Journal of Engineering Sciences
Vol 11, Issue 10,OCT /2020
ISSN NO:0377-9254

Fuzzy Logic Controller Based automatic generation control of a multi-area ST – Thermal power system using Grey Wolf Optimizer algorithm.

K.Swetha[1] G.Chandralekha[2]
[1] Assistant Professor of Electrical and Electronics Engineering, S.R.K.R Engineering College, Bhimavaram.
[2] M.Tech Student, Electrical and Electronics Engineering, S.R.K.R Engineering College, Bhimavaram.

Abstract:
This paper present automatic generation control (AGC) of a three area thermal system incorporating solar thermal power plant (STPP) in one of the area by using Fuzzy logic controller.. Single reheat turbine and appropriate generation rate constraints is provided in the conventional thermal system. The performances of integral (I), proportional plus integral (PI), and proportional plus integral plus derivative (PID) controller are evaluated in the system with and without incorporating STPP along with fuzzy logic controller. A new computational evolutionary technique called grey wolf optimizer algorithm (GWO) is used for the optimization of secondary controller gains for first time in AGC. Investigations reveal that GWO optimized Fuzzy controller's performance is better than others in terms of settling time, peak overshoot and magnitude of oscillations in the system with or without STPP. Sensitivity analysis reveals that that GWO optimized PID controller gains obtained in nominal conditions and parameters are healthy and not necessary to reset for large change in system conditions and parameters. This paper implemented in MATLAB/SIMULINK software in windows environement.

Introduction:

It is necessary to maintain system frequency and tie line power at their schedule values for efficient and reliable operation of the power system. The system frequency and tie line power exchange deviates due change in load and other abnormal conditions. These deviations must be zero automatically. Automatic generation control (AGC) maintain the system frequency and tie line power exchange at their nominal values and to keep the generation of each unit at their economic value. Many investigations on AGC of interconnected systems are available in literature [1–3]. Sahu et al. [1] have presented the AGC study in a two area thermal system. Their work is limited to two area system without generation rate constraints (GRC). GRC imposes practical limits on the rate of change in power generation. Saikia et al. [2] have studied various multi-area systems such as two area, three area, and five area system. They have considered thermal system with GRC but only thermal generation is considered in their work. AGC of two and three area thermal system have been taken for investigations by Shabani et al. [3]. All the above studies [1–3] mainly focus on the AGC of the conventional generation (thermal generation). However, no attention has been paid for a system having non conventional energy sources. Due to carbon emission issues and rapidly decreasing conventional energy resources, there is a need to find some alternative sources so that future energy demands can be met. Solar energy and wind energy sources are such alternatives. Solar energy has large potential and according to recent studies, it has potential to be energy source of future. The basic concepts of modeling and integration of renewable energy sources in power system have been presented in literature [4–9]. Asano et al. [4] have introduced the concepts of integrating the photovoltaic system in AGC. They have developed the mathematical model of photovoltaic (PV) system to analyze its impact on AGC. But their study is limited to rooftop PV generating stations only. Kumar et al. [5] have studied the AGC for a distributed generation system. They have considered a micro grid having many generating sources. Bevrani et al. [6,7] have introduced new area control error (ACE) concept of AGC with renewable energy sources. They have included the deviation in power generated from non conventional energy sources. But the investigations are limited to PV systems only. Concentrated solar power has the ability to store energy in form of thermal energy. The stored thermal energy can be utilized to produce electricity in absence of solar irradiance. Wang et al. [8] have introduced the concept of solar concentrated grid connected ocean thermal energy conversion system. The same concept is not applied for AGC problem of interconnected power systems. Though, Das et al. [9] have introduced the concept of integration of solar thermal power plant (STPP) for AGC study, however, their study is restricted to an isolated system only and they have not applied any control strategy for STPP. The solar energy is a clean energy available in abundant. Conversion of solar energy into electric energy does not emit green house gases. Also the use of this nonconventional energy reduces the consumption of conventional sources of energy. Till now, no study on AGC in multi area system incorporating STPP is available in the literature. Hence, AGC of multi-area system incorporating solar thermal power plant (STPP) is important for further studies.

The AGC has two control modes. The primary control which is very fast and the slow secondary control. Governors are responsible for primary control. For secondary control, controllers are needed. Now a days, almost all research on AGC is centred on the design of secondary controllers [1–3,10–16]. The system considered in these literatures is either multi area thermal system or hydrothermal system. The considered system in these literatures does not incorporate any nonconventional energy sources. Conventional classical controllers such as Integral (I), proportional-integral (PI), proportional-integral-derivative (PID) and two degree of freedom PID controllers are used as secondary controllers in the above literature. However, performance of such types of controllers is not evaluated in multi area system including non conventional power plant such as STPP. Hence it is necessary to study the performance of above controllers in a system where STPP is included while used for optimization provides suboptimal result in most of the cases [2]. To obtain the better optimum values, GA [13] has been used for simultaneous optimization of controller gains and other parameters. However, there are some deficiencies of GA performance which are identified in [14]. The advantages of Particle Swarm Optimization (PSO) are depicted in [13]. Like GA, PSO [13] is susceptible to getting trapped in local optimum. These difficulties are overcome in Bacterial Foraging (BF) technique. The BF technique is successfully applied in AGC for optimization of variables [2]. Authors in reference [14], shows that the tuning performance of ABC algorithm is better than PSO algorithm. A new algorithm known as ‘‘Firefly Algorithm’’ (FA) is available and successfully applied in AGC by Saikia et al. [15]. A metaheuristic algorithm called Cuckoo Search (CS) is also successfully applied by Dash et al. [16] in AGC. Recently, another meta heuristic algorithm called Grey Wolf Optimizer (GWO) developed by Mirjalili et al. [17] is available and inspired by hunting mechanism and democratic behaviour of grey wolves pack in the wild [17]. The authors [18] have shown the advantages of GWO over differential evolution (DE), PSO, and ABC algorithm. The GWO is powerful in terms of exploration, exploitation, local optima avoidance, and convergence which motivate the authors to use this algorithm for optimization. Also, it is seen that the same is not applied in AGC for optimization of variables. This requires extensive investigations. But its ability is still somewhat dependent or limited on some of the mechanisms in the balance between exploration and exploitation. Recently the improved version of GWO (IGWO) is introduced by Muangkote et al. [19]. Like GWO, IGWO recently some new algorithms such as Ant Lion Optimizer (ALO), Multi Verse Optimizer (MVO) are proposed by authors in [20] and [21]. Like GWO, IGWO, ALO, and MVO not applied for optimization in AGC studies. Since, this paper mainly focuses on application of GWO optimized controllers, ALO and MVO will be taken for future work. The operating conditions of a power system are not constant always. So, it is necessary to the controller to work properly in varying conditions. For this, controller performance is analyzed at changed system parameters and changed system loading conditions. Sensitivity analysis is an indication of the healthiness of the optimum values of controller gains obtained at nominal conditions [2,15,16]. It is observed that sensitivity analysis is done for a controller in almost all literatures in a system either thermal or hydrothermal system. However, such observation is not done for GWO optimized secondary controllers used in a system incorporating STPP. This requires further study. Thus, the following are the main objective of present work:

(a) Modelling and integration of solar thermal power plant in unequal three area thermal system for AGC.

(b) Application of GWO algorithm for the optimization of controller gains in a three unequal area system.

(c) Comparison of dynamic responses of different conventional controllers such as I, PI and PID in presence and absence of solar thermal power plant to find the best one in each case,

(d) Sensitivity analysis of optimum gains of best controller obtained at nominal system conditions in presence of solar thermal power plant.

The system Considered:

The considered system is a three unequal area thermal system having solar thermal power plant. The capacity ratio of the areas is area1:area2:area3 is 1:2:4. The area1 comprise of solar thermal power plant (STPP) and thermal. The area2 and area3 are thermal systems. Thermal systems are considered with generation rate constraints (GRC) of 3%/minute. The nominal parameters for thermal systems are taken from [2] and for solar thermal power plant from [8] and [9]. Several classical controllers such as I, PI and PID are considered for secondary controllers. The system dynamics are obtained considering 1% step load perturbation (SLP) in area-1. The transfer function model of the system is shown in Fig. 1. The controller gains and other parameters are optimized using GWO technique. The cost function used in this optimization is integral squared error (ISE) given by Eq. (1).

$$J = \int_0^t \left\{(\Delta f_i)^2 + \left(\Delta P_{tiei-j}\right)^2\right\} dt \quad (1)$$

Where i,j=area number, for I=1,2,3 and j=2,3($j \not\approx i$)

Solar energy has large potential. Photovoltaic (PV) system and concentrated solar power (CSP) are the systems which can produce power from solar energy. CSP is growing rapidly throughout the world. CSP system has a large area of collector field. Reddy et al. [22] have made a comparative study of solar thermal power plants with many numbers of collectors like flat plate collector, dish sterling engine, parabolic trough collector. The main function of these collectors is to focus the solar irradiance to the pipes carrying working fluids such as water or molten salt. This hot working fluid is used to produce steam in heat exchangers. Valenzuela et al. [23] have proposed a method of direct steam generation in solar boilers. This steam is used to drive a turbine. The changing weather and alteration of day and night enforced us to incorporate heat storage technology to supply energy continuously. Fontalvo et al. [24] have proposed hybrid solar-fossil fuel power plants. They have also

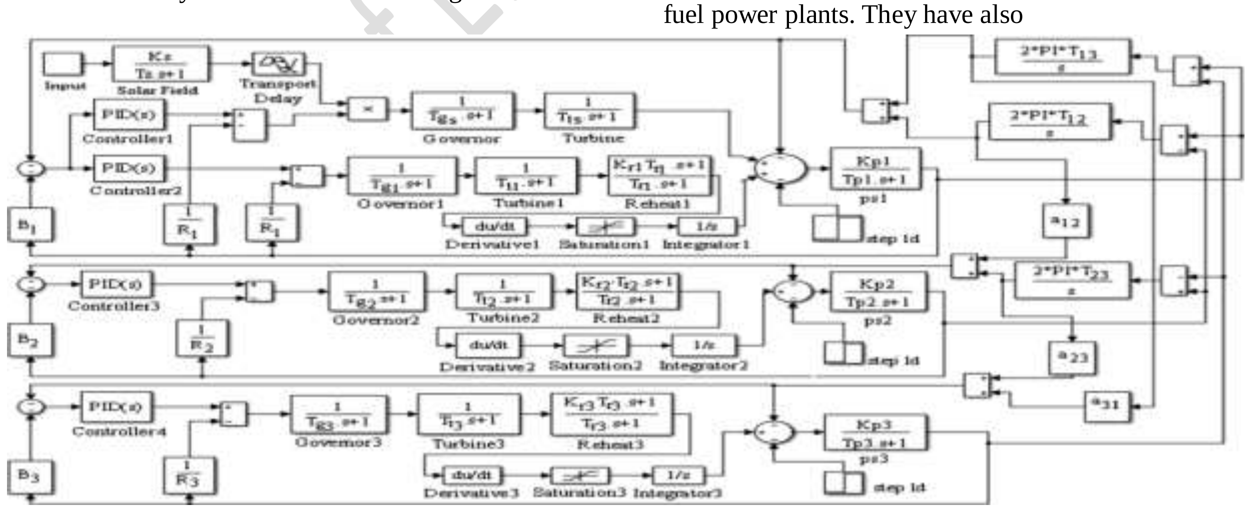

Fig. 1. Transfer function model of conventional topology for a three area system incorporating solar thermal power plant in area-1 of classical controllers.

proposed the automatic controlling of hybrid power plant. Molten salt, high temperature oil and water are three storage mediums. This technology enables us to supply constant power output during the fluctuations in solar intensity. For modelling of solar thermal power plant, first the need is to model solar field. Buzás et al. [25] have proposed the modelling of the same. The rate of change of output temperature is given by Eq. (2).

$$\frac{dT_0(t)}{dt} = \frac{A\eta_0}{C} I(t) - \frac{U_L A}{C}[T_a(t) - T_e(t)] + \frac{v(t)}{V}[T_a(t) - T_e(t)] \qquad (2)$$

Where $T_a(t) = \frac{T_i(t)+T_0(t)}{2}$

It has been assumed the constant flow rate V(t) of working fluid [22]. Hence Eq. (2) becomes Eq. (3)

$$\frac{dT_0(t)}{dt} + \frac{v}{V} + \frac{U_L A}{2C} T_0(t) = \frac{A\eta_0}{C} I(t) + \left[\frac{v}{V} - \frac{U_L A}{2C}\right] T_i(t) + \frac{U_L A}{C} T_e(t) \qquad (3)$$

The Laplace transformation of Eq. (3) is given by Eq. (4).

$$T_0(s) = \frac{T_s}{T_s s+1}\frac{A\eta_0}{C} I(s) + \frac{T_s}{T_s s+1}\left[\frac{v}{V} - \frac{U_L A}{2C}\right] T_i(s) + \frac{T_s}{T_s s+1} * \frac{U_L A}{C} T_e(s) \qquad (4)$$

where Ts is the time constant of solar collector and it is given by Eq. (5)

$$T_s = 1/\frac{U_L A}{2C} + \frac{v}{V} \qquad (5)$$

The change in inlet and environment temperature are very small, hence transfer function of solar field with respect to solar irradiance is given by Eq. (6).

$$G(s) = \frac{K_s}{1+T_s S} \qquad (6)$$

Where Ks is the gain of solar field. Thus the steam will be produced in heat exchangers and it drives the turbine. One second delay is also considered for the various processes of solar thermal power plant

3. Grey Wolf Optimizer (GWO) algorithm

This algorithm is developed by Mirjalili and Mirjalili [17]. This algorithm reflects the behavior of grey wolf in searching and hunting of their prey [17]. Grey wolf belongs to Canidae family and are predators. Grey wolves prefer to live in a group size of 5–12 members on average. Group is called pack. They have very strict social dominant hierarchy. The leaders of pack are a male and a female. There are four categories in a pack, alpha(a), beta(b), delta(d) and omega(x). Alpha is the first level and is mostly responsible for making decisions. The decisions of alpha are dictated to the pack. Alpha is not necessarily the strongest member of the pack but the best in terms of managing the group. behaviour of the pack shows that organization and discipline of a group are important than its strength. The second level is beta. Beta is the second level of wolf and they help the alpha in decision making or in other activities. The beta wolf can be either male or female. Beta can take charge of the pack in absence of the alpha. Beta wolf reinforces the alpha's command throughout the pack and gives feedback to the alpha. Third level in ranking is delta. Delta is the third level and this level includes scouts, sentinels, hunters, and caretakers. Scouts are responsible for watching the boundaries of territory. They issue warning to the pack in case of any danger. Sentinels are responsible for safety of the pack. Hunters help the alphas and betas when hunting the prey. The lowest ranking of the pack is omega. Omega wolves have to submit to all the dominant wolves. They are last wolves that are allowed to eat. The main phases of grey wolf hunting are (1) Tracking, encircling the prey, (2) Attack toward the prey. The encircling property of prey can be represented by Eq. (7)

$$\vec{D} = \left|\vec{C}\overrightarrow{X_p}(t) - \vec{X}\right| \qquad (7)$$

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A}.\vec{D} \qquad (8)$$

$$\vec{A} = 2\overrightarrow{ar_1} - \vec{A}$$

$$\vec{A} = 2\overrightarrow{r_2}$$

Where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\overrightarrow{X_p}$ is the position vectors of prey, and $\vec{X}$ indicates the position vector of a grey wolf. Where components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and r1, r2 are

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ISSN NO:0377-9254

random vectors in [0,1]. The hunting property of alpha, beta and delta are given by (9–11).

$$\overrightarrow{D_\alpha} = |\overrightarrow{C_1}\,\overrightarrow{X_\alpha}(t) - \vec{X}| \qquad (9)$$

$$\overrightarrow{D_\beta} = |\overrightarrow{C_2}\,\overrightarrow{X_\beta}(t) - \vec{X}| \qquad (10)$$

$$\overrightarrow{D_\delta} = |\overrightarrow{C_3}\,\overrightarrow{X_\delta}(t) - \vec{X}| \qquad (11)$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1}.\overrightarrow{D_\alpha}$$

$$\overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2}.\overrightarrow{D_\beta}$$

$$\overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3}.\overrightarrow{D_\delta} \qquad (12)$$

In this way the positions of alphas, betas and deltas are updated and it has been assumed that alpha is the best solution. The pseudo code of GWO algorithm is given below.

begin
Objective function f(x), x = (x_1, . . ., x_d)T;
Initial a population of n grey wolf xi (i = 1, 2, . . ., n);
Initialize a, A and C
Calculate fitness of each search agent
x_α best search agent, x_β second best search agent,
x_δ third best search agent
while (t < MaxGeneration) or (stop criterion);
for each search agent
update the position of current search agent by Eq. (12);
end for
update a, A and C
calculate the fitness of all search agents;
update x_α, x_β, x_δ
t = t + 1;
end while
Return x_α
end

The tuned values of parameters used in this optimization are number of search agent, n = 5, maximum iterations = 100.

.FUZZY LOGIC CONTROLLER:

Fuzzy logic is a basic control system that relies on the degrees of state of the input and the output depends on the state of the input and rate of change of this state. Fuzzy logic works on the concept of deciding the output based on assumptions. It works based on sets. Each set represents some linguistic variables defining the possible state of the output. Each possible state of the input and the degrees of change of the state are a part of the set, depending upon which the output is predicted. It works on the principle of If-else-the, i.e. If A AND B Then Z.

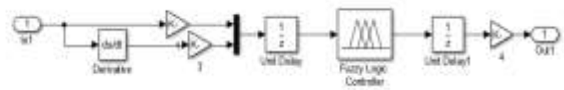

Fig.2 shows the topology of the Fuzzy Logic Controller

It takes input variables in the form of membership functions. Membership functions can be of various types like triangular, Gaussian, trapezoidal, etc. Here, a triangular membership function is used. Every input variable is assigned with a specific number of membership functions that contain values of certain limits. These values are assigned with some linguistic terms . This step is known as fuzzification. After fuzzification there comes the rule base of the fuzzy logic controller. In the rule base, rules are assigned formulated on the knowledge of the system. Outputs are also given linguistic terms and input variable mapping is done to assign a particular output linguistic variable following the given matching of input linguistic variables. The full rule base considered in the system is mentioned in the following section. In the final step that is defuzzification, the output linguistic variables are changed to corresponding numbers which decide the controlling action accordingly

Generally, the variables of the set are the state of the inputs and the degrees of changes of the input and the membership of the output depends on the logic of AND operation of the state of the input and the rate of change of the input. For a multi-input system, the variables can also be the different inputs and the output can be the possible result of the AND operation between the variables. It calculates the error accurately. So, response of reaction is makes quick. Hence overall efficiency of the system improves.

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Vol 11, Issue 10,OCT /2020
ISSN NO:0377-9254

COMPARISION RESULTS:

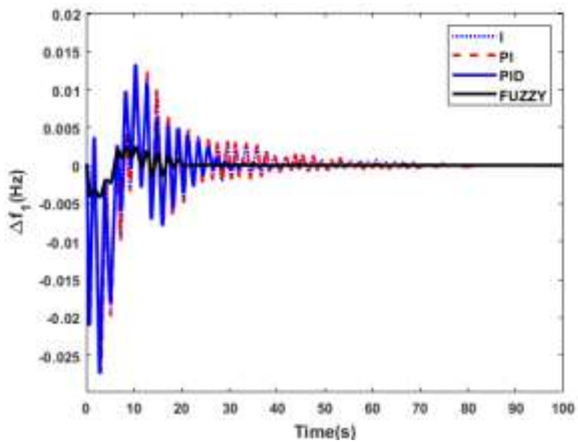

Fig. 3.a)

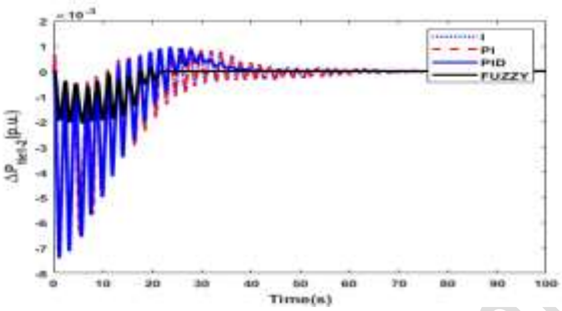

Fig. 3. b)

Fig. 3. Comparison of the dynamic responses of the system for I, PI, PID and Fuzzy controllers. (a) Deviation in frequency in area-1 vs. time, (b) deviation in tie line power connecting area-1 and area-2 vs. time.

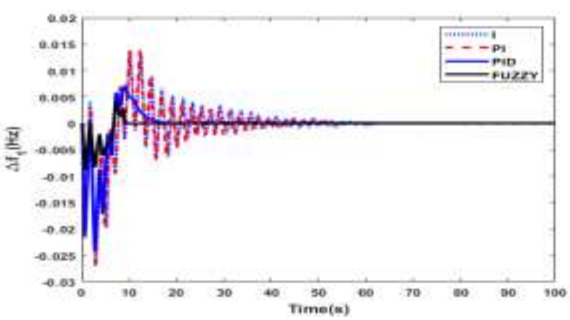

Fig. 4 a)

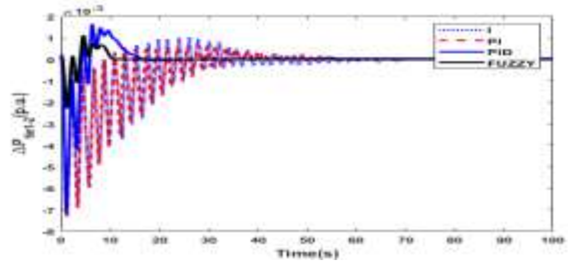

Fig. 4 b)

Fig. 4. Comparison of the dynamic responses vs. time for I, PI, PID and fuzzy controllers of the system with solar thermal power plant in area-1. (a) Deviation in frequency area-1, and (b) deviation in tie line power connecting area-1 and area-2.

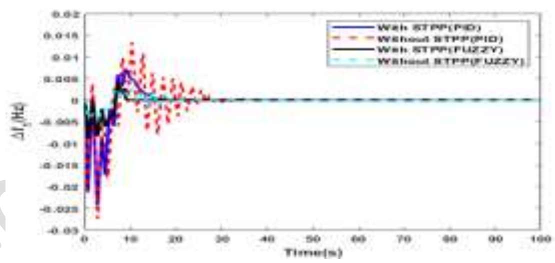

Fig.5. a)

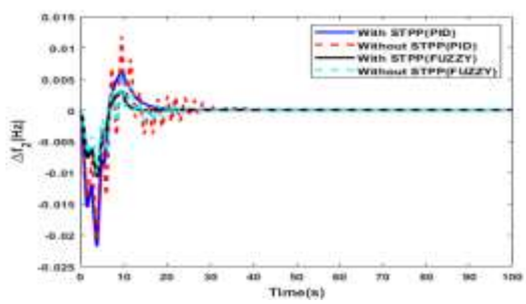

Fig.5. b)

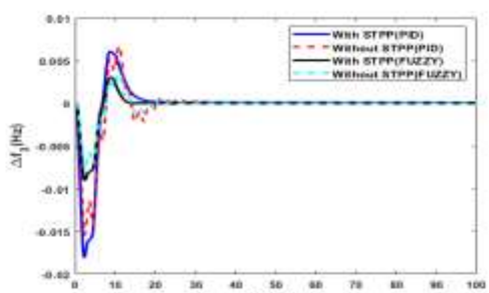

Fig.5. c)

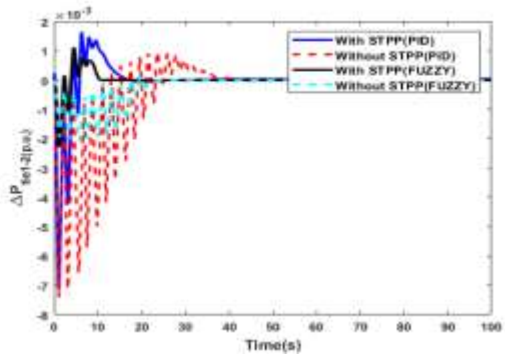

Fig.5. d)

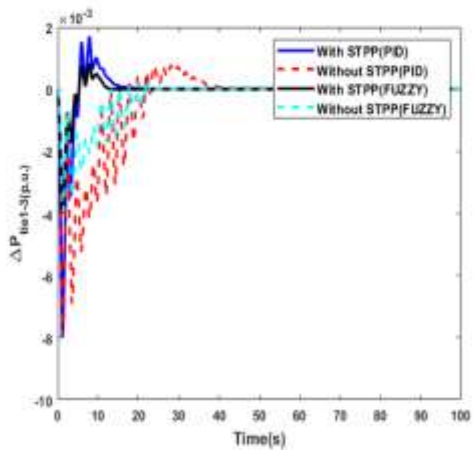

Fig.5. e)

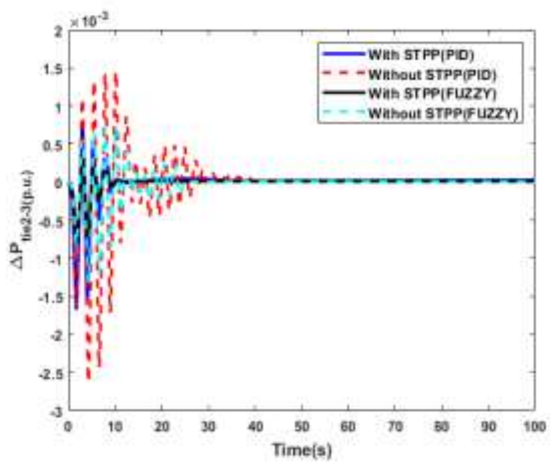

Fig.5. f)

Fig.5. Comparison of the dynamic responses of a three area system for presence and absence of STPP in area-1. (a) Deviation in frequency area-1 vs. time, (b) deviation in frequency area-2 vs. time, (c) deviation in frequency area-3 vs. time, (d) deviation in tie line power connecting area-1 and area-2 vs. time, (e) deviation in tie line power connecting area-1 and area-3 vs. time, and (f) deviation in tie line power connecting area-1 and area-3 vs. time.TABLE-I Settling Time for figure 5 with PID and Fuzzy Logic Controller.

Figure	Without STPP (sec)		With STPP(sec)	
	PID	Fuzzy	PID	Fuzzy
A	34.81	25.72	24.47	18.86
B	35.56	28.69	23.35	19.02
C	32.35	21.32	21.81	17.79
D	42.84	24.78	21.26	10.67
E	41.67	20.98	24.11	17.96
F	38.82	29.69	32.97	12.68

TABLE-II Peak Overshoot for Figure 5 with PID and Fuzzy Logic Controller.

Figure	Without STPP (sec)		With STPP(sec)	
	PID	Fuzzy	PID	Fuzzy
A	0.01432	0.008964	0.007231	0.002365
B	0.01213	0.006732	0.006335	0.002887
C	0.006886	0.002881	0.006087	0.002009
D	0.001026	0.000790	0.001814	0.0008976
E	0.0007518	0.0003901	0.001761	0.007685
F	0.001709	0.000852	0.0008671	0.0004021

TABLE-III Undershoot for figure 5 with PID and Fuzzy Logic Controller.

Figure	Without STPP (sec)		With STPP(sec)	
	PID	Fuzzy	PID	Fuzzy
A	0.02826	0.009878	0.02494	0.007674
B	0.02151	0.01198	0.0222	0.01065
C	0.01606	0.007998	0.01811	0.00865
D	0.00764	0.00370	0.00749	0.00537

	5	6	2	
E	0.00857 9	0.00394 5	0.00838 6	0.00353
F	0.00294 7	0.00145 6	0.00176 6	0.00087

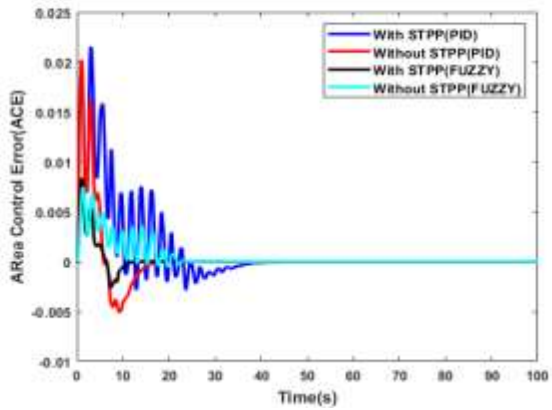

Fig. 6. Comparison of ACE of area-1 with STPP and without STPP along with fuzzy controller.Table IV. Values of settling time, of ACE in area-1 for Fuzzy & PID controllers optimized by GWO.for figure 6.

Figure	Without STPP		With STPP	
	PID	FUZZY	PID	FUZZY
Fig.6	43.94	24.98	19.90	14.67

Parameters used in this paper was shows below:

Nominal parameter of the system are f = 60 Hz; T_{gs} = 1.0s; T_{g1},$T_{g\ 2}$, T_{g3} = 0.08 s; T_{ts} = 3.0s; T_{t1}, T_{t2}, T_{t3} = 0.3 s; T_{ri} = 10 s; K_{ri} = 0.5; K_{pi} = 120 Hz/pu MW; T_{pi} = 20 s; T_{12} = T_{23} = T_{13} = 0.086 MW/rad; H_i = 5s; D_i = 8.33*10^{-3} pu MW/Hz; B_i = b_i = 0.425 pu MW/Hz; R_i = 2.4 Hz/pu MW; loading = 50%; K_s = 1.8; Ts = 1.8 s, SLP = 1% in area1

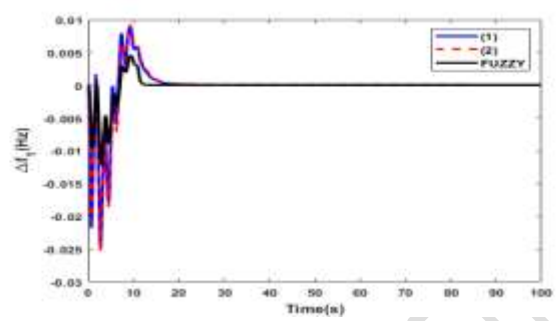

Fig.7a)

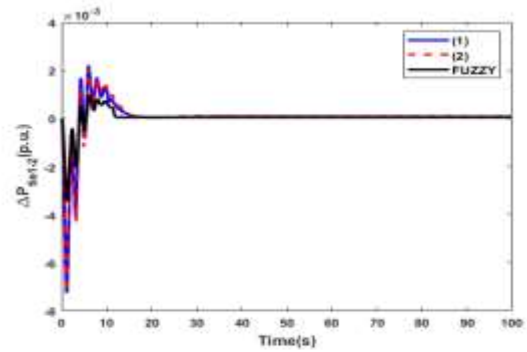

Fig.7b)

Fig.7. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for 25% loading with KPi; KIi; K Di corresponding to 50% loading and 25% loading along with fuzzy controller. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-2.

Table V Values of Peak overshoot, of ACE in area-1 for Fuzzy & PID controllers optimized by GWO for figure 6.

Figure	Without STPP		With STPP	
	PID	FUZZY	PID	FUZZY
Fig.6	0.02466	0.0118	0.0229	0.0145

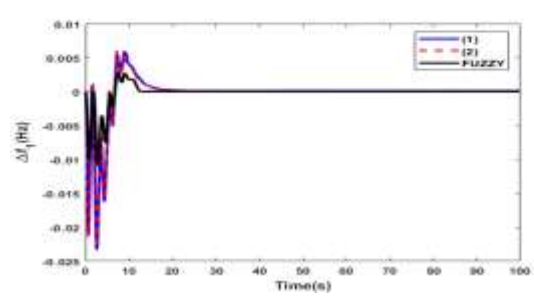

Fig.8a)

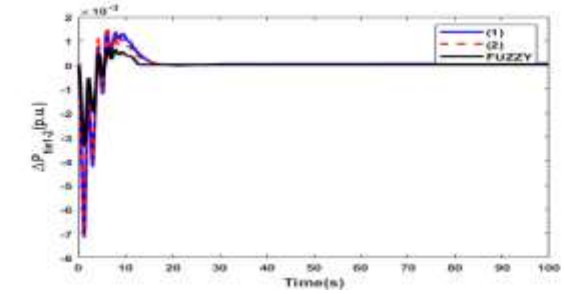

Fig.8 b)

Fig.8. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for 75% loading with KPi; KIi; KDi corresponding to 50% loading and 75% loading along with fuzzy controller. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-2.

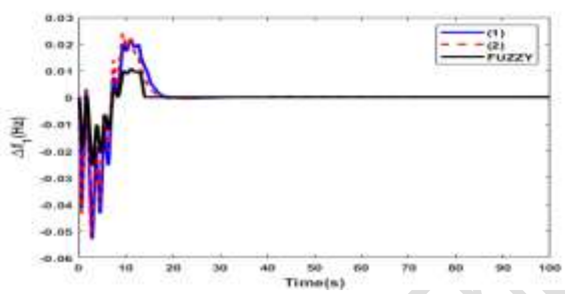

Fig.9 a)

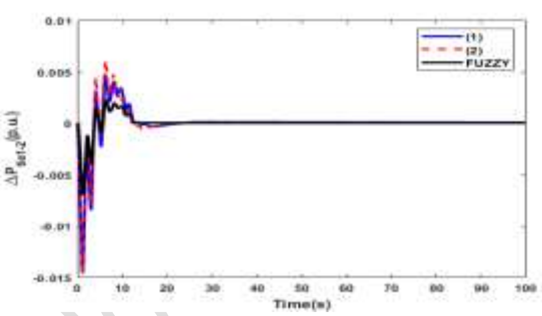

Fig.9 b)

Fig.9. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for 2% SLP in area-1 with KPi; KIi; K Di corresponding to 1% SLP and 2% SLP. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-2.

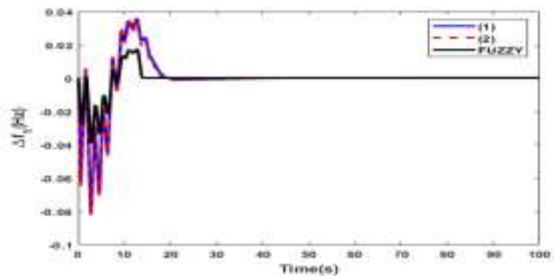

Fig.10 a)

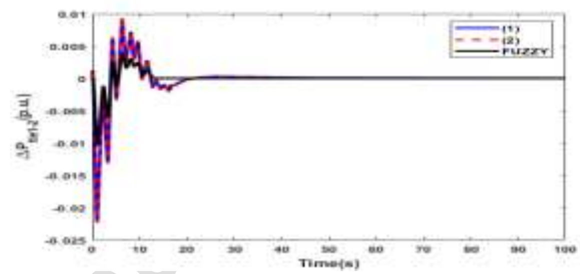

Fig.10 b)

Fig.10. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for 3% SLP in area-1 with KPi; KIi; KDi corresponding to 1% SLP and 3% SLP along with fuzzy controller. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-2.

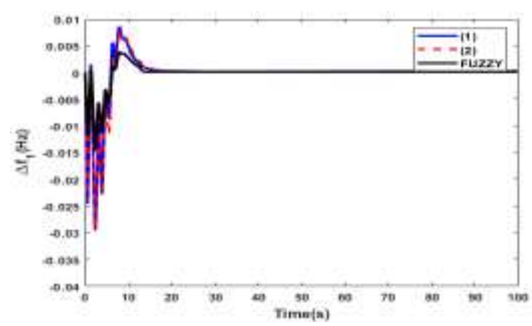

Fig.11 a)

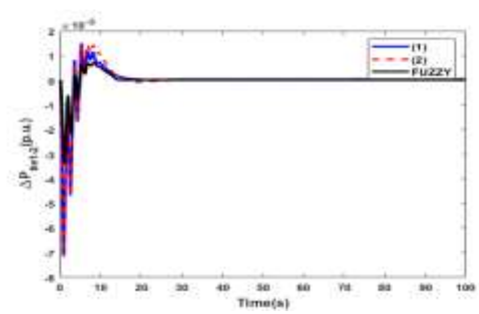

Fig.11 b)

Fig.11. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for H = 3.75 s with KPi; KIi; KDi corresponding to H = 5.0 s and H = 3.75 s. along with fuzzy controller. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-2.

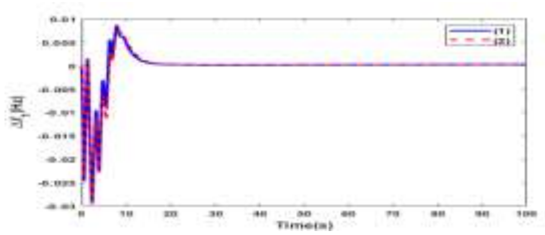

Fig.12.a)

CONCLUSION:

A three unequal areas of solar thermal power plant for automatic generation control was seen above by using Fuzzy logic controller was observed. Grey Wolf Optimizer (GWO) algorithm was used to control the areas and good results were observed. The dynamic responses of different areas were calculated and discussed above. In all responses the Fuzzified method was shown better performance in different control areas. The settling time, and Peak overshoot and Undershoot responses were good for fuzzy model as compared with previous modes(PID,PI,I). Instead of Grey Wolf Optimizer (GWO) concept different algorithms like Ant Lion Optimizer (ALO), Multi Verse Optimizer (MVO) are available and can be applied for optimization in AGC in future.

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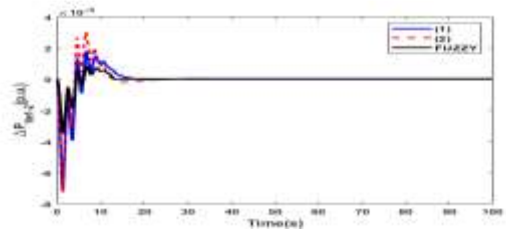

Fig.12.b)

Fig.12. Comparison of the dynamic responses of a three area system incorporating solar thermal power plant in area-1 for H = 6.25 s with KPi; KIi; KDi corresponding to H = 5.0 s and H = 6.25 s. along with fuzzy controller. (a) Deviation in frequency in area-1vs. time, (b) deviation in tie line power connecting area-1 and area-

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