Elimination of Chattering Using Fuzzy Sliding Mode Controller for Drum Boiler Turbine System

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Abstract: This paper presents the application of Fuzzy logic based Sliding Mode Control (FSMC) to a drum-type boiler–turbine system. Proportional Integral (PI) controller, Sliding Mode Control (SMC) and FSMC are designed with the linearization of the nonlinear plant model. Then, the control performance of the FSMC based on the drum type boiler turbine system model is evaluated. Drum water-level dynamics has severe nonlinearity; it is observed that the simulation of the linearized model shows satisfactory results. Chattering effect of both controllers is examined and controller performance are measured.

Keywords: Boiler–turbine control, PI, SMC and FSMC

1. INTRODUCTION

A common way to generate electric power is to use drum boilers to produce steam and to drive the turbo generators to generate electricity. Two types of configurations exist for this purpose:

A header is used to accommodate all the steam produced from several boilers and the steam is then distributed to several turbines through the header. The capacity of the boilers used in this configuration is usually small. The steam can be used for generating electricity as well as other purposes. This configuration is commonly used in industrial utility plants.

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 modelled with a Multi-Input– Multi-Output (MIMO) nonlinear system (Bell and Astrom).

The controller design for a boiler-turbine unit has attracted much attention in last two decades. (Tan *et al.*, 1998) 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 (*Wang et al.,* 1997). It should be noted that modern control techniques might achieve better performance than the conventional PID controller. (Zhuang *et al.,* 1994) proposed multivariable PID controllers. (Shiu and Huang, 1998) discussed sequential design method for multivariable decoupling and multiloop PID controllers. Modern control techniques have been applied to improve unit performance, e.g., LQG/LTR (Kwon *et al.,*1989) predictive control (Zhao *et al.,* 1999) and fuzzy control (Moon and Lee, 2003), etc.

(Utkin, 1977) introduced sliding mode control as a control of variable structure systems. (Decarlo *et al.,* 1988) discussed about variable structure control of nonlinear systems. Atsushi (Ishigame *et al.,*1993) introduced fuzzy inference in sliding mode control of nonlinear systems. (Yu *et al.,* 1998) proposed the idea of amalgamating linearized points using fuzzy logic.

(Almutairi and Zribi, 2006) implemented SMC for coupled tank systems. (Roopaei and Zolghadri 2009) proposed chattering free FSMC for uncertain systems. (Biswas *et al.,* 2009) implemented SMC for Quadruple Tank Process and proved its superiority over decentralized PI controllers. (Benamor *et al.,* 2011) implemented SMC with integrator for three tank system.

(Yiguo Li *et al.,* 2012) presented a model predictive control (MPC) strategy based on genetic algorithm to solve the boiler–turbine control problem. A Takagi–Sugeno (TS) fuzzy model based on gap values is established to approximate the behaviour of the boiler–turbine system then a specially designed Genetic Algorithm (GA) is employed to solve the resulting constrained MPC problem.

A discrete-time piecewise affine (PWA) model has been proposed for a nonlinear model of boiler–turbine unit using plant operating points (Keshavarz *et al.,* 2010). The explicit model predictive control performance has been compared with the linear controller obtained using H∞ approach. The results are illustrated by simulations. They show that the explicit MPC method has suitably improved the system performance, especially the quantity of control efforts is smaller and without saturation compared with that of H∞ control system.

A novel coordinated robust nonlinear control scheme for a boiler-turbine-generator system, in which, the approximate dynamic feedback linearization is established by constructing a family of second-order extended state observers that can estimate and compensate the system nonlinearities and disturbances (Yu, 2010).

(Pang-Chia Chen, 2013) investigated controller design approaches for nonlinear boiler-turbine dynamics subject to actuator magnitude and rate constraints. By using linear matrix inequality algorithms, magnitude and rate constraints on the actuator and the deviations of fluid density and water level were formulated while tracking capabilities on drum pressure and power output are optimized in terms of H_∞ performance.

The outline of the paper is as follows. A nonlinear model for the boiler turbine system is derived in section 2. Simple multi-loop PI control SMC and FSMC are discussed in section 3. The results and conclusions are presented in sections 4 and 5 respectively.

2. BOILER–TURBINE SYSTEM MODEL

2.1 A. Nonlinear Boiler–Turbine System Model

The model of (Bell and Astrom) is assumed as a real plant among various nonlinear models for the boiler–turbine system. The model represents a 160 MW oil-fired drum-type boiler-turbine generator for overall wide-range simulations and is described by a third-order MIMO nonlinear state equation as follows (Bell and Astrom).

$$
\begin{aligned}
\dot{x}_1 &= -0.0018u_2x_1^{9/8} + 0.9u_1 - 0.15u_3 \\
\dot{x}_2 &= \frac{\left[(0.73u_2 - 0.16)x_1^{9/8} - x_2\right]}{10} \\
\dot{x}_3 &= \frac{\left[141u_3 - (1.1u_2 - 0.19)x_1\right]}{85} \\
y_1 &= x_1 \\
y_2 &= x_2 \\
y_3 &= 0.05\left(0.13073x_3 + 100\alpha_{cs} + \frac{q_c}{9} - 67.975\right)
\end{aligned}
\tag{1}
$$

Where

$$
\begin{aligned}
\alpha_{cs} &= \frac{(1-0.001538x_3)(0.8x_1-25.6)}{x_3(1.0394-0.0012304x_1)} \\
q_c &= (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.514u_3 - 2.096
\end{aligned}
\tag{2}
$$

The three state variables x_1, x_2, and x_3 are drum steam pressure (P in kg/cm^2), electric power (E in MW), and steam water fluid density in the drum (ρf in kg/m^2) respectively. The three outputs y_1, y_2 , and y_3 are drum steam pressure (x_1), electric power (x_2), and drum water-level deviation (L in meters), respectively. The y_3, drum water-level L, is calculated using two algebraic calculations α_{cs} and q_c that are the steam quality (mass ratio) and the evaporation rate (kilograms per second), respectively.

The three inputs u_1, u_2 and u_3 are normalized positions of valve actuators that control the mass flow rates of fuel, steam to the turbine, and feed water to the drum, respectively.

2.2. Step-Response Model With Linearization

Using the nonlinear model, (1)–(2) is linearized using Taylor series expansion at the operating point,

$$
\begin{aligned}
\bar{y}_o &= (y_{10}, y_{20}, y_{30}), \\
\bar{x}_o &= (x_{10}, x_{20}, x_{30}), \\
\bar{u}_o &= (u_{10}, u_{20}, u_{30})
\end{aligned}
$$

The result of linearization is as follows:

$$
\begin{aligned}
\dot{\bar{x}} &= A\bar{x}(t) + B\bar{u}(t) \\
\bar{y}(t) &= C\bar{x}(t) + D\bar{u}(t)
\end{aligned}
\tag{3}
$$

where

$$
A = \begin{bmatrix} -\frac{0.0162}{8}ux & 0 & 0 \\ \left(\frac{6.57}{80}u - \frac{1.44}{80}\right)x & -\frac{1}{10} & 0 \\ \left(\frac{0.19}{85} - \frac{1.1}{85}u\right) & 0 & 0 \end{bmatrix}
$$

$$
B = \begin{bmatrix} 0.9 & -0.0018x & -0.15 \\ 0 & \frac{0.73}{10}x & 0 \\ 0 & -\frac{1.1}{85}x & \frac{141}{85} \end{bmatrix}
$$

$$
C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \left(5\frac{\partial}{\partial x}\alpha + \frac{0.05}{9}\frac{\partial}{\partial x}q\right) & 0 & \left(0.065 + 5\frac{\partial}{\partial x}\alpha\right) \end{bmatrix}
$$

$$
D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.2533 & 0.00473x & -0.014 \end{bmatrix}
\tag{4}
$$

The variables $\bar{x}, \bar{y}$ and $\bar{u}$ are the differences of the state, output and input, respectively, from the corresponding operating points.

The operating points are determined based on a nominal operation of the plant. Considering that the model represents a 160 MW unit, the operating point for power output y_2 is assumed as 85 MW, which is around its midpoint. This yields the corresponding pressure y_1 to be 115 kg/cm^2 from thebalance of the plant model. The operating point for water level y_3 is zero in order to keep the water level in the middle of the drum.

The resulting operating points are

$$\bar{y}_o = (115,85,0),$$
$$\bar{x}_o = (115,85,402.759),$$
$$\bar{u}_o = (0.4147,0.7787,0.5436)$$

The constant matrices A, B, C, and D are evaluated at these operating points as follows

$$A=\begin{bmatrix} -0.002854 & 0 & 0 \\ 0.083152 & -0.1 & 0 \\ -0.007842 & 0 & 0 \end{bmatrix}$$
$$B=\begin{bmatrix} 0.9 & -0.374591 & -0.15 \\ 0 & 15.191754 & 0 \\ 0 & -0.148126 & 1.658824 \end{bmatrix}$$
$$C=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0.007566 & 0 & 0.004257 \end{bmatrix}$$
$$D=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.2533 & 0.543056 & -0.014 \end{bmatrix} \quad (5)$$

3. CONTROLLER DESIGN

3.1 PI Controller Design

Relative Gain Array (RGA)

The RGA was introduced by Ed Bristol as a measure of interaction in multivariable control systems (Wayne Bequette B, 2004). The RGA Λ is defined as

$$\Lambda = G(0) \times G^{-T}(0) \quad (6)$$

where x denotes the element by element matrix multiplication and –T inverse transpose.

Properties of RGA:

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) $\lambda 11+\lambda 12+\lambda 13=1 \qquad \lambda 11+\lambda 21+\lambda 31=1$

$\lambda 12+\lambda 22+\lambda 32=1 \qquad \lambda 21+\lambda 22+\lambda 23=1$

$\lambda 13+\lambda 23+\lambda 33=1 \qquad \lambda 31+\lambda 32+\lambda 33=1$

Use of RGA to determine variable pairing.

It is desirable to pair output i and input j such that λij is as close to 1 as possible.

PI controller design of a boiler turbine unit is shown in Fig.1. The RGA depends on the valve actuators that control the mass flow rates of fuel, steam to the turbine, and feed water to the drum.

$$\text{RGA} \quad \Lambda=\begin{bmatrix} -0.4728 & 0.0029 & 1.4699 \\ -0.0234 & 0.9971 & 0.0262 \\ 1.4962 & 0.0000 & -0.4962 \end{bmatrix} \quad (7)$$

From RGA Y_3 is paired with U_1, Y_2 is paired with U_2 and Y_1 is paired with U_3.

PI controllers have the form (Reddya, 1997)

$$C_l(s) = K_l\left(1+\frac{1}{T_{il}s}\right), \quad l = 1,2,3 \ \& \ i = 1,2,3 \quad (8)$$

where $K_1=0.17$, $K_{11}=0.296$

$K_2=0$, $\quad K_{22}=0.0003$

$K_3=5$, $\quad K_{33}=0.1$

The controller parameter values are tuned by using auto tuning procedure.

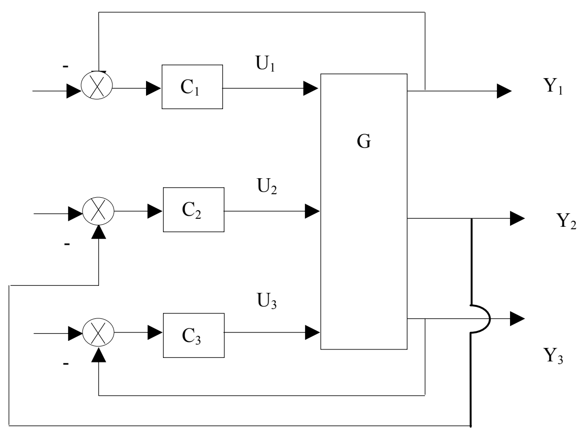

Fig.1. PI Controller Design.

3.2 Sliding Mode Control

In the SMC theory, control dynamics have two sequential modes (Utkin VI, 1977), the first is the reaching mode and the second is the sliding mode. The Lyapunov sliding condition forces system states to reach a hyperplane and keeps them sliding on this hyperplane, so a SMC design is composed of two phases, hyperplane design and controller design. A hyperplane is designed via pole placement approach as in state space model, a controller design is based on the sliding condition.

Consider a Single Input Single Output system (Pan Y *et al.*, 2000).

$$\dot{x} = Ax + B(u + f_m), \qquad y=Cx \quad (9)$$

where

$$x \in \Re^n,\ u \in \Re,\ y \in \Re,\ 0<r \le n \text{ and } f_m \in \Re$$

represents the matched uncertainty. Then ther output derivatives can be written as

$$y = Cx$$
$$\dot{y} = CAx$$
$$.$$
$$.$$
$$y^{(r)} = CA^{(r)}x + CA^{(r-1)}B(u + f_m) \qquad (10)$$

The sliding surface is defined to be

$$s = c_1 y + c_2 \dot{y} + \dots\dots + c_r y^{(r-1)} + y^{(r)} \equiv FY \qquad (11)$$

where ci, (i =1, 2 ….. , r) are the scalar design parameters and F=[c1 …..cr 1], Y=[y .. y(r-1) yr]T. The design criterion is on the selection of F such that the following polynomial is stable.

$$c_1 + c_2\zeta + \dots\dots + c_r\zeta^{r-1} + \zeta^r = 0 \qquad (12)$$

where ζ denotes the Laplace operator. The controller of the following type

$$u = -\Upsilon \int_{t_0}^{t} \mathrm{sgn}(s)dt \qquad (13)$$

Dynamics of the type

$$u_{eq} = -(CA^{r-1})^{-1} F \begin{bmatrix} C \\ . \\ . \\ CA^r \end{bmatrix} x - f_m \equiv \Gamma x - f_m \qquad (14)$$

The closed-loop system becomes a state feedback dynamics

$$\dot{x} = (A - B\Gamma)x \; .$$

where $(A - B\Gamma)x$ should be stable for internal stability.

MIMO linear uncertain system with m inputs, p outputs and relative degree r which is denoted by a triple (A,B,C) in the form of equation (9). Define $C_k = CA_k$, k=0,1,2,..., r, then the r derivatives of output in equation (10) represented by Ck becomes

$$\dot{y} = C_1 x$$
$$.$$
$$.$$
$$y^{(r-1)} = C_{r-1}x$$
$$y^{(r)} = C_r x + C_{r-1}B(u + f_m) \qquad (15)$$

Consider the new system (A, B, Cr-1) instead of original (A,B,C). Based on the output canonical decomposition (Edwards and Spurgeon, 1995), then (A, B,Cr-1) in the transformed coordinate can be written as

$$\begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \\ \dot{\bar{x}}_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \bar{x}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ B_2 \end{bmatrix} (u + f_m)$$

$$y = \begin{bmatrix} 0 & T \end{bmatrix} \bar{x} \equiv T \begin{bmatrix} \bar{x}_2 \\ \bar{x}_3 \end{bmatrix} \qquad (16)$$

where

$\bar{x}_1 \in \Re^{n-p}$, $\bar{x}_2 \in \Re^{p-m}$, $\bar{x}_3 \in \Re^m$ and Aij, (i,j=1, 2, 3) are system sub matrices portioned accordingly to the dimensions of $\bar{x}_1$, $\bar{x}_2$ and $\bar{x}_3$.

Matrix $T \in \Re$ is orthogonal and $B_2 \in \Re^{m \times m}$ is square of rank m. In addition, once the invariant zeros of (A,B,Cr-1) exist, then with another transformation , submatrices A11 and A21 will have a particular structure written as

$$A_{11} = \begin{bmatrix} A_{11}^0 & A_{12}^0 \\ 0 & A_{22}^0 \end{bmatrix}$$

$$A_{21} = \begin{bmatrix} 0 & A_{21}^0 \end{bmatrix} \qquad (17)$$

where

$A_{11}^0 \in \Re^{q \times q}, A_{22}^0 \in \Re^{(n-p-q)\times(n-p-q)}, A_{21}^0 \in \Re^{(p-m)\times(n-p-q)}$ with (A220, A210) is an observable pair. The number of q denotes the number of invariant zeros of (A, B, Cr-1).

3.3 Fuzzy Sliding Mode Control

Due to the discontinuous control component in the SMC control law, there exists chattering in the control output. The feature of a smooth control action of Fuzzy Logic Control (FLC) is used to overcome the chattering of SMC to form a Fuzzy Sliding Mode Controller (FSMC) (Qiao *et al.,* 2003). This method is capable of handling the chattering problem of SMC effectively.

Structure of FSMC is shown in the Fig. 2.

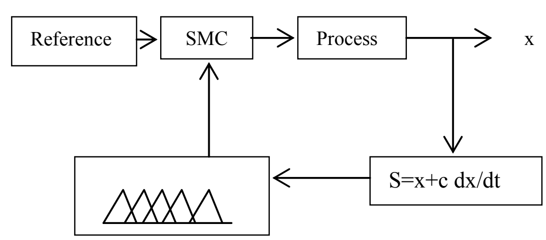

Fig. 2. Structure of Fuzzy sliding mode controller.

In the control law of SMC instead of the function Sgn(S), a fuzzy system is used which is of Mamdani type. Inputs to the system are sliding function and its derivative and output is FSMC, which varies from -120 to +120. The input and output membership functions are as shown in the Fig. 3 and 4 respectively.

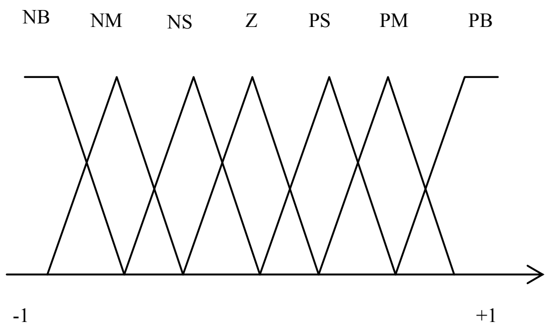

Fig. 3. Input Membership Function.

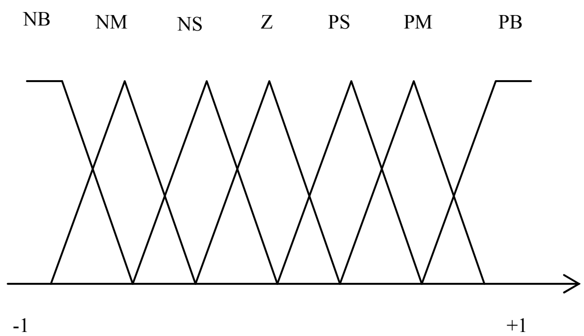

Fig. 4. Output Membership Function.

Vertices and bases of the membership functions are tuned for a given Drum boiler turbine system to get required response. Once the membership functions are created, the next step is the formation of rules between input and output membership functions. Fuzzy rules are given in Table 1.

Table 1. Fuzzy Rules.

E / DE	PI	NB	NM	NS	ZR	PS	PM	PB
NB		NB	NB	NM	NB	NB	PS	ZR
NM		NB	NB	NM	NM	NM	ZR	PS
NS		NB	NB	NM	NS	ZR	PM	PM
ZR		NB	NM	NS	ZR	PS	PM	PB
PS		NB	NM	ZR	PS	PS	PM	PB
PM		NB	ZR	NS	PM	PS	PM	PB
PB		ZR	ZR	ZR	PB	PS	PB	PB

4. RESULTS AND DISCUSSION

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 and IAE) for the three controlled outputs drum steam pressure, electrical power and drum water level. The design of the disturbance is also shown for characterizing the performance of the three different control strategies.

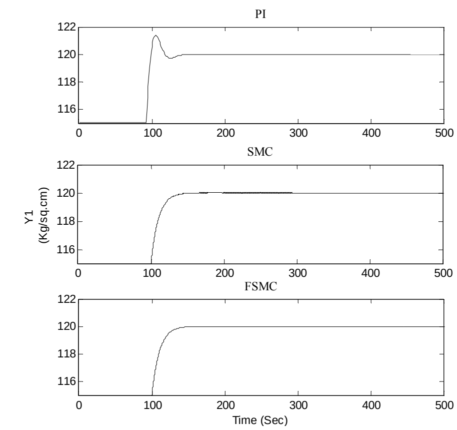

Fig. 5. Closed loop response of drum water level.

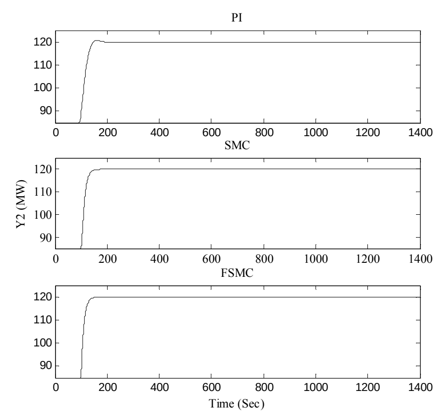

Fig. 6. Closed loop response of Electrical Power.

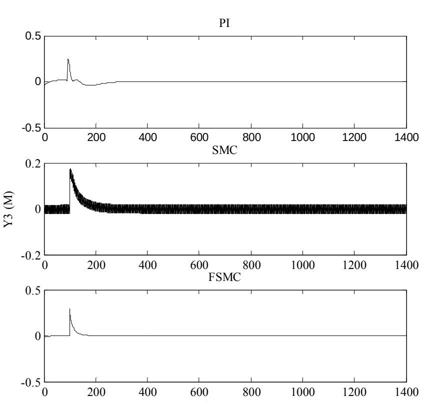

Fig. 7. Closed loop response of Electrical Power.

Fig 5, Fig 6 and Fig 7 are the closed loop response of the drum steam pressure, electrical power and drum water level for PI control, SMC and FSMC respectively. In Fig.5 and Fig.6 the peak over shoot is present for PI control and in Fig 5 and 7 the chattering effect is present for SMC. From the simulation results, it can be seen that there is no chattering effect in the FSMC.

Table 2. Performance comparison of various controllers (Drum Steam Pressure).

Type of Controller	Drum Steam Pressure	
	ISE	IAE
Decentralized PI	7229	1373
SMC	993	240
FSMC	991	234

Table 3. Performance comparison of various controllers (Electric Power).

Type of Controller	Electric Power	
	ISE	IAE
Decentralized PI	857	245
SMC	857	244
FSMC	847	227

Table 4. Performance comparison of various controllers (Steam water fluid density).

Type of Controller	Steam water fluid density	
	ISE	IAE
Decentralized PI	0.0499	0.9183
SMC	4.833	151.4
FSMC	0.365432	6.846

From Table 2 and Table 3 the ISE and IAE values of FSMC is less when compared to decentralized PI and SMC. In Table 4 the ISE and IAE values of decentralized PI is less.

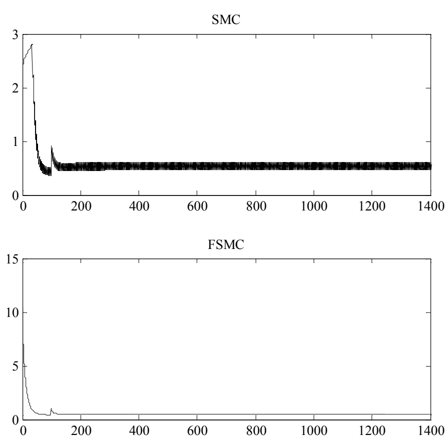

Fig. 8. Input response of drum steam pressure.

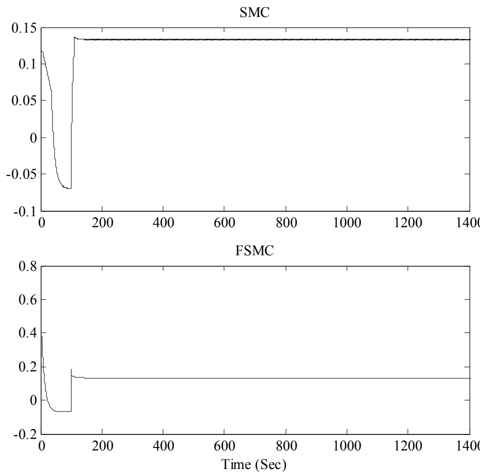

Fig. 9. Input response of electrical power.

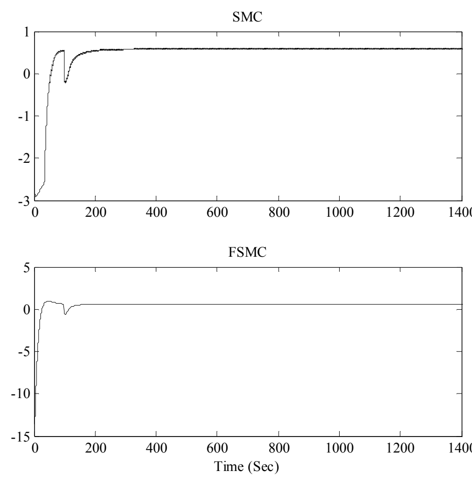

Fig. 10. Input response of steam water fluid density.

Figs 8 to 10 are the input response of drum steam pressure, electrical power and steam water fluid density. It can be noted that there is no chattering effect in FSMC.

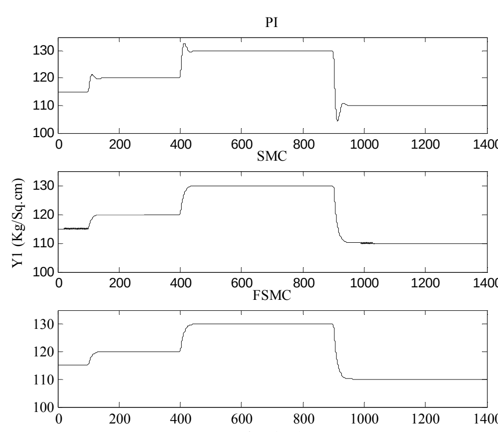

Fig. 11. Servo response of drum steam pressure.

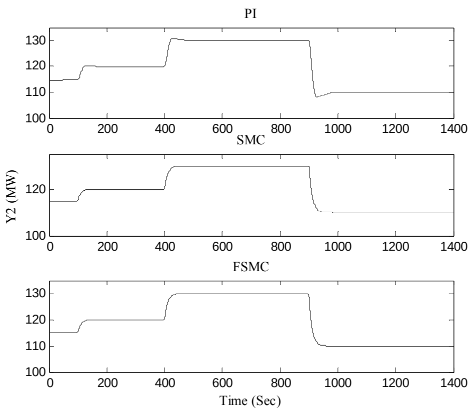

Fig. 12. Servo response of Electrical Power.

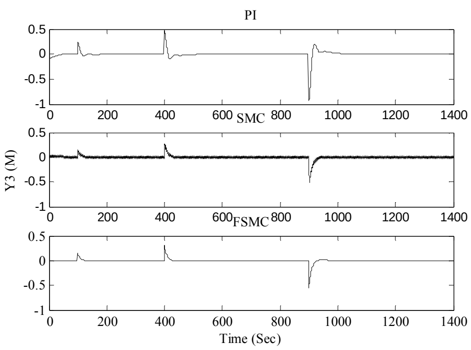

Fig. 13. Servo response of drum water level.

Figs 11 to 13 are the servo response of drum steam pressure, electrical power and steam water fluid density. Initially the drum steam pressure is settled at the set point of 120kg/sq.cm. After that it increased from 120kg/sq.cm to 130kg/sq.cm for 400th sec. At 900th sec the drum steam pressure is decreased to110kg/sq.cm. The same procedure is applied for electrical power and steam water fluid density.

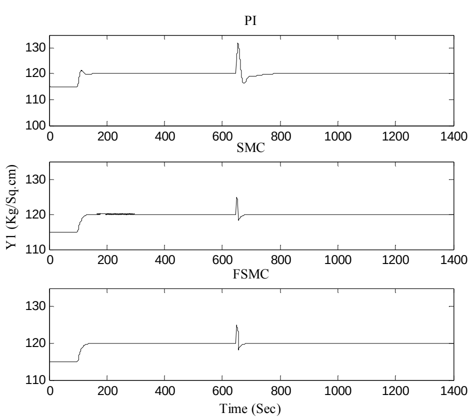

Fig. 14. Regulatory response of Drum Steam Pressure.

Figs 14 to 16 are the regulatory response of drum steam pressure, electrical power and steam water fluid density. Initially the drum steam pressure is settled at the set point of 120kg/sq.cm. After 600th sec a sudden external disturbance is applied. From the above response FSMC settles quickly. It is to be noted that the chattering phenomena occurs at SMC for drum water level. While in the case of FSMC there is no chattering effect.

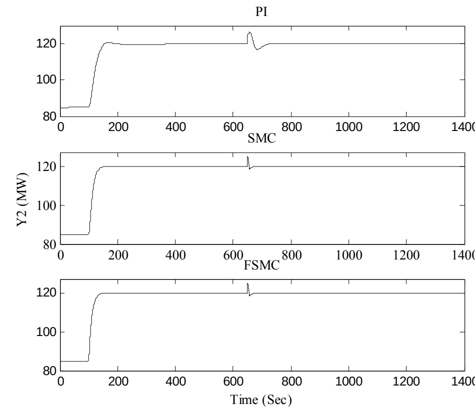

Fig. 15. Regulatory response of Electrical Power.

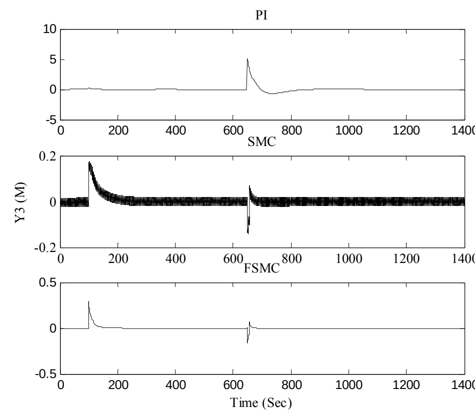

Fig. 16. Regulatory response of Drum water level.

5. CONCLUSION

This paper presented the application of Fuzzy logic based Sliding Mode Control (FSMC) to a drum-type boiler–turbine system. Proportional Integral (PI) controller, Sliding Mode Control (SMC) and FSMC were developed with the linearization of the nonlinear plant model. For drum steam pressure response the peak over shoot is 1.15 and settles at 142 sec. Whereas in the case of SMC and FSMC there is no peak overshoot, but SMC there is a chattering problem and FSMC has no chattering problem.

In Drum water level response for PI controller settles after 250sec, SMC and FSMC settles quickly. But in this case also there is a chattering problem in SMC. From the above responses it is to be concluded that the FSMC gives satisfactory closed loop, servo and regulatory responses.

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