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Realisation of Optimum Main Steam Temperature Control in Gas Fired Utility Boiler by Combined Usage of Feedback, Cascade, Multiple Iterative Feedforward and Iterative Learning Control

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Abstract:
The paper explores cost effective technique to achieve optimum main steam temperature control of a Gas Fired Utility Boiler of Power Plant or Ethylene Cracker Unit by implementation of combination cascade, multiple iterative feed forward control and iterative learning control. The paper shows how by using of said control technique the difficulties of conventational control technique i.e. Feedback and Cascade can be overcomed without addition any extra hardware or cost. The paper outlines complete implementation technique of proposed control specification in modern day DCS(Distributed Control System) from selection of variables to algorithm. At the same time the paper provides datas and trends of practical application of the control technique in a gas fired 80TPH utility boiler for the better understanding. The next section of the paper deals with advantages of this technique with conventional control algorithm.

Keywords: *Main stream temperature control, iterative learning control, multiple iterative feed forward control*

1. Introduction

Steam temperature is one of the most critical control loops in a boiler of a Power Plant or Ethylene Cracker Unit because it is highly nonlinear and has a long dead time and time lag. Adding to the criticality, steam temperature is affected by boiler load, rate of change of boiler load, steam flow rate, fuel flow rate, feed water flow and numbers of burners in service.

After separation from the boiler water in the drum, the steam is superheated to improve the thermal efficiency of the boiler-turbine unit. In Modern day boilers the steam temperature is raised to around 1000F (538C), which approaches the creep (slow deformation) point of the steel. Steam temperatures above this point, even for small periods of time, can shorten the lifetime of the boiler. Again negative excursion of the temperature leads to reduction in cycle efficiency. Maintaining constant steam temperature is also necessary and essential for minimizing thermal stresses on the boiler and turbine driven equipments.

Steam temperature is normally controlled by spraying water into the steam between the primary/platen and second-stage /secondary/Final Superheater to cool it down. Water injection is done in a equipment called an attemperator or desuperheater. The spray water comes from either an intermediate stage of the boiler feedwater pump (for reheater spray) or from the pump discharge (for superheater spray). Other methods of steam temperature control include flue gas recirculation, flue gas bypass, and tilting the angle at which the burners fire into the furnace. This discussion will focus on steam temperature control through attemperation.

The target is to keep the steam temperature within +/-5 degree centigrade. With conventional cascade PID control, this is not achievable in most of cases, leading shoot up or sudden decrease of temperature. This paper represents the method and algorithm for a combination of cascade, multiple iterative feedforward control and iterative learning control to achieve the main steam temperature control and proves that usage of such type algorithm can keep temperature within limits. The technique involves no additional cost as it can be implemented in existing DCS system of the Plant and no additional hardware is required.

2. The Control Schematic: Evolution to Optimization

2.1. Basic Feedback Control

The simplest method for controlling steam temperature is by measuring the main steam temperature, and changing the spray water valve position to correct deviations from the steam temperature set point. This control loop should be tuned for the fastest possible response without overshoot, but even then the loop will respond relatively slowly due to the long dead time and time lag of the superheater.

2.2. Cascaded Steam Temperature Control

Because of the slow response of the main steam temperature control loop, improved disturbance rejection can be achieved by implementing a secondary (inner) control loop at the desuperheater. This loop measures the desuperheater outlet temperature and manipulates the control valve position to match the desuperheater outlet temperature to its set point coming from the main steam temperature controller (Figure 2).

Here Desuperheater Outlet Temperature has been chosen as secondary variable for following reasons:

1) The Desuperheater Outlet Temperature indicate the occurrence of an important disturbance i.e. changes of this temperature definitely changes final steam temp.

2) Have a causal relationship with the spray control valve i.e. opening/closing of spray control valve decreases/increases the de-superheater outlet temperature.

3) Have a faster response than the primary variable i.e. final steam temperature.

The spray water comes from upstream of the feed water control valves, so changes in feed water control valve position will cause changes in spray water pressure, and therefore disturb the spray water flow rate. The desuperheater outlet temperature control loop will provide a gradual recovery when this happens. If the spray water flow rate to the attemperator is measured, a flow control loop can be implemented as a tertiary inner loop to provide very fast disturbance rejection. However, in most of the power plants/Process Plant either spray water flow meter is not present or its repeatability (not accuracy) is a concern, so this flow loop cannot be implemented.

2.3. Multiple Iterative Feedforward

Even with the above arrangement, large deviation occurs in the steam temperature when major disturbances occur like taking another burner in-line or tripping of one of the boiler feed water pumps etc.

A closer look at the system gave us five measurable disturbances. They are as follows:

a)Fuel Flow(FG):

As fuel flow increases temperature of steam increases. So, more spray water is required to control the temperature of the steam.

b)Differential Pressure between Feed Water Pressure and Boiler Drum Pressure(DP):

The feed water flow is proportional to differential pressure between Feed Water Pressure and Boiler Drum Pressure As feed water flow increases more spray water flow occurs for same opening of the valve.

c) Main Steam flow (FS):As Load increase, MS flow increases, and steam temperature decreases.

d) Temperature of Steam at Desuperheater Inlet : As temperature increases, more water required to decrease steam temp.

e) Temperature of Steam at Desuperheater Outlet : As temperature increases, more water required to decrease steam temp.

f) Change in Set point by Operator;

g) Drum Pressure;

These disturbances take different quantum of time to disturb the Main Steam temperature. In Cascade Control scheme Temperature Controller starts taking action after the change occurs in main steam temperature. These make the control action slow and oscillating in nature. This type of control scheme is acceptable until quantum of disturbance of not very high.

If the response of the system for each disturbance is known, effect of disturbance can be added to PV input of temperature controller. This is like telling lie to controller. For example suppose in steady state condition (Constant Boiler Load and unchanged other condition), Fuel Flow increases suddenly due to malfunction of valve or operator mistake. The Temp Controller will compensate this effect (rather try to keep the main steam temperature constant) by increasing command to spray control valve. But this may be too late to resulting the steam temperature overshoot.

Now when the flow increases we can give PV value to main temperature controller as follows:

PV= Main Steam Temperature+ X1;

=Main Steam Temperature+ (K1*Change of Fuel Flow);

So, when fuel flow increases even if the main steam temperature do not increase, the controller will be informed that the temperature is increasing and it will start taking necessary action(This is why I told earlier that this is like telling lie to the controller)

Now, how much we need to lie to the controller?

K1 will be zero until Change in Fuel Flow (Fuel Flow-Delayed input of Fuel Flow) is below a defined level; otherwise there will be unnecessary fluctuation. The rate of change can be adjusted by changing value of delay timer.

Again, we can limit X1 to positive value and a negative value says +5 to -5.

Now K1 is a variable constant which iterates to the limit, this is to ensure that input to final control element is a ramp not step.

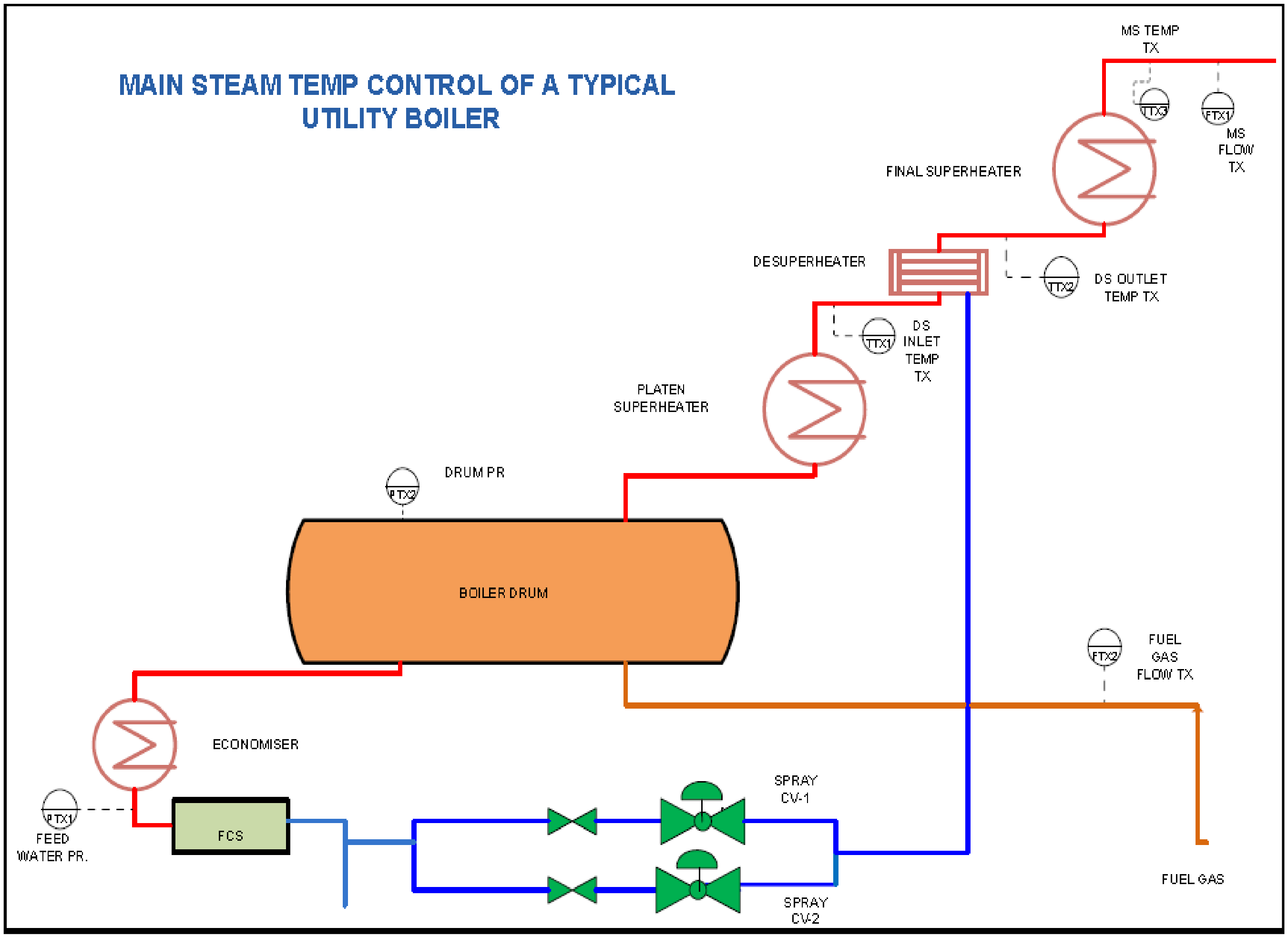

Figure 1

3. Practical Implementation in DCS

The above scheme can be implemented in DCS (Distributed Control System) by using simple control blocks like Arithmetic Blocks, Calculation Blocks, Delay Timer, PID Controller etc which are available in all major DCS supplier like Yokogawa, Honeywell, Max DNA etc.

The author of this journel implemented above schematic in a 80TPH gas fired utility boiler. The next portion of this paper deals with how different feedforward inputs are measured, modulated and fed into the PID controller and how the Main Steam temperature behaves upon various disturbances.

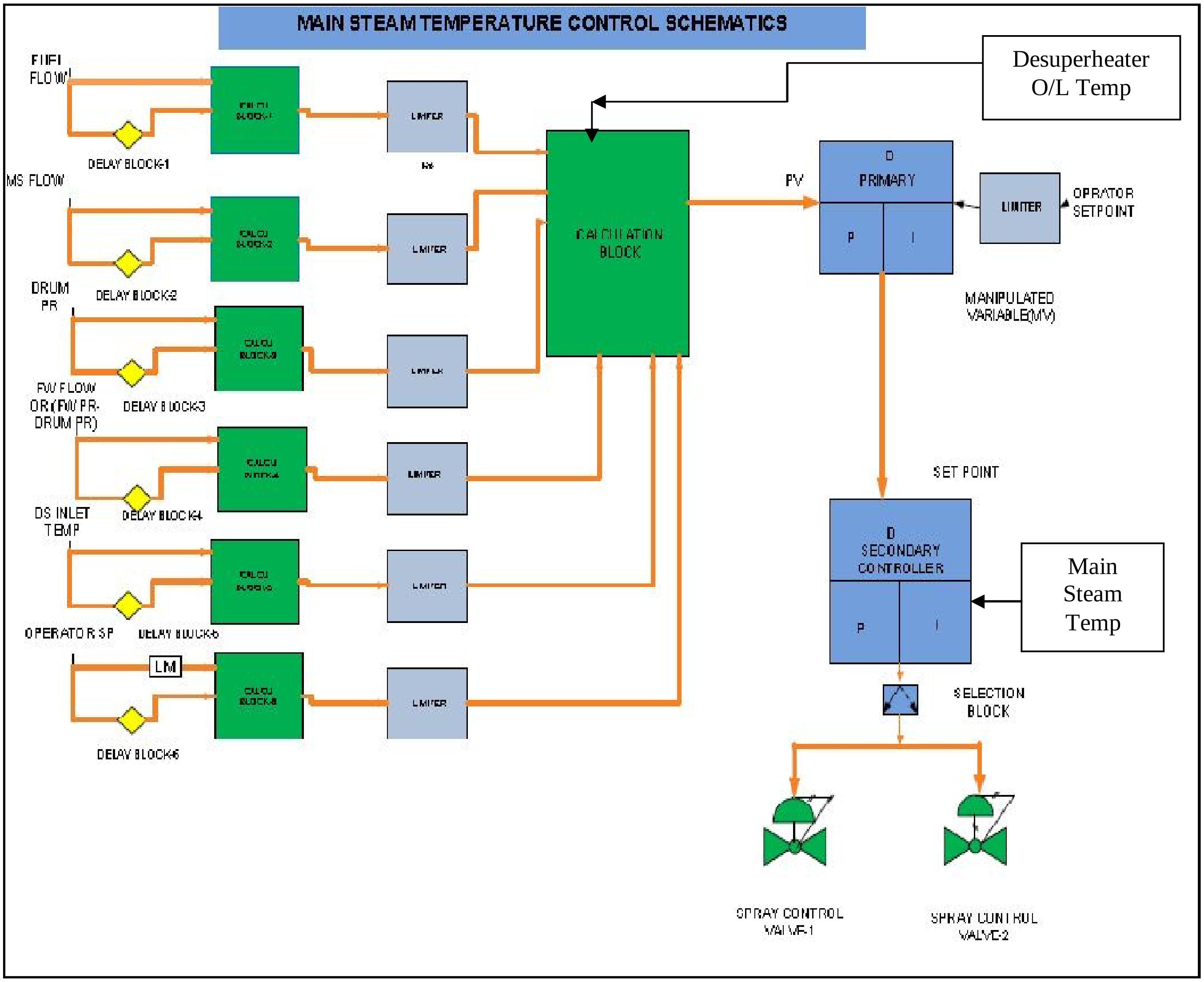

Figure 2

3.1. Effect of Fuel Flow

As fuel flow increases temperature of steam increases. So, more spray water is required to control the temperature of the steam. Hence, Controller action is direct.

→ Calculation Block 1:

A=Fuel Flow;

B=Delayed(Delay of 2.33 Min) Fuel Flow;

Y1=Lim {-35, (A-B)*0.0255, 35};

Y2=Lim {-10, Y2+ (Y2-Y1)*0.05, 10};

Out=Lim {-35, Y1+Y2, 35};

(Note: Calculation Block can perform complex calculation. The order of calculation is Y1 to Y6 and then Out)

Result of above iteration can be tabulated as follows:

Time	2.33SEC					2.33 Sec					2.33 Sec					2.33 Sec				
Iteration No.	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th	19th	20th
A (Fuel Flow Actual)	7000	7020	7012	7006	7045	7050	7500	7203	7202	7201	7201	7202	7201	7203	5000	7200	7203	7202	7201	7204
B (Delayed input of Fuel Flow)	5000	4980	4988	5001	4980	7000	7020	7012	7006	7045	7050	7202	7203	7202	7201	7201	7202	7201	7203	7201
Y1	51.00	52.02	51.61	51.13	52.66	1.275	12.24	4.8705	4.998	3.978	3.85	0.00	-0.05	0.03	-56.13	-0.03	0.03	0.03	-0.05	0.08
Y2	2.55	5.02	7.35	9.54	11.70	11.18	11.23	10.91	10.62	10.28	9.96	9.46	8.99	8.54	5.31	5.04	4.79	4.55	4.32	4.11
OUT	53.55	57.04	58.96	60.67	64.35	12.45	23.47	15.78	15.61	14.26	13.81	9.46	8.94	8.57	-50.82	5.01	4.82	4.58	4.27	4.19
LIMIT OUT	35.00	35.00	35.00	35.00	35.00	12.45	23.47	15.78	15.61	14.26	13.81	9.46	8.94	8.57	-50.82	5.01	4.82	4.58	4.27	4.19
PV INPUT TO FSH PID	54.25	54.25	54.25	54.25	54.25	19.30	36.38	24.46	24.20	22.11	21.41	14.67	13.85	13.28	-78.77	7.77	7.46	7.09	6.62	6.49
APPLY LIMIT	45.00	45.00	45.00	45.00	45.00	19.30	36.38	24.46	24.20	22.11	21.41	14.67	13.85	13.28	-45.00	7.77	7.46	7.09	6.62	6.49

Table 1

In above case intial fuel flow was 5000 NM3/Hr.After 2.33 min the fuel flow becomes 7000 Nm3/Hr, maybe due to taking another burner in line.Now the physics of boiler tells us that,if all other conditions remains constant, an increase in fuel flow will increase the Main Steam Temperature after certain quantum of time.

By using above control schematic,the controller starts taking control action much before the temperature rises by appending output of above control block to the PV value. Again, by limiting output of control block, reduction of oscillation of final control parameter have been ensured.

3.2. Effect of Main Steam Flow

As MS flow increases, steam temperature decreases. Hence Controller actions reverse.

→ Calculation Block 2:

In C= Main Steam Flow;

In D= Delayed input of Main Steam Flow(Delay of)

Y3=Lim(-10,((D-C)*0.175),10;

Y4=Lim(0,(Y4+(0.5*Y3-Y4)*0.0001),Y3);

Out=Lim(-10,(Y4-Y4)*1.55,10);

Result of above iteration can be tabulated as follows:

Time															
Iteration No	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**	**11th**	**12th**	**13th**	**14th**	**15th**
MS Flow Actual	70	72	73	73	72	71	71	72	73	74	50	52	53	51	52
MS Flow Delayed	50	60.5	61	62	63	70	72	73	73	72	70	72	73	73	72
Y3	-3.50	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0	-0.4	3.50	3.50	3.50	3.85	3.50
Limit(Y3)	-3.50	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0.00	-0.35	3.50	3.50	3.50	3.85	3.50
Y4	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00
Limit(Y4)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Output(#290)	-3.50	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0.00	-0.35	3.50	3.50	3.50	3.85	3.50
Limit Output	-3.50	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0.00	-0.35	3.50	3.50	3.50	3.85	3.50
Final output from in 312(to be added with PV Value of FSH PID)	-5.43	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0.00	-0.35	3.50	3.50	3.50	3.85	3.50
Limit Final O/P	-5.43	-2.01	-2.10	-1.93	-1.58	-0.18	0.18	0.18	0.00	-0.35	3.50	3.50	3.50	3.85	3.50

Table 2

3.3. Effect of Drum Pressure

As demand of steam increases, steam flow increases and drum pressure decreases and this will decrease the steam temperature in turn. So, when drum pressure decreases PV value needs to be reduced to take faster correction of change of control parameter.

Effect of variation of steam temperature due to change in drum pressure can be compensated through following algorithm:

→ Calculation Block 3:

In A: Drum Pressure;

In B: Delayed Input of Drum Pressure;

Y1=Lim(-10,(B-A)*1.75,10);

Y2= Lim(-5,(Y2+(Y1-Y2)*0.001,5);

Y5=Lim(-5,(Y5+((Y1+Y2)*2-Y5)*0.001,5);

Y6=Lim(-5,(0.5*Y1+Y2+Y5,5);

OUT=Lim(-10,Y6*1.55,10);

The iteration value can be tabulated as follows:

Time	2 Min				2 Min				2 Min			
Iteration No	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
Drum Pressure(A)	150	151	150	150	150	155	156	156	155	154	156	158
Drum Pressure Delayed(B),Delay-2 Min	152	153	134	132	150.00	151.00	150.00	150.00	150.00	155.00	156.00	156.00
Y1	3.50	3.50	-28.00	-31.50	0.00	-7.00	-10.50	-10.50	-8.75	1.75	0.00	-3.50
LIMIT Y1	3.50	3.50	-10.00	-10.00	0.00	-7.00	-10.00	-10.00	-8.75	1.75	0.00	-3.50
Y2	0.04	0.07	-0.03	-0.13	-0.13	-0.20	-0.30	-0.39	-0.48	-0.45	-0.45	-0.48
LIMIT Y2	0.04	0.07	-0.03	-0.131	-0.13	-0.20	-0.30	-0.39	-0.48	-0.45	-0.45	-0.48
Y5	0.01	0.01	-0.01	-0.026	-0.03	-0.04	-0.06	-0.08	-0.10	-0.10	-0.10	-0.11
LIMIT Y5	0.01	0.01	-0.01	-0.03	-0.03	-0.04	-0.06	-0.08	-0.10	-0.10	-0.10	-0.11
Y6	1.79	1.83	-5.04	-5.16	-0.16	-3.74	-5.36	-5.48	-4.95	0.32	-0.55	-2.34
LIMIT Y6	1.79	1.83	-5.00	-5.00	-0.16	-3.74	-5.00	-5.00	-4.95	0.32	-0.55	-2.34
OUTPUT	1.79	1.83	-5	-5	-0.16	-3.74	-5.00	-5.00	-4.95	0.32	-0.55	-2.34
FINAL O/P	2.78	2.84	-7.75	-7.75	-0.24	-5.80	-7.75	-7.75	-7.68	0.50	-0.85	-3.62
Limit Final O/p(to be used in PV input of FSH PID)	2.78	2.84	-7.75	-7.75	-0.24	-5.80	-7.75	-7.75	-7.68	0.50	-0.85	-3.62

Table 3

3.4. Effect of Feed Water Flow Rate

Feed water flow is another important parameter that affects the main steam temperature. If there is no Feed Water Flow meter for individual boiler we can use difference between Feed Water Pressure at the discharge of BFW and Drum Pressure. As feed water flow increases, main steam temperature is set to increases which can be compensated by adding a equivalent amount to the PV input of Primary Temperature Controller.

Effect of variation of steam temperature due to change in drum pressure can be compensated through following algorithm:

In A= (Feed Water Pressure at Discharge of BFW Pumps-Drum Pressure);

In B=Delayed(Delay of 30 Sec) input of (Feed Water Pressure at Discharge of BFW Pumps-Drum Pressure);

→ Calculation Block 4:

Y1=Lim(-10,(A-B)*0.135,10);

Y2=Lim(0,(Y2+(Y1-Y2)*0.005),Y1);

Y3=Lim(-10,(Y1+Y2),10);

OUT=Lim(-10,Y6*0.75,10);

The iteration value can be tabulated as follows:

TIME	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC	30 SEC
ITERATION NO	1ST	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Feed Water Pressure at Discharge of BFW Pumps-Drum Pressure	20	22	23	21.00	13.00	15.00	18.00	19.00	20.00	21
Delayed Input of Pressure Difference(Delay of 30 Sec)	12.00	20.00	22.00	23.00	21.00	13.00	15.00	18.00	19.00	20.00
Y1	1.08	0.27	0.14	-0.27	-1.08	0.27	0.41	0.14	0.14	0.14
LIMIT Y1	1.08	0.27	0.135	-0.27	-1.08	0.27	0.41	0.14	0.14	0.135
Y2	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
LIMIT Y2	0.01	0.01	0.01	-0.27	-1.08	0.00	0.00	0.00	0.01	0.01
Y3	1.09	0.28	0.14	-0.54	-2.16	0.27	0.41	0.14	0.14	0.14
LIMIT Y3	1.09	0.28	0.14	-0.54	-2.16	0.27	0.41	0.14	0.14	0.14
FINAL O/P OR INPUT TO TEMP CONTROLLER PV INPUT	0.42	0.11	0.05	-0.21	-0.83	0.10	0.16	0.05	0.05	0.05

Table 4

3.5. Effect of Desuperheater Inlet Temperature

→ Calculation Block5:

In A=Desuperheater Inlet Temp;

In B= Delayed input of Desuperheater Inlet;

Y1=Lim(-10,(A-B)*0.375,10);

Y2=Lim(-5,Y2+(Y1-Y2)*0.005,5)

OUT=LIM(-10,(Y1+Y2),10);

3.6. Effect of Relative Change between Set Point and Main Steam Temperature

→ Calculation Block 6:

In A: Main Steam Outelt Temperature;
In B: Temperature Setpoint given by operator;
Y1=Lim(0.3,Y1+If(abs(A-Y5)<5,-0.001,0.001),0.5);
Y2=Lim(A-Y5)*Y1=E;
F=Delayed input of E by 20 sec;
Y3=Lim(-25,(Y1*Y2*0.25+2*(E-F)),25);
Y5=Lim((Y5-0.05),B,(Y5+0.05));
Y6=Lim(0,Y6+(Y3-Y6)*0.001,2*Y3);
Out=Lim(-25,(2*Y3-Y6)*(Lim(0,(1-Y1),1)),25);
The iteration table for above algorithm is as follows:

TIME	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**	**20SEC**
ITERATION NO.	**1ST**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**	**11th**	**12th**	**13th**
Main Steam Outlet Temperature	500	500	497	497	499	500	505	480	482	488	490	495	494
Main Steam Temperature Setpoint	495	495	495	495	495	495	495	495	495	495	495	495	495
Y1	0.001	0.001	-0.001	-0.001	-0.001	0.001	0.001	0.001	0.001	0.001	0.001	-0.001	-0.001
Limit Y1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Y2	1.5	1.5	0.6	0.6	1.2	1.5	3	-4.5	-3.9	-2.1	-1.5	0	-0.3
E	1.5	1.5	0.6	0.6	1.2	1.5	3	-4.5	-3.9	-2.1	-1.5	0	-0.3
F(DELAYED INPUT OF E BY 20 SEC)		1.5	1.5	0.6	0.6	1.2	1.5	3	-4.5	-3.9	-2.1	-1.5	0
Y3	3.00	0.00	-1.80	0.00	1.20	0.60	3.00	-15.00	1.20	3.60	1.20	3.00	-0.60
LIMIT Y3	3.00	0.00	-1.80	0.00	1.20	0.60	3.00	-15.00	1.20	3.60	1.20	3.00	-0.60
Y5	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00
LIMIT Y5	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00	495.00
Y6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00
LIMIT Y6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
OUT	0.00	0.00	-2.52	0.00	1.68	0.84	4.20	-20.99	1.68	5.04	1.68	4.20	-0.84
LIMIT OUT	0.00	0.00	-2.52	0.00	1.68	0.84	4.20	-20.99	1.68	5.04	1.68	4.20	-0.84

Table 5

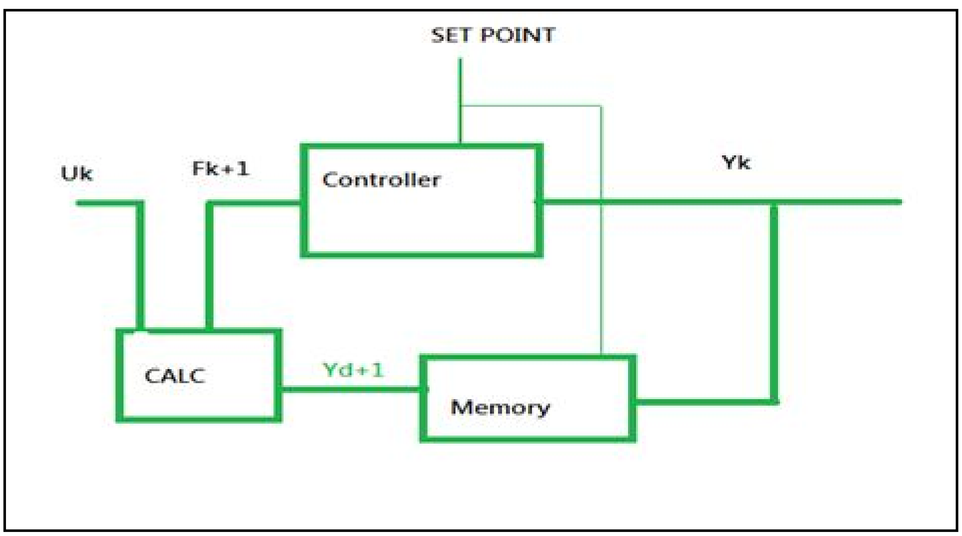

Figure 3

In this case instead of conventional feedback control, we have used Iterative Learning Control(ILC).

In this case current error value, Process Variable (PV) value and set point values are used in the next iteration to change the PV value and the process iterates until error becomes zero or minimum specified value which is in this case 5 degree centigrade. This is explained in Figure 3.

Finally, output of all 6 control blocks are added with the desuperheater outlet temperature and fed as PV input of Primary controller (Figure 2). The constatnts used in all the above control blocks are derived by calculated trial and error method, no mathematical formulation have been used.For application in a different Plant the values of the constants will change depending on the size and type of the boiler, but the basic algorithm remains the same. The best way to achieve the constant values is to track the real time trend in different disturbed condition.

During initial testing of the loops the Outputs of the control blocks should be limited to the lowest possible value to avoid any abnormal condition due to human error. The Control Valve also can be put in manual initially, the valve can be put in auto after all the checkings are complete.

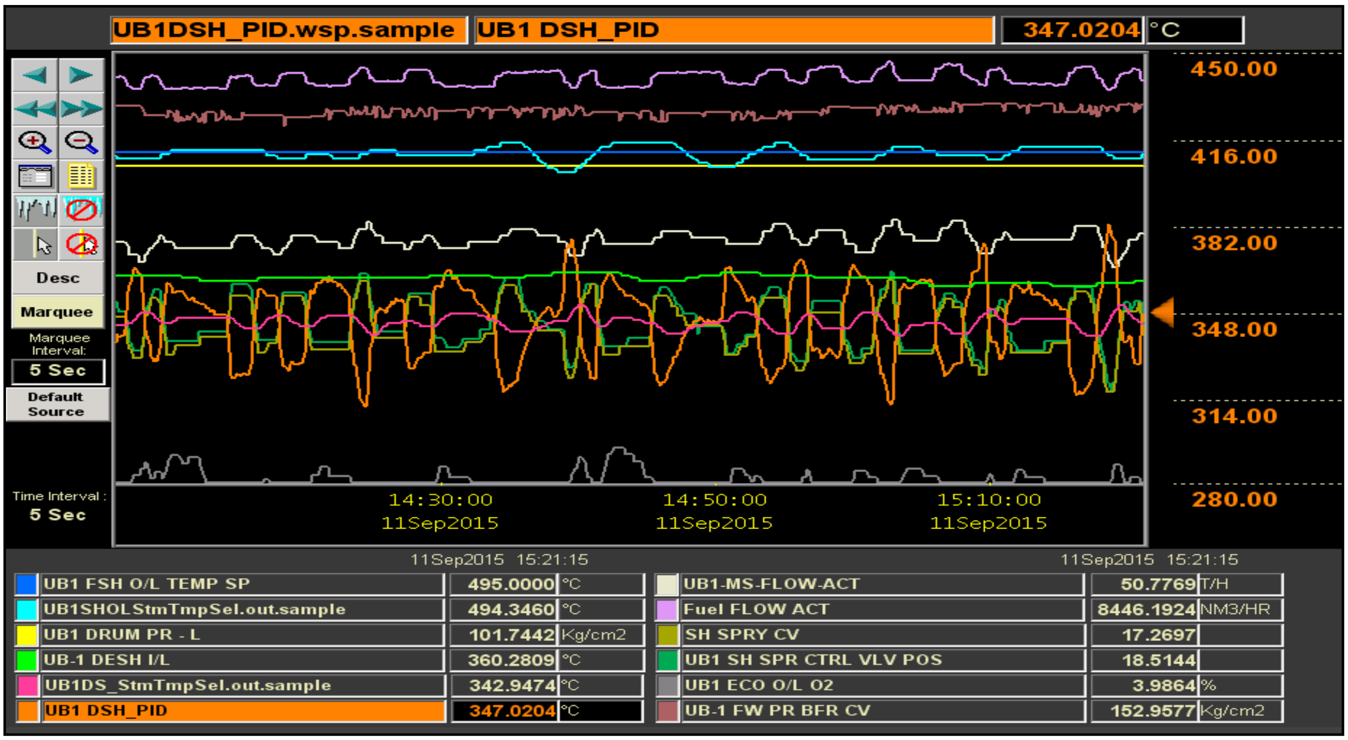

Figure 4

4. Summary

To summarize optimum main steam temperature control can be achieved by judicious usage of combination of Feedback, Cascade, Multiple Iterative Learning Feed Forward and Iterative Learning Control.

We have applied above control specification in 80TPH gas fired utility boiler and optimum main steam control is achieved even in case of major system upset. Real time trend is attached in Figure 4.

5. Advantages

i. Optimum control achieved. Savings of money.
ii. Minimum operator interference required,even saves the system from human error i.e. giving wrong set point.
iii. Not highly dependent on valve response.
iv. Accuracy of transmitters do not matters.
v. Smooth auto /manual transition as there is set point tracking.

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