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Multiloop Controller Design for Co-Ordinated Control of Boiler Turbine Unit

M.S. Murshitha Shajahan, T.R. Rangaswamy and P. Abitha

Department of EIE, B.S. Abdur Rahman University, Chennai, India

Abstract: This paper proposes a Boiler Turbine coordinated multiloop controller design. The system controls three main boiler-turbine parameters i.e., the drum pressure, drum level and electric power output. As the system is a highly nonlinear MIMO process, we will encounter a lot of interactions and cross couplings among the controllers. To reduce such effects a coordinated-control scheme with a compensator is presented. The compensator is used to reduce the interaction effects to a degree manageable by the controllers. Difficulties caused by the interactions are always encountered in the design of multi-loop control systems for MIMO processes. To overcome the difficulties, a multi-loop system is decomposed into a number of equivalent single loops for design.

Key words: Fossil fuel power plant · Co-ordinated control · Interaction compensator

INTRODUCTION

A typical power plant often consists of a boiler-turbine unit, which is generally considered to be a highly nonlinear and strongly coupled complex system, in which the chemical energy of coal is transformed into mechanical energy acting on the turbine and generator, which in turn transforms the mechanical energy into electricity. In recent years, there have been dramatic changes in the electric power generation industry. The changing market demands and competition have forced the older conventional coal-fired power plants to operate in a much more dynamic environment. For the boiler-turbine control system, the main objective is to adjust the power output to meet the demands while maintaining the steam pressure and temperature within desired ranges. The standard multi-loop single-input-single output (SISO) strategies are turbine following and boiler following configurations. In boiler follow mode, the power output is controlled by the boiler firing rate, whereas in turbine follow mode, the power output is controlled by the throttle valve position as the power output is directly proportional to the amount of steam supplied to the turbine. Generally, the turbine follow mode can provide minimal variations to steam temperature and pressure, but it cannot track the load demand quickly due to the slow steam generation in conventional coal-fired power plants. In contrast, by opening the throttle valve, different amount of steam can be supplied immediately, but this is at the expense of depleting stored energy in the boiler leading to main steam pressure variations. To overcome this co-ordinated control of boiler-turbine unit is preferred.

This paper is organized as follows: Section 2 describes the coordinated mode of a boiler-turbine unit and the mathematical modeling of Boiler Turbine system (BTS). Section 3 describes the Interaction Decoupler design of BTS. Section 4 describes the multiloop controller design for Boiler-Turbine unit.Section 5 describes simulation results & conclusion is presented at the end.

Simple Boiler-Turbine Unit: Operation of Fossil Fuel Power Units (FFPUs), the most widely-used kind of units for power generation, has been heavily affected. Firstly, a FFPU must support the main objective of the power system that is to meet the load demand for electric power at all times, at constant voltage and at constant frequency. Xiao Wu *et al*. [1] presented the control of a boiler-turbine coordinated system using multiple-model predictive strategy which integrates constrained model predictive algorithm with stability assurance into multiple-model approach based on piecewise linearization. Donghai Li *et al*. [2] proposed the method can asymptotically estimate and compensate the nonlinearity, coupling and disturbances owing to its observation ability for Multivariable Nonlinear Controller (MNC) to a

Corresponding Author: M.S. Murshitha Shajahan, Department of EIE, B.S. Abdur Rahman University, Chennai, India.

multivariable nonlinear boiler-turbine unit.. A decentralized MNC system is obtained for a nonlinear boiler-turbine model, and then evaluated under a wide range of operating conditions and perturbations. A Wen Tan *et al*. [3] proposed distance measure via the gap metric in this paper, and the concept is applied to a boiler-turbine unit to analyse its dynamics. It is shown that the unit shows severe nonlinearity, but the nonlinearity can be avoided by careful choice of the operating range and a single linear controller can be designed to work in such an operating range. Pang-Chia Chen *et al*. [4] presented a gain-scheduled approach for boiler-turbine controller design. The objective of this controller design is to achieve tracking performance in the power output and drum pressure while regulating water level deviation. Also, the controller needs to take into account the magnitude and rate saturation constraints on actuators. Raul Garduno-Ramirez *et al*. [5] presented the first evaluation of a multiloop control scheme with a feed forward-equivalent compensator, which can be designed from input-output process data. Simulation experiments show that the proposed compensator is numerically well conditioned, and effectively handles control loop interaction. Robert Dimeo *et al*. [6] proposed the application of a genetic algorithm to control system design for a boiler-turbine plant. The ability of the genetic algorithm to develop a proportional-integral (PI) controller and a state feedback controller for a non-linear multiinput/ multi-output (MIMO) plant model. R.D Bell *et al*. [7] presented a report for overall response evaluation of large scale fossil fueled boiler-turbine alternator power generation units. such models can be used for control studies as well as macro design simulations. K.J Astrom *et al*. [8] presented a simple model for boiler drum. it describes the response in output power due to variations in three inputs, fuel flow,feedwater flow and steam valve position. the model has only one state variable which accounts for the major energy storage. K.J Astrom *et al*. [9] presented a paper for drum boiler whose purpose is to describe the gross behavior of the 160 MW boiler. The major control variables are fuel flow and control valve setting. The output variables are drum pressure and active output power.

Coordinate Mode: The coordinated boiler-turbine control system is a key element in the operation of large modern fossil-fuelled steam-electric generating stations. In this mode the turbine inlet pressure and firing rate are manipulated to regulate throttle steam pressure and turbine speed. The structure of coordinated control system is shown in Figure 1, where the dominant behavior of unit is governed by actuating elements (turbine valves and fuel/air supply) influenced simultaneously by load and pressure for matching the boiler output pressure with the turbine demand.

It achieves the responsiveness of boiler-following mode but with the stability of turbine-following mode. Hence overshoot and instability is avoided.

Boiler Turbine Mathematical Model: The dynamics of a FFPU for overall widerange simulations have been captured for 160 MW oil fired drum-type unit through a third order nonlinear model (Bell and Astrom, 1987). The inputs are the positions of valve actuators that control the mass flow rates of fuel (u1 in pu), steam to the turbine (u2 in pu), and feedwater to the drum (u3 in pu). The three outputs are drum steam pressure (P in kg/cm^2), electric power (E in MW), and drum water level deviation (L in m). The state equations are:

$$\dot{x}_1 = -0.0018\, u_2 x_1^{\frac{9}{8}} + 0.9u_1 - 0.15u_3$$

$$\dot{x}_2 = (0.073u_2 - 0.016)x_1^{\frac{9}{8}} - 0.1x_2$$

$$\dot{x}_3 = (143u_3 - (1.1u_2 - 0.19)x_1)/85$$

The three state variables are drum steam pressure (P), electric output (E) and density of steam (ρ_f). The drum water level output is calculated with the following algebraic equations:

$$X_w = 0.05(0.1307 + 100a_{cs} + \frac{q_e}{9} - 67.975$$

where,

$$a_{cs} = \frac{(1 - 0.001538x_3)(0.8x_1 - 25.6)}{x_3(1.0394 - 0.00123404x_1)}$$

$$q_e = (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.514u_3 - 2.096$$

where a_{cs} is the steam quality, and q_e is the evaporation rate (kg/sec).Pressure and power output are just the first two state variables.

A linear state-space model can be obtained from the Taylor series expansion of the nonlinear equations or by using jacobian method around an equilibrium point defined by u = [0.34,0.69,0.436] with y= [108,66.65,0] as the corresponding output. Table 1 shows the various operating points of the plant. Hence, the system matrices are:

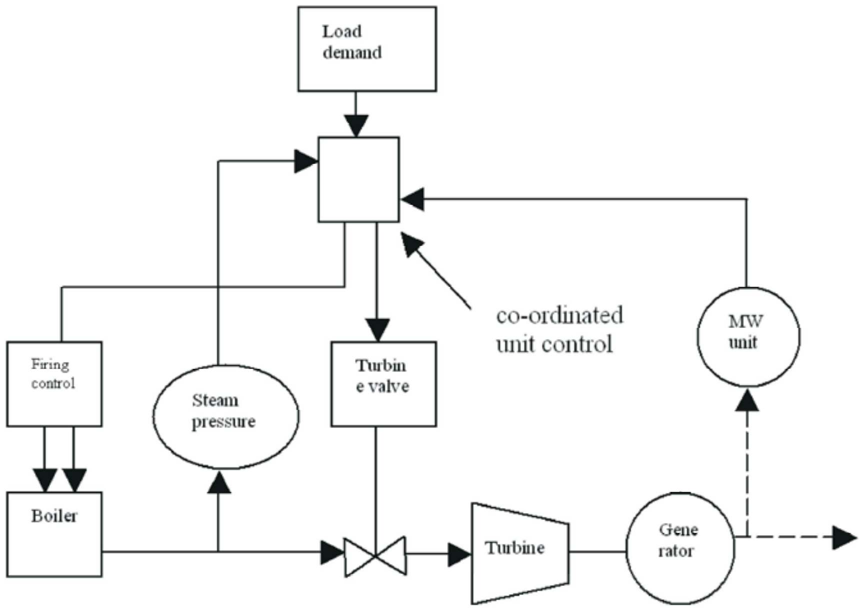

Fig. 1: Schematic Diagram of Coordinate mode

Table 1: Operating points of plant

OP	1	2	3	4	5	6
x1	86.4	97.3	108	118.7	129.7	140.5
x2	36.65	50.63	66.65	85.06	105.8	128.9
x3	306.9	348.3	428	482.2	553.6	604.8
u1	0.209	0.271	0.34	0.418	0.505	0.6
u2	0.552	0.621	0.69	0.759	0.828	0.897
u3	0.256	0.34	0.436	0.543	0.663	0.793

$$A = \begin{bmatrix} -2.509 \times 10^{-3} & 0 & 0 \\ 6.94 \times 10^{-2} & -0.1 & 0 \\ -6.67 \times 10^{-3} & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 6.34 \times 10^{-3} & 0 & 4.71 \times 10^{-3} \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.253 & 0.512 & -0.014 \end{bmatrix}$$

The transfer function model can be obtained from the MATLAB command or by directly from the linear state-space model using the Laplace transform. The elements of the transfer function matrix are found to be:

$$G11 = \frac{0.9}{S + 0.002509}$$

$$G12 = \frac{-0.349}{S + 0.002509}$$

$$G13 = \frac{-0.15}{s + 0.002509}$$

$$G21 = \frac{0.06246}{S^2 + 0.1025\ S + 0.0002509}$$

$$G22 = \frac{14.15\ S + 0.01129}{S^2 + 0.1025\ S + 0.0002509}$$

$$G23 = \frac{-0.01041}{S^2 + 0.1025\ S + 0.0002509}$$

$$G31 = \frac{0.0253S^2 + 0.006341\ S - 2.87e^{-005}}{S^2 + 0.002509\ S}$$

$$G32 = \frac{0.512\ S^2 - 0.007513\ S - 5.557e^{-006}}{S^2 + 0.002509}$$

$$G33 = \frac{-0.014S^2 + 0.006828\ S + 2.432e^{-005}}{S^2 + 0.002509\ S}$$

Interaction Decoupler Design: A popular approach to deal with control loop interactions is to design a decoupling control schemes. The role of decouplers is to decompose a multi variable process into a series of independent single-loop sub-systems. If such a controller is designed, complete or ideal decoupling occurs and the multivariable process can be controlled using independent loop controllers.

The fossil fuel power unit is designed as a static decoupling compensator, that is, instead of using the process dynamic transfer functions only the steady-state gain of the process transfer functions are used. The main advantages of static, or steady-state, decoupling are that the design involves simple numerical computations, the decoupling compensator is always realizable, and the design only requires knowledge of the process steady-state gain matrix.

Design Procedure: The compensator is designed as in the simplified decoupling case, and is implemented with the inverse decoupling structure to approximate, in steady-state, the simple fully decoupled apparent transfer functions of the ideal decoupling case. Given the FFPU transfer matrix model, G(s) as:

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix}$$

The steady-state gain matrix is given by:

$$k = \lim_{s\to 0} G(s)$$

Whose gain elements are calculated using,

$$k_{11} = \lim_{s\to 0} G_{11}(s) = \frac{A_{12}B_{21}}{A_{11}A_{22}}$$

$$k_{12} = \lim_{s\to 0} G_{12}(s) = \frac{A_{12}B_{22} - A_{22}B_{12}}{A_{11}A_{22}}$$

$$k_{13} = \lim_{s\to 0} G_{13}(s) = \frac{A_{12}B_{23}}{A_{11}A_{22}}$$

$$k_{21} = \lim_{s\to 0} G_{21}(s) = \frac{-B_{21}}{A_{22}}$$

$$k_{22} = \lim_{s\to 0} G_{22}(s) = \frac{-B_{22}}{A_{22}}$$

$$k_{23} = \lim_{s\to 0} G_{23}(s) = \frac{-B_{23}}{A_{22}}$$

$$k_{31} = \lim_{s\to 0} G_{31}(s) = \lim_{s\to 0}\left(\frac{-A_{32}B_{21}C_{33}}{sA_{22}}\right) = \lim_{s\to 0}\left(\frac{\gamma_{31}}{s}\right)$$

$$k_{32} = \lim_{s\to 0} G_{32}(s) = \lim_{s\to 0}\left(\frac{-A_{22}B_{32}C_{33} - A_{32}B_{22}C_{33}}{sA_{22}}\right) = \lim_{s\to 0}\left(\frac{\gamma_{32}}{s}\right)$$

$$k_{33} = \lim_{s\to 0} G_{33}(s) = \lim_{s\to 0}\left(\frac{-A_{22}B_{33}C_{33} - A_{32}B_{23}C_{33}}{sA_{22}}\right) = \lim_{s\to 0}\left(\frac{\gamma_{33}}{s}\right)$$

where γ_{31}, γ_{32}, and γ_{33}, are appropriately defined for the equalities to hold.

RGA Analysis: It can be seen that the steady-state matrix K_{31}, K_{32}, and K_{33} is undetermined because there is an s term present in the denominator. This problem is always present when level dynamics (integrative processes) are involved (i.e., drum water level, dearator water level, and condenser water level in a power plant). Fortunately, the RGA provides a simple mechanism to deal with these cases, and allows the definition of an apparent gain matrix that can be used to design the interaction compensator. This leads to the direct calculation of the RGA through the Hadamard product (element by element):

$$\Lambda = (K^{-1})^T * K$$

To calculate the RGA, the gain matrix, *K*, may be written as:

$$K = \lim_{s\to 0}\begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ \frac{\gamma_{31}}{s} & \frac{\gamma_{32}}{s} & \frac{\gamma_{33}}{s} \end{bmatrix}$$

$$K = \lim_{s\to 0}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{S} \end{bmatrix}\begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix}$$

Then,

$$K^{-1} = \lim_{s\to 0}\begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix}^{-1}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & s \end{bmatrix}$$

Introducing *L*, appropriately defined:

$$K^{-1} = \lim_{s\to 0}\begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & s \end{bmatrix}$$

$$= \begin{bmatrix} L_{11} & L_{12} & L_{13}S \\ L_{21} & L_{22} & L_{23}S \\ L_{31} & L_{32} & L_{33}S \end{bmatrix}$$

Taking the Hadamard product, canceling *s*, and taking the limit:

$$\Lambda = \begin{bmatrix} L_{11}k_{11} & L_{12}k_{12} & L_{13}k_{13} \\ L_{21}k_{21} & L_{22}k_{22} & L_{23}k_{23} \\ L_{31}\gamma_{31} & L_{32}\gamma_{32} & L_{33}\gamma_{33} \end{bmatrix}$$

This would be the same if K was simply given by,

$$K = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix}$$

This can be taken as the gain matrix of the FFPU to design the interaction compensator. Therefore the steady state gain matrix is found to be:

$$k = \begin{bmatrix} 358.70 & -139.09 & -59.78 \\ 248.94 & 44.99 & -41.49 \\ -0.01126 & -0.00221 & 0.00969 \end{bmatrix}$$

Compensator Design: The simplified decoupling approach, as would be applied in steady-state, requires the product of the FFPU gain matrix and the interaction compensator to be of the form:

$$\begin{bmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \begin{bmatrix} 1 & D_{12} & D_{13} \\ D_{21} & 1 & D_{23} \\ D_{31} & D_{32} & 1 \end{bmatrix}$$

where M_1, M_2, and M_3, would be the decoupled steady-state gains for the power, pressure, and level control loops, respectively. Carrying out the product on the right side of the above equation and equalizing to zero the resulting off-diagonal elements, yields the following equation systems:

$$0 = K_{21} + K_{22}D_{21} + K_{23}D_{31}$$

$$0 = K_{31} + K_{32}D_{21} + K_{33}D_{31}$$

$$0 = K_{11}D_{12} + K_{12} + K_{13}D_{32}$$

$$0 = K_{31}D_{12} + K_{32} + K_{33}D_{32}$$

$$0 = K_{11}D_{13} + K_{12}D_{23} + K_{13}$$

$$0 = K_{21}D_{13} + K_{22}D_{23} + K_{23}$$

The equation systems can be solved simultaneously, by pairs, giving:

$$D_{12} = \frac{k_{13}k_{32} - k_{12}k_{33}}{k_{11}k_{33} - k_{31}k_{13}} = 0.433$$

$$D_{13} = \frac{k_{23}k_{12} - k_{22}k_{13}}{k_{22}k_{11} - k_{21}k_{12}} = 0.1666$$

$$D_{31} = \frac{k_{32}k_{21} - k_{31}k_{22}}{k_{33}k_{22} - k_{23}k_{32}} = -0.126$$

$$D_{21} = \frac{k_{31}k_{23} - k_{21}k_{33}}{k_{33}k_{22} - k_{23}k_{32}} = -5.64$$

$$D_{23} = \frac{k_{21}k_{13} - k_{23}k_{11}}{k_{22}k_{11} - k_{21}k_{12}} = 0$$

$$D_{32} = \frac{k_{31}k_{12} - k_{32}k_{11}}{k_{11}k_{33} - k_{31}k_{13}} = 0.8413$$

The above equations define the desired interaction compensator, whose implementation is carried out as in the inverse decoupling approach. Hence, as for the ideal decoupling case, the steady-state gains of the decoupled FFPU will be:

$$M_1 = K_{11}$$

$$M_2 = K_{22}$$

$$M_3 = K_{33}$$

The compensator is first designed as in the simplified decoupling case and then it is implemented with the inverse decoupling structure as shown in the Figure 2.

Multiloop Controller Design for Boiler-turbine Unit: Difficulties caused by the interactions are always encountered in the design of multi-loop control systems for MIMO processes. To overcome the difficulties, a multi-loop system is decomposed into a number of equivalent single loops for design. Many design methods have been reported in literature for the designing of Multiloop controllers. In the detuning methods, each controller in the system is designed based on the corresponding diagonal element and ignore the interactions from other loops. The controllers are then detuned to take into accounts the interactions until some prescribed limit (e.g. the biggest log-modulus) is attained. The BLT tuning methods for PI and PID controllers are examples of these methods. The simplicity of this method is its major advantage. But, the disadvantage results from the fact that loop performance and stability cannot be clearly defined through the detuning procedures.

Steps for Tuning PI Control Systems: Each controller is first designed, ignoring process interactions. Then interactions are taken into account by detuning each controller (Detuning method).

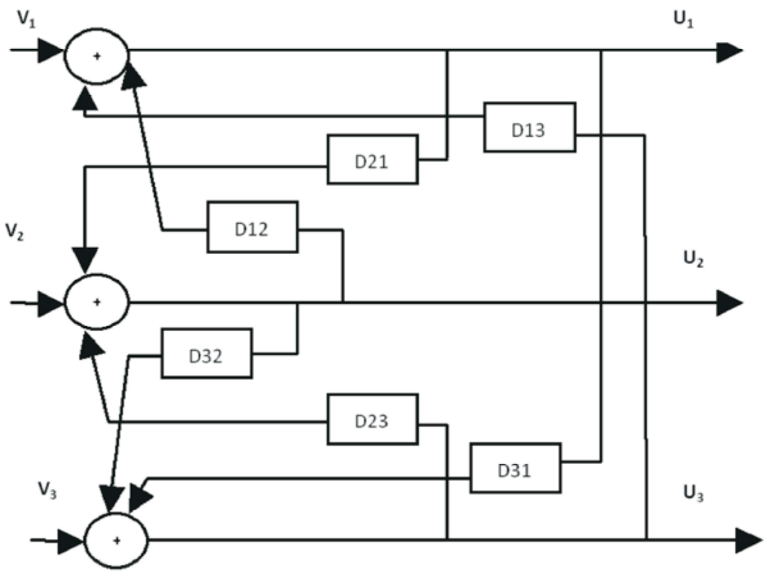

Fig. 2: Inverse decoupling structure

Table 2: Controller parameters for different values of F

1st controller	F=2	F=2.5	F=3	F=3.5	F=4	F=4.5	F=5
	K_P=22.237	27.796	33.35	38.91	44.47	50.03	55.59
	K_I=1.65×10^{-3}	1.32×10^{-3}	1.1×10^{-3}	9.42×10^{-4}	8.25×10^{-4}	7.3×10^{-4}	6.64×10^{-4}
2nd controller	F=2	F=2.5	F=3	F=3.5	F=4	F=4.5	F=5
	K_P=8×10^{-3}	0.01	0.012	0.014	0.016	0.018	0.02
	K_I=4.65×10^{-3}	3.72×10^{-3}	1.1×10^{-3}	2.65×10^{-3}	0.001	2.06×10^{-3}	1.86×10^{-3}
3rd controller	F=2	F=2.5	F=3	F=3.5	F=4	F=4.5	F=5
	K_P=2.326	2.90	3.48	4.07	4.65	5.23	5.81
	K_I=9.3×10^{-3}	7.44×10^{-3}	6.2×10^{-3}	5.31×10^{-3}	4.65×10^{-3}	4.31×10^{-3}	3.72×10^{-3}

Table 3: Different values for ISE, IAE and ITAE for three controllers

F=2	ISE	284.7	1.389e+004	32.4
	IAE	24.87	433.8	180
	ITAE	1.062e+004	3713	9e+004
F=2.5	ISE	226.6	1.302e+004	32.4
	IAE	19.25	389.4	180
	ITAE	7981	2838	9e+004
F=3	ISE	188	1.233e+004	32.4
	IAE	14.69	355.3	180
	ITAE	6232	2214	9e+004
F=3.5	ISE	160.7	1.178e+004	30
	IAE	12.31	330.6	176
	ITAE	5197	1759	9e+002
F=4	ISE	144.7	1.719e+004	29
	IAE	6.008	690.1	172
	ITAE	1005	1.119e+004	8e+006
F=4.5	ISE	122.8	1.093e+004	28
	IAE	10.21	335	180
	ITAE	4313	1777	9e+004
F=5	ISE	151.2	1.059e+004	34.4
	IAE	6.419	571	185
	ITAE	1205	2856	9e+004

Calculate Z-N PI controller settings for each control loop $K_{C,ZN}$, = $0.45K_{cu}$, $\tau_{I,ZN} = \frac{P_U}{1.2}$. Assume a factor F, typical values between 2 and 5. Calculate new values of controller parameters by $k_{ci} = \frac{K_{ci,ZN}}{F}$, $F\tau_{Ii,ZN}$ were i=1,2,3…n. Table 2 shows the different values of controller after changing the values of F between 2 to 5.

After changing and finding the different values F between 2 to 5, the values of Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (IAE) are calculated. Table 3 shows the different values for ISE, IAE and ITAE for three controllers.

Simulation Results: Simulations studies were carried out to evaluate the response of the three decoupled outputs.viz .drum steam pressure, electrical power and drum water level. Fig. 3 shows the unit step response is applied to all the three compensated system which shows that compensator is effectively reducing the interaction among the control loops, thus achieving the controllers to achieve the proposed goals. Fig. 4 shows the Tuned responses for pressure, power and drum water level using Multiloop controller

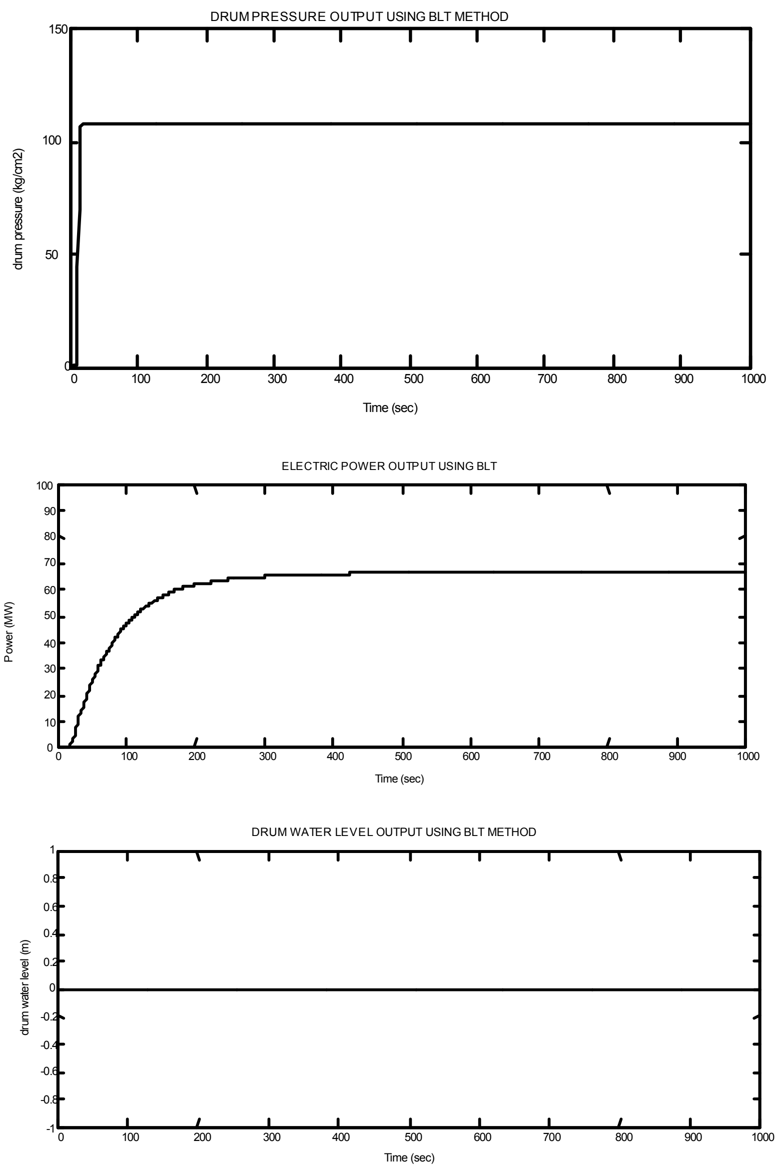

Fig. 4: Tuned responses for pressure, power and drum water level using Multiloop controller

CONCLUSION

Coordinated control with interaction compensator using static method was presented. Because of the presence of integrative term in the third loop, there was a problem in designing a compensator. This was solved using RGA based interaction analysis using process steady state gain matrix. A multiloop controller is also designed for process and different values of F between 2 to 5 are varied to know the best tuning parameter and the corresponding values of ISE,IAE and ITAE are also calculated.

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