BBO BASED CONTROLLERS FOR A MULTIVARIABLE SYSTEMS

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Abstract: This paper presents the design of coordinated controller design for boiler turbine units and decentralized controller design for a four tank system using Biogeography Based Optimization (BBO) technique with regulatory effects and set point changes in dynamic system. A complete analysis for each technique is presented in time domain. Performance of both controllers is examined and control performance measures for common input changes. Integral Square Error (ISE) is used as performance index for designing the controllers. Finally, a comparative assessment of each controller on the system performance is presented and discussed. The BBO results give better performance in servo and regulatory responses.

Index Terms— Co-ordinated control, Boiler Turbine Units, Decentralized PI, Four tank system and BBO.

I. INTRODUCTION

Multiloop single-input-single-output (SISO) controllers are often used for controlling interacting multivariable processes because of their simplicity in implementation, namely, they are easily understandable to control engineers and require fewer parameters to tune than multivariable controllers. Two multivariable systems are presented in this paper namely boiler turbine units and four tank system. Advantage of the multiloop controllers is that loop failure tolerance of the resulting control system can be easily obtained. Since some loops can be in manual mode or the manipulated variables of some loops can be saturated to their limits, the loop failure tolerance is important for practical applications [1].

The controller design for a boiler-turbine unit has attracted much attention in last two decades. Tan et al, [2] proposed a PID reduction procedure for a centralized controller and showed that the performance of the PI controller for a boiler - turbine unit did not degrade much from the original loop-shaping H_∞ controller. A method for auto-tuning fully cross-coupled multivariable PID controllers from decentralized relay feedback is proposed [3]. It should be noted that modern control techniques might achieve better performance than the conventional PID controller. Zhuang et al, [4] proposed multivariable PID controllers and Shiu et al, [5] discussed sequential design method for multivariable decoupling and multiloop PID cntrollers.

Interaction analysis of multivariable systems has been an important issue for control structure design (such as input output pairing) and decentralized control problems. The first quantitative measure of interaction was the Relative Gain Array (RGA) introduced by Bristol [6].

A single boiler is used to generate steam that is directly fed to a single turbine. This configuration is usually called a boiler-turbine unit. The capacity of the boiler used in this configuration is very large. The control system for a power plant is usually divided into several subsystems. For example, the feed water control subsystem is used to regulate the drum level. The temperature control subsystem is used to regulate the steam temperature and the air control subsystem is used to regulate the excess oxygen. Since the coupling between the drum level, the steam temperature and the excess oxygen are not strong, then these subsystems can be designed independently. Thus the boiler-turbine unit can be modeled as a 2X2 system. The two inputs are boiler firing rate (or fuel flow rate, assuming air flow rate is regulated well by air control subsystem) and governor valve position and the two outputs are electric power and throttle pressure [7].

A boiler–turbine system provides high-pressure steam to drive the turbine in thermal electric power generation. The purpose of the boiler–turbine system control is to meet the load demand of electric power while maintaining the pressure and water level in the drum within tolerance. This boiler–turbine

system is usually modeled with a Multi-Input–Multi-Output (MIMO) nonlinear system [8].

The four tank process is a laboratory process that consists of four interconnected water tanks. The multivariable zero dynamics of the system can be made both minimum phase and non-minimum phase by simply changing a valve. This makes the four tank system suitable for illustrating many concepts in linear and nonlinear multivariable control [9].

A new algorithm for PID controller tuning based on a combination of the foraging behavior of E coli Bacteria Foraging (BF) and Particle Swarm Optimization (PSO) is presented [10]. The E coli algorithm depends on random search directions, which had led to delay in reaching the global solution. The PSO algorithm may also lead to possible entrapment in local minimum solutions.

Dan Simon [11] discussed the natural biogeography and its mathematics, and can be used to solve optimization problems. It demonstrates the performance of Biogeography Based Optimization (BBO) on a set of 14 standard benchmarks and compares it with seven other biology-based optimization algorithms. A real-world sensor selection problem for aircraft engine health estimation is also demonstrated.

To enhance the performance of BBO, features borrowed from Evolutionary Strategies (ES) and immigration refusal were added to BBO [12].

Provas Kumar Roy et al [13] presented BBO technique for solving constrained economic dispatch problems in power system. Many nonlinear characteristics of generators, like valve point loading, ramp rate limits, prohibited zone, and multiple fuels cost functions are considered. Two Economic Load Dispatch (ELD) problems with different characteristics are applied to investigate the effectiveness of the proposed algorithm [14].

Aniruddha Bhattacharya and Pranab Kumar Chattopadhyay [15] presented a BBO algorithm to solve both convex and non-convex ELD problems of thermal plants. An application of the BBO algorithm to the traveling salesman problem is discussed [16].

Haiping Maa and Dan Simon [17] proposed a generalized sinusoidal migration model curve and is applied to solve different ELD problems with a new design concept based on predator-prey approach.

Dan Simon [18] derived a dynamic system model for BBO that is asymptotically exact as the population size approaches infinity. The states of the dynamic system are equal to the proportion of each individual in the population. The dynamic system model allows us to derive the proportion of each individual in the population for a given optimization problem.

Dan Simon et al [19] presented the comparisons between BBO and Genetic Algorithm with Global Uniform Recombination (GA/GUR) for combinatorial optimization problems, include the traveling salesman, the graph coloring, and the bin packing problems.

In Section II a simple model for a boiler-turbine unit and a nonlinear model for the four tank system based on physical data are derived. Multi-loop PID control of the boiler turbine unit using BBO and four tank system are discussed in section III. The results and conclusions are presented in Sections IV and V respectively.

II. PHYSICAL MODEL

1. SIMPLE BOILER TURBINE MODEL

A First-Order Plus Dead Time (FOPDT) model is often used for PID tuning for single-variable stable systems [7]. Tuning of controller for a boiler-turbine unit is important because it is helpful to find a simple model that can capture the essential dynamics, especially the coupling effect between the generated electricity and the throttle pressure.

A simple diagram of a boiler turbine unit is given in Fig.1 and it shows the energy balance relation and the essential nonlinear characteristics of the boiler-turbine system.

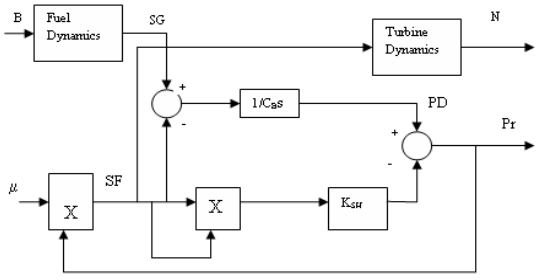

Fig. 1. Simple Diagram of a boiler turbine unit

• *Energy balance relation:*

Drum pressure P_D relates the balance between the steam generation S_G and the turbine steam flow S_F

$$\Delta S_G - \Delta S_F = C_B \frac{d\Delta P_D}{dt} \quad (1)$$

where C_B - Boiler storage constant

• *Nonlinear characteristics:*

1. The pressure drop between the drum pressure P_D and the steam pressure P_T is related to the steam flow S_F by

$$P_D - P_T = K_{SH} S_F^2 \quad (2)$$

where K_{SH} - Super heater friction drop coefficient

2. The steam flow S_F is the product of the throttle pressure P_T and the turbine governor position μ

$$S_F = \mu P_T \quad (3)$$

A linearized model of a boiler turbine unit [2] is

$$\begin{bmatrix} \Delta N \\ \Delta P_T \end{bmatrix} = \begin{bmatrix} \frac{m_{11}(\alpha T_2 s+1)}{(T_1 s+1)(T_0 s+1)(T_2 s+1)} & \frac{m_{12}(\alpha T_2 s+1)}{(T_0 s+1)(T_2 s+1)} \\ \frac{m_{21}}{(T_1 s+1)(T_0 s+1)} & -\frac{m_{22}(T_b s+1)}{T_0 s+1} \end{bmatrix} X \begin{bmatrix} \Delta B \\ \Delta \mu \end{bmatrix} \quad (4)$$

where

$$\Delta B = \frac{\Delta S_G (T_1 s+1)}{K_1}, \quad \Delta N = \frac{(\alpha T_2 s+1) K_2}{T_2 s+1} \Delta S_F$$

$$m_{11} = k_1 k_2, \quad m_{12} = \frac{P_T C_B K_1}{\mu}, \quad m_{21} = \frac{K_1}{\mu}, \quad m_{22} = \frac{P_T}{\mu}$$

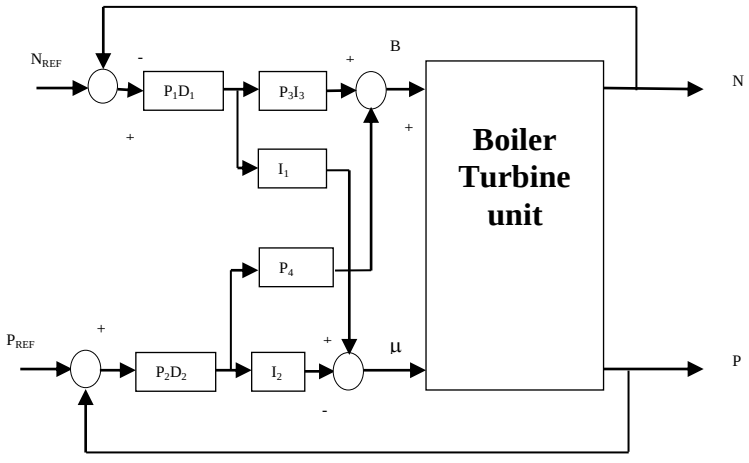

Fig. 2. Coordinated control structure of a boiler turbine unit

Fig.2 shows that the coordinated control structure of a boiler turbine unit [7]. The co-ordinated PID controller for the boiler-turbine unit is

$$[K_c(s)] = \begin{bmatrix} \frac{(T_1 + T_b)s+1}{m_{11} s} & \frac{m_{12}}{m_{11} m_{22}} \\ \frac{m_{21}}{m_{11} m_{22} s} & -\frac{1}{m_{22} s} \end{bmatrix} X \begin{bmatrix} PD_1 & 0 \\ 0 & PD_2 \end{bmatrix} \quad (5)$$

2. FOUR TANK SYSTEM

A schematic diagram of the four tank system is shown in Fig. 3. The target is to control the level in the lower two tanks with two pumps. The process inputs are voltages to the pumps and the outputs are voltages from level measurement devices.

Mass balances and Bernoulli's law yield the following simple nonlinear equations [9]

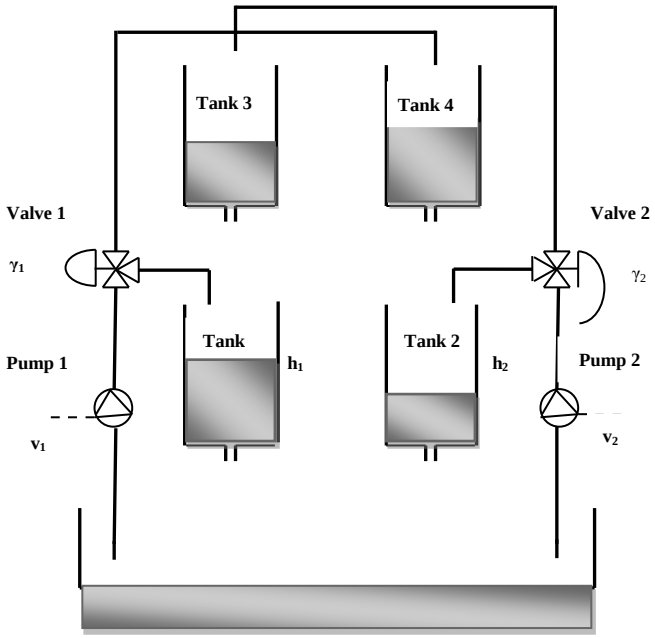

Fig 3.Schematic diagram of the four tank system.

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1} v_1$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2} v_2$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2) k_2}{A_3} v_2$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1) k_1}{A_4} v_1 \quad (6)$$

where

A_i Cross-section of Tank i

a_i Cross-section of the outlet hole

h_i Water level.

The voltage applied to pump i is v_i and the corresponding flow is $k_i v_i$. The parameters γ_1, $\gamma_2 \in (0,1)$ are determined from how the valves are set prior to an experiment. The flow to Tank 1 is $\gamma_1 k_1 v_1$ and the flow to Tank 4 is $(1-\gamma_1)k_1 v_1$ and similarly for Tank 2 and Tank 3. The acceleration of gravity is denoted g. The measured level signals are $k_c h_1$ and $k_c h_2$. The linearized state-space equation is given by

$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1 T_3} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2 T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix} x + \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_2} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix} x \qquad (7)$$

where the time constants are

$$T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_i^0}{g}}, i=1,...4 \qquad (8)$$

The corresponding transfer function matrix is

$$G(s) = \begin{bmatrix} \frac{\gamma_1 c_1}{1+sT_1} & \frac{(1-\gamma_2)c_1}{(1+sT_3)(1+sT_1)} \\ \frac{(1-\gamma_1)c_2}{(1+sT_4)(1+sT_2)} & \frac{\gamma_2 c_2}{1+sT_2} \end{bmatrix} \qquad (9)$$

where $c_1 = T_1 k_1 k_c / A_1$ and $c_2 = T_2 k_2 k_c / A_2$.

Fig 4. Experimental setup of the four tank system.

Fig.4 shows the experimental setup of the QTP consisting of four interconnected tanks with common water source. This setup is interfaced with a window - based PC via interfacing modules and USB ports. This setup consists of a water supply tank with two positive displacement pumps for water circulation, two pneumatic control valves, four transparent process tanks fitted with level transmitters and rotameters (0-440 lph). Process signals from the four tank level transmitters are interfaced with the PC and it sends outputs to the individual control valves through interfacing units using LabVIEW software. Tanks 1 and 2 are mounted below the other two tanks 3 and 4 for receiving water flow by gravity. Each tank outlet opening is fitted with a valve. Both pumps 1 and 2 takes water by suction from the ground level supply tank. Pump 1 discharges water to tank 1 and tank 4 simultaneously and the flows are indicated by rotameters 1 and 4. Similarly, pump 2 discharges water to tank 2 and tank 3 and the flows are indicated by rotameters 2 and 3. Split of flow from pump 1 and pump 2 can be varied by manual adjustment of valves in tank 1 and tank 2. They also receive water by gravity flow from tank 3 and tank 4, respectively. Opening of these flows split valves in the rotameters can be manually adjusted to substantially alter the characteristics of the system. The parameters of four tank process are given in Table 1.

TABLE 1.PROCESS PARAMETER VALUES

i	$A_i(cm^2)$	$a_i(cm^2)$	$h_i^0(cm)$
1	176.71	2.01	9.53
2	176.71	2.01	7.56
3	176.71	2.01	2.27
4	176.71	2.01	7.82

The time constants are T_1=42.48 sec, T_2=55.64 sec, T_3=39.86 sec and T_4=55.68 sec.

$$G(s) = \begin{bmatrix} \frac{0.3811}{42.48S+1} & \frac{0.2334}{(42.48S+1)(39.86S+1)} \\ \frac{0.1998}{(55.68S+1)(55.64S+1)} & \frac{0.3934}{55.68S+1} \end{bmatrix} \qquad (10)$$

Relative Gain Array (RGA)

The RGA was introduced by Ed Bristol [6] as a measure of interaction in multivariable control systems. The RGA Λ is defined as

$$\Lambda = G(0) \times G^{-T}(0) \qquad (11)$$

Where $\times$ denotes the element by element matrix multiplication and $^{-T}$ inverse transpose.

Properties of RGA:

1. Sum of rows and columns property of the RGA

   Each row of the RGA sums to 1.0 and each column of the RGA sums to 1.0.

   (ie) $\lambda_{11}+\lambda_{12}=1$ $\lambda_{11}+\lambda_{21}=1$

   $\lambda_{12}+\lambda_{22}=1$ $\lambda_{21}+\lambda_{22}=1$

2. Use of RGA to determine variable pairing

It is desirable to pair output i and input j such that λ_{ij} is as close to 1 as possible.

The RGA is only depending on the valve settings and no other physical parameters.

$$\text{RGA } \Lambda = \begin{bmatrix} 1.4515 & -0.4515 \\ -0.4515 & 1.4515 \end{bmatrix}$$

2.1. Decentralized PI Control

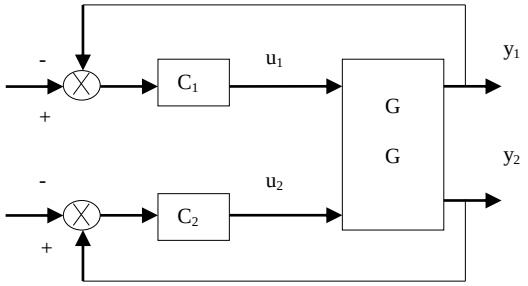

Fig.5 Decentralized control structure with two PI controllers

The decentralized controller structure is shown in Fig.5 and the decentralized control law [9] u=diag{C_1,C_2}(r-y)

PI controllers of the form [20]

$$C_l(s) = K_l\left(1+\frac{1}{T_{il}s}\right), \quad l=1,2 \tag{12}$$

$$K_l = \frac{T_{il}}{K_P T_c}$$

$$T_c = 0.5T_{il} \tag{13}$$

III. BIOGEOGRAPHY BASED OPTIMIZATION

BBO technique [14] has been developed based on the theory of Biogeogrphy. BBO concept is mainly based on Migration and Mutation. The concept and mathematical formulation of Migration and Mutation steps are given below.

A. Migration

This BBO algorithm [11] is similar to other population based optimization techniques where population of candidate solutions is represented as vector of real numbers. Each real number in the array is considered as one Suitability Index Variable (SIV). Fitness of each set of candidate solution is evaluated using SIV. In BBO a term Habitat Suitability Index (HSI) is used which is analogous to fitness function of other population-based techniques, to represent the quality of each candidate solution set. High HSI solutions represent better quality solution and low HSI solutions represent inferior solution in optimization problem.

The emigration and immigration rates of each solution are used to probabilistically share information between habitats. Using Habitat Modification Probability each solution is modified based on other solutions. Immigration rate, λ of each solution is used to probabilistically decide whether or not to modify each suitability index variable (SIV) in that solution. After selecting the SIV for modification, emigration rates, μ of other solutions are used to probabilistically select which solutions among the population set will migrate. The main difference between recombination approach of evolutionary strategies (ES) and migration process of BBO is that in ES, global recombination process is used to create a completely new solution, while in BBO, migration is used to bring changes within the existing solutions. In order to prevent the best solutions from being corrupted by the immigration process, few elite solutions are kept in BBO algorithm.

B. Mutation

Due to some natural calamities or other events HSI of a natural habitat can change suddenly and it may deviate from its equilibrium value. In BBO, this event is represented by the mutation of SIV and species count probabilities are used to determine mutation rates. The probability of each species count can be calculated using the differential equation (14) [11] given below:

$$P_S = \begin{cases} -(\lambda_S+\mu_S)P_S+\mu_{S+1}P_{S+1} & S=0 \\ -(\lambda_S+\mu_S)P_S+\lambda_{S-1}P_{S-1}+\mu_{S+1}P_{S+1} & 1\le S\le S_{max}-1 \\ -(\lambda_S+\mu_S)P_S+\lambda_{S-1}P_{S-1} & =S_{max} \end{cases} \tag{14}$$

where

P_s : the probability of habitat contains exactly S species,

λ,μ_s : the immigration and emigration rate for habitat contains S species.

Immigration rate (λ) and emigration rate (μ_s) can be evaluated by the equation (15) and (16) [15] given below:

$$\lambda = I\left(1 - \frac{S}{S}\right) \quad (15)$$

$$\mu_s = \frac{ES}{S_{max}} \quad (16)$$

Each population member has an associated probability, which indicates the likelihood that it exists as a solution for a given problem. If the probability of a given solution is very low then that solution is likely to mutate to some other solution. Similarly if the probability of some other solution is high then that solution has very little chance to mutate. Therefore, very high HSI solutions and very low HSI solutions are equally improbable for mutation i.e. they have less chances to produce more improved SIVs in the later stage. But medium HSI solutions have better chances to create much better solutions after mutation operation. Mutation rate of each set of solution can be calculated in terms of species count probability using the equation (17) [15]:

$$m(s) = m_{max}\left(\frac{1-P_s}{P_{max}}\right) \quad (17)$$

where m_{max} : maximum mutation rate
m(s) : the mutation rate for habitat contains S species,
P(s) : maximum probability

This mutation scheme tends to increase diversity among the populations. Without this modification, the highly probable solutions will tend to be more dominant in the population. This mutation approach makes both low and high HSI solutions likely to mutate, which gives a chance of improving both types of solutions in comparison to their earlier values. Few elite solutions are kept in mutation process to save the features of a solution, so if a solution becomes inferior after mutation process then previous solution (solution of that set before mutation) can revert back to that place again if needed. So, mutation operation is a high-risk process. It is normally applied to both poor and better solutions. Since medium quality solutions are in improving stage so it is better not to apply mutation on medium quality solutions. Here, mutation of a selected solution is performed simply
by replacing it with randomly generated new solution set.

The following BBO parameters are selected for the training cycle for the QTP

1. Imigration rate
2. Emigration rate
3. The probability of each species count

Mutation rate

The controller performance is evaluated in terms of Integral Square Error (ISE) given by,

1. Boiler turbine unit

$$F = ISE1 + ISE2$$

$$ISE1 = [\sum(N - N_{REF})]^2$$

$$ISE2 = [\sum(P - P_{REF})]^2 \quad (18)$$

2. Four tank system

$$F = ISE1 + ISE2$$

$$ISE1 = [\sum(y_1 - y_{1REF})]^2$$

$$ISE2 = [\sum(y_2 - y_{2REF})]^2 \quad (19)$$

The following BBO parameters are selected for the training cycle for

1. Boiler turbine unit

Population size = 10
Maximum generation = 100
Number of Variables = 9
Mutation Probability = 0.05

2. Four tank system

Population size = 10
Maximum generation = 100
Number of Variables = 4
Mutation Probability = 0.05

IV. RESULTS AND DISCUSSION

1. BOILER TURBINE UNIT

Example 1. Consider a boiler-turbine unit with the following transfer function which was obtained by fitting the step response data [7]

$$G_1(s) = \begin{pmatrix} \frac{4.247(3.4s+1)}{(100s+1)(20s+1)(10s+1)} & \frac{3.224s(3.4s+1)}{(100s+1)(10s+1)} \\ \frac{0.224}{(100s+1)(20s+1)} & -\frac{0.19(20s+1)}{100s+1} \end{pmatrix}$$

Simulations are carried out to evaluate the proposed control method by utilizing the

Matlab program. The performance of the different control strategies are compared based on the performance criteria (ISE) for the two controlled outputs electrical power and throttle pressure. The design of the disturbance is also shown for characterizing the performance of the two different control strategies.

The controller parameters values are tuned using BBO based Coordinated Controller (BBOCC) is tabulated in Table 2.

TABLE 2
CONTROLLER PARAMETER VALUES

Controller parameters		Type of Controller	
		Coordinated controller	BBOCC
P_1D_1	P_1	0.1	0.1
	D_1	2.5	3.1
P_2D_2	P_2	0.1	0.1
	D_2	2.5	5.1
P_3I_3	P_3	9.4	9
	I_3	0.24	0.2
I_1		0.28	0.4
I_2		5.3	10
P_4		3.9	2.04

Fig 6 shows that the variation of the fitness function with number of generations using BBOCC.

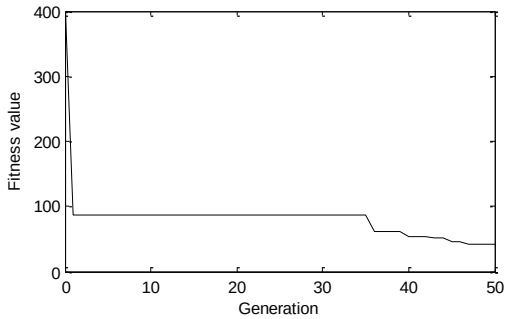

Fig. 6. Iteration Graph

Fig 7 and 8 are the closed loop responses of the electrical power output and throttle pressure for coordinated controller and BBOCC. It settles quickly and the peak over shoot is less when compared to coordinated controller.

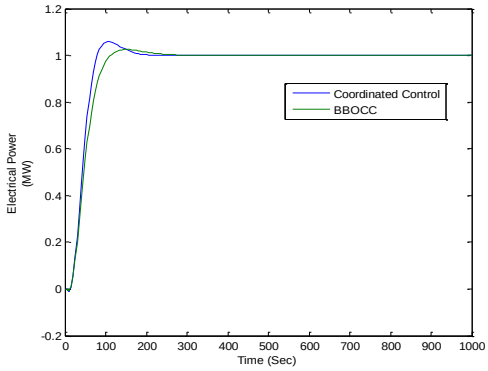

Fig.7 Closed Loop response Electrical power output

ISE and IAE of the controllers for both the unit step input of N and P are given in Table 3.

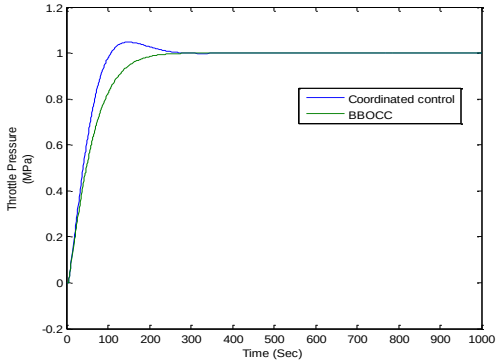

Fig.8 Closed Loop response of Throttle pressure

TABLE 3
PERFORMANCE COMPARISION OF VARIOUS CONTROLLERS

Type of Controller	Electrical Power		Throttle Pressure	
	ISE	*IAE*	*ISE*	*IAE*
Coordinated Controller	23.51	26.04	21.52	25.73
BBOCC	21.97	25.02	21.3	25.2

In order to test the strength of the proposed design procedure of BBOCC, simulation was carried out for the servo and regulatory operations.

The set points tracking responses of the electrical power output and throttle pressure for coordinated control and BBOCC are given in Fig 9 and 10 respectively. At 500^{th} sec the set point is changed from 1MW to 5MW and at 1000^{th} sec the set point is decreased from 5MW to 2MW and the response is plotted. Similarly the same procedure is repeated for throttle pressure also.

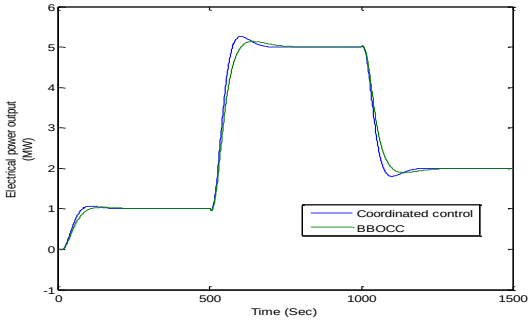

Fig.9.Setpoint tracking Responses of Electrical power output

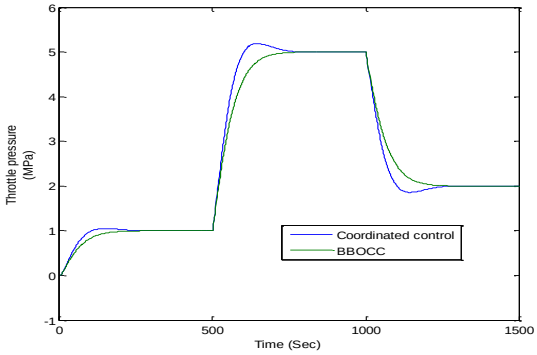

Fig.10.Setpoint tracking Responses of Throttle pressure

The performance comparison of the set point tracking of the controllers for electrical power and throttle pressure are given in Table 4 and 5 respectively.

TABLE 4
PERFORMANCE COMPARISION OF ELECTRICAL POWER OUTPUT

Type of Controllers	Set point (1MW)		Set point (5MW)		Set point (2MW)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*
Coordinated controller	6.3	55	5.05	504	11.1	257
BBOCC	3.4	53	2.7	450	3.6	227

TABLE 5
PERFORMANCE COMPARISION OF THROTTLE PRESSURE

Type of Controllers	Set point (1MW)		Set point (5MW)		Set point (2MW)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*
Coordinated controller	4.58	56	3.66	471	7.6	243
BBOCC	-	50	-	392	-	202

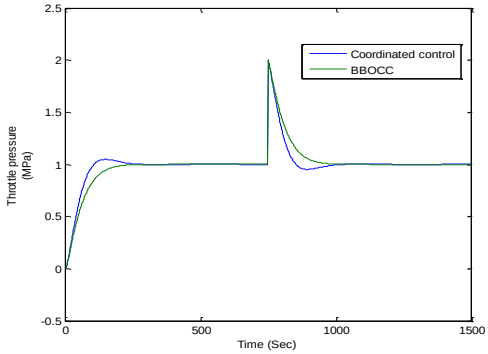

Fig.11.Regulatory Responses of Electrical power output

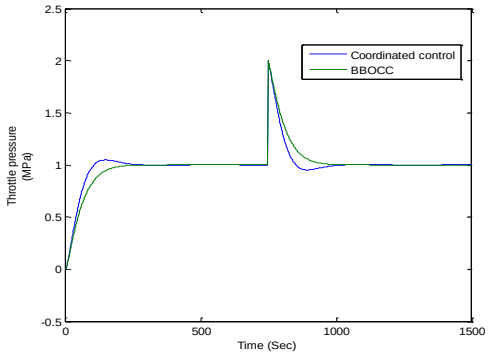

Fig.12.Regulatory Responses of Throttle pressure

Fig 11 and 12 are the regulatory response of electrical power output and throttle pressure. Initially the electrical power output and throttle pressure are maintained at steady state of 1MW and 1 MPa. After 750thsec a sudden disturbance (1MWand 1MPa) is given. From the above response BBOCC settles quickly and undershoot is also less.

Example 2. Consider a 300-MW coal-fired once-through boiler-turbine unit. At full load, the following transfer function was obtained by fitting the step response data [7]

$$G2(s)=\begin{pmatrix} \frac{2.069(311s+1)}{(149s+1)(22.4s+1)} & \frac{4.665s(99s+1)}{(582s+50s+1)(4.1s+1)} \\ \frac{0.124(205s+1)}{(128s+1)(11.7s+1)} & -\frac{0.139(2.8s+1)}{70s+1} \end{pmatrix}$$

The controller parameter values are tabulated in Table 6.

TABLE 6
CONTROLLER PARAMETER VALUES

Controller parameters		Type of Controller	
		Coordinated controller	BBOCC
P_1D_1	P_1	0.08	0.2525
	D_1	5.824	7.9192
P_2D_2	P_2	0.007	0.1020
	D_2	0	50
P_3I_3	P_3	8.83	50.18
	I_3	0.48	0.40
I_1		0.43	0.51
I_2		7.19	0.41
P_4		16.22	0.51

Fig 13 is the variation of the fitness function with number of generations using BBOCC.

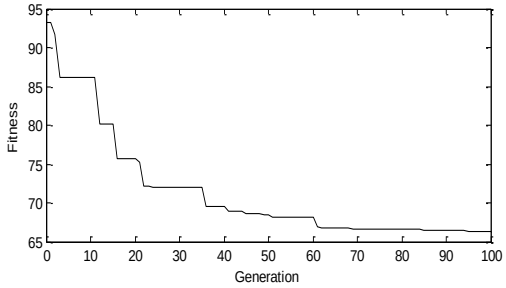

Fig.13.Iteration graph

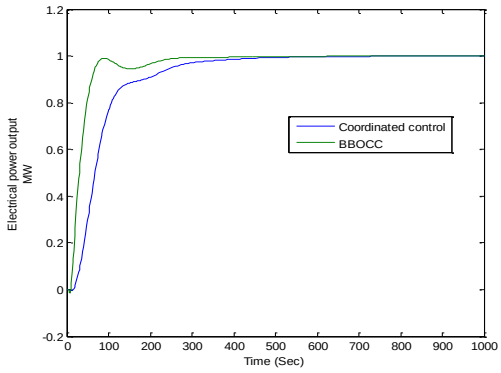

Fig.14. Closed Loop response Electrical power output

Fig 14 and 15 are the closed loop responses of the electrical power output and throttle pressure for coordinated controller and BBOCC. ISE and IAE of the controllers for both N and P are tabulated in Table 7.

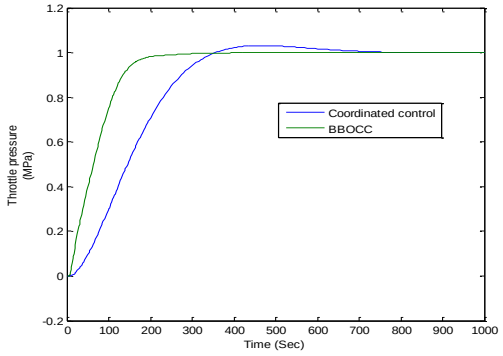

Fig.15. Closed Loop response Throttle pressure

TABLE 7
PERFORMANCE COMPARISION OF VARIOUS CONTROLLERS

Type of Controller	Electrical Power		Throttle Pressure	
	ISE	*IAE*	*ISE*	*IAE*
Coordinated Controller	42.45	53.88	62.6	80.5
BBOCC	28.57	35.09	38.36	47.93

The set points tracking responses of the electrical power output and throttle pressure for both controllers are given in Fig 16 and 17 respectively.

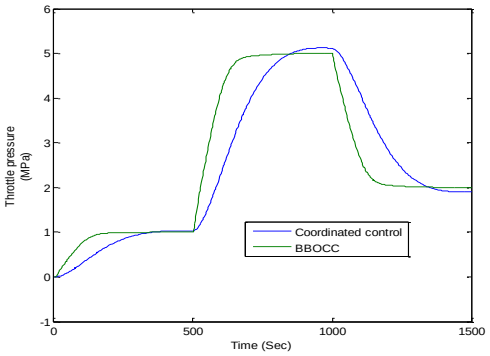

Fig.16.Setpoint tracking Responses of Electrical power output

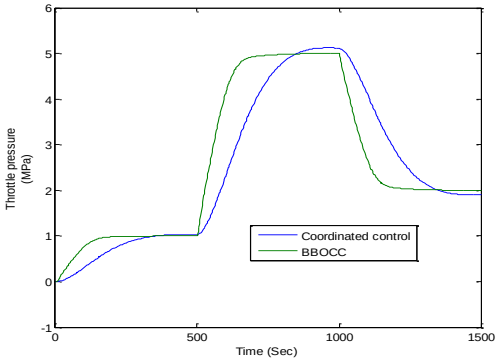

Fig.17.Setpoint tracking Responses of Throttle pressure

Performance comparisons are given in Table 8 and 9 respectively.

TABLE 8
PERFORMANCE COMPARISION OF ELECTRICAL POWER OUTPUT

Type of Controllers	Set point (1MW)		Set point (5MW)		Set point (2MW)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*
Coordinated controller	-	59	-	504	-	257
BBOCC	-	55	-	450	-	227

TABLE 9
PERFORMANCE COMPARISION OF THROTTLE PRESSURE

Type of Controllers	Set point (1MW)		Set point (5MW)		Set point (2MW)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*
Coordinated controller	3	56	2.36	471	5.09	244
BBOCC	-	53	-	392	-	202

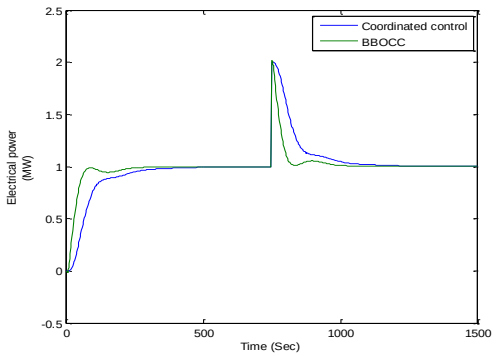

Fig.18.Regulatory Response of Electrical power output

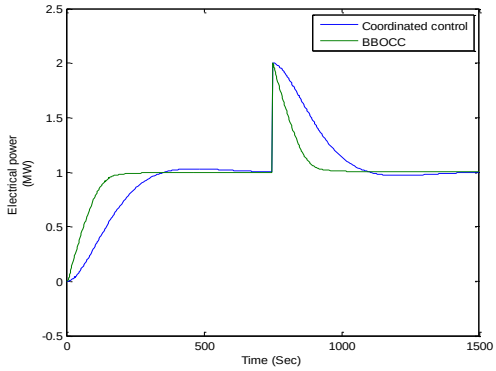

Fig.19.Regulatory Response of Throttle pressure

Fig 18 and 19 are the regulatory response of electrical power output and throttle pressure. Initially the electrical power output and throttle pressure are maintained at steady state of 1MW and 1 MPa. After 750thsec a sudden disturbance (1MWand 1MPa) is applied.

2. FOUR TANK SYSTEM

Consider a four tank system real time set up, the following transfer function is obtained by open loop response data.

$$G(s)=\begin{bmatrix} \dfrac{0.3811}{42.48S+1} & \dfrac{0.2334}{(42.48S+1)(39.86S+1)} \\ \dfrac{0.1998}{(55.68S+1)(55.64S+1)} & \dfrac{0.3934}{55.68S+1} \end{bmatrix}$$

Experimental results are carried out to evaluate the proposed control method by utilizing the LabVIEW software. The performance of the different control strategies are compared based on ISE and IAE for the two controlled outputs h_1 and h_2. The design of the disturbance is also satisfactory for characterizing the performance of the two different control strategies. Decentralized PI controller and tuning the PI parameters using BBO (BBOPI) are designed and implemented in the experimental four tank system.

Table 10 gives the controller parameter values of four tank system.

TABLE 10
CONTROLLER PARAMETER VALUES

Type of Controller	**Controller parameters**			
	K_1	**K_2**	**K_{i1}**	**K_{i2}**
Decentralized PI controller	10.01	20.34	0.12	0.09
BBOPI	8	20	0.39	0.2449

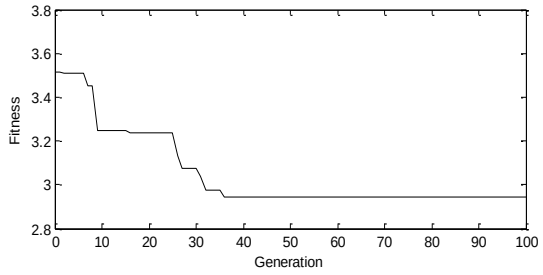

Fig. 20. Iteration Graph

Fig 20 is the variation of the fitness function with number of generations using BBOPI.

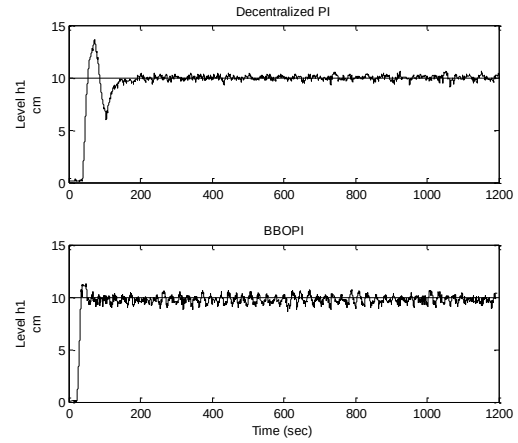

Fig.21. Experimental results for Closed Loop response of level h_1

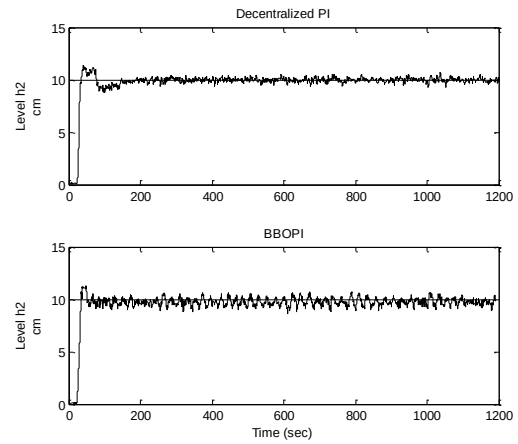

Fig.22. Experimental results for Closed Loop response of level h_2

Fig 21 and 22 are the closed loop response of the level h_1 for decentralized PI and BBOPI. The BBO controller settles quickly. The performance index (ISE and IAE) of BBOPI is less when compared to decentralized PI in Table 11.

TABLE 11
PERFORMANCE COMPARISION OF VARIOUS CONTROLLERS

Type of Controller	Tank 1		Tank2	
	ISE	*IAE*	*ISE*	*IAE*
Decentralized PI controller	23.06	5.06	17.06	6.02
BBOPI	20.27	4.45	15.52	3.33

The set point tracking responses of the water level of h_1 and h_2 for the decentralized PI, BBOPI are given in Fig 23 and 24 respectively. At 1200^{th} sec, the set point is increased from 10cm to 12cm and at 2400^{th} sec the set point is decreased from 12cm to 10cm. After that the set point is increased to 16cm at 3600^{th} sec, and the response is plotted. The performance comparison of the set point tracking of the controllers for level h_1 and h_2 are given in Tables 12 and 13 respectively.

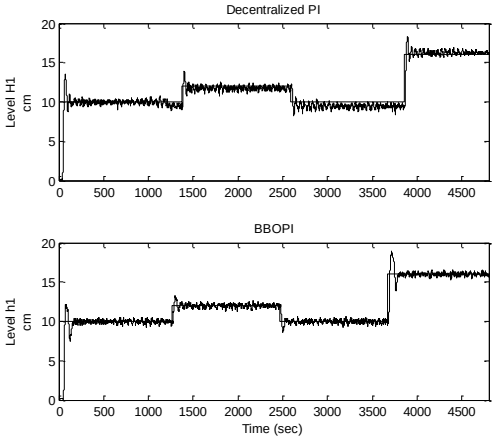

Fig.23.Setpoint tracking for the Responses of the water level (h_1)

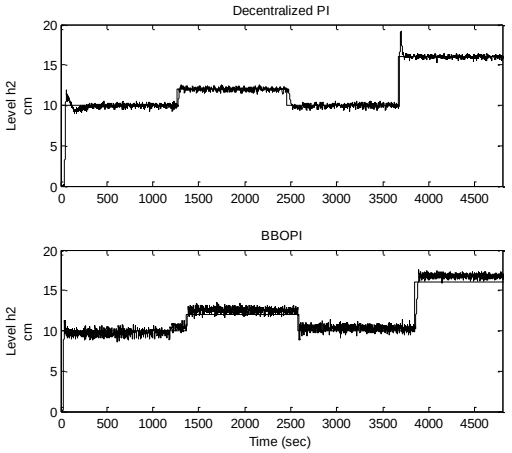

Fig.24.Setpoint tracking for the Responses of the water level (h_2)

TABLE 12
PERFORMANCE COMPARISION OF SETPOINT CHANGES (TANK 1)

Type of Controllers	Set point (10 cm)		Set point (12 cm)		Set point (10 cm)		Set point (16 cm)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*	*Peak Over Shoot (%)*	*ISE*
Decentralized PI controller	31	23	14	.5	18.1	0.2	18	1.1
BBOPI	15.9	6	9.3	.4	7.82	0.1	13	0.9

TABLE 13
PERFORMANCE COMPARISION OF SETPOINT CHANGES (TANK 2)

Type of Controllers	Set point (10 cm)		Set point (12 cm)		Set point (10 cm)		Set point (16 cm)	
	Peak Over Shoot (%)	*ISE*	*Peak Over Shoot (%)*	*ISE*	*Under Shoot (%)*	*ISE*	*Peak Over Shoot (%)*	*ISE*
Decentralized PI controller	28	17	7.9	0.3	8.6	0.3	19	1.3
BBOPI	11	6.3	7.19	0.1	4.9	0.2	7.24	1.1

Fig 25 and 26 shows the regulatory response of water levels h_1 and h_2. Initially the level of tank 1 and tank 2 are maintained at a steady state of 10cm. After 20 minutes, a sudden external disturbance (1000ml of water) is appended in tank 1 and tank 2 at 1200 sec. From the above response BBOPI settles quickly and the overshoot is also less.

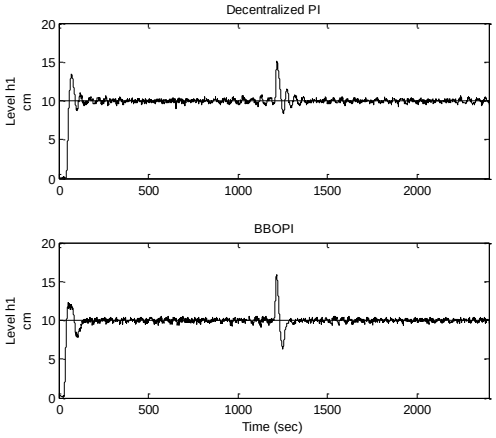

Fig.25.Regulatory Responses of the water level (h_1)

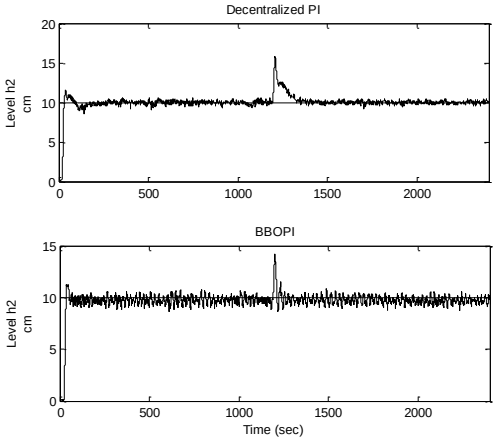

Fig.26.Regulatory Responses of the water level (h_2)

The system response of the levels h_1 and h_2 (Fig. 23- 26) show the effectiveness of the BBOPI for both servo and regulatory operations.

V. CONCLUSION

The performance trade-off comparison among the coordinated controller, and BBOCC are designed to control the electric power and throttle pressure for boiler turbine units. Decentralized PI and BBOPI controllers are designed to control the liquid level of the laboratory four tank system. The BBOCC and BBOPI responses are compared with Co-ordinated and decentralized PI responses. From these responses it is observed that the ISE and IAE values are low with BBOCC and BBOPI than with Co-ordinated and decentralized PI. The results show that BBO performance is better and is effective for both servo and regulatory responses. The design of

BBO is tested for an operating condition and the servo and regulatory responses are proved and established.

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