixed variable structural optimization using firefly algorithm," *Computers & Structures*, vol. 89, no. 23, pp. 2325–2336, 2011.
- [3] I. Fister, X.-S. Yang, and J. Brest, "Modified firefly algorithm using quaternion representation," *Expert Systems with Applications*, vol. 40, no. 18, pp. 7220–7230, 2013.
- [4] X.-S. Yang, "Firefly algorithms for multimodal optimization," in *International symposium on stochastic algorithms*, pp. 169–178, Springer, 2009.
- [5] K. Naidu, H. Mokhlis, A. Bakar, V. Terzija, and H. Illias, "Application of firefly algorithm with online wavelet filter in automatic generation control of an interconnected reheat thermal power system," *International Journal of Electrical Power & Energy Systems*, vol. 63, pp. 401–413, 2014.
- [6] N. J. Cheung, X.-M. Ding, and H.-B. Shen, "Adaptive firefly algorithm: parameter analysis and its application," *PloS one*, vol. 9, no. 11, p. e112634, 2014.
- [7] M. Subotic, M. Tuba, and N. Stanarevic, "Parallelization of the firefly algorithm for unconstrained optimization problems," *Latest Advances in Information Science and Applications*, vol. 22, no. 3, pp. 264–269, 2012.
- [8] H. Wang, Z. Cui, H. Sun, S. Rahnamayan, and X.-S. Yang, "Randomly attracted firefly algorithm with neighborhood search and dynamic parameter adjustment mechanism," *Soft Computing*, pp. 1–15, 2016.
- [9] X.-S. Yang, "Chaos-enhanced firefly algorithm with automatic parameter tuning," *Int J Swarm Intell Res*, vol. 2, no. 4, pp. 125–36, 2012.

- [10] L. dos Santos Coelho, D. L. de Andrade Bernert, and V. C. Mariani, "A chaotic firefly algorithm applied to reliability-redundancy optimization," in *Evolutionary Computation(CEC), 2011 IEEE Congress on*, pp. 517–521, IEEE, 2011.
- [11] L. dos Santos Coelho and V. C. Mariani, "Firefly algorithm approach based on chaotic tinkerbelle map applied to multivariable pid controller tuning," *Computers & Mathematics with Applications*, vol. 64, no. 8, pp. 2371–2382, 2012.
- [12] R. Arul, S. Velusami, and G. Ravi, "Chaotic firefly algorithm to solve economic load dispatch problems," in *Green Computing, Communication and Conservation of Energy (ICGCE), 2013 International Conference on*, pp. 458–464, IEEE, 2013.
- [13] A. Gandomi, X.-S. Yang, S. Talatahari, and A. Alavi, "Firefly algorithm with chaos," *Communications in Nonlinear Science and Numerical Simulation*, vol. 18, no. 1, pp. 89–98, 2013.
- [14] O. Abdel-Raouf, M. Abdel-Baset, and I. El-henawy, "Chaotic firefly algorithm for solving definite integral," *International Journal of Information Technology and Computer Science (IJITCS)*, vol. 6, no. 6, p. 19, 2014.
- [15] Iztok Fister, Xin-She Yang, Janez Brest, Iztok Fister Jr., On the randomized firefly algorithm, in: *Cuckoo Search and Firefly Algorithm*, Springer, 2014, pp.27–48.
- [16] M. Mishra, U. Chaturvedi, and S. K. Pal, "A multithreaded bound varying chaotic firefly algorithm for prime factorization," in *Advance Computing Conference (IACC), 2014 IEEE International*, pp. 1322–1325, IEEE, 2014.
- [17] A. Baykasoglu and F. B. Ozsoydan, "Adaptive firefly algorithm with chaos for mechanical design optimization problems," *Applied soft computing*, vol. 36, pp. 152–164, 2015.

- [18] C. Concordia and L. Kirchmayer, "Tie-line power and frequency control of electric power systems," Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems, vol. 72, no. 2, pp. 562–572, 1953.
- [19] N. Cohn, "Some aspects of tie-line bias control on interconnected power systems," Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems, vol. 75, no. 3, pp. 1415–1436, 1956.
- [20] O. I. Elgerd and C. E. Fosha, "Optimum megawatt-frequency control of multiarea electric energy systems," IEEE Transactions on Power Apparatus and Systems, no. 4, pp. 556–563, 1970.
- [21] C. E. Fosha and O. I. Elgerd, "The megawatt-frequency control problem: A new approach via optimal control theory," IEEE Transactions on Power Apparatus and Systems, no. 4, pp. 563–577, 1970.
- [22] G. Ray, A. Prasad, and G. Prasad, "A new approach to the design of robust load-frequency controller for large scale power systems," Electric power systems research, vol. 51, no. 1, pp. 13–22, 1999.
- [23] H. Shayeghi, A. Jalili, and H. Shayanfar, "Multi-stage fuzzy load frequency control using PSO," Energy Conversion and Management, vol. 49, no. 10, pp. 2570–2580, 2008.
- [24] W. Tan, "Tuning of pid load frequency controller for power systems," Energy Conversion and Management, vol. 50, no. 6, pp. 1465–1472, 2009.
- [25] W. Tan, "Unified tuning of pid load frequency controller for power systems via imc," IEEE Transactions on power systems, vol. 25, no. 1, pp. 341–350, 2010.
- [26] K. S. Parmar, S. Majhi, and D. Kothari, "Multi-area load frequency control in a power system using optimal output feedback method," in Power Electronics, Drives and Energy

Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on, pp. 1–5, IEEE, 2010.

[27] D. G. Padhan and S. Majhi, “A new control scheme for pid load frequency controller of single-area and multi-area power systems,” *ISA transactions*, vol. 52, no. 2, pp. 242–251, 2013.

[28] U. K. Rout, R. K. Sahu, and S. Panda, “Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system,” *Ain Shams Engineering Journal*, vol. 4, no. 3, pp. 409–421, 2013.

[29] S. Padhan, R. K. Sahu, and S. Panda, “Application of firefly algorithm for load frequency control of multi-area interconnected power system,” *Electric power components and systems*, vol. 42, no. 13, pp. 1419–1430, 2014.

[30] R. K. Sahu, S. Panda, and G. C. Sekhar, “A novel hybrid pso-ps optimized fuzzy PI controller for agc in multi area interconnected power systems,” *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 880–893, 2015.

[31] R. K. Sahu, S. Panda, and P. C. Pradhan, “Design and analysis of hybrid firefly algorithm pattern search based fuzzy pid controller for lfc of multi area power systems,” *International Journal of Electrical Power & Energy Systems*, vol. 69, pp. 200–212, 2015.

[32] I. Fister, M. Perc, and S. M. Kamal, “A review of chaos-based firefly algorithms: perspectives and research challenges,” *Applied Mathematics and Computation*, vol. 252, pp. 155–165, 2015.

[33] X.-S. Yang, *Nature-inspired optimization algorithms*. Elsevier, 2014.

[34] I. Fister, X.-S. Yang, and J. Brest, “A comprehensive review of firefly algorithms,” *Swarm and Evolutionary Computation*, vol. 13, pp. 34–46, 2013.

- [35] D. Corne, M. Dorigo, and F. Glover, "New ideas in optimization mcgraw-hill," London, UK, 1999.
- [36] J. Kennedy and R. C. Eberhart, "The particle swarm: social adaptation in information processing systems," in *New ideas in optimization*, pp. 379–388, McGraw-Hill Ltd., UK, 1999.
- [37] D. Karaboga and B. Basturk, "A powerful and efficient algorithm for numerical function optimization: artificial bee colony (abc) algorithm," *Journal of global optimization*, vol. 39, no. 3, pp. 459–471, 2007.
- [38] S. Abd-Elazim and E. Ali, "Load frequency controller design via bat algorithm for nonlinear interconnected power system," *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 166–177, 2016.
- [39] X.-S. Yang, *Nature-inspired metaheuristic algorithms*. Luniver press, 2010.
- [40] G. Beni and J. Wang, "Swarm intelligence in cellular robotic systems," in *Robots and Biological Systems: Towards a New Bionics?*, pp. 703–712, Springer, 1993.
- [41] S. M. Lewis and C. K. Cratsley, "Flash signal evolution, mate choice, and predation in fireflies," *Annu. Rev. Entomol.*, vol. 53, pp. 293–321, 2008.
- [42] M. H. Sulaiman, H. Daniyal, and M. W. Mustafa, "Modified firefly algorithm in solving economic dispatch problems with practical constraints," in *Power and Energy (PECon), 2012 IEEE International Conference on*, pp. 157–161, IEEE, 2012.
- [43] J. R. De Wet, K. Wood, M. DeLuca, D. R. Helinski, and S. Subramani, "Firefly luciferase gene: structure and expression in mammalian cells.," *Molecular and cellular biology*, vol. 7, no. 2, pp. 725–737, 1987.

- [44] Xin-She Yang, Analysis of firefly algorithms and automatic parameter tuning, in: Emerging Research on Swarm Intelligence and Algorithm Optimization, IGI Global, 2015, pp. 36–49.
- [45] Iztok Fister, Xin-She Yang, Janez Brest, Iztok Fister Jr., On the randomized firefly algorithm, in: Cuckoo Search and Firefly Algorithm, Springer, 2014, pp.27–48.
- [46] David P. Feldman, Chaos and Fractals: An Elementary Introduction, OUP Oxford, 2012.
- [47] M. Jamil and X.-S. Yang, “A literature survey of benchmark functions for global optimization problems,” International Journal of Mathematical Modelling and Numerical Optimisation, vol. 4, no. 2, pp. 150–194, 2013.
- [48] M. N. Anwar and S. Pan, “A new pid load frequency controller design method in frequency domain through direct synthesis approach,” International Journal of Electrical Power & Energy Systems, vol. 67, pp. 560–569, 2015.
- [49] C. Chen and L. Shieh, “An algebraic method for control systems design,” International Journal of Control, vol. 11, no. 5, pp. 717–739, 1970.
- [50] D. G. Padhan and S. Majhi, “A new control scheme for pid load frequency controller of single-area and multi-area power systems,” ISA transactions, vol. 52, no. 2, pp. 242–251,2013.
- [51] Gundes AN, Chow L. Controller synthesis for single-area and multi-area power systems with communication delays. In: American control conference (ACC), Washington, DC, USA; June 17–19, 2013.

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## Computer Science, 2009

Publication

- 
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| <b>6</b>  | Abdel-Raouf, Osama, Mohamed Abdel-Baset, and Ibrahim El-henawy. "Chaotic Firefly Algorithm for Solving Definite Integral", International Journal of Information Technology and Computer Science, 2014.<br><small>Publication</small>            | % <b>1</b>  |
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## Computation, 2010

Publication

- 
- 13** Huang, Congzhi, and Hebertt Sira-Ramirez. "Flatness-based active disturbance rejection control for linear systems with unknown time-varying coefficients", *International Journal of Control*, 2015. <math>\leq 1</math>
- Publication
- 
- 14** S. Velusami. "Design of Decentralized Biased Dual Mode Controllers for Load-Frequency Control of Interconnected Power Systems", *Electric Power Components and Systems*, 10/1/2006. <math>\leq 1</math>
- Publication
- 
- 15** Pandey, Shashi Kant, Soumya R. Mohanty, and Nand Kishor. "A literature survey on load-frequency control for conventional and distribution generation power systems", *Renewable and Sustainable Energy Reviews*, 2013. <math>\leq 1</math>
- Publication
- 
- 16** Gautam, Saumya Kr., and Nakul Goyal. "Improved particle swarm optimization based load frequency control in a single area power system", *2010 Annual IEEE India Conference (INDICON)*, 2010. <math>\leq 1</math>
- Publication
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