BEHAVIOR RESPONSES AND CONTROL MODELING BASED CASCADED PID CONTROLLER SCHEME FOR COMBUSTION OF A UTILITY BOILER

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Abstract – The main objective of the combustion controller in a thermal power plant is to regulate fuel and air in proper ratio to maintain the desired steam pressure at the turbine inlet, irrespective of the changes in steam demand. To achieve a continuous supply of steam at the desired pressure conditions is difficult to cope with inherent time delay, nonlinearity due to uncertainty of the combustion process and frequent load changes. This paper deals with the design of behavior response computation based approach to get the optimal PID controller parameters for the combustion control of utility boiler. A separate control model is developed for Fuel and Air system. The control model for fuel will drive the Fuel controller which is cascaded with Air controller. PID controller for Air and Fuel system will use the optimum PID parameter derived from response based computation method. Many steady state and dynamic behavioral responses were analyzed for different load conditions. A lab scale experimental setup is fabricated in the laboratory for fuel and air control and tests were carried out for several load conditions. Optimal PID controller parameters were obtained when the experimental responses have good agreement with the real time behavior responses. The advantages of the proposed design are highlighted.

Key words: utility boiler, PID controller, combustion control

I. INTRODUCTION

The utility boilers are large capacity steam generators used purely for the electrical power generation. In a Thermal power station, steam is produced in a boiler, is expanded in the prime mover (Turbine) and condensed in a condenser before feeding it into the boiler again. The turbine shaft is coupled with generator, which is used to produce electricity.

Combustion control in a utility boiler is one of the most important control loops in a power plant. The combustion system consist of airflow and the fuel flow control loops that are driven by the firing rate demand signal through master steam pressure controller. Conventional PID (Proportional – Integral – Derivative) controller used for combustion control is simple in structure, reliable in operation and robust to certain extent in performance. But they are not generally suitable for non-linear, higher order, time delayed and complex systems that have no precise mathematical models. Further it needs frequent tuning, which is not an easy task and is also time consuming

Ma Su-xia et al [1] designed software for static behaviors of circulating fluidized bed boiler to provide precious technical support for optimization operation of the boiler, and provide technical methods for the development of advanced circulating fluidized bed combustion technology. Farshad et al [2] analyzed reliability indices for all parts of generation unit (Thermal Power Plants) by using new method of modeling. Huan Zhao et al[3] in order to improve boiler efficiency and to reduce the NOx emission of a coal-fired utility boiler using combustion optimization, a hybrid model, by combining support vector regression (SVR) with simplified boiler efficiency model, was proposed to express the relation between operational parameters of the utility boiler and both NOx emission and boiler efficiency. Fang et al [4] described accurately the status of boiler furnace combustion in simulation, analysis and optimization of power generation process and to improve the accuracy of simulation. Several researchers developed dynamic models [5] for boilers. The complexity involved in obtaining the reasonably accurate models is high. If assumptions were made to reduce complexity in obtaining models, it would yield degraded performance of controllers. Further linear [6] and nonlinear [7] controllers were designed and developed. Yinsong et al [8] first introduced a nonlinear model combining boiler-turbine-generator dynamic characteristics for a thermal-power-generation unit. Based on the nonlinear model, a new coordinated control design is proposed using the backstepping method incorporating the coordinated passivation approach that considers the entire boiler-turbine-generator system as a whole. Lee et al [9] investigated a large-scale once-through-type ultra supercritical boiler power plant for the development of an analyzable model for use in developing an intelligent control system. Widd et al [10] proposed predictive controllers based on linearization of the model. Further cluster [11] based performance optimization were developed. Horn et al [12] demonstrated an intelligent concepts superior to a standard PI controller with a setting found by classic tuning rules through sliding-mode controller. Biswal et al [13] proposed for development and implementation of supervisory control and data acquisition (SCADA) based process control and monitoring system.

Bezerra et al [14] developed a stochastic optimization model for the creation of a bidding strategy for a generator in an energy call option auction. Rajanikanth et al [15] proposed a new approach based on finite difference method for the simulation of electrical conditions in a dc energized wire-duct electrostatic precipitator with and without dust loading.

In order to utilize the robustness and advantages of the PID controller, a behavior modeling approach has been proposed to get optimum PID parameters.

The present paper is organized as follows: Section 2 deals with the design of Response behaviors approach to obtain optimum PID parameters for fuel and air controllers using fabricated hardware set up in the laboratory. Section 3 deals with Control modeling of a Boiler combustion system. Section 4 deals lab scale experimental setup. Section 5 describes the simulation studies of conventional PID & behavior responses and control modeling based cascaded PID controller for combustion process. Section 6 presents the comparison of performances of PID & behavior responses and control modeling schemes and Section 7 gives the summary & conclusions.

II. RESPONSE BEHAVIORS

In the present work, many behavior responses for load vs. pressure, fuel flow and airflow with respect to steady state and dynamic states were obtained from thermal power plant during real time operation and are shown in Figures (1-6).

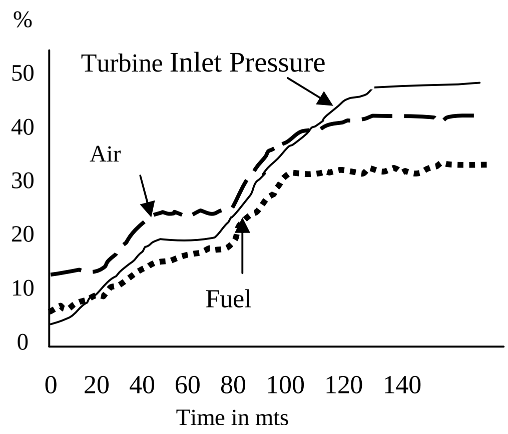

Fig.1. Boiler Start-Up curve

Fig.1 shows the real time start-up response. While starting the boiler, the drum pressure should be increased slowly to avoid thermal stress to the boiler tubes. The rate of raise of drum pressure will be around 1kg per minute and it will vary depending on the furnace volume of the boiler. While increasing the drum pressure, proper air-fuel ratio is maintained for combustion.

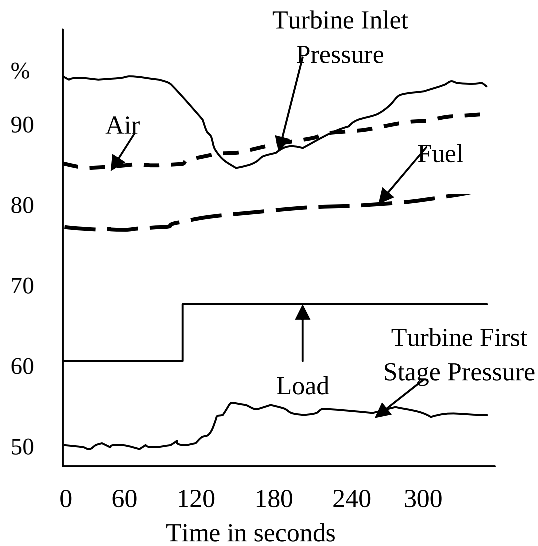

Fig. 2. 10% change in ramp load

Fig.2. shows the response of 10% positive change in ramp load from 60% to 70%. Immediately after load increases, the turbine first stage pressure increases and turbine inlet pressure decreases. In order to keep the turbine inlet pressure at the desired value, corrective action for air and fuel flow is achieved smoothly by the controller.

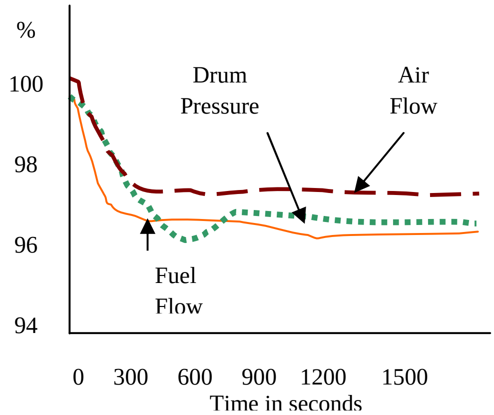

Fig.3.Open Loop (Δ fuel flow 100% to 95%)

Fig. 3 shows the open loop behavior for change of fuel flow in the negative direction from 100% to 95%.

Fig.4 shows the open loop behavior for change of fuel flow in the positive direction from 95% to 100%. Airflow also follows the fuel flow to maintain required excess air for complete combustion.

Drum pressure takes long time to reach steady state value than fuel and air flow. This effect is because of shrinking and swelling action of the water inside the drum.

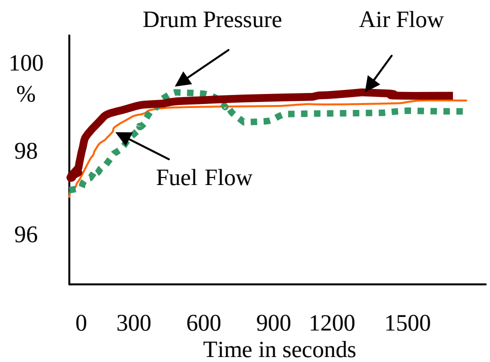

Fig.4.Open Loop (Δ fuel flow from 95% to 100%)

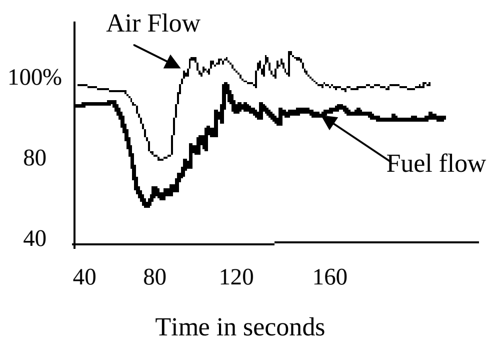

Fig. 5. Sudden load change due to grid disturbance

Fig.5. shows the behavior of air and fuel flow to maintain desired turbine inlet pressure and also boiler drum pressure during sudden load change due to grid disturbance. Grid disturbance may be due to large and sudden variation in the demand. Sudden variation in drum pressure due to change in the steam demand should be brought back to normal by adjusting the fuel and air flow in proper ratio.

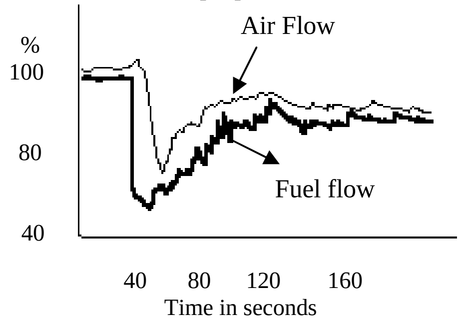

Fig. 6. Sudden run back of load due to auxiliary failure

There are two feed water pumps to feed the water and two forced draft fans to supply required air flow to the boiler at full load. If anyone fails there is an automatic reduction of load to 60% of maximum continuous rating to avoid tripping of boiler due to low drum level and low airflow. Fig.6. shows the behavior of air and fuel flow to maintain desired turbine inlet pressure and also boiler drum pressure during sudden run back of load due to failure of any one of the auxiliaries mentioned above.

After obtaining the behavior responses from power plant, real time simulations were carried out, by mimicking all the above-mentioned cases, on the lab scale experimental set-up for fuel and airflow.

In order to obtain optimum PID controller parameters an illustrative response for fuel flow is shown in Fig. 7.

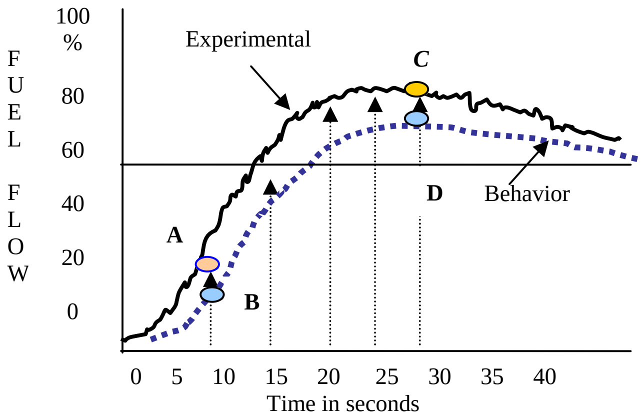

Fig.7. Closed loop behavior and experimental responses to obtain optimum PID parameters.

Point 'A' = $f(k_1)$ = Experimental Fuel flow sample at k_1^{th} instant.

Point 'B' = $f(k_1)$ = Behavior Fuel flow sample at k_1^{th} instant.

Point 'C' = $f(k_n)$ = Experimental Fuel flow sample at k_n^{th} instant.

Point 'D' = $f(k_n)$ Behavior Fuel flow sample at k_n^{th} instant.

The following algorithm is proposed for mimicking each behavior response.

Step 1: Initialize K_p, K_I and K_d the Proportional, Integral and Differential gains respectively of PID controller for both fuel and air flow.

Step 2: Conduct experiments and plot the response for one behavior for different load conditions.

Step 3: Find out deviations between behavior and experimental response at different sampling times.

Step 4: Find average of all deviations.

Step 5: Adjust k_p, k_I and k_d of the fuel and air controllers.

Step 6: Repeat the experiment until deviations between behavior and experimental response become zero.

Step 7: Note down the final value of k_p, k_I and k_d of the fuel and air controllers, which are taken as optimum PID parameters for particular behavior.

Repeat the procedure for all the behaviors mentioned above.

TABLE 1. Optimal PID controller parameters for different behavior responses

Behavior Responses	**PID parameters**					
	K_P		**K_I**		**K_D**	
	Fuel	Air	Fuel	Air	Fuel	Air
Boiler Start-Up	2	1.5	1.8	1.2	0.3	0.4
10% change in ramp load from 60% to 70%	1.8	2	1.2	1	0.5	0.5
Open Loop Response (Change in Fuel Flow 100% to 95%)	1.8	1.7	1.5	1.2	0.3	0.5
Open Loop Response (Change in Fuel Flow 95% to 100%)	1.8	1.7	1.5	1.2	0.3	0.5
Sudden load change due to grid disturbance	2.5	1.7	1.5	1.2	0.3	0.5
Sudden run back of load due to auxiliary failure	2.5	2	2	1.8	0.5	0.5
Sudden Load throw off to House Load	3	2.5	2.5	2.1	0.5	0.5

Keeping the above optimum PID parameters as guidance, again several simulations were carried out on the lab-scale experimental set-up for all the behavior responses. Finally, one set of overall optimal PID controller parameter, which will mimic almost same way for all the types of dynamic behaviors mentioned above was found out. The overall optimum PID parameters obtained for air and fuel flow controllers suitable for any kind of dynamic behavior of combustion process in utility boiler is presented in Table2.

TABLE 2. Overall Optimum PID Controller Parameters for Fuel and Air

Control loop	Optimum PID parameter		
	K_P	K_I	K_D
Fuel Controller	1.75	1.0	0.2
Air Controller	1.5	0.8	0.2

These optimal PID parameters are used to the Fuel/Air controller through error signal derived from control models.

III. CONTROL MODELLING OF A BOILER COMBUSTION SYSTEM

Assumption1: The turbo – generator is not on automatic load dispatch control.
Assumption2: The steam demand variation is due to load (MW) disturbance only.
Assumption3: The unit control is under boiler follow mode.

With the above assumptions a control model has been developed to get variable fuel error.

P_l –Turbine first stage steam pressure … (1)
P_t - Throttle steam pressure (Turbine inlet pressure) … (2)
$\dot{P}_d$- Drum pressure differential … (3)
P_s - is the set point for the throttle pressure ... (4)

Control balance error is proportional to (Required Pressure) - (applied pressure) ... (5)

This is proportional to the fuel error at any load varying condition. This will track a desired trajectory within the boundary region.

Fuel error = $(P_l / P_t)\ P_s$ - (applied pressure) ... (6)

Fuel error = $(P_l / P_t)\ P_s - (P_1 \pm \dot{P}_d)$ ... (7)

When load increases, the steam demand increases, throttle pressure decreases. The difference between the set-point & throttle pressure will produce the error signal to the combustion controller which will increase the airflow first & then the fuel flow to bring back the throttle pressure to the desired value. There will be a time delay between the application of the input to the combustion controller and the resulting effect on it, which will degrade the total performance. To improve the performance, a control balance model has been developed to give the variable fuel error to the PID controller for fuel.

A control model for air has been developed which is proportional to variable fuel error is presented below.

For combustion control, if only the theoretical air required for complete combustion of fuel is supplied, substantial amount of soot and Carbon Monoxide will be observed in the flue gases. For achieving complete combustion excess air over and above the theoretically required quantity will have to be supplied to the boiler.

To maintain excess air, the set value for the air controller is proposed with respect to the fuel error derived from equation (7).

Set value for air controller = $e_{f\ Model} + (e_{f\ Model} *$ Weight factor) ... (8)
Where Weight factor = $(W/100) * e_{f\ Model}$ … (9)

W=12 for less than 30% of load or steam flow ... (10)
W = 15 for 30 % to 50% of load or steam flow ... (11)
W = 20 for 51 % to 75% of load or steam flow … (12)
W = 25 for 76 % to 100% of load or steam flow ... (13)

The proposed value of the weight factor “W” for air is arrived after considering several dynamics of the boiler and also the knowledge obtained from the experts of thermal power station. This will also satisfy the control balance derived by practicing engineers and researchers.

The above control balance model based air set value will change the airflow immediately after dynamic or programmed load disturbance, which will always be in excess to the theoretical value.

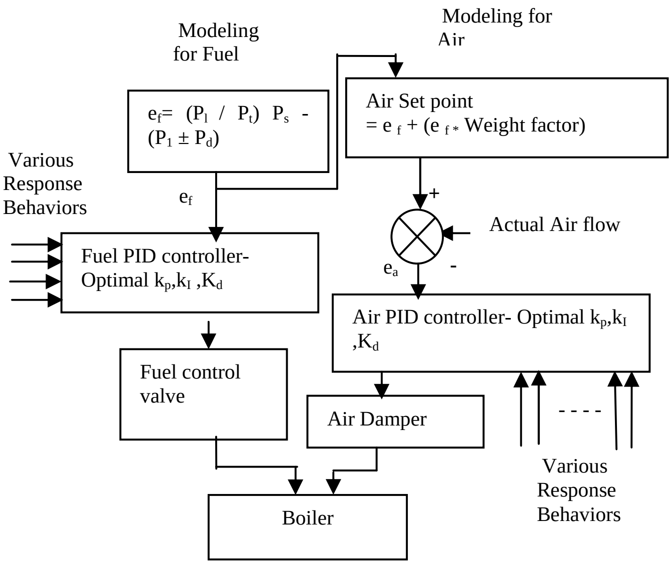

Fig.8 .Modeling Based Cascaded PID Control for Fuel and Air

The cascaded controller diagram is shown in fig. 8. Fuel error derived from the fuel model is cascaded to air model. When there is dynamic change due to grid disturbance the control balance model is proposed by considering turbine first stage pressure change, which is the first and immediate response, due to load disturbance and considered as feed forward information. Optimal k_p, k_I and k_d values were obtained from behavior responses method will be used by Air/Fuel controller.

IV. LAB SCALE EXPERIMENTAL SET-UP

In order to find out optimum PID controller parameters and also to carry out the closed loop studies of PID and behavior schemes for air and fuel flow, a lab scale experimental set-up is designed and fabricated as shown in Fig. 9.

Using the optimal PID parameter algorithm, simulations on the experimental setup for various behavior responses were carried out. The values of optimal PID parameters obtained by trial and error method are presented in Table1. These values are considered as optimum for particular behavior response because of satisfactory agreement with the real time response obtained from 210 MW thermal power plant.

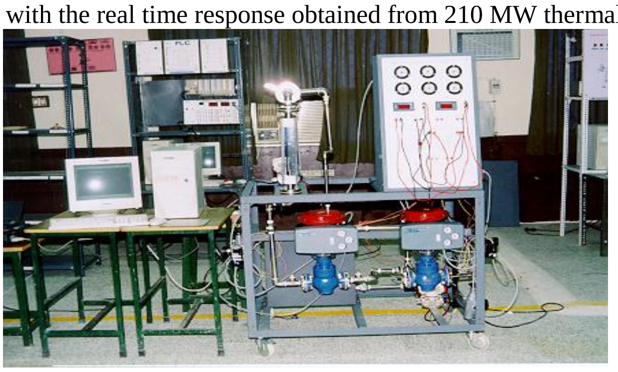

Fig.9 Experimental Set Up

V. SIMULATION STUDIES

Several experiments were conducted on the experimental set-up and the performances for both changes in the set point as well as in the load perturbation were studied. The responses obtained for positive and negative step change in load are shown in Figs. 10-13.

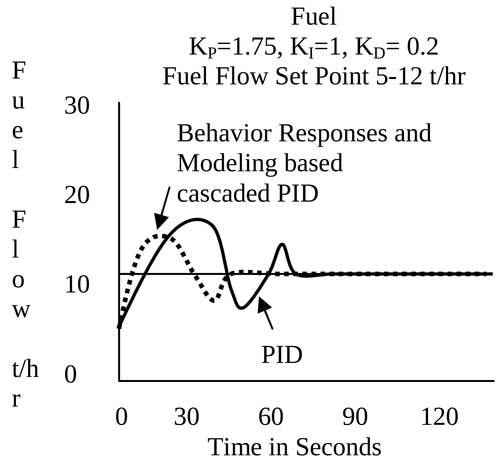

Fig.10 Fuel flow response
LOAD 21MW-42MW

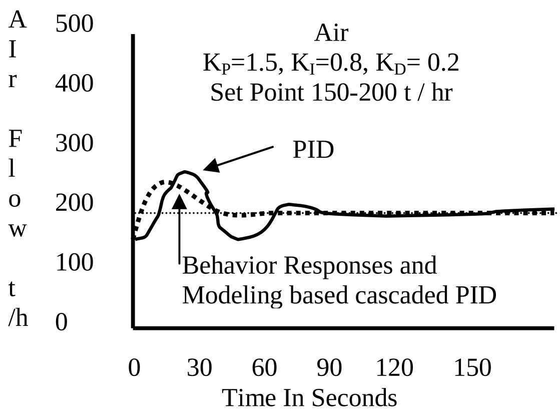

Fig.11. Air Flow Response
Load 21MW-42MW

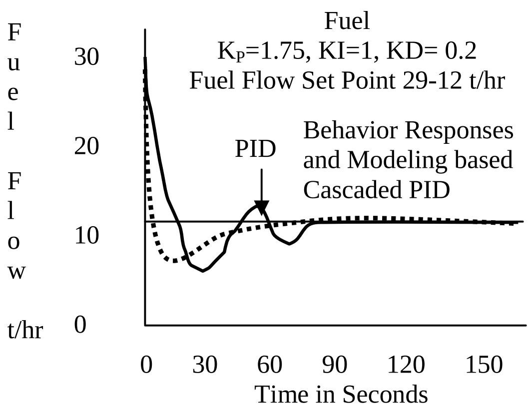

Fig.12 Fuel flow response for
110 to 42 MW change in load

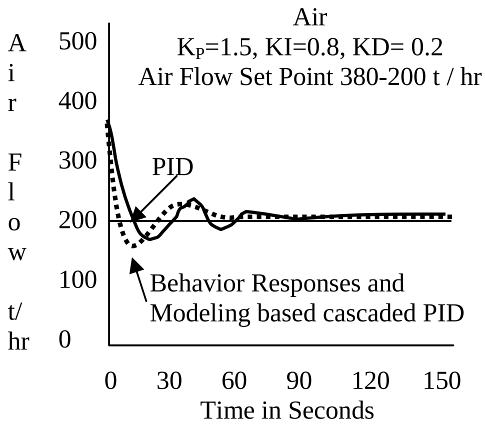

Fig.13 Air flow response for
110 to 42 MW change in load

VI. COMPARISON OF PERFORMANCES OF BEHAVIOR RESPONSES AND CONTROL MODELING SCHEME WITH PID SCHEME

After implementing PID and Behavior Responses & Control Modeling Based Cascaded PID controllers, their closed loop behaviors are compared. The comparisons of time-domain specifications and performance of the two controllers for positive step change in load are presented in Table 3&4.

TABLE 3. Comparison of Time Domain Specifications

Controller scheme	Controller loop	Rise time	Peak time	Settling time
PID	Air flow	21	26	83
	Fuel Flow	32	39	74
Behavior Responses and Modeling based Cascaded PID	Air flow	14	17	40
	Fuel Flow	12	18	41

TABLE 4. Comparison of Performances

Controller scheme	Controller loop	ISE	IAE
PID	Air flow	5756	5128
	Fuel Flow	4988	5023
Behavior Responses and Modeling based Cascaded PID	Air flow	3072	4150
	Fuel Flow	3276	4092

VII. CONCLUSIONS

The results of this paper highlight the robustness of the conventional PID with behavior responses and control modeling based cascaded PID controller scheme for step changes in loads. The response of conventional control system has 26% overshoot for air and 39% for fuel flow. It settles down after about 83 and 74 steps of increment for air and fuel respectively. The closed loop response of the behavior responses and control modeling based cascaded PID controller scheme shows satisfactory transient response without much overshoot and settles down after about 33 and 31 steps of increment for air and fuel respectively. This shows 55% improvement over conventional schemes in settling time for both air and fuel. The proposed controller scheme results in least ISE and IAE values for the step changes in load showing 24% improvement for air and 30% improvement for fuel control when compared to conventional schemes. The qualitative and quantitative comparisons of the performance of the various control schemes reveal the superiority of the behavior responses and modeling based cascaded PID controller scheme over the conventional control schemes.

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