The Journal of CPRI,
Vol. 10, No. 3, September 2014 pp. 453-464

Adaptive polar fuzzy load frequency controller for nonlinear multi-area power system

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Fuzzy logic controller is based on human experience. Human experience is encoded in the form of fuzzy rule base to control the system. It is difficult to decide the size of fuzzy rule base. As the number of rules increases the performance of controller is better. At the same time its complexity increases which in turn affects the computation time and memory requirements. To overcome these problems, a Polar Fuzzy logic controller (PFC) is proposed for the load frequency control problem of nonlinear three area interconnected power system. In this paper, The PFC is made adaptive using Real Coded Genetic algorithm- fuzzy system (RCGAF) approach. The performance of simple PFC and adaptive PFC using RCGAF is compared with fuzzy and conventional PI controller.

Keywords: *Load frequency control, adaptive polar fuzzy logic, real coded genetic algorithm, power systems.*

1.0 INTRODUCTION

The large-scale power systems is consisting of interconnected control areas. In these large scale interconnected power systems the disturbance in any area affects the frequency of other areas too. These inter modal oscillations sometimes create a big problem in the system and may lead to complete blackout. Hence, Load Frequency Control (LFC) problem is a very important to keep the system frequency and the inter-area tie line power as close as possible to the scheduled values [1]. The mechanical input power to the generators is changed to control the frequency of electrical power and to maintain the power exchange between the areas as scheduled. A well designed power system should cope with these changes on the load side and high level of power quality can be achieved by maintaining both voltage and frequency within limits [2, 3].

The primary objective of LFC is to maintain each unit's generation at the most economic value [4]. Several strategies for LFC have been proposed. Although a majority of these studies have considered the conventional control techniques [13], several studies using novel and intelligent control techniques for LFC are also reported in the literature [9]. These controllers have shown good results in load frequency control. Application of a adaptive Polar Fuzzy controller to LFC is described in this paper. Its Performance on a single area and a three area system is described, and compared with Fuzzy controller and the conventional proportional integral (PI) controller.

2.0 FUZZY LOGIC CONTROLLER

Fuzzy control is based on a fuzzy logic system which is much closer to human thinking and natural language than classical logic systems

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[1- 5, 12, 14, 16]. The Fuzzy logic controller is consisting of mainly fuzzification, approximate reasoning and defuzzification blocks [6-7, 10, 15, 17]. The pre-processing and post processing blocks also required to present the data in proper format.

Five triangular membership functions are taken for both input (i.e. error and integral of error) and output of fuzzy logic controller.

Whenever, there are two or more than two inputs in a fuzzy logic controller, the fuzzy rule base has compound rules and there is an aggregation operator to aggregate these inputs to find the fuzzy output. In fuzzy logic controller considered here uses intersection aggregation operator for load frequency control problem as given in Appendix Table A1. It increases computational complexity. The computational complexity of controller also depends on the number of rules in a fuzzy logic controller. The fuzzy logic based controller with 25-rules indeed gives a consistently better performance than the conventional controller for LFC, but the mathematical operation with several rules is rather complex and time consuming. To overcome these drawbacks of fuzzy logic controller, the adaptive polar fuzzy controller is proposed in this paper.

3.0 ADAPTIVE POLAR FUZZY CONTROLLER

For the load frequency control problem, one alternative is to represent the two states of the system, namely deviation in system frequency, Δf, and the integral of change of frequency in polar form, and fuzzy controller output is calculated based on the angle θ of polar form [14]. The control signal can be determined based on the magnitude R of polar form and controller output as shown in Figure 1.

Two fuzzy membership functions are defined for each input angle θ and output u (Table 1).

Fuzzy Input: Angle θ (degrees)

= {Low(L) High (H) }

Fuzzy sets for output u:

= {Positive (P), Negative (N)}

In Polar Fuzzy logic based controller, there is no need to use two separate input gains for Δf and integral of Δf as in conventional controller. In PFC only one input, angle of the polar quantity that depends on the ratio of the properly scaled inputs is used. Thus, only one gain, K, is considered. The gain K decides as to which variable, Δf and integral of Δf has more weight in the polar quantity. The maximum and minimum control action is fixed at angles 45° and 135° respectively. But due to the scaling factor K, all the points in the phase plane are relocated and sometimes system conditions may also require these points to be relocated. Hence, for better tuning of the controller, there is a need for clockwise or anti clockwise rotation. This can be done by adding or subtracting an angle ‘β’ from phase plane angle ‘θ’ of the polar form.

TABLE 1

DEFINING FUZZY SETS FOR PFC

Variables	**Fuzzy sets**	**Membership at variable value**	
		zero	**One**
Input (θ)	L	0 and 400°	200°
	H	250°	0 and 400°
Output (u)	N	-1 and -0.5	-0.75
	P	0.5 and 1	0.75

The required control strategy can be layout as:

a) In first quadrant, both scaled Δf and integral of Δf are positive, so output u is positive high.

b) In second quadrant,

    i. Scaled Δf is large positive and scaled integral of Δf is small negative then control signal should be low positive.

    ii. Scaled Δf is small positive and scaled integral of Δf is large negative then control signal should be low negative.

c) In third and fourth quadrant the situations are completely opposite to the situation mentioned above, hence the control action is also just opposite.

Fuzzy Output of FLC is based on two linguistic variables ‘P’ and ‘N’, which are triangular membership functions. So, here only two simple rules are considered:

Rule 1 - If θ is H then u is P.

Rule 2 - If θ is L then u is N.

The output of FLC of PFC is u=f1(θ), and final output UPFC= u* R

Where:

f1–Non-linear fuzzy functional mapping

θ – Angle in degree,

R – Magnitude

β –Tuning angle in degree,

For typical values of Δf and integral of value of Δf angle θ is determined and then the outputs for these fuzzy inputs from above mentioned 2-rules.

Δf integral of Δf

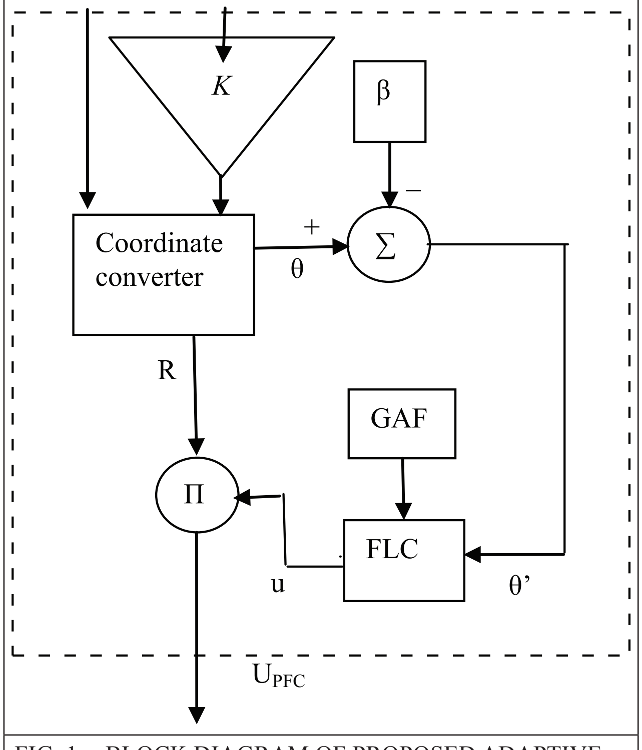


FIG. 1 BLOCK DIAGRAM OF PROPOSED ADAPTIVE POLAR FUZZY LOGIC CONTROLLER

This PFC is made adaptive by changing the range of input fuzzy set membership functions using adaptive real coded Genetic algorithm (RCGA). In RCGA the chromosomes contain real numbers (variables). The RCGA convergence is slow and depends upon the number of variables. To improve the convergence of RCGA, its parameters like cross over probability (Pc) and mutation probability (Pm) are modified using some fuzzy rules dynamically during execution in genetic algorithm with fuzzy system (GAF).

In the beginning high value of Pc and low value of Pm give good results because the initial population is well diversified and cross over operation alone can give better results. But as fitness value increases and reaches near one, the fitness of all strings is almost equal and the effect of crossover is minimum or insignificant in the particular population. Hence by increasing the mutation rate of the chromosomes inculcates new characteristics in the existing population and therefore diversifies the population. The flowchart of RCGA with Fuzzy system (RCGAF) is given in Figure 2.

a. Chromosome structure and fitness function evaluation

Here the chromosomes are consisting of gains (K) and the range of PFC controller and modeled as genes of RCGAF.

The goal is to minimize the deviation and oscillation in the frequency as area control error (ACE). An optional penalty term is added in objective function of RCGAF to take care of settling time and oscillation. The objective function for single area system is given by:

$$F = \int_{0}^{Tsim} |\Delta\omega| dt + P$$

Where P is optional penalty and it is

P=α*Ts

Where

α = Penalty factor

Ts = Settling time

and the objective function for two area system, F is

$$F = \int_0^t |\Delta\omega_1| dt + \int_0^t |\Delta\omega_2| dt + \int_0^t |\Delta P_{ti12}| dt + P$$

RCGAF is used to maximize the fitness function, which is a measure of quality of each candidate solution. Then the fitness function is calculated as

$$\text{Fitness function} = \frac{1}{(1+F)}$$

The normalize range of fitness function is between 0 and 1. The fitness function value depends on the controller performance. Hence, the PFC parameters changed through RCGAF to obtain the optimal performance and finally increase the fitness function value of RCGAF.

b. Initial Population

Chromosomes of RCGAF contains range of input membership and gain of PFC, which are basically affect the behavior of PFC. To get optimal performance of PFC it is necessary to optimize the range of input membership and gain of PFC. Hence, the chromosome may be written as follows

Chromosome = [xlxuk]

Where

xl– lower value of range

xu – Upper value of range

k – PFC gain

The upper and lower limits of these PFC parameters are given in Table 2.

TABLE 2

UPPER AND LOWER LIMITS OF PFC PARAMETERS

	Parameters	**Lower Limit**	**Upper Limit**
Range of Input membership	Lower Range x_l	-5	0
	Upper Range x_u	0	11
Gain	PFC gain k	0.1	8

The initial population is randomly generated using MATLAB in the specified interval (0, 1) and then converted in the upper and lower limits as mentioned in Table 2.

c. Reproduction or selection operator

The main aim of reproduction operator is to make duplicates of good solutions and eliminate bad solution in a population, while keeping the population size constant.

There are number of ways to achieve the above tasks. Some common methods are roulette wheel selection, tournament selection, proportionate selection and ranking selection [8]. In the RCGAF tournament selection operator has been used.

d. Crossover operator

The crossover operator is not usually applied to all pairs of chromosomes in the intermediate population to get better population in next generation. A random choice is made, where the likelihood of crossover being applied depends on probability defined as the crossover probability, Pc. The crossover operator plays a central role in RCGAF. It is one of the important factors which improve the RCGAF behavior [11]. Here the optimized value of crossover probability is found with the help of fuzzy logic using FAM Table 3. The value of Pc is changed based on highest fitness value (HF), number of iterations in which there is no significant change in fitness, (NCF) and variance (VAR) of fitness of individuals in a population. In this simple one point crossover, the crossover point is randomly chosen.

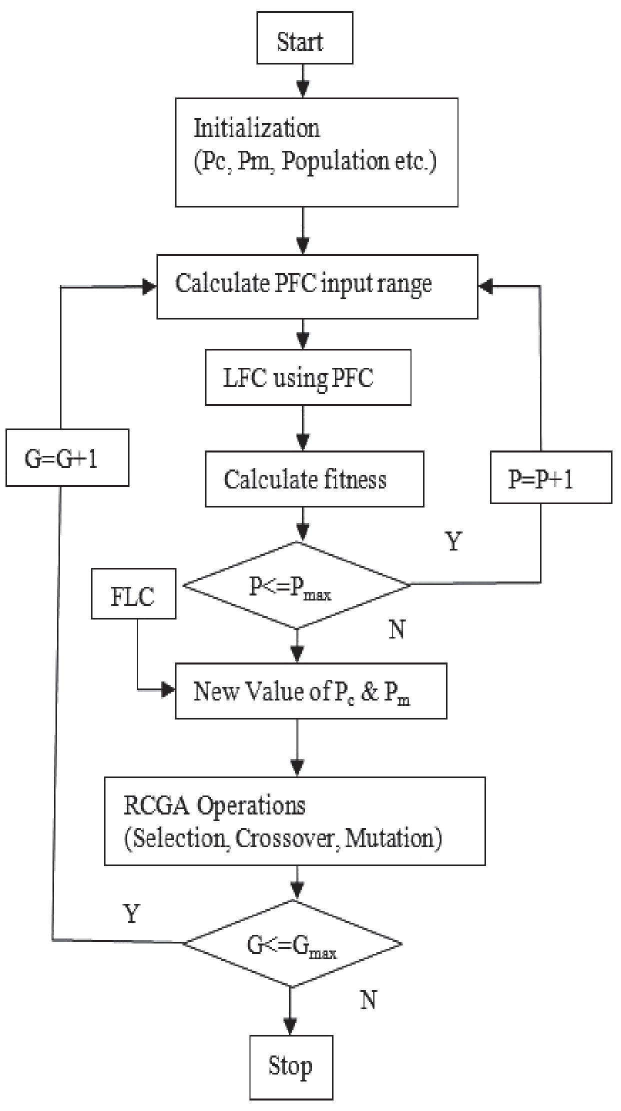


FIG. 2 FLOW CHART OF ADAPTIVE PFC USING RCGAF

e. Mutation Operator

In RCGAF random mutation operator is used.

Let us suppose $C = (c_1, \ldots \ldots, c_i, \ldots \ldots, c_n)$ a chromosome and $c_i \in [a_i, b_i]$ a gene to be mutated. Next, the gene,c_inew, resulting from the application random mutation operator is shown. c_inew is a random number from domain $[a_i, b_i]$.

Each selected bit of a chromosome in the population undergoes a random change according to a probability defined by a mutation rate, the mutation probability, Pm. Here also the optimized value of mutation probability Pm is found with the help of fuzzy logic using FAM Table 4.

TABLE 3

FAM TABLES FOR CONTROLLING PC

NCF HF	L	M	H
L	H	H	H
M	H	M	
H	H	M	

VAR NCF	L	M	H
H	L	L	M

TABLE 4

FAM TABLE FOR CONTROLLING PM

NCF HF	L	M	H
L	L	L	L
M	L	M	
H	L	M	

VAR NCF	L	M	H
H	L	L	M

5.0 APPLICATION OF ADAPTIVE POLAR FUZZY LOGIC CONTROLLER FOR LOAD FREQUENCY CONTROL

a. Single area Thermal system with backlash system

The adaptive PFC with RCGAF is used for controlling the single area as shown in Figure 3. From the simulation results it is found that adaptive polar fuzzy controller with RCGAF settled the frequency deviation in much lesser time than fix rule polar fuzzy controller. These results are shown in Figures 4(a-i). For adaptive PFC with RCGAF approach the variations of maximum fitness and average fitness value per generation are shown in Figures 4(c-d). In RCGAF approach, Pc and Pm are dynamically changed during execution and governed by fuzzy rules as shown in Figure 4(e-f) and variations of different parameters of PFC during execution are shown from Figures 4(g-i).

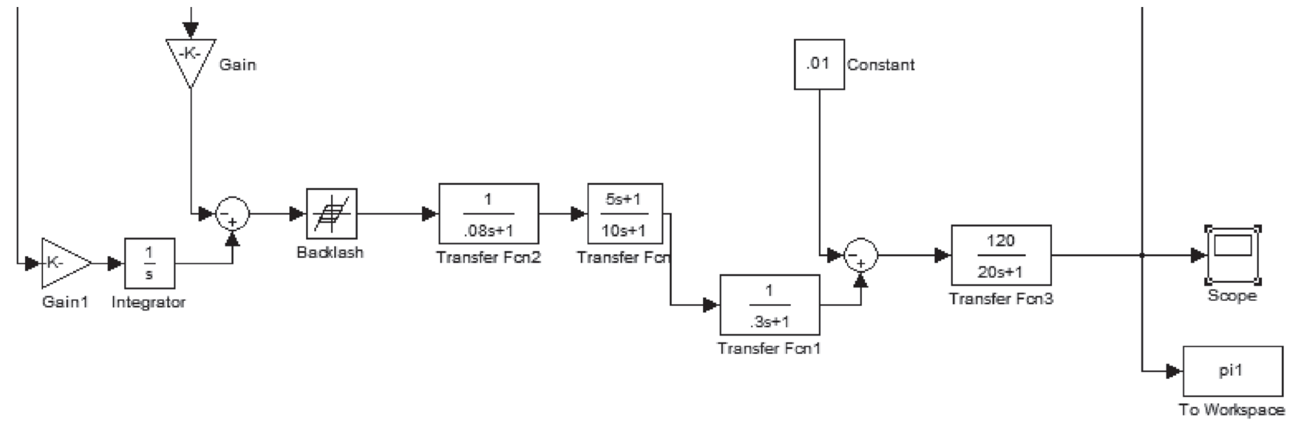
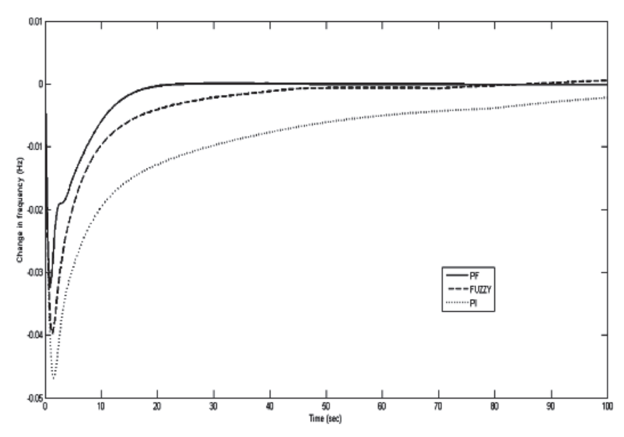
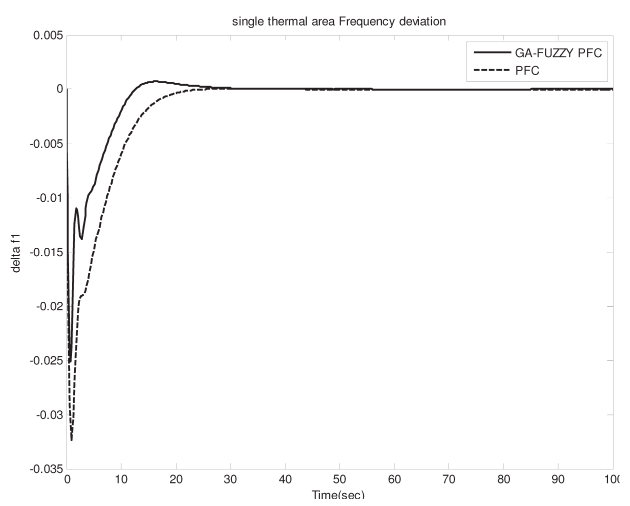


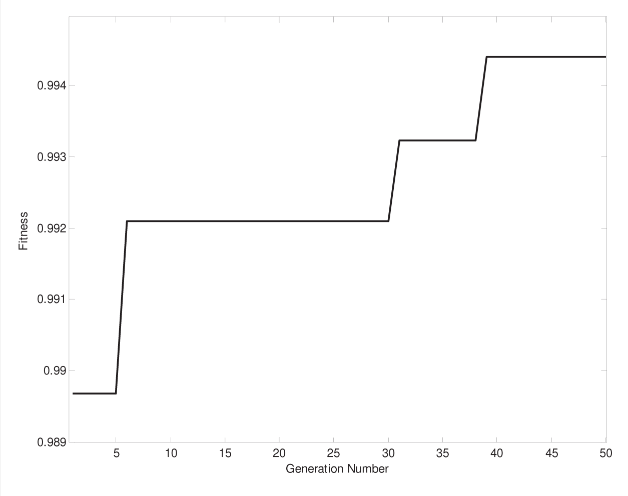
FIG. 3 SINGLE AREA THERMAL SYSTEM WITH BACKLASH NON-LINEARITY



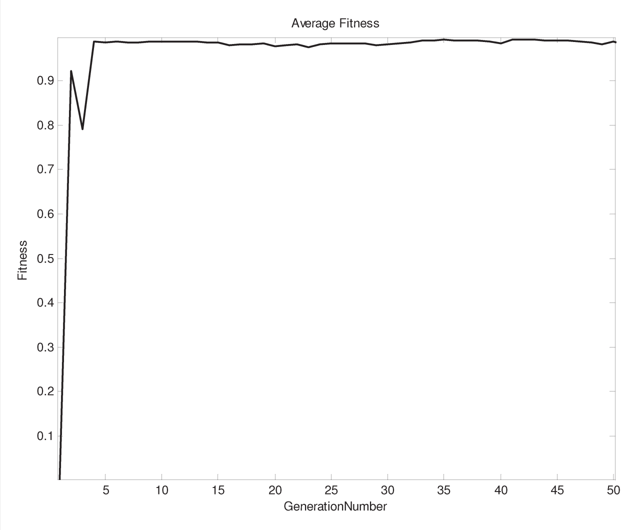
(A) PERFORMANCE OF DIFFERENT CONTROLLERS



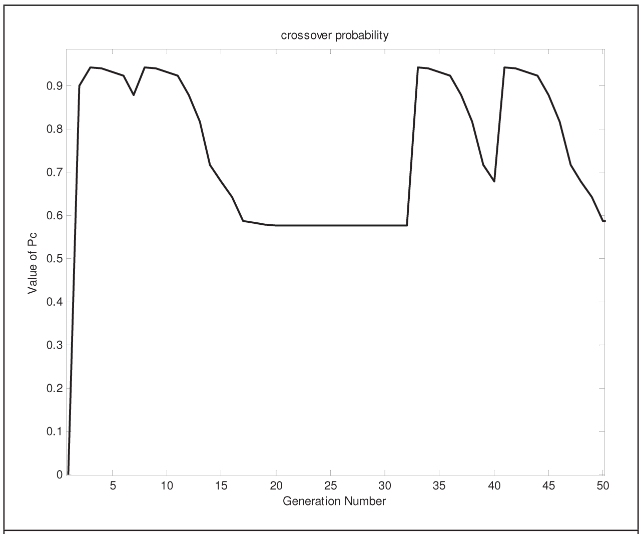
(B) RESPONSE OF PFC WITH RCGAF AND PFC WHEN 1% DISTURBANCE IS APPLIED IN SINGLE AREA SYSTEM WITH BACKLASH NONLINEARITY



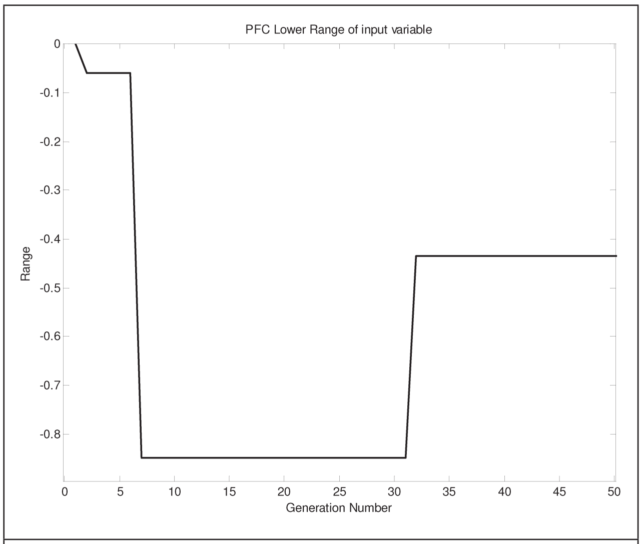
(C) MAX FITNESS IN EACH GENERATION



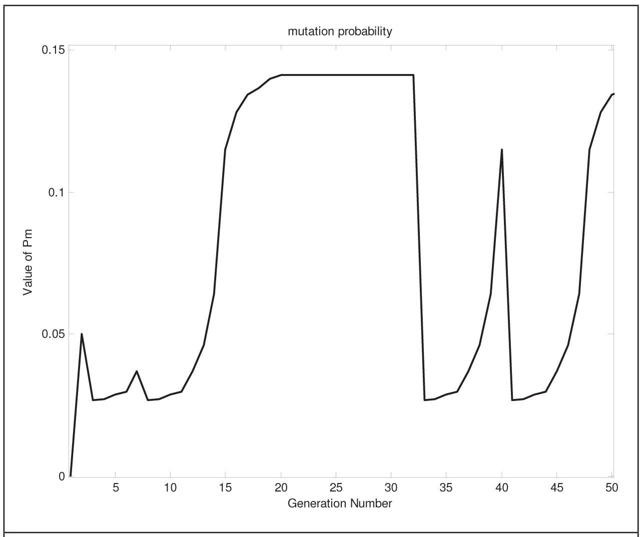
(D) AVERAGE FITNESS IN EACH GENERATION



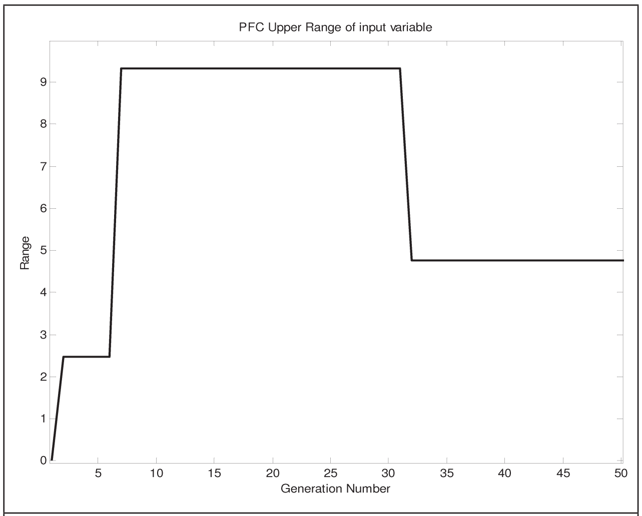
(E) CROSSOVER PROBABILITY VARIATION IN EACH GENERATION



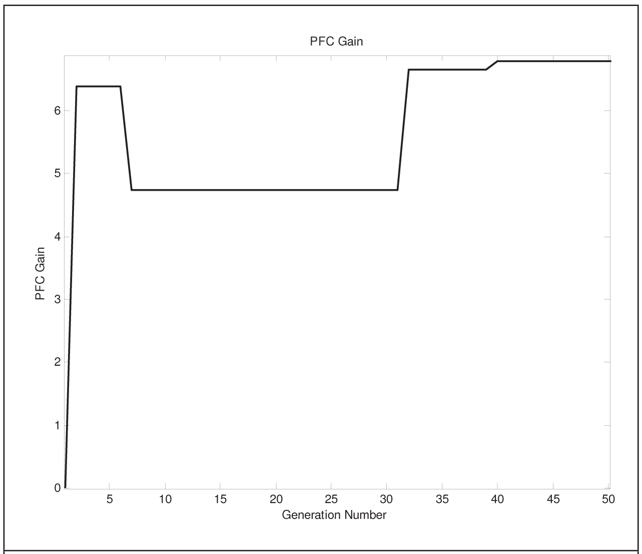
(H) PFC LOWER RANGE FOR INPUT MEMBERSHIP FUNCTION



(F) MUTATION PROBABILITY IN EACH GENERATION



(I) PFC UPPER RANGE FOR INPUT MEMBERSHIP FUNCTION



(G) PFC GAIN IN EACH GENERATION

FIG. 4 SINGLE AREA THERMAL SYSTEM WITH BACKLASH NONLINEARITY WHEN 1% DISTURBANCE IN SYSTEM

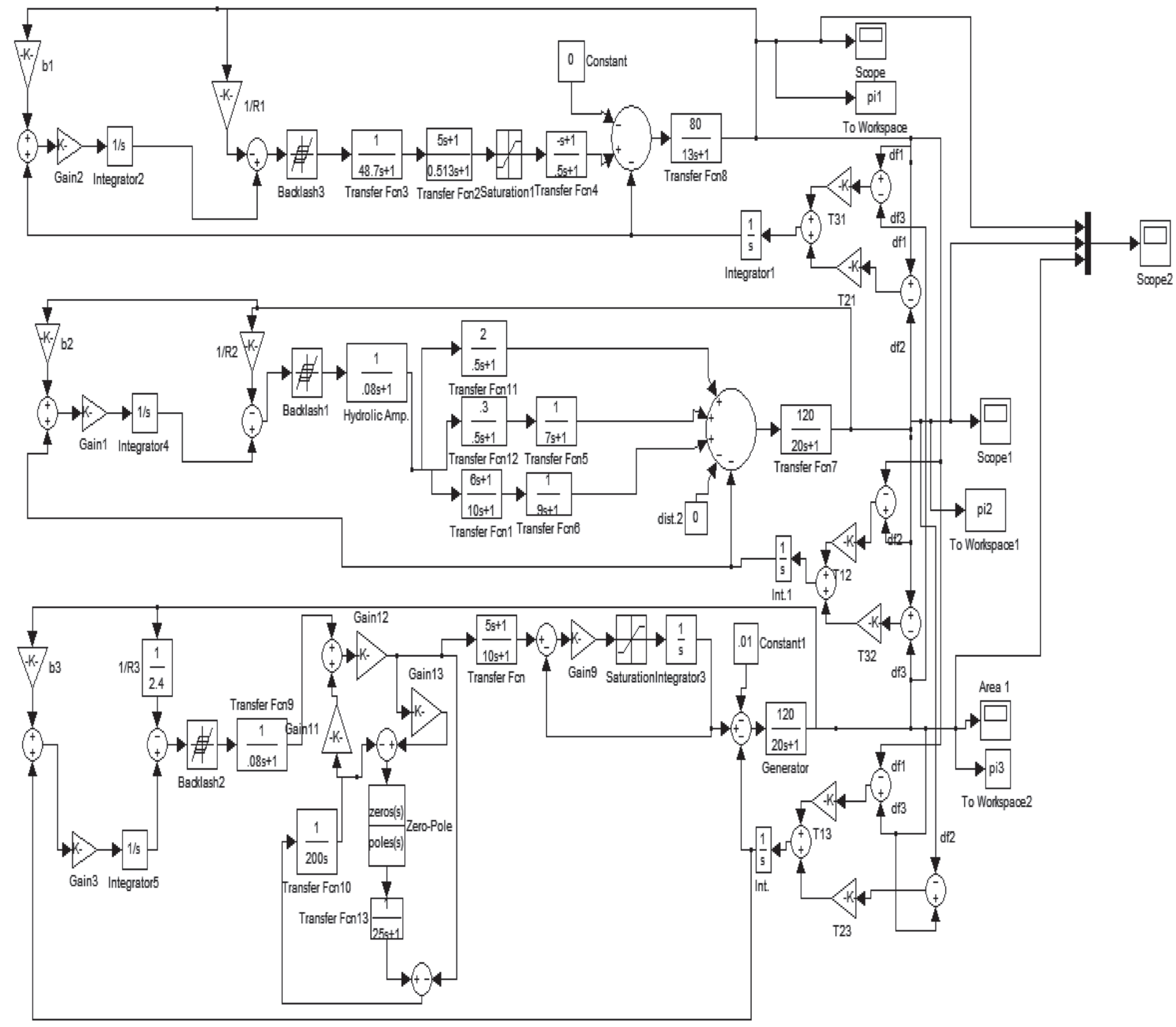
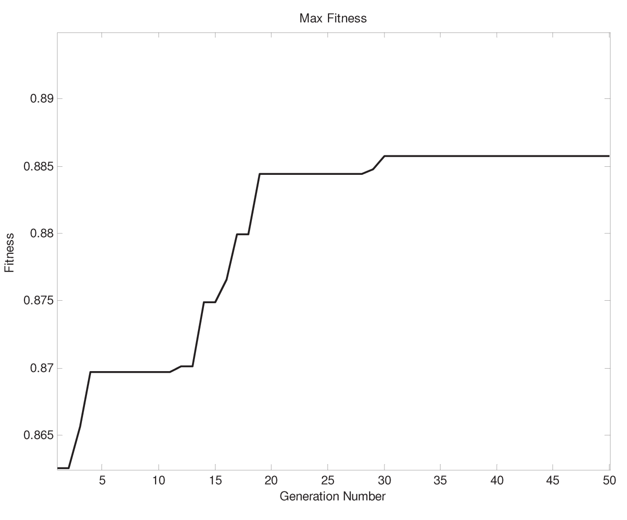


FIG. 5 SIMULATION MODEL OF A THREE AREA HYDRO-NUCLEAR-THERMAL SYSTEM WITHOUT NONLINEARITIES AND WITH PI CONTROLLER

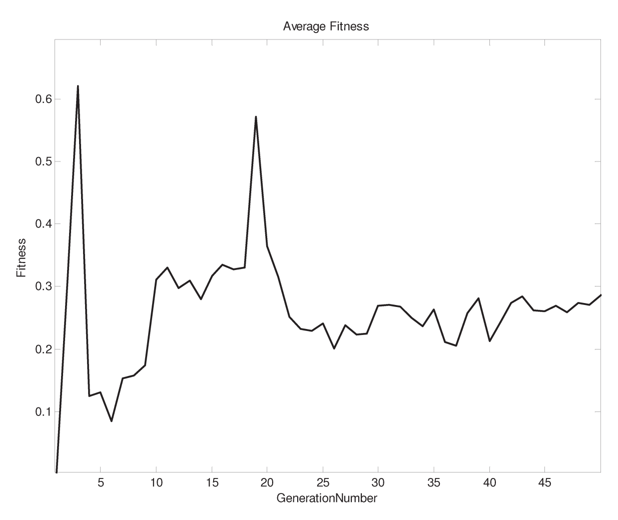
b. A three area hydro-nuclear-thermal system with nonlinearity when disturbance in both thermal and nuclear area

In three area system as shown in Figure 5 is consisting of hydro system as area 1 and nuclear system as area 2 and thermal system as area 3. This three area system is simulated for 1% disturbance in thermal system. This three area system is modeled with different nonlinearities such as GRC and backlash and boiler dynamics.

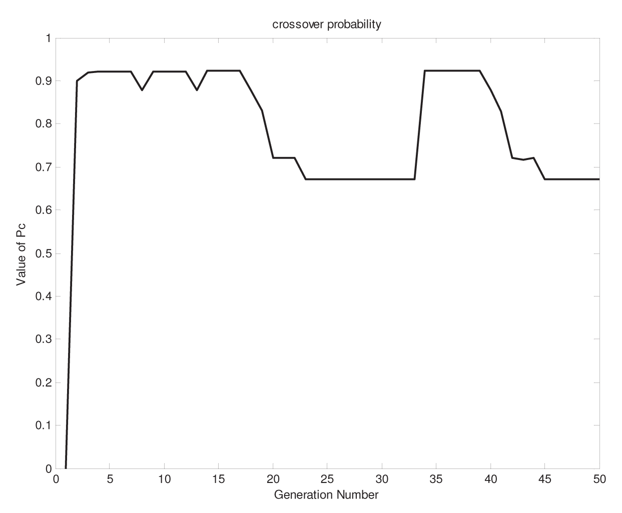
Adaptive PFC with RCGAF approach is used to control when 1% disturbance is applied in the thermal area. The results of PFC with RCGAF controller performance are shown in Figures 6 (a-j). During execution dynamically changed values of Pc and Pm are governed by fuzzy rules as shown in Figures 6(c-d) and variations of different parameters of PFC during execution are shown from Figures 6(e-g).



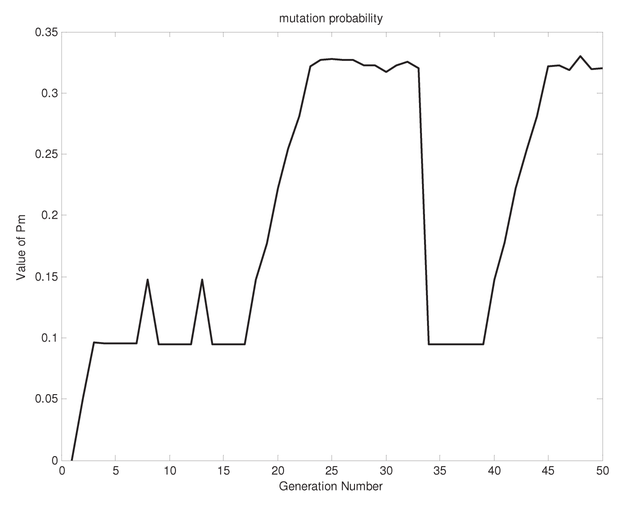
(A) MAX FITNESS IN EACH GENERATION



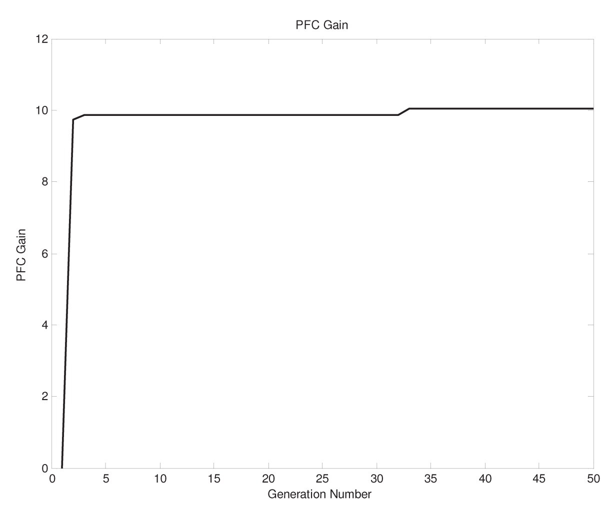
(B) AVERAGE FITNESS IN EACH GENERATION



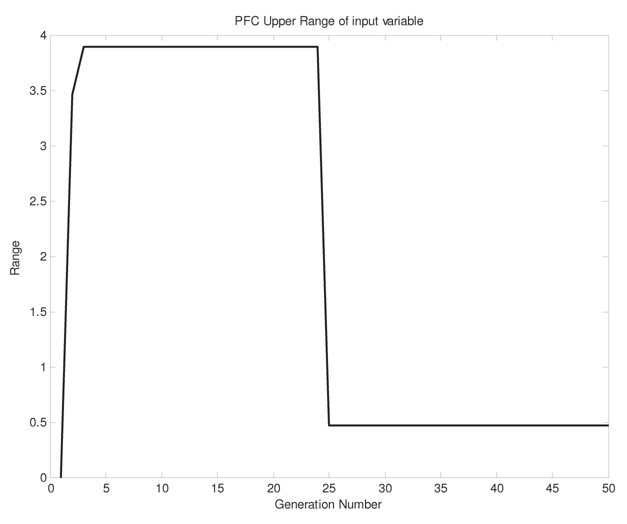
(C) CROSSOVER PROBABILITY IN EACH GENERATION



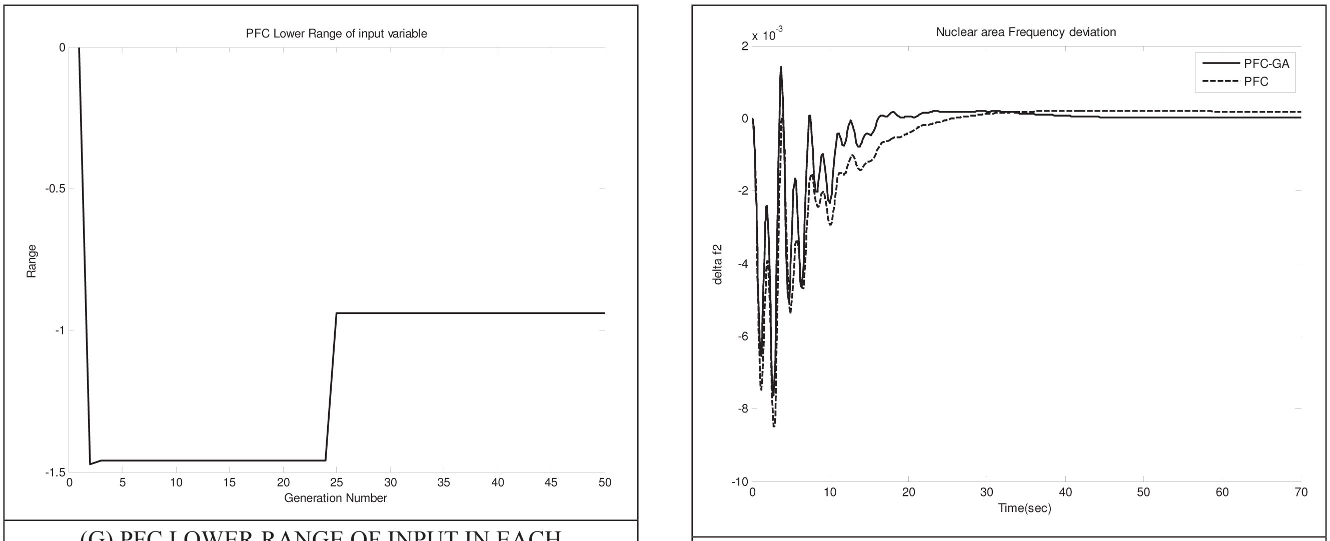
(D) MUTATION PROBABILITY IN EACH GENERATION



(E) PFC GAIN IN EACH GENERATION

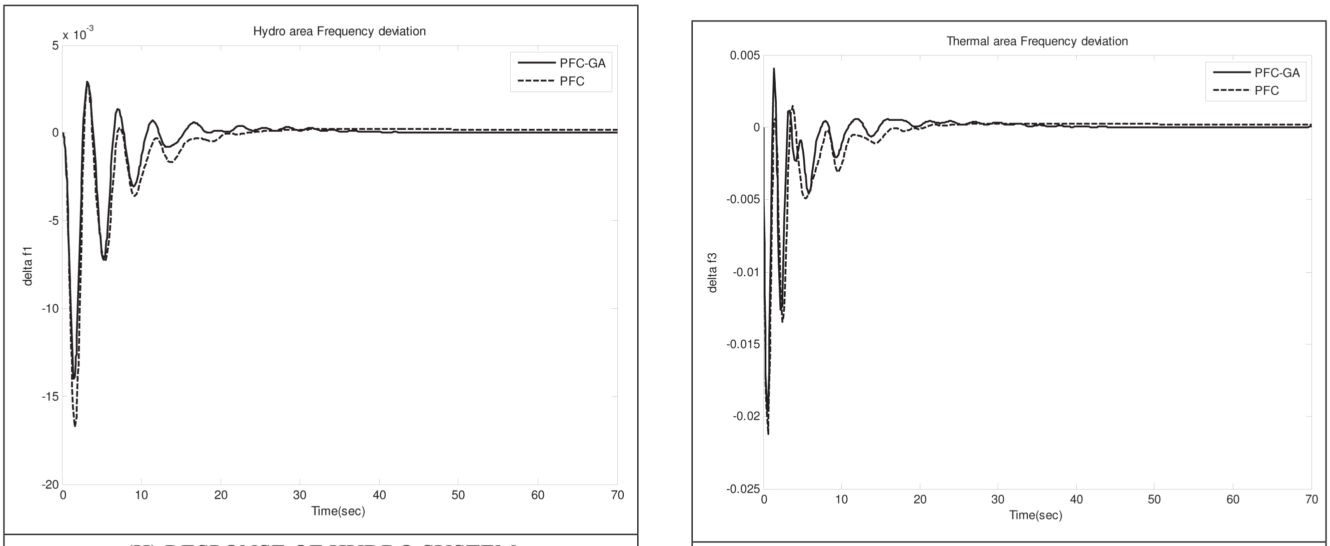


(F) PFC UPPER RANGE OF INPUT IN EACH GENERATION



(G) PFC LOWER RANGE OF INPUT IN EACH GENERATION

(I) RESPONSE OF NUCLEAR SYSTEM



(H) RESPONSE OF HYDRO SYSTEM

(J) RESPONSE OF THERMAL SYSTEM

FIG. 6 RESULTS OF A THREE AREA SYSTEM WITH NONLINEARITIES WITH 1% DISTURBANCE IN THERMAL AREA

5.0 CONCLUSIONS

In this paper, LFC of three area systems using conventional PI, FLC PFC and Adaptive PFC with RCGAF controllers have been developed and simulated for disturbances in different areas. The performance of all these controllers has been compared. It is found that adaptive polar fuzzy controller using RCGAF gave good performance in terms of settling time, less frequency dip, and minimum oscillations.

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APPENDIX

TABLE A1 FAM TABLE FOR FUZZY LOGIC CONTROLLER FOR LFC

		ACE						
Error		nb	nm	ns	z	ps	pm	pb
	nb	pb	pb	pm	pm	ps	ps	z
	nm	pb	pb	pm	pm	ps	z	z
	ns	pb	pm	pm	pm	z	ns	ns
	z	pb	pm	pm	z	ns	nm	nb
	ps	pm	pm	ns	ns	nm	nb	nb
	pm	ps	ps	ns	nm	nb	nm	nb
	pb	ns	ns	nm	nm	nm	nm	nb

TABLE A2 INITIAL PARAMETERS OF RCGAF

Crossover Probability (Pc)	=	0.9
Mutation Probability (Pm)	=	0.05
Length of chromosome	=	3
Number of Generations	=	50
Population Size	=	300