Modeling and Simulation of prototype of boiler drum level control

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Abstract - This paper represents an approach for controlling a very crucial parameter of boiler i.e. level of the boiler drum using PID controller. IMC based PID tuning method is used with feed forward and feedback strategy is used to control two element drum level. Besides this paper is also describes the modeling of the process for level control and implemented it in simulink. Hardware model has also been developed and proved open loop validation for theoretically derived model & practical model, further practical and simulation responses are compared with respect to rise time, settling time and maximum peak overshoot.

Keywords – Drum level, IMC based PID technique, Feed forward – feedback control strategy, Modeling.

I. INTRODUCTION

Boiler is defined as a closed vessel in which steam is produced from water by the combustion of fuel. In boilers, steam is produced by the interaction of hot flue gases with water pipes which is coming out from the fuel mainly coal or coke. Also, chemical energy of stored fuel is converted into the heat energy and heat energy is absorbed by the water which converted in to a steam.

Drum Level Control Systems are used extensively throughout the process industries. Control system is used to control the level of boiling water contained in boiler drums and provide a constant supply of steam. If the level is too high, flooding of steam purification equipment can occur. If the level is too low, reduction in efficiency of the treatment and recirculation function. Pressure can also build to dangerous levels. A drum level control system tightly controls the level whatever the disturbances, level change, increase/decrease of steam demand, feed water flow variations appears.

This work represents an approach for controlling a very crucial parameter of boiler i.e. level of the boiler drum using PID controller. Besides, this paper is also describes the modeling of the process for level control.

II. BOILER DRUM LEVEL CONTROL

Boiler drum level control is critical for the protection of plant and safety of equipment. The purpose of the drum level controller is to bring the drum level up to the given set point and maintain the level at constant steam load. An intense decrease in this level may expose boiler tubes, allowing them to become overheated and damaged. An increase in this level may cause interference with the process of separating moisture from steam within the drum, thus the efficiency of the boiler reduces and carrying moisture into the turbine [2]. Typically, there are three strategies used to control drum level. With each successive strategy, a refinement of the previous control strategy has been taken place. For extent of the load change requirements, the control strategy depends on the measurement and control equipment.

The three main options available for drum level control are discussed below:

A. Single Element Drum Level Control

The single element control is the simplest method for boiler drum level control system. It is least effective form of drum level control which requires a measurement of drum water level and feed water control valve. It is mainly recommended for boilers with modest change requirement and relatively constant feed water condition. The process variable coming from the drum level transmitter is compared to a set point and the difference is a deviation value. This signal is given to the controller which generates corrective action output. The output is then passed to the boiler feed water valve, which adjusts the level of feed water flow into the boiler drum.

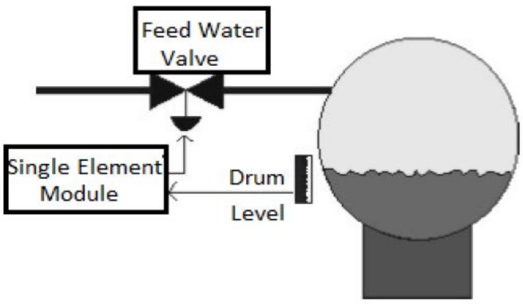

Fig. 1. Single element drum level control

B. Two Element Drum Level Control

A two-element system can do good job under most operating conditions. Two-element control involves adding the steam flow as a feed forward signal to the feed-water valve . Two-element control is primarily used on intermediate-size boilers, in which volumes and capacities of the steam and water system would make the simple total level control inadequate because of "swell." Total level control is undesirable when it is detected by sensors that are insensitive to density variations, such as the conductivity type. Displacement and Differential pressure type transmitter sensors are preferred from this perspective because they respond to hydrostatic pressure. Smaller boilers, in which load changes may be rapid, frequent, or of large magnitude, will also require the two-element system

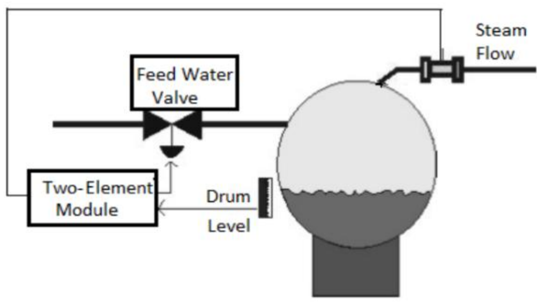

Fig. 2. Two element drum level control

C. Three Element Drum Level Control

This control system is ideally suited where a boiler plant consists of multiple boilers and multiple feed water pumps or feed water valve has variation in pressure or flow. It requires the measurement of drum level, steam flow rate, feed water flow rate and feed water control valve. By using cascade control mechanism level element act as a primary loop and flow element act as a secondary loop and steam flow element act as a feed forward controller. Level element and steam flow element mainly correct for unmeasured disturbances within the system such as boiler blow down. Feed water flow element responds rapidly to variations in feed water demand either from the feed water pressure and steam flow rate of feed forward signal.

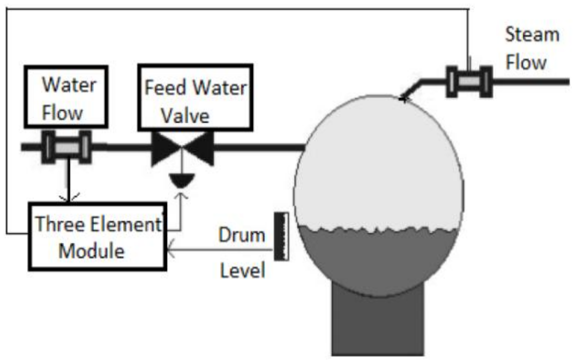

Fig.3. Three element drum level control

III. CONTROL STRATEGY

The feed forward strategy is applied in this work is described below:

Consider the generalized process shown in fig 4. It has an output y, a potential disturbance d, and an available manipulated variable m.

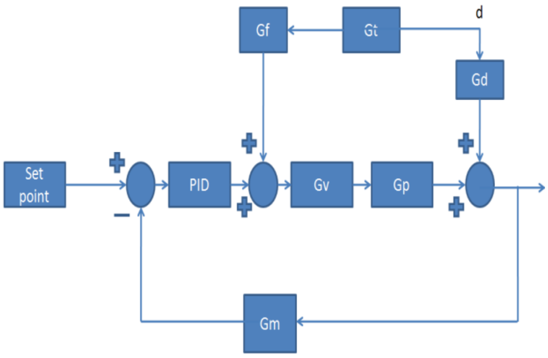

Fig. 4. Block diagram of feed-forward controller

The disturbance d (also known as load and process load) changes in an unpredictable manner and our control objective are to keep the value of the output y at desired levels. A feedback control action takes the following steps:

- Measures the value of the output (flow, pressure, liquid level, temperature, composition) using the appropriate measuring device. Let y_m be the value indicated by the measuring sensor.
- Compares the indicated value y_m to the desired value y_{sp} (set point) of the output. Let the deviation (error) be $e = y_{sp} - y_m$.
- The value of the deviation e is supplied to the main controller. The controller in turn changes the value of the manipulated variable m in such a way as to reduce the magnitude of the deviation e. usually, the controller does not affect the manipulated variable directly but through another device (usually a control valve), known as the final control element.
- The feedback controlled system of fig 4 which is called closed loop. Also, when the value of d or m changes, the response of the first is called open loop response while that of the second is the closed loop response.

Feedback controller takes action as:

By reducing the block diagram of fig 4, we have

$$y = \frac{G_p G_v (G_c + G_f) y_{sp}}{1 + G_p G_v G_c G_m} + \frac{(G_d + G_p G_v G_f G_t) d}{1 + G_p G_v G_c G_m}$$

If set point does not change output must not change in ideal case.

$$y = 0, y_{sp} = 0, d \neq 0;$$

$$G_f = -\frac{G_d}{G_t G_v G_p}$$

So, from above calculation forward controller is classical lead lag type compensator.

IV. MODELING

The mathematical model of the boiler system is described in this section where two main equations has been obtained i.e. the drum level and pressure equations. Both equations consider the level and pressure as state variables, and are obtained using mass and energy balances of the boiler system considering both liquid and steam phases.

The following assumptions are made for this model:

- The drum is a perfect cylinder.
- The heat exchange surface between vapor and liquid is planar.
- The water in both phases (liquid and vapor) at the drum is at the saturated conditions.

Mass flow rate balance [3]

Based on mass flow rate balance, the equations are as follows:

$D =$ height of water in the boiler drum.
$W_{sh} =$ mass steam flow.
$W_{fe} =$ mass water flow.
$Q_{sww} =$ heat flow rate between the furnace metal and liquid.
$\rho_1 =$ density of saturated water.
$\rho_v =$ density of saturated stead.
$d =$ height of the boiler drum.
$h_1 =$ enthalpy of saturated water.
$h_v =$ enthalpy of saturated steam

$$W_{sh} - W_{fe} = \frac{\partial[\rho_v V_v + \rho_1 V_1]}{\partial t} \quad \text{----------------------- [1]}$$

$$W_{sf} - W_{fwf} = v_v\frac{\partial}{\partial t}\rho_v + \rho_v\frac{\partial}{\partial t}v_v + v_1\frac{\partial}{\partial t}\rho_1 + \rho_1\frac{\partial}{\partial t}v_1 \quad \text{----- [2]}$$

$$\rho_v = a_0 + a_1 P + a_2 P^2$$

$$\rho_1 = b_0 + b_1 P + b_2 P^2$$

$$\frac{\partial \rho_v}{\partial P} = k_1 = a_1 + 2a_2 P$$

$$\frac{\partial \rho_1}{\partial P} = k_2 = b_1 + 2b_2 P$$

$$V_1 = \pi r^2 D$$

$$\frac{\partial V_1}{\partial t} = \pi r^2 \frac{\partial D}{\partial t}$$

$$W_{sh} - W_{fe} = V_v \frac{\partial \rho_v}{\partial P}\frac{\partial P}{\partial t} + V_1 \frac{\partial \rho_1}{\partial P}\frac{\partial P}{\partial t} + \rho_v \frac{\partial V_v}{\partial t} + \rho_1 \frac{\partial V_1}{\partial t} \quad [3]$$

$$W_{sh} - W_{fe} = -V_1 K_1 \frac{\partial P}{\partial t} + V_1 K_2 \frac{\partial P}{\partial t} - \rho_v \frac{\partial V_1}{\partial t} + \rho_1 \frac{\partial V_1}{\partial t} [4]$$

$$W_{sh} - W_{fe} = -V_1 K_1 \frac{\partial P}{\partial t} + V_1 K_2 \frac{\partial P}{\partial t} - \rho_v \pi r^2 \frac{\partial D}{\partial t} + \rho_1 \pi r^2 \frac{\partial D}{\partial t} \quad \text{--------- [5]}$$

$$W_{sh} - W_{fe} = \frac{\partial P}{\partial t}[V_1 k_2 - V_1 K_1] + \frac{\partial D}{\partial t}[\rho_1 \pi r^2 - \rho_v \pi r^2] \quad \text{-------------- [6]}$$

Energy balance:

$$W_{sh} h_v - W_{fe} h_{eo} + Q_{sww} = \frac{\partial[\rho_1 h_1 V_1 + \rho_v h_v V_v]}{\partial t}$$

$V_v = -V_1$; Because, steam volume decrease or increase as water level increase or decrease.

$$W_{sh} h_v - W_{fe} h_{eo} + Q_{sww} = \frac{\partial[\rho_1 h_1 V_1 - \rho_v h_v V_1]}{\partial t}$$

$$W_{sh} h_v - W_{fe} h_{eo} + Q_{sww} = V_1 h_1 \frac{\partial \rho_1}{\partial t} + \rho_1 h_1 \frac{\partial V_1}{\partial t} + \rho_1 V_1 \frac{\partial h_1}{\partial t} - h_v V_1 \frac{\partial \rho_v}{\partial t} - \rho_v V_1 \frac{\partial h_v}{\partial t} - \rho_v h_v \frac{\partial V_1}{\partial t} \quad \text{------- [7]}$$

$$W_{sh} h_v - W_{fe} h_{eo} + Q_{sww} = V_1 h_1 \frac{\partial \rho_1}{\partial P}\frac{\partial P}{\partial t} + \rho_1 h_1 \frac{\partial V_1}{\partial t} + \rho_1 V_1 \frac{\partial h_1}{\partial P}\frac{\partial P}{\partial t} - h_v V_1 \frac{\partial \rho_v}{\partial P}\frac{\partial P}{\partial t} - \rho_v V_1 \frac{\partial h_v}{\partial P}\frac{\partial P}{\partial t} - \rho_v h_v \frac{\partial v_1}{\partial t} \quad \text{--------- [8]}$$

Putting the value of K_1, K_2, K_3, K_4 in equation 8

$W_{sh} h_v - W_{fe} h_{eo} + Q_{sww} = \frac{\partial P}{\partial t}[\pi r^2 dh_1 k_2 +$ ρ1πr2dk4−hvπr2dk1−ρvπr2dk3+∂D∂t[ρ1h1πr2−ρvhvπr2] --------- [9]

From equation 6

$$\frac{\partial P}{\partial t} = \frac{W_{sh} - W_{fe} - \frac{\partial D}{\partial t}[\rho_1 \pi r^2 - \rho_v \pi r^2]}{[\pi r^2 dk_2 - \pi r^2 dk_1]}$$

Putting the value of $\frac{\partial P}{\partial t}$ in to equation no. 10

$$A = \pi r^2 dh_1 k_2 + \rho_1 \pi r^2 dk_4 - h_v \pi r^2 dk_1 - \rho_v \pi r^2 dk_3$$

$$\frac{\partial D}{\partial t} = \frac{[W_{sh} h_v - W_{fe} h_{eo} + Q_{sww}][\pi r^2 dk_2 - \pi r^2 dk_1] - AW_{sh} + AW_{fe}}{[\rho_1 h_1 \pi r^2 - \rho_v h_v \pi r^2][\pi r^2 dk_2 - \pi r^2 dk_1] - A}$$

On substituting the appropriate values, we have

$$\frac{\partial D}{\partial t} = 1.87 \times 10^{-3}$$

Converting equation in to Laplace transform

$SD(S) = 1.87 \times 10^{-3}$

$$D(S) = \frac{1.87 \times 10^{-3}}{S}$$

V. PID TUNING METHOD

IMC based PID tuning procedure is used in this work whose description is as follows: [4][5]

Consider a process model Gp*(s) for an actual process or plant Gp(s). The controller Qc(s) is used to control the process in which the disturbances d(s) enter into the system. The various steps in the Internal Model Control (IMC) system design procedure are

Factorization: It means factoring a transfer function into invertible (good stuff) and non invertible (bad stuff) portions. The factor containing right hand plane (RHP) or zeros or time delays become the poles in the inverts of the process model when designing the controller. So this is non invertible portion which has to be removed from the system.

Mathematically it is given as

$$G_p^*(s) = G_p^*(+)(s) G_p^*(-)(s)$$

Where,

$$G_p^*(+)(s) \ is\ non\ vertible\ portion$$
$$G_p^*(-)(s) \ is\ vertible\ portion$$

Usually we use all pass factorization.

Ideal IMC controller:

The ideal IMC controller is the inverse of the invertible portion of the process model.

It is given as

Qc*(s) = inv[Gp*(-)(s)]

Adding Filter: Now we add a filter to make our controller proper.A transfer function is said to be proper if the order of the denominator is at least as great as the order of the numerator. If they are exactly of the same order the transfer function is said to be semi-proper.If the order of the denominator is greater than the order of the numerator the transfer functions is strictly proper. Thus a controller can be physically implemented if it is proper. So to make the controller proper mathematically it is given as

Qc(s) = Qc*(s) f(s) = inv [Gp*(-)(s)] f(s)

Where f(s) is a low pass filter.

Low pass filter [f(s)]: In order to improve the robustness of the system the effect of model mismatch should be minimized. Since mismatch between the actual process and the model usually occur at high frequency end of the systems frequency response, a low pass filter f(s) is usually added to attenuate the effects of process model mismatch.

Thus the internal model controller is usually designed as the inverse of the process model in series with the low pass filter i.e

Qc(s) = Qc*(s) f(s) = inv[Gp*(-)(s)] f(s).

Where f(s) = 1/(lem* s+1) ^ n

Where, lem is the filter tuning parameter to vary the speed of the response of closed loop system. Now the low pass filter can be of three types:

If we focus on setpoint changes, the form of filter used is f(s) = 1/(lem* s+1) ^ n. Here, n is the order of the process.

If we focus on good tracking of ramp set point changes the filter of the form used is

f(s) = (n. lem. s + 1)/ (lem* s+1) ^ n

If we focus on good rejection of step input load disturbances the filter of the form use is f = (gamma.s+1)/(lem* s+1) ^ n where gamma is any constant.

Equivalent standard feedback controller:[6]

Now we compare with PID Controller transfer function

For first order : Gc(s) = [Kc . (Ti .s + 1)]/ (Ti . s)

And find Kc and Ti (PI tuning parameters).

Similarly for 2^{nd} order we compare with the standard

PID controller transfer function given by :

Gc(s) = Kc . [(Ti .Td .s^2+Ti . s+1)/Ti . s]. [1/ Tf . s+1]

Where
T = Tau (any constant)
Ti = integral time constant
Td = derivative time constant
Tf = filter tuning factor
Kc = controller gain

Now we perform closed loop simulations for above procedure and adjust lem (lemda) considering a trade off between performance and robustness (sensitivity to model error).

Drum level control Transfer function:

$$G_p = \frac{1.78 \times 10^{-3}}{s}$$

$$f_s = \frac{1}{\lambda s + 1}$$

$$q_s = G_p^{-1} f_s$$

$$q_c = \frac{q_s}{1 - q_s G_p}$$

$$q_c = \frac{s \times 1000}{1.78 \times (\lambda s + 1) - 1000 \times 1.78 \times 10^{-3}}$$

$$q_c = \frac{1}{1.78 \times 10^{-3} \times \lambda}$$

If, λ=1, then $k_c = 561.80$
If, λ=2,then $k_c = 280.90$

VI. SIMULATION

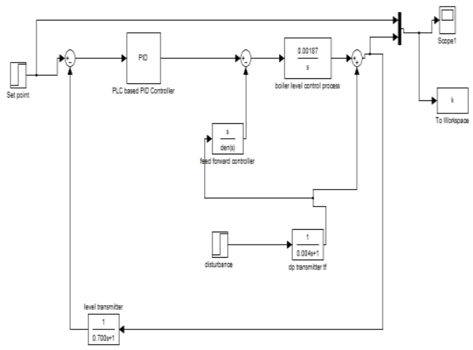

Fig. 5. Simulink model of two element drum level control

Open loop validation:

In our process we have derived theoretically boiler drum level control process is pure integrator process. if we give small step change to integrator in open loop strategy it will go to the infinity mode so we have implemented in closed loop mode to control the process. open loop mode prove that our theoretically derived process validate to the practical system. open loop practical response is shown below.

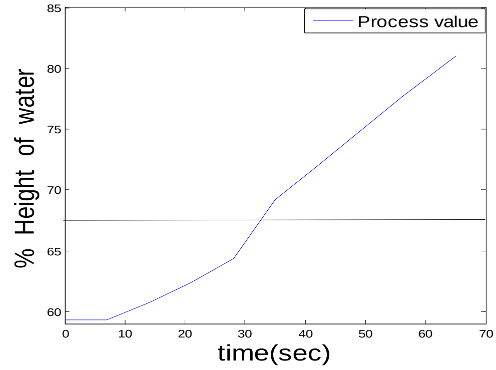

Fig. 6. Open loop validation

With different lemda value imc based pid tuning response is shown below, lemda is tuning parameter that will vary the speed of response.

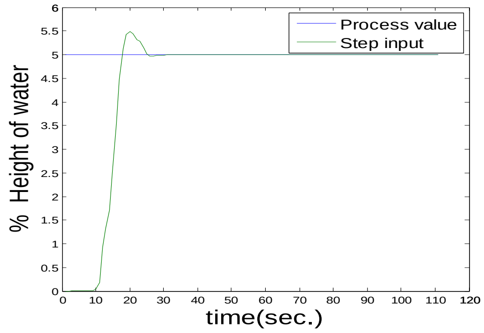

Fig. 7.IMC lambda=2 response.

Ideal response of imc based PID tuning by lemda=2 chosen because it is giving minimum overshoot.

Practical imc based pid tune in PLC for boiler drum level control that was give below practical response.

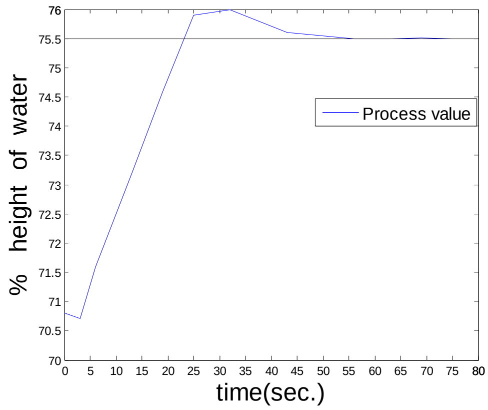

Fig.8. Response of simulink model

Practical swelling & shrinking response by applying disturbance 10 second on & off by solenoid valve in steam flow, below graph is shown

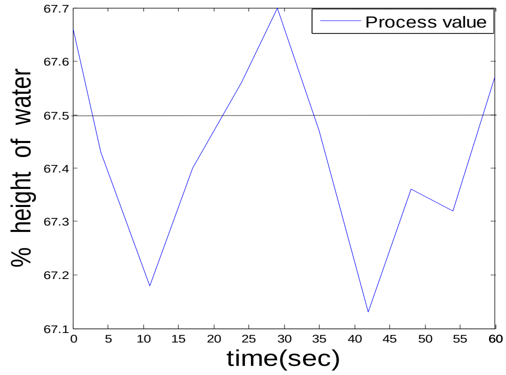

Fig.9. Swelling and shrinking response

	Delay time(td)	Rise time(tr)	Max peak overshoot	Settling time(ts)
Ideal	14 sec.	6 sec.	0.4	25 sec
Practical	15 sec.	13sec.	0.5	50 sec

VII. CONCLUSION

IMC based pid tuning for lemda = 2 is implemented because it’s give less overshoot. In above comparison table of delay time, rise time, settling time is shown. Difference between ideal & practical is due to transfer function of control valve & i/p converter, which is not kept in ideal simulation. Difference for Delay time & rise time is due to pump pressure which is injecting water inside the drum is not matching ideally & practically

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