Soft Computing Based Partial-Retuning of Decentralised PI Controller of Nonlinear Multivariable Process

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Abstract. Recent developments in nature-inspired algorithms motivate the control engineers to work towards its application in industrial processes. Almost all the industrial processes are difficult to control since it involves many variables, strong interactions and inherent nonlinearities. In the present work the authors propose cuckoo search, a recent metahuristic algorithm to fine tune the parameters of decentralised PI controller of coal gasifier which is a highly nonlinear multivariable process having strong interactions among the control loops. With the existing controller parameters the response does not able to meet the performance requirements at 0% load for sinusoidal pressure disturbance test. The PI controller for pressure loop is retuned using Cuckoo search algorithm and the best optimal values for its parameters are obtained. Performance of the system with tuned optimal controller settings is evaluated for pressure disturbance test, load change test and coal quality test.

Keywords: Coal gasifier, Cuckoo search algorithm, metahuristic algorithm, multivariable process, nonlinear systems, PID Controller tuning.

1 Introduction

Integrated Gasification Combined Cycle (IGCC) is an efficient method of clean power and energy generation. Here Coal reacts with air (oxygen) and steam, converted into syngas (also called producer gas) under certain pressure and temperature. Purified syngas runs the gas turbine to generate power and exhaust gas from the gas turbine enters Heat Recovery Steam Generator (HRSG) to produce steam which in turn runs the steam turbine. Coal gasifier, an important and primary element in IGCC, is a highly non-linear, multivariable process, having five controllable inputs (char flow rate, air flow rate, coal flow rate, steam flow rate and limestone flow rate), few non-control inputs (boundary conditions, PSink and coal quality) and four outputs (fuel gas calorific value, bed mass, fuel gas pressure and fuel gas temperature) with a high degree of cross coupling between them. The process is a four-input, four output regulatory problem for the control design (keeping limestone at constant value). It exhibits a complex dynamic behaviour with mixed fast and slow

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dynamics and it is highly difficult to control. The full model of coal gasifier has 25 states and the ultimate requirement is to find the controller constants (Kp, Ki) of PI controller such that all the constraints are met for all the specified loads as given in the challenge problem [1]. Control specification includes sink pressure step and sinusoidal disturbance tests (at the three different operating points), ramp change in load from 50% to 100%, and coal quality change (±18%). Until recently a group of researchers have attempted to analyze the system, design controllers and retune the baseline controller to meet the performance objectives at all the load conditions [2-10]. Apart from the conventional techniques, soft computing approaches such as MOGA [11] and NSGA II [12] are also used to design the controller.

2 Cuckoo Search Based Optimization

Optimization is the process of finding a best optimal solution to meet the desired objective function. Nature-inspired metahuristic algorithms (PSO, BFO, FA, Bee Colony, ANT Colony, BAT, etc.,) are most widely used in a variety of optimization Problems including process control. One of such new algorithm is Cuckoo search algorithm developed by Xin-She Yang [13-15], which uses the breeding behaviour of certain species of cuckoos. Cuckoos lay their eggs in other birds' nests even it may remove others' eggs to increase the hatching probability of their own eggs. If a host bird discovers the eggs that are not their own, they will either throw these alien eggs away or abandon its nest and build a new nest elsewhere. Some cuckoo species are often very specialized in the mimicry in colour and pattern of the eggs of a few chosen host species so that increases their reproductivity. Cuckoo search algorithm is based on the following rules:

- Each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest.
- The best nests with high quality of eggs will carry over to the next generation.
- With fixed number of available host nests, the egg laid by a cuckoo is discovered by the host bird with a probability $p_a \in [0,1]$ discovering operate on some set of worst nests, and discovered solutions dumped from further calculations.

For a maximization problem, the fitness of a solution is directly proportional to the objective function and here each egg in a nest represents a solution, and a cuckoo egg represent a new solution, the aim is to use the new and potentially better solutions (cuckoos) to replace a not-so-good solution in the nests. This algorithm can be extended to the more complicated case where each nest has multiple eggs representing a set of solutions. For this present work, the authors use a simplest approach where each nest has only a single egg. The rules can be integrated to form the Cuckoo search algorithm as shown in figure 1. When generating new solutions $x_i(t+1)$ for the i^{th} cuckoo, the following Levy flight is performed

$$x_i(t+1)=x_i(t) + \alpha \oplus \text{Lèvy} \quad (1)$$

Where, $\alpha > 0 =$ step sizes the step size; $\oplus =$ entry-wise multiplications.

Step-lengths of Lèvy flight are distributed as

$$\text{Lèvy} \;\; u = t^{-\lambda}, \quad 1 < \lambda < 3 \quad (2)$$

Consecutive steps of a cuckoo form a random walk process which obeys a power-law step-length distribution with a heavy tail. In real world, if a cuckoo's egg is very similar to a host's eggs, then this cuckoo's egg is less likely to be discovered, thus the fitness should be related to the difference in solutions. Therefore, it is a good idea to do a random walk in a biased way with some random step sizes [16].

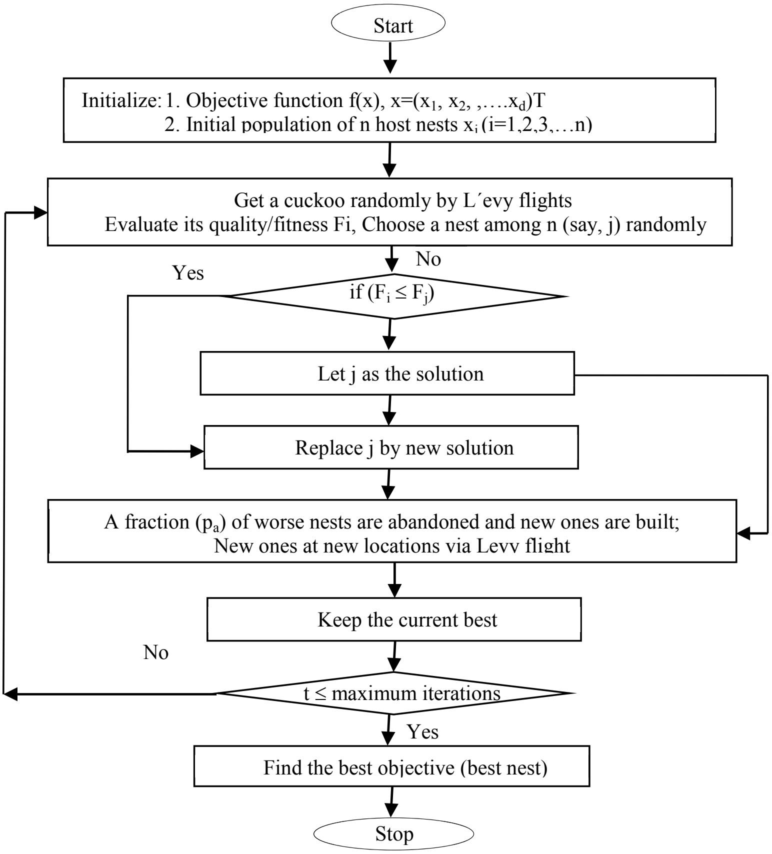


Fig. 1. Flow chart for Cuckoo search algorithm

3 Controller Structure

The complete transfer function model of the gasifier can be represented in the form as:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} \\ G_{31} & G_{32} & G_{34} & G_{34} & G_{35} \\ G_{41} & G_{42} & G_{43} & G_{44} & G_{45} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} + \begin{bmatrix} G_{d1} \\ G_{d2} \\ G_{d3} \\ G_{d4} \end{bmatrix} \times d \tag{3}$$

Where, G_{ij}=transfer function from ith input to jth output; y_1, y_2, y_3 and y_4 = Outputs; u_1, u_2,u_3,u_4 and u_5 = Inputs; d =sink pressure (PSink);

Limestone flow rate is set to 10% of coal flow rate and thus the process can be reduced to 4X4 MIMO process for control purpose. For a multivariable process, decentralised control schemes are usually preferred. The structure of decentralised controller used in gasifier control. It employs three PI controllers and one feedforward+feedback controller for coal flow rate.

$$G_c(s) = \begin{pmatrix} 0 & \left(K_p + \frac{1}{\tau_i s}\right) & 0 & 0 \\ K_f & 0 & K_p & 0 \\ 0 & 0 & 0 & \left(K_p + \frac{1}{\tau_i s}\right) \\ \left(K_p + \frac{1}{\tau_i s}\right) & 0 & 0 & 0 \end{pmatrix} \tag{4}$$

Gasifier process fails to satisfy the constraints [1] at 0% load operating point with the given controller structure (i.e. PGAS exceeds the limit of ±0.1bar). This major drawback can be rectified by retuning the controller parameters of the baseline controller.

4 Problem Formulation

Figure 2 shows the proposed scheme for Cuckoo search based retuning of pressure loop PI controller. The objective of this scheme is to meet the performance requirements at 0% load conditions.

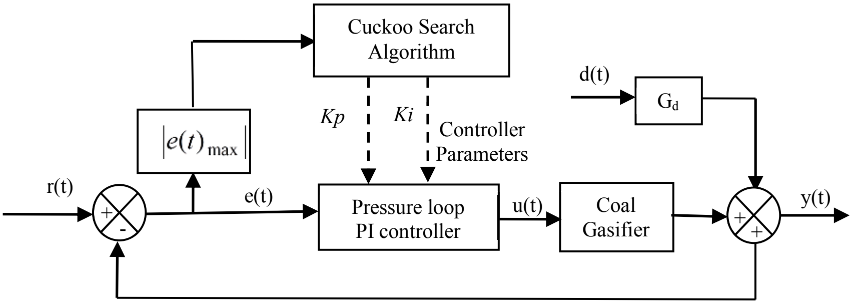


Fig. 2. Block diagram of Optimization scheme

Since control at 0% load is difficult the authors choose pressure loop PI controller to retune its parameters at 0% operating point. Proportional gain (K_p) and integral time(T_i) of Pressure loop PI controller are taken as decision variables while the maximum Absolute Error (AE) at 0% operating point and sinusoidal pressure disturbance is considered as the objective function. Input constraints are associated with Simulink model and it is not included in the desired specifications. The controller should respond quickly enough so that the output variables do not deviate from the set point more than the specified constraints. Hence the sampling time is selected as 0.5 seconds. With the above settings Cuckoo search algorithm is executed, and maximum Absolute Error is calculated. Optimum controller settings are obtained after running the simulation for several times. The obtained proportional gain and integral time of decentralised PI controller and default controller parameters [1], provided with the challenge pack is shown in table 1.

Table 1. Controller parameters

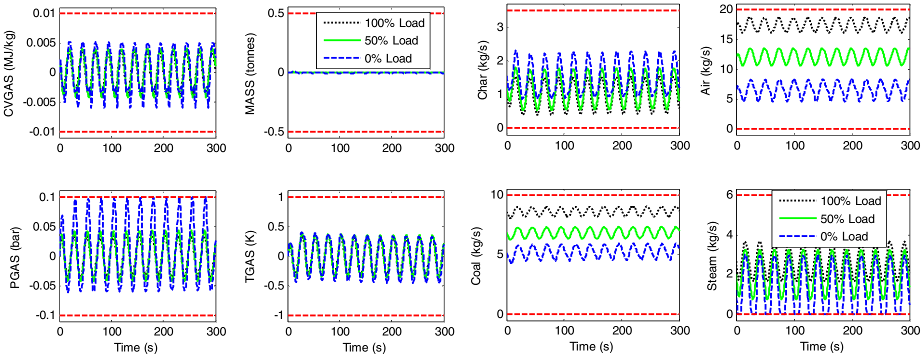
Parameter	Dixon-PI	Cuckoo search based PI controller
Pr_Kp	0.00020189	0.000354275
Pr_Ki	2.64565668e-05	7.010235151e-08

5 Performance Tests

Robustness of Cuckoo search based decentralised PI controller is verified by conducting performance tests (pressure disturbance, load change and coal variation). The requirement is that the response should meet the constraints [1] at 0%, 50% and 100% operating points for all performance tests.

5.1 Pressure Disturbance Tests

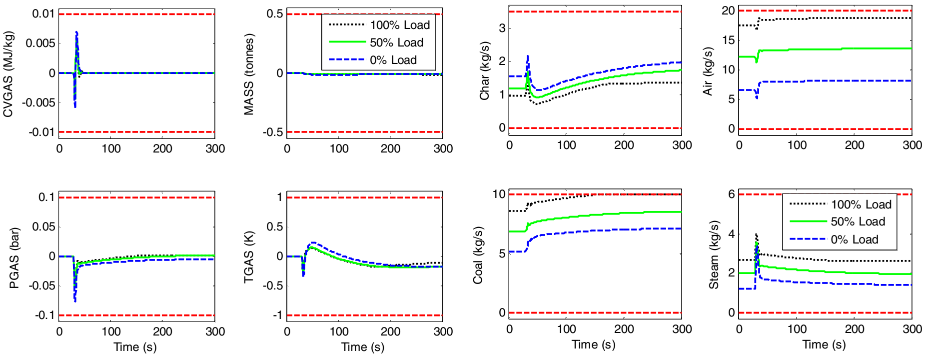
At 100% load a sinusoidal pressure disturbance (PSink) with a magnitude of 0.2bar and frequency of 0.04Hz, is applied to the gasifier. Maximum Absolute Error (AE) and Integral of Absolute Error (IAE) are calculated over a period of 300 second. This procedure is repeated for 50% and 0% operating points. Figure 3 shows the response of gasifier Cuckoo search based decentralised PI controller at 0%, 50% and 100% loads for sinusoidal pressure disturbance. All the outputs oscillate around their steadystate values and the magnitudes of these outputs are similar to [1] except for PGAS where the magnitude is reduced appreciably. The outputs meet the performance requirements comfortably, but with the existing baseline PI controller, PGAS violates the constraints at 0% load for sinusoidal pressure disturbance.



(a) Outputs and Limits (b) Inputs and Limits

Fig. 3. Response to sinusoidal disturbance at 0%, 50% and 100% load

Above procedure is repeated for step disturbance with a magnitude of 0.2 bar and further analysis is carried out. Figure 4 shows the response of gasifier with Cuckoo search based decentralised PI controller at 0%, 50% and 100% loads for step pressure disturbance. The shown outputs are the deviation from the steadystate values.



(a) Outputs and Limits (b) Inputs and Limits

Fig. 4. Response to step disturbance at 0%, 50% and 100% load

Table 2. Summary of test output results

Test Description	Output	Maximum Absolute Error		IAE	
		Cuckoo-PI	Dixon-PI[1]	Cuckoo-PI	Dixon-PI[1]
100% Load, Step Disturbance	CVGAS	5422.38	4885.23	63878.92	60989.48
	MASS	6.94	6.94	1546.51	1597.03
	PGAS	4439.46	5018.94	173884.61	78475.47
	TGAS	0.26	0.24	62.98	65.09
50% Load, Step Disturbance	CVGAS	5864.79	5102.16	68379.15	64766.48
	MASS	8.45	8.45	887.24	840.04
	PGAS	5262.17	5790.93	226809.25	94310.73
	TGAS	0.29	0.27	73.78	77.13
0% Load, Step Disturbance	CVGAS	7048.03	5875.95	86780.39	86561.16
	MASS	11.05	11.05	1122.64	1330.92
	PGAS	7597.60	7714.53	497654.43	120167.73
	TGAS	0.36	0.32	70.52	77.05
100% Load, Sinusoidal Disturbance	CVGAS	3694.67	4101.30	1381309.32	1545471.04
	MASS	10.68	10.89	4156.20	4154.65
	PGAS	3471.73	4981.41	1297515.31	1857629.38
	TGAS	0.34	0.38	121.76	134.44
50% Load, Sinusoidal Disturbance	CVGAS	4238.37	4715.68	1569922.39	1759740.23
	MASS	12.61	12.87	5039.63	5041.36
	PGAS	4304.03	6209.91	1603092.22	2307614.42
	TGAS	0.38	0.42	134.70	149.47
0% Load, Sinusoidal Disturbance	CVGAS	5904.44	5869.69	1987706.29	2074977.65
	MASS	16.21	16.35	6178.99	6016.65
	PGAS	9995.70	11960.42	2831464.84	3845931.81
	TGAS	0.45	0.48	155.57	159.09

All the outputs meet the performance requirements comfortably. Marginal changes in other output variables are also observed. This is due to the interactions among the control loops i.e., changes in one input variable affects all the outputs. Table 2 shows the performance indices for sinusoidal and step pressure disturbance tests. All the outputs meet the performance requirement comfortably without violating the constraints.

5.2 Load Change Test

Stability of the gasifier and controller function across the working range of the plant is verified by load change test. For this purpose the system is started at 50% load in steady state and ramped it to 100% over a period of 600 seconds (5% per minute). The actual load, CVGAS and PGAS track their demands quickly to setpoint while Bedmass takes more time to reach its steady state, though manipulated inputs coal flow and char flow have reached their steady state immediately.

5.3 Coal Quality Test

The quality of syngas depends on the coal quality (carbon content and moisture content). In this test, the quality of coal increased and decreased by 18% (the maximum possible change in coal quality), and the above pressure disturbance test are conducted to verify the robustness of the controller. Input-output responses for sinusoidal and step change in PSink are verified for 300 seconds. Table 3 shows the violation of the variables under positive and negative change in cola quality. Since input constraints are inbuilt in the actuator limits, output constraints are considered to be the actual violation. TGAS and PGAS violate the limits under change in coal in coal quality for sinusoidal pressure disturbance and no output variable is found for step pressure disturbance

Table 3. Violation variables under coal quality change (±18%) (↑ - the variable reaches its upper limit, ↓ the variable reaches its lower limit)

Load	100%		50%		0%	
Disturbance type	Sine	Step	Sine	Step	Sine	Step
Coal quality increase (+18%)	Char↓ Tgas↑	Char↓	Char↓ Tgas↑	Within limits	Char↓ WStm↓ Pgas↑	Within limits
Coal quality decrease (-18%)	Coal↑ Tgas↓	Coal↑	Within limits	Coal ↑	Char↑ WStm↓ Pgas ↑	Char↑

6 Conclusion

This paper uses Cuckoo search algorithm to retune the parameters of decentralised PI controller for pressure loop of Coal gasifier. Existing controller with tuned parameters does not satisfy the performance requirements at 0% load for sinusoidal disturbance. And hence optimal tuning parameters are obtained using Cuckoo search algorithm. Pressure loop PI controller parameters are replaced by obtained controller parameters and performance tests are conducted. Pressure disturbance test shows excellent results and meets the performance requirement satisfactorily even at 0% load. Load change test and coal quality tests also provide good results. For the allowable limits of coal quality variations (±18%), test results shows that the Cuckoo search based decentralised PI controller provides good results. Finally it can be concluded that Cuckoo search can be used to get the optimum controller parameters results and further the response can be improved by the use of Multi-Objective Cuckoo search Algorithm.

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