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Comparative Analysis Of Boiler Drumlevel Control Using Advanced Classical Approaches

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Abstract**—*****One of the most important controls used in chemical process industries is the steam drum water level control. The proper and safe control of the steam drum water level is the most crucial operation of the boiler. The boiler may get damaged due to overheating, if the level is too low, and also, due to overflow of water and improper function of separator, if the level is too high. Therefore, there exists an optimum interface level between steam and water within the boiler drum. The steam boiler drum level is characterized by a high extent ofnonlinearity, uncertainty, disturbance and overshoot. The tuning of parameters of conventional feedback PID controller control mechanism involves performing exhaustive mathematical modeling and control analysis. The system complexity requires adapting to complex and multi-variable control systems. This paper makes a comparative analysis of the control performance of advanced approachesnamely cascaded control, internal model control (IMC), feedback-feedforward (FB-FF)and Fuzzy Logic control (FLC). The results of proposed control systems demonstrate the optimized performances in terms of overshoot, rise time, settling time and tracking of set point.A comparison of results for such variables indicates that IMC based FB-FF cascade controller and FLC have reasonably better performance versus others in terms of steam water flow pressure disturbance rejecton capability.The designed model of drum level has been simulated in MATLAB environment.***

Index Terms— **Boiler drum, Cascade controller, Feedforward controller, Fuzzy logic controller, Internal model controller,PID controller.**

I. INTRODUCTION

The water level of boiler drumis one of the crucial control parameters for any process industries, which reflects the control of mainly boiler load and feed water indirectly[1]. If the water level is critically high, it may destroy the separation capability of steam-water separatingdevice. If the water level is unusually low, it may adversely affectthe vapor-water cycle, which may lead to a serious explosion of the boiler. For instance, latelya boiler drum explosion took place in a plywood factory inTalkatora Industrial Area, Lucknow, India, on 23 February, 2011. It is reasoned to have occurred due to superheating of the boiler drum, as the water level became critically low. Boiler drum is one of the typical multi-input multi-output system, and also shows high non-linearities, time varying response and a transportation lag. Conventionally, such a system has been controlled in the past using control methods, such as,Proportional-Integral-derivative (PID) [2]. However, the conventional PID controller when combined with cascaded configuration [3], feedback-feedforward (FB-FF) configuration [4] and IMC theory [5]could exhibit a lot of advantages, such as fast response, small rise time, small settling time, small overshoot, strong set point tracking and strong robustness. The fuzzy logic controller (FLC)is advantageous to use as it doesnot requirea precise mathematical model [6,7]. A fuzzy PID controlis one of most effective methods for stochastic system control[8].

In this work, two types of controller systemshave been designed and simulated. The first one, isan IMC based cascaded FB-FF, andanother, is a two-input and three-output based self adaptive fuzzy PID controller. Both the controllers are simulatedwith and without compensation for steam flux disturbances. Finally, acomparative analysis is performed amongst the feedback control without any control, PID control, FB-FF cascade control, IMC based control and FLC. The various control models have been compared, for parameters such asrise time, settling time, overshoot and set-point tracking capability,to finally decide the best controller design in terms of steam water flow pressure disturbance rejecton capability.

II. METHODOLOGY

The generalized block diagram of a closed loop control system is shown in Fig.1.

A. *Feedback Controller*

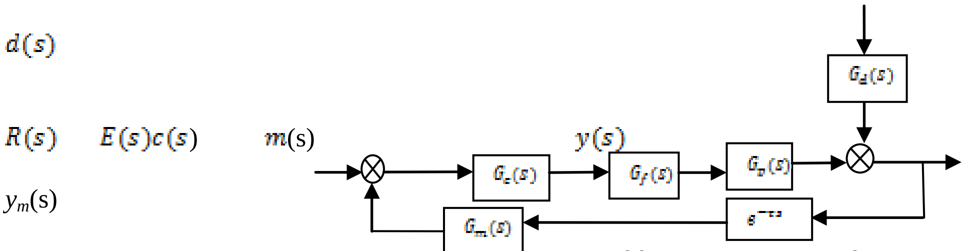


Fig. 1 (Generalized block diagram of feedback control configuration)

If the transportation lag or dead time is neglected, then the transfer function across such blocks may be defined as:

Process:

$$Y(s) = G_p(s)m(s) + G_d(s)d(s) \quad (1)$$

Feedback system:

$$Y_m(s) = G_m(s)e^{-\tau s}y(s) \quad (2)$$

Controller :

Comparator signal $E(s) = R(s) - y_m(s)$ (3)

Controller signal $C(s) = E(s)G_c(s)$ (4)

Final Control Element (FCE):

$$m(s) = c(s)G_f(s) \quad (5)$$

Using (1), (2), (3), (4) and (5), the system may be represented as

$$y(s) = \frac{G_p(s)G_f(s)G_c(s)e^{-\tau s}}{1+G_p(s)G_f(s)G_c(s)G_m(s)}R(s) + \frac{G_d(s)e^{-\tau s}}{1+G_p(s)G_f(s)G_c(s)G_m(s)}d(s) \quad (6)$$

Transfer function of closed loop control system consists of two terms, the first shows the effect of change of set point in the output, and the second shows the effect on the output due to changes in the disturbance.The problem presented is important and assumes complexity when the disturbance is random.

B. *FeedforwardController*

Feedforward control is always used along with feedback control because a feedback control system is required to track setpoint changes and to suppress unmeasured disturbances that are always present in any real process.The primary objective of drum boiler in the process plant is to keep the water level constant. There are twodisturbances occurred in boiler drum level, first is the steam flow from the drum boiler, and the other is feed water flow. In the case of feed-forward controller, the disturbances are directly dictated, i.e., steam flow pressure from boiler to further downstream is measured and then controlled by the feedforward controller, and the control signal is sent to the final control elements (FCE) valve [10] which controls the flow of feed water in drum.

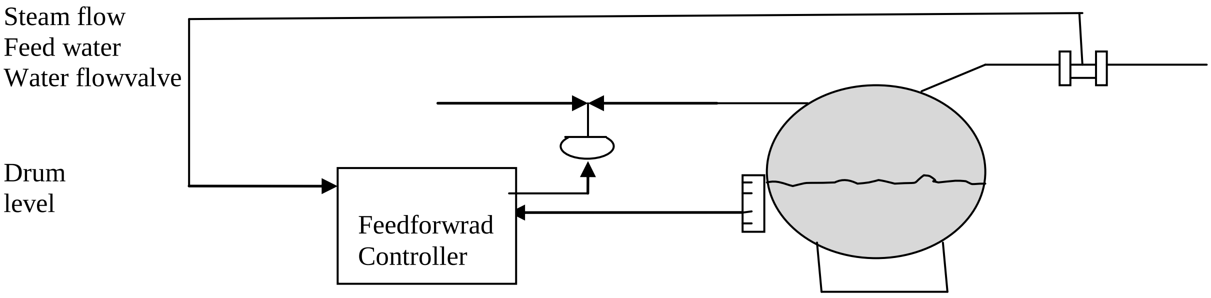


Fig. 2 (Feedforward controller of drum boiler)

The disturbance of boiler drum is given by the transfer function $\frac{0.25s-0.25}{2s^2+s}$, and valve transfer function is given by $\frac{1}{0.15s+1}$.

Cascade Controller

The two controllers of a cascade control system are feedback controllers (i.e., P, PI, PID). Generally, a proportional controller is used for the secondary loop, although a PI controller with small integral action is not unusual. Any offset value by P-control in the secondary loop is not important. Controlling of the secondary process is not an issue in cascade control.The effect of steam pressure which acts as a disturbance in boiler drum can be compensated by using secondary control loops which are shown in Fig. 3.

The set point of the flow control loop,U_M, is manipulated by the level controller output. It controls the inner loop level,h, of the boiler drum, if the level is critically low the flow loop will be increased, and vice versa. The flow loop controls the flow rate of feed water in the boiler drum,F_w, in normal way. However, if suddenly the pressure in the drum,P_s, increases due to a transient drop in steam disturbance,F_s, then the flow loop will respond quickly by opening the valve to maintain the feed water flow rate,F_w, at the rate demanded by the level controller.

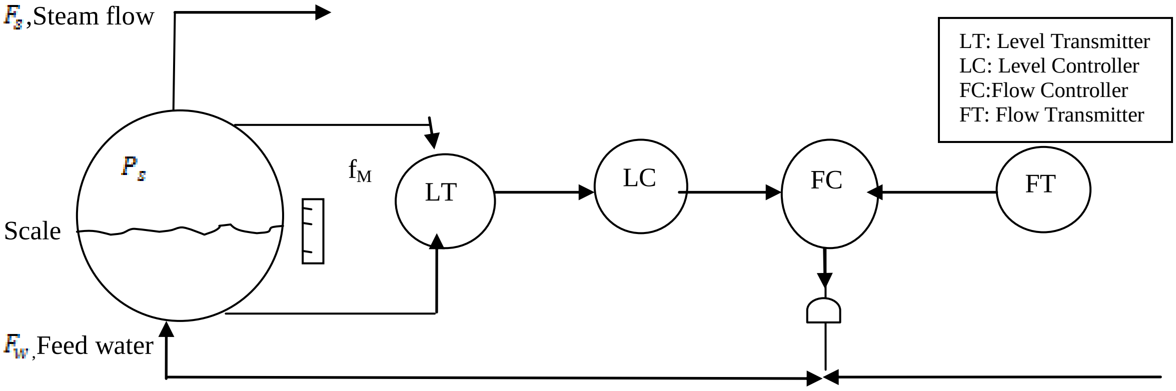


Fig.3 (Cascade controller of boiler drum)

The generalized block diagram of cascaded boiler drum level control is shown in Fig.4.

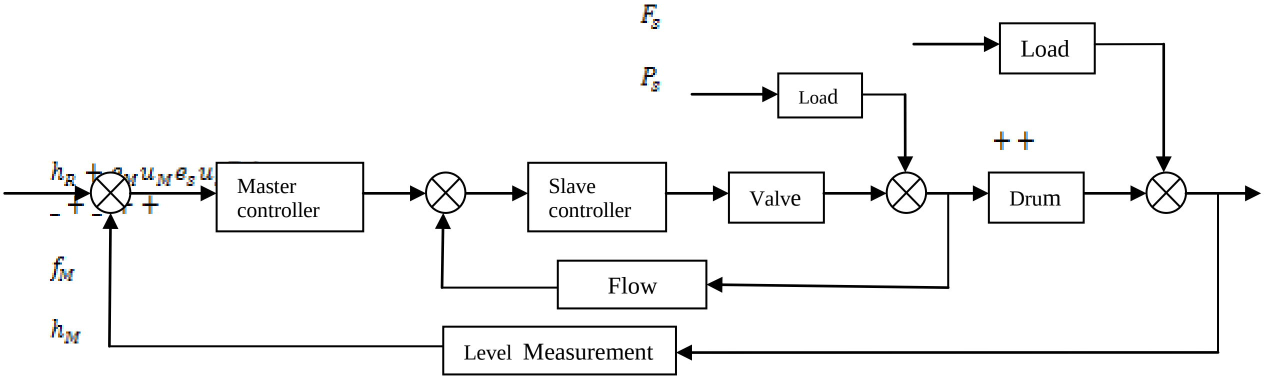


Fig. 4 (Generalized block diagram of Cascaded Controller for boiler drum)

C. *The IMC Structure*

Internal Model Controller (IMC) provides a transparent framework for control-system design and tuning. The principle behind IMC is that control can be achieved only if the control system encapsulates, either implicitly or explicitly, some representation of the process to be controlled. The process model is embedded in the controller in case of IMC structure. By explicit knowledge of process & virtue of the process mode, performance can be improved. It is assumed that the dynamics of boiler drum level process [11] is represented by a linear transfer model and i.e., it is an open loop stable. The input-output relationship is as shown in Fig.5.

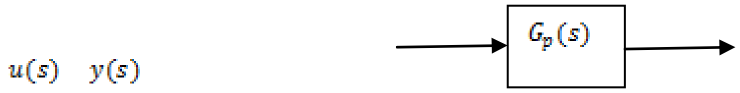


Fig.5 (Open loop process system)

Where u is the input variable (feed water) and$y$ is output variable (steam flow rate).

When the process is at steady state and there are no disturbances, then no control scheme is required, i.e., input and output are zero. Now, consider a desired change in the output y as shown in Fig.6.

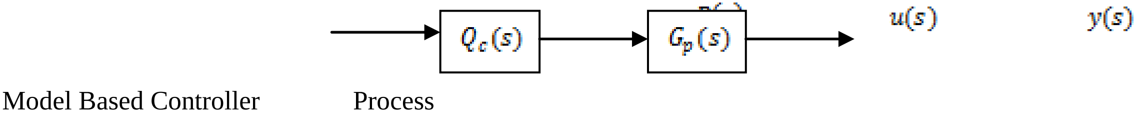


Fig.6 (Open loop model based control system)

Using the above Fig. 6, output y(s) can be written as,
$y(s) = G_p(s)Q_c(s)R(s)$ (7)

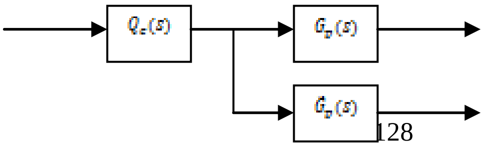
Static control law :

Assuming that $Q_c(s)$ is constant and equal to k_q, and if the process is assumed to be first order, then the process transfer function is given by -
$G_p(s) = \frac{k_p}{1+\tau_p s}$,
then $y(s) = \frac{k_p k_q}{1+\tau_p s} R(s)$
And, if input R(s) is step, then
$y(s) = \frac{k_p k_q}{1+\tau_p s}\frac{1}{s}$, (8)
This yields, $y(t) = k_p k_q(1 - e^{-t/\tau_p})$ (9)
Therefore, for the offset-free performance, $k_q = \frac{1}{k_p}$, is a necessary condition. For fastest response, the dynamic control law is to be proposed.

Dynamic Control Law:

If the controller transfer function is given by $Q_c(s) = \frac{1}{G_p(s)}$ (10)
Then, $y(s) = G_p(s)d_c(s)R(s) = G_p(s)\frac{1}{G_p(s)}R(s) = R(s)$(11)
In such a case, perfect control can be achieved. Hence, output perfectly tracks the set point.
Hence, $Q_c(s) = \frac{1}{G_p(s)} = \frac{1+\tau_p s}{k_p}$ (12)
But,practically, perfect control cannot be achieved.
Now, $u(s) = Q_c(s)R(s) = \frac{1+\tau_s}{k_p}R(s)$
$= \frac{1}{k_p}(1 + \tau_p s)R(s)$ (13)
Since, $R(s) = \frac{1}{s}$ the unit step input, then we get $u(t) = \frac{1}{k_p}r(t) + \frac{1}{k_p}\tau_p\frac{dr}{dt}$ (14)
It is very clear that it is not possible to take the derivative of step input due to discontinuity at the origin. Therefore,
$u(s) = \frac{1}{k_p}R(s) + \frac{1}{k_p}\tau_p\, s\, R(s) = \frac{1}{k_p}\frac{1}{s} + \frac{\tau_p}{k_p} = \frac{\tau_p}{k_p}\delta(t) + \frac{1}{k_p}$ (15)
Where $\delta(t)$ isthe impulse function.
In order to design a physical realizable controller for the first order process, low pass filter is designed
$f(s) = \frac{1}{\lambda s+1}$, where λ is a filter tuning parameter.
Hence, $Q_c(s) = \frac{f(s)}{G_p(s)} = G_p^{-1}(s)F(s) = \frac{1+\tau_p(s)}{k_p}\frac{1}{\lambda s+1} = \frac{1}{k_p}\left(\frac{1+\tau_p(s)}{\lambda s+1}\right)$(16)
Equation (16) represents a lead- lag compensator .
And therefore, $y(s) = G_p(s)Q_c(s)R(s) = G_p(s)G_p^{-1}(s)f(s)R(s) = f(s)R(s) = \frac{1}{\lambda s+1}R(s)$(17)
Equation (17) yields a first order response with a time constant of λ.
However,the form of actual process transfer function is never known exactly. Hence, transfer function of the process is represented in two ways. In first method, process is the unknown, and in the other the process model is known exactly.Mathematically, unknown process is given by $G_p(s)$, andthe modelgiven by $\tilde{G}_p(s)$.If the process has right hand pole (RHP) zero, factorization has been performed so that the RHP zero oes not form a RHP pole in the controller. Therefore, factor of the process model is-
$\tilde{G}_p(s) = \tilde{G}_{p+}(s)\tilde{G}_{p-}(s)$ (18)
where, $\tilde{G}_{p+}(s)$ contains noninvertible elements, and $\tilde{G}_{p-}(s)$ contains invertible elements. And also, if there is dead time in the process, it cannot be removed by any physicallyrealizable controller.Therefore, in such case, invert the invertible portion of the process model, and cascade with a filter that makes the controller $Q_c(s)$proper.
$Q_c(s) = \tilde{Q}_p^{-1}(s)f(s)$(19)
Let us consider open loop process model in parallel with the actual process as shown in Fig. 7.

$R(s)$ $u(s)$ $y(s)$process output



$\tilde{y}(s)$model output

Fig.7 (Process model in parallel with the actual process)

The model error in presence of disturbances and feedback as shown in Fig. 8

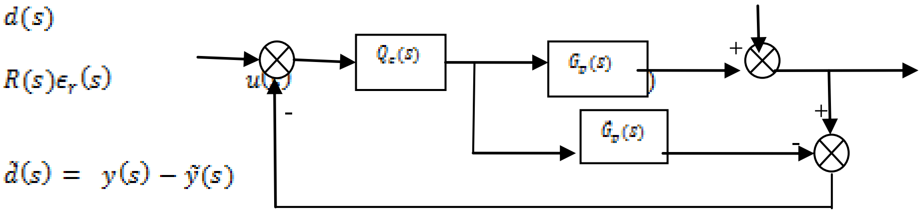


Fig. 8 (Process model incorporating the process disturbance steam pressure)

D. *Cascade IMC*

The implementation of cascaded IMC structure [12] is also possible. In this structure primary controller is IMC, while the secondary controller is PID,as shown in Fig.9. The internal model controller should be designed based on following model that includes the flow control loop dynamics described by -

$$G_{p_{des}}(s) = G_p(s)\,\tilde{G}_{c2cl}(s) \qquad (20)$$

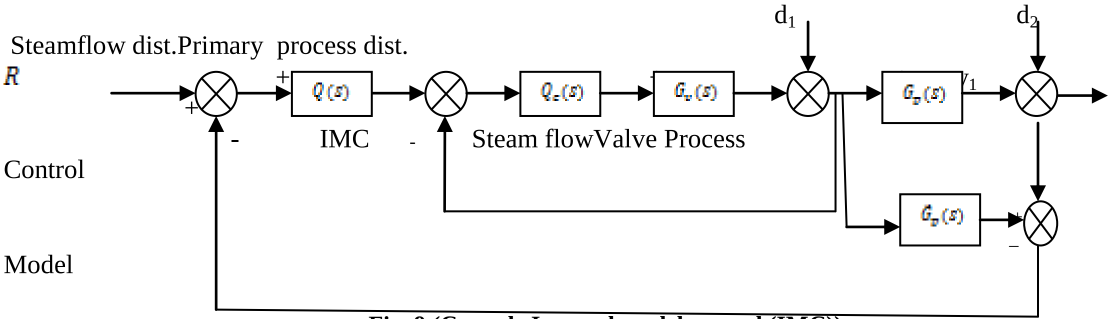


Fig. 9 (Cascade Internal model control (IMC))

E. *Fuzzy Logic Controller (FLC)*

Fuzzy logic is a way to make machines more intelligent, enabling them to reason in a fuzzy manner like humans.Fuzzy models “think” the way as humans do, and include verbal expressions instead of numbers. It is preferable when the mathematical problem is hard to derive, and when decisions have to be made with estimated values under incomplete information.The rules used in the FLS are of IF–THEN type. The main elements of a FLC are fuzzification, rules evaluation, and defuzzification as shown in Fig. 10.

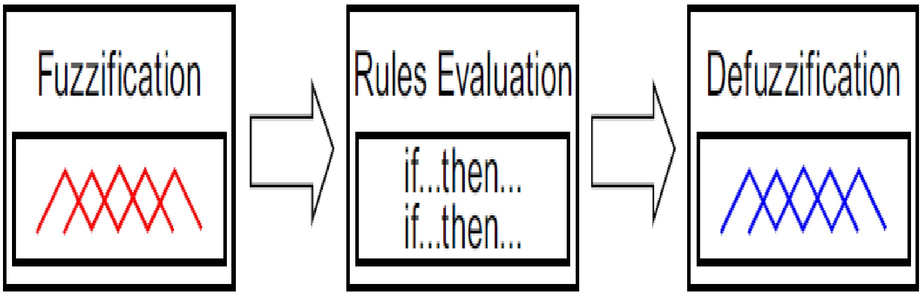
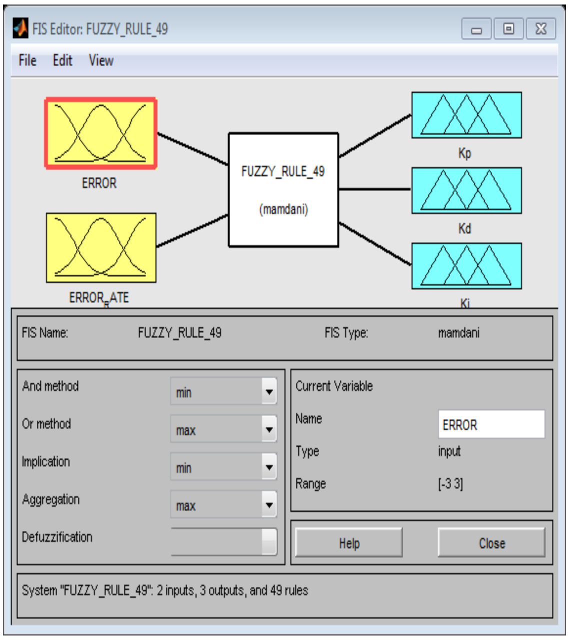


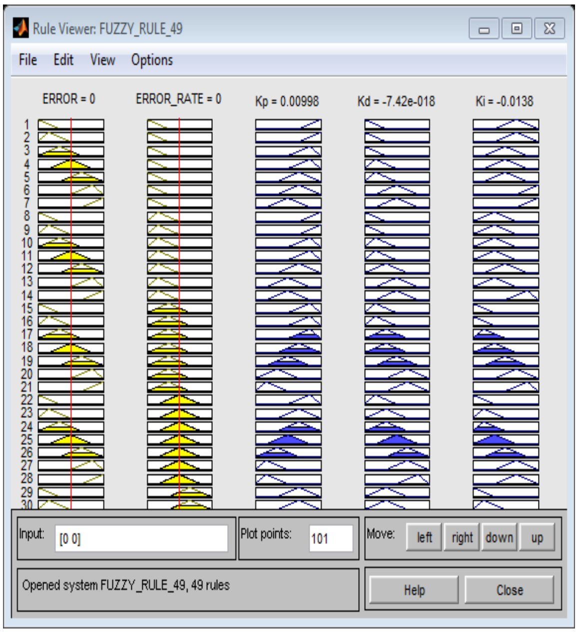
Fig.10 (Elements of Fuzzy logic control (FLC))

Fuzzificaton [13] is the process where the crisp quantities are converted to fuzzy (crisp to fuzzy). By identifying some of the uncertainties present in the crisp values, we form the fuzzy values. The conversion of fuzzy values is represented by the membership functions. A fuzzy inference system is the process of formulating the mapping from a given input to an output using fuzzy logic. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators, and if-then rules. The required thing during the synthesis of the fuzzy controller is to make the performance of the control algorithm be dependable on parameters that can be stored in the controller’s knowledge baseand can be adjusted later by controller’s learning mechanism. Knowledge basecan contain the information about the scaling gains of the universes of discourses of the controller’s linguistic input and output variables, data bases for the on-line generation of control rules in fuzzy controller’s rule base, learning rates, rule bases for inputs’ preprocessing fuzzy decision making systems and other information concerning the use of data in the rules.

In this paper, two input and three output Mamdani type FLC controller are used to tune online proportional coefficient,k_p, integral coefficient,k_i, and derivative coefficient,k_d,of PID controller. The Gaussian membership is defined on $(-3,3)$ and centroid defuzzification method is used. Nonlinear function is approximated by using fuzzy rules. Each input variable and output variable are fuzzified by seven fuzzy sets, namely, “Negative Big” (NB), “Negative Medium” (NM), “Negative Small” (NS), “Zero” (Z), “Positive Small” (PS), “Positive Medium” (PM), “Positive Big” (PB). The fuzzy controller and Fuzzy rule viewer areillustrated in Fig.11 and 12, respectively. In this online operation process, the control system automatically tunes and self corrects PID parameters of the main controller, through fuzy rules. Surface viewer andmemebership function are shown in Fig. 13.a & Fig. 13. b.



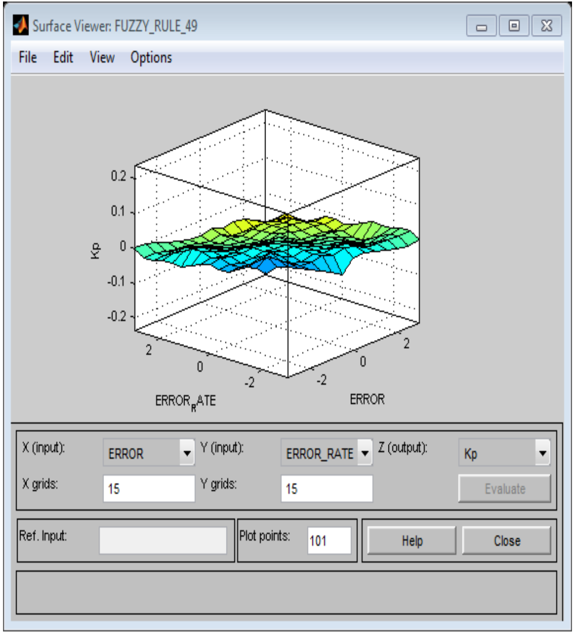
FIS Name: FUZZY_RULE_49
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification:
Current Variable
Name: ERROR
Type: input
Range: [-3 3]
System "FUZZY_RULE_49": 2 inputs, 3 outputs, and 49 rules



ERROR = 0
ERROR_RATE = 0
Kp = 0.00998
Kd = -7.42e-018
Ki = -0.0138
Input: [0 0]
Plot points: 101
Opened system FUZZY_RULE_49, 49 rules

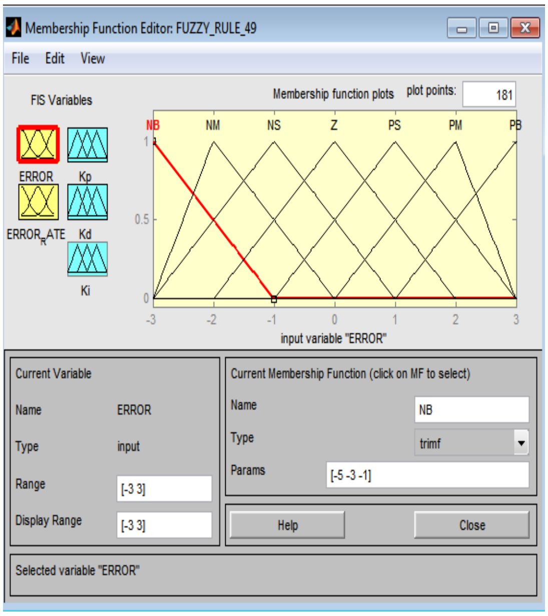
Fig.11 (Fuzzy controller view)

Fig.12 (Fuzzy rule base view)



X (input): ERROR
Y (input): ERROR_RATE
Z (output): Kp
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101

Fig.13. a (surface viewer)



plot points: 181

Name ERROR
Type input
Range [-3 3]
Display Range [-3 3]

Name NB
Type trimf
Params [-5 -3 -1]

Selected variable "ERROR"

Fig. 13. b (Membership Function viewer)

III. BOILER DRUM LEVEL CONTROL

The relationship between the feed water flow rate and drum level for drum boiler level process are given by the equations 21-23 described below. The equations expressed here in terms of process function, $G_p(s)$, valve function, $G_v(s)$, and disturbance function, $G_d(s)$ [14].

$$G_p(s) = \frac{[0.25(-s+1)]}{[s(2s+1)]} \tag{21}$$

$$G_v(s) = \frac{1}{[0.15\ s+1]} \tag{22}$$

And also,

$$G_d(s) = \frac{[-0.25\ (-s+1)]}{[s\,(s+1)(2s+1)]} \tag{23}$$

The gain parameter of PID controller is automatically tuned by MATLAB tuner.The IMC based PID structure uses the process model as in IMC design.

The simulink model of boiler drum for steam boiler drum conventional PID control, IMC-cascade and the FLC control systemwithout considering the steam pressure as load is shown in Fig. 14, and after considering the steam pressure disturbance in Fig. 15. The value of K_p, K_i and K_d, for PID control without disturbance and disturbance are tuned automatically in MATLAB PID tuner and their value are 0.0228, 0.00004496, 0.040 and 0.0691, 0.0002, 0.1394, respectively.

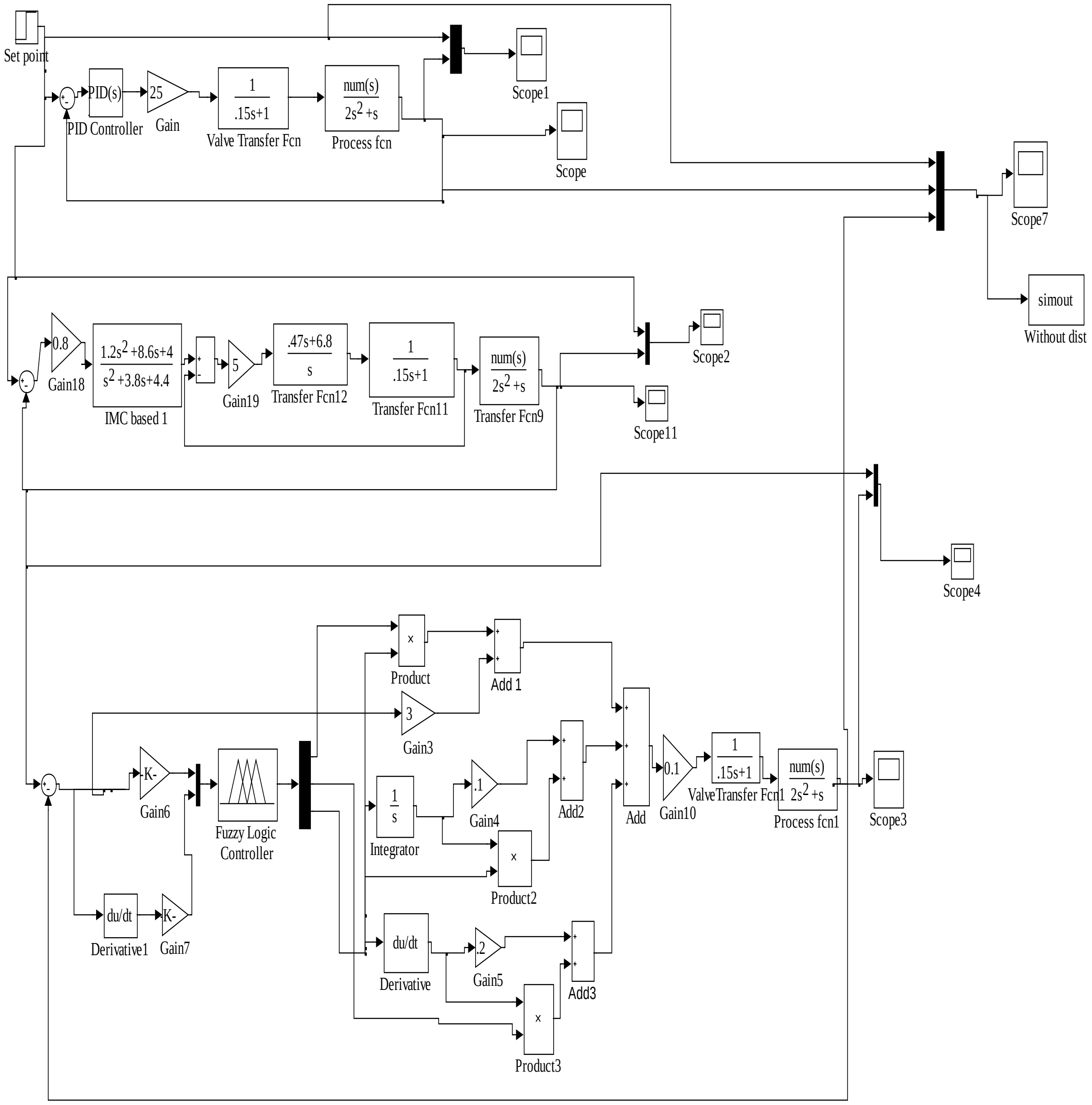


Fig.14(Simulink model of boiler drum using PID, IMC-cascade and FLC, without consideration of steam flow pressure as disturbance)

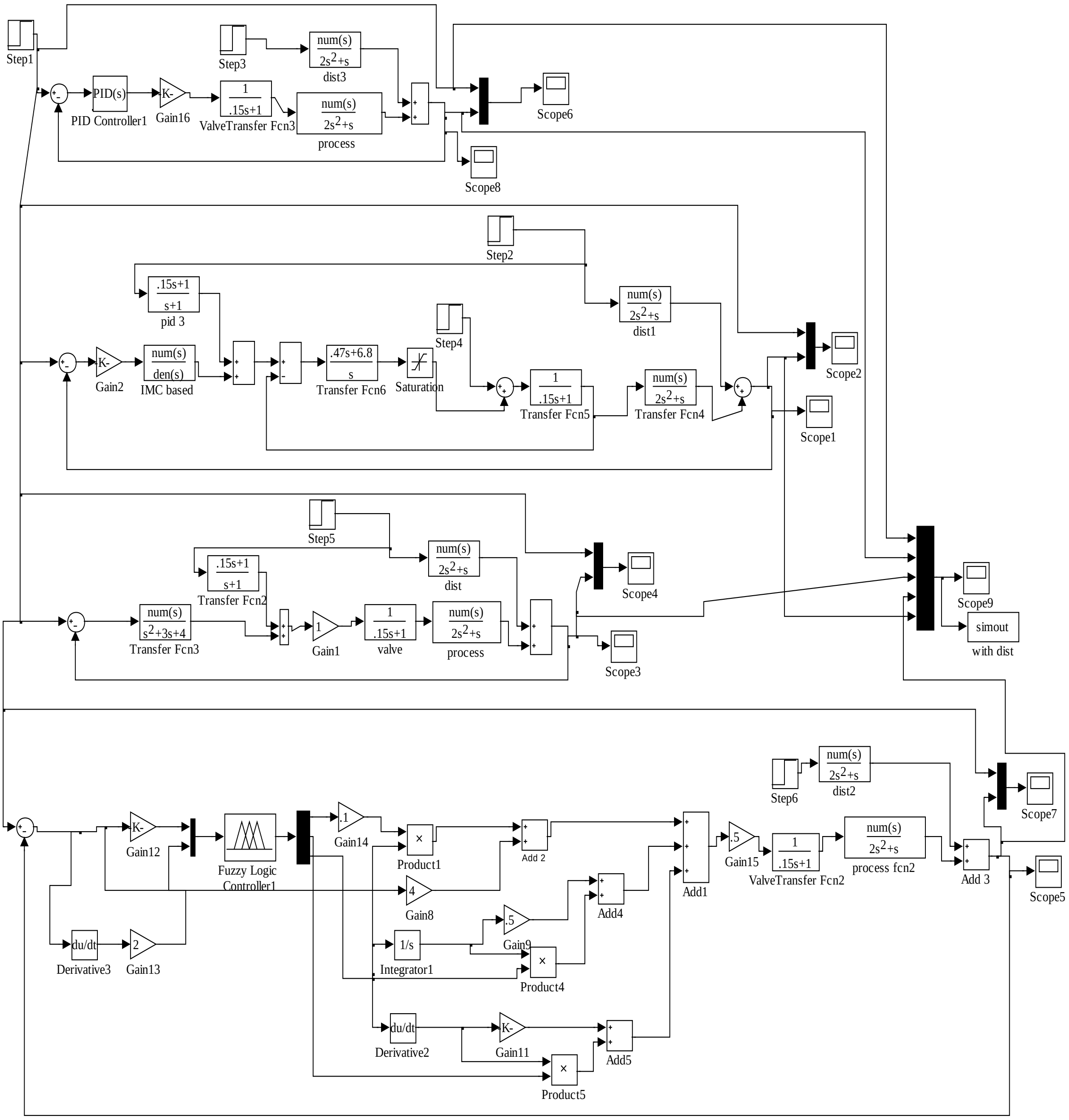


Fig.15 (Simulink model of boiler drum using PID, IMC-cascade and FLC, with consideration of steam flow pressure as disturbance)

IV. RESULTS & DISCUSSIONS

In this paper, design parameters of boiler drum using different and advanced controller strategies have been exhaustively explored. The performance indices obtained are rather straight forward and simple. The results of the output response to a step response in drum level using the described simulink models for steam boiler drum conventional PID control, IMC-cascade and the FLC control systemwithout disturbance control are presented in Fig. 16. The output response variation after considering the steam pressure as load for various control approaches are presented in Fig. 17. It is observed from the results that the designed IMC-FF-Cascade controller possesses better tracking capability, and also less overshoot, whereas, FLC controller has lesser rise time compared to others. The results are further compared quantitatively in Table 1 and Table 2. Table 1 lists the control parameters for various controllerswithout disturbance control, and Table 2 presents these for disturbance control condition.

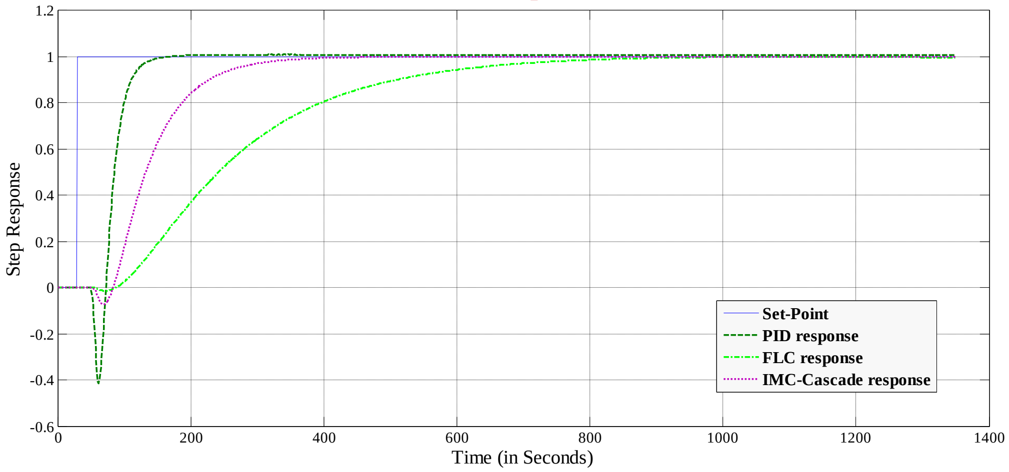


Fig. 16 (Step response of boiler drum using PID, IMC-cascade and FLC without consideration of steam flow pressure as disturbance)

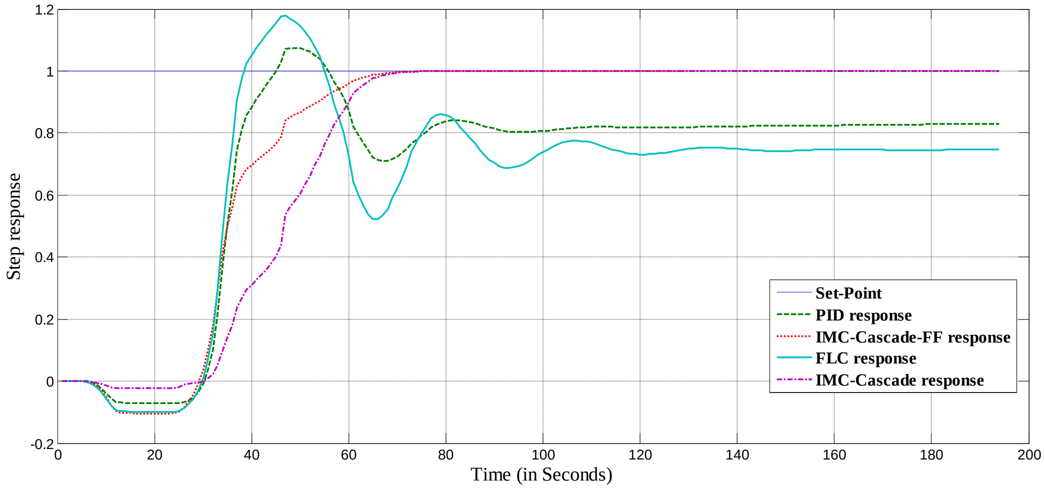


Fig. 17 (Step response of boiler drum using PID, IMC-FF-Cascade, IMC-FF and FLC with steam flow consideration of disturbance)

FLC controller, although shows sluggishness by having high rise time (22.05s) when not considering disturbance, it shows the fastest rise (rise time ~2.78s) when considering disturbance. The IMC-Cascade controller shows the best settling time than others for both cases -with and without disturbance. In case of control with disturbance, IMC-Cascade with FF shows the best settling time of 10.63s compared to IMC Cascade controller (12.4s). PID and FLC Controller show a poor settling behavior, and the values cannot be quantified as these never reach in 5% tolerance band. With regards to overshoot, FLC shows the least value -1.3% approx., and hence, the best behavior, compared to other controllers (PID, -41.4% and IMC-cascade, -7.2%approx.) when not considering disturbance. When disturbance is considered, the IMC cascade controller shows best performance (-2.29%) verses IMC-FF (-10.36%), PID (7%) and FLC (18%).

Table.1 (Control parameters of boiler drum without considering steam boiler pressure disturbance)

Controller strategies	Parameters (without consideration of steam flow pressuer as disturbance)			
	Rise-Time (t_r) (in sec)	Settling-Time (5%Tolerance-Band) (in sec)	Overshoot (Mp) (in %)	Tracking Capability
PID Controller	2.06	4.85	-41.4	Good
IMC-Cascade Controller	8.74	13.2	-7.2	Better
FLC Controller	22.05	33.2	-1.3	Better

Table. 2 (Control parameters of boiler drum without considering steam boiler pressure disturbance)

Controller strategies	Parameters (with consideration of steam flow pressuer as disturbance)			
	Rise-Time (t_r) (in sec)	Settling-Time (5%Tolerance-Band TB) (in sec)	Overshoot (Mp) (in %)	Tracking Capability
PID Controller	3.37	Never reach in 5% TB	7	Fair
IMC-Cascade Controller	7.57	12.4	-2.29	Good
IMC-FF-Cascade Controller	6.8	10.63	-10.36	Better
FLC Controller	2.78	Never reaches in 5% TB	18	Fair

V. CONCLUSION

The results presented provide us with the direction for the boiler drum control problem presented in this work. The set point tracking is observed best for PID controller (without disturbance) and IMC-Cascade controller (with disturbace). Based on these observations, it is concluded that IMC-cascaded controller has better disturbance rejection capability than others, due to its good tracking capability, low overshoot and settling time. However, when a better rise time is desired, FLC can be proposed to be better for process control (with disturbance), though it suffers from high overshoot and large settling time.

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